# Quantum Information Division
# Fachverband Quanteninformation (QI)

Guido Burkard
Universität Konstanz
Fachbereich Physik
78457 Konstanz
Guido.Burkard@uni-konstanz.de

Otfried Gühne
Universität Siegen
Walter-Flex-Str. 3
57068 Siegen
otfried.guehne@uni-siegen.de

## Overview of Invited Talks and Sessions

(Lecture halls HS II, HS IV, HS VIII, and HS IX; Posters Tent)

### Invited Talks

| | | | | |
|---|---|---|---|---|
| QI 1.1 | Mon | 11:00–11:30 | HS IX | **Sound and Efficient Quantum System Quizzing** — •Mariami Gachechiladze, Jan Nöller, Martin Kliesch, Nikolai Miklin |
| QI 3.1 | Mon | 11:00–11:30 | HS II | **Conveyor-mode shuttling of electron spin qubits in Si/SiGe for scalable architectures** — Tom Struck, Mats Volmer, Max Beer, Ran Xue, Alex Willmes, Max Oberländer, Till Huckemann, Arnau Sala, Łukasz Cywiński, Hendrik Bluhm, •Lars R. Schreiber |
| QI 5.1 | Mon | 17:00–17:30 | HS IX | **Representation Theory for Quantum Algorithms and Protocols** — Dmitry Grinko, •Adam Burchardt, Maris Ozols |
| QI 6.1 | Mon | 17:00–17:30 | HS VIII | **Precision measurement with nanoscale resolution** — •Joerg Wrachtrup |
| QI 7.1 | Mon | 17:00–17:30 | HS II | **Trapped-ion quantum computers based on chip-integrated microwave control** — •Christian Ospelkaus |
| QI 8.1 | Mon | 17:00–17:30 | HS IV | **Quantum Informatics - From Quantum Gates to Quantum Software Engineering** — •Ina Schaefer |
| QI 11.1 | Tue | 11:00–11:30 | HS II | **Systematic High-Fidelity Operation and Transfer in Semiconductor Spin-Qubits** — •Maximilian Rimbach-Russ |
| QI 12.1 | Tue | 11:00–11:30 | HS IV | **Classical reasoning methods for quantum circuit analysis** — •Tim Coopmans, Lieuwe Vinkhuijzen, Arend-Jan Quist, Jingyi Mei, Alfons Laarman |
| QI 14.1 | Tue | 14:00–14:30 | HS IX | **Certification of high-dimensional and multipartite entanglement with imperfect measurements** — •Simon Morelli, Hayata Yamasaki, Marcus Huber, Armin Tavakoli |
| QI 19.1 | Wed | 14:30–15:00 | HS IX | **Wave-Function Expansion with Optically Levitated Nanoparticles** — •Martin Frimmer |
| QI 20.1 | Wed | 14:30–15:00 | HS VIII | **Generating entangled states in quantum networks** — •Nikolai Wyderka, Justus Neumann, Tulja Varun Kondra, Kiara Hansenne, Lisa T. Weinbrenner, Hermann Kampermann, Otfried Gühne, Dagmar Bruss |
| QI 21.1 | Wed | 14:30–15:00 | HS II | **Mesoscopic physics challenges (in) superconducting quantum devices** — •Ioan Pop |
| QI 26.1 | Thu | 11:00–11:30 | HS IX | **Device-independent randomness amplification** — •Ramona Wolf |
| QI 27.1 | Thu | 11:00–11:30 | HS VIII | **Fault-tolerant compiling of quantum algorithms** — •Dominik Hangleiter |
| QI 28.1 | Thu | 11:00–11:30 | HS II | **Quantum-Classical Hybrid Theories - Feedback Control and Environment Purification** — •Patrick P. Potts |
| QI 29.1 | Thu | 11:00–11:30 | HS IV | **Measurement-induced entanglement and complexity in shallow 2D quantum circuits** — •Max McGinley, Wen Wei Ho, Daniel Malz |

## Invited Talks of the joint Symposium SAMOP Dissertation Prize 2025 (SYAD)

See SYAD for the full program of the symposium.

| | | | | |
|---|---|---|---|---|
| SYAD 1.1 | Mon | 14:30–15:00 | HS 1+2 | **A simple method to separate single- from multi-particle dynamics in time-resolved spectroscopy** — •Julian Lüttig |
| SYAD 1.2 | Mon | 15:00–15:30 | HS 1+2 | **Time-resolving quantum dynamics in atoms and molecules with intense x-ray lasers and neural networks** — •Alexander Magunia |
| SYAD 1.3 | Mon | 15:30–16:00 | HS 1+2 | **How rotation shapes the decay of diatomic carbon anions** — •Viviane C. Schmidt |
| SYAD 1.4 | Mon | 16:00–16:30 | HS 1+2 | **Interstellar stardust from stellar explosions recorded in a deep-ocean ferromanganese crust within the last 10 million years** — •Dominik Koll |

## Invited Talks of the joint Symposium Quantum Science and more in Ghana and Germany (SYGG)

See SYGG for the full program of the symposium.

| | | | | |
|---|---|---|---|---|
| SYGG 1.1 | Tue | 11:00–11:05 | WP-HS | **Welcome Adress** — •Birgit Münch |
| SYGG 1.2 | Tue | 11:05–11:20 | WP-HS | **Quantum Education in Ghana** — •Dorcas Attuabea Addo |
| SYGG 1.3 | Tue | 11:20–11:45 | WP-HS | **Mathematical and Computational Physics Research In Ghana: To Cultivate a Knowledge-Based and Sustainable Development Economy** — •Henry Martin, Henry Elorm Quarshie, Mark Paal, Francis Kofi Ampong, Eric Kwabena Kyeh Abavare, Matteo Colangeli, Alessandra Continenza, Jaime Marian |
| SYGG 1.4 | Tue | 11:45–12:10 | WP-HS | **Forecasting the Economic Health of Ghana Using Quantum-Enhanced Long Short-Term Memory Model** — •Peter Nimbe, Henry Martin, Dorcas Attuabea Addo, Nicodemus Songose Awarayi |
| SYGG 1.5 | Tue | 12:10–12:40 | WP-HS | **Quantum Technology with Spins** — •Joerg Wrachtrup |
| SYGG 1.6 | Tue | 12:40–13:00 | WP-HS | **Renewable Energy Technologies for Rural Ghana: The Role of Appropriate Technology for Tailored solutions** — •Michael Kweku Edem Donkor |

## Invited Talks of the joint Symposium Foundations of Quantum Theory (SYQT)

See SYQT for the full program of the symposium.

| | | | | |
|---|---|---|---|---|
| SYQT 1.1 | Wed | 11:00–11:30 | HS 1+2 | **Against 'local causality'** — •Guido Bacciagaluppi |
| SYQT 1.2 | Wed | 11:30–12:00 | HS 1+2 | **Philosophy of Quantum Thermodynamics** — •Carina Prunkl |
| SYQT 1.3 | Wed | 12:00–12:30 | HS 1+2 | **Can quantum information be the underpinning of quantum physics?** — •Paolo Perinotti |
| SYQT 1.4 | Wed | 12:30–13:00 | HS 1+2 | **Spin-bounded correlations: rotation boxes within and beyond quantum theory** — Albert Aloy, •Thomas Galley, Caroline Jones, Stefan Ludescher, Markus Müller |

## Invited Talks of the joint Symposium Hidden Variables: Contributions of Women to Quantum Physics (SYWQ)

See SYWQ for the full program of the symposium.

| | | | | |
|---|---|---|---|---|
| SYWQ 1.1 | Thu | 11:00–11:30 | HS 1+2 | **Reshaping the History of Quantum Physics: Paths to Gender Equality** — •Andrea Reichenberger |
| SYWQ 1.2 | Thu | 11:30–12:00 | HS 1+2 | **Lucy Mensing: Forgotten Pioneer of Quantum Mechanics** — •Gernot Münster |
| SYWQ 1.3 | Thu | 12:00–12:30 | HS 1+2 | **Roller-coasting women scientific trajectories: New frontiers to accelerate (quantum) science** — •Marilù Chiofalo |
| SYWQ 1.4 | Thu | 12:30–13:00 | HS 1+2 | **Who decides scientific authority and how?** — •Anna Sanpera |

## Prize and Invited Talks of the joint Awards Symposium (SYAS)

See SYAS for the full program of the symposium.

| | | | | |
|---|---|---|---|---|
| SYAS 1.1 | Thu | 14:30–15:10 | HS 1+2 | **A journey in mathematical quantum physics** — •Reinhard F. Werner |
| SYAS 1.2 | Thu | 15:10–15:50 | HS 1+2 | **Precision Tests of the Standard Model at Low Energies Using Stored Exotic Ions in Penning Traps** — •Klaus Blaum |
| SYAS 1.3 | Thu | 15:50–16:30 | HS 1+2 | **Controlling light by atoms and atoms by light: from dark-state polaritons to many-body spin physics** — •Michael Fleischhauer |
| SYAS 1.4 | Thu | 16:30–16:35 | HS 1+2 | **Quantum history at your fingertips: Launch of the DPG's Quantum History Wall** — •Arne Schirrmacher |

## Sessions

| | | | | |
|---|---|---|---|---|
| QI 1.1–1.5 | Mon | 11:00–12:30 | HS IX | **Certification and Benchmarking of Quantum Systems** |
| QI 2.1–2.7 | Mon | 11:00–12:45 | HS VIII | **Quantum Machine Learning I** |
| QI 3.1–3.5 | Mon | 11:00–12:30 | HS II | **Semiconductor Spin Qubits I: Silicon** |
| QI 4.1–4.7 | Mon | 11:00–13:00 | AP-HS | **Quantum Networks, Repeaters, and QKD I (joint session Q/QI)** |
| QI 5.1–5.5 | Mon | 17:00–18:30 | HS IX | **Quantum Entanglement I** |
| QI 6.1–6.6 | Mon | 17:00–18:45 | HS VIII | **Quantum Metrology and Sensing (joint session QI/Q)** |
| QI 7.1–7.6 | Mon | 17:00–18:45 | HS II | **Atom and Ion Qubits (joint session QI/Q)** |
| QI 8.1–8.7 | Mon | 17:00–19:00 | HS IV | **Quantum Computing Theory I** |
| QI 9.1–9.6 | Tue | 11:00–12:30 | HS IX | **Quantum Entanglement II** |
| QI 10.1–10.7 | Tue | 11:00–12:45 | HS VIII | **Quantum Machine Learning II** |
| QI 11.1–11.6 | Tue | 11:00–12:45 | HS II | **Semiconductor Spin Qubits II: Si, Ge, and Color Centers** |
| QI 12.1–12.6 | Tue | 11:00–12:45 | HS IV | **Quantum Computing Theory II** |
| QI 13.1–13.8 | Tue | 11:00–13:00 | AP-HS | **Quantum Networks, Repeaters, and QKD II (joint session Q/QI)** |
| QI 14.1–14.5 | Tue | 14:00–15:30 | HS IX | **Quantum Entanglement III** |
| QI 15.1–15.6 | Tue | 14:00–15:30 | HS II | **Quantum Computing Implementations (joint session QI/Q)** |
| QI 16.1–16.6 | Tue | 14:00–15:30 | HS IV | **Quantum Computing Theory III** |
| QI 17.1–17.6 | Wed | 11:00–12:30 | HS V | **Quantum Sensing I (joint session Q/QI)** |
| QI 18.1–18.8 | Wed | 11:00–13:00 | AP-HS | **Quantum Networks, Repeaters, and QKD III (joint session Q/QI)** |
| QI 19.1–19.6 | Wed | 14:30–16:15 | HS IX | **Mechanical, Macroscopic, and Continuous-variable Quantum Systems (joint session QI/Q)** |
| QI 20.1–20.8 | Wed | 14:30–16:45 | HS VIII | **Quantum Networks (joint session QI/Q)** |
| QI 21.1–21.6 | Wed | 14:30–16:15 | HS II | **Superconducting Qubits** |
| QI 22.1–22.7 | Wed | 14:30–16:15 | HS IV | **Quantum Simulation** |
| QI 23.1–23.7 | Wed | 14:30–16:30 | HS Botanik | **Quantum Technologies (Color Centers and Ion Traps) I (joint session Q/QI)** |
| QI 24.1–24.6 | Wed | 14:30–16:15 | HS I | **Open Quantum Systems I (joint session Q/QI)** |
| QI 25 | Wed | 17:00–18:30 | HS 7 | **Members' Assembly** |
| QI 26.1–26.6 | Thu | 11:00–12:45 | HS IX | **Quantum Communication I: Theory** |
| QI 27.1–27.5 | Thu | 11:00–12:30 | HS VIII | **Quantum Error Correction** |
| QI 28.1–28.6 | Thu | 11:00–12:45 | HS II | **Decoherence and Open Quantum Systems (joint session QI/Q)** |
| QI 29.1–29.8 | Thu | 11:00–13:15 | HS IV | **Quantum Information: Concepts and Methods I** |
| QI 30.1–30.8 | Thu | 11:00–13:00 | AP-HS | **Quantum Computing and Simulation I (joint session Q/QI)** |
| QI 31.1–31.6 | Thu | 11:00–12:45 | HS I PI | **Quantum Sensing II (joint session Q/QI)** |
| QI 32.1–32.8 | Thu | 14:30–16:30 | HS IX | **Quantum Communication II: Implementations (joint session QI/Q)** |
| QI 33.1–33.8 | Thu | 14:30–16:30 | HS VIII | **Quantum Materials and Many-Body Systems** |
| QI 34.1–34.8 | Thu | 14:30–16:30 | HS II | **Quantum Control I** |
| QI 35.1–35.9 | Thu | 14:30–16:45 | HS IV | **Quantum Information: Concepts and Methods II** |
| QI 36.1–36.69 | Thu | 17:00–19:00 | Tent | **Poster – Quantum Information (joint session QI/Q)** |
| QI 37.1–37.45 | Thu | 17:00–19:00 | Tent | **Poster – Quantum Information Technologies (joint session Q/QI)** |
| QI 38.1–38.9 | Fri | 11:00–13:15 | HS IX | **Quantum Thermodynamics** |
| QI 39.1–39.8 | Fri | 11:00–13:00 | HS VIII | **Quantum Foundations** |

| | | | | |
|---|---|---|---|---|
| QI 40.1–40.8 | Fri | 11:00–13:00 | HS II | **Quantum Control II (joint session QI/Q)** |
| QI 41.1–41.7 | Fri | 11:00–13:00 | AP-HS | **Quantum Computing and Simulation II (joint session Q/QI)** |
| QI 42.1–42.7 | Fri | 11:00–13:00 | HS Botanik | **Quantum Technologies (Color Centers and Ion Traps) II (joint session Q/QI)** |
| QI 43.1–43.8 | Fri | 11:00–13:00 | HS I | **Open Quantum Systems II (joint session Q/QI)** |
| QI 44.1–44.7 | Fri | 14:30–16:15 | AP-HS | **Quantum Technologies (Detectors and Photon Sources) (joint session Q/QI)** |
| QI 45.1–45.8 | Fri | 14:30–16:30 | HS I | **Quantum Technologies (Solid State Systems) (joint session Q/QI)** |

## Members' Assembly of the Quantum Information Division

Wednesday 17:00–18:30 HS 7
An invitation including the agenda will be sent by email.

# QI 1: Certification and Benchmarking of Quantum Systems

Time: Monday 11:00–12:30 Location: HS IX

**Invited Talk** QI 1.1 Mon 11:00 HS IX

**Sound and Efficient Quantum System Quizzing** — •Mariami Gachechiladze[1], Jan Nöller[1], Martin Kliesch[2], and Nikolai Miklin[2] — [1]TU Darmstadt, Darmstadt, Germany — [2]TUHH, Hamburg, Germany

The rapid advancement of quantum hardware necessitates the development of reliable methods to certify their correct functioning. Existing certification techniques often fall short: they are either prohibitively expensive and rely on flawless state preparation and measurement (SPAM), or they fail to provide robust guarantees. While current SPAM-robust methods are complete, they lack soundness, meaning they do not ensure the correct implementation of quantum devices. In our recent work, we introduce quantum system quizzing, a simple yet sound certification protocol that enables the certification of entire quantum models in a black-box scenario under the dimension assumption. The protocol identifies deterministic input-output correlations of the ideal target model, which are tested during each round. This black-box approach inherently eliminates SPAM errors. For single-qubit models, we derive rigorous sampling complexity guarantees. Most notably, we establish an inverse linear relationship between average gate infidelities and the number of successful protocol rounds, making the method highly practical for contemporary experimental setups. For multi-qubit quantum computers, we provide sound certification proof in the infinite statistics regime and discuss the methods to derive sample complexity results in the finite statistics regime.

QI 1.2 Mon 11:30 HS IX

**Self-testing of memory-bounded quantum computers** — •Jan Nöller[1], Nikolai Miklin[2], Martin Kliesch[2], and Mariami Gachechiladze[1] — [1]TU Darmstadt — [2]TU Hamburg

The rapid advancement of quantum computers makes it particularly important to develop methods for certifying their correct functioning. In a single-device setup, we propose a simple protocol called quantum system quizzing. This protocol achieves self-testing of an entire quantum model given by state preparation, gates, and measurement in a black-box scenario under the dimension assumption only. Due to the self-testing approach, this certification method is inherently free of state preparation and measurement errors.

The protocol is fundamentally based on testing deterministic inputouput correlations which have been previously identified to be chracteristic for the targeted system. These input-output relations are tested on a quantum computer in each protocol round.

A particular challenge here is to recover the tensor-product structure of subsystems purely from the input-output relations, since space-like separation cannot be imposed in such a black-box scenario. Our work is the first to solve this issue without relying on computational assumptions.

For the simplest case of a single-qubit model, we additionally derive rigorous sampling complexity guarantees. Most interestingly, we prove an inverse linear relation between the average gate infidelities and the number of successful rounds in the protocol, rendering our method highly relevant for current experimental setups.

QI 1.3 Mon 11:45 HS IX

**Scalable correlated readout error mitigation without randomized measurements** — •Adrian Skasberg Aasen[1,2], Andras Di Giovanni[3], Hannes Rotzinger[3], Alexey Ustinov[3], and Martin Gärttner[2] — [1]Kirchhoff-Institut für Physik, Universität Heidelberg, Heidelberg, Germany — [2]Institut für Festkörpertheorie und -optik, Friedrich-Schiller-Universität Jena, Jena, Germany — [3]Physikalisches Institut, Karlsruher Institut für Technologie, Karlsruhe, Germany

Recently, quantum error mitigation techniques have increasingly focused on addressing readout errors. Key attributes sought in these protocols include scalability, practicality, and assumption-free noise models. Among the favored approaches are those utilizing randomized measurements. Despite their favorable scaling in sample complexity, randomized measruemnets are complex to implement. We present an alternative method which avoids randomized measurements, is scalable to large quantum systems, uses only single-qubit Pauli measurements, and captures a very broad class of correlated noise models. It builds on a robust readout error mitigated state tomograpy [1] and makes it scalable by using an efficient characterization of correlated POVMs. The method reconstructs overlapping readout error mitigated reduced density matrices, which gives access to arbitrary low- to medium-order correlators. We demonstrate that they are sample efficient with noisy POVMs extracted from superconducting qubit experiments.

[1] Aasen, A.S. et al. Readout error mitigated quantum state tomography tested on superconducting qubits. Commun Phys 7, 301.

QI 1.4 Mon 12:00 HS IX

**Shadow-based characterization of superconducting quantum processors** — •Pedro Joaquin Weiler Perez, Florentin Reiter, Thomas Wellens, and Martin Koppenhöfer — Fraunhofer Institut für Angewandte Festkörperphysik (IAF), Freiburg im Breisgau, Deutschland

Characterization techniques for quantum processors have become an important tool to improve quantum gate operations, qubit initialization, and read-out processes. Moreover, efficient characterization techniques guide the development of efficient quantum-error-correction and quantum-error-mitigation strategies, and they allow one to build error models for a more realistic simulation of quantum algorithms. For these different purposes, a variety of benchmarking methods has been developed (e.g., randomized benchmarking tools as well as quantum state, process, and gate-set tomography). Typically, characterization techniques that provide a larger level of detail come at the cost of a higher computational complexity. Recently, it has been pointed out that one can extract many relevant features of a quantum system without having to perform a full tomography. So-called classical shadow tomography emerged as a promising and flexible new characterization technique with provably efficient sampling. In this talk, we discuss our approach to shadow-based characterization of quantum states and quantum processes on superconducting quantum processors

QI 1.5 Mon 12:15 HS IX

**Detecting high-dimensional time-bin entanglement in a fiber-loop architecture** — •Niklas Euler and Martin Gärttner — Institut für Festkörpertheorie und Optik, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany

Many quantum-communication protocols require the distribution of entanglement between the different participating parties. One example of such a protocol is quantum key distribution (QKD), an application which has matured to the brink of commercial use in recent years. However, difficulties remain, especially with noise resilience and channel capacity in long-distance communication. One way to overcome these problems is to use high-dimensional entanglement, which has been shown to be more robust to noise and facilitates higher secret-key rates. It is therefore important to have access to certifiable high-dimensional entanglement sources to confidently implement advanced QKD protocols. Here, we investigate a fiber-loop setup that allows the scalable creation of time-bin entanglement and its certification on the same device. Our certification method builds on previous proposals for the certification of angular-momentum entanglement in photon pairs. In particular, measurements in only two experimentally accessible bases are sufficient to obtain a lower bound on the entanglement dimension for both two- and multiphoton quantum states. Numerical simulations show that the method is robust against typical experimental noise effects and works well even with limited measurement statistics, thus establishing time-bin encoded photons as a viable candidate for high-dimensional QKD.

# QI 2: Quantum Machine Learning I

Time: Monday 11:00–12:45 Location: HS VIII

QI 2.1 Mon 11:00 HS VIII

**Self-Adaptive Physics-Informed Quantum Machine Learning for Solving Differential Equations** — •Abhishek Setty[1,2,3], Rasul Abdusalamov[1], and Felix Motzoi[2,3] — [1]Department of Continuum Mechanics, RWTH Aachen University, Germany — [2]Forschungszentrum Jülich, Institute of Quantum Control (PGI-8), D-52425 Jülich, Germany — [3]Institute for Theoretical Physics, University of Cologne, D-50937 Cologne, Germany

Chebyshev polynomials have shown significant promise as an efficient tool for both classical and quantum neural networks to solve linear and nonlinear differential equations. In this work, we adapt and generalize this framework in a quantum machine learning setting for a variety of problems, including the 2D Poisson's equation, second-order linear differential equation, system of differential equations, nonlinear Duffing and Riccati equation. In particular, we propose in the quantum setting a modified Self-Adaptive Physics-Informed Neural Network (SAPINN) approach, where self-adaptive weights are applied to problems with multi-objective loss functions. We further explore capturing correlations in our loss function using a quantum-correlated measurement, resulting in improved accuracy for initial value problems. We analyse also the use of entangling layers and their impact on the solution accuracy for second-order differential equations. The results indicate a promising approach to the near-term evaluation of differential equations on quantum devices.

QI 2.2 Mon 11:15 HS VIII

**Automation of Quantum Machine Learning** — •Marco Roth — Fraunhofer IPA, Stuttgart

Applying quantum machine learning (QML) presents unique challenges that often demand expertise in fields such as machine learning and quantum computing. To address these challenges and facilitate broader applications, automation offers a promising solution. In this talk, we introduce two approaches that leverage this concept. The first is AutoQML, a framework designed to create end-to-end QML pipelines for a range of supervised learning scenarios, including time series classification and tabular regression and classification tasks. Additionally, we propose a novel method that employs reinforcement learning techniques to develop problem-specific encoding circuits, enhancing the performance of QML models in a sample-efficient way.

QI 2.3 Mon 11:30 HS VIII

**Expressive power of reservoir-based quantum machine learning** — •Nils-Erik Schütte[1,2], Niclas Götting[2], Hauke Müntinga[1], Meike List[1,3], and Christopher Gies[2] — [1]German Aerospace Center, Institute for Satellite Geodesy and Inertial Sensing, Bremen, Germany — [2]Institut für Physik, Fakultät V, Carl von Ossietzky Universität Oldenburg — [3]University of Bremen

Quantum machine learning merges quantum computing and artificial intelligence, two transformative technologies for data processing. While gate-based quantum computing employs precise unitary operations on qubits, noisy intermediate-scale quantum (NISQ) devices face limitations in implementing high-depth circuits, yet remain promising for machine learning applications. In contrast, quantum reservoir computing (QRC) leverages physical systems as quantum neural networks, relying on Hamiltonian dynamics rather than controlled gate operations, with learning performed at the output layer. Despite their differing foundations, these approaches share connections and can be formally mapped onto each other.

We discuss this analogy by realizing a transverse-field Ising model on a gate-based quantum computing architecture. We quantify expressivities of either approach and explore the potential of gate-based quantum computers over QRC that rely on quantum circuit design and the possibility to optimize the circuits for specific tasks. Furthermore, we discuss the balance of the influence of the input encoding and the complexity of the reservoir on the output functions that a QRC approach has access to.

QI 2.4 Mon 11:45 HS VIII

**Generating reservoir state descriptions with random matrices** — •Tobias Fellner[1], Samuel Tovey[1], Christian Holm[1], and Michael Spannowsky[2] — [1]Institute for Computational Physics, University of Stuttgart — [2]Institute of Particle Physics Phenomenology, University of Durham

We demonstrate a novel approach to reservoir computation measurements using random matrices. We do so to motivate how atomic-scale devices could be used for real-world computational applications. Our approach uses random matrices to construct reservoir measurements, introducing a simple, scalable means of generating state descriptions. In our studies, two reservoirs, a five-atom Heisenberg spin chain and a five-qubit quantum circuit, perform time series prediction and data interpolation. The performance of the measurement technique and current limitations are discussed in detail, along with an exploration of the diversity of measurements provided by the random matrices. In addition, we explore the role of reservoir parameters such as coupling strength and measurement dimension, providing insight into how these learning machines could be automatically tuned for different problems. This research highlights the use of random matrices to measure simple quantum reservoirs for natural learning devices, and outlines a path forward for improving their performance and experimental realization.

QI 2.5 Mon 12:00 HS VIII

**Quantum reservoir computing maps data onto the Krylov space** — •Saud Cindrak, Lina Jaurigue, and Kathy Lüdge — Technische Universität Ilmenau, Ilmenau, Deutschland

The field of Krylov complexity has deepened our understanding of quantum systems, from field theories to chaos, and shed light on quantum evolution. However, classical computation of these complexities becomes infeasible for larger systems. We address this by defining a measurable basis to construct the Krylov space and introducing **Krylov expressivity** to capture the phase space dimension [1]. Additionally, we define **Krylov observability**, which quantifies how much of the phase space is observed. This work examines fidelity, spread complexity, Krylov expressivity, and Krylov observability as expressivity measures in quantum reservoir computing. In this approach, data is encoded into the system's state, evolved through the quantum system, and measured observables construct a readout vector, which is trained to predict chaotic attractors and compute the information processing capacity. Our findings show that fidelity and spread complexity provide limited insights, while **Krylov expressivity** effectively captures task performance [2]. Notably, **Krylov observability** and the information processing capacity exhibit almost identical behavior, demonstrating that a quantum reservoir maps data onto the Krylov space.

[1] S. Čindrak, L. Jaurigue, K.Lüdge, J. High Energ. Phys 2024, 83
[2] S. Čindrak, L. Jaurigue, K.Lüdge, arxiv.org/abs/2409.12079

QI 2.6 Mon 12:15 HS VIII

**Investigating the Quantum Circuit Born Machine** — •Michael Krebsbach[1], Florentin Reiter[1], Abedi Ali[2], Hagen-Henrik Kowalski[2], and Thomas Wellens[1] — [1]Fraunhofer IAF, Tullastraße 72, 79108 Freiburg — [2]Bundesdruckerei GmbH, Kommandantenstraße 18, 10969 Berlin

The Quantum Circuit Born Machine (QCBM) is a generative quantum machine learning algorithm that can be used to synthetically extend a dataset that is expensive or otherwise difficult to enlarge. This is achieved by training a parameterized quantum circuit to encode the data distribution $p(x)$ in its output state $|\psi\rangle \approx \frac{1}{\sqrt{N}} \sum_x p(x)|x\rangle$. Measuring $|\psi\rangle$ in the computational basis allows to efficiently sample new data points from the distribution.

In this talk, we present our investigation of the trainability and generalization properties of QCBMs. We discuss how the type of data can affect the trainability, and show how it can be improved using several simple techniques. Lastly, we outline how QCBMs could be extended to solve a wider range of tasks including conditional generation and classification.

QI 2.7 Mon 12:30 HS VIII

**Optimal recoil-free state preparation in an optical atom tweezer** — •Lia Kley[1,2], Nicolas Heimann[1,2,3], Aslam Parvej[1,2], Lukas Broers[1,2], and Ludwig Mathey[1,2,3] — [1]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany — [2]Institut für Quantenphysik, Universität Hamburg, 22761 Hamburg, Germany — [3]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg, Germany

Quantum computing in atom tweezers requires high-fidelity implementations of quantum operations. Here, we demonstrate the optimal implementation of the transition $|0\rangle \rightarrow |1\rangle$ of two levels, serving as a qubit, of an atom in a tweezer potential, driven by a single-photon Rabi pulse. The Rabi pulse generates a photon recoil of the atom, due to the Lamb-Dicke coupling between the internal and motional degree of freedom, driving the system out of the logical subspace. This detrimental effect is strongly suppressed in the protocols that we propose. Using pulse engineering, we generate optimal protocols composed of a Rabi protocol and a force protocol, corresponding to dynamically displacing the tweezer. We generate these for a large parameter space, from small to large values of the Rabi frequency, and a range of pulse lengths. We identify three main regimes for the optimal protocols, and discuss their properties. In all of these regimes, we demonstrate infidelity well below the current technological standard, thus mitigating a universal challenge in atom tweezers and other quantum technology platforms.

## QI 3: Semiconductor Spin Qubits I: Silicon

Time: Monday 11:00–12:30 Location: HS II

**Invited Talk** QI 3.1 Mon 11:00 HS II

**Conveyor-mode shuttling of electron spin qubits in Si/SiGe for scalable architectures** — Tom Struck[1], Mats Volmer[1], Max Beer[1], Ran Xue[1], Alex Willmes[1], Max Oberländer[1], Till Huckemann[1], Arnau Sala[1], Łukasz Cywiński[2], Hendrik Bluhm[1,3], and •Lars R. Schreiber[1,3] — [1]JARA-FIT Institute for Quantum Information, Forschungszentrum Jülich GmbH and RWTH Aachen University, Germany — [2]Institute of Physics, Polish Academy of Sciences, Warsaw, Poland — [3]ARQUE Systems GmbH, Germany

Long-range coherent qubit coupling is a missing functional block for a scalable architecture of a spin-qubit based quantum computer. In a conveyor-mode shuttle, the spin-qubit is adiabatically transported while confined to a propagating sinusoidal potential in a gate-defined quantum channel [1]. Its key feature is the all-electrical operation by only few easily tunable input terminals. I present progress on conveyor-mode single electron shuttling in Si/SiGe. In a 10 micron long shuttle device, we experimentally demonstrate a shuttle fidelity of 99.7 % across the full device and back and a shuttle-based charge initialization of 34 quantum dots [2]. We observe spin coherent shuttling by separation and rejoining of a spin EPR pair [3] and map electrostatic disorder and the valley splitting [4]. Recent progress on silicon foundry fabrication and in shuttling through T-junctions could enable two-dimensional sparse qubit-architecture hosting millions of spin-qubits.

[1] Langrock ea. PRX Quantum 4, 020305 (2023). [2] Xue ea. Nat. Commun. 15, 2296 (2024). [3] Struck ea. Nat. Commun. 15, 1325 (2024). [4] Volmer ea. npj Quantum Inf. 10, 61 (2024).

QI 3.2 Mon 11:30 HS II

**Long distance spin shuttling enabled by few-parameter velocity optimization** — •Alessandro David[1], Akshay Menon Pazhedath[1,2], Lars R. Schreiber[3,4], Tommaso Calarco[1,2,5], Hendrik Bluhm[3,4], and Felix Motzoi[1,2] — [1]PGI-8, Forschungszentrum Jülich, Germany — [2]Theoretical Physics, University of Cologne, Germany — [3]JARA-FIT Forschungszentrum Jülich and RWTH Aachen, Germany — [4]ARQUE Systems GmbH, Germany — [5]Università di Bologna, Italy

Spin qubit shuttling via moving conveyor-mode quantum dots in Si/SiGe offers a promising route to scalable miniaturized quantum computing. Recent modeling of dephasing via valley degree of freedom and well disorder dictate a slow shutting speed which seems to limit errors to above correction thresholds if not mitigated. We increase the precision of this prediction, showing that typical errors for 10 $\mu$m shuttling at constant speed results in O(1) error, using fast, automatically differentiable numerics and including improved disorder modeling and potential noise ranges. However, remarkably, we show that these errors can be brought to well below fault-tolerant thresholds using trajectory shaping with very simple parametrization with as few as 4 Fourier components, well within the means for experimental in-situ realization, and without the need for targetting or knowing the location of valley near degeneracies.

QI 3.3 Mon 11:45 HS II

**Single-qubit gates with enhanced and intrinsic spin-orbit interaction via electron shuttling** — •Akshay Menon Pazhedath[1,2], Alessandro David[1], Tommaso Calarco[1,2,3], and Felix Motzoi[1,2] — [1]Peter Grünberg Institute-Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, Zülpicher Straße 77, 50937 Cologne, Germany — [3]Dipartimento di Fisica e Astronomia, Università di Bologna, 40127 Bologna, Italy

Electric Dipole Spin Resonance (EDSR) is a technique mediated by the spin-orbit interaction to obtain high-fidelity single-qubit gates with semiconductor spins. To overcome the weak intrinsic spin-orbit coupling of silicon-based devices, a synthetic spin-orbit field is usually introduced by a carefully designed micro-magnet. However, micromagnets also increase the coupling of the spin with voltage noise and their placement is challenging for industrial fabrication processes. In this work we look at the larger spatial mobility of the recently emerging spin-shuttling architectures as an opportunity to perform EDSR without the help of a micro-magnet. We simulate the use of large amplitude oscillations to increase the resonance strength for various spin-orbit settings of the silicon heterostructure. We also explore the effect that the valley degree of freedom has on gate times and fidelities. Furthermore, we investigate the feasibility of performing fast high-fidelity single-qubit gates by employing simple optimal control techniques.

QI 3.4 Mon 12:00 HS II

**Landau Zener Stückelberg Majorana Interferometry for valley states in conveyor-mode spin-shuttler** — •Priyanka Yashwantrao[1,2], Alessandro David[1], Tommaso Calarco[1,3,4], and Felix Motzoi[1,3] — [1]PGI-8, FZJ, Jülich, Germany — [2]Universität Bonn, Bonn, Germany — [3]THP, Universität Köln, Köln, Germany — [4]University of Bologna, Bologna, Italy

Spin-shuttling devices coherently transport the spin state of a solid-state charge carrier for tens of micrometers, enabling the scalability of semiconductor quantum processors as in the proposed SpinBus architecture [1]. In Si/SiGe heterostructure the transport fidelity is deteriorated by the presence of valley [2] which depends on the atomic arrangement. The information about spacial distribution of valley splitting and eigenstate orientation would help to perform better transport experiments. Although it is currently possible to measure the valley splitting [3], this information is not complete as valley models [4] predict the orientation of the eigenstates to be a sequence of non-linear avoided crossings. In this work, we simulate numerically the technique of 'LZSM Interferometry' [5] to predict the valley behavior along a spin-shuttler. The excited valley population is studied as a function of position, amplitude and frequency. We elaborate on techniques to characterize and extract information about the valley Hamiltonian.

[1] Künne et al., Nat Commun 15, 4977 (2024) [2] Zwanenburg et al., Rev. Mod. Phys. 85, 961 (2013) [3] Volmer et al., npj Quantum Inf 10, 61 (2024) [4] Wuetz et al., Nat Commun 13, 7730 (2022) [5] Shevchenko, et al., Phys. Rept. 492, 1 (2010)

QI 3.5 Mon 12:15 HS II

**Superadiabatic Landau-Zener model and the valley transitions during electron shuttling in Si** — •Jonas de Lima and Guido Burkard — Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

The transition dynamics of two-state systems with time-dependent energy levels is one of the basic models in quantum physics and has been used to describe various physical systems. We propose here a generalization of the Landau-Zener (LZ) problem characterized by distinct paths of the instantaneous eigenstates as the system evolves in time, while keeping the instantaneous eigenenergies exactly as in the standard LZ model [1]. We show that these paths play an essential role in the transition probability P between the two states, and can lead to a substantial reduction of P. We find that it is even possible to achieve P=0 in an instructive extreme case, as well as large P even in the absence of any anticrossing point. The superadiabatic LZ model can describe valley transition dynamics during charge and spin shuttling in semiconductor quantum dots and leads to strategies to enhance the valley shuttling fidelity that constitute a drastic improvement compared with previous strategies.

[1] J. R. F. Lima and G. Burkard, arXiv:2408.03173

## QI 4: Quantum Networks, Repeaters, and QKD I (joint session Q/QI)

Time: Monday 11:00–13:00 Location: AP-HS

**Invited Talk** QI 4.1 Mon 11:00 AP-HS

**An array of neutral atoms coupled to an optical cavity: A versatile quantum network node** — Raphael Benz, Sebastián Alejandro Morales Ramirez, Micha Kappel, Vincent Beguin, Krishna Relekar, and •Stephan Welte — 5. Physikalisches Institut, Center for Integrated Quantum Science and Technology and CZS Center QPhoton, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

I will present the plans of a recently established research group in Stuttgart focused on developing multi-qubit quantum network nodes. Our approach leverages an array of tweezer-trapped atomic qubits positioned at the center of a high-finesse optical cavity. All atoms in the array are positioned to ensure strong coupling to the cavity, thus establishing a connection to a photonic quantum channel. I will discuss the prospects of this system as a versatile quantum network node for both quantum computation and communication. Employing the system, a series of experiments is envisioned. I will outline these experiments, including photon-mediated quantum information processing between the intra-cavity atoms, the generation of photonic cluster states, and the generation of optical Gottesman-Kitaev-Preskill qubits. Finally, I will outline the prospects of connecting several atom-cavity systems in a quantum internet architecture.

QI 4.2 Mon 11:30 AP-HS

**Quantum network nodes based on neutral atoms in an optical cavity** — •Sebastián Alejandro Morales Ramírez, Raphael Benz, Micha Kappel, Vincent Beguin, Krishna Relekar, and Stephan Welte — 5. Physikalisches Institut, Center for Integrated Quantum Science and Technology and CZS Center QPhoton, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany.

The practical implementation of a quantum network is an outstanding challenge that is pursued in several different hardware platforms. Single neutral atoms trapped at the centre of an optical cavity are a promising platform, where many of the required capabilities to build a quantum network were demonstrated. The ability to position and individually control an array of atoms with optical tweezers is a key ingredient for the implementation of multi-qubit quantum network nodes. We will outline the plans of our research group to realize such a setup. Employing the system, a series of experiments is envisioned. We will outline these experiments comprising photon-mediated quantum information processing between the intra-cavity atoms, the generation of photonic cluster states, and the generation of optical Gottesman-Kitaev-Preskill qubits.

QI 4.3 Mon 11:45 AP-HS

**Heralded Generation of Atom-Photon Entanglement** — •Gianvito Chiarella, Tobias Frank, Pau Farrera, and Gerhard Rempe — Max Planck Institute for Quantum Optics, Hans-Kopfermann-Straße 1, 85748 Garching bei München

Reducing inefficiencies and infidelity errors in quantum information processes is crucial for the successful implementation of advanced quantum communication and computation protocols. In this work, we introduce a novel method to mitigate such errors during the generation of atom-photon entanglement. The approach utilizes cascaded two-photon emission from a single atom coupled to two crossed optical cavities. The polarization state of one photon is entangled with the spin degree of freedom of the atom, while the emission of a second photon serves as a herald, signaling the successful entanglement generation. This heralding process effectively mitigates inefficiencies and infidelities in the entanglement, and we highlight the potential of our source for quantum communication applications over long distances.

QI 4.4 Mon 12:00 AP-HS

**Quantum repeater segment with trapped $^{40}Ca^{+}$ ions** — •Max Bergerhoff, Pascal Baumgart, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken, Germany

The quantum repeater (QR) segment, as part of a QR link [1], is a fundamental building block for the realization of large-distance quantum networks. By dividing a transmission link into segments and cells it is possible to overcome the exponential loss of direct transmission. Experiments that create atom-atom entanglement with single atoms [2] or single ions in cavities [3] have demonstrated the potential of the atom/ion platform for a QR segment.

We report the implementation of a QR segment with free-space coupled photons from two $^{40}Ca^{+}$ ions in the same Paul trap as memories. Atom-photon entanglement is produced [4] by controlled emission of single photons from the ions via excitation with nanosecond laser pulses and separate single-mode fiber coupling. Atom-atom entanglement is then generated by a photonic Bell-state measurement. A full QR link will combine the QR segment with the already demonstrated QR cell [5]; this will require a new ion trap setup with integrated sub-mm cavity, currently under construction.

[1] P. van Loock et al., Adv. Quantum Technol., 3: 1900141 (2020)
[2] T. van Leent et. al., Nature 607, 69-73 (2022)
[3] V. Krutyanskiy et al., Phys. Rev. Lett. 130, 050803 (2023)
[4] M. Bock et al., Nat. Commun. 9, 1998 (2018)
[5] M. Bergerhoff et al., Phys. Rev. A 110, 032603 (2024)

QI 4.5 Mon 12:15 AP-HS

**Hong-Ou-Mandel interference of photons generated with nanosecond laser pulses from two co-trapped $^{40}Ca^{+}$ ions** — •Pascal Baumgart, Max Bergerhoff, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken

Entangling remote quantum memories is an essential step in the realisation of a quantum repeater segment [1]. It requires the ability to create indistinguishable single photons capable of Hong-Ou-Mandel interference on a beam splitter [2]. When generating single photons by exciting a Raman transition in a single atom, back decays and re-excitations on the driven transition lead to an uncertainty in the photon emission time, degrading their temporal indistinguishability [3]. A common approach that limits the number of back decays is excitation via short laser pulses, in the order of the excited-state lifetime. We present a setup to generate few-nanosecond 393-nm laser pulses to excite the $S_{1/2} \rightarrow P_{3/2} \rightarrow D_{5/2}$ Raman transition in single trapped $^{40}Ca^{+}$ ions and create single 854-nm photons. Using two ions in the same trap, we demonstrate Hong-Ou-Mandel interference of the Raman photons. We investigate the dependence of the interference visibility on the pulse length and amplitude, both experimentally and theoretically.

[1] P. van Loock et al., Adv. Quantum Technol., 3: 1900141 (2020)
[2] D. L. Moehring et al., Nature 449, 68-71 (2007)
[3] P. Müller et al., Phys. Rev. A 96, 023861 (2017)

QI 4.6 Mon 12:30 AP-HS

**Cavity-enhanced Diamond Color Centers as Quantum Network Nodes** — •Yanik Herrmann[1], Julius Fischer[1], Stijn Scheijen[1], Cornelis F. J. Wolfs[1], Julia M. Brevoord[1], Colin Sauerzapf[1], Leonardo G. C. Wienhoven[1], Laurens J. Feije[1], Matteo Pasini[1], Martin Eschen[1,2], Maximilian Ruf[1], Matthew J. Weaver[1], and Ronald Hanson[1] — [1]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands — [2]Netherlands Organisation for Applied Scientific Research (TNO), P.O. Box 155, 2600 AD Delft, The Netherlands

In the realization of quantum networks, efficient interfaces between stationary qubits and optical photons are a key requirement. Diamond color centers are on the forefront of solid state qubits due to their long spin coherence and spin register capabilities in combination with spin-state selective optical transitions. To boost the efficiency of the spin-photon interface, open microcavities can be utilized to Purcell-enhance optical transitions of the color centers. We realized a fiber-based microcavity setup at low-temperature with a high passive stability and microwave integration. This setup is used to Purcell-enhance single Tin-Vacancy centers, demonstrating quantum non-linear effects in the coherent coupling regime. Furthermore, we will present our latest results on implementing a cavity-enhanced quantum network node based on Nitrogen-Vacancy centers.

QI 4.7 Mon 12:45 AP-HS

**Towards a quantum repeater with trapped Yb+ ions in an optical cavity** — •Santhosh Surendra and Michael Köhl — Physikalisches Institut, Universität Bonn, Bonn, Germany

In a quantum network where entangled photons are used as travelling qubits, a critical challenge is in overcoming the absorption loss of optical fibers. One promising approach is to use *quantum repeaters* to 'purify' the state of photons after a certain optical path length by utilizing matter qubits. Such a node is necessary to scale the size of a distributed quantum computer, and quantum communication networks.

We have designed, and are constructing such a repeater node where a sub-millimeter optical cavity can be integrated into a linear Paul trap. Utilization of Purcell effect will allow us efficient extraction, and injection of entangled photons into the fiber-optic network. Furthermore, our system offers independent access to all vibrational modes of ions, enabling us to work directly with the ionic memory qubits. We will share our recent experimental progress, and the challenges we are addressing.

## QI 5: Quantum Entanglement I

Time: Monday 17:00–18:30 Location: HS IX

**Invited Talk** QI 5.1 Mon 17:00 HS IX

**Representation Theory for Quantum Algorithms and Protocols** — Dmitry Grinko, •Adam Burchardt, and Maris Ozols — QuSoft, University of Amsterdam, Centrum Wiskunde & Informatica, Amsterdam, The Netherlands

In this talk, we highlight the relevance of representation theory in various quantum information tasks. Our focus is on the (mixed) Schur transform and its applications. In particular, we present an efficient quantum circuit for implementing the mixed Schur transform. We then demonstrate how this transform can be applied to Port-Based Teleportation (PBT). Specifically, we provide efficient quantum circuits for optimal measurements in various PBT schemes, which use the mixed Schur transform as a subroutine. This presentation is based on two recent papers: arXiv:2310.02252 and arXiv:2312.03188.

QI 5.2 Mon 17:30 HS IX

**Ket.jl: Toolbox for quantum information, nonlocality, and entanglement** — Mateus Araújo[1], Peter Brown[2], Sébastien Designolle[3], •Carlos de Gois[4], and Lucas Porto[5] — [1]Universidad de Valladolid — [2]Télécom Paris — [3]Zuse-Institut Berlin — [4]Universität Siegen — [5]Universidade Estadual de Campinas

Ket.jl is a versatile toolbox for doing quantum information in the Julia programming language. This contribution will offer a brief, hands-on introduction to its capabilities. Key features to be discussed include parallelized algorithms for computing local bounds of Bell inequalities, a generic see-saw method for maximizing the quantum value of any Bell functional, and tools for computing the incompatibility robustness of quantum measurements. For entanglement theory, the library offers, among others, methods for computing the entanglement entropy and the Schmidt number of quantum states, and to construct witnesses for genuine multipartite entanglement – all of which leverage an implementation of the symmetric extensions hierarchy.

Notably, Ket.jl provides flexible implementations for subsystem permutation, partial trace and partial transpose, designed to work with abstract data types. This flexibility enables integration with JuMP for formulating optimization programs. Additional features include utilities for generating random operators, computing norms and entropies, and constructing mutually unbiased bases and symmetric informationally complete POVMs with arbitrary precision.

QI 5.3 Mon 17:45 HS IX

**Metrological entanglement criteria** — •Szilárd Szalay[1] and Géza Tóth[1,2] — [1]Wigner Research Centre for Physics, Budapest, Hungary — [2]University of the Basque Country UPV/EHU, Bilbao, Spain

We show that the Quantum Fischer Information in quantum metrology puts a lower bound on the Average Size of Entangled Subsystems. This is a particular case of a new kind of multipartite entanglement criteria, restricting the relative weights of the pure states of different average size of entangled subsystems in the mixture. We illustrate the strength of this convex criterion and compare it to the original metrological entanglement criterion in terms of the usual entanglement depth.

QI 5.4 Mon 18:00 HS IX

**New methods for high dimensional entanglement in PPT states** — •Robin Krebs and Mariami Gachechiladze — Technische Universität Darmstadt, Darmstadt, Hesse, Germany

Creation and manipulation of high dimensional entanglement is fundamental for quantum information protocols. To understand the structure of high-dimensional entanglement and attain the optimal witnesses to certify the entanglement dimension, analyzing the Schmidt Number (SN) of PPT states is necessary, which is notoriously hard to do. In this work, we take a step forward in developing novel methods for finding high SN PPT states. To do this, we work with the so-called projection property of high-dimensional entangled states: Any bound entangled state with SN $k$ can be obtained via local projections on a higher dimensional PPT state with SN $(k+1)$. This larger state can be viewed as an extended state. More generally, this defines a convex cone of PPT extensions of a fixed initial state. Then, the (extremal) intersection geometry of the extension cone and PPT set in the corresponding dimension is investigated. This way, it is possible to obtain new candidates of high SN states. For such extreme points of the PPT set, we derive a necessary and sufficient SN criterion applicable to the extended states. On various examples, we observe that extensions of low degrees do not increase the SN, which constrains the search process. Instead, here, we discover patterns for the original fixed state that lead to high SN extensions. This way, we find the smallest known instance of three-dimensional PPT entanglement in $4 \times 5$-dimensional Hilbert spaces, improving our results for $5 \times 5$-dimensional states.

QI 5.5 Mon 18:15 HS IX

**Chiral Symmetries of Multiparticle Entanglement** — •Sophia Denker[1], Satoya Imai[2], and Otfried Gühne[1] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany — [2]QSTAR, INO-CNR, and LENS, Largo Enrico Fermi 2, 50125 Firenze, Italy

Symmetries play a central role in physics. Particularly in entanglement theory many works investigate the separability of states with certain symmetries. However, while in bipartite systems quantum states can show symmetric or antisymmetric behavior, when exploring multipartite systems also quantum states with chiral symmetries can appear.

In this work we investigate chiral subspaces with respect to their entanglement properties. Starting with the case of three qubits we show that theses subspaces are highly entangled with respect to their geometric measure of entanglement and are further related to measurements that are useful to estimate entanglement. We then consider these spaces in higher dimensions and define operators related to the structure constants of Lie algebras whose eigenspace coincides with the sum of those chiral subspaces. While we find that these operators are sums of permutations and therefore invariant under unitary transformations, we further translate those operators to sums of permutations and their partial transposed leading to subspaces invariant under orthogonal transformations, which are even more entangled.

## QI 6: Quantum Metrology and Sensing (joint session QI/Q)

Time: Monday 17:00–18:45 Location: HS VIII

**Invited Talk** QI 6.1 Mon 17:00 HS VIII

**Precision measurement with nanoscale resolution** — •Joerg Wrachtrup — University of Stuttgart, Center for Applied Quantum Technologies, 70569 Stuttgart — Max Planck Insitute for Solid State Research, Stuttgart, Germany

Solid state quantum sensors quantitatively measure a variety of parameters on nanometer length scales. In the talk I will show and discuss measurements on correlated electron materials. Recently we were e.g. measuring magnetic order in 2D twisted magnetic monolayers to uncover their Moiré periodicity of magnetization. It turns out that at specific twist angles new magnetic phases beyond the Moiré wavelength emerge which can be interpreted by a gradual modulation of anisotropy parameters. We also probe superconductivity in the 2D limit. We observe fractional vortices in two dimensional 2D NbSe2 superconductors. A close inspection reveals vortex dynamics leading to enhanced dephasing of the quantum spin probe. Our results hint at charge dynamics related to the unconventional band structure of the material.

QI 6.2 Mon 17:30 HS VIII

**A comprehensive study of various optically pumped magnetometer schemes** — •Marco Decker[1,2], Rafael Rothganger De Paiva[1,3], and René Reimann[1] — [1]Quantum Research Center, Technology Innovation Institute, Abu Dhabi, UAE — [2]Department of Physics and Research center OPTIMAS, RPTU Kaiserslautern-Landau — [3]Universidade Federal do ABC, Santo Andre, Sao Paulo, Brazil

Highly precise and accurate magnetic field sensing has real-world applications in non-destructive testing [1], biomedical imaging [2], and positioning and navigation [3]. Optically pumped magnetometers (OPMs) have proven to be a highly suitable choice to meet the requirements of these applications [4]. In this work, we present a comprehensive study of various OPM schemes and evaluate their feasibility for multiple use cases.

Comparing measurement schemes from published works is challenging due to varying gas mixtures, laser setups, and shielding conditions. We systematically evaluate the free induction decay (FID), nonlinear magneto-optical rotation (NMOR), Bell-Bloom, and other setup types, tested with Cs-133 vapor for various buffer gases and coatings. After comparing sensitivity, bandwidth, and dynamic range, we assess the suitability of these schemes for different deployment scenarios.

[1] S. Youssef, Journal of Nondestructive Testing 21, 19390 (2016); [2] P. K. Mandal, Front. Comput. Neurosci. 12 (2018); [3] A. J. Canciani, AFIT, Dissertation, https://scholar.afit.edu/etd/251 (2016); [4] D. Budker and M. Romalis, Nature Physics 3, 227-234 (2007)

QI 6.3 Mon 17:45 HS VIII

**Spin Quantum Magnetometry and Gradiometry: Towards clinical applications in unshielded environments** — •Magnus Benke, Jixing Zhang, Michael Kübler, Yihua Wang, Anjana Karuvayalil, and Jörg Wrachtrup — 3rd Physics Institute, University of Stuttgart, Stuttgart

Highly sensitive magnetometers are an essential tool for material analysis and medical applications. The Nitrogen Vacancy (NV) centers in diamond provides a promising candidate for a quantum sensor offering high sensitivity together with an exceptional spatial resolution while operating at ambient conditions. Current comparable technology also only has a limited dynamic range which makes it susceptible to background magnetic noise outside of shielded environments. The NV sensor with its broad dynamic range does not suffer from this limitation and can be used to form a gradiometric sensor array of two or more magnetometers to cancel any background fields. This enables unshielded measurements of small magnetic fields orders of magnitude smaller than the surrounding environment.

In this work we present a DC-broadband magnetometer with improved sensitivity reaching a photon shot noise limit of sub-pT/$\sqrt{\mathrm{Hz}}$ using a CW-ODMR (Continuous-Wave Optically Detected Magnetic Resonance) measurement scheme. With two of these highly sensitive magnetometers, we build a gradiometer and achieved a reduction of an artificial background signal by 40 times without decreasing an applied test signal. These advancements open the door to magnetic field-related clinical applications in unshielded environments.

QI 6.4 Mon 18:00 HS VIII

**Enhancing NV-center magnetometer sensitivity for quantum sensing using flux concentrators** — •Anjana Karuvayalil[1], Jixing Zhang[1], Michael Kübler[1], Stephan Erlhoff[2], Magnus Benke[1], Yi hua Wang[1], Pascal Schmidt[1], Andrej Denisenko[1], Cheuk Cheung[1], and Jörg Wrachtrup[1] — [1]3rd Institute of Physics, University of Stuttgart — [2]Max Planck Institute, Stuttgart

Magnetic field sensing is a critical tool in fields such as geophysics, medical science, and magnetic field mapping. Existing magnetic field sensors, including OPMs and SQUIDs, provide high sensitivity but often come with limitations such as complexity or operational constraints. This work highlights the nitrogen-vacancy (NV) center-based magnetometer for its exceptional quantum properties making it more reliable for quantum sensing. The NV-center magnetometer achieved photon shot noise-limited sensitivity in the sub-picotesla range. This sensitivity can be further enhanced by incorporating flux concentrators near the diamond. These flux concentrators, designed and optimized using high permeable materials like MnZn and Permalloy, are capable of amplifying weak magnetic fields and significantly improving the effective sensitivity of the magnetometer. They are precisely machined to integrate seamlessly into the experimental setup. Continuous-Wave Optically Detected Magnetic Resonance (CW ODMR) is employed for measurements, with results showing that the use of flux concentrators leads to a 16-fold enhancement in sensitivity. This approach helps the detection of weak biosignals from muscles, the heart, and the brain.

QI 6.5 Mon 18:15 HS VIII

**Activation of metrologically useful genuine multipartite entanglement** — •Róbert Trényi[1,2,3,4], Árpád Lukács[1,4,5], Paweł Horodecki[6,7], Ryszard Horodecki[6], Vértesi Tamás[8], and Géza Tóth[1,2,3,4,9] — [1]Dept. of Th. Phys., UPV/EHU, Bilbao, Spain — [2]EHU Quantum Center, UPV/EHU, Bilbao, Spain — [3]DIPC, San Sebastián, Spain — [4]HUN-REN Wigner RCP, Budapest, Hungary — [5]Dept. of Math. Sci., Durh. Univ., UK — [6]Int. Cnt. for Theory of Quant. Tech., UG, Gdansk, Poland — [7]Fac. of Appl. Phys. and Math., Nat. Quant. Inf. Cnt., GUT, Gdansk, Poland — [8]HUN-REN Inst. for Nucl. Research, Debrecen, Hungary — [9]IKERBASQUE, Bilbao, Spain

Quantum states with metrologically useful genuine multipartite entanglement (GME) outperform all states without GME in metrology. States reaching the maximal utility in metrology all belong to this convex set of quantum states. With our proposed scheme, we can identify a broad class of practically important states that possess metrologically useful GME in the case of several copies, even though in the single copy case these states can be non-useful, i.e., not more useful than separable states. Thus, we essentially activate quantum metrologically useful GME. We discuss how our findings are related to error correction. We also analyze the iterative method applied to maximize the metrological usefulness for a given quantum state. In particular, we carry out an optimization of the metrological performance over possible local Hamiltonians with a see-saw method.

QI 6.6 Mon 18:30 HS VIII

**Simulators of Quantum Dissipative systems** — •Durga Dasari, Jixing Zhang, and Joerg Wrachtrup — 3. Physics Institute, University of Stuttgart, Stuttgart, GERMANY

Multipartite quantum correlations play a central role in our understanding of many-body physics, as they make them classically hard to compute. This difficulty is stimulating great efforts to quantum simulate these systems, i.e. to solve their dynamics using a highly controlled quantum spin system. Quantum simulators based on large spin ensembles can massively increase the Hilbert space, as control and readout happen globally. Equally, with controlled dissipation and decoherence, they can be ideal candidates to simulate open-quantum systems which are computationally more demanding when compared to Hamiltonian systems that are currently simulated. It is now an open question to demonstrate that the control is still sufficient to show a quantum advantage in these large systems, to simulate complex quantum many-body dynamics such that classical methods are systematically outperformed. In this talk we will show how such dissipative Quantum simulators can be realized in central spin systems theoretically, and present some initial experimental studies using the dipolar-coupled NV center ensembles in diamond.

# QI 7: Atom and Ion Qubits (joint session QI/Q)

Time: Monday 17:00–18:45 Location: HS II

**Invited Talk** QI 7.1 Mon 17:00 HS II

**Trapped-ion quantum computers based on chip-integrated microwave control** — •Christian Ospelkaus — Institut für Quantenoptik, Leibniz Universität Hannover, Germany — Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

We pursue the implementation of quantum gates using chip-integrated microwave conductors rather than the widely used laser beams for scalability, gate fidelity and chip-level integration of functionality. Previous demonstrations of this method have used a single carefully crafted two-qubit gate combined with single-qubit addressing pulses. Here we show for the first time the execution of arbitrary algorithms on a pair of qubits by implementing the cycle benchmarking protocol and thus a universal computation register. To further integrate the control of the qubits at the chip structure, we demonstrate the generation of the microwave control signals qubits using a cryogenic DDS chip that can be directly integrated with the trap chip. Recent advances in the fabrication of scalable trap structures will be presented, in particular the implementation of through-substrate vias (TSVs) and hybrid integration methods. We present two cryogenic quantum computer demonstrator setups that are currently under construction, combining the computation register with storage and preparation/readout registers and interconnected through an X-junction.

This work has been supported by the Ministry of Science and Culture of Lower Saxony through the QVLS-Q1 project, by BMBF through the “MIQRO”, “ATIQ” and “QuMIC” projects and by the EU through Millenion-SGA1.

QI 7.2 Mon 17:30 HS II

**Scalable, high-fidelity all-electronic control of trapped-ion qubits** — Clemens Löschnauer, Jacopo Mosca Toba, Amy Hughes, Steven King, •Marius Weber, Raghavendra Srinivas, Roland Matt, Rustin Nourshargh, David Allcock, Chris Ballance, Clemens Matthiesen, Maciej Malinowski, and Thomas Harty — Oxford Ionics, Oxford, United Kingdom

The central challenge of quantum computing is implementing high-fidelity quantum gates in a scalable fashion. Our all-electronic qubit control architecture combines laser-free gates with local tuning of electric potentials to enable site-selective single- and two-qubit operations in multi-zone quantum processors. Chip-integrated antennas deliver control fields common to all qubits, while voltages applied to local tuning electrodes adjust the position and motion of ions in each zone, thus enabling local coherent control. We experimentally implement low-noise, site-selective single- and two-qubit control in a microfabricated 7-zone ion trap, demonstrating 99.99916(7)% fidelity for single-qubit gates, and two-qubit Bell state generation with 99.97(1)% fidelity. These results validate the path to directly scaling these techniques to large-scale quantum computers based on electronically controlled trapped-ion qubits.

QI 7.3 Mon 17:45 HS II

**Implementation of Quantum Token Protocol with Trapped Ions** — •Manika Bhardwaj[1], Jan Thieme[1], Bernd Bauerhenne[1], Moritz Göb[1], Bo Deng[1,2], and Kilian Singer[1] — [1]Experimental Physics I, Institute of Physics, University of Kassel, Heinrich-Plett-Straße 40, 34132 Kassel — [2]Institute of Applied Physics, University of Bonn, Wegelerstraße 8, 53115 Bonn

We present a novel quantum token protocol [1] with trapped ions. This quantum token protocol is based on ensembles exploiting the quantum projection noise. Trapped ions are suitable for implementing a robust quantum token protocol due to their long coherence times and single-shot readout. Specifically, we aim to utilise the $4^2S_{1/2} - 3^2D_{5/2}$ transition of $^{40}Ca^+$ ions for this purpose. The protocol requires preparing the ions in a superposition state, where uniform state preparation across the ensemble is critical for obtaining protocol fidelity. To address potential variations in state preparation due to inhomogeneous control parameters, we will employ tailored composite pulses [2].

[1] K. Singer, C. Popov, and B. Naydenov, Verfahren zum Erstellen eines Quanten-Datentokens (DE 10 2022 107 528 A1) DE-Patent (2023).
[2] G. T. Genov, M. Hain, N. V. Vitanov, and T. Halfmann, PRA 101, 013827 (2020).

QI 7.4 Mon 18:00 HS II

**Correction formulas for the Mølmer-Sørensen gate under strong driving** — Susanna Kirchhoff[1,2], Frank Wilhelm-Mauch[1,2], and •Felix Motzoi[1,3] — [1]Forschungszentrum Juelich (PGI 8 and 12) — [2]Saarland University — [3]University of Cologne

The Mølmer-Sørensen gate is a widely used entangling gate for ion platforms with inherent robustness to trap heating. The gate performance is limited by coherent errors, arising from the Lamb-Dicke (LD) approximation and sideband errors. Here, we provide explicit analytical formulas for errors up to fourth order in the LD parameter, by using the Magnus expansion to match numerical precision, and overcome significant, orders-of-magnitude underestimation of errors by previous theory methods. We show that fourth order Magnus expansion terms are unavoidable, being in fact leading order in LD, and are therefore critical to include for typical experimental fidelity ranges. We show how these errors can be dramatically reduced compared to previous theory by using analytical renormalization of the drive strength, by calibration of the Lamb-Dicke parameter, and by the use of smooth pulse shaping.

arXiv:2404.17478

QI 7.5 Mon 18:15 HS II

**Distributed quantum computing between two trapped-ion processors** — Dougal Main, Peter Drmota, •David P. Nadlinger, Ellis M. Ainley, Ayush Agrawal, Bethan C. Nichol, Raghavendra Srinivas, Gabriel Araneda, and David M. Lucas — Dept. of Physics, University of Oxford, Oxford, U.K.

Modular, hybrid quantum systems, where matter qubits are linked via photonic interconnects, hold vast potential across a wide gamut of applications including quantum communication, large-scale computing, and quantum-enhanced metrology. In this talk, I describe an elementary two-node quantum network where $^{88}Sr^+$ acts as the optical interface to generate remote Bell pairs with state-of-the-art performance (fidelities of $\sim 97.0\%$ at rates 100 $s^{-1}$). By co-trapping $^{43}Ca^+$ ions, which provide a long-lived memory undisturbed by any network activity (remote Bell state coherence times >10 s), we demonstrate the first distributed quantum computation across two optically linked quantum processors using deterministic, repeatable quantum gate teleportation [1]. To illustrate the postselection-free execution of consecutive remote two-qubit gates, we benchmark distributed iSWAP- and SWAP-class circuits along with two-qubit instances of Grover's search algorithm. Finally, we examine how emitter motion impacts atom–photon entanglement generation through phase uncertainty, recoil, and coupling efficiency, proposing an intuitive framework applicable to both conventional optics and waveguide-based systems.

[1] D. Main et al., "Distributed Quantum Computing across an Optical Network Link", Nature (accepted, arXiv:2407.00835)

QI 7.6 Mon 18:30 HS II

**Optimizing the circularization of Rydberg atoms** — •Matthias Hüls[1,2], Robert Zeier[1], Eloisa Cuestas[1], Felix Motzoi[1,2], and Tommaso Calarco[1,2,3] — [1]Forschungszentrum Jülich GmbH, Quantum Control (PGI-8), Jülich, Germany — [2]University of Cologne, Institute for Theoretical Physics, Köln, Germany — [3]Università di Bologna, Dipartimento di Fisica e Astronomia, Bologna, Italy

Atoms in Circular Rydberg states, with a large principal quantum number $n$ and maximal magnetic quantum number $m = n - 1$, exhibit long state lifetimes and strong, long-range interactions. This renders them a promising platform for quantum simulation and quantum sensing. Yet their preparation is complex and includes a multi-state transfer through a large Rydberg state manifold of dimension $n^2$ driven by the interaction with radio frequency (RF) pulses. Pulse shapes that achieve the latter with a high fidelity can be designed using optimal control techniques and have enabled a fast and precise circularization of non-interacting atoms in the experiment [1]. With the aim of constructing pulses suitable to circularize arrays of interacting Rydberg atoms, we extend this previous efforts by additional field terms and optimization methods. Further, we study how interactions between atoms affect the performance of current optimized pulses. We therefore build a simulation of the experiment and subsequently use it to optimize RF pulse shapes. [1] Larrouy A, Patsch S, Richaud R, Raimond J-M, Brune M, Koch CP, Gleyzes S. Fast navigation in a large Hilbert space using quantum optimal control. PRX.10:021058 (2020)

# QI 8: Quantum Computing Theory I

Time: Monday 17:00–19:00 Location: HS IV

**Invited Talk** QI 8.1 Mon 17:00 HS IV

**Quantum Informatics - From Quantum Gates to Quantum Software Engineering** — •Ina Schaefer — KIT, Karlsruhe, Germany

While quantum computing hardware is becoming more and more available, the demand for quantum software is also increasing. As in classical computing, the expectation is that after quantum computing hardware has reached a certain maturity, the main value creation in quantum computing will be obtained from quantum software. In order to facilitate the use of quantum computing to solve industrial-scale applications, advances in quantum informatics, and especially in quantum software engineering are needed.

In this presentation, I will explore the relationship between quantum computing and classical software engineering by focusing on three main aspects. First, I will show what can be learnt from classical programming language and compiler technology for the implementation of quantum programming languages. Second, for scaling the development of quantum programs, I will present first results on design patterns for quantum programming. Third, in order to ensure correctness of quantum programs, I will focus on verification techniques and correctness-by-construction development for quantum programs.

QI 8.2 Mon 17:30 HS IV

**Tensor-Programmable Quantum Circuits for Solving Differential Equations** — Pia Siegl[1,2], •Greta Sophie Reese[1,3], Tomohiro Hashizume[1], Nis-Luca van Hülst[1], and Dieter Jaksch[1,4] — [1]Institute for Quantum Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]Institute of Software Methods for Product Virtualization, German Aerospace Center (DLR), Zwickauerstraße 46, 01069 Dresden, Germany — [3]The Hamburg Centre for Ultrafast Imaging, Hamburg, Germany — [4]Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK

We present a quantum approach for solving partial differential equations, leveraging a versatile matrix product operator (MPO) representation. By incorporating mid-circuit measurements and a state-dependent norm correction, this method bypasses the limitations of unitary operators, enabling the direct implementation of a wide range of differential equations that describe both classical and quantum system dynamics.

QI 8.3 Mon 17:45 HS IV

**Real-time measurement error mitigation for one-way quantum computation** — Tobias Hartung[1], •Stephan Schuster[2], Joachim von Zanthier[2], and Karl Jansen[3] — [1]Northeastern University - London — [2]Quantum Optics and Quantum Information Group, Friedrich-Alexander-Universität Erlangen-Nürnberg — [3]Center for Quantum Technology and Applications (CQTA), Desy Zeuthen

We present a quantum error mitigation method for single-qubit measurements, particularly suited for one-way quantum computation. Our method is capable of mitigating errors of single-shot measurements in real-time, i.e., during the processing measurements of a one-way quantum computation and avoids any preceding calibration measurements. For that, we utilize an ancillary qubit register which is entangled with the to-be measured qubit and is additionally measured afterwards. Occurring measurement errors can then be mitigated in real-time by applying a voting protocol to all measurement outcomes, while the computation proceeds. We provide analytical expressions for the remaining missidentifaction probability of a measurement outcome, in dependence of the error rate and the ancilla register size, and for the required register size to fall below a certain missidentification rate, in dependence of the measurement error rate. Additionally, we show in proof-of-principle simulations that our method can reduce the measurement errors significantly using only a small number of ancilla qubits.

QI 8.4 Mon 18:00 HS IV

**Robustness of optimal quantum annealing protocols** — Niklas Funcke and •Julian Berberich — Institute for Systems Theory and Automatic Control, University of Stuttgart, 70569 Stuttgart, Germany

Quantum annealing addresses optimization problems by smoothly interpolating between two Hamiltonians. When implementing quantum annealing protocols on current hardware, errors can cause significant problems and may destroy any potential computational advantages. In this contribution, we study the robustness of optimal quantum annealing protocols against coherent control errors, which correspond to over- or underrotation errors and were shown to be particularly detrimental. We prove that the influence of coherent control errors on quantum annealing is bounded by the norm of the Hamiltonian that is applied to the system. We then leverage this bound to design robust quantum annealing protocols which minimize not only the cost Hamiltonian but also an additional regularization term penalizing the norm of the Hamiltonian. The regularization is weighted by a tuning parameter which allows to trade off two objectives: optimality and robustness. Next, using tools from optimal control theory, we analyze the optimal structure of robust quantum annealing protocols. We prove that the regularization causes a fundamental change of the structure, leading to a higher preference of smooth annealing phases over bang-bang solutions. This provides theoretical evidence that quantum annealing is more robust than variational quantum optimization techniques. Numerical simulations confirm our theoretical findings.

QI 8.5 Mon 18:15 HS IV

**Adaptive Lie-algebra ansatz for ground-state calculations in a globally-driven Rydberg platform** — •Marco Dall'Ara, Martin Koppenhöfer, Thomas Wellens, Florentin Reiter, and Walter Hahn — Fraunhofer Institute for Applied Solid State Physics IAF, Tullastr. 72, 79108 Freiburg, Germany

Hybrid quantum-classical algorithms have emerged as a promising tool to accurately determine ground states, for example of molecules, on quantum computers and quantum simulators. We propose a novel method for the variational preparation of ground states of Hamiltonians on a globally-driven Rydberg-atom platform. This novel method is based on a dynamical-Lie-algebra ansatz combined with an adaptive construction of the pulse sequence. When using our method to determine the ground state of molecules in numerical simulations, it outperforms a brute-force ansatz and shows clear advantages with respect to the dCRAB algorithm of quantum optimal control regarding the number of free parameters and expectation-value evaluations. In particular, we introduce an effective dynamical Lie algebra to avoid the calculation of the full dynamical Lie algebra, which is computationally intractable for larger systems. The method proposed is applicable to simulators beyond the Rydberg-atom architecture and to quantum computers.

QI 8.6 Mon 18:30 HS IV

**Increasing Accuracy of the Variational Quantum Eigensolver with the Inverted-Circuit Zero-Noise Extrapolation** — •Tobias Nauck, Kathrin König, Walter Hahn, and Thomas Wellens — Fraunhofer IAF

Simulating entangled quantum states is inherently challenging for classical computers, which makes this task a prime target for quantum computers. The Variational Quantum Eigensolver (VQE) is a promising method for approximating molecular ground states, but current quantum hardware's noise hinders its practical implementation. In this talk, we discuss results achieved by using the recently proposed noise mitigation technique Inverted-Circuit Zero-Noise Extrapolation (IC-ZNE) [1] in VQE calculations. We present noisy simulations of VQE circuits comparing IC-ZNE with the standard Zero-Noise Extrapolation method for various molecules and show an increased accuracy of the results when using IC-ZNE.

[1] https://journals.aps.org/pra/abstract/10.1103/PhysRevA.110.042625

QI 8.7 Mon 18:45 HS IV

**Why we should expect that quantum computers cannot factor efficiently** — •Liam McGuinness — University of Ulm, Ulm, Germany

Quantum information science currently poses a troubling contradiction. It can be summarized as:

1) To factor efficiently, quantum computers must perform exponentially precise energy estimation.

2) Exponentially precise energy estimation is impossible according to the Heisenberg time-energy uncertainty principle.

It is surprising that such a dramatic contradiction exists between two accepted predictions of quantum mechanics, and yet this contradiction is not widely discussed. It is even more surprising when one notes it is not a minor discrepancy – the two statements differ by an exponential margin. Not only that, whether 1) or 2) is correct is of fundamental importance to the realisation of most quantum technologies. If 2) is correct, then quantum computers are much less powerful than expected.

This talk surveys the available experimental evidence regarding this contradiction. I highlight that all current evidence agrees with 2). I also give clear theoretical reasons why only 2) is consistent with quantum mechanics. In short there are strong reasons to expect that quantum computers cannot factor efficiently.

## QI 9: Quantum Entanglement II

Time: Tuesday 11:00–12:30 Location: HS IX

QI 9.1 Tue 11:00 HS IX

**Full classification of Pauli Lie algebras** — •Gerard Aguilar, Simon Cichy, Jens Eisert, and Lennart Bittel — Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany

Lie groups, and therefore Lie algebras, are fundamental structures in quantum physics that determine the space of possible trajectories of evolving systems. However, their classification and characterization often becomes impractical for large systems. This work provides a comprehensive classification of Lie algebras generated by an arbitrary set of Pauli operators, from which an efficient method to characterize them follows. Mapping the problem to a graph setting, we identify a reduced set of equivalence classes for connected graphs: the free-fermionic Lie algebra, the set of all anti-symmetric Paulis, the Lie algebra of symplectic Paulis, and the space of all Pauli operators on n qubits, as well as controlled versions thereof. Out of these, we distinguish 6 Clifford inequivalent cases, for which we give a physical interpretation of their dynamics. We then extend this result to general graphs with arbitrarily many connected components. Our findings reveal a no-go result for the existence of small Lie algebras beyond the free-fermionic case in the Pauli setting and offer efficiently computable criteria for universality and extendibility of gate sets. These results bear significant impact in ideas in a number of fields like quantum control, quantum machine learning, or classical simulation of quantum circuits

QI 9.2 Tue 11:15 HS IX

**Closed-Form Expressions for Two- and Three-Colorable States** — •Konstantinos-Rafail Revis[1,2], Hrachya Zakaryan[1,2], and Zahra Raissi[1,2] — [1]Department of Computer Science, Paderborn University, Paderborn, Germany — [2]Institute for Photonic Quantum Systems (PhoQS), Paderborn University, Paderborn, Germany

Graph states are a class of multi-partite entangled quantum states, where colorability, a property rooted in their mathematical foundation, has significant implications for quantum information processing. In this talk, we investigate the properties of graph states, focusing mainly on two-colorable and three-colorable graphs, but results for any colorability will be also discussed. A closed-form expression for all two-colorable graphs is presented. This result is tightly connected with the so-called orthogonal arrays and the minimum value of the Schmidt measure. Furthermore, we extend our analysis to every three-colorable graph state, revealing that they are equivalent via local operators to quantum orthogonal arrays, with a minimal number of Schmidt measure. The aforementioned results are extended to an arbitrary number of colors.

https://www.arxiv.org/abs/2408.09515

QI 9.3 Tue 11:30 HS IX

**The exact convex roof for GHZ-W mixtures for three qubits and beyond** — •Andreas Osterloh — TII, QRC, Abu Dhabi, UAE

I present an exact solution for the convex roof of the square root of the threetangle of GHZ-W mixtures for all states within the Bloch sphere. The key to the exact solution is the characteristic pattern for the pure states on the Bloch sphere surface that take part in the optimal decomposition. The method used here can be applied to arbitrary SL-invariant tangles of degree 2d specifically to their d-th root.

QI 9.4 Tue 11:45 HS IX

**Super-activation and incompressibility of genuine multipartite entanglement** — •Lisa T. Weinbrenner[1], Klára Baksová[2], Sophia Denker[1], Simon Morelli[3], Xiao-Dong Yu[4], Nicolai Friis[2], and Otfried Gühne[1] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany — [2]Atominstitut, TU Wien, Vienna, Austria — [3]Basque Center for Applied Mathematics (BCAM), Bilbao, Spain — [4]Department of Physics, Shandong University, Jinan 250100, China

Quantum correlations in the form of entanglement, quantum steering or Bell non-locality are resources for various information-processing tasks, but their detailed quantification and characterization remains complicated. One counter-intuitive effect is the phenomenon of super-activation of correlations, meaning that two copies of a quantum state may exhibit forms of correlations which are absent on the single-copy level.

In this contribution, we develop a systematic approach towards a full understanding of this phenomenon using the paradigm of genuine multipartite entanglement [1]. We introduce systematic methods for studying super-activation of entanglement based on symmetries and generalized notions of multipartite distillability. With this, we present novel criteria for super-activation as well as a quantitative theory of it. Moreover, we uncover forms of incompressible entanglement on multi-copy systems, which cannot be reduced to the single-copy level.

[1] Yamasaki et al., Quantum 6, 695 (2022); Palazuelos & de Vicente, Quantum 6, 735, (2022)

QI 9.5 Tue 12:00 HS IX

**Non-symmetric GHZ states; weighted hypergraph and controlled-unitary graph representations** — •Hrachya Zakaryan[1,2], Konstantinos-Rafail Revis[1,2], and Zahra Raissi[1,2] — [1]Department of Computer Science, Paderborn University, Paderborn, Germany — [2]Institute for Photonic Quantum Systems (PhoQS), Paderborn University, Paderborn, Germany

Non-symmetric GHZ states, represent a significant yet underexplored class of multipartite entangled states with potential applications in quantum information. Despite their importance, the lack of a well-defined stabilizer formalism and corresponding graph representation has hindered their comprehensive study. We address this gap by introducing two novel graph formalisms and stabilizers for non-symmetric GHZ states. We provide a weighted hypergraph representation and demonstrate that non-symmetric GHZ states are local unitary (LU) equivalent to fully connected weighted hypergraphs. We provide stabilizers using local operations, and an ancilla. We further extend this framework to qudits, offering a specific form for non-symmetric qudit GHZ states and their LU equivalent weighted qudit hypergraphs. Lastly, we propose a graph formalism using controlled-unitary (CU) operations, showing that non-symmetric qudit GHZ states can be described using star-shaped CU graphs.

https://arxiv.org/abs/2408.02740

QI 9.6 Tue 12:15 HS IX

**Beating the Optimal Verification of Entangled States via Collective Strategies** — •Ye-chao Liu[1] and Jiangwei Shang[2] — [1]Zuse-Institut Berlin, Takustraße 7, 14195 Berlin, Germany — [2]Key Laboratory of Advanced Optoelectronic Quantum Architecture and Measurement (MOE), School of Physics, Beijing Institute of Technology, Beijing 100081, China

In the realm of quantum information processing, the efficient characterization of entangled states poses an overwhelming challenge, rendering the traditional methods including quantum tomography unfeasible and impractical. To tackle this problem, we propose a new verification scheme using collective strategies, showcasing arbitrarily high efficiency that beats the optimal verification with global measurements. Our collective scheme can be implemented in various experimental platforms and scalable for large systems with a linear scaling on hardware requirement, and distributed operations are allowed. More importantly, the approach consumes only a few copies of the entangled states, while ensuring the preservation of unmeasured ones, and even boosting their fidelity for any subsequent tasks. Furthermore, our pro-

tocol provides additional insight into the specific types of noise affecting the system, thereby facilitating potential targeted improvements. These advancements hold promise for a wide range of applications, offering a pathway towards more robust and efficient quantum information processing.

## QI 10: Quantum Machine Learning II

Time: Tuesday 11:00–12:45 Location: HS VIII

QI 10.1 Tue 11:00 HS VIII

**Quantum Machine Learning for Natural Language Processing** — •Charles Varmantchaonala M.[1], Jean Louis E. K. Fendji[2,3], and Christopher Gies[1] — [1]Institut für Physik, Fakultät V, Carl von Ossietzky Universität Oldenburg, 26129 Oldenburg — [2]Department of Computer Engineering, University Institute of Technology, University of Ngaoundere, P.O. Box 454 Ngaoundere, Cameroon — [3]Stellenbosch Institute for Advanced Study (STIAS), Wallenberg Research Centre at Stellenbosch University, Stellenbosch, South Africa

Quantum Machine Learning (QML) offers exciting possibilities for improving many fields by leveraging the unique properties of quantum mechanics to solve problems more efficiently. Natural Language Processing (NLP) is a key area of artificial intelligence that focuses on helping machines understand and work with human language. The intersection of NLP and QML – Quantum Natural Language Processing (QNLP) – is a new and intriguing research field [1], as it could lead to major improvements in how machines understand human languages, process meaning, and handle complex linguistic tasks. Exploring how QML and NLP can work together is important, as it may provide better solutions and more accurate models for language understanding. This talk will explore the current progress in both QML and QNLP, and explore the aspect of classical-to-quantum sentence or sequence encoding.

[1] Varmantchaonala, C. M., Fendji, J. L. E., Schöning, J., & Atemkeng, M. (2024). Quantum Natural Language Processing: A Comprehensive Survey. IEEE Access.

QI 10.2 Tue 11:15 HS VIII

**Pulse Engineering via Projection of Response Functions** — •Nicolas Heimann[1,2,3], Lukas Broers[1,2], and Ludwig Mathey[1,2,3] — [1]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany — [2]Institut für Quantenphysik, Universität Hamburg, 22761 Hamburg, Germany — [3]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg, Germany

We present an iterative optimal control method of quantum systems, aimed at an implementation of a desired operation with optimal fidelity. The update step of the method is based on the linear response of the fidelity to the control operators, and its projection onto the mode functions of the corresponding operator. Our method extends methods such as gradient ascent pulse engineering and variational quantum algorithms, by determining the fidelity gradient in a hyperparameter-free manner, and using it for a multi-parameter update, capitalizing on the multi-mode overlap of the perturbation and the mode functions. This directly reduces the number of dynamical trajectories that need to be evaluated in order to update a set of parameters. We demonstrate this approach, and compare it to the standard GRAPE algorithm, for the example of a quantum gate on two qubits, demonstrating a clear improvement in convergence and optimal fidelity of the generated protocol.

QI 10.3 Tue 11:30 HS VIII

**sQUlearn - A Python Library for Quantum Machine Learning** — David Kreplin, •Moritz Willmann, Jan Schnabel, Frederic Rapp, Manuel Hagelüken, and Marco Roth — Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany

sQUlearn introduces a user-friendly, NISQ-ready Python library for quantum machine learning (QML), designed for seamless integration with classical machine learning tools like scikit-learn. The library's dual-layer architecture serves both QML researchers and practitioners, enabling efficient prototyping, experimentation, and pipelining. sQUlearn provides a comprehensive toolset that includes both quantum kernel methods and quantum neural networks, along with features like customizable data encoding strategies, automated execution handling, and specialized kernel regularization techniques. By focusing on NISQ-compatibility and end-to-end automation, sQUlearn aims to bridge the gap between current quantum computing capabilities and practical machine learning applications. The library provides substantial flexibility, enabling quick transitions between the underlying quantum frameworks Qiskit and PennyLane, as well as between simulation and running on actual hardware.

QI 10.4 Tue 11:45 HS VIII

**How bandwidth-tuned quantum kernels become classically tractable** — •Roberto Flórez Ablan, Marco Roth, and Jan Schnabel — Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany

Quantum Kernels have been a popular approach in Quantum Machine Learning (QML). However, they have generally not been shown to outperform classical ML methods. A key reason for this is that QKs suffer from the exponential concentration problem. As the number of qubits increases, the overlap between states vanishes, preventing generalization. One strategy to mitigate this problem is to rescale the data points entering the quantum model. This technique, known as bandwidth tuning, has been shown to enable generalization in QKs. However, it has been numerically demonstrated that this method results in QKs that fail to provide a quantum advantage over classical methods in terms of generalization. Here, we propose an explanation for this phenomenon. We show that due to the size of the optimal rescaling factors, QKs become similar to classical kernels. Furthermore, we numerically demonstrate and propose an analytical toy model that captures how key quantities of the kernel in classification experiments are modified as a function of bandwidth. Our results align with recent trends in QML, which suggest that successful QML models become classically simulatable.

QI 10.5 Tue 12:00 HS VIII

**Quantum Kernel Methods under Scrutiny** — •Jan Schnabel, Roberto Flórez Ablan, and Marco Roth — Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany

Quantum kernel methods (QKMs) have emerged as a promising approach in quantum machine learning, offering both practical applications and theoretical insights. Two primary strategies for computing the Gram matrix in QKMs are fidelity quantum kernels (FQKs) and projected quantum kernels (PQKs). Benchmarking these methods is crucial to gain robust insights and to understand their practical utility.

In this talk, we present a comprehensive large-scale study examining QKMs based on FQKs and PQKs across a manifold of design choices, covering both classification and regression tasks. Our work spans five dataset families and 64 datasets, resulting in over 20,000 models trained and optimized using a state-of-the-art hyperparameter search. We delve into the importance of hyperparameters on model performance scores and provide a thorough analysis addressing the design freedom of PQKs and explore the underlying principles responsible for learning. Rather than pinpointing the best-performing models for specific tasks, our goal is to uncover the mechanisms that drive effective QKMs and reveal universal patterns. These insights contribute to better understand certain properties of QKMs and what distinguishes good from bad models.

QI 10.6 Tue 12:15 HS VIII

**Quantum Support Vector Machines Kernel Generation with Classical Post-Processing** — •Anant Agnihotri, Thomas Wellens, and Michael Krebsbach — Fraunhofer IAF, Tullastrasse 72

We investigate the optimization of kernel generation for quantum support vector algorithms for data classification. Classical post-processing techniques are employed to improve the efficiency of classification. First, high-dimensional data is preprocessed using Principal Component Analysis (PCA) to reduce dimensionality while retaining significant features. A training kernel is then generated using the ZZ feature map. In the post-processing step, the overlap with all states (not only the all-zero state, as it is the case for the standard quantum kernel) is utilized, where the kernel entry is computed as a weighted sum of these overlaps. This allows us to determine the kernel entries with reduced number of shots. The method is run on MNIST dataset to distinguish between handwritten digits *0* and *1*. We compare the kernel score, i.e., the fraction of unseen datapoints correctly identified by the standard quantum kernel, on the one hand, and the kernel with our post-processing method, on the other hand. Our findings indicate that the post-processed version outperforms the standard version especially for higher numbers of qubits.

QI 10.7 Tue 12:30 HS VIII

**An SPSA-based Adaptive Shot Optimizer for variational algorithms** — •Matteo Antonio Inajetovic and Anna Pappa — Technische Universität Berlin, Berlin, Germany

Adaptive shot optimizers dynamically adjust shot budget based on gradient variance, ensuring efficient shot allocation and significantly reducing the number of shots required for variational quantum algorithms. This is especially critical for concrete applications on noisy intermediate-scale quantum (NISQ) devices, where limited hardware access and high measurement costs pose substantial challenges. This work introduces adaptiveSPSA, a novel optimization method combining Simultaneous Perturbation Stochastic Approximation (SPSA) with adaptive shot strategies. Unlike other shot-frugal optimizers that rely on parameter-shift rules, adaptiveSPSA, leveraging the inherent efficiency of SPSA, computes gradient estimates using only two circuit executions per optimization step. Therefore, the proposed work is more robust to problem scaling, as the parameter-shift rule requires a number of gradient evaluations that scales linearly with the number of parameters, whereas SPSA maintains a constant number of evaluations regardless of parameter count. Numerical experiments on the Quantum Approximate Optimization Algorithm benchmark demonstrate that adaptiveSPSA outperforms Rosalin, one of the state-of-the-art methods, achieving superior performance still using a small amount of shots. These results underscore its potential to enhance the scalability and efficiency of variational quantum algorithms in practical applications with nowadays devices.

## QI 11: Semiconductor Spin Qubits II: Si, Ge, and Color Centers

Time: Tuesday 11:00–12:45 Location: HS II

**Invited Talk** QI 11.1 Tue 11:00 HS II

**Systematic High-Fidelity Operation and Transfer in Semiconductor Spin-Qubits** — •Maximilian Rimbach-Russ — QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands

Spin-based semiconductor quantum dot qubits are a promising contender for realizing a fault-tolerant quantum processor. Their similarity to classical transistor allows for industrial fabrication techniques, relevant for scaling to fault-tolerant device sizes.

Recent developments have shown that high-fidelity shuttling, movement of the charge carrier while preserving spin-coherence, can be experimentally realized [1]. At the same time, novel control mechanisms that make full use of artificial or intrinsic spin-orbit interaction can be used to enable power efficient, fast, and high-fidelity quantum control [2,3,4]. Furthermore, optimized pulse control allows for an additional dynamic protection and speed to further increase the fidelity of qubit transfer and operations [5,6].

[1] M. De Smet et al., arXiv:2406.07267.
[2] C.-A. Wang et al., Science 385, 6707, 447 (2024)
[3] M. Rimbach-Russ et al., arXiv:2412.13658.
[4] V. John et al., arXiv:2412.16044.
[5] M. Rimbach-Russ, S.G.J. Philips, X. Xue, and L.M.K. Vandersypen, Quantum Sci. Technol. 8, 045025 (2023).
[6] C. V. Meinersen, S. Bosco, and M. Rimbach-Russ, arXiv:2409.03084.

QI 11.2 Tue 11:30 HS II

**Singlet-triplet and exchange-only flopping-mode spin qubits** — •Simon Stastny and Guido Burkard — University Konstanz, Konstanz, Germany

Electron or hole spins in quantum dots coupled to a microwave cavity are an established platform to realize qubits. In the first part of this work we combine the $ST_0$ qubit with the versatile flopping-mode method to achieve tunable cavity coupling. We therefore introduce a spin qubit consisting of two electrons in three quantum dots in a magnetic field gradient. Tunnel couplings between the dots allow for an orbital degree of freedom. The system operates in the $ST_0$ regime near the $|1,0,1\rangle \leftrightarrow |0,1,1\rangle$ charge transition. We calculate the effective transversal and longitudinal spin-photon couplings in this regime and investigate them by observing the cavity transmission near the dressed $ST_0$ resonance. In the second part of this work these calculations are extended to the exchange-only qubit, a setup which comprises four dots and three electrons is introduced. This system can be controlled only by the electrically tunable exchange parameters. In addition a analysis of the three charge states of this system and possible coupling protocols are discussed.

QI 11.3 Tue 11:45 HS II

**Mitigating Crosstalk in Single Hole-Spin Qubits in Anisotropic Semiconductor Systems** — •Yaser Hajati, Irina Heinz, and Guido Burkard — Physics department, Konstanz, University of Konstanz

Spin qubits based on valence band hole states in silicon (Si) and germanium (Ge) are highly promising candidates for quantum information processing, owing to their strong spin-orbit coupling and ultrafast operation speeds. As these systems scale up, achieving high-fidelity single-qubit operations becomes crucial. However, mitigating crosstalk between neighboring qubits in larger arrays, especially for anisotropic qubits with strong spin-orbit coupling such as hole spins in Ge, presents a significant challenge. In this study, we explore the impact of crosstalk on qubit fidelities during single-qubit operations and derive an analytical equation that provides a synchronization condition to eliminate crosstalk in anisotropic media. Our analysis suggests optimized driving field conditions that can robustly synchronize Rabi oscillations, minimizing crosstalk and showing a strong dependence on qubit anisotropy and the orientation of the external magnetic field. By incorporating experimental data, we identify a set of parameters that enable nearly crosstalk-free single-qubit gates, thereby advancing the development of scalable quantum computing architectures.

QI 11.4 Tue 12:00 HS II

**Characterization of NV implanted diamond for NV dipolar coupled pairs** — •Annarita Ricci and Rebekka Eberle — Fraunhofer Institute for Applied Solid State Physics, Tullastr. 72 , 79108, Freiburg im Breisgau

Recent advancement on the fabrication of diamond and the high precision control on single ion implantation techniques have opened new paths in the study of NV dipolar coupled pairs. Th magnetic interaction between the electron spins of two near-by NV centers is highly influenced by their relative spatial arrangement and orientation of the spins. Thus, in this research we focus on the characterization of different NV pairs systems in a sample variation. First, we show the magnetic resonance of NV-NV spin pairs and the quantification of the dipolar coupling strength. The coherence time is then measured by employing the Spin Echo protocol and Dynamical Decoupling techniques (DD). Furthermore, we analyze the coherent sources of errors, and an estimation of the best parameters to use is given, to optimize the control of the system. The finding contributes to a deeper understanding of NV centers pairs in diamond and their potential for advancing and scaling quantum technology.

QI 11.5 Tue 12:15 HS II

**Coupling Silicon-Vacancy Color Center Spin Qubits with Acoustic Modes in Diamond HBARs** — •Stefan Pfleging[1,2], Arianne Brooks[1,2], Chris Adambukulam[1,2], and Yiwen Chu[1,2] — [1]Department of Physics, ETH Zürich, Otto-Stern-Weg 1, CH-8093 Zurich, Switzerland — [2]Quantum Center, ETH Zürich, Otto-Stern-Weg 1, CH-8093 Zurich, Switzerland

The silicon-vacancy (SiV) color center's electronic spin is a promising platform for realizing a quantum memory in hybrid quantum system devices. It is highly strain susceptible and exhibits coherence times in the order of 10 ms at milli-Kelvin temperatures. Incorporating it into diamond high-overtone bulk acoustic wave resonators (HBARs) exhibiting high quality factors would allow for acoustic coupling to the defect. We first characterize the strain response of the SiV by applying an acoustic drive to it and sweeping the laser frequency across one of the optical transitions of the SiV. The intensity of the sidebands that the transition is expected to exhibit in its optical emission signal allows for quantifying the coupling of the acoustic mode to the color center. We then present an approach to manipulate the spin qubit with modes of the HBAR and show suitable conditions for efficient spin driving and optical readout. The sample architecture we use consists of a diamond, HBARs that contain SiVs, bonded to a chip with antennas used for piezoelectric driving of the HBAR modes. By measuring our device at milli-Kelvin temperatures, we aim to demonstrate coherent coupling between the HBAR modes and the SiV spin qubit.

QI 11.6 Tue 12:30 HS II

**Entangling high nuclear spin memory qudits via electron spin communication qubits** — •Wolf-Rüdiger Hannes and Guido Burkard — Department of Physics, University of Konstanz, 78457 Konstanz, Germany

Solid-state defects with optically addressable electron spin and long-lived nuclear spin hold promise for use as quantum network nodes. Of particular interest are nuclear isotopes with high spin quantum number $I$, which could be exploited in efficient error-correction [1] or high-dimensional one-way quantum processing [2]. Here we demonstrate a scheme to maximally entangle $d = 2I + 1$-dimensional memory qudits in separate nodes by repeated entanglement transfer from the electron spin qubits, each time prepared in two-qubit cluster states. The transfer uses a controlled-phase like gate mediated by the hyperfine coupling, and higher nuclear spins further require broad radio-frequency driving. Depending on $I$, this results in a nearly perfect scheme or it can be further improved by varying the coupling, e.g., through the use of alternating rotating frames or occupying different pairs of electron levels in the case of spin triplets.

[1] J. A. Gross, Phys. Rev. Lett. **127**, 10504 (2021).
[2] C. Reimer et al., Nature Physics **15**, 148 (2019).

## QI 12: Quantum Computing Theory II

Time: Tuesday 11:00–12:45 Location: HS IV

**Invited Talk** QI 12.1 Tue 11:00 HS IV

**Classical reasoning methods for quantum circuit analysis** — •Tim Coopmans[1,2], Lieuwe Vinkhuijzen[3], Arend-Jan Quist[3], Jingyi Mei[3], and Alfons Laarman[3] — [1]QuTech, Delft, The Netherlands — [2]EEMCS, Delft University of Technology, The Netherlands — [3]Leiden University, Leiden, the Netherlands

Simulating, evaluating and optimizing quantum circuits is provably difficult, yet we will still need to do so to bring theoretical proposals for scalable quantum computers closer to what can be demonstrated in experiments. Fortunately, computationally-hard tasks also feature heavily in the well-established field of classical reasoning, a branch of classical computer science which focus on developing logic-based algorithms for searching large yet structured spaces.

In this talk, I will show how we merged one such classical-reasoning technique, decision diagrams, with the stabilizer formalism for quantum circuit simulation. And that, asymptotically, the resulting decision diagram provably scales incomparably to other techniques such as Matrix Product States and Clifford+T circuit simulation. If time allows, I will also show how quantum-circuit simulation can also be done using another classical-reasoning technique, weighted #SAT.

QI 12.2 Tue 11:30 HS IV

**Quantum Optimization using LR-QAOA** — •Karthik Jayadevan, Vanessa Dehn, and Thomas Wellens — Fraunhofer Institut für Angewandte Festkörperphysik (IAF)

The Quantum Approximate Optimization Algorithm (QAOA) is a promising approach for solving Combinatorial Optimization Problems (COPs) potentially more efficiently than classical algorithms. However, standard QAOA faces challenges owing to the complexity of optimizing the variational parameters, which itself is an NP-hard optimization problem [1], thus limiting its expected advantage. Recent work has suggested that fixed linear ramp schedules could serve as a universal set of QAOA parameters, potentially offering scaling advantages [2]. In this study, we investigate the application of a modified QAOA variant utilizing Linear Ramp QAOA (LR-QAOA) to certain COPs. Since LR-QAOA significantly reduces the parameter optimization complexity, it enables the determination of good candidates for circuit parameters through extrapolation from smaller to larger problem sizes. Further, we examine the runtime scaling of LR-QAOA for these use cases and compare it with the best-known classical methods.

[1] L. Bittel and M. Kliesch, Physical review letters 127, 120502 (2021).

[2] J. A. Montanez-Barrera and K. Michielsen, Towards a universal QAOA protocol: Evidence of a scaling advantage in solving some combinatorial optimization problems, 2024.

QI 12.3 Tue 11:45 HS IV

**Quantum spatial searches with long-range hopping** — •Emma King[1], Moritz Linnebacher[1], Peter Orth[1], Matteo Rizzi[2], and Giovanna Morigi[1] — [1]Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany — [2]Institut fuer Theoretische Physik, Universität zu Köln, D-50937 Köln, Germany

Grover's search algorithm is paradigmatic for quantum computing, demonstrating how quantum coherence might lead to a supremacy of quantum over classical information processing. A continuous-time implementation of Grover search can be achieved with a quantum walk on a graph, where vertices represent the elements of the database and the target state is tagged by an energy shift. Defining optimal search as an algorithm achieving near unit fidelity in time $T = \mathcal{O}(\sqrt{N})$, this analog realization of quantum search executed on $d$-dimensional hypercubic lattices with nearest-neighbor hopping is optimal when $d > 4$. We extend these results to consider lattices with hopping terms scaling as a power law $1/r^{\alpha}$ with the intersite distance $r$. In the presence of this tuneable connectivity, we assess the requirements on the exponent $\alpha$ for which the spatial search can achieve Grover's optimal scaling, and then relate the result to the spectral dimension $d_s$. At $d_s = 4$ we identify a continuous transition from a region where optimal search exists to a region of suboptimality. Numerically, we demonstrate that the search is robust to disorder in the lattice onsite energy. These results enhance our understanding of analog quantum search in low spatial dimensions and could be accessible experimentally using trapped ultracold atoms.

QI 12.4 Tue 12:00 HS IV

**Ordering operators for an effective ansatz in VQE calculations** — •Sahil Sarbadhikary, Walter Hahn, and Thomas Wellens — Fraunhofer IAF, Freiburg im Breisgau, Germany

The Variational Quantum Eigensolver (VQE) is a promising candidate for a quantum algorithm with near-term applications. It aims to solve a problem central to quantum chemistry: computing the ground state energy of a Hamiltonian describing a molecule. To implement an ansatz for the variational wave function on a quantum computer, the first-order Suzuki-Trotter expansion is usually used, which entails the problem of the non-equivalent order of the operators defining the ansatz. In this talk, we explore the effect of the order of operators in the ansatz on the accuracy of VQE calculations by considering different molecules. We show that the order of operators has an impact on the accuracy of VQE calculations and evaluate possible effective ordering schemes.

QI 12.5 Tue 12:15 HS IV

**Solving the travelling salesman problem on a quantum system** — •Kapil Goswami[1], Rick Mukherjee[1,2], and Peter Schmelcher[1,3] — [1]The Center for Optical Quantum Technologies, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]Quantum Center, The University of Tennessee, 701 East Martin Luther King Boulevard, Chattanooga, USA — [3]The Hamburg Centre for Ultrafast Imaging, University of Hamburg, Germany

The Traveling Salesman Problem (TSP) is a well-known NP-hard combinatorial optimization problem that seeks the optimal route for visiting a set of cities once and returning to the starting point. Current quantum methods for solving TSPs typically use gate-based or binary variable-based encoding, which is resource-intensive and less effective than classical algorithms, even for small problems. We present a framework that solves TSP using a single qubit, utilizing quantum parallelism. In this approach, cities are represented as quantum states on the Bloch sphere, allowing simultaneous exploration of multiple paths through superposition states. By employing optimal control techniques, a selective superposition of quantum states is created to find the shortest route. Numerical simulations for four to nine cities yield exact solutions. Our algorithm can be implemented on any quantum platform capable of rotating a qubit and facilitating state tomography. It demonstrates greater resource efficiency and accuracy compared to existing quantum methods, with potential for scalability and a polynomial speed-up over classical algorithms.

QI 12.6 Tue 12:30 HS IV

**Impact of unital and non-unital noise on quantum phase estimation and Grover search algorithms** — •Muhammad Faryad, Muhammad Faizan, and Amber Riaz — Department of Physics, Lahore University of Management Sciences, Lahore, Pakistan

Quantum phase estimation (QPE) and Grover search algorithms are basic sub-routines in many advanced quantum algorithms. To understand the impact of noise on these algorithms, we computed the phase estimated using the QPE and the probability of success of the Grover algorithm as a function of error probability induced by noise. We consider both unital noise processes such as depolarization noise and non-unital processes such as amplitude damping noise. This noise is modeled as a trace-preserving quantum channel. In the absence of amplitude damping, the performance of the QPE and Grover algorithm strongly depends upon the error probability of bit-flip, phase-flip, and depolarizing noise channel. However, the presence of amplitude damping seems to suppress the impact of unital noise processes.

References: [1] Ijaz and Faryad, Scientific Reports, 13, 20144 (2023). [2] Faizan and Faryad, Proc. SPIE, 12911-88 (2024).

## QI 13: Quantum Networks, Repeaters, and QKD II (joint session Q/QI)

Time: Tuesday 11:00–13:00 Location: AP-HS

QI 13.1 Tue 11:00 AP-HS

**Standalone mobile quantum memory system** — •Martin Jutisz[1], Alexander Erl[2,3], Janik Wolters[2,3], Mustafa Gündoğan[1], and Markus Krutzik[1,4] — [1]Humboldt-Universität zu Berlin and IRIS Adlershof, Berlin, Germany — [2]Technische Universität Berlin, Berlin, Germany — [3]Deutsches Zentrum für Luft- und Raumfahrt, Berlin, Germany — [4]Ferdinand-Braun-Institut (FBH), Berlin, Germany

Quantum memories (QMs) are central to many applications in quantum information science. As a necessary element of quantum repeaters, these devices should be able to operate in non-laboratory environments, and as such their future deployment in space could advance global quantum communication networks [1]. In this context, warm-vapor QMs are particularly promising due to their low complexity and low size, weight and power.

We will present the implementation and performance analysis of a portable rack-mounted standalone warm vapor quantum memory system [2]. The optical memory is based on hyperfine ground states of Cesium which are connected to an excited state via the $D_1$ line at 895 nm in a lambda-configuration. The memory is operated with weak coherent pulses containing on average $< 1$ photons per pulse. The long-term stability of the memory efficiency and storage fidelity is demonstrated over a period of 28 hours together with operation in a non-laboratory environment.

[1] M. Gündoğan et al., npj Quantum Information 7, 128 (2021)
[2] M. Jutisz et al., arXiv:2410.21209 (2024)

QI 13.2 Tue 11:15 AP-HS

**On-demand storage of single quantum-dot photons in a warm-vapour quantum memory** — •Norman Vincenz Ewald[1,2,3], Benjamin Maass[1,3], Avijit Barua[3], Elizabeth Robertson[1], Kartik Gaur[3], Suk In Park[4], Sven Rodt[3], Jin-Dong Song[4], Stephan Reitzenstein[3], and Janik Wolters[1,3] — [1]DLR, Institute of Optical Sensor Systems, Berlin — [2]PTB, FB 8.2 Biosignals, Berlin — [3]TU Berlin — [4]KIST, Seoul, Republic of Korea

On-demand storage and retrieval of quantum information in coherent light–matter interfaces is key to optical quantum communication. Warm-alkali-vapour memories offer scalable and robust high-bandwidth storage at high repetition rates which makes them a natural fit for interfaces with solid-state single-photon sources. Recently, we deterministically stored and retrieved single photons from an InGaAs quantum dot after a storage time of 17(2) ns [1], an order of magnitude longer than previously reported [2]. Electro-optical laser pulse control allows for variable retrieval times from our ladder-type quantum memory that operates on the Cs D1 line at 895 nm [3]. Employing weak coherent pulses with 0.06(2) photons per pulse, we achieve an internal memory efficiency of $\eta_{\text{int}} = 15(1)\%$, a $1/e$-storage time of $\tau_s \approx 32$ ns, and a high SNR of 830(80). The memory's wide spectral acceptance window of 560(60) MHz enables storage of broadband photons from sources prone to spectral diffusion and frequency drifts.

[1] Manuscript under peer review. [2] S.E. Thomas et al., *Sci. Adv.* **10**, eadi7346 (2024). [3] B. Maaß, N.V. Ewald, A. Barua, S. Reitzenstein, and J. Wolters, *Phys. Rev. Appl.* **22**, 044050 (2024).

QI 13.3 Tue 11:30 AP-HS

**All-optical control and readout of individual $^{167}$Er nuclear spin qubits** — Alexander Ulanowski, •Fabian Salamon, Johannes Früh, Adrian Holzäpfel, and Andreas Reiserer — Technical University of Munich, TUM School of Natural Sciences and Munich Center for Quantum Science and Technology (MCQST), 85748 Garching, Germany

Nuclear spins in solids exhibit exceptional coherence times and their coupling to nearby electron spins can enable optical interfacing [1]. In this work, we focus on the nuclear spin of $^{167}$Er dopants, which feature an optical transition within the low-loss wavelength window of optical fibers. Using a high-finesse cryogenic Fabry-Perot cavity [2], we achieve all-optical control and readout of individual $^{167}$Er dopants in a thin yttrium orthosilicate crystal. In our experiment we demonstrate a single-shot readout fidelity of 92(1)% and a hyperfine coherence time exceeding 0.2 s under dynamical decoupling. This makes our system well-suited for spin-photon entanglement, an important step towards developing long-range, fiber-based quantum networks and quantum repeaters.

[1] M. Zhong, M. Hedges, R. Ahlefeldt et al., Nature 517, 177-180 (2015).
[2] A. Ulanowski, J. Früh, F. Salamon, A. Holzäpfel & A. Reiserer, Adv. Optical Mater., 12, 2302897 (2024).

QI 13.4 Tue 11:45 AP-HS

**Single-Shot Readout and Coherent Control of a GeV-$^{13}$C System for a Multi-Qubit Quantum Repeater Node** — •Prithvi Gundlapalli[1], Katharina Senkalla[1], Philipp J. Vetter[1], Nick Grimm[1], Jurek Frey[2,3], Tommaso Calarco[4,5,6], Genko Genov[1], Matthias M. Müller[4], and Fedor Jelezko[1] — [1]Institute for Quantum Optics, Ulm University, Albert-Einstein-Allee 11, 89081 Ulm, Germany — [2]Peter Grünberg Institute-Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany — [3]Theoretical Physics, Saarland University, D-66123 Saarbrücken, Germany — [4]Peter Grünberg Institute-Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany — [5]Institute for Theoretical Physics, University of Cologne, D-50937 Germany — [6]Dipartimento di Fisica e Astronomia, Università di Bologna, 40127 Bologna, Italy

Quantum repeater nodes with efficient spin-photon interfaces and long-lived quantum memories are key to enabling practical quantum networks. We present our results on high-fidelity single-shot readout exceeding 90 % on the germanium-vacancy center in diamond and discuss the implementation of a real-time 'blink check' to improve the fidelity. We further present the efficient characterization of a proximal $^{13}$C using pulsed optically detected magnetic resonance and correlation spectroscopy and discuss optimization of its coherent control. Leveraging the long coherence times exceeding 20 ms and 2.5 s of the germanium-vacancy and $^{13}$C respectively, this work highlights the potential of this system as an efficient multi-qubit quantum repeater node.

QI 13.5 Tue 12:00 AP-HS

**Simulation of a heterogeneous quantum network using Net-**

**Squid** — •Daniel Ventker, Ann-Kathrin Müller, and Florian Elsen — Chair for Laser Technology, RWTH Aachen University

As the relevance of advancing quantum computers continues to grow, so does the need to establish quantum channels between various laboratories to create quantum networks. A quantum internet should be capable of connecting multiple types of qubit platforms, e.g. allowing the use of separate computing and storage nodes or the readout of distinct quantum sensors within the network. The fundamental resource required for such a network is entanglement shared among spatially separated nodes. One way to entangle states over larger distances is through Bell state measurements. In this process, locally entangled photons are emitted from individual nodes to interfere at a central midpoint. This in turn creates entanglement, that transfers over to the respective nodes.

The design of experimental implementations of heterogeneous networks is a complex task. The optimal working point is determined by the characteristics and performance of each individual component. For this reason, a simulation based on the Python package "NetSquid" is developed to combine the theoretical model with the parameters of real components. The goal is to analyze how each of the components influences the overall system and what needs to be considered when designing a new setup. Specifically, this work addresses a heterogeneous connection between an NV-center and a quantum dot, focusing on the system's behavior concerning a quantum frequency converter.

QI 13.6 Tue 12:15 AP-HS

**Outlining the design for the receiver module for a scalable free-space quantum network** — •Karabee Batta[1,2], Michael Steinberger[1,2], Moritz Birkhold[1,2], Adomas Baliuka[1,2], Harald Weinfurter[1,2,3], and Lukas Knips[1,2,3] — [1]Ludwig Maximilian University (LMU), Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Max Planck Institute of Quantum Optics (MPQ), Garching, Germany

QKD leverages principles of quantum mechanics to generate encryption keys that are resistant to eavesdropping. Here, we present the design for a modular receiver unit to establish secure quantum links for polarization-encoded quantum states for ground-based and low-earth orbit satellite systems. The receiver addresses key challenges, such as polarization drift and spatial mode mismatch, which are critical for maintaining high-fidelity quantum links. It does so by employing automated polarization-compensation mechanisms and spatial filtering to avoid dedicated QKD attacks. A key application of this will be communication with the QUBE-II satellite.

QI 13.7 Tue 12:30 AP-HS

**Optical single-shot readout of spin qubits in silicon** — •Jakob Pforr, Andreas Gritsch, Alexander Ulanowski, Stephan Rinner, Johannes Früh, Florian Burger, Jonas Schmitt, Kilian Sandholzer, Adrian Holzäpfel, and Andreas Reiserer — Technical University of Munich, TUM School of Natural Sciences and Munich Center for Quantum Science and Technology (MCQST), 85748 Garching, Germany

Individual erbium emitters are a promising hardware platform for quantum networks as their coherent optical transitions exhibit low loss in optical fibers. Using silicon as a host crystal for erbium allows for scalable fabrication using established processes of the semiconductor industry [1]. To address single dopants, we integrate them into nanophotonic resonators with high $Q \sim 10^5$ and small $V \sim \lambda^3$, thus reducing their lifetime by more than a factor of 60 via the Purcell effect [2]. We then optically initialize the spin, implement high-fidelity optical single-shot readout and realize coherent control of the spin with microwaves [3]. These advances constitute a major step towards quantum information processing with Er:Si. We will further present our measurements of the coherence of photons emitted by individual dopants, which paves the way towards the generation of remote entanglement.

[1] Rinner et. al., Nanophotonics 12(17): 3455-3462, 2023.
[2] Gritsch et. al., Optica 10: 783-789, 2023.
[3] Gritsch et. al., arXiv: 2405.05351, 2024.

QI 13.8 Tue 12:45 AP-HS

**Tomography of a Rb-87 Quantum Memory** — •Yiru Zhou[1,2], Florian Fertig[1,2], Pooja Malik[1,2], and Harald Weinfurter[1,2,3] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Max-Planck-Institut für Quantenoptik, Garching, Germany

Neutral atoms with long coherence times are a promising platform for future quantum networks. While recent advances have significantly improved the coherence time of neutral atom quantum memories [1], a deeper understanding of the dynamics of the entangled states remains crucial for further optimization.

In this talk, we present an Rb-87 neutral atom quantum memory that uses magnetically less sensitive atomic qubits, $\{|F=1, m_F=-1>, |F=2, m_F=+1>\}$ or $\{|F=1, m_F=+1>, |F=2, m_F=-1>\}$, as the basis for quantum memory. To investigate the dynamics of quantum states stored in this memory in detail, we perform a series of overcomplete Pauli tomography measurements and reconstruct the density matrices of entangled state. These measurements enable us to analyze the impact of various experimental improvements on the fidelity of the entangled state, providing detailed insights into the evolution of the coherence and dephasing processes.

[1] Y. Zhou et al., PRX Quantum 5, 020307 (2024)

## QI 14: Quantum Entanglement III

Time: Tuesday 14:00–15:30 Location: HS IX

**Invited Talk** QI 14.1 Tue 14:00 HS IX

**Certification of high-dimensional and multipartite entanglement with imperfect measurements** — •Simon Morelli[1], Hayata Yamasaki[2], Marcus Huber[1], and Armin Tavakoli[3] — [1]Atominstitut, Technische Universität Wien, Austria — [2]University of Tokyo, Japan — [3]Lund University, Sweden

Deciding whether an unknown quantum state is entangled is a central challenge in quantum information. The most common approach are entanglement witnesses, where one assumes the state to be close to a known target and then finds suitable measurements that can reveal its entanglement. In principle, this allows for the detection of every entangled state. However, it requires the experimenter to flawlessly perform the stipulated measurements.

We move away from this idealized scenario to the more realistic situation in which measurement devices are not perfectly controlled, but operate with bounded inaccuracy. We formalize this through an operational notion of inaccuracy that can be estimated directly in the laboratory and investigate the impact of measurement errors on standard entanglement detection techniques. To demonstrate the relevance of this approach, we show that small magnitudes of inaccuracy can significantly compromise several renowned entanglement witnesses.

We extend this analysis to the detection of high-dimensional and multipartite entanglement. To support our theoretical findings experimentally, we explicitly construct states that lead to a wrongful detection of high Schmidt number or genuine multipartite entanglement when the inaccuracies in the measurements are not accounted for.

QI 14.2 Tue 14:30 HS IX

**Making entanglement witnesses robust to measurement errors** — •Elisa Monchietti and Otfried Gühne — Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany

In recent years, various methods have been developed to characterise entanglement, one of the most widely studied are so-called entanglement witness operators. These are observables with the property that if their expectation value is greater than a predetermined quantity C, we can then ensure that the state is entangled, or that it possesses the type of entanglement that this witness allows us to characterize. In real practice, however, the measurement process is not ideal, and despite sophisticated error mitigation techniques complete elimination of errors due to external factors is not possible. If we assume that the measuring devices are not perfectly aligned, we find states whose result when the entanglement witness is applied is greater than the mentioned constant C, but which do not have the type of entanglement we are looking for, i.e., we obtain false positives. Our general aim is to provide methods to characterise quantum correlations in a more realistic way, considering the role of imprecise measurements. To do so, we study potential correction terms, which can be used to counteract the effects of misalignment and imperfections of measurement devices. First we are going to consider a simple scenario of two qubits, to understand possible correction terms. After this, the idea is to study the multipartite case, to develop a framework for error-robust entanglement witnesses for multiqubit systems.

QI 14.3 Tue 14:45 HS IX

**Entanglement between dependent degrees of freedom: Quasiparticle correlations** — •Franziska Barkhausen, Laura Ares Santos, Stefan Schumacher, and Jan Sperling — Paderborn University, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 100, D-33098 Paderborn, Germany

Common notions of entanglement are based on well-separated subsystems with independent degrees of freedom. However, obtaining such independent degrees of freedom is not always possible because of physical constraints leading to dependent degrees of freedom. We theoretically explore the impact of dependent degrees of freedom on quantum entanglement [1]. As an application for interacting light-matter systems, we specifically study quantum correlation features for quasi-particle descriptions in fermion-boson systems in the Jaynes-Cummings model. Non-entangled quasi-particle states can be expressed through projections that act on tensor-product states leading to linear dependencies and states that are non-entangled although they would be entangled when only focusing on the common, independent description. For example, this enables us to construct NOON-type states which are not entangled for dependent degrees of freedom, unlike their counterparts for independent degrees of freedom. Therefore, we provide new insights into the resourcefulness of quantum correlations within the rarely discussed context of dependent degrees of freedom for light-matter links in quantum information applications. [1] F. Barkhausen et al. arXiv:2410.14290, (2024)

QI 14.4 Tue 15:00 HS IX

**Quantum particle in the wron box - the perils of finite dimensional approximations** — •Felix Fischer, Davide Lonigro, and Daniel Burgarth — FAU Erlangen

When numerically simulating a quantum mechanically system, one usually treats the Hamiltonian as an infinite dimensional matrix given in some basis. Then, one truncates this matrix to some finite dimension and diagonalizes the approximate, finite dimensional Hamiltonians. In general, the spectra of these truncated Hamiltonians do not converge towards the spectra of the original Hamiltonian. We show that this happens in the text book example for a quantum mechanical system - The Particle in a Box. When choosing a boundary agnostic basis, the numerics converge towards the particle in box with Dirichlet boundary conditions - independently of the boundary conditions one aims to simulate. In this talk we outline why these problems arise and show that the numerics always converge to one specific Hamiltonian - the Friedrichs extension of the restriction of the original Hamiltonian onto the finite dimensional span of the basis.

QI 14.5 Tue 15:15 HS IX

**Statistical evaluation and optimization of entanglement purification protocols** — •Francesco Preti[1,2] and József Zsolt Bernád[1] — [1]Forschungszentrum Juelich, Institute of Quantum Control (PGI-8), D-52425 Juelich, Germany — [2]Institute for Theoretical Physics, University of Cologne, D-50937 Koeln, Germany

Quantitative characterization of two-qubit entanglement purification protocols is introduced. Our approach is based on the concurrence and the hit-and-run algorithm applied to the convex set of all two-qubit states. We demonstrate that pioneering protocols are unable to improve the estimated initial average concurrence of almost uniformly sampled density matrices, however, as it is known, they still generate pairs of qubits in a state that is close to a Bell state. We also develop a more efficient protocol and investigate it numerically together with a recent proposal based on an entan- gling rank-2 projector. Furthermore, we present a class of variational purification protocols with continuous parameters and optimize their output concurrence. These optimized algorithms turn out to surpass former proposals and our protocol by means of not wasting too many entangled states.

## QI 15: Quantum Computing Implementations (joint session QI/Q)

Time: Tuesday 14:00–15:30 Location: HS II

QI 15.1 Tue 14:00 HS II

**Theory and Experimental Demonstration of Wigner Tomography of Unknown Unitary Quantum Gates** — •Amit Devra[1], Leo Van Damme[1], Frederik vom Ende[2], Emanuel Malvetti[1], and Steffen J. Glaser[1] — [1]Technical University of Munich — [2]Freie University Berlin

We investigate the tomography of unknown unitary quantum processes within the framework of a finite-dimensional Wigner-type representation. This representation provides a rich visualization of quantum operators by depicting them as shapes assembled as a linear combination of spherical harmonics. These shapes can be experimentally tomographed using a scanning-based phase-space tomography approach. However, so far, this approach was limited to known target processes and only provided information about the controlled version of the process rather than the process itself. To overcome this limitation, we introduce a general protocol to extend Wigner tomography to unknown unitary processes. This new method enables experimental tomography by combining a set of experiments with classical post-processing algorithms introduced herein to reconstruct the unknown process. We also demonstrate the tomography approach experimentally on IBM quantum devices and present the specific calibration circuits required for quantifying undesired errors in the measurement outcomes of these demonstrations.

QI 15.2 Tue 14:15 HS II

**High Energy Quantum Simulation on a Trapped-Ion Quantum Processor** — •Christian Melzer[1], Stephan Schuster[2], Diego Alberto Olvera Millán[1], Janine Hilder[1], Ulrich Poschinger[1], Karl Jansen[3], and Ferdinand Schmidt-Kaler[1] — [1]QUANTUM, Institut für Physik, Johannes Gutenberg-Universität Mainz — [2]Quantum Optics and Quantum Information Group, Friedrich-Alexander-Universität Erlangen-Nürnberg — [3]Center for Quantum Technology and Applications, DESY Zeuthen

Currently, quantum processors are noisy and only exhibit few qubits. Still, there are executable applications that show potential for future advantages. We investigate the multi-flavor Schwinger model with non-zero chemical potential. This model stems from the field of high energy physics [1] and describes a phase transition in quantum electrodynamics in one space and one time dimension. For classical computing, this fermionic simulation becomes intractable even for small system sizes due to the notorious sign problem. Using our shuttling-based trapped-ion quantum processor [2], we solve instances of this problem by a variational approach (VQE). Thereby, we find the lowest energy eigenstate of the system and determine the phase transition.

[1] Schuster et al., Phys. Rev. D 109, 114508 (2024)
[2] Hilder et al., Phys. Rev. X 12, 011032 (2022)

QI 15.3 Tue 14:30 HS II

**Demonstrations of system-bath physics on gate-based quantum computer** — Pascal Stadler, Matteo Lodi, Andisheh Khedri, Rolando Reiner, Kirsten Bark, Nicolas Vogt, Michael Marthaler, and •Juha Leppäkangas — HQS Quantum Simulations GmbH, Rintheimer Straße 23, 76131 Karlsruhe, Germany

We develop a quantum algorithm that can be used to perform algorithmic cooling on noisy quantum computers. The approach utilizes inherent qubit noise to simulate the equilibration of an interacting spin system towards its ground state, when coupled to a simulated dissipative auxiliary-spin bath. We test the algorithm on IBM-Q devices and demonstrate the relaxation of system spins to ferromagnetic and antiferromagnetic ordering, controlled by the definition of the system Hamiltonian. The ordering is stable as long as the algorithm is run. We are able to perform cooling and state stabilization for global systems of up to three system spins and four auxiliary spins.

QI 15.4 Tue 14:45 HS II

**Variational quantum algorithm based self-consistent calcula-**

**tions for the two-site DMFT model on noisy quantum computing hardware** — Jannis Ehrlich, •Daniel F. Urban, and Christian Elsässer — Fraunhofer-Institut für Werkstoffmechanik IWM, Freiburg, Germany

Dynamical Mean Field Theory (DMFT) is one of the powerful computational approaches to study electron correlation effects in solid-state materials and molecules. Its practical applicability is, however, limited by the quantity of numerical resources required for the solution of the underlying auxiliary Anderson impurity model. Here, the possibility of a one-to-one mapping between electronic orbitals and the state of a qubit register suggests a significant computational advantage for the use of a Quantum Computer (QC) for solving DMFT models. In this work we present a QC approach to solve a two-site DMFT model based on the Variational Quantum Eigensolver (VQE) algorithm. We discuss the challenges arising from stochastic errors and suggest a means to overcome unphysical features in the self-energy. We thereby demonstrate the feasibility to obtain self-consistent results of the two-site DMFT model based on VQE simulations with a finite number of shots. We systematically compare results obtained on simulators with calculations on the IBMQ Ehningen QC hardware.

QI 15.5 Tue 15:00 HS II

**Robust Microwave-Driven Quantum Gates in a Cryogenic Surface-Electrode Trap** — •Judi Parvizinejad, Sebastian Halama, Giorgio Zarantonello, Celeste Torkzaban, and Christian Ospelkaus — Institute für Quantenoptik, Leibniz University Hannover, Welfengarten 1, 30167 Hannover

A fault-tolerant quantum computer requires a large number of qubits with high gate fidelities, ability to generate entanglement between many qubits, and sufficiently long coherent time. Surface-electrode ion traps [1] have emerged as a promising solution due to their high gate fidelities, long coherence times, and the ability to physically move them around into different zones, which are key requirements for scalable multi-quit operations [1, 4]. Alongside laser-based techniques, microwave-driven gates [2] are promising for advancing fault-tolerant quantum computing. In our cryogenic experiments, 9Be+ ions are confined at a distance of 70 $\mu$m above a surface-electrode Paul trap where a strong microwave gradients field generated by an embedded microwave meander is for driving entangling gates [3]. We will present our recent advancements in achieving high-fidelity microwave-driven gate operations, and will share our plan for demonstrating simple quantum error correction algorithms for quantum metrology.

[1] C. Ospelkaus et al., Phys. Rev. Lett. 101, 090502 (2008). [2] C. Ospelkaus et al., Nature 476, 181-184 (2011). [3] M. Carsjens et al., Appl. Phys. B 114, 243 (2014). [4] D. Kielpinski et al., Nature, 417, 709-711 (2002).

QI 15.6 Tue 15:15 HS II

**Quantum teleportation of a Bell state via cluster states on IBM Quantum** — •Branislav Ilich[1,2] and Nikolay Vitanov[1,2] — [1]Sofia University St. Kliment Ohridski — [2]Center for Quantum Technologies

We report experimental results on the teleportation of a two-qubit entangled Bell state across a six-qubit entangled system on ibm_sherbrooke. The teleportation protocol begins with the generation of a four-qubit cluster state on Bob's subsystem and the preparation of a two-qubit Bell state on Alice's subsystem. The entangled state is then teleported to the last two qubits of Bob's cluster state through a series of controlled-NOT (CNOT) gates.

To maximize the fidelity of the protocol, we implemented targeted optimizations within IBM's transpiler, enabling precise control over gate placement and error mitigation. These modifications were critical in achieving a protocol fidelity of 90%, which represents the upper limit for IBM's quantum hardware.

Our findings demonstrate the feasibility of reliably teleporting entangled states across distributed quantum systems and highlight the importance of hardware-aware optimization strategies in achieving high-fidelity quantum information processing. This work serves as a step forward in scaling entanglement distribution protocols, with implications for quantum communication and distributed quantum computing.

## QI 16: Quantum Computing Theory III

Time: Tuesday 14:00–15:30 Location: HS IV

QI 16.1 Tue 14:00 HS IV

**Time-Evolution Approach for Dynamical Mean Field Theory Calculations on a Quantum Computer** — •Jannis Ehrlich and Daniel F. Urban — Fraunhofer-Institut für Werkstoffmechanik IWM, Freiburg, Germany

Dynamical Mean Field Theory (DMFT) has become a powerful tool for investigating the physics of materials that exhibit strong electronic correlations, like high-temperature superconductivity or metal-insulator transitions. The numerically challenging part is the calculation of the Greens function of the underlying auxiliary model due to the explicit treatment of electron interactions. We present a time-evolution approach for extracting the Greens function by simulating the quantum system on a quantum computer. We explicitly investigate the influence of errors on the results and show that an efficient treatment of the time-evolution operator along with proper error mitigation strategies allows for simulations even on current NISQ devices.

QI 16.2 Tue 14:15 HS IV

**Preparing ground-states of frustration-free Hamiltonians using measurement-and-feedback algorithms** — •Tobias Schmale[1], Maria Kalabakov[2], and Hendrik Weimer[1,2] — [1]Institut für Theoretische Physik, Appelstr. 2, 30167 Hannover — [2]Institut für Theoretische Physik, Hardenbergstr. 36, 10623 Berlin

Many physically interesting Hamiltonians are frustration-free, meaning that the global ground-state is also a local ground-state. We investigate a measurement-and-feedback scheme for preparing such ground-states on a quantum computer: First partition the (possibly non-commuting) local terms of a given Hamiltonian into sublattices, such that terms of the same sublattice commute. Then, repeatedly iterate through the sublattices and perform simultaneous measurements of commuting terms of the Hamiltonian, and remove excitations by making use of unitary operations and of the classical knowledge about the location of the excitations. Of particular interest here are situations where it can be guaranteed, that these "correction" unitaries do not create new excitations on any sublattice. We present numerical examples of this scheme converging to the ground-state of physically interesting Hamiltonians, as well as some examples where the ground-state is reached in a time independent of system size. We show that in general the runtime is bounded by the Hamiltonian gap, and present further efforts into an analytic understanding of convergence criteria and convergence rates of this scheme.

QI 16.3 Tue 14:30 HS IV

**First hitting time of a monitored quantum walk with long-range hopping** — •Sayan Roy[1], Shamik Gupta[2], and Giovanna Morigi[1] — [1]Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany — [2]Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India

The time needed by a quantum walker to reach a target site on a lattice can be minimized by implementing a resetting protocol, which lets the walker restart its motion at the initial site if it did not reach the target within a certain interval. This requires monitoring the target site by means of a detector. The optimal resetting rate is intimately related to the evolution of the probability that the detector clicks. We analyse the characteristic timescales of the monitored dynamics when the coupling between sites at distance $d$ decays algebraically as $d^{-\alpha}$ with $\alpha \in (0, \infty)$ and the dynamics induced by the detector is encompassed by a non-Hermitian Hamiltonian. Our study allows to determine the optimal resetting time as a function of $\alpha$. We identify three different behaviors: For $\alpha > 2$, the optimal resetting time can be understood in terms of the walker's wave packet propagating causally towards the target: Resetting faster this characteristic time will localize the walker about the initial site giving rise to an effective Zeno-effect. For $\alpha \in (1/2, 2)$, the optimal resetting time decreases monotonously with the lattice size and finally for $\alpha \in (0, 1/2)$, convergence is warranted only by continuously resetting, thereby realizing a dynamics that is reminiscent of an anti-Zeno effect.

QI 16.4 Tue 14:45 HS IV

**Quantum combinatorial optimization beyond the variational paradigm: simple schedules for hard problems** — •Tim Bode, Krish Ramesh, and Tobias Stollenwerk — Institute for Quantum Computing Analytics, Forschungszentrum Jülich

Advances in quantum algorithms suggest a tentative scaling advantage on certain combinatorial optimization problems. Recent work, however, has also reinforced the idea that barren plateaus render variational algorithms ineffective on large Hilbert spaces. Hence, finding annealing protocols by variation ultimately appears to be difficult. Similarly, the adiabatic theorem fails on hard problem instances with first-order quantum phase transitions. Here, we show how to use the spin coherent-state path integral to shape the geometry of quantum adiabatic evolution, leading to annealing protocols at polynomial overhead that provide orders-of-magnitude improvements in the probability to measure optimal solutions, relative to linear protocols. These improvements are not obtained on a controllable toy problem but on randomly generated hard instances (Sherrington-Kirkpatrick and Maximum 2-Satisfiability), making them generic and robust. Our method works for large systems and may thus be used to improve the performance of state-of-the-art quantum devices.

QI 16.5 Tue 15:00 HS IV

**Hybrid Quantum-Classical Method for Excited-State Calculations** — •Sumeet Sumeet, Max Hörmann, and Kai Phillip Schmidt — Chair for Theoretical Physics V, FAU Erlangen-Nürnberg, Germany

We present a comprehensive hybrid quantum-classical framework for calculating excited-state energies in the thermodynamic limit, integrating the variational quantum eigensolver (VQE) with numerical linked-cluster expansions (NLCE), a method we call NLCE+VQE [1]. This methodology introduces a cost function designed to minimize the off-diagonal elements of the Hamiltonian, decoupling subspaces of the Hamiltonian via a single unitary transformation, $T$, derived from the periodic-Hamiltonian variational ansatz.

The transformation $T'$ is subsequently reformulated into a manifestly local unitary operator, $T$, through a projective cluster-additive transformation[2], ensuring the preservation of cluster additivity. This localized quasi-particle representation is systematically extended to the entire lattice using NLCE.

We validate the proposed approach by benchmarking its performance against traditional NLCEs with exact diagonalization (ED) for several non-integrable one-dimensional spin models and the transverse-field Ising model (TFIM) on the square lattice. The results demonstrate the efficacy of the method in capturing excited-state physics.

[1] Sumeet, M. Hörmann, and K. P. Schmidt, Phys. Rev. B 110, 155128 (2024).

[2] M. Hörmann, K. P. Schmidt, SciPost Phys. 15, 097 (2023).

QI 16.6 Tue 15:15 HS IV

**Limitations of Quantum Approximate Optimization in Solving Generic Higher-Order Constraint-Satisfaction Problems** — Thorge Müller[1,3], •Ajainderpal Singh[2], Frank K. Wilhelm[2,3], and Tim Bode[2] — [1]German Aerospace Center (DLR), Institute for Software Technology, Department High-Performance Computing, 51147 Cologne, Germany — [2]Institute for Quantum Computing Analytics (PGI-12),Forschungszentrum Jülich, 52425 Jülich, Germany — [3]Theoretical Physics, Saarland University, 66123 Saarbrücken, Germany

The ability of the Quantum Approximate Optimization Algorithm (QAOA) to deliver a quantum advantage on combinatorial optimization problems is still unclear. Recently, a scaling advantage over a classical solver was postulated to exist for random 8-SAT at the satisfiability threshold. At the same time, the viability of quantum error mitigation for deep circuits on near-term devices has been put in doubt. Here, we analyze the QAOA's performance on random Max-kXOR as a function of k and the clause-to-variable ratio. As a classical benchmark, we use the Mean-Field Approximate Optimization Algorithm (MF-AOA) and find that it performs better than or equal to the QAOA on average. Still, for large k and numbers of layers p, there may remain a window of opportunity for the QAOA. However, by extrapolating our numerical results, we find that reaching high levels of satisfaction would require extremely large p, which must be considered rather difficult both in the variational context and on near-term devices.

## QI 17: Quantum Sensing I (joint session Q/QI)

Time: Wednesday 11:00–12:30 Location: HS V

QI 17.1 Wed 11:00 HS V

**Coherent Control in Quartz-Enhanced Photoacoustics: Fingerprinting a Trace Gas at ppm-Level within Seconds** — •Simon Angstenberger, Moritz Floess, Luca Schmid, Pavel Ruchka, Tobias Steinle, and Harald Giessen — 4th Physics Institute and Stuttgart Research Center of Photonic Engineering, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

Quartz-enhanced photoacoustic spectroscopy (QEPAS) has become a versatile tool for detection of trace gases at extremely low concentrations, leveraging the high quality (Q)-factor of quartz tuning forks. However, this high Q-factor imposes an intrinsic spectral resolution limit for fast wavelength sweeping with tunable laser sources due to the long ringing time of the tuning fork. Here, we introduce a technique to coherently control the tuning fork by phase-shifting the modulation sequences of the driving laser [1]. Particularly, we send additional laser pulses into the photoacoustic cell with a timing that corresponds to a $\pi$ phase shift with respect to the tuning fork oscillation, effectively stopping its oscillatory motion. This enables acquisition of a complete methane spectrum spanning 3050-3450 nm in just three seconds, preserving the spectral shape. Our measured data is in good agreement with the theoretically expected spectra from the HITRAN database when convolved with the laser linewidth of $< 2\,\mathrm{cm}^{-1}$. This will leverage the use of QEPAS with fast-sweeping OPOs in real-world gas sensing applications beyond laboratory environments with extremely fast acquisition speed enabled by our novel coherent control scheme.

[1] S. Angstenberger, M. Floess, L. Schmid, *et al.*, Optica, accepted.

QI 17.2 Wed 11:15 HS V

**Photonic Integrated Circuit Platforms for Scalable Quantum Sensors** — •Fatemeh Salahshoori[1], Suat Icli[1,2], Carl-Frederik Grimpe[1], Guochun Du[1], Rangana Banerjee Chaudhuri[1], Elena Jordan[1], Klaus Boller[3], Alexander Bachmann[5], Sonia M. Garcia-Blanco[4], and Tanja E. Mehlstäubler[1,2,6] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany — [3]Laser Physics and Nonlinear Optics Group, MESA+ Institute of Nanotechnology, University of Twente, Enschede, The Netherlands — [4]Integrated Optical Systems, MESA+ Institute of Nanotechnology, University of Twente, Enschede, The Netherlands — [5]TOPTICA Photonics, Gräfelfing, Germany — [6]Laboratorium für Nano- und Quantenengineering, Leibniz Universität Hannover, Hannover, Germany

As part of the EU project "QU-PIC," we aim to develop scalable photonic integrated circuit (PIC) modules designed to meet the stringent requirements of quantum sensor applications. These modules will feature multiwavelength tunable lasers ranging from UV to the near-IR, specialized light conditioning systems, and photonic-integrated ion trap chips, all engineered for the realization of an ion trap-based quantum sensor demonstrator. This talk will give an overview of the individual components and detail on ring resonator couplers for PIC-based lasers and grating outcouplers based on an $Al_2O_3$ platform, using benchmarking protocols for 3D beam tomography of the PIC-based ion-trap system.

QI 17.3 Wed 11:30 HS V

**Vector Magnetometry Using Shallow NV Centers with Waveguide-Assisted Dipole Excitation and Readout** — •Sajedeh Shahbazi[1], Giulio Coccia[2], Argyro N. Giakoumaki[2], Johannes Lang[1], Vibhav Bharadwaj[1], Fedor Jelezko[1], Shane M. Eaton[2], and Alexander Kubanek[1] — [1]Institute for Quantum Optics, Ulm University, D-89081 Ulm, Germany — [2]Institute for Photonics and Nanotechnologies (IFN) - CNR, Piazza Leonardo da Vinci,

32, Milano 20133, Italy

On-chip magnetic field sensing with NV centers in diamond requires scalable integration of 3D waveguides into diamond substrates. Here, we develop a sensing array device with an ensemble of shallow implanted NV centers integrated with arrays of laser-written waveguides for excitation and readout of NV signals. Our approach enables an easy-to-operate on-chip magnetometer with a pixel size proportional to the Gaussian mode area of each waveguide. The performed continuous wave optically detected magnetic resonance on each waveguide gives an average dc-sensitivity value of $195 \pm 3\text{nT}/\sqrt{\text{Hz}}$. We apply a magnetic field to separate the four NV crystallographic orientations of the magnetic resonance and then utilize a DC current through a straight wire antenna close to the waveguide to prove the sensor capabilities of our device. We reconstruct the complete vector magnetic field in the NV crystal frame using three different NV crystallographic orientations. The waveguide mode's polarization allows B-filed projection into the lab frame[1]. Ref.1: Shahbazi et al.(2024), arXiv:2407.18711

QI 17.4 Wed 11:45 HS V

**Limits of absolute vector magnetometry with NV centers in diamond** — •Dennis Lönard, Isabel Cardoso Barbosa, Stefan Johansson, Jonas Gutsche, and Artur Widera — Department of Physics and State Research Center OPTIMAS, University of Kaiserslautern-Landau, 67663 Kaiserslautern, Germany

The nitrogen-vacancy (NV) center in diamond has established itself as a promising quantum sensing platform. Most notably, vector magnetometry can be performed by observing the Zeeman splitting of the NV's spin resonance frequencies. Relative magnetometry has been shown to reach magnetic-field sensitivities down to fT/rt(Hz), and the current literature contains many examples of how to improve these sensitivities. However, the accuracy of absolute magnetometry is limited by factors other than sensitivity, and formulas for computing the magnetic-field vector are often only approximated.

In this talk, we discuss exact, analytical, and fast-to-compute formulas for calculating the magnetic-field vector from measured resonance frequencies and vice versa. We do not use any approximations and find solutions that are exact within the measurement accuracy, valid for all ranges of magnetometry and all types of NV diamonds, and are much faster to compute than comparable numerical techniques. Finally, we discuss often-used approximations for these calculations and assess their validity and accuracy for different magnetic-field regimes. We developed an open-source Python package that includes all the shown formulas.

QI 17.5 Wed 12:00 HS V

**Ultra-stable miniaturized optical systems for compactatom-based quantum sensors** — •Conrad Zimmermann, Marc Christ, Sascha Neinert, and Markus Krutzik — Ferdinand-Braun-Institut (FBH), Berlin, Germany

The transition of atom-based quantum sensors from laboratory experiments towards compact field-usable devices demands for specialized miniaturization and integration technologies. On that path we develop and qualify a versatile technology toolbox enabeling robust and ultra-stable miniaturized optical systems to trap, probe and manipulate atomic ensembles. We set up a micro-integrated optical dipole trap system with a system volume of about 25 ml. It creates two high-power laser beams which precisely overlap in their focal points ($\omega_0 = 32\,\mu$m) at an angle of 45°. After two years of operation with up to 2.5 W of optical power and no signs of degradation, we share measurements demonstrating the mechanical stability and the capabilities and potentials of used technologies [1].

In addition, we utilize additive manufacturing of ceramics [2] and metals to realize functionalized components such as micro-optical benches, mounts and vacuum systems. We also report on our efforts regarding ultra-high vacuum (UHV) compatibility of components and bonds using our dedicated outgassing qualification system.

[1] M. Christ et al. *Opt. Express* 32, 40806-40819 (2024)
[2] M. Christ et al. *Adv. Quantum Technol.*, 2400076 (2024)

QI 17.6 Wed 12:15 HS V

**A Miniaturized Fiber-Based Magnetic Field Sensor Based on Nitrogen-Vacancy Centers** — •Stefan Johansson, Dennis Lönard, Isabel Cardoso Barbosa, Jonas Gutsche, and Artur Widera — Physics Department and State Research Center OPTIMAS, RPTU Kaiserslautern-Landau, 67663 Kaiserslautern, Germany

Sensing based on quantum effects is believed to be one of the technologies of the near future. Among other quantum magnetic field sensors, such as optically pumped magnetometers and superconducting interference devices, the nitrogen-vacancy (NV) center in diamond is a prime candidate for measuring magnetic fields. It provides a solid crystalline platform operating under ambient conditions without extensive cooling or encapsulation. This chemically and physically robust diamond platform allows measurements in direct contact with a sample, making it highly sensitive to an emitted field, e.g., from muscle signals or magnetic surfaces. While many fiber-based sensors have been published, only a few are portable or provide the capability to measure vectorial magnetic fields using optically detected magnetic resonance measurements. Here, we present our flexible, portable, yet robust fiber-based sensor. The design allows the use of lithographic processes such as direct laser writing of elementary silver and polymer structures on the optical fiber tip. The silver structure allows excitations using microwaves, while the polymer waveguide structure guides excitation and fluorescence light and is used to fixate a 15 $\mu$m-sized diamond to the tip of the optical fiber. We verify the capabilities of our sensor in vectorial measurements of a magnetic coil system.

## QI 18: Quantum Networks, Repeaters, and QKD III (joint session Q/QI)

Time: Wednesday 11:00–13:00 Location: AP-HS

QI 18.1 Wed 11:00 AP-HS

**Diamond Membrane with strained SiV color centers coupled to a fabry perot microcavity** — •Florian Feuchtmayr[1], Robert Berghaus[1], Selene Sachero[1], Gregor Bayer[1], Julia Heupel[2], Tobias Herzig[3], Jan Meijer[3], Cyril Popov[2], and Alexander Kubanek[1] — [1]Institut für Quantenoptik Universitat Ulm — [2]Institute of Nanostructure Technologies and Analytics, Center for Interdisciplinary Nanostructure Science and Technology, University of Kassel — [3]Division of Applied Quantum Systems, Felix Bloch Institute for Solid State Physics, University Leipzig

Group IV color centers in diamond, such as silicon vacancy (SiV), are promising for quantum optics because of their optical transitions, spin access, and good coherence properties. SiV centers typically require millikelvin temperatures, but increasing the ground state splitting improves coherence, allowing operation at higher temperatures. Here, we demonstrate the integration of a single-crystal diamond membrane into a high-finesse microcavity (F = 3000), achieving significant lifetime shortening with a Purcell factor of 2.2 in a liquid helium atmosphere. Absorption and strain spectroscopy confirm enhanced ground-state splitting, paving the way for a spin-photon interface.

QI 18.2 Wed 11:15 AP-HS

**Indistinguishability of quantum-dot molecule based single photon sources** — •Steffen Wilksen[1], Alexander Steinhoff[2], and Christopher Gies[1] — [1]Institut für Physik, Fakultät V, Carl von Ossietzky Universität Oldenburg — [2]Institut für theoretische Physik, Universität Bremen

Quantum-dot molecules (QDMs) consist of two self-assembled semiconductor quantum dots on top of each other separated by a thin tunnelling barrier, allowing charge carriers to tunnel between dots and form delocalized states. Due to their high tunability and rich level scheme, they provide a promising entanglement-generation platform for use in quantum communication and measurement-based quantum computing.

A key property of the emitted individual photons is their indistinguishability. Due to interaction with the environment during the emission process, the photons lose their coherence and ability to interfere with one another. These influences are of particular relevance in semiconductor systems, and to minimize their effects, one aims to reduce external noise while decreasing the emission time using optical cavities.

We investigate the indistinguishability of single photons emitted from a QDM solving both the independent boson model and the Jaynes-Cummings model using both analytic and numerical approaches. We extend the independent-boson model to account for a more realistic behaviour of phonons while keeping it exactly solvable. When a cavity is included, we use exact diagonalization to calculate the attainable indistinguishability.

QI 18.3 Wed 11:30 AP-HS

**Large-Range Tuning and Stabilization of the Optical Transition of Diamond Tin-Vacancy Centers by In-Situ Strain Control** — •Julia M. Brevoord[1], Leonardo G. C. Wienhoven[1], Nina Codreanu[1], Tetsuro Ishiguro[1,2], Elvis van Leeuwen[1], Mariagrazia Iuliano[1], Lorenzo DeSantis[1], Christopher Waas[1], Hans K.C. Beukers[1], Tim Turan[1], Carlos Errando-Herranz[1,3], Kenichi Kawaguchi[2], and Ronald Hanson[1] — [1]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft 2628 CJ, Netherlands — [2]Quantum Laboratory, Fujitsu Limited, 10-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0197, Japan — [3]Department of Quantum and Computer Engineering, Delft University of Technology, Delft 2628 CJ, Netherlands

Quantum technologies, such as quantum networking based on photonic links rely on entanglement generation via indistinguishable photons from the qubits. The tin-vacancy (SnV) center in diamond has emerged as a promising platform, offering good optical and spin properties. However, variations in local strain and electronic environments have posed significant challenges to photon indistinguishability, limiting scalability. In this work, we achieve large-range optical frequency tuning and active stabilization of SnV centers using microelectromechanical strain control integrated into photonic waveguide devices. These results represent a critical step forward in overcoming scalability challenges and enabling the development of robust, large-scale quantum networks.

QI 18.4 Wed 11:45 AP-HS

**Feasibility of Long-Distance Multi-Photon Interference in Satellite-Based Quantum Networks** — •Baghdasar Baghdasaryan[1], Karen Lozano Méndez[2], Meritxell Cabrejo Ponce[2], Stephan Fritzsche[3,4], and Fabian Steinlechner[1,2] — [1]Institut für Angewandte Physik, Jena, Germany — [2]Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Jena, Germany — [3]Theoretisch-Physikalisches Institut, Jena, Germany — [4]Helmholtz-Institut, Jena, Germany

Interference of multi-photon states involves the interaction of two photons on a beam splitter, where the photons must be indistinguishable across all degrees of freedom. Temporal indistinguishability occurs when the photons can not be distinguished based on their arrival times. This can be achieved with time-synchronized pulsed photon sources by controlling photon generation times. However, time synchronization is challenging in satellite-based communication systems due to satellite motion. A promising alternative is the use of photon sources with continuous emission. Temporally indistinguishable photons can be post-selected by carefully measuring the respective arrival times. While post-selection eliminates the need for active time synchronization, the finite resolution of detectors limits the precision of time-resolved detection. Here, we examine the impact of limited detector resolution on the efficiency of multi-photon interference with a focus on entanglement swapping. We estimate the maximum achievable entangled photon pair rate by optimizing the performance of the source and analyzing potential losses in a Earth-satellite link.

QI 18.5 Wed 12:00 AP-HS

**Towards compensation of component imperfections in polarization-based BB84 QKD transmitters** — •Silas Eul[1,2,3], Joost Vermeer[1,3], Domenico Paone[2], Ömer Bayraktar[1,3], Julian Struck[2], and Christoph Marquardt[1,3] — [1]Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 7, 91058 Erlangen, Germany — [2]Tesat-Spacecom GmbH & Co. KG, Gerberstr. 49, 71522 Backnang, Germany — [3]Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany

Quantum key distribution systems typically rely on components that are highly polarization-dependent, such as polarization splitters and waveplates, as well as components that are intended to keep the polarization intact, such as fibers or non-polarizing beam splitters. In a real case scenario, there are no perfect components and the polarization errors generally increase when using smaller components, for example when transitioning from free space to fiber-based to photonic integrated circuit-based setups. In this work the influence of these components is discussed and possibilities to compensate, minimize or bypass these problems are highlighted. Here we focus on transmitters for polarization-based BB84 for free space and satellite applications.

QI 18.6 Wed 12:15 AP-HS

**Detection of Intercept-Resend Blinding Attacks for Quantum Key Distribution with Waveguide-Integrated Superconducting Nanowire Single-Photon Detectors** — •Connor A. Graham-Scott[1,3,4], Roland Jaha[2,3,4], Konstantin Zaitsev[5], Polina Acheva[5], Robin Terhaar[2,3,4], Wolfram Pernice[2,3,4], Vadim Makarov[5], and Carsten Schuck[1,3,4] — [1]Department of Quantum Technologies, University of Münster, Germany — [2]Kirchhoff-Institute for Physics, University of Heidelberg, Germany — [3]Center for Nanotechnology, Münster, Germany — [4]Center for Soft Nanoscience, Münster, Germany — [5]Quantum Hacking and Certification Lab, Vigo Quantum Communication Center, Spain

Quantum key distribution (QKD) offers secure communication via quantum mechanics but is vulnerable to eavesdroppers exploiting single-photon detectors with high-intensity optical pulses to blind and control them. Superconducting nanowire single-photon detectors (SNSPDs) can be attacked by manipulating the decaying-edge of the signal around a comparator trigger voltage, enabling quantum key replication.

We demonstrate that waveguide-integrated SNSPDs counteract such attacks by inducing a permanent resistive latching state above single-photon optical intensities without compromising performance. Testing devices with kinetic inductance from 625nH to 41nH revealed that lower-inductance devices (41nH) latched under multi-photon pulses, exposing eavesdropping attempts. This establishes waveguide-integrated SNSPDs as a secure solution for eavesdropping in QKD.

QI 18.7 Wed 12:30 AP-HS

**QKD with Single Photons from Semiconductor Quantum Dots** — •Joscha Hanel[1], Jingzhong Yang[1], Jipeng Wang[1], Vincent Rehlinger[1], Zenghui Jiang[1], Frederik Benthin[1], Tom Fandrich[1], Jialiang Wang[1], Fabian Klingmann[2], Raphael Joos[3], Stephanie Bauer[3], Sascha Kolatschek[3], Ali Hreibi[4], Eddy Rugeramigabo[1], Michael Jetter[3], Simone Portalupi[3], Michael Zopf[1,5], Peter Michler[3], Stefan Kück[4], and Fei Ding[1,5] — [1]Institut für Festkörperphysik, Leibniz Universität Hannover — [2]Fraunhofer-Institut für Photonische Mikrosysteme, Dresden — [3]Institut für Halbleiteroptik und Funktionelle Grenzflächen, IQST and SCoPE, University of Stuttgart — [4]Physikalisch-Technische Bundesanstalt, Braunschweig — [5]Laboratorium für Nano-und Quantenengineering, Leibniz Universität Hannover

We present a BB84 QKD system based on single photons from a quantum dot (QD) source embedded into a circular bragg grating (CBG). The QD emits directly into the telecom C-band with high brightness and a low $g^{(2)}(0)$ of 0.7%. The encoding scheme features a phase modulator in a Sagnac configuration to inscribe four polarization states at a high modulation speed of 76MHz and with a low quantum bit error rate (QBER) on the order of 1%. We demonstrate the QKD capabilities of the system over increasing transmission distances in fiber, utilizing live polarization drift compensation and software-based synchronization, and show that it is fit for use on an intercity scale.

[1] Yang, J. et al., https://doi.org/10.1038/s41377-024-01488-0
[2] Nawrath et al., https://doi.org/10.1002/qute.202300111

QI 18.8 Wed 12:45 AP-HS

**Photonic-integrated components for satellite-based QKD aboard the launched mission QUBE** — •Ömer Bayraktar[1,2], Jonas Pudelko[1,2], Joost Vermeer[1,2], and Christoph Marquardt[1,2] — [1]Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany — [2]Max Planck Insitute for the Science of Light, Erlangen, Germany

Satellite-based quantum key distribution (SatQKD) presents a promising advancement in secure communications. CubeSats, in particular, offer a cost-effective means for conducting QKD over long distances; however, they necessitate the creation of highly integrated optical systems. Within the framework of the QUBE mission, we have developed an integrated sender for modulated weak coherent states and an integrated quantum random number generator. Following the successful launch of the QUBE satellite in August 2024, we report on the progress achieved and the challenges encountered in one of only a few missions testing components for SatQKD in space.

## QI 19: Mechanical, Macroscopic, and Continuous-variable Quantum Systems (joint session QI/Q)

Time: Wednesday 14:30–16:15 Location: HS IX

**Invited Talk** QI 19.1 Wed 14:30 HS IX

**Wave-Function Expansion with Optically Levitated Nanoparticles** — •Martin Frimmer — ETH Zürich, Zürich, Switzerland

Optomechanical systems provide testbeds for applications ranging from quantum information processing to fundamental searches for potential limitations of quantum theory with increasingly large masses. All quantum optomechanical protocols require purification of the motional state of the mass under scrutiny. Staying in the realm of Gaussian states, the only pure state of motion of a harmonic oscillator is the quantum ground state. Accordingly, ground-state cooling has been the main aim of the opto-mechanics community. It has been achieved with the help of laser cooling and, for the vast majority of experiments, of cryogenic cooling. Only recently, first systems have demonstrated quantum optomechanics at room temperature. A promising experimental platform in this context are optically levitated nanoparticles. Their center-of-mass motion and also their orientation (in case of optically anisotropic particles) resemble harmonic-oscillator degrees of freedom of mechanical motion. In our work, we prepare the highest-purity opto-mechanical oscillator to date. By coupling the rotational degree of freedom of an optically levitated nano-cluster to an optical cavity, we cool the libration mode to a phonon occupation of 0.04 quanta. Notably, we set this purity record in a room-temperature experiment, opening the door towards high-purity quantum optomechanics without the need for cryogenic cooling.

QI 19.2 Wed 15:00 HS IX

**Macroscopic quantum sizes of mechanical systems** — •Benjamin Yadin[1] and Matteo Fadel[2] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany — [2]Department of Physics, ETH Zürich, 8093 Zürich, Switzerland

Whether quantum theory holds true in the macroscopic realm – or breaks down at some size scale – is unknown. Many experimental platforms are probing this question by creating quantum states of ever-increasing size, for example with high masses or involving entanglement between many particles. Measures of 'macroscopicity' are designed to quantify the extent to which a system displays quantum behaviour at a large scale; however, these are often difficult to clearly interpret or fail to apply to a large variety of systems and states.

Here, we propose two measures corresponding to properties originally identified as crucial by Leggett: the 'extensive size', measuring the spread of quantum coherence over a physical size scale; and the 'entangled size', quantifying many-body entanglement between constituent parts of the system. These measures are mathematically well-defined for any state and lower bounds are readily obtainable from experimental data. We demonstrate this through application to mechanical systems – using data from mechanical oscillators and molecular interferometers. As part of this, we show the dependence on temperature of many-body entanglement between atoms in an oscillator.

QI 19.3 Wed 15:15 HS IX

**How non-classical is a quantum state?** — •Martina Jung and Martin Gärttner — Friedrich-Schiller-Universität Jena, Germany

Non-classicality, defined in the sense of quantum optics, is a resource: If a non-classical state is superimposed with vacuum in a beamsplitter, the resulting state will be entangled. Hence, quantifying the non-classicality of a quantum state is crucial to gauge its potential for quantum advantage - for instance in a Boson Sampler. However, conventional non-classicality measures often fail as a practical tool in experimental setups.

Here, we implement a data-driven, devise-specific approach which quantifies the non-classicality of a state by the ability of a neural network to distinguish the state from a classical one. In this approach, snapshots from photon-number measurements are input to a permutation invariant Vision Transformer. By studying the model's attention map, our goal is to identify signatures of non-classical states that might uncover yet unknown non-classicality witnesses.

QI 19.4 Wed 15:30 HS IX

**Learning quantum states of continuous-variable systems** — Francesco Mele[1], Antonio Mele[2], •Lennart Bittel[2], Jens Eisert[2], Vittorio Giovannetti[1], Ludovico Lami[3], Lorenzo Leone[2], and Salvatore Oliviero[1] — [1]NEST, Scuola Normale Superiore and Istituto Nanoscienze, Piazza dei Cavalieri 7, IT-56126 Pisa, Italy — [2]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — [3]Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, the Netherlands

Quantum state tomography, aimed at deriving a classical description of an unknown state from measurement data, is a fundamental task in quantum physics. In this work, we analyse the ultimate achievable performance of tomography of continuous-variable systems, such as bosonic and quantum optical systems. We prove that tomography of these systems is extremely inefficient in terms of time resources. On a more positive note, we prove that tomography of Gaussian states is efficient. To accomplish this, we answer a fundamental question for the field of continuous-variable quantum information: if we know with a certain error the first and second moments of an unknown Gaussian state, what is the resulting trace-distance error that we make on the state? Lastly, we demonstrate that tomography of non-Gaussian states prepared through Gaussian unitaries and a few local non-Gaussian evolutions is efficient and experimentally feasible.

QI 19.5 Wed 15:45 HS IX

**Entanglement detection in continuous-variable systems using two states** — •Elena Callus[1], Tobias Haas[2], and Martin Gärttner[1] — [1]Institute of Condensed Matter Theory and Optics, Friedrich-Schiller-Universität Jena, Germany — [2]Centre for Quantum Information and Communication, Université Libre de Bruxelles, Belgium

The Shchukin-Vogel hierarchy gives necessary conditions for the separability of continuous-variable systems in terms of moments of the mode operators. However, higher-order moments, which are essential for non-Gaussian entanglement detection, are hard to extract efficiently. While recent work has shown the general usefulness of multiple state copies for entanglement witnessing in this regard, the therein proposed measurement schemes require at least three copies that would need to be phase-matched and interfered simultaneously. In this work, we demonstrate the capabilities from using only two states that are interfered on a beam-splitter with variable phase and photon-number detectors. This allows us to access certain classes of moments of the mode operators up to arbitrarily high orders. With their associated separability criteria, we witness entanglement in non-Gaussian classes of N00N states, with arbitrarily large N, and two-mode Schrödinger cat states.

QI 19.6 Wed 16:00 HS IX

**Detecting genuine non-Gaussian entanglement** — •Serge Deside, Tobi Haas, and Nicolas Cerf — ULB, Brussels, Belgium

Efficiently certifying non-Gaussian entanglement in continuous-variable quantum systems is a central challenge for advancing quantum information processing, photonic quantum computing, and metrology. Here, we put forward continuous-variable extensions of the recently introduced entanglement criteria based on moments of the partially transposed state, together with simple readout schemes that require only passive linear optics and local particle number measurements over a handful of state replicas. Our method enables the detection of genuine non-Gaussian entanglement for relevant state families overlooked by all standard approaches, which includes the entire class of NOON states. Further, it is robust against realistic experimental constraints (losses, imperfect copies, and finite statistics), which we demonstrate by an in-depth simulation.

# QI 20: Quantum Networks (joint session QI/Q)

Time: Wednesday 14:30–16:45 Location: HS VIII

**Invited Talk** QI 20.1 Wed 14:30 HS VIII

**Generating entangled states in quantum networks** — •Nikolai Wyderka[1], Justus Neumann[1], Tulja Varun Kondra[1], Kiara Hansenne[2], Lisa T. Weinbrenner[2], Hermann Kampermann[1], Otfried Gühne[2], and Dagmar Bruss[1] — [1]Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, 40225 Düsseldorf, Germany — [2]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany

Which states can be generated in quantum networks? We investigate this question in n-partite quantum networks connected by bipartite sources, assuming local operations and shared randomness (LOSR). We show that for many target states, the question can be reduced to the tripartite network scenario.

Consequently, we show that for the class of multipartite graph states, the reducibility is connected to the task of Greenberger-Horne-Zeilinger (GHZ) state extraction. Here, one asks whether n parties that share a graph state and are distributed into three groups can create a GHZ state shared between them using only group-local unitary operations. We show that for each connected graph state, it is always possible to find a tripartition that yields at least one GHZ state.

Finally, we exploit our findings to derive fidelity bounds on states preparable in LOSR networks with any graph state by deriving strong fidelity bounds in tripartite quantum networks.

QI 20.2 Wed 15:00 HS VIII

**Designing a Microwave-to-Optical Transducer based on a High-Overtone Bulk Acoustic-Wave Resonator** — •Tom Schatteburg[1,2], Maxwell Drimmer[1,2], Rodrigo Benevides[1,2], Samuel Pautrel[1,2], Hugo Doeleman[1,2], Benjamin Neubauer[1,2], Luca Ben Herrmann[1,2], and Yiwen Chu[1,2] — [1]Department of Physics, ETH Zürich, Zurich, Switzerland — [2]Quantum Center, ETH Zürich, Zürich, Switzerland

Microwave to optical transducers convert quantum states from platforms such as superconducting circuits into the thermal noise-free optical regime, promising a route towards a quantum network using telecom fibers as links. A widespread approach is to use a mechanical resonator as intermediate system that couples to both microwaves and optical photons. High-overtone bulk acoustic-wave resonators (HBARs) are a platform for which both electromechanical and optomechanical strong coupling as well as optomechanical ground state operation has been demonstrated. Here we present the design and intermediate results of building a microwave to optical transducer which uses an HBAR as intermediary. We demonstrate the insensitivity to laser light absorption of the acoustic mode as key advantage of the HBAR, and outline the path to combining microwave, acoustics and optics into one system. We discuss overcoming the challenges that arise when building the transducer, such as making high-frequency superconducting qubits, multimode dynamics, cryogenic alignment, and developing new materials.

QI 20.3 Wed 15:15 HS VIII

**Hollow-core light cage waveguides for atomic vapor quantum memories** — •Esteban Gómez-López[1], Dominik Ritter[1], Jisoo Kim[2], Harald Kübler[3], Markus Schmidt[2,4], and Oliver Benson[1] — [1]Humboldt-Universität zu Berlin, 12489, Berlin, Germany — [2]Leibniz Institute of Photonic Technology, 07745, Jena, Germany — [3]Universität Stuttgart, 70550, Stuttgart, Germany — [4]Otto Schott Institute of Material Research, 07743, Jena, Germany

Quantum memories play a fundamental role in synchronizing quantum network nodes. Using electromagnetically induced transparency (EIT) in hot atomic vapors provides easy-to-handle systems capable of storing light for up to seconds [1] and at the single photon level [2]. Recently we have shown that a novel photonic structure, a nanoprinted hollow-core light cage (LC), can enhance the effects of EIT when interfaced with Cs vapor, with the advantage of faster diffusion of atoms inside the core compared to other hollow-core structures [3]. In this work, we show the storage of faint coherent light pulses in the atomic medium confined within the core of the LC for hundreds of nanoseconds. The intrinsic efficiency of the memory was optimized by performing a parameter scan on the signal bandwidth and control power driving the memory. This paves the way towards an on-chip integrated module for quantum memories and as a platform for coherent interaction of light and warm atomic vapors. [1] Katz, O. and Firstenberg, O., Nat. Commun. 9, 2074 (2018). [2] Wolters, J., et al., Phys. Rev. Lett. 119(6), 060502 (2017). [3] Davidson-Marquis, F., et al., Light. Sci. Appl. 10, 114 (2021).

QI 20.4 Wed 15:30 HS VIII

**Entanglement purification in multipartite quantum router setups with multiplexing** — •Julia Alina Kunzelmann, Hermann Kampermann, and Dagmar Bruss — Heinrich Heine University Düsseldorf

Quantum routers are essential for transmitting quantum information over long distances in quantum networks. To enhance the entanglement distribution rate memory multiplexing can be used. However, quantum memories will decohere, which we compensate by entanglement purification. Our work presents an extended protocol that includes both multiplexing and entanglement purification. For entanglement purification, we use the protocol from Deutsch et al. (1996), which we apply pairwise to the quantum memories before performing GHZ measurements. Depolarized qubits in the quantum memories can be replaced or purified by new arriving qubits with higher fidelities. We analyze the fidelity of the distributed GHZ states under various network conditions. Further, we discuss different purification strategies based on our numerical simulations.

QI 20.5 Wed 15:45 HS VIII

**Graph states fidelity bound in networks with local operation and shared randomness** — •Justus Neumann[1], Tulja Varun Kondra[1], Nikolai Wyderka[1], Kiara Hansenne[2], Lisa Weinbrenner[2], Hermann Kampermann[1], Otfried Gühne[2], and Dagmar Bruss[1] — [1]Heinrich-Heine-Uinversität Düsseldorf — [2]Universität Siegen

We analyze quantum networks of spatially separated parties, where some parties are connected by quantum channels (links), enabling the distribution of pairwise entangled states. Additionally, each party has access to a shared classical random variable. Quantum states generated under these conditions are referred to as LOSR states (Local Operations and Shared Randomness). Characterizing this class of network states is often challenging, as determining whether a given state can be realized within a given network configuration is non-trivial. We derive an analytical upper bound on the fidelity of the set of LOSR states with any connected graph state, with particular emphasis on the GHZ state.

QI 20.6 Wed 16:00 HS VIII

**Genuine networks bounds on distillable GHZ and conference key in pair-entangled networks** — •Anton Trushechkin, Hermann Kampermann, and Dagmar Bruss — Heinrich Heine University Düsseldorf, Faculty of Mathematics and Natural Sciences, Institute for Theoretical Physics III, Universitätsstr. 1, Düsseldorf 40225

A fundamental problem of the bipartite entanglement theory is the derivation of upper bounds on distillable entanglement (EPR pairs) and distillable secret key if a source of bipartite (entangled) states is given and LOCC (local operations and classical communication) or LOPC (local operations and public communication) maps are allowed. The same fundamental problems arises in the network scenario. We consider networks where nodes are connected with bipartite entangled sources.

Obviously, GHZ or conference key distillation is not easier than EPR or bipartite secret key distillation between two subsets of nodes constituting an arbitrary bipartition of nodes. Thus, we can apply known bipartite bounds. The existing network bounds are based on this idea of bipartition.

In the present talk, we propose genuine network bounds on distillable GHZ and conference key in pair-entangled networks, i.e. which are not reduced to bipartitions of nodes. To do this, we introduce suitable LOCC and LOPC monotones originating from putting together ideas from classical and quantum information theory and graph theory.

QI 20.7 Wed 16:15 HS VIII

**Collective quantum phases emerging in superconducting qubits networks** — •Benedikt J.P. Pernack, Mikhail V.

Fistul, and Ilya M. Eremin — Theoretische Physik III, Ruhr-Universität Bochum, Bochum 44801, Germany

We present a theoretical study of collective quantum phases occurring in exemplary vertex-sharing superconducting qubits networks, i.e., frustrated sawtooth chains of Josephson junctions embedded in a dissipationless transmission line. The building block of such networks is a triangular superconducting cell containing two 0-Josephson junctions and one $\pi$-Josephson junction. In the frustrated regime, the low-energy quantum dynamics of a single cell is governed by the presence of persistent currents flowing (anti)clockwise corresponding to (anti)vortex configurations. The direct embedding of $\pi$-Josephson junctions to the transmission line results in short- or long-range interactions between vortices and antivortices of different cells. Employing a variational approach the quantum dynamics of such qubits networks was mapped to an effective $XX$ spin model where the exchange interaction between spins decays with distance as $x^{-\beta}$, and the local terms represent the coherent quantum superposition of vortex-antivortex pairs [1]. Combining exact numerical diagonalization and quasi-classical mean field approach, we identified various collective quantum phases such as the paramagnetic ($P$), compressible superfluid ($CS$) and weakly compressible superfluid ($w$-$CS$) states.

[1] B.J.P. Pernack, M.V. Fistul, I.M.Eremin, Phys. Rev. B 110, 184502 (2024).

QI 20.8 Wed 16:30 HS VIII

**Towards a Suburban Quantum Network Link** — •Pooja Malik[1,2], Florian Fertig[1,2], Yiru Zhou[1,2], Tommy Block[1,2], Maya Bueki[3], Tobias Frank[3], Gianvito Chiarella[3], Marvin Scholz[3], Pau Ferrera[3], Gerhard Rempe[3], and Harald Weinfurter[1,2,3] — [1]Fakultät für Physik, Ludwig- Maximilians-Universität, Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Max-Planck Institut für Quantenoptik, Garching, Germany

Distributed quantum computing, quantum sensing and secure quantum communication are all much anticipated applications of quantum networks. The primary blocks of these networks are quantum nodes and the foremost task is to distribute entanglement between distant quantum nodes. Here we present a quantum node based on a single Rb87 atom capable of distributing entanglement between a single atom and a single photon over a 23 km deployed telecom fiber. To achieve transfer in commercial fiber network the single photons are converted to telecom wavelength to evade high attenuation loss at 780 nm. With active polarization compensation over the deployed fiber and long atomic coherence time of 7 ms [1] we measure atom-photon entanglement fidelity of more than 80%. This is a crucial step to realize a city-to-city scale quantum network link when, in the future, connecting to another Rb87 atom node at the remote end of fiber link [2]. [1] Y. Zhou et al., PRX Quantum 5, 020307, 2024 [2] M. Brekenfeld et al., Nature Physics 16, 647-651 (2020)

## QI 21: Superconducting Qubits

Time: Wednesday 14:30–16:15 Location: HS II

**Invited Talk** QI 21.1 Wed 14:30 HS II

**Mesoscopic physics challenges (in) superconducting quantum devices** — •Ioan Pop — Karlsruhe Institute of Technology

Superconducting quantum bits, or qubits, are at the forefront of quantum computing research. Harnessing the low loss properties of superconductors and the nonlinearity of Josephson junctions, in recent processors tens of superconducting qubits can be engineered to exist in quantum superposition states and can be entangled. However, due to the innate complexity of solid-state physics, superconducting qubits still have to cope with various loss and decoherence mechanisms, certainly to the chagrin of quantum computing scientists, but also to the joy of mesoscopic physicists. I will discuss three mesoscopic physics phenomena which significantly complicate the task of engineering coherent superconducting hardware: ionizing radiation interactions with the device substrate, long lived two level systems which imprint a memory in the qubit's environment, and fluctuations in the transparency of aluminum oxide tunnel barriers which are at the heart of Josephson junctions.

QI 21.2 Wed 15:00 HS II

**Time-resolved noise characterization tool to track fluctuating noise effects in superconducting qubits** — •Abhishek Agarwal[1], Ke Wang[2,3], Brian Marinelli[2,3], Lachlan P Lindoy[1], Deep Lall[1], Yannic Rath[1], David I Santiago[2,3], Irfan Siddiqi[2,3], and Ivan Rungger[1,4] — [1]National Physical Laboratory, Teddington, United Kingdom — [2]Quantum Nanoelectronics Laboratory, Department of Physics, University of California, Berkeley, USA — [3]Applied Math and Computational Research Division, Lawrence Berkeley National Lab, Berkeley, USA — [4]Department of Computer Science, Royal Holloway, University of London, Egham, United Kingdom

Superconducting qubits have seen rapid increases in their coherence in the last few decades. However, low-frequency noise present in the qubits still causes non-Markovian errors and qubit instability. Collectively characterising different sources of low-frequency noise can be challenging, and typically noise sources such as charge parity switching and coupling to thermal fluctuators are characterised independently. In order to characterise the combined noise, we develop a tool that uses few-shot data to detect and diagnose qubit frequency fluctuations, as well as a time series segmentation tool to further disambiguate different sources of fluctuations. We demonstrate the tool by computing time and spectrally resolved noise properties. Our framework for fluctuation detection and disambiguation can be used to thoroughly characterize low-frequency noise in qubits as well as develop methods to mitigate the noise.

QI 21.3 Wed 15:15 HS II

**Fast parity measurements for continuous quantum error correction on superconducting qubits** — •Anton Halaski and Christiane P. Koch — Freie Universität Berlin, Berlin, Germany

Continuous quantum error correction (QEC) is required in many situations in which the limit of a strong projective measurement cannot be applied. Recently, Atalaya et al. [*Phys. Rev. A* **103**, 042406 (2021)] proposed a continuous QEC scheme for quantum information applications which involve continuously varying Hamiltonians. This scheme relies on a sufficiently strong and continuous two-qubit parity measurement to extract the error syndromes. To implement such a measurement is particularly challenging, since one has to perform a fast, nonlocal measurement while at the same time not introducing any errors to the information encoded in the qubits. We investigate to what extent this task can be accomplished using current circuit QED architecture. Recent proposals for continuous parity measurements in this field rely on the so-called dispersive regime in which the transmons are far detuned from a resonator which acts as the meter for the parity measurement. As a result, transmons and resonator are only weakly coupled and the measurement is slow. We explore how one can achieve speedups by going to the quasi-dispersive regime. Measurements based on the quasi-dispersive regime could then be utilized to enhance the resilience of Atalaya et al.'s and future QEC protocols.

QI 21.4 Wed 15:30 HS II

**Exploring the Fidelity of Flux Qubit Measurement in Different Bases via Quantum Flux Parametron** — •Yanjun Ji[1], Susanna Kirchhoff[1,2], and Frank K. Wilhelm[1,2] — [1]Institute for Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich, 52045 Jülich, Germany — [2]Theoretical Physics, Saarland University, 66123 Saarbrücken, Germany

High-fidelity qubit measurement is essential for building practical quantum computing systems. We investigate methods for maximizing the measurement fidelity of flux qubits using a quantum flux parametron (QFP) readout scheme. Theoretical modeling and numerical simulations are conducted to explore the impact of different measurement bases on the fidelity for single flux qubit and coupled two-qubit systems. Our simulations show that for single qubit systems dressed bases consistently outperform bare bases. For coupled qubit systems, two measurement schemes are compared: sequential and simultaneous. Both schemes focus on reading out a single target qubit within coupled qubit systems. The results indicate that the highest fidelity can be achieved through either sequential measurement in the dressed basis over a longer duration or simultaneous measurement in the bare basis over a shorter duration. However, sequential measurement schemes offer more robust readouts with higher fidelity than simultaneous schemes, which introduce complexity from interactions between QFPs. Our analysis quantifies achievable fidelities for various configurations, offering valuable insights for optimizing measurement processes in emerging quantum computing architectures.

QI 21.5 Wed 15:45 HS II

**High-derivative DRAG for error reduction in two-qubit and qudit gates** — •Boxi Li[1,2], Francisco Cárdenas-López[1], José Jesus[1,2], Adrian Lupascu[3], Tommaso Calarco[1,2,4], and Felix Motzoi[1,2] — [1]Forschungszentrum Jülich — [2]University of Cologne — [3]University of Waterloo — [4]Università di Bologna

To overcome the challenges posed by the finite coherence time of quantum systems, an important task is devising rapid and precise control schemes. For superconducting qubits, analytical control methods based on the system's Hamiltonian are often favoured over general numerical optimization for practical experimental implementation. In this presentation, we introduce an analytical control framework using multi-derivative pulse shaping, based on the Derivative Removal via Adiabatic Gate (DRAG) technique. This approach provides an efficient, parameterized pulse Ansatz that can simultaneously suppress multiple control errors, including nonperturbative effects and multiphoton dynamics.

In this presentation, we apply this control method both to the Cross-Resonance CNOT gate and to two-level rotations in a Transmon qudit. In both cases, multiple errors are present due to the presence of a much larger Hilbert space than the targeted computational levels, where single-derivative correction brings little help. Correction of errors beyond leakage such as ZZ error is also demonstrated. Experimental testing on IBM's quantum platform results in a two to three-fold improvement for the CNOT gate on several publicly available qubits.

QI 21.6 Wed 16:00 HS II

**High-derivative DRAG for error reduction in single-qubit gates** — •José Diogo da Costa Jesus[1,2], Boxi Li[1,2], Francisco Cárdenas-López[1,2], Felix Motzoi[1,2], and Tommaso Calarco[1,2,3] — [1]Forschungszentrum Jülich — [2]University of Cologne — [3]Università di Bologna

To overcome the challenges posed by the finite coherence time of quantum systems, an important task is devising rapid and precise control schemes. For superconducting qubits, analytical control methods based on the system's Hamiltonian are often favoured over general numerical optimization for practical experimental implementation. We introduce an analytical control framework using multi-derivative pulse shaping, based on the Derivative Removal via Adiabatic Gate (DRAG) technique. This approach provides an efficient, parameterized pulse Ansatz that can simultaneously suppress multiple control errors, including nonperturbative effects and multi-photon dynamics.In this presentation, we show that multiple leakage channels are present in single-qubit gates when approaching the speed limit. By introducing high-derivative corrections, these errors can be systematically removed. We also show that a better understanding of the effective model reveals improved prediction of pulse parameters, significantly simplifying the experimental calibration procedure. We derive and optimize different DRAG pulses to minimize leakage and maximize the fidelity of single-qubit gates, demonstrating the need for pulses beyond the current standard for faster single-qubit gates.

## QI 22: Quantum Simulation

Time: Wednesday 14:30–16:15 Location: HS IV

QI 22.1 Wed 14:30 HS IV

**Optimized Squeezing Source for Gaussian Boson Sampling** — Kai Hong Luo, •Florian Lütkewitte, Simone Atzeni, Jan-Lucas Eickmann, Michael Stefszky, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098, Paderborn, Germany

Gaussian boson sampling (GBS) is a promising platform for demonstrating photonic quantum advantage and noisy intermediate-scale quantum computing (NISQ). The implementation requires the production of high-quality single-mode squeezed states, and furthermore, one needs reliable verification. In our system, we produce these states by interfering the modes of a decorrelated, spectrally indistinguishable two-mode squeezed state on a balanced beam-splitter. The performance of our high mean-photon-number ($\langle n\rangle \gg 1000$) squeezing source based on potassium titanyl phosphate (KTP) is verified using various characterization methods, including correlation measurements and Hong-Ou-Mandel (HOM) interference. The advanced characterization reveals near single-spectral-mode performance (effective modes $K \approx 1.1$) and high spectral indistinguishability (visibility $V \approx 96\%$), confirming the source's suitability for use in large optical networking applications.

QI 22.2 Wed 14:45 HS IV

**Thin Nuclear Spin Layers in Diamond for Room-Temperature Quantum Simulation** — •Philipp J. Vetter[1,2], Christoph Findler[1,2,3], Matthias Kost[4,2], Antonio Verdú[5], Rémi Blinder[1,2], Johannes Lang[3], Martin B. Plenio[4,2], Javier Prior[5], and Fedor Jelezko[1,2] — [1]Institute for Quantum Optics, Ulm University, Albert-Einstein-Allee 11, 89081 Ulm, Germany — [2]Center for Integrated Quantum Science and Technology (IQST), 89081 Ulm, Germany — [3]Diatope GmbH, Buchenweg 23, 88444 Ummendorf, Germany — [4]Institute of Theoretical Physics, Ulm University, Albert-Einstein-Allee 11, 89081 Ulm, Germany — [5]Departamento de Física, Universidad de Murcia, 30071 Murcia, Spain

We demonstrate the deterministic fabrication of a thin, sub-1 nm nuclear spin layer in diamond, in close proximity to single nitrogen vacancy (NV) centers embedded in a spin-free host environment. The nuclear spin layer is studied via dynamical decoupling sequences to obtain deep insights into the fabrication process. By utilizing the coupling to a nearby NV center, we demonstrate the polarization, readout and coherent control of the nuclear spin layer at room-temperature and investigate its spin properties, confirming a strong dipolar interaction between the nuclear spins. Through periodic driving, this strong interaction gives rise to discrete time-crystalline order, leading to robust, long-living temporal correlations.

QI 22.3 Wed 15:00 HS IV

**Data Efficient Prediction of Excited State Properties using Quantum Neural Networks** — •Manuel Hagelüken[1], Marco Huber[1,2], and Marco Roth[1] — [1]Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, D-70569 Stuttgart, Germany — [2]Institute of Industrial Manufacturing and Management IFF, University of Stuttgart, Allmandring 35, Stuttgart, 70569, Germany

Understanding the properties of excited states of complex molecules is crucial for many chemical and physical processes. Calculating these properties on quantum computers is often significantly more resource-intensive than calculating their ground state counterparts. We present a quantum machine learning model that combines a symmetry-invariant quantum neural network and a conventional neural network to predict observables of interest for different molecular configurations. The model is trained directly on the molecular ground state wave function, which allows for accurate prediction of excited state properties using only a few training data points. The proposed procedure is fully NISQ compatible. This is achieved through a QNN that requires a number of parameters linearly proportional to the number of molecular orbitals and a parameterized measurement observable, reducing the number of necessary measurements. We benchmark the algorithm on three different molecules by evaluating its performance in predicting excited state transition energies and transition dipole moments. We show that in many instances, the procedure is able to outperform various classical models that rely only on classical features.

QI 22.4 Wed 15:15 HS IV

**Developing a Framework for Predicting Useful Quantum Advantage in the Calculation of Molecule NMR Spectra** — Keith Fratus, Andisheh Khedri, Juha Leppäkangas, Michael Marthaler, and •Jan-Michael Reiner — HQS Quantum Simula-

tions, Rintheimer Straße 23, 76131 Karlsruhe

Demonstrating useful quantum advantage remains a primary goal of quantum computing efforts in the NISQ era. Key to such efforts is the ability to estimate the accuracy and performance of competing classical approximation methods when exact comparisons are not available. In this talk we report on our efforts to develop and understand the behavior of various classical approximation methods which aim to solve a specific class of chemical simulation problems. In particular, we develop classical simulation methods designed to predict molecule NMR spectra, with the aim of being able to quantify the accuracy and computational requirements of performing these simulations, even for parameter regimes which we do not directly simulate. Using such methods, we work towards a framework for predicting for which parameter regime, system size, and target accuracy one can expect the failure of classical methods for this class of systems, thus allowing for the possibility of quantum advantage.

QI 22.5 Wed 15:30 HS IV

**Optimising measurement of correlators for fermionic quantum simulators** — •Ahana Ghoshal, Carlos de Gois, Kiara Hansenne, Otfried Guehne, and Hai-Chau Nguyen — Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany

Simulating many-body fermionic systems on conventional quantum computers poses significant challenges due to the overheads associated with the encoding of fermionic statistics in qubits, leading to the proposal of native fermionic simulators as an alternative. This raises the question of characterising the state of a fermionic simulator, which often boils down to measuring certain overlapping sets of few-point correlators from the output of the quantum simulation. We present a systematic framework for optimising the measurement of two- and four-point correlators in fermionic simulators based on their native fermionic gates. This is obtained by developing a graph representation for the set of correlators to be measured, which is then overlaid by a graph describing the constraints from the fermionic gates. Optimising measurement settings is then mapped to graph theoretical problems, for which various algorithms can be applied. We illustrate our methods for the recently proposed fermionic simulators with various sets of two- and four-point correlators as examples.

QI 22.6 Wed 15:45 HS IV

**Quantum Simulation of Excitons in Dipolar Fermi Gases within Optical Lattices** — •Florian Hirsch[1], Oriana Diessel[2], Rafal Oldziejewski[3], and Richard Schmidt[1] — [1]Institute for Theoretical Physics, Heidelberg University, Philosophenweg 16, 69120 Heidelberg, Germany — [2]ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, US — [3]Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

Ultracold atoms have emerged as a powerful platform for simulating condensed matter phenomena, offering insights into effects difficult to access in solid-state systems. Inspired by the robust excitonic physics found in two-dimensional materials, we investigate the formation of analogues of excitons in a system of single-component Fermions with strong dipole-dipole interactions. Using a hexagonal lattice with an energy offset between the trigonal sublattices to open a non-zero band gap at the K/K' points, we use variational methods to predict the existence of bound atom-hole pairs (atomic excitons) in cold atom systems. To probe these states, we propose an experimental procedure using time-of-flight spectroscopy and suggest applications for high-resolution quantum gas microscopes. This work lays the foundation for simulating more complex states with the exciton as building block, opening new avenues for the exploration of strongly correlated quantum phenomena in both semiconductor systems and ultracold atoms.

QI 22.7 Wed 16:00 HS IV

**Symmetry analysis for variational quantum eigensolvers on a Rydberg-atom quantum simulator** — •Juhi Singh[1,2], Andreas Kruckenhauser[3,4,5], Rick van Bijnen[3,4,5], and Robert Zeier[1] — [1]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), 52425 Jülich, Germany — [2]Institute of Theoretical Physics, University of Cologne — [3]Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria — [4]Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, 6020 Innsbruck, Austria — [5]PlanQC GmbH, 85748 Garching, Germany

As quantum computing moves through the noisy intermediate-scale quantum era, the variational quantum eigensolver (VQE) has been proposed for ground state preparation using current or near-term quantum devices. However, a major challenge in VQE implementations is to understand and predict whether a given quantum architecture can even reach the target ground state, particularly in the presence of inherent symmetries. We develop and study reachability conditions for VQE using symmetry and Lie-algebraic methods, while building on smaller-scale examples. Applying our symmetry analysis to a Rydberg-atom quantum simulator, we evaluate its ability to reach certain Ising and Heisenberg ground states. These results are also validated with numerical VQE simulations. While inherent symmetries can limit the success of VQE implementation, they also point to additional quantum resources required to overcome these limitations and thus offer practical guidance to enhance quantum simulation architectures.

## QI 23: Quantum Technologies (Color Centers and Ion Traps) I (joint session Q/QI)

Time: Wednesday 14:30–16:30 Location: HS Botanik

**Invited Talk** QI 23.1 Wed 14:30 HS Botanik

**Integration of fiber Fabry-Perot cavities for sensing applications and cavity optomechanics** — •Hannes Pfeifer[1], Lukas Tenbrake[2], Carlos Saavedra[3], Florian Giefer[2], Jana Blechmann[2], Johanna Stein[2], Daniel Stachanow[2], Dieter Meschede[2], Karol Krzempek[4], Randall Goldsmith[3], Witlef Wieczorek[1], Stefan Linden[2], and Sebastian Hofferberth[2] — [1]Chalmers University of Technology, Gothenburg, Sweden — [2]University of Bonn, Germany — [3]University of Wisconsin-Madison, USA — [4]Wroclaw University of Science and Technology, Poland

Since their first realization during the 2000s, fiber-based Fabry-Perot cavities (FFPCs) have found their way into an increasing manifold of optical experiments. Driven by the accessibility of their optical mode volume, quantum systems down to single atoms and up to macroscopic mechanical oscillators have been interfaced through FFPCs. Besides their unique features: the strong miniaturization, direct fiber coupling, and large optical access; key challenges such as their experiment integration, coupling efficiency, susceptibility to mechanical vibration, and thermal load remain. In my talk, I will report on the developments from the Bonn Fiber Lab addressing these issues, with a focus on the integration of sensing applications and cavity optomechanics experiments within FFPCs. I will touch upon the realization of highly sensitive readout schemes for gas spectroscopy and single molecule detection, and discuss the structural integration of mechanical resonators using direct laser writing. Finally, I will discuss the prospects of using FFPCs to interface and manipulate mechanical multimode systems.

QI 23.2 Wed 15:00 HS Botanik

**Ion trap chips for two-dimensional coupling experiments** — •Michael Pfeifer[1,2], Simon Schey[1,3], Fabian Anmasser[1,2], Jakob Wahl[1,2], Matthias Dietl[1,2], Marco Valentini[2], Marco Schmauser[2], Michael Pasquini[2], Eric Kopp[2], Philip Holz[4], Martin van Mourik[4], Thomas Monz[2,4], Christian Roos[2], Clemens Rössler[1], Yves Colombe[1], and Philipp Schindler[2] — [1]Infineon Technologies Austria AG, Villach, Austria — [2]University of Innsbruck, Innsbruck, Austria — [3]Stockholm University, Stockholm, Sweden — [4]Alpine Quantum Technologies GmbH, Innsbruck, Austria

Ion trap quantum processors need two-dimensional connectivity between ions to harness their full potential **[1]**. We report on industrially fabricated ion trap chips designed to investigate radial and axial double-well potentials as building blocks of two-dimensional scalable architectures. The coupling between ions in the double-wells on the chips can be tuned by variation of the radial and/or axial separations.

The ion trap chips are fabricated on dielectric substrates - Fused Silica and Sapphire - at Infineon Technologies **[2,3]**. We discuss the design and fabrication of the ion traps as well as recent developments.

**[1]** M. Valentini *et al.*, arXiv:2406.02406 (2024)

**[2]** S. Auchter *et al.*, Quantum Sci. Technol. **7**, 035015 (2022)
**[3]** P. Holz *et al.*, Adv. Quantum Technol. **3**, 2000031 (2020)

QI 23.3 Wed 15:15 HS Botanik

**Integrated Cryo-Electronics for Scalable 2D Surface Ion Traps** — •Fabian Anmasser[1,2], Mohammad Abu Zahra[3,4], Matthias Brandl[3], Klemens Schueppert[2], Jens Repp[3], Matthias Dietl[1,2], Yves Colombe[2], Clemens Roessler[2], Philipp Schindler[1], and Rainer Blatt[1,5] — [1]Institute for Experimental Physics, Innsbruck, Austria — [2]Infineon Technologies Austria AG, Villach, Austria — [3]Infineon Technologies AG, Neubiberg, Germany — [4]Technical University of Munich, Germany — [5]Institute for Quantum Optics and Quantum Information, Innsbruck, Austria

2D surface ion traps provide a promising foundation for building scalable quantum computers. However, as the number of ions increases, so does the number of independently controllable electrodes, leading to a "wiring challenge". Current surface traps require individual routing of electrodes out of the cryogenic system, which becomes impractical for traps with over 1000 qubits.

We present a solution to the wiring challenge by integrating cryogenic electronics underneath a surface ion trap. Our approach involves a control chip that multiplexes 37 inputs to 199 DC electrodes, enabling control of a large number of electrodes with reduced connections. The surface trap is glued on top of the control chip, with electrical connections made using gold wire bonds. Initial Ca+ ion trapping trials have been conducted, and future steps include measuring heating rates and exploring advanced DC shuttling techniques. This work paves the way for scalable surface ion trap devices, bringing us closer to a practical quantum computer.

QI 23.4 Wed 15:30 HS Botanik

**Micro fabricated ion trap with integrated optics** — •Jakob Wahl[1,2], Alexander Zesar[1,3], Marco Schmauser[2], Martin van Mourik[2], Marco Valentini[2], Klemens Schüppert[1], Clemens Rössler[1], Philipp Schindler[2], and Christian Roos[2] — [1]Infineon Technologies Austria — [2]Universität Innsbruck — [3]Technische Universität Graz

Trapped ions have shown great promise as a platform for quantum computing, with long coherence time, high fidelity quantum logic gates, and the successful implementation of quantum algorithms. However, to take trapped-ion quantum computers from laboratory setups to practical devices for solving real-world problems, the number of controllable qubits must be increased while improving error rates. One of the major challenges for scaling trapped-ion quantum computers is the need to switch from free-space to integrated optics, to achieve lower drift and vibrations of light relative to the ion, and therefore more stable and scalable ion-addressing.

In this talk, we show an ion trap produced at Infineon's industrial semiconductor facilities that has integrated femtosecond laser-written waveguides. We show details of the fabrication and present recent measurements and results on the performance of the trap. We compare the trapping behavior with and without the integrated features that expose dielectric to the ion, and potentially increase stray fields and heating rates. This work paves the way towards ion traps with robust and integrated ion addressing.

QI 23.5 Wed 15:45 HS Botanik

**Advancements in Ultra-High Vacuum Technology for Trapped Ion Quantum Computing** — •Helin Özel, Tabea Stroinski, Julian Harald Wiener, Felix Stopp, Björn Lekitsch, and Ferdinand Schmidt-Kaler — Johannes Gutenberg University, Mainz, Germany

We present experimental results on advancements in ultra-high vacuum (UHV) technology to support the development of next-generation quantum processor systems for continuous and stable operation at room-temperature. Our research focuses on improving UHV technology by applying innovative coating techniques. We optimize the pumping speed and achieve improved pressure levels alongside with reduced degassing rates, which are essential for maintaining the stability of quantum systems. Additional improvements address optical alignment and in-vacuum designs to support long-term operation. For preservation of qubit coherence we use three layers of Mu-metal shielding against magnetic noise, while a Halbach magnet configuration is employed to generate a stable magnetic quantization field. These advancements will enhance the reliability and operation quality of the trapped ion processor.

QI 23.6 Wed 16:00 HS Botanik

**Implementing the SUPER Scheme for Tin-Vacancy Spin Qubit Manipulation and Entanglement** — •Cem Güney Torun[1], Mustafa Gökçe[1], Thomas K. Bracht[2], Mariano Isaza Monsalve[1], Sarah Benbouabdellah[1], Özgün Ozan Nacitarhan[1], Marco E. Stucki[1,3], Domenica Bermeo Alvaro[1,3], Matthew L. Markham[4], Tommaso Pregnolato[1,3], Joseph H. D. Munns[1], Gregor Pieplow[1], Doris E. Reiter[2], and Tim Schröder[1,3] — [1]Department of Physics, Humboldt-Universität zu Berlin, 12489 Berlin, Germany — [2]Condensed Matter Theory, Department of Physics, TU Dortmund, 44221 Dortmund, Germany — [3]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, 12489 Berlin, Germany — [4]Element Six, Harwell, OX110 QR, United Kingdom

We investigate the SUPER scheme, a detuned coherent excitation method enabling spectral separation of excitation and emission fields, for spin qubit inversion in tin-vacancy center in diamond. Simulations show high-fidelity inversion of spin superposition is achievable with optimized parameters, while spin $T_1$ measurements confirm that the broadband pulses do not induce significant spin mixing. Additionally, we propose a spin-spin entanglement protocol leveraging broadband excitation to encode photons in the frequency domain, enabling remote entanglement generation.

QI 23.7 Wed 16:15 HS Botanik

**Coupling of alkali vapors and rare gases for quantum memories** — •Denis Uhland[1], Norman Vincenz Ewald[2,3], Alexander Erl[2,3], Andrés Medina Herrera[3], Wolfgang Kilian[3], Jens Voigt[3], Janik Wolters[2,4], and Ilja Gerhardt[1] — [1]Leibniz University Hannover, Institute of Solid State Physics, Light and Matter Group, Hannover — [2]Deutsches Zentrum für Luft- und Raumfahrt, Institute of Optical Sensor Systems, Berlin — [3]Physikalisch-Technische Bundesanstalt, 8.2 Biosignals, Berlin — [4]Technische Universität Berlin, Institute of Optics and Atomic Physics, Berlin

Optical quantum memories allow for the storage and retrieval of quantum information encoded in photons. Despite using an optical interface for photons stored in collective spin excitation via EIT with milliseconds storage time [1], hot mixtures of alkali and rare gas atoms can achieve coherence times up to several hours [2], resulting from spin-exchange collisions, where the optically addressable alkali metals couple to the nuclear spin of the rare gas. R. Shaham et al. [3] discussed how to achieve strong coupling between the electron spin of potassium and the nuclear spin of helium, allowing for efficient spin transfer. We follow the proposed scheme to achieve strong coupling between a hot ensemble of rubidium and xenon, which paves the way towards an efficient quantum memory device and fundamental studies of spin dynamics. [1] L. Esguerra *et al.*, Phys. Rev. A (2023) 107, 042607, [2] C. Gemmel *et al.*, Eur. Phys. J. D (2010) 57, 303, [3] R. Shaham *et al.*, Nat. Phys. L (2022), Vol. 18, No. 5

## QI 24: Open Quantum Systems I (joint session Q/QI)

Time: Wednesday 14:30–16:15 Location: HS I

Invited Talk QI 24.1 Wed 14:30 HS I

**Effective Lindblad master equations for atoms coupled to dissipative bosonic modes** — •Simon Balthasar Jäger — Physikalisches Institut, University of Bonn, Nussallee 12, 53115 Bonn, Germany

We develop atom-only Lindblad master equations for the description of atoms that couple with and via dissipative bosonic modes. We employ a Schrieffer-Wolff transformation to decouple the bosonic from the atomic degrees of freedom in the parameter regime where the decay of the bosonic degrees is much faster than the typical relaxation time of the atoms. In this regime we derive the transformation which includes the most relevant retardation effects between the bosonic and the atomic degrees of freedom. After the application of this transformation, the effective Lindblad master equation is obtained by tracing over the bosonic degrees of freedom and captures the atomic interactions and dissipation mediated by the bosons. We use this approach to derive Lindblad master equations which can describe the phase transitions, steady states, and dynamics in the dissipative Dicke model. In addition, we show that such master equations can be used in presence of resonant periodic driving and predict the formation and stabilization of dissipative Dicke time crystals. We also discuss how to extend the theory to describe systems with continuous symmetries where descriptions with the Redfield master equation fail. Our work provides general methods for the efficient theoretical description of retarded boson-mediated interactions and dissipation.

QI 24.2 Wed 15:00 HS I

**Accurate Master Equation Formalism for Molecular Quantum Optics Systems** — •Burak Gurlek[1], Claudiu Genes[2], and Angel Rubio[1,3] — [1]Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany — [2]Max Planck Institute for the Science of Light, Erlangen, Germany — [3]Center for Computational Quantum Physics, The Flatiron Institute, New York, USA

Molecules are compact, hybrid quantum systems that provide access to electronic, vibrational and spin degrees of freedom spanning a broad range of energy and time scales. They already been shown to realize efficient single-photon sources and nonlinear quantum optical element, and hold great promise for advancing quantum technologies. These developments require a thorough understanding of complex molecular interactions in open quantum settings, typically modeled using the standard Lindblad master equation formalism.

In this work, we demonstrate that strong optomechanical interactions in an important class of dye molecules lead to couplings between reservoirs within the standard master equation framework, resulting in erroneous predictions. To address this, we derive a dressed master equation, and recover previous experimental observations. We complement this with analytical expressions for spectral observables derived from quantum Langevin equations, using a standard master equation in the polaron frame. Our results highlight the importance of strong optomechanical interactions in molecular systems and demonstrate how to accurately account for these effects in the dynamics of open molecular quantum system.

QI 24.3 Wed 15:15 HS I

**Open system dynamics with quantum degenerate gases** — •Julian Lyne[1,2], Nico Bassler[2,1], Kai Phillip Schmidt[2], and Claudiu Genes[1,2] — [1]Max Planck Institute for the Science of Light, Staudtstraße 2, D-91058 Erlangen, Germany — [2]Department of Physics, Friedrich-Alexander Universität Erlangen-Nürnberg (FAU), Staudtstraße 7, D-91058 Erlangen, Germany

An ensemble of coupled two-level quantum emitters may display collective radiative effects such as super- and subradiance. Such systems are usually treated within the standard open system theory of quantum optics, where small emitter separations lead to collective decay channels and coherent dipole-dipole interactions. This approach can be extended to the quantum degenerate regime [1], where there is an interplay between the particle statistics and the effects brought on by the cooperative radiative response. In the quantum degenerate regime already for independent emitters the rate of spontaneous emission can be enhanced for bosons, as intuitively expected by the symmetrization condition of the wavefunction, and may be completely suppressed for fermions, owing to the Pauli exclusion principle. We present our recent work investigating radiative properties of harmonically trapped fermionic and bosonic atomic gases using a master equation approach, where we investigate some restricted many-body scenarios and employ cumulant expansion methods.

[1] M. Lewenstein et al., Physical Review A 50, 2207 (1994).

QI 24.4 Wed 15:30 HS I

**Collective excitations of dissipative time crystals** — •Gage Harmon[1], Giovanna Morigi[1], and Simon Jäger[2] — [1]Saarland University — [2]University of Bonn

We present a Floquet-theoretic description of atoms interacting periodically with a dissipative optical cavity. We derive an effective atom-only master equation, valid in the bad cavity regime. Using this theory, we analyze the excitation spectrum of the atoms across the transition from a normal phase to a time-crystalline phase. We identify features in the excitation spectra, such as mode softening when crossing a continuous equilibrium transition, that suggest a dynamical phase transition. We then analyze the excitation spectra when the periodic drive crosses a bistable regime and observe sudden jumps in the oscillation frequencies and relaxation rates. Finally, we discuss how these results can be detected experimentally by probing the cavity with an additional monochromatic drive. Our work provides important tools for analyzing the response of dynamical out-of-equilibrium phases.

QI 24.5 Wed 15:45 HS I

**Continuous similarity transformations for Lindbladians** — •Lea Lenke and Kai Phillip Schmidt — FAU Erlangen-Nürnberg

The established approach of perturbative continuous unitary transformations (pCUTs) constructs effective block-diagonal quantum many-body Hamiltonians as a perturbative series. We extend the pCUT method to similarity transformations – dubbed pcst$^{++}$ – allowing for more general and non-Hermitian operators [1]. We apply the pcst$^{++}$ method to the Lindbladian describing the dissipative transverse field Ising chain. In the subsequent treatment of the obtained effective Lindbladian, we take advantage of its block-diagonal structure and perform a linked-cluster expansion obtaining results that are valid in the thermodynamic limit. In the next step, we aim at generalizing the method of directly evaluated enhanced perturbative continuous unitary transformations (deepCUTs) to non-Hermitian operators.

[1] L. Lenke, A. Schellenberger, and K. P. Schmidt, "Series expansions in closed and open quantum many-body systems with multiple quasiparticle types", Phys. Rev. A 108, 013323 (2023).

QI 24.6 Wed 16:00 HS I

**Heat transport between small spherical objects** — •Nico Strauss and Stefan Yoshi Buhmann — Institute of Physics, University of Kassel, 34132 Kassel, Germany

The second law of thermodynamics dictates that heat naturally flows from warm to cold objects, thereby providing a direction of time [1]. In the context of quantum optics within nonreciprocal media [2], an arrow of time is alternatively provided by the observation that optical paths cannot be reversed. How are these two notions compatible at the level of quantum electrodynamics?

To address this question, we investigate nanoscale heat transfer between three small spherical media that display a temperature gradient of $T_3 > T_2 > T_1$ [3]. We express the result in terms of the spheres' polarizabilities and analyze the impact of various material properties and external fields on the heat transfer occurring between the spheres, as well as their interplay with the second law of thermodynamics in the near-field regime.

[1] Volokitin, A. I., Persson, B. N. J. Rev. Mod. Phys. **4**, 79 (2007).
[2] S. Y. Buhmann, et al, New J. Phys. **14**, 083034 (2012).
[3] K. Joulain, et al, Surface Science Reports **57**, 59*112 (2005).

## QI 25: Members' Assembly

Time: Wednesday 17:00–18:30 Location: HS 7

**All members of the Quantum Information Division are invited to participate.**

# QI 26: Quantum Communication I: Theory

Time: Thursday 11:00–12:45 Location: HS IX

**Invited Talk** QI 26.1 Thu 11:00 HS IX

**Device-independent randomness amplification** — •Ramona Wolf — Universität Siegen

Randomness is a regular part of our (more or less) daily lives: from drawing lottery numbers to running computer simulations and the security of cryptographic schemes, various applications rely on random numbers. But does true randomness actually exist? If so, can we create truly random numbers in our labs? Conventional random number generators based on classical physical processes face a fundamental problem, namely the possibility that attackers can predict their results by examining the microscopic degrees of freedom, thereby eroding their fundamental unpredictability. Fortunately, quantum physics exhibits intrinsic randomness, which opens up the possibility of creating perfect randomness from an imperfect and even publicly accessible source. However, its practical realisation relies on the successful execution of a Bell test with sufficiently high Bell violation and repetition rate, making it a challenging endeavour.

In this talk, I will discuss what is necessary to realize quantum random number generators, starting with how to properly define randomness (which is a surprisingly nontrivial task!) up to explaining how to design protocols for experimentally generating truly random numbers, and reporting on recent experimental progress.

QI 26.2 Thu 11:30 HS IX

**Quantum Steering for Security Analysis of Quantum Key Distribution Protocols** — •Ritu Dhaulakhandi and Ramona Wolf — Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany

Quantum Key Distribution (QKD) protocols exploit fundamental quantum mechanical principles to ensure secure communication, even in the presence of adversaries with unlimited computational resources. The use of quantum steering, particularly steering inequalities, provides a powerful framework for analysing correlations in scenarios involving untrusted or semi-trusted devices. Inspired by the CHSH inequality, this research explores the construction and application of asymmetric CHSH-like steering inequalities (allows adaptation to unbalanced measurement settings or noise levels between communicating parties) to establish security based on locally verifiable assumptions for QKD protocols. The inequality bounds the set of correlations explainable by local hidden variable local hidden state (LHV-LHS) models, ensuring that any violation implies genuine quantum correlations. The geometric insights from the convex characterisation of the LHV-LHS model provide a robust method to verify security while minimising trust assumptions. We investigate how such inequalities can quantify the nonlocal correlations required for secure key generation and establish their operational significance in one-sided device-independent (1SDI) QKD protocols. The steering criteria derived is tailored to practical QKD setups, allowing identification of the noise and loss thresholds necessary for their violation.

QI 26.3 Thu 11:45 HS IX

**Iterative Sifting in QKD** — •Yien Liang, Hermann Kampermann, and Dagmar Bruss — Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstr. 1, D-40225 Düsseldorf, Germany

We investigate the security of a QKD scheme, where Bob announces publicly his choice of measurement basis right after each detection. Such a scheme saves memory and avoids sending all the classical information only at the end of each block. In previous work the security of such a scheme is based on Azuma's inequality [1], with reduced key rate in comparison to conventional sifting. Our work improves the bound for iterative sifting, restoring the key rate of conventional sifting. We will additionally show how to save classical communication for privacy amplification in the conventional and the iterative scheme.

Reference:
[1] Kiyoshi Tamaki et al 2018 Quantum Sci. Technol. 3 014002

QI 26.4 Thu 12:00 HS IX

**Secure quantum bit commitment from separable operations** — •Ziad Chaoui[1], Anna Pappa[1], and Matteo Rosati[2] — [1]Technische Universität Berlin, Berlin, Germany — [2]Università degli studi di Roma Tre, Rome, Italy

Bit Commitment is a fundamental cryptographic primitive in both classical and quantum cryptography and a building block for many two party cryptographic protocols, such as zero-knowledge proofs. However it has been proven that unconditionally secure quantum bit commitment cannot exist. We show that restricting the committing party to separable operations leads to secure quantum bit commitment schemes. Specifically, we prove that in any perfectly hiding bit commitment protocol, a committing party restricted to separable operations will be detected with high probability when attempting to switch their commitment. To illustrate our results, we present an example protocol.

QI 26.5 Thu 12:15 HS IX

**Security of an ensemble based quantum token against optimized atacks** — •Bernd Bauerhenne[1], Lucas Tsunaki[2], Malwin Xibraku[1], Boris Naydenov[2], Martin Garcia[1], and Kilian Singer[1] — [1]Department of Physics, University of Kassel, Heinrich-Plett-Str. 40, 34132 Kassel, Germany — [2]Helmholtz-Zentrum Berlin, Hahn-Meitner-Platz 1, 14109 Berlin, Germany

We introduce quantum coins, which are composed of discrete quantum tokens, each containing an ensemble of identical qubits. These quantum coins are initialized by a banking entity that encodes a unique, secret quantum state into each token by aligning all qubits in a token to a uniform state. The integrity of the coin is subsequently verified through sequential assessments of these quantum tokens. During this verification process, the bank executes measurements on the qubits using the known secret angles from the initialization. A quantum token is deemed valid if a critical threshold number of its qubits are measured in the ground state. A coin is considered authentic and accepted if it contains a sufficient number of validated tokens.

Our discussion also explores potential vulnerabilities to forgery, examining scenarios wherein a malicious actor attempts to replicate the quantum coins. We present a detailed analysis of various attack strategies and demonstrate that, even with optimized methods, the probability of such counterfeit coins being accepted by the bank is negligibly small. This analysis not only emphasizes the robustness of our proposed quantum coin system against duplication attempts but also enhances its application potential in secure quantum currency systems.

QI 26.6 Thu 12:30 HS IX

**Security of Super Dense Coding under Pauli Noise** — •Ghislaine Coulter-de Wit, Hermann Kampermann, and Dagmar Bruss — Institute for Theoretical Physics III, Heinrich Heine University Düsseldorf, D-40225 Düsseldorf, Germany

Super dense coding is a form of quantum communication utilizing shared entanglement such that - in the simplest formulation - Bob receives a message 2 bits long from one qubit sent by Alice.

The real world contains noise and untrustworthy parties (eavesdroppers). Building off the work of Zarah Shadman et al. [New Journal of Physics 12, 073042 (2010)] on noisy super dense coding, we are interested in the security of the transmitted classical data. As such, we focus on the amount of information that a disreputable party could determine. To do this, we consider Pauli noise for different scenarios of the entanglement distribution. We compare and contrast the super dense coding capacity for the given scenarios through the Holevo quantity and explore bounds on the information which an eavesdropper can obtain.

## QI 27: Quantum Error Correction

Time: Thursday 11:00–12:30 Location: HS VIII

**Invited Talk** QI 27.1 Thu 11:00 HS VIII
**Fault-tolerant compiling of quantum algorithms** — •Dominik Hangleiter — Simons Institute, UC Berkeley

As we are entering the era of early quantum fault-tolerance, the question how to most efficiently make use of fault-tolerant quantum resources comes into focus. This question is addressed by fault-tolerant compiling, meaning a codesign of an error-correcting code, an algorithm, and the physical hardware. I will introduce this idea using two examples. First, I will describe the fault-tolerant compilation of a family of IQP circuits implemented transversally using quantum Reed-Muller codes in reconfigurable atom arrays. This yields a path towards fault-tolerant quantum advantage. Second, I will sketch an encoding in which coherent implementations of classical arithmetic—a crucial but highly expensive building block of quantum algorithms—can be achieved naturally in a reconfigurable architecture, which can give savings for certain tasks.

QI 27.2 Thu 11:30 HS VIII
**Experimental measurement and a physical interpretation of quantum shadow enumerators** — •Daniel Miller[1,2], Kyano Levi[1], Lukas Postler[3], Alex Steiner[3], Lennart Bittel[1], Gregory A.L. White[1], Yifan Tang[1], Eric J. Kuehnke[1], Antonio A. Mele[1], Sumeet Khatri[1,4,5], Lorenzo Leone[1], Jose Carrasco[1], Christian D. Marciniak[3], Ivan Pogorelov[3], Milena Guevara-Bertsch[3], Robert Freund[3], Rainer Blatt[3,6], Philipp Schindler[3], Thomas Monz[3,7], Martin Ringbauer[3], and Jens Eisert[1] — [1]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — [2]Institute for Theoretical Nanoelectronics (PGI-2), Forschungszentrum Jülich, 52428 Jülich, Germany — [3]Universität Innsbruck, Institut für Experimentalphysik, Technikerstrasse 25, 6020 Innsbruck, Austria — [4]Department of Computer Science, Virginia Tech, Blacksburg, Virginia 24061, USA — [5]Virginia Tech Center for Quantum Information Science and Engineering, Blacksburg, Virginia 24061, USA — [6]Institut für Quantenoptik und Quanteninformation, Österreichische Akademieder Wissenschaften, Otto-Hittmair-Platz 1, 6020 Innsbruck, Austria — [7]Alpine Quantum Technologies GmbH, 6020 Innsbruck, Austria

We show that Rains shadow enumerators are the same as triplet probabilities in two-copy Bell sampling. We measure them in experiments.

QI 27.3 Thu 11:45 HS VIII
**Leading Order Measurement-Free Quantum Error Correction Optimized for Rydberg Atoms** — •Katharina Brechtelsbauer[1], Sebastian Weber[1], Friederike Butt[2,3], David F. Locher[2,3], Santiago Higuera Quintero[1], Markus Müller[2,3], and Hans Peter Büchler[1] — [1]Institute for Theoretical Physics III and Center for Integrated Quantum Science and Technology, University of Stuttgart, Stuttgart, Germany — [2]Institute for Quantum Information, RWTH Aachen University, Aachen, Germany — [3]Institute for Theoretical Nanoelectronics (PGI-2), Forschungszentrum Jülich, Jülich, Germany

Large scale quantum computation requires the implementation of quantum error correction. As different platforms come along with different challenges it can be helpful to design error correction protocols and logical gate sets considering the features of the specific platform. For example, in the case of neutral atom platforms where measurements are slow, measurement-free error correction schemes offer a great alternative to feed-forward correction. Furthermore, for neutral atom platforms two- and multiqubit gates are expected to be the dominating source of noise and careful design of the gates allows to further reduce the noise model to Pauli-Z errors. In this work, we show that for such a biased noise model the measurement-free error correction protocol of the seven-qubit Steane code can be reduced. Furthermore, we develop a measurement-free universal gate set that is fault tolerant with respect to the assumed noise model. In addition, we sketch possible implementations on neutral atom platforms.

QI 27.4 Thu 12:00 HS VIII
**Characterization of errors in a CNOT between surface code patches** — •Bálint Domokos[1], Áron Márton[1], and János K. Asbóth[1,2] — [1]Budapest University of Technology and Economics — [2]HUN-REN Wigner Research Centre for Physics

As current experiments already realize small quantum circuits on error corrected qubits, it is important to fully understand the effect of physical errors on the logical error channels of these fault-tolerant circuits. Here, we investigate a lattice-surgery-based CNOT operation between two surface code patches under phenomenological error models. (i) For two-qubit logical Pauli measurements – the elementary building block of the CNOT – we optimize the number of stabilizer measurement rounds, usually taken equal to $d$, the size (code distance) of each patch. We find that the optimal number can be greater or smaller than $d$, depending on the rate of physical and readout errors, and the separation between the code patches. (ii) We fully characterize the two-qubit logical error channel of the lattice-surgery-based CNOT. We find a symmetry of the CNOT protocol, that results in a symmetry of the logical error channel. We also find that correlations between X and Z errors on the logical level are suppressed under minimum weight decoding.

QI 27.5 Thu 12:15 HS VIII
**Optimal number of stabilizer measurement rounds in an idling surface code patch** — •Janos Asboth[1] and Aron Marton[2] — [1]Budapest University of Technology and Economics — [2]RWTH Aachen University

Logical qubits can be protected against environmental noise by encoding them into a highly entangled state of many physical qubits and actively intervening in the dynamics with stabilizer measurements. In this work [1], we numerically optimize the rate of these interventions: the number of stabilizer measurement rounds for a logical qubit encoded in a surface code patch and idling for a given time. We model the environmental noise on the circuit level, including gate errors, readout errors, amplitude and phase damping. We find, qualitatively, that the optimal number of stabilizer measurement rounds is getting smaller for better qubits and getting larger for better gates or larger code sizes. We discuss the implications of our results to some of the leading architectures, superconducting qubits, and neutral atoms.

[1] arXiv:2408.07529

## QI 28: Decoherence and Open Quantum Systems (joint session QI/Q)

Time: Thursday 11:00–12:45 Location: HS II

**Invited Talk** QI 28.1 Thu 11:00 HS II
**Quantum-Classical Hybrid Theories - Feedback Control and Environment Purification** — •Patrick P. Potts — University of Basel, Switzerland

Quantum-classical hybrid theories describe scenarios where quantum degrees of freedom interact with classical degrees of freedom. The need for such theories becomes particularly clear in feedback control, where classical measurement outcomes are fed back to a quantum system to influence its dynamics. Additionally, quantum-classical hybrid theories can be used to model a quantum system interacting with a large but finite-sized environment. In this case, the classical degree of freedom can be the magnetization of the environment.

I will present two examples of quantum-classical hybrid theories. The quantum Fokker-Planck master equation (QFPME) that describes continuous feedback control and the extended microcanonical master equation (EMME) that describes a qubit coupled to a bath of two-level systems. The QFPME allows for obtaining analytical results for feedback scenarios that previously were only accessible using numerical methods. The EMME allows for keeping track of the magnetization of the bath, as well as the classical correlations between system and bath. These methods will be illustrated with simple but relevant examples.

QI 28.2 Thu 11:30 HS II

**Emergent decoherent histories from first principles** — •Philipp Strasberg — Instituto de Física de Cantabria (IFCA), Santander, Spain

I overview recent progress about the emergence of decoherent histories from first principles, i.e., without the use of ensembles or approximations to the Schroedinger dynamics — akin to approaches in pure state statistical mechanics. After briefly reviewing the importance of decoherent histories to understand a unitarily evolving quantum Universe, I show that generic (non-integrable) many-body systems are characterized by an exponential suppression of interference effects (as a function of the particle number of the system) whereas integrable systems are characterized by a much weaker form of decoherence. I conclude with an outlook about how (long) (de/re)coherent histories shape the structure of the Multiverse, a hitherto unappreciated phenomenon.

QI 28.3 Thu 11:45 HS II

**Quantum synchronization of twin limit-cycle oscillators** — •Tobias Kehrer[1], Parvinder Solanki[2], and Christoph Bruder[1] — [1]Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland — [2]Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

Limit cycles in classical systems are closed phase-space trajectories to which the system converges regardless of its initial state. Their quantum counterparts have been proposed for open quantum systems, exhibiting steady-state phase-space representations with ring-like structures of stable radius but no phase preference. The synchronization of such quantum systems has been studied extensively in the past decade, where an external drive can localize the phase of the steady state. Unlike in classical systems, quantum synchronization can exhibit coherence cancellations, leading to a synchronization blockade.

In this work, we propose a quantum system whose classical analogue features two limit cycles. In the classical analogue, the system can end up in either one of the limit cycles, defined by their basins of attraction and choice of initial states. In the quantum system, both limit cycles coexist independently of the initial state, i.e., the Wigner function of the steady state features two rings. Adding an external drive to a single oscillator, its limit cycles localize to distinct phases, exhibiting different synchronization behaviors within the same system. Furthermore, we demonstrate that coupling two such twin limit-cycle oscillators leads to simultaneous synchronization and synchronization blockades between different limit cycles of oscillator A and B.

QI 28.4 Thu 12:00 HS II

**Exact Floquet Dynamics of Strongly Damped Open Quantum Systems** — •Konrad Mickiewicz, Valentin Link, and Walter T. Strunz — Institut für Theoretische Physik, Technische Universität Dresden, D-01062, Dresden, Germany

Recent developments in simulating open quantum systems utilize Matrix Product Operator (MPO) representations to capture the temporal correlations of strongly coupled non-Markovian environments. A novel highly effective approach based on infinite MPO methods [1] yields a semigroup propagator for the open system evolution. We present how this semigroup structure can be exploited to efficiently describe periodically driven dynamics in the presence of strongly interacting environments. In particular, we are able to construct an exact Floquet propagator, enabling the direct extraction of asymptotic Floquet states without resorting to real-time evolution. We apply our results to the driven spin-boson and two-spin-boson models. In the latter, we show that the amount of entanglement generated between the qubits can be increased significantly via local driving of the system. [1] V. Link, H.-H. Tu, and W. T. Strunz, "Open quantum system dynamics from infinite tensor network contraction" Phys. Rev. Lett. 132, 200403 (2024)

QI 28.5 Thu 12:15 HS II

**Open System Semigroup Dynamics beyond the Lindblad Class** — •Nadine Diesel, Charlotte Bäcker, and Walter Strunz — TUD Dresden University of Technology, Dresden, Germany

Open quantum systems are of interest in many fields of study, e.g., quantum computation and quantum optics. A powerful tool in treating dissipation in open quantum system dynamics are quantum master equations. The Lindblad (GKSL) master equation is well-known for ensuring completely positive dynamical semigroup evolution, a natural framework for physical dynamics. However, is it possible to extend the class of semigroup generators beyond the Lindblad framework? We relax the strict requirement of complete positivity by introducing the concept of local (complete) positivity. Here, dynamics are defined as locally (completely) positive if a nonempty proper subset of initial states give rise to (completely) positive quantum dynamics. We analyze the existence of such dynamics for qubits and examine their potential physical implications.

QI 28.6 Thu 12:30 HS II

**Entanglement phase transitions in boundary-driven open quantum systems** — •Darvin Wanisch[1,2], Nora Reinić[1,2], Daniel Jaschke[1,2,3], Pietro Silvi[1,2], and Simone Montangero[1,2,3] — [1]Dipartimento di Fisica e Astronomia "G. Galilei", Università di Padova, I-35131 Padova, Italy — [2]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Padova, I-35131 Padova, Italy — [3]Institute for Complex Quantum Systems & Center for Integrated Quantum Science and Technology, Ulm University, 89069 Ulm, Germany

We present a numerical framework based on tree tensor networks that enables large-scale simulations of open quantum many-body systems and the efficient computation of entanglement monotones. We apply this framework to a paradigmatic open-system problem, the boundary-driven XXZ spin-chain. Our results demonstrate the framework's capability to probe entanglement in open systems and distinguish it from correlations with the environment. Furthermore, we find that the system undergoes entanglement phase transitions in both the coupling to the environment and the anisotropy parameter. Regarding the latter, our results connect the known transport regimes of the model to different entanglement phases, i.e., separable, area-law, and volume-law. Our work paves the way toward exploring entanglement in open systems, a necessary step for the development of scalable quantum technologies.

## QI 29: Quantum Information: Concepts and Methods I

Time: Thursday 11:00–13:15 Location: HS IV

**Invited Talk** QI 29.1 Thu 11:00 HS IV

**Measurement-induced entanglement and complexity in shallow 2D quantum circuits** — •Max McGinley[1], Wen Wei Ho[2], and Daniel Malz[3] — [1]Cambridge University, UK — [2]NUS, Singapore — [3]University of Copenhagen, Denmark

There has been a great deal of recent interest in understanding how measurements can influence the dynamics of entanglement in many-body systems. In this talk, I will elucidate how long-ranged entanglement can be generated by measuring states prepared by constant-depth 2D quantum circuits, and discuss implications for the complexity of random circuit sampling. We introduce a new theoretical technique, based on ideas from multi-user quantum Shannon theory, which allows us to establish a rigorous lower bound on the amount of entanglement generated by measurements in this setting. Our method avoids the so-called replica approach—the main tool employed for studying such problems so far—which gives concrete results only in the simplest of scenarios. Using this technique, we prove a recent conjecture about generic (random) 2D shallow circuits followed by measurements: Namely, that above some $O(1)$ critical depth, extensive long-ranged measurement-induced entanglement is produced, even though the pre-measurement state is strictly short-ranged entangled. As a consequence of this result, we establish strong evidence that sampling from generic shallow-depth quantum circuits yields a quantum advantage, and analogously that contracting random 2D tensor networks is classically hard above a constant critical bond dimension.

QI 29.2 Thu 11:30 HS IV

**Learning Feedback Mechanisms for Measurement-Based Variational Quantum State Preparation** — •Daniel Alcalde Puente[1,2] and Matteo Rizzi[1,2] — [1]Forschungszentrum Jülich, Institute of Quantum Control, Peter Grünberg Institut (PGI-8), 52425 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, 50937 Köln, Germany

This work introduces a self-learning protocol that incorporates measurement and feedback into variational quantum circuits for efficient quantum state preparation. By combining projective measurements with conditional feedback, the protocol learns state preparation strategies that extend beyond unitary-only methods, leveraging measurement-based shortcuts to reduce circuit depth. Using the spin-1 Affleck-Kennedy-Lieb-Tasaki state as a benchmark, the protocol learns high-fidelity state preparation by overcoming a family of measurement induced local minima through adjustments of parameter update frequencies and ancilla regularization. Despite these efforts, optimization remains challenging due to the highly non-convex landscapes inherent to variational circuits. The approach is extended to larger systems using translationally invariant ansätze and recurrent neural networks for feedback, demonstrating scalability. Additionally, the successful preparation of a specific AKLT state with desired edge modes highlights the potential to discover new state preparation protocols where none currently exist. These results indicate that integrating measurement and feedback into variational quantum algorithms provides a promising framework for quantum state preparation.

QI 29.3 Thu 11:45 HS IV

**Stabilizer entropies are monotones for magic-state resource theory** — •Lorenzo Leone and Lennart Bittel — FU Berlin

Magic-state resource theory is a powerful tool with applications in quantum error correction, many-body physics, and classical simulation of quantum dynamics. Despite its broad scope, finding tractable resource monotones has been challenging. Stabilizer entropies have recently emerged as promising candidates (being easily computable and experimentally measurable detectors of nonstabilizerness) though their status as true resource monotones has been an open question ever since. In this Letter, we establish the monotonicity of stabilizer entropies for $\alpha \geq 2$ within the context of magic-state resource theory restricted to pure states. Additionally, we show that linear stabilizer entropies serve as strong monotones. Furthermore, we extend stabilizer entropies to mixed states as monotones via convex roof constructions, whose computational evaluation significantly outperforms optimization over stabilizer decompositions for low-rank density matrices. As a direct corollary, we provide improved conversion bounds between resource states, revealing a preferred direction of conversion between magic states. These results conclusively validate the use of stabilizer entropies within magic-state resource theory and establish them as the only known family of monotones that are experimentally measurable and computationally tractable.

QI 29.4 Thu 12:00 HS IV

**Channels and Dynamics Are Almost Always Diagonalizable** — •Frederik vom Ende — Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany

While the Choi matrix of a quantum channel can always be diagonalized—even unitarily—it remains a surprisingly common misconception that the same is true for the channel itself (or, equivalently, for its representation matrix in the standard basis). To clarify this, we provide simple examples of channels that exhibit non-trivial Jordan blocks. The main contribution of this work then is a proof of the statement: *"The collection of all elements of $\mathcal{S}$ that have only simple eigenvalues is dense in $\mathcal{S}$"* for various sets $\mathcal{S}$, including: all quantum channels, unital channels, positive trace-preserving maps, Lindbladians (GKSL-generators), and time-dependent Markovian channels. In particular, this result demonstrates that any element from each of these sets can be approximated to arbitrary precision by diagonalizable elements within the same set.

QI 29.5 Thu 12:15 HS IV

**Information processing without directional reference** — •Konrad Szymański[1] and Fynn Otto[2] — [1]Research Center for Quantum Information, Bratislava — [2]Universität Siegen, Siegen

If a quantum operation commutes with a group of transformations, it is called group-covariant. In practical scenarios, the unknown group transformation may contribute to noise, represent a parameter to be estimated, or intentionally scramble information. In all these cases, there exist nontrivial operations which can be applied before or after the transformation with the same final result. Here, we present the recent observations related to SU(2) covariance. This group can be interpreted as physical spin rotations or passive 2-mode optical interferometry. We demonstrate how to characterize the states accessible with SU(2)-covariant operations, and discuss the applicability of this theory to quantum information processing tasks, including a variant of quantum key distribution performed without a shared reference frame, and probabilistic amplification of interferometer sensitivity.

QI 29.6 Thu 12:30 HS IV

**Towards constructing a parity interferometer** — •Freyja Ullinger, Kaisa Laiho, and Matthias Zimmermann — German Aerospace Center (DLR), Institute of Quantum Technologies, 89081 Ulm, Germany

In continuous-variable quantum information [1], it is important to characterize quantum states in order to verify the quality of the preparation and to test the output of protocols [2]. For this purpose, we apply the quantum-mechanical parity operator which enables the reconstruction of the phase-space representation of a quantum state [3,4]. However, the implementation of a parity measurement is a subtle issue as many existing schemes are restricted to the particular sets of states to be probed.

In this talk, we present a scheme for parity measurements independent of the physical quantum system. In particular, we reveal the key components necessary for the construction of a parity interferometer. The output of our device measures the parity of a general initial state. We further exploit possible implementations and discuss limitations in such experimental arrangements.

[1] A. L. Braunstein und A. K. Pati, Quantum Information with Continuous Variables (Kluwer Academic Publishers, Dordrecht, 2001).

[2] A. I. Lvovsky and M. G. Raymer, Rev. Mod. Phys. **81**, 299 (2009).

[3] A. Royer, Phys. Rev. A **15**, 449 (1977).

[4] F. Ullinger, 'Interference effects in quadratic potentials', Master's thesis (Ulm University, Ulm, 2022).

QI 29.7 Thu 12:45 HS IV

**Symmetry analysis of Two-Local Quantum Spin Dynamics** — •Roberto Gargiulo[1,2] and Robert Zeier[1] — [1]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), 52425 Jülich, Germany — [2]University of Cologne, Institute for theoretical physics (THP), 50937 Cologne, Germany

Fundamental tools in the study of dynamics of quantum systems are Lie groups and Lie algebras, which have various applications: In the context of quantum control a Lie-theoretic approach can provide answers to reachability and simulability. In addition to reachability, the knowledge of the Lie algebras corresponding to the given ansätze is necessary for understanding optimization problems in variational quantum algorithms. In many-body systems, these tools lead to a systematic description of physical models based on dynamical properties and in special cases to classical simulability.

We build upon recent work (see [1, 2, 3]), by providing a structured study and classification of Lie algebras obtained by interactions of pairs of qubits with given graph connectivity. Specifically, we consider certain sums of Pauli strings as generators, whereas previous work mainly focused on dynamics generated by single Pauli strings.

[1] Sujay Kazi et al. arXiv: 2410.05187 [quant-ph]

[2] Gerard Aguilar et al. arXiv: 2408.00081 [quant-ph]

[3] Efekan Kökcü et al. arXiv: 2409.19797 [quant-ph]

QI 29.8 Thu 13:00 HS IV

**Quantifying the rotating-wave approximation of the Dicke model** — •Leonhard Richter, Daniel Burgarth, and Davide Lonigro — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstraße 7, 91058 Erlangen, Germany

We analytically find quantitative, non-perturbative bounds to the validity of the rotating-wave approximation (RWA) for the multi-atom generalization of the quantum Rabi model: the Dicke model. Precisely, we bound the norm of the difference between the evolutions of states generated by the Dicke model and its rotating-wave approximated counterpart, that is, the Tavis-Cummings model. The intricate role of the parameters of the model in determining the bounds is discussed and compared with numerical results. Our bounds are intrinsically state-dependent and, in particular, are significantly different in the cases of entangled and non-entangled states; this behaviour also seems to be confirmed by the numerics.

# QI 30: Quantum Computing and Simulation I (joint session Q/QI)

Time: Thursday 11:00–13:00 Location: AP-HS

QI 30.1 Thu 11:00 AP-HS

**Simulating scalar quantum field theories on integrated photonics platforms** — •Mauro D'Achille[1], Martin Gärttner[1], and Tobias Haas[2] — [1]Friedrich Schiller Universität, Jena, Germany — [2]Université Libre de Bruxelles, Bruxelles, Belgium

Photonic multimode systems are an emerging quantum simulation platform ideally suited for emulating non-equilibrium problems in quantum field theory. I will present a new decomposition*for the time evolution generated by a large class of field-theoretic quadratic Hamiltonians*in terms of optical elements. The peculiarity of this decomposition consists in the way the time parameter is taken into account. Indeed, for such a class, it is always possible to decouple the time evolution in time-dependent phase shift transformations by means of a proper time-independent symplectic transformation composed by squeezers and beam splitters. I will conclude with physically relevant examples and applications aimed to analyze and simulate how the entanglement entropy associated to local and non-local theories spreads over time.

QI 30.2 Thu 11:15 AP-HS

**Photonic Qubit Z-Gate Scheme from Scattering with Atomic Vapors in a 1D Waveguide Slot** — •Evangelos Varvelis and Joachim Ankerhold — Institute for complex quantum systems, University of Ulm

Photonic quantum computing offers a promising platform for quantum information processing, benefiting from the long coherence times of photons and their ease of manipulation. This paper presents a scheme for implementing a deterministic Z-gate for frequency-encoded photonic qubits, leveraging a silicon slot waveguide filled with thermal rubidium vapor. This system enhances atom-photon interactions via the Purcell effect, allowing dynamic control of nonlinearity at the few-photon level while operating efficiently at room temperature. Using a transfer matrix approach, we develop a protocol for Z-gate operation, demonstrating its robustness against non-waveguide mode coupling and disorder. Finally, we will relax the idealized assumption of monochromatic light in favor of finite bandwidth pulses. Despite these realistic considerations, our results indicate high fidelity for the proposed Z-gate.

QI 30.3 Thu 11:30 AP-HS

**Modeling Fabrication Tolerances in RF Junctions for Register-Based Trapped-Ion Quantum Processors** — •Florian Ungerechts[1], Rodrigo Munoz[1], Janina Bätge[1], Mohammad Masum Billah[1], Axel Hoffmann[1,2], Giorgio Zarantonello[1,3], and Christian Ospelkaus[1,4] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Germany — [2]Institut für Hochfrequenztechnik und Funksysteme, Leibniz Universität Hannover, Germany — [3]QUDORA Technologies GmbH, Braunschweig, Germany — [4]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Radiofrequency (RF) junctions are crucial elements for enabling two-dimensional structures in the Quantum Charge-Coupled Device (QCCD) architecture and are thus essential for scaling trapped-ion quantum processors. As the resulting pseudopotential and its attributes depend on the specific junction geometry, they are susceptible to fabrication tolerances. To address this challenge, our study incorporates common microfabrication errors, including feature over- and underexposure and corner rounding, into the simulation models. Utilizing this comprehensive toolset, we evaluate an optimized RF X-junction in a surface-electrode trap, assessing its robustness against typical errors encountered in the multilayer microfabrication process.

QI 30.4 Thu 11:45 AP-HS

**Local Control in a Sr quantum computing demonstrator** — •Kevin Mours[1,3], Eran Reches[1,3], Robin Eberhard[1,3], Dimitrios Tsevas[1,3], Zhao Zhang[1,3], Lorenzo Festa[1,3], Max Melchner[1,2,3], Andrea Alberti[1,2,3], Sebastian Blatt[1,2,3], Johannes Zeiher[1,2,3], and Immanuel Bloch[1,2,3] — [1]Max-Planck Institut für Quantenoptik, 85748 Garching, Germany — [2]Fakultät für Physik, Ludwig-Maximilians-Universität München, 80799 Munich, Germany — [3]Munich Center for Quantum Science and Technology, 80977 Munich, Germany

Digital quantum simulations and quantum error correction protocols require the application of local gates. We demonstrate such local control in a neutral atom array platform by locally shifting the qubit's frequency using off-resonant light. We show precise, highly parallel, local Z-rotations with low crosstalk. Together with global X-rotations, which have been optimized for minimizing motional entanglement using optimal control, this approach can be used to locally implement universal single-qubit operations.

QI 30.5 Thu 12:00 AP-HS

**Programmable Fermionic Quantum Simulation with Ground-State Optical Tweezer Arrays** — •Jin Zhang[1], Naman Jain[1], Marcus Culemann[1,2], Kirill Khoruzhii[1,2], Jun Ong[1], Xinyi Huang[1], Pragya Sharma[1], and Philipp Preiss[1,3] — [1]Max Planck Institute of Quantum Optics, Garching — [2]Ludwig-Maximilians-Universität, Munich — [3]Munich Center for Quantum Science and Technology

Programmable quantum simulation using ultracold fermions in optical lattices has emerged as a powerful approach to investigating many-body phenomena and non-equilibrium dynamics. Nonetheless, the initialization of arbitrary quantum states remains a significant challenge. Recent advances in optical tweezer arrays offer a promising solution for creating programmable initial states. Leveraging the reconfigurability of tweezers, atoms can be arranged into arbitrary spatial configurations. When combined with optical lattices and site- and spin-resolved imaging techniques, this setup establishes an ideal platform for quantum information studies. In this presentation, we demonstrate the rapid and high-fidelity preparation of optical tweezer arrays, achieving deterministic trapping of fermionic atom pairs in the motional ground state of each tweezer. We showcase spin-dependent free-space imaging, efficient loading and evaporation protocols, as well as deterministic control of atom numbers within the tweezer arrays. These advancements expand the scope of quantum simulation beyond ground-state Hubbard physics, enabling exploration of quantum chemistry and fermionic quantum information processing.

QI 30.6 Thu 12:15 AP-HS

**Towards cavity-mediated entanglement within an atomic array** — •Johannes Schabbauer[1], Stephan Roschinski[1], Franz von Silva-Tarouca[1], and Julian Leonard[1,2] — [1]TU Wien, Atominstitut, Vienna Center for Quantum Science and Technology (VCQ), Stadionallee 2, 1020 Wien, Austria — [2]Institute of Science and Technology Austria (ISTA), Am Campus 1, 3400 Klosterneuburg, Austria

Creating multi-particle entangled states deterministically is one of the big challenges for quantum information processing. While this was achieved locally in several systems, for instance with arrays of optical tweezers using Rydberg interactions between atoms, we set up an experiment to engineer non-local interactions between single atoms in optical tweezers by strong coupling to an optical cavity. In our experiment we reach the single-atom strong-coupling regime using a fiber cavity (C=80). Our cavity setup also enables good optical access for high resolution microscopes, which are used for trapping, site-resolved imaging and addressing of single atoms in optical tweezers. Our experiment enables us to study multi-particle entangled states and many-body systems with programmable interactions. The dispersive shift of the cavity resonance can be used to perform non-destructive measurements and to implement protocols for dissipative state preparation.

QI 30.7 Thu 12:30 AP-HS

**Neutral Ytterbium atoms in optical tweezers for quantum computing and simulation** — •Jonas Rauchfuss[1], Tobias Petersen[1], Nejira Pintul[1], Clara Schellong[1], Jan Deppe[1], Carina Hansen[1], Koen Sponselee[1], Alexander Ilin[1], Klaus Sengstock[1,2], and Christoph Becker[1,2] — [1]Center of Optical Quantum Technologies University of Hamburg, Luruper Chaussee 149, 22761 Hamburg — [2]Institute for Quantum Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg

In recent years, neutral atoms have emerged as a promising platform for quantum computing and quantum simulation, featuring scalable and highly coherent quantum systems with high-fidelity single-atom control as well as engineerable strong long range interactions. We use the alkaline-earth-like element ytterbium, whose fermionic isotope $^{171}$Yb features a rich level structure, allowing e.g. for optical trapping and manipulation of Rydberg states, as well as metastable states, offering the realisation of sophisticated qubit schemes.

In this talk, we introduce our experimental setup, show characterisations of tweezer loading and imaging, and present our current progress towards building a neutral-atom quantum simulator. We further present efforts to overcome known limitations of current quantum computation and simulation platforms, like arbitrary atom addressing techniques and efficient suppression of servo induced laser noise for highest fidelity excitation schemes.

QI 30.8 Thu 12:45 AP-HS

**Eigen-SNAP gate of two photonic qubits coupled via a transmon** — •Marcus Meschede[1] and Ludwig Mathey[1,2,3] — [1]Institut für Quantenphysik, Universität Hamburg, 22761 Hamburg, Germany — [2]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany — [3]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg, Germany

In the pursuit of robust quantum computing, bosonic qubits encoded in cavity modes have emerged as a promising platform. Full control over single bosonic qubits can be achieved through bosonic mode displacement drives and the driving of a dispersively coupled ancilla. However, the implementation of two-qubit gates depends heavily on the specifics of the coupling between the two bosonic modes. Building on the design of the selective number-dependent phase (SNAP) gate for the single cavity system, we extend this concept to develop the eigen-SNAP gate. This gate operates on the eigenmodes of the two coupled bosonic modes. Using the eigen-SNAP gate, we implement an entangling gate on a system of two logical bosonic qubits. Further, we use numerical optimization to determine the optimal version of the entangling gate $\sqrt{\mathrm{SWAP}}$. The fidelities of these optimal protocols are limited by the coherence times of the system's components. The entangling gate is compatible with bosonic error-correctable encodings and is agnostic to the specific encoding within this class of logical qubits, paving the way to continuous variable quantum computing.

## QI 31: Quantum Sensing II (joint session Q/QI)

Time: Thursday 11:00–12:45 Location: HS I PI

**Invited Talk** QI 31.1 Thu 11:00 HS I PI

**New Opportunities for Sensing via Continuous Measurement** — •Dayou Yang, Susana F. Huelga, and Martin B. Plenio — Institute of Theoretical Physics, University of Ulm, Ulm, Germany

The continuous monitoring of driven-dissipative quantum optical systems provides key strategies for the implementation of quantum metrology, with prominent examples ranging from the gravitational wave detectors to the emergent driven-dissipative many-body sensors. Fundamental questions about the ultimate performance of such a class of sensors remain open—for example, how to perform the optimal continuous measurement to unlock their ultimate precision; how to effectively enhance their precision scaling towards the Heisenberg limit? In this talk I will present our recent theoretical efforts towards answering these questions. In the first part I will present a universal backaction evasion strategy for retrieving the full quantum Fisher information from the nonclassical, temporally correlated fields emitted by generic open quantum sensors, thereby to achieve their fundamental precision limit. In the second part I will introduce dissipative criticality as a resource for nonclassical precision scaling for continuously monitored open quantum sensors, by establishing universal scaling laws of the quantum Fisher information in terms of critical exponents of generic dissipative critical points.

QI 31.2 Thu 11:30 HS I PI

**Efficient simulations for long time dynamics of interacting quantum gases** — •Annie Pichery and Naceur Gaaloul — Institut für Quantenoptik, Leibniz Universität Hannover, Germany

Ultra-cold atomic ensembles are a prime choice for sources in quantum sensing experiments. In the case of atom interferometry, long interrogation times are highly desirable to obtain high precision results. This requires a great control of the input states in term of size and position dynamics, as well as an efficient description of the dynamics along the different steps of the evolution time.

Space provides an environment where atom clouds can float for extended times of several seconds, as well as miscibility conditions not possible on ground. However, simulating such dynamics of single species Bose-Einstein Condensates (BEC) or interacting dual species BEC mixtures presents computational challenges due to the long expansion times and centre of mass motion induced by a displacement of the atom clouds. In this contribution, we present scaling techniques to overcome these limits. We focus also on simulation methods to interpret experiments with non-harmonic potentials or including effects of wavefront aberrations during the pulse sequences of atom interferometry.

QI 31.3 Thu 11:45 HS I PI

**Measuring Beam Displacements via Weak Value Amplification** — •Carlotta Versmold[1,2,3], Jan Dziewior[1,2,3], Florian Huber[1,2,3], Lev Vaidman[4], and Harald Weinfurter[1,2,3] — [1]Ludwig-Maximilians-Universität, Germany — [2]Max-Planck-Institut für Quantenoptik, Germany — [3]Munich Center for Quantum Science and Technology, Germany — [4]Tel-Aviv University, Israel

Weak value amplification enables precise measurement of a laser beam's small angular and spatial displacements using interferometric setups. While traditionally limited to detecting displacements inside the interferometer, we present a system that detects external beam displacements through amplification in the dark port of the interferometer. Simultaneously, the beam can be spatially filtered since displacements are suppressed in the bright port. Using a Sagnac-type interferometer with a dove prism in one arm, external displacements are mirrored in this arm, which induces a relative deflection between the two interferometer arms, shifting the center of mass of the interference pattern. This shift is given by the initial displacements amplified by the weak value of the pre- and postselected interferometer states. With an amplification by a factor of up to 20, this experiment clearly demonstrates and also extends the applicability of the weak value measurement methods.

QI 31.4 Thu 12:00 HS I PI

**Probing free-electron-photon entanglement with quantum eraser experiments** — •Jan-Wilke Henke[1,2], Hao Jeng[1,2], and Claus Ropers[1,2] — [1]Max Planck Institute for Multidisciplinary Sciences, Göttingen, Germany — [2]University of Göttingen, 4th Physical Institute, Göttingen, Germany

Quantum entanglement is central to most emerging quantum technologies including quantum computation and sensing. While the interaction of free electrons with optical fields is expected to induce free electron-photon entanglement [1,2], its demonstration remains an outstanding challenge.

In this presentation, we propose a tangible experiment for generating and verifying quantum entanglement between free electrons and photons based on quantum erasure [3]. We introduce the basic concept, before describing possible implementations employing multiple electron beams in an electron microscope and demonstrating selected experimental key aspects. Finally, we discuss extending this scheme to entanglement tests and generating electron-electron entanglement. Such a demonstration of electron-photon entanglement will be a cornerstone of free electron quantum optics and could enable quantum-enhanced sensing in electron microscopy.

[1] O. Kfir, Phys. Rev. Lett. 123, 103602 (2019); [2] A. Konečňa, F. Iyikanat, and F. J. García de Abajo, Sci. Adv. 8, eabo7853 (2022); [3] J.-W. Henke, H. Jeng & C. Ropers, arXiv:2404.11368 (2024)

QI 31.5 Thu 12:15 HS I PI

**Theoretical treatment of a closed-loop excitation scheme for phase-sensitive RF E-field sensing using Rydberg atom-based sensors** — •Matthias Schmidt[1,2], Stephanie Bohaichuk[1], Vijin Venu[1], Harald Kübler[1,2], and James P. Shaffer[1] — [1]Quantum Valley Ideas Laboratories, 485 Wes Graham Way, Waterloo, ON N2L 0A7, Canada — [2]5. Physikalisches Institut and IQST, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

In this talk, we present theoretical work aimed at understanding radio frequency phase measurement using all-optical, atom-based electric field sensors. Atom-based radio frequency field sensors have a number of applications in communications, radar and test and measurement. All of these applications benefit from being able to detect phase, but Rydberg atom-based sensors in the steady state are square law detectors. We investigate closed-loop excitations in cesium that preserve phase information in a probe laser signal transmission amplitude coupled to one transition of the loop. Insight into the mechanisms that enable phase determination is gained by analyzing the closed-loop processes. We developed an experimental protocol that allows to measure the amplitude and phase of the incident RF wave over a wide range of parameters. Furthermore, we apply the weak probe approximation to the Lindblad-master equation and find an analytic expression for the absorption coefficient. With this expression, we gain a deeper understanding of the multi-photon interference and how this applies to phase readout in the atom-based radio frequency sensors.

QI 31.6 Thu 12:30 HS I PI

**A localized impurity in a mesoscopic system of SU($N$) fermions** — Juan Polo[1], Wayne Jordan Chetcuti[1], Anna Minguzzi[2], •Andreas Osterloh[1], and Luigi Amico[1] — [1]TII, QRC, Abu Dhabi, UAE — [2]Université Grenoble Alpes, CNRS, LPMMC, Grenoble, France

We investigate the effects of a static impurity, modeled by a localized barrier, in a one-dimensional mesoscopic system comprised of strongly correlated repulsive SU($N$)-symmetric fermions. For a mesoscopic sized ring under the effect of an artificial gauge field, we analyze the particle density and the current flowing through the impurity at varying interaction strength, barrier height and number of components. We find a non-monotonic behaviour of the persistent current, due to the competition between the screening of the impurity, quantum fluctuations, and the phenomenon of fractionalization, a signature trait of SU($N$) fermionic matter-waves in mesoscopic ring potentials. This is also highlighted in the particle density at the impurity site. We show that the impurity opens a gap in the energy spectrum selectively, constrained by the total effective spin and interaction. Our findings hold significance for the fundamental understanding of the localized impurity problem and its potential applications for sensing and interferometry in quantum technology.

## QI 32: Quantum Communication II: Implementations (joint session QI/Q)

Time: Thursday 14:30–16:30 Location: HS IX

QI 32.1 Thu 14:30 HS IX

**Darmstadt quantum local area network (DaQLAN)** — •Maximilian Tippmann[1], Florian Niederschuh[1], Maximilian Mengler[1], Erik Fitzke[2], Oleg Nikiforov[2], and Thomas Walther[1] — [1]TU Darmstadt, Institute of Applied Physics, 64289 Darmstadt — [2]Deutsche Telekom Technik GmbH, Darmstadt, Deutschland

Quantum computers can threaten today's IT infrastructure e.g. by implementing Shor's algorithm. Quantum key distribution (QKD) enables users to share a random secret, thus offering resilience against such attacks by choosing other cryptographic primitives. Many QKD systems based on various protocols have been tested. Often, these protocols are susceptible to drifts in the properties of the transmission link (e.g. changing polarization) and do not offer scalability to more than two users, hence, they are not ideal for real-world applications. We present a city-wide field test of our star-shaped QKD network enabling scalability to more than 100 users. A central untrusted node acts as a photon pair source. The phase-time coding protocol makes our setup independent of polarization drifts in the transmission links. We show results with four parties all being placed at different locations within the city and connected via field-deployed fibers exchanging pairwise keys. Our system features a complete post-processing allowing to generate real-time secure keys. Additionally, we demonstrate the plug-and-play flexibility of our network by showcasing various operation modes and combinations of receiver pairs.

QI 32.2 Thu 14:45 HS IX

**A Compact Receiver for Polarisation Encoded BB84 Quantum Key Distribution** — •Michael Steinberger[1,2], Moritz Birkhold[1,2], Michael Auer[1,2,3], Adomas Baliuka[1,2], Harald Weinfurter[1,2,4], and Lukas Knips[1,2,4] — [1]Ludwig Maximilian University (LMU), Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Universität der Bundeswehr, Neubiberg, Germany — [4]Max Planck Institute of Quantum Optics (MPQ), Garching, Germany

Quantum Key Distribution (QKD) provides secure exchange of shared secret keys, solely by exploiting the laws of quantum mechanics. Free-space optical communication allows for a range of different QKD use-cases, including short ground-to-ground links for urban environments up to key exchange with stallites. Current hardware uses telescopes with complex optics and highly efficient single-photon detection devices. To make QKD suitable for scenarios offering less space and profiting from a higher degree in mobility, our goal is to develop a very compact and integrated detection system for polarization-encoded BB84 QKD. We show how using a CMOS single photon avalanche detector array (provided by the Technical University of Vienna) with new compact electronics - trading in performance - the scalability and integrability can be clearly increased. Together with a microoptics based concept this enables a miniaturized polarisation analysis unit (PAU) on the millimeter scale.

QI 32.3 Thu 15:00 HS IX

**Optical system for bi-directional tracking in free-space quantum key distribution link** — •Akhil Gupta[1,4], Michael Auer[1,3,4], Michael Steinberger[1,4], Adomas Baliuka[1,4], Moritz Birkhold[1,4], Manpreet Kaur[1,2,4], Harald Weinfurter[1,2,4], and Lukas Knips[1,2,4] — [1]Ludwig Maximilian University of Munich, Munich, Germany — [2]Max Planck Institute of Quantum Optics, Garcing, Germany — [3]Universität der Bundeswehr München , Munich, Germany — [4]Munich Center for Quantum Science and Technology, Munich, Germany

Quantum Key Distribution (QKD) offers a secure alternative to traditional cryptographic algorithms to generate shared secret keys. We aim to establish a secure ground-to-ground communication on the few kilometers scale using simple and sturdy systems. This talk highlights the critical role of telescopes in free-space communication, enabling efficient signal transmission and reception. Our symmetrical telescope design functions as both transmitter and receiver, optimized for 850 nm (QKD signal) and 1550 nm (tracking, synchronization, and classical communication). The system addresses atmospheric challenges to ensure bidirectional stability, enabling low-loss transmission for reliable and secure quantum communication.

QI 32.4 Thu 15:15 HS IX

**Frequency conversion in a hydrogen-filled hollow core fiber** — •Anica Hamer[1], Frank Vewinger[2], Thorsten Peters[3], and Simon Stellmer[1] — [1]Physikalisches Institut, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany — [2]Institut für Angewandte Physik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany — [3]Institut für Angewandte Physik, Technische Universität Darmstadt, Darmstadt, Germany

Quantum networks, as envisioned for quantum computation and quantum communication applications, are based on a hybrid architecture. Such a layout may include solid-state emitters and network nodes based on photons as so-called flying qubits. This concept requires an efficient and entanglement-preserving exchange of photons between the individual components, which often entails frequency conversion of the photon.

Our approach is based on coherent Stokes Raman scattering (CSRS) in a dense molecular hydrogen gas. This four-wave mixing process sidesteps the limitations of nonlinear crystals, it is intrinsically broadband and does not generate an undesired background. We present broadband and polarization-preserving frequency conversion in a hydrogen-filled anti-resonant hollow-core fiber between 863 nm (InAs/GaAs quantum dots) and the telecom O-band. Disparate from related experiments that employ a pulsed pump field, we here take advantage of two coherent continuous-wave pump fields.

QI 32.5 Thu 15:30 HS IX

**QUBE-II: Compact and economical satellite-based quantum key distribution** — •Joost Vermeer for the QUBE-II-Collaboration — Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 7, 91058 Erlangen, Germany — Max Planck Institute for the Science of Light (MPL), Staudtstr. 2, 91058 Erlangen, Germany

The range of fiber-based quantum key distribution (QKD) systems is limited by the fiber's attenuation. To overcome this limit, several projects have been started in the past decade to develop satellite-based QKD systems. The cost of these systems is for a large part determined by the size, weight and power of the satellite.

Built upon predecessor mission QUBE, the goal of the QUBE-II mission is to use a small 8U CubeSat ($10 \times 20 \times 40$ cm$^3$) to perform QKD between the CubeSat and a ground station. Two integrated QKD transmitters implement polarization- and phase-encoded versions of the BB84 decoy protocol. Random optical quantum states are generated using a photonic integrated onboard quantum random number generator and transmitted to the ground station using an 80 mm optical telescope. For post-processing the same optical path is used to establish a bidirectional classical data link.

In this work, we will present the nominal operations of the QUBE-II mission. We will discuss the requirements needed for a successful QKD link and a secure quantum key, the effect hardware limitations have on the requirements and the effect these requirements have on the hardware design.

QI 32.6 Thu 15:45 HS IX

**QKD satellite QUBE - Launched and commissioned** — •Moritz Birkhold für die QUBE Konsortium-Kollaboration — Ludwig Maximilian University, Munich, Germany — Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 Munich, Germany

Since its inception in 1984, ongoing efforts have been made to bring the distinct advantages of Quantum Key Distribution (QKD)- secure generation of a cryptographic key-into practical use outside of laboratory environments. With the emergence of larger and longer fiber-based QKD networks used in urban environments, solutions for a truly global QKD backbone are being sought. Using satellites as trusted nodes can offer this solution.

The QUBE missions attempt to achieve downlink QKD with small nanosatellites using the CubeSat platform. Extensive development produced energy-efficient electronics and highly compact, robust optics based on vertical-cavity surface-emitting lasers and integrated photonics, to make this scalable form factor usable. The first of these satellites QUBE, a pathfinder mission towards QKD with nanosatellites, was launched in August 2024 and is currently in the comissioning phase, allowing for the first QKD experiments in Q1 of 2025. We will show the most recent progress of the project, most recent ground measurements as well as updates on the measurement campaign, that will lead towards the sucessor mission QUBE 2, a nanosatellite with full QKD capabilities.

QI 32.7 Thu 16:00 HS IX

**Pulse shape optimization against Doppler shifts and delays in optical quantum communication** — •Emanuel Schlake[1,2,3], Roy Barzel[1,2], Dennis Rätzel[1,2], and Claus Lämmerzahl[1,2] — [1]ZARM, University of Bremen, 28359 Bremen, Germany — [2]Gauss-Olbers Space Technology Transfer Center, University of Bremen, 28359 Bremen, Germany — [3]Department of Communications Engineering, University of Bremen, 28359 Bremen, Germany

High relative velocities and large distances in space-based quantum communication with satellites in lower earth orbits can lead to significant Doppler shifts and delays of the signal impairing the achievable performance if uncorrected. We analyze the influence of systematic and stochastic Doppler shift and delay in the specific case of a continuous variable quantum key distribution (CV-QKD) protocol and identify the generalized correlation function, the ambiguity function, as a decisive measure of performance loss. Investigating the generalized correlations as well as private capacity bounds for specific choices of spectral amplitude shape (Gaussian, single- and double-sided Lorentzian), we find that this choice has a significant impact on the robustness of the quantum communication protocol to spectral and temporal synchronization errors. We conclude that optimizing the pulse shape can be a building block in the resilient design of quantum network infrastructure.

QI 32.8 Thu 16:15 HS IX

**Dynamic Polarization State Preparation for Single-Photon Quantum Cryptography** — •Anastasios Fasoulakis, Koray Kaymazlar, Martin von Helversen, and Tobias Heindel — Institut für Festkörperphysik, Technische Universität Berlin, 10623 Berlin, Germany

Quantum Key Distribution (QKD) is the most developed application in the field of quantum information science. Prepare-and-measure type protocols thereby rely on a fast, random qubit-state preparation. In this contribution we discuss our progress in the development of fast polarization-state encoders for single-photon implementations of BB84-QKD as well as cryptographic primitives beyond QKD. Using high-bandwidth free-space optical as well as fiber-based electro-optical modulators in combination with commercial and self-built control-electronics, solid-state quantum light sources emitting at different wavelengths can be modulated. We characterise and optimise the system's performance in terms of its extinction ratio and repetition rate and gauge its potential applications in future QKD systems.

## QI 33: Quantum Materials and Many-Body Systems

Time: Thursday 14:30–16:30 Location: HS VIII

QI 33.1 Thu 14:30 HS VIII

**Criteria for Matrix-Product Representations of Quantum Many-Particle States** — •Lukas Pausch and Matthias Zimmermann — DLR e.V., Institut für Quantentechnologien, Ulm

Tensor networks [1] and in particular matrix-product states [2] have proven extremely useful for the investigation of quantum many-body states, such as, e.g., ground states of local many-body Hamiltonians. They provide an efficient description of these states, avoiding the exponential increase of Hilbert space with particle number at the cost of limiting the entanglement. In particular for matrix-product states, the relation between area laws of Rényi entanglement entropies and efficient simulability of quantum states is nowadays well understood [3]. However, it is not always clear a priori whether or not the relevant states of a given quantum system (e.g., its eigenstates) fulfil such an area law and can thus efficiently be represented by matrix-product states. By investigating specific states of relevance for many-body quantum dynamics, in particular symmetric states and Fock states, we here aim to derive criteria beyond the area law to assess for which quantum systems a description by matrix-product states or more general tensor networks is beneficial.

[1] S. Montangero, Introduction to Tensor Networks (Springer, Cham, 2018)

[2] J. I. Cirac, D. Pérez-García, N. Schuch, and F. Verstraete, Rev. Mod. Phys 93, 045003 (2021)

[3] N. Schuch, M. W. Wolf, F. Verstraete, and J. I. Cirac, Phys. Rev. Lett. 100, 030504 (2008)

QI 33.2 Thu 14:45 HS VIII

**Quantum features from classical entropies** — Yannick Deller[1], Martin Gärttner[2], •Tobias Haas[3], Markus K. Oberthaler[1], Moritz Reh[1,2], and Helmut Strobel[1] — [1]Kirchhoff-Institut für Physik, Universität Heidelberg — [2]Institut für Festkörpertheorie und Optik, Friedrich-Schiller-Universität Jena — [3]Centre for Quantum Information and Communication, Université libre de Bruxelles

Local quantum entropies are of utmost interest in characterizing quantum fields, many-body systems, and gravity. Despite their importance, being nonlinear functionals of the underlying quantum state often hinder their theoretical as well as experimental accessibility. Here, we show that suitably chosen classical entropies of standard measurement distributions capture the very same features as their quantum analogs while remaining accessible even in high-dimensional Hilbert spaces.

We demonstrate the presence of the celebrated area law for classical entropies for typical states, such as ground and excited states of a scalar quantum field. Further, we consider the post-quench dynamics of a multi-well spin-1 Bose-Einstein condensate from an initial product state, in which case we observe the dynamical build-up of quantum correlations signaled by the area law, as well as local thermalization

revealed by a transition to a volume law, both in regimes characterized by non-Gaussian quantum states and small sample numbers.
arXiv:2404.12320, 2404.12321, 2404.12323.

QI 33.3 Thu 15:00 HS VIII

**Quantum-critical interplay between continuous-symmetry breaking and topological order in the long-range interacting spin-one Heisenberg chain** — •Patrick Adelhardt[1,2], Sean R. Muleady[2], Alexey V. Gorshkov[2], and Kai P. Schmidt[1] — [1]Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany — [2]Joint Quantum Institute and Joint Center for Quantum Information and Computer Science, University of Maryland and National Institute of Standards and Technology, College Park, Maryland, USA

Recent experiments with AMO quantum simulators have demonstrated continuous symmetry breaking (CSB) in low-dimensional systems with long-range interactions, circumventing the constraint imposed by the Mermin-Wagner theorem in their short-ranged counterparts. Simultaneously, these platforms have enabled the investigations of symmetry-protected topological (SPT) phases in one-dimensional spin systems. Motivated by these experimental developments, we study the quantum phase diagram of the spin-one Heisenberg chain with staggered long-range interactions and single-ion anisotropy using matrix product states (MPS) techniques. Our study reveals the emergence of a multicritical point at the intersection of the SPT phase and CSB phases. We investigate the critical behavior along the various phase boundaries and at the multicritical point extracting critical exponents and elucidating their quantum-critical properties.

QI 33.4 Thu 15:15 HS VIII

**Fracton and topological order in the XY checkerboard toric code** — Max Vieweg and •Kai Phillip Schmidt — Frichdrich-Alexander Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germany

Topological and fraction phases are of great importance in current research due to their fascinating physical properties like entangled ground states, exotic excitations with non-trivial particle statistics or restricted mobility as well as potential applications in quantum technologies. The 2D toric code is the most paradigmatic, simplest, and exactly solvable model displaying topological order, which has been proposed as quantum memory and is relevant for quantum error correction. Consequently, the toric code plays an important role in several domains of research covering condensed matter physics, quantum optics, and quantum information.

However, the toric code has so far not been linked to the field of fracton physics. Here we introduce the XY checkerboard toric code (XYTC) connecting for the first time topological and fracton order in two dimensions within the same model. The XYTC represents a generalization of the conventional toric code with two types of star operators and two anisotropic star sublattices forming a checkerboard lattice. The quantum phase diagram is deduced exactly by a duality transformation displaying topological and type-I fracton phases.

QI 33.5 Thu 15:30 HS VIII

**Threetangle in the XY-model class with a non-integrable field background** — •Andreas Osterloh[1] and Jörg Neveling[2] — [1]TII Abu Dhabi, UAE — [2]Software Engineering, Konecranes GmbH, Düsseldorf, Germany.

The square root of the threetangle is calculated for the transverse XY-model with an integrability-breaking in-plane field component. To be in a regime of quasi-solvability of the convex roof, here we concentrate here on a 4-site model Hamiltonian. In general, the field and hence a mixing of the odd/even sectors, has a detrimental effect on the threetangle, as expected. Only in a particular spot of models with no or weak inhomogeneity $\gamma$ does a finite value of the tangle prevail in a broad maximum region of the field strength $h \approx 0.3 \pm 0.1$. There, the threetangle is basically independent of the non-zero angle $\alpha$. This system could be experimentally used as a quasi-pure source of three-tangled states or as an entanglement triggered switch depending on the experimental error in the field orientation.

QI 33.6 Thu 15:45 HS VIII

**Efficient optimization and conceptual barriers with projected entangled-pair states** — •Erik Weerda[1], Daniel Alcalde[1,2], Konrad Schröder[1], and Matteo Rizzi[1,2] — [1]University of Cologne, Cologne, Germany — [2]Forschungszentrum Jülich

Finite projected entangled-pair states (PEPS) are becoming a widely used tool in the computational study of strongly correlated systems. However, no standard set of computational tools has yet emerged to exploit the power of this approach. In this work we investigate a promising approach to ground state search with PEPS based on sampling methods. Along with presenting strategies for more efficient optimisation, we also discuss conceptual barriers associated with this approach. A benchmark illustrates the power of these tools in the study of ground states of frustrated magnetic models.

QI 33.7 Thu 16:00 HS VIII

**Post-measurement Quantum Monte Carlo** — •Kriti Baweja[1], David Luitz[1], and Samuel Garratt[2] — [1]Institute of Physics, University of Bonn, Nußallee 12, 53115 Bonn, Germany — [2]Department of Physics, University of California, Berkeley, CA 94720, USA

We study the effects of extensive measurements on many-body quantum ground and thermal states using Quantum Monte Carlo (QMC). Measurements generate density matrices composed of products of local non-unitary operators, which we expand into operator strings via a generalised stochastic series expansion (SSE). This 'post-measurement SSE' employs importance sampling of operator strings contributing to a measured thermal density matrix. Our algorithm is applied to the spin-1/2 Heisenberg antiferromagnet on a square lattice. Thermal states of this system exhibit SU(2) symmetry, which is preserved through SU(2)-symmetric measurements. We identify two classes of post-measurement states: one where correlations can be efficiently computed using deterministic loop updates, and another where SU(2)-symmetric measurements induce a QMC sign problem in any site-local basis. Using this approach, we demonstrate measurement-induced phenomena, including the creation of long-range Bell pairs, symmetry-protected topological order, and enhanced antiferromagnetic correlations. This method offers a scalable way to simulate measurement-induced collective effects, providing numerical insights to complement experimental studies. Our work opens the door to exploring how measurements influence many-body quantum systems, enabling deeper understanding of their dynamics. [1] arXiv:2410.13844

QI 33.8 Thu 16:15 HS VIII

**Symmetry-Resolved Out-of-Time-Order Correlators with Projected Matrix Product Operators** — •Martina Gisti, David Luitz, and Maxime Debertolis — Institute of Physics, University of Bonn, Nußallee 12, 53115 Bonn, Germany

Out-of-Time-Order Correlators (OTOCs) are key measures of quantum many-body chaos and information spreading. We systematically analyse OTOCs as a function of particle number for interacting spinless fermions in one dimension. With the concept of generalized operator charge, we develop a formalism for the time evolution of symmetry-projected matrix product operators, which we use to resolve the scrambling behaviour by particle number sector. Our results reveal a crossover from ballistic to diffusive dynamics at early times and a saturation regime at late times.

# QI 34: Quantum Control I

Time: Thursday 14:30–16:30 Location: HS II

QI 34.1 Thu 14:30 HS II

**Controlling Many-Body Quantum Chaos** — •Lukas Beringer[1], Mathias Steinhuber[1], Juan Diego Urbina[1], Klaus Richter[1], and Steven Tomsovic[1,2] — [1]Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany — [2]Department of Physics and Astronomy, Washington State University, Pullman, WA USA

Controlling chaos is a well-established technique that leverages the exponential sensitivity of classical chaotic systems for efficient control. This concept has been generalized to single-particle quantum systems

[1] and, more recently, extended to bosonic many-body quantum systems described by the Bose-Hubbard model [2]. In direct analogy to the classical paradigm, a localized quantum state can be transported along a specific trajectory to a desired target state. In the latter context, this approach reduces to time-dependent control of the chemical potentials, making it suitable for implementation in optical lattice experiments. Highlighted potential applications are rapid, customizable state preparation and stabilization of quantum many-body scars in one-, two-, and three-dimensional lattices. Recent progress includes potential applications to large time-crystal platforms and preparation protocols for entangled states, such as cat-like states.

[1] S. Tomsovic, J. D. Urbina, and Klaus Richter, Controlling Quantum Chaos: Optimal Coherent Targeting, PRL 130.2 (2023): 020201.

[2] L. Beringer, M. Steinhuber, J. D. Urbina, K. Richter, S. Tomsovic, Controlling many-body quantum chaos: Bose-Hubbard systems, New J. Phys (2024): 26 073002.

QI 34.2 Thu 14:45 HS II

**Distance to unreachability and quantum speed limits** — •Marco Wiedmann and Daniel Burgarth — Friedrich-Alexander Universität Erlangen-Nürnberg

Quantum speed limits provide a fundamental lower bound on how fast quantum systems can evolve towards a given target. This is particularly interesting for applications in quantum control, where decoherence limits the time available to the experimentalist. We present lower bounds on the time needed to implement any given unitary operation in a given control system. The bound crucially depends on the size of the minimal perturbation to the control system that renders the target operation unreachable. Further, we extend the result to the use case of analogue quantum simulation by bounding the minimal time needed to simulate a given Hamiltonian time evolution in the worst case.

QI 34.3 Thu 15:00 HS II

**Classical surrogates of quantum control landscapes** — •Martino Calzavara[1,2], Tommaso Calarco[1,2,3], and Felix Motzoi[1,2] — [1]Peter Grünberg Institute - Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Straße, 52428 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, Zülpicher Straße 77, 50937 Cologne, Germany — [3]Dipartimento di Fisica e Astronomia, Università di Bologna, 40127 Bologna, Italy

Since the introduction of the GRAPE algorithm for efficiently computing fidelity gradients, piecewise-constant controls have become a widely adopted ansatz for studying Quantum Optimal Control problems. The time evolution for this class of time-dependent Hamiltonians can be represented as a Parametrized Quantum Circuit, allowing us to analyze the properties of the fidelity as a function of the control pulses - the so-called Quantum Control Landscape - by employing concepts and techniques borrowed from Quantum Machine Learning (QML) and Variational Quantum Algorithms (VQA). Among these techniques are classical surrogate models, which represent the output of a quantum circuit as a linear combination of non-linear feature maps, providing valuable insights into the representational power of QML models and the structure of VQA landscapes. In this work, we employ classical surrogate models as a theoretical tool to investigate the properties of Quantum Control Landscapes, and to learn approximate representations of such landscapes using supervised learning.

QI 34.4 Thu 15:15 HS II

**Neural-network-based preparation of quantum state families: Theory and experiment** — Hector Hutin[1], •Pavlo Bilous[2], Florian Marquardt[2,3], and Benjamin Huard[1] — [1]Ecole Normale Supérieure de Lyon, CNRS, Laboratoire de Physique, 69342 Lyon, France — [2]Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany — [3]Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

Fast preparation of quantum states is a crucial ingredient for scaling up quantum computing devices. Along with the established techniques like GRadient Ascent Pulse Engineering (GRAPE), the neural-network (NN) methods are being increasingly employed for this task. However, using a NN for preparation of a fixed single quantum state implies a very slow training from scratch once a different quantum state is required.

We present a way to teach a NN quantum state preparation for a continuous family of states instead of a single state. Once trained on a random selection from the family, the NN is able to predict control signals for *any* quantum state from the family. Building up on the original theoretical proposal from Ref. [1], we introduced further theoretical developments and demonstrated the method experimentally for Schrödinger cat states [2]. The method can be useful e.g. for implementation of parametrized quantum gates requiring fast switching between quantum states.

[1] F. Sauvage and F. Mintert, Phys. Rev. Lett. 129, 050507 (2022).

[2] H. Hutin, P. Bilous et. al. arxiv.org:2409.05557 (2024).

QI 34.5 Thu 15:30 HS II

**Dissipative preparation of few-particle fractional Chern insulators** — •Luis Calvin Steinfadt, Francesco Petiziol, and André Eckardt — TU Berlin, Institut für Theoretische Physik, Hardenbergstraße 36, Berlin 10623, Germany

Fractional Chern insulators (FCIs) are lattice analogs of fractional quantum Hall systems, where the interplay of particle interactions and topological effects leads to the emergence of interesting many-body phenomena, such as long-range entanglement and anyonic excitations. These features make such systems of significant interest, especially due to their potential for quantum information technology. The purpose of investigating FCIs in a clean and controllable setting motivates efforts toward their realization in quantum simulations. Key difficulties in this context are implementing the relevant Hamiltonian through quantum simulation schemes and also driving the system toward the correlated FCI ground state. We explore the use of reservoir engineering, as can be realized in superconducting circuits, to stabilize the FCI ground state of the Harper-Hofstadter-Hubbard model. In particular, we consider realizations of the Hamiltonian based on Floquet engineering, as experimentally realized in quantum gas microscopes [1] and superconducting qubits [2]. It has been shown that these ingredients can be successfully combined to effectively prepare target Floquet states [3]. Here, they are applied to prepare small-scale bosonic Laughlin states.

[1] J. Léonard et al., Nature 619, 495-499 (2023)

[2] C. Wang et al., Science 384, 579-584 (2024)

[3] F. Petiziol, A. Eckardt, Phys. Rev. Lett. 129, 233601 (2022)

QI 34.6 Thu 15:45 HS II

**Platonic dynamical decoupling for multi-spin systems** — •Colin Read, Eduardo Serrano-Ensástiga, and John Martin — University of Liège, Liège, Belgium

In the NISQ era, where quantum information processing is hindered by the decoherence and dissipation of elementary quantum systems, developing new protocols to extend the lifetime of quantum states is of considerable practical and theoretical importance. A prominent method, called dynamical decoupling, uses a carefully designed sequence of pulses applied to a quantum system, such as a qudit, to suppress the coupling Hamiltonian between the system and its environment, thereby mitigating dissipation.

In this work, we design decoupling sequences composed solely of SU(2) operations and based on the tetrehedral, octahedral and icosahedral point groups, which we call Platonic sequences. We use a generalization of the Majorana representation for operators to develop a simple framework for establishing the decoupling properties of each sequence, whose potential application is demonstrated for many relevant quantum systems, such as spin ensembles and large atomic spins, and which are highly robust to both finite-duration pulses and systematic control errors.

QI 34.7 Thu 16:00 HS II

**Robust composite Molmer-Sorensen gate** — •Kaloyan Zlatanov, Svetoslav Ivanov, and Nikolay Vitanov — Center for Quantum Technologies, Sofia, Bulgaria

The Mølmer-Sørensen (MS) gate is a two-qubit rotational gate in ion traps that is highly valued due to its ability to preserve the motional state of the ions. However, its fidelity is obstructed by errors affecting the motion of the ions as well as the rotation of the qubits. In this work, we propose an amplitude-modulated composite MS gate which features fidelity which is robust to gate timing, detuning and coupling errors.

QI 34.8 Thu 16:15 HS II

**The Sub-harmonic Driving Theory and Its Applications** — •Longxiang Huang[1,2], Jacquelin Luneau[1,2], Stefan Filipp[1,2,3], Peter Rabl[1,2,3], and Klaus Liegener[1,2] — [1]Technical University of Munich, Department of Physics, Garching, Germany — [2]Walther-Meißner-Institut, Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), München, Germany

Nonlinear processes have gained significant attention in physics. In parametrically driven pendulums, sub-harmonic oscillations have revealed steady-state solutions at integer multiples of the driving frequency. Conversely, anharmonic oscillators driven at fractions of frequency will oscillate, a phenomenon known as sub-harmonic driving. In this talk, we extend this concept into the quantum realm. Starting from a general quantum system driven by multiples of a singular tone, we employ Floquet theory and degenerate perturbation theory. By this, we obtain an effective Hamiltonian within a degenerate two-level subspace, demonstrating n-th order sub-harmonic oscillations. We test this framework on transmon qubits and predict resonant frequency shifts and Rabi rates, improving previous results relying on the rotating wave approximation (RWA). Additionally, our analysis is valid in regimes where RWA fails, allowing us to study, e.g., fluxonium qubits: higher-order contributions result in frequency shifts and Rabi rates that align closely with experimental results at large driving amplitudes. Furthermore, this framework can be applied to other systems, such as the two-photon Raman transition in trapped ions and Rydberg atoms and the three-photon excitation in quantum dots.

# QI 35: Quantum Information: Concepts and Methods II

Time: Thursday 14:30–16:45 Location: HS IV

QI 35.1 Thu 14:30 HS IV

**Teaching Quantum Information in High School** — •Mariana Filipova — University of Library Studies and Information Technologies, Sofia, Bulgaria

Quantum science and technology are developing at an ever faster and larger scale, and this necessitates new educational approaches and updates. School education aims, on the one hand, to prepare students for university and the labor market, and on the other hand, to motivate with its applicability and inspiring realizations towards the students' next choices, incl. STEM professions. In order to inspire young people at the most appropriate time to make these choices and strengthen the academy-business connection, it is increasingly necessary that secondary school students also become familiar with the basics of Quantum Information. This study aims to demonstrate the feasibility of teaching quantum science concepts to school-aged students by adapting content and using appropriate and varied methodologies. The aim is to explain the seemingly complex science in an accessible way to middle schoolers and also to inspire young minds for future challenges. The current research highlights the need to update the curriculum and ways of applying recent STEM trends to the work of school-age students to meet the new demands of time and student interests, making quantum science both accessible and exciting for them.

QI 35.2 Thu 14:45 HS IV

**Ultradecoherence model of the measurement process** — •Hai-Chau Nguyen — University of Siegen

Measurements remain as an interesting topic of research since the formulation of quantum theory. Attempts to model quantum measurements by unitary processes are prone to various foundational issues. Here, it is proposed that measurement devices can be modelled to have an open decoherence dynamics that is faster than any other relevant timescale, which is referred to as the ultradecoherence limit. In this limit, it is shown that the clicking rate of measurement devices can be derived from its underlying parameters, not only for the von Neumann ideal measurement devices but also for photon detectors in equal footing. This study offers a glimpse into the intriguing physics of measurement processes in quantum mechanics, with many aspects open for further investigation.

QI 35.3 Thu 15:00 HS IV

**Entangled quantum trajectories in relativistc systems** — •Yannick Noel Freitag[1], Julien Pinske[2], and Jan Sperling[1] — [1]Theoretical Quantum Science, Institute for Photonic Quantum Systems (PhoQS), Paderborn University, Warburger Straße 100, 33098 Paderborn, Germany — [2]Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark

Quantum entanglement is a key resource for quantum technologies, including emerging ground-to-satellite quantum communication. In such a scenario, an important challenge is to consider entanglement between two or more quantum particles in different inertial frames. In this talk, we present a consistent framework that overcomes this challenge. To this end, we establish the notion of factorizable and entangled multi-time trajectories and derive a class of Euler–Lagrange equations under the constraint of a non-entangling behavior. Comparing this restricted evolution to the solutions of the unrestricted equations of motion allows one to investigate the trajectory-based entanglement of general systems. We solve our equations for interacting particles in a Klein–Gordon-type setting, thereby quantifying the dynamic and relativistic impact of entanglement in a self-consistent manner.

QI 35.4 Thu 15:15 HS IV

**Exploring Photon-Number-Encoded High-dimensional Entanglement from a Sequentially Excited Quantum Three-Level System** — Daniel A. Vajner[1], •Nils D. Kewitz[1], Martin von Helversen[1], Stephen C. Wein[2], Yusuf Karli[2], Florian Kappe[3], Vikas Remesh[3], Saimon F. Covre da Silva[4,5], Armando Rastelli[4], Gregor Weihs[3], Carlos Anton-Solanas[6], and Tobias Heindel[1] — [1]Institute of Solid State Physics, Technische Universität Berlin, Germany — [2]Quandela, Massy, France — [3]Institut für Experimentalphysik, Universität Innsbruck, Austria — [4]Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Austria — [5]Universidade Estadual de Campinas, Instituto de Física Gleb Wataghin, Brazil — [6]Departamento de Física de Materiales, Instituto Nicolás Cabrera, Instituto de Física de la Materia Condensada, Universidad Autónoma de Madrid, Spain

Here, we experimentally implement a sequential two-photon resonant excitation process driving a solid-state 3-level system, represented by a semiconductor quantum dot [1]. The resulting light state exhibits entanglement in time and energy, encoded in the photon-number basis. Performing energy- and time-resolved correlation experiments together with detailed theoretical modeling, we are able to partially retrieve the entanglement structure of the generated state and extract an upper bound for the fidelity to the entangled target state of $\mathcal{F} \leq 70\%$ before loss.

[1] Vajner et al., Optica Quantum, DOI:10.1364/OPTICAQ.538134 (2024)

QI 35.5 Thu 15:30 HS IV

**Exploring Imaginary Coordinates: Disparity in the Shape of Quantum State Space in Even and Odd Dimensions** — Simon Morelli[1], Santiago Llorens[2], and •Jens Siewert[3,4] — [1]Atominstitut, Technische Universität Wien, 1020 Vienna, Austria — [2]Física Teórica: Informació i Fenómens Quántics, Universitat Autónoma de Barcelona, 08193 Bellaterra, Spain — [3]University of the Basque Country UPV/EHU and EHU Quantum Center, 48080 Bilbao, Spain — [4]Ikerbasque, Basque Foundation for Science, 48013 Bilbao, Spain

The state of a finite-dimensional quantum system is described by a density matrix that can be decomposed into a real diagonal, a real off-diagonal and and an imaginary off-diagonal part. The latter plays a peculiar role. While it is intuitively clear that some of the imaginary coordinates cannot have the same extension as their real counterparts the precise relation is not obvious. We give a complete characterization of the constraints in terms of tight inequalities for real and imaginary Bloch-type coordinates. Our description entails a three-dimensional Bloch ball-type model for the state space. We uncover a surprising qualitative difference for the state-space boundaries in even and odd dimensions.

QI 35.6 Thu 15:45 HS IV

**Deciding finiteness of Hamiltonian algebras** — •David Edward Bruschi — Institute for Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich, Jülich, Germany

Determining exactly the dynamics of a physical system is the paramount goal of any branch of physics. Quantum dynamics are characterized by the non-commutativity of operators, which implies that the dynamics usually cannot be tackled analytically and require ad-hoc solutions or numerical approaches. A priori knowledge on the ability to obtain exact results would be of great advantage for many tasks of modern interest, such as quantum computing, quantum simulation and quantum annealing.

In this work we build on our approach previously introduced to determine the dimensionality of a Hamiltonian Lie algebra by appropriately characterizing its generating terms. In the original exact and fully general approach, we started to develop new tools to determine the final dimension of the algebra itself. We here extend the initial proposal by including a time-independent free Hamiltonian drift term, which improves the original proposal by allowing to tackle all bosonic Hamiltonians.

We are able to provide statements on the ultimate ability to exactly control the dynamics or simulate specific classes of physical systems of coupled quantum harmonic oscillators. This work has important implications not only for theoretical physics, but it also aids our understanding of the structure of the Hilbert space, as well as Lie algebras.

QI 35.7 Thu 16:00 HS IV

**A Color Center based Scheme for the Storage and Retrieval of a Quantum Token** — •Yannick Strocka, Mohamed Belhassen, Gregor Pieplow, and Tim Schröder — Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Deutschland

Quantum tokens are of growing interest in the era of secure communication in large scale quantum networks. Compared to classical tokens they are unforgeable because of the no-cloning principle. A quantum token can be a multi-qubit state comprised of single or entangled qubits. Such multi-qubit states can be efficiently produced using single photon sources, such as quantum dots or color centers in diamond. For a practical implementation of a quantum token scheme a token has to be issued and a user has to have the ability to save and redeem the token. In this work we focus on the user, possessing a register of quantum memories based on group-IV color centers in diamond. Such defects are promising due to their long spin coherence times and reduced sensitivity to electric field noise when integrated into nanostructures. In our proposed scheme, saving the token using the color centers' spin requires the use of a spin rotation and spin dependent reflection of the incoming photons. For performing such a rotation quickly we investigate optical spin gates using a Raman scheme. We analyze the impact of imperfections of the photon source, spin rotations and measurement on the resulting fidelity of the quantum token. We also study the overall performance of the spin based quantum memory register for receiving and sending quantum tokens.

QI 35.8 Thu 16:15 HS IV

**Entropic witness for quantum memory** — •Charlotte Bäcker[1], Konstantin Beyer[2], and Walter Strunz[1] — [1]TUD Dresden University of Technology, 01062, Dresden, Germany — [2]Stevens Institute of Technology, Hoboken, New Jersey, 07030, USA

In quantum physics, non-Markovian processes arise from the interaction between the quantum system and its environment whenever memory effects play a role. The question of whether the memory provided by the environment can be considered classical or requires a quantum description is part of an ongoing debate. We present a witness for quantum memory based on entropy, which can be computed for any dimension of the quantum system of interest. This approach will be illustrated by an application of the witness to qudit dynamics as well as to continuous-variable Gaussian dynamics.

QI 35.9 Thu 16:30 HS IV

**Characterising quantum memory via constrained separability problems** — •Ties-Albrecht Ohst[1], Shijun Zhang[3], Hai Chau Nguyen[1], Martin Plávala[2], and Marco Túlio Quintino[3] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Siegen 57068, Germany — [2]Institut für Theoretische Physik, Leibniz Universität Hannover, Hannover, Germany — [3]Sorbonne Université, CNRS, LIP6, F-75005 Paris, France

Quantum memories are a crucial precondition in many protocols for processing quantum information. A fundamental problem that illustrates this statement is given by the task of channel discrimination, in which an unknown channel drawn from a known random ensemble should be determined by applying it for a single time. In this talk, we characterise the quality of channel discrimination protocols when the quantum memory, quantified by the auxiliary dimension, is limited. This is achieved by formulating the problem in terms of separable quantum states with additional affine constraints that all of their factors in each separable decomposition obey. We discuss the computation of upper and lower bounds to the solutions of such problems which allow for new insights into the role of memory in channel discrimination. Moreover, the versatility of constrained separability problems in exploring general memory effects, whether classical or quantum, in quantum processes will be showcased.

## QI 36: Poster – Quantum Information (joint session QI/Q)

Time: Thursday 17:00–19:00 Location: Tent

QI 36.1 Thu 17:00 Tent

**Classicality, Markovianity and local detailed balance in isolated quantum systems** — •Philipp Strasberg — Instituto de Física de Cantabria (IFCA), Santander, Spain

This poster reviews how the familiar description of stochastic thermodynamics, based on classical Markov processes obeying local detailed balance, emerges from an underlying quantum description from first principles. Here, "first principles" means that we avoid ensemble averages and any assumptions breaking the unitarity of the underlying quantum dynamics (e.g., Born or Markov approximations). Connections to a general approach of thermodynamic entropy (production) and the structure of the Multiverse are also indicated.

QI 36.2 Thu 17:00 Tent

**Intensity Stabilization in Fiber Amplifiers: Effects on Phase Noise, Linewidth, and Qubit Coherence** — •Jia-Yang Gao, Jasper Phua Sing Cheng, Morteza Ahmadi, and Manas Mukherjee — Centre for Quantum Technologies, National University of Singapore

Intensity noise is a factor limiting the coherence time of qubits in trapped ion quantum systems. Previously, we observed that using a Thulium-doped fiber amplifier (TDFA) introduces intensity fluctuations to the input seed laser, thus limiting the coherence time. To address this issue, we developed an intensity stabilization setup for a 1762 nm laser used for quadrupole transition, employing an acousto-optic modulator (AOM) with an electrical feedback servo. Our results demonstrate that this setup can reduce intensity noise by up to 20 dB from DC to 10 kHz without introducing additional phase noise and broadening the linewidth to the input signal. The phase noise and linewidth of the laser was analyzed using delayed self-heterodyne interferometry (DSHI). We also cross-check the stabilized beam using a single ion in our ion trap setup. Based on the Rabi oscillation results at different power levels, we observe an improvement in coherence time.

QI 36.3 Thu 17:00 Tent

**Preparation and Control of Logical Qubits in the Hyperfine Structure of $^{173}$Yb$^{+}$** — •Selena-Maria Bota, Monika Leibscher, and Christiane P. Koch — Freie Universität Berlin, Berlin, Germany

Recent research proposes robust encoding of quantum information in high angular momentum atomic or molecular states, where the logical qubits are protected against most common errors [1]. Such codewords can be built in the hyperfine structure of trapped $^{173}$Yb$^{+}$, namely using metastable states in the $^2F^0_{7/2}$ manifold [2]. This work focuses on the preparation of such robust qubits with sequences of microwave pulses. We present a theoretical description of the atom's hyperfine structure and the transitions between hyperfine levels driven by time-dependent magnetic fields. We furthermore simulate the population dynamics driven by sequences of microwave pulses and optimise the pulse sequences in order to excite the desired codewords.

[1] Jain, Shubham P., et al. "Æ codes." arXiv preprint arXiv:2311.12324 (2023).

[2] Xiao, Di, et al. "Hyperfine structure of Yb+ 173: Toward resolving the Yb 173 nuclear-octupole-moment puzzle." Physical Review A 102.2 (2020): 022810.

QI 36.4 Thu 17:00 Tent

**Measurable Entanglement lower bounds for Cold Atom Quantum Simulators using kinetic operators** — •Maike Reckermann[1], Niklas Euler[1,2], and Martin Gärttner[1] — [1]Institut für Festkörpertheorie und Optik, Friedrich-Schiller-Universität Jena, Deutschland — [2]Physikalisches Institut, Universität Heidelberg, Deutschland

The entanglement dimension plays a key role for understanding quantum many-body phenomena such as topological order, recently realized with cold atoms in lattice geometries. However, for cold atom quantum simulators, determining the entanglement spectrum from measurements is a challenge for experiments as it generally requires the full reconstruction of the quantum state.

Here, we propose a new method to bound the entanglement dimension, which is the number of non-zero values in the spectrum, using the information contained in the measurement of kinetic operators in double wells, which was recently pioneered with ultracold bosonic atoms in a 2D optical lattice. Using also positivity constraints, non-measured elements of the density matrix can be bounded through the fidelity to a reference state, that is optimized in post-processing. We show through numerical simulations, that the entanglement dimension can be lower bound by information form the new measurement operators for a few body system with 2 distinguishable particles in a 1D lattice.

The protocol to bound the entanglement dimension with this measurement method is more efficient than previous methods and could be generalized to a 2D lattice or to create bounds on other observables.

QI 36.5 Thu 17:00 Tent

**Polarization Independent Frequency Conversion into the UV** — •Katrin Schatzmayr, Anica Hamer, and Simon Stellmer — Rheinische Friedrich Wilhelms Universität Bonn

As the performance of quantum computers grows, quantum networks become more significant. A possible implementation of such a network is a hybrid architecture based on solid state emitters, network nodes, and photons serving as flying qubits. This exchange often requires frequency conversion of the photons while preserving entanglement.

We have successfully developed a polarization-independent frequency conversion setup based on nonlinear crystals that converts photons from the wavelength of a quantum dot at 853 nm (InAs/GaAs) to the wavelength of trapped Yb+ ions at 370 nm.

QI 36.6 Thu 17:00 Tent

**Comparative analysis of loan risk forecasting using quantum machine learning and classical machine learning models** — •Mohammed Mustapha Adamu[1,2], Peter Nimbe[1], and Abdul Razak Nuhu[1] — [1]Department of Computer Science and Informatics, University of Energy and Natural Resources — [2]Savannah Regional Health Directorate

Non-performing loans present a significant challenge to financial institutions, driven by the complexity of the dataset, default probability, and default correlation(Bellotti et al., 2019). To mitigate this risk, this study investigates the potential of Classical Machine Learning (ML) and Quantum Machine Learning (QML) algorithms for forecasting loan risk. Using a dataset from Kaggle, we conducted a comparative analysis between Support Vector Machine (SVM) and Quantum Support Vector Machine (QSVM). Our result using a dataset of 12,368 records and 12 features shows that the QSVM model outperformed SVM, with a higher true positive rate (93.2.%) and true negative rate (87.6%), demonstrating better performance in identifying both default and non-default cases. Additionally, QSVM exhibits a lower false negative rate indicating its superior ability to minimize clients likely to default. The AUC score of 1.0 for the QSVM further demonstrates its exceptional ability in loan prediction. While the dataset used allowed for a solid comparison, QSVM demonstrated its capacity to continue improving with larger datasets, showing its scalability and strong potential application in loan risk forecasting especially with larger datasets.

QI 36.7 Thu 17:00 Tent

**Surgical Procedure Recognition Using Quantum Machine Learning** — •Abdul Razak Nuhu[1,2], Peter Nimbe[1], Mohammed Mustapha Adamu[1], and Eliezer Ofori Odei-Lartey[2] — [1]Department of Computer Science and Informatics, UENR, P. O. Box 214, Sunyani, Ghana — [2]Kintampo Health Research Centre, Kintampo, Ghana

Surgical procedure recognition is a critical field in robotic-assisted surgery that focuses on identifying complex surgical tasks like suturing, needle passing, and knot tying. This research explores Quantum Machine Learning (QML) algorithms, specifically the Quantum Support Vector Classifier (QSVC), to analyze surgical gestures more effectively than traditional methods. Using the JIGSAWS dataset with 76 motion characteristics, the study compared QSVC performance against a conventional Support Vector Classifier (SVC) using metrics like accuracy, precision, recall, and F1-score. The results demonstrated that QML-derived models significantly outperform classical machine learning techniques in processing surgical kinematic data. The research suggests that QML has transformative potential in surgical robotics and gesture recognition, particularly as quantum computing advances. By providing more sophisticated analysis of surgical procedures, this approach promises to enhance real-time surgical support, improve medical education, and ultimately develop more context-aware surgical systems that could improve patient care.

QI 36.8 Thu 17:00 Tent

**Photon Fusion Analysis with Imperfect Sources** — •Ruolin Guan and Klemens Hammerer — Institut für Theoretische Physik, Leibniz Universität Hannover, Germany

Photon fusion, a process integral to various quantum technologies, relies heavily on the availability of high-quality photon sources. However, real-world implementations often contend with imperfect sources, introducing inefficiencies and challenges in optimizing fusion outcomes. We explore theoretical frameworks and practical simulations to quantify the impact of imperfections on fusion success rate and outcomes. This work enhances the reliability of photon fusion in practical scenarios.

QI 36.9 Thu 17:00 Tent

**Witnessing quantum memory in dynamics using quantum processors** — •Krishna Palaparthy, Charlotte Bäcker, and Walter Strunz — TUD Dresden University of Technology, Dresden, Germany

Quantum simulations on noisy quantum computers can help us understand the role of quantum memory in quantum dynamics, for quantum computations and information processing tasks. To demonstrate local disclosure of quantum memory on the NISQ quantum processors, our simulation makes use of a collision model of sequentially applied two-qubit unitaries realizing the dynamics of a non-Markovian amplitude-damping channel. We investigate the relaxation dynamics and its influence on the entanglement dynamics with ancilla that are crucial for the proof of quantum memory.

QI 36.10 Thu 17:00 Tent

**Quantum vs. classical: A comprehensive benchmark study for time series prediction using variational quantum algorithms** — •Tobias Fellner[1], David Kreplin[2], Samuel Tovey[1], and Christian Holm[1] — [1]Institute for Computational Physics, University of Stuttgart — [2]Fraunhofer Institute for Manufacturing Engineering and Automation (IPA)

Recently, a wide range of variational quantum algorithms have been proposed for time series processing, promising potential advantages in handling complex sequential data. However, whether and how these quantum machine learning models outperform established classical approaches remains unclear. In this work, we conduct a comprehensive benchmark study comparing a variety of classical machine learning models and variational quantum algorithms for time series prediction. We evaluate their performance on time series prediction tasks of chaotic systems of varying complexity. Our results show that in many cases quantum machine learning models are able to achieve prediction accuracies comparable to classical models. At the same time, we also discuss the current practical value as well as the limitations of variational quantum algorithms for time series forecasting.

QI 36.11 Thu 17:00 Tent

**Efficient simulation of microscopic master equations using tensor product states** — •Junyi Zhang, André Eckardt, and Alexander Schnell — Technische Universität Berlin

In this work, we address the efficient simulation of global master equations by mapping them to local form. We utilize a novel local Redfield master equation in Lindblad form [1]. By leveraging tensor network methods and quantum trajectory algorithms, we describe steady states and explore transport in boundary-driven systems. Through characterization of the current, we examine how interactions and external fields influence transport properties of an XXZ spin chain in presence of finite-temperature reservoirs. This provides insights into dissipative dynamics in quantum many-body systems. This approach offers a computationally feasible alternative for analyzing large Hilbert spaces without full density matrix propagation, allowing us to extend the applicability of rigoriusly derived master equations in complex quantum systems.

[1] A. Schnell, arXiv:2309.07105 (2023)

QI 36.12 Thu 17:00 Tent

**Synchronizing Detector Dead Times to Accelerate Quantum Key Distribution** — •Maximilian Mengler, Maximilian Tippmann, and Thomas Walther — TU Darmstadt, Institute for Applied Physics, 64289 Darmstadt

Most Quantum-key-distribution setups consist of photon detection systems with multiple single-photon detectors. Upon measuring a photon these detectors will enter a dead time but due to security reasons only events that are registered when all detectors are ready may contribute to a key for various protocols, e.g. BBM92. This especially constrains systems relying on cheaper detectors like single-photon-avalanche-diodes because of the detectors' long dead times. At high detection rates, two detectors might block each other alternately with one detector entering a new dead time before the other finished its own. We implement a method that utilizes inverse gating signals sent to all detectors upon registration of an incident photon. This leads to the synchronization of the detectors' dead time and ensures that all the detectors are active for the maximum amount of time. We tested this method with our QKD system for various losses between the receiving parties and investigated its effect. In doing so, we were able to increase the secure key rate by up to 75%.

QI 36.13 Thu 17:00 Tent

**Implementing post-processing algorithms for a star-shaped quantum key hub** — •Tobias Liebmann, Maximilian Tippmann, and Thomas Walther — TU Darmstadt, Institute of Applied Physics, 64289 Darmstadt

The recent advances in quantum computing pose a threat to the security of conventional cryptographic algorithms like the Rivest-Shamir-Adleman (RSA) public key scheme. In particular, Shor's algorithm makes it possible to decode such encryption in polynomial time. Quantum key distribution (QKD) offers a solution to this problem, which not only provides computational security like post-quantum cryptography but information theoretic security. However, to ensure this level of security, the exchanged raw quantum keys must undergo a detailed post-processing procedure. We present recent advances regarding the implementation of the post-processing algorithms on our star-shaped QKD network.

QI 36.14 Thu 17:00 Tent

**A quantum-network register assembled with optical tweezers in an optical cavity** — •Matthias Seubert[1], Lukas Hartung[1], Stephan Welte[1,2], Emanuele Distante[1,3], and Gerhard Rempe[1] — [1]Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany — [2]5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany — [3]CFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain

Quantum networks offer great potential for secure communication, distributed computing, and precision sensing. However, optical losses and errors between distant nodes make quantum information exchange slow and unreliable. One solution is to use more qubits as a register at each node, allowing multiplexed communication and error correction.

We present recent results [1] demonstrating the potential of a platform that integrates optical tweezer arrays with a macroscopic optical cavity for scalable quantum network nodes. By assembling one- and two-dimensional registers of up to 6 atoms, we address each individual atom to generate atom-photon entanglement via vacuum-stimulated Raman adiabatic passages. As the number of qubits in the register increases, the entanglement fidelity remains constant, an indication of scalability. By generating atom-photon entanglement in a multiplexed manner, we achieved a source-to-detection probability of up to $\sim$90% per run. This is an important step towards the deterministic distribution of entanglement in networks.

[1] L. Hartung et al. Science Vol 385, Issue 6705 pp. 179-183 (2024)

QI 36.15 Thu 17:00 Tent

**Three axis magnetic field control setup for nitrogen-vacancy color center magnetometry** — •Ricky-Joe Plate, Jan Thieme, Bernd Bauerhenne, and Kilian Singer — Experimental Physics I, Institute of Physics, University of Kassel, Heinrich-Plett-Straße 40, 34132 Kassel, Germany

Nitrogen-vacancy (NV) centers in diamond provide a promising platform for room-temperature quantum sensing and information processing owing to their unique optical and spin properties and precise fabrication methods allowing for photonic structures such as nano pillars [1]. Precise quantum magnetometry requires an accurate and stable adjustment of the external magnetic field. Our solution incorporates a motorized magnetic system that allows for precise angular alignment relative to the NV-axis and offers adjustable magnetic field strengths. The system is engineered to be highly stable against external disturbances, ensuring consistent and reliable operation over extended measurement periods. Additionally, a custom designed algorithm performs optimal alignment of the magnetic field with regard to the NV center axis.

[1] Schmidt, A., Bernardoff, J., Singer, K., Reithmaier, J.P. and Popov, C. (2019), Fabrication of Nanopillars on Nanocrystalline Diamond Membranes for the Incorporation of Color Centers. Phys. Status Solidi A, 216: 1900233.

QI 36.16 Thu 17:00 Tent

**Atom-Photon entanglement across a metropolitan network** — •Maya Büki[1], Tobias Frank[1], Marvin Scholz[1], Gianvito Chiarella[1], Pau Farrera[1], Pooja Malik[2], Yiru Zhou[2], Florian Fertig[2], Harald Weinfurter[1,2], and Gerhard Rempe[1] — [1]Max-Planck-Institute of Quantum Optics, Garching, Germany — [2]Ludwig-Maximilians-University, Munich, Germany

Building a scalable quantum network is a key challenge in quantum information science. A critical step in this endeavor is the establishment of robust quantum links capable of transmitting entangled quantum states over long distances. Here, we present the successful demonstration of atom-photon entanglement over a distance of 23 km, spanning the Munich metropolitan area. Within this scope, we can efficiently entangle the spin states of Rubidium (Rb) atoms with optical polarization qubits. This experiment addresses critical challenges, including transmission losses through optical fiber, polarisation drifts and noise. By leveraging quantum frequency conversion from $\lambda_{\mathrm{Rb}} = 780$ nm to the telecom band and tailored filtering techniques, we successfully preserved entanglement fidelity over the link. By converting back the wavelength of the photon to 780 nm it might be possible to write the qubit information onto a heralded quantum memory consisting of a Rubidium atom inside two crossed optical fiber cavities [1]. With this goal in mind we made a first but decisive step towards a real world quantum network link within the Munich metropolitan area.

[1] M. Brekenfeld et al. Nat. Phys. 16, 647 - 651 (2020)

QI 36.17 Thu 17:00 Tent

**Solving optimization problems on quantum systems.** — •Kapil Goswami[1], Rick Mukherjee[1,2], Herwig Ott[3], and Peter Schmelcher[1,4] — [1]The Center for Optical Quantum Technologies, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]Quantum Center, The University of Tennessee, 701 East Martin Luther King Boulevard, Chattanooga, USA — [3]Department of Physics and Research Center OTIMAS, RPTU Kaiserslautern-Landau, Kaiserslautern, Germany — [4]The Hamburg Centre for Ultrafast Imaging, University of Hamburg, Germany

Solving industry-related optimization problems using classical computers is challenging as they are NP-hard. The current quantum computers are characterized by limited qubits, high levels of noise, and imperfect gates. Hence, exploring resource-efficient encoding schemes can lead to practical quantum advantage. These problems are formulated either as a quadratic unconstrained binary optimization (QUBO) or integer programming (IP). Our first work provides a novel framework to solve QUBO problems such as Maximum Cut (Max-Cut) and Maximum Independent Set (MIS) on the Rydberg platform with local-light shifts, providing a favorable scaling of the number of atoms with problem size compared to existing schemes. In our second work, an algorithm is introduced that directly solves an IP problem using a single atom. Specifically, we use multi-levels of a Rydberg atom and selectively transfer the population between the Rydberg manifolds to find the optimal solution. Both of the quantum algorithms utilize quantum optimal control to reach the solution of the problems.

QI 36.18 Thu 17:00 Tent

**Generation and characterization of entangled photon source**

**through the spontaneous parametric down conversion** — •Chandana Rao Attigadde Shashikirana[1,2,3], Umakant D Rapol[1], and Anindita Bannerjee[2] — [1]Indian Institute of Science Education and Research, Pune, India — [2]Centre for Development of Advanced Computing (CDAC), Pune, India — [3]Department of Computer Science, Paderborn University, Warburger str.100, 33098, Paderborn, Germany

The work is on the generation and characterization of an entangled photon source using a type-1 crossed Beta-Barium Borate (BBO) crystal through spontaneous parametric down-conversion (SPDC), with a focus on understanding the quantum entanglement phenomenon.

Various experimental tests, including the Hanbury Brown and Twiss (HBT) experiment, visibility measurements, the Clauser Horne-Shimony-Holt (CHSH) inequality, and polarization correlation measurements, were conducted to characterize the entangled photon source. Additionally, the quantum state tomography technique was used to reconstruct the density matrix of the entangled photons.

The results show that the source generates entangled, single photons, which violate the Bell inequality as evidenced by the CHSH parameter of 2.629. The concurrence value of 0.708 and linear entropy of 0.244 provide estimates of the degree of entanglement and the noise present in the entangled photons, respectively.

QI 36.19 Thu 17:00 Tent

**Multi-Pass Quantum Process Tomography** — •Stancho Stanchev and Nikolay Vitanov — Center for Quantum Technologies, Faculty of Physics, Sofia University, James Bourchier 5 blvd., 1164 Sofia, Bulgaria

We introduce a method to enhance the precision and accuracy of Quantum Process Tomography (QPT) by mitigating errors caused by state preparation and measurement (SPAM), readout, and shot noise. Instead of performing QPT on a single gate, we propose applying QPT to a sequence of multiple applications of the same gate. The method involves the measurement of the Pauli transfer matrix (PTM) by standard QPT of the multipass process, and then deduce the single-process PTM by two alternative approaches: an iterative approach which in theory delivers the exact result for small errors, and a linearized approach based on solving the Sylvester equation. We apply the method to CNOT gate tomography, as well as to evaluate the quality of single-qubit composite gates, constructed by composite pulses and compare them to pre-existing gates. We assess the method's performance through simulations on IBM Quantum, using IBM Simulator and real quantum processors.

QI 36.20 Thu 17:00 Tent

**Surface-electrode ion trap testing apparatus for the QTZ at PTB** — •Marco Bonkowski[1], Sebastian Halama[1], and Christian Ospelkaus[1,2] — [1]Leibniz Universität Hannover, Institut für Quantenoptik, Welfengarten 1, 30167 Hannover — [2]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig

One of the main challenges in performing useful quantum computations outside of purely academic interest is the need for a higher number of high-fidelity qubits. Surface-electrode ion traps have the potential to be a suitable solution for this scalability problem. [1] The ongoing research in this field often requires complicated, expensive setups and highly trained personnel which proves to be challenging for smaller facilities. The quantum technology competence center (QTZ) at the Physikalisch-Technische Bundesanstalt will support the industrial development of quantum technology by providing the necessary infrastructure to test and characterize quantum components such as ion traps. Our group has developed a cryogenic ion trap apparatus for trap testing that was first set up at the LUH and will be used to verify the results of the QuMIC project and then will be transferred to the QTZ. Within the QuMIC project highly integrated BiCMOS chips are developed and used for the microwave generation in the microwave near-field approach [2] to control the qubits. We describe the setup of the apparatus and the associated laser system for trapping beryllium ions.

[1] Chiaverini et al., Quantum Inf Comput 5, 419-439 (2005)
[2] Ospelkaus et al., Phys. Rev. Lett. 101, 090502 (2008)

QI 36.21 Thu 17:00 Tent

**Continuous-variable QKD with rate-adaptive error correction for the QuNet initiative** — •Stefan Richter[1,2], Hüseyin Vural[1,2], Lukas Eisemann[1,2], Jan Schreck[1,2], Kevin Jaksch[1,2], Ömer Bayraktar[1,2], Thomas Dirmeier[1,2], Wenjia Elser[1,2], Dominique Elser[1,2], and Christoph Marquardt[1,2] — [1]Lehrstuhl für Optische Quantentechnologien, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany — [2]Max-Planck-Institut für die Physik des Lichts, 91052 Erlangen, Germany

Continuous-variable quantum key distribution (CV-QKD) offers a way to establish symmetrically encrypted secure communication over untrusted channels and backed by security proofs not reliant on assumptions of mathematical complexity. Here, we present our progress on implementating a CV-QKD system designed for metropolitan fiber optical links, which was deployed as part of a large-scale technology demonstration in October 2024 for the QuNet initiative. Our approach is based on discrete modulations (DM) of coherent states and optical homodyne detection, with separate and free-drifting sender and receiver lasers. As such, it is similar and widely compatible with modern fiber optical communication techniques. We discuss some of the unique technical challenges associated with deploying our prototype in a larger network, as well as our proposed mitigations. Secret key rates attained with a complete post-processing stack based on fixed rate error correction are contrasted with the results of using a novel rate-adaptive implementation instead, highlighting the practical advantages of the latter.

QI 36.22 Thu 17:00 Tent

**What can we learn from the phase of the momentum wave function?** — •André Knoll[1], Leon Cohen[2], and Wolfgang Schleich[1] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany — [2]Department of Physics, Hunter College of the City University of New York, 695 Park Ave., New York, NY 10065, United States of America

Due to the Born rule of quantum mechanics, the amplitude of the wave function is often emphasized, while the phase is frequently overlooked. However, a closer examination reveals that the phase, particularly when encoded by the Fourier transform of position space, contains critical information about the original wave function. Building on signal processing techniques introduced by Oppenheim et al. in 1981 (Proc. IEEE, 69, 5, pp. 529-541), we adapt and extend these methods to the quantum mechanical framework. In particular, we show that even when we replace the amplitude of the momentum wave function by a constant, the phase of the momentum wave function allows a partial reconstruction of the position wave function. Our findings underscore the fundamental role of the phase in Fourier-based transformations, offering new insights into quantum mechanics and potential applications in quantum information science.

QI 36.23 Thu 17:00 Tent

**AQuRA: A software package for simulating quantum computing with continuous variables** — •Sebastian Luhn and Matthias Zimmermann — DLR e.V., Institut für Quantentechnologien, Ulm

There are a variety of simulation tools for digital quantum computers based on qubits. However, simulation tools for analog quantum computers based on continuous-variable quantum systems (e.g. the position of a quantum particle) are rare. Indeed, simulating these quantum systems also comes with a huge demand for computational power. Here we present a self-build simulation package that can calculate a huge variety of continuous quantum systems on powerful HPC hardware as well as on a local pc. Our software does support many well-known codes like GKP or cat codes and offers several predefined gates for simulating operations acting on single and multiple quantum systems.

QI 36.24 Thu 17:00 Tent

**Spectral Compatibility and Analytical Constraints in Quantum Marginal Problems** — •van Dellen Lea, Wyderka Nikolai, Bruss Dagmar, and Kampermann Hermann — Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Germany

The compatibility of quantum marginals, or reduced density matrices, is a cornerstone of quantum mechanics, underlying phenomena like entanglement and non-locality. A fundamental variant of this problem concerns the compatibility of spectra, rather than the reduced density matrices themselves. Specifically, given eigenvalues $\vec{\lambda}_{AB}$ and $\vec{\lambda}_{BC}$ for subsystems $AB$ and $BC$, the task is to determine whether there exists a joint quantum state $\rho_{ABC}$ such that its reduced density matrices $\rho_{AB} = tr_C(\rho_{ABC})$ and $\rho_{BC} = tr_A(\rho_{ABC})$ exhibit these spectra. If such a state exists, the spectra are deemed compatible; otherwise, they are incompatible.

Recently, a hierarchy of semidefinite programs was developed to address this challenge [1]. This hierarchy is complete and provides dimension-free certificates of incompatibility for all local dimensions.

In this work we present additional analytical conditions for spectral compatibility, by solving the second level of the hierarchy. From this, we systematically derive spectral compatibility constraints for multipartite qudit systems and relate them to inequalities of linear entropies.

[1]: F. Huber, N.Wyderka, arXiv:2211.06349

QI 36.25 Thu 17:00 Tent

**Super-Heisenberg scaling of the quantum Fisher information using spin-motion states** — •Venelin Pavlov and Peter Ivanov — St. Kliment Ohridski University of Sofia, James Bourchier 5 blvd, 1164 Sofia, Bulgaria

We propose a spin-motion state for high-precision quantum metrology with super-Heisenberg scaling of the parameter estimation uncertainty using a trapped ion system. Such a highly entangled state can be created using the Tavis-Cummings Hamiltonian which describes the interaction between a collective spin system and a single vibrational mode. Our method relies on an adiabatic evolution in which the initial motional squeezing is adiabatically transferred into collective spin squeezing. In the weak squeezing regime, we show that the adiabatic evolution creates a spin-squeezed state, which reduces the quantum projective noise to a sub-shot noise limit. For strong bosonic squeezing we find that the quantum Fisher information follows a super-Heisenberg scaling law $\propto N^{5/2}$ in terms of the number of ions $N$. Furthermore, we discuss the spin squeezing parameter which quantifies the phase sensitivity enhancement in Ramsey spectroscopic measurements and show that it also exhibits a super-Heisenberg scaling with $N$. Our work enables the development of high-precision quantum metrology based on entangled spin-boson states that lead to faster scaling of the parameter estimation uncertainty with the number of spins.

QI 36.26 Thu 17:00 Tent

**Thermodynamic Consistency of Markovian Embeddings of Open Quantum Systems** — •Shreesha S. Hegde, Adrian Romer, and Christiane P. Koch — Freie Universität Berlin, Berlin, Germany

The Surrogate Hamiltonian is an approximation method used to simulate open quantum systems [1]. Here, an infinite bath is represented by a surrogate bath made up of a finite number of two-level systems that strongly interact with the system we are interested in. This is then simulated as a closed system. As expected, this model works only for short simulation times before recurrences are seen in the system due to the unitary evolution of the system and the surrogate bath.

The Stochastic Surrogate Hamiltonian is a Markovian embedding technique that improves on this greatly by implementing a stochastic reset of the surrogate modes to their original thermal state. This is done as a way of mimicking the steady thermal state in an infinite bath and allows for extended simulation times [2]. However, implementing this scheme under conditions that are consistent with thermodynamics can be computationally expensive. We aim to achieve an approximate realization of these conditions under which we can still attain a thermodynamically consistent steady state on the system.

[1] Baer et al., J. Chem. Phys. 106, 8862 (1997)
[2] Katz et al., J. Chem. Phys. 129, 034108 (2008)

QI 36.27 Thu 17:00 Tent

**Wigner Negativity and Nonclassicality** — •Michael E. N. Tschaffon and Matthias Freyberger — Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany

The Wigner function is a well-established tool in quantum physics to study quantum states in phase space. It serves as a quantum analogue of a classical probability distribution. However, in contrast to its classical counterpart it can obtain negative values, which are thus naturally associated with nonclassical features, that is, nonclassicality, of the underlying quantum state. The relation between these negative values, i.e., Wigner negativity, and nonclassicality is quantitatively not well understood. For this purpose, we examine Wigner negativity for bipartite states. We show that, using Bell inequalities with a pseudo spin, nonclassical correlations are monotonically related to Wigner negativity. In particular, we separate the part of Wigner negativity contributing to nonclassical correlations from the one already present in single particle nonclassicality. As a consequence, we find that Wigner negativity is not sufficient to have nonclassical correlations.

QI 36.28 Thu 17:00 Tent

**Composite pulses for robust ensemble based quantum tokens with Nitrogen Vacancy color centers** — •Jan Thieme, Josselin Bernardoff, Ricky-Joe Plate, Bernd Bauerhenne, and Kilian Singer — Experimental Physics I, Institute of Physics, University of Kassel, Heinrich-Plett-Straße 40, 34132 Kassel, Germany

We report on both analytical and experimental outcomes related to the application of tailored composite pulses [1] to effectively address ensembles of nitrogen-vacancy color centers within a novel ensemble based protocol for quantum tokens [2]. Utilizing analytical techniques specific to the Rosen-Zener excitation model, we have developed broadband excitation profiles to compensate for experimental fluctuations in resonance frequency and pulse area. This is especially important for a quantum token application with ensembles. These custom pulses are applied using an arbitrary waveform generator to precisely control individual NV color centers [3]. Future work aims to enhance this strategy to further reduce the susceptibility to technical limitations, thereby improving the overall robustness and effectiveness of the protocol [4].

[1] G. T. Genov, D. Schraft, T. Halfmann and N. V. Vitanov, Phys. Rev. Lett. 113, 043001 (2014). [2] K. Singer, C. Popov,B. Naydenov, Verfahren zum Erstellen eines Quanten-Datentokens (DE 10 2022 107 528 A1) DE-Patent (2023) [3] A. Schmidt, J. Bernardoff, K. Singer, J. P. Reithmaier and C. Popov, Physica Status Solidi A, 216, 1900233 (2019). [4] G. T. Genov, M. Hain, N. V. Vitanov, and T. Halfmann, Phys. Rev. A, 101, 013827(2020)

QI 36.29 Thu 17:00 Tent

**Efficient tensor network simulation of open quantum systems with realistic environments** — •Matteo Garbellini, Valentin Link, and Walter Strunz — Institut für Theoretische Physik, Technische Universität Dresden, D-01062, Dresden, Germany

We utilize novel numerical techniques for open quantum systems in order to simulate qubit dynamics in experimentally realized quantum devices. Our approach is based on a recently introduced tensor network based method that efficiently generates auxiliary environments for non-Markovian Gaussian baths [1]. In this framework, the combination of multiple noise sources still has exponential scaling. We overcome this issue by employing a matrix product state representation for the system-and-bath degrees of freedom and then performing real-time evolution via TEBD. As an example problem we consider a recent experiment where a Landau-Zener sweep was performed in a superconducting flux qubit [2]. By carefully taking into account both transverse and longitudinal noise, we reach excellent quantitative agreement with the experimental data over large parameter regimes.

[1] Link, V., Tu, H.H., & Strunz, W. Open Quantum System Dynamics from Infinite Tensor Network Contraction. Phys. Rev. Lett., 132, 200403 (2024)
[2] Lupascu, A. et al. Dissipative Landau-Zener tunneling: crossover from weak to strong environment coupling, arXiv:2207.02017v1 (2022)

QI 36.30 Thu 17:00 Tent

**Blind Grover Search for Gate-based Quantum Computers** — •Alexander Sauer[1], Alexander von Consbruch[2], and Matthias Zimmermann[1] — [1]DLR e.V., Institute of Quantum Technologies, Ulm — [2]University of Göttingen

While quantum computers might offer several computational benefits, their application within a quantum network is also of interest in regard to privacy, data protection and computational security. One promising application is blind quantum computing, where a client with limited quantum capacities utilizes the computational power of a quantum computer located at a quantum computing center without revealing any information about the computation or data involved. Several schemes for blind quantum computation have emerged, with the most advanced relying on measurement-based quantum computing [1]. However, many current quantum computer designs are based on gate-based state manipulation. While blind quantum computing is also possible in this scenario, it requires a permanent exchange of quantum information between client and server [2]. To reduce the communication overhead for the involved parties, we study a relaxed scenario of blind quantum computing, where the server gets some information about the algorithm. In particular, we propose a protocol to hide an n-qubit Grover search algorithm by utilizing additional qubits on a quantum server which are initialized by the clients.

[1] Fitzsimons, J. F. (2017), npj Quantum Information, 3(1), 23.
[2] A. Childs, A. (2005), Quantum Inform. Comput., 5, 456-466.

QI 36.31 Thu 17:00 Tent

**Metrology for magnetic moments in transmission electron microscopes** — •Michael Gaida[1], Santiago Beltran Romero[2,3], Stefan Nimmrichter[1], Dennis Rätzel[4], and Philipp Haslinger[2,3] — [1]Universität Siegen, Adolf-Reichwein-Straße 2a, 57076 Siegen, Deutschland — [2]Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria — [3]University Service Centre for Transmission Electron Microscopy, TU Wien, Wiedner Hauptstraße 8-10/E057-02, 1040 Wien, Austria — [4]ZARM, Unversität Bremen, Am Fallturm 2, 28359 Bremen, Germany

In transmission electron microscopy (TEM), an electron beam passes through a thin sample layer, producing an interference pattern that reveals atomic-scale structures. While TEM is well-established, quantum metrology offers potential enhancements. Building on the experimental proposal in reference [1], which aims to detect individual quantum spins' magnetic moments using electron beams, we extend the analysis to include scattering dynamics in the paraxial high-energy regime. We calculate the quantum Fisher information for estimating magnetic moments using analytical and numerical methods, comparing it to classical methods with position-resolving electron detectors. Our goal is to determine the experimental conditions required to detect a single Bohr magneton with focused electron beams.

[1]P. Haslinger, S. Nimmrichter, and D. Rätzel, Spin resonance spectroscopy with an electron microscope, QST 9, 035051 (2024).

QI 36.32 Thu 17:00 Tent

**Scalable, high-fidelity all-electronic control of trapped-ion qubits** — •Clemens Löschnauer, Jacopo Mosca Toba, Amy Hughes, Steven King, Marius Weber, Raghavendra Srinivas, Roland Matt, Rustin Nourshargh, David Allcock, Chris Ballance, Clemens Matthiesen, Maciej Malinowski, and Thomas Harty — Oxford Ionics, Oxford, United Kingdom

The central challenge of quantum computing is implementing high-fidelity quantum gates in a scalable fashion. Our all-electronic qubit control architecture combines laser-free gates with local tuning of electric potentials to enable site-selective single- and two-qubit operations in multi-zone quantum processors. Chip-integrated antennas deliver control fields common to all qubits, while voltages applied to local tuning electrodes adjust the position and motion of ions in each zone, thus enabling local coherent control. We experimentally implement low-noise, site-selective single- and two-qubit control in a microfabricated 7-zone ion trap, demonstrating 99.99916(7)% fidelity for single-qubit gates, and two-qubit Bell state generation with 99.97(1)% fidelity. These results validate the path to directly scaling these techniques to large-scale quantum computers based on electronically controlled trapped-ion qubits.

QI 36.33 Thu 17:00 Tent

**Towards a real-time controlled cryogenic eight qubit quantum processor** — •Erik Dunkel[1], Kevin Rempel[1], Sebastian Halama[1], Celeste Torkzaban[1], and Christian Ospelkaus[1,2] — [1]Leibniz Universität Hannover, Hannover — [2]Physikalisch-Technische Bundesanstalt, Braunschweig

Ions confined by surface-electrode Paul traps represent a promising technology for quantum computing and quantum simulation. In our group, the qubits are encoded in two hyperfine levels of $^9Be^+$ ions and controlled by trap-integrated microwave conductors, which allow us to manipulate both the internal and motional states of the ions.

We will implement a cryogenic linear ion-trap array for eight ions with all electrical supplies necessary to apply microwave currents, DC- and RF-voltages. The trap array allows linear transport of ions, features independent storage zones and a detection register.

In addition, we will report on the status of the ongoing future-proof upgrade to the ARTIQ control system. This enables nanosecond timing pulse generation, radio-frequency synthesis and data acquisition executed on a dedicated FPGA hardware and interfaced with a Python-based programming language.

QI 36.34 Thu 17:00 Tent

**Mitigation of longitudinal electric field components in a tweezer-sized standing-wave optical dipole trap** — •Florian Fertig[1,2], Pooja Malik[1,2], Yiru Zhou[1,2], Chengfeng Xu[1,2], and Harald Weinfurter[1,2,3] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Max-Planck-Institut für Quantenoptik, Garching, Germany

Long coherence times are vital for large-scale quantum networks to distribute high-quality entanglement. Single atoms, trapped optically in an optical dipole trap (ODT), with an efficient light-matter interface for atom-photon entanglement have shown to be an excellent system for future quantum nodes. However, dephasing from fluctuations of external magnetic fields, but also effective magnetic fields arising from longitudinal electric field components in tightly focused tweezer beams (beam waist $w_0 \approx 2\mu m$), currently limit the coherence time.

Here, we present the successful implementation and characterization of a novel, tweezer-sized standing-wave ODT for single neutral atoms. This trap geometry effectively mitigates these effective magnetic fields. By overlapping two counterpropagating ODT beams, we create a standing wave, where the effective magnetic fields from each beam cancel each other out. Our measurements confirm the significant reduction of longitudinal field components, resulting in an increase in coherence time. Additionally, this trap architecture holds potential for multiplexing applications, offering a pathway to higher entanglement rates and enhanced quantum processing capabilities.

QI 36.35 Thu 17:00 Tent

**Integration of 3D glass structures for scalable trapped-ion quantum computing** — •Victoria Schwab[1,2], Klemens Schueppert[2], Max Glantschnig[2,4], Alexander Zesar[2,5], Adrian Woyke[2,6], Philipp Hurdax[3], Bernhard Lamprecht[3], Marco Valentini[1], Marco Schmauser[1], and Philipp Schindler[1] — [1]Institute for Experimental Physics, Innsbruck, Austria — [2]Infineon Technologies Austria AG, Villach, Austria — [3]Johanneum Research Materials, Weiz, Austria — [4]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [5]Karl-Franzens Universität Graz, Graz, Austria — [6]École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

Trapped-ion quantum computing is one of the most promising platforms in quantum information processing, where qubits are realized as energy levels of single ionized atoms. The preparation, manipulation and read out of the states are driven by laser light, requiring the implementation of optical access into the ion trap.

We present the fabrication route of an ion trap with multiple metal layers on a structured glass substrate. In cooperation with Johanneum Research, the glass substrate is structured by employing a selective laser etching technique, such that it allows additional optical access through the backside of the trap and thus higher flexibility in the laser setup. At Infineon Technologies in Villach, the implementation of the fabrication flow for multi-metal deposition is realized. Future steps include the prototype testing and development of the high optical access laser setup, contributing to making scalable ion traps a reality.

QI 36.36 Thu 17:00 Tent

**Observing Product of Weak Values** — •Vinay Tumuluru[1,2,3], Jan Dziewior[1,2,3], Carlotta Versmold[1,2,3], Florian Huber[1,2,3], Lev Vaidman[4], and Harald Weinfurter[1,2,3] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, 80797 München — [2]MPI für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching — [3]Munich Center for Quantum Science and Technology (MCQST), 80797 München — [4]Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Israel

When a quantum system which was weakly coupled to a measuring 'pointer' system is suitably pre- and post-selected, one can observe a large shift in the state of the pointer. This shift is characterised by the 'weak value' of the pre- and post-selected system [1]. Weak values can be realised via optical interferometers where the path degree of freedom (system) is coupled with the transverse mode of the optical beam (pointer) [2]. Additionally, the polarisation degree of freedom can instead be employed as the system and coupled to the same pointer. This enables multiple systems to interact with the pointer individually and simultaneously. Interesting cases are explored, such as when weak values corresponding to each interaction are complex, but their product is real. Furthermore, a potential entanglement between the observed degrees of freedom can in turn lead to the violation of the product rule of weak values [3]. Ref: [1] Y. Aharonov et al, PRL. 60, 1351 (1988) [2] P. B. Dixon et al, PRL. 102 (2009) [3] X. Xu et al, PRL. 122, 100405 (2019)

QI 36.37 Thu 17:00 Tent

**Range of operation and oversqueezed regime of squeezing transfer as means of generating spin-entangled states in trapped ions** — •Nadezhda Markova — Center for Quantum Technologies, Department of Physics, Sofia University, Bulgaria

A state is regarded as both squeezed along the direction $\vec{n}_3$ and entangled when the parameter $\xi^2(\vec{n}_3) < 1$ [2]. A necessary and sufficient condition for entanglement is given by $\chi^2 = \frac{N}{F_Q} < 1$ [2], where $F_Q$ is the QFI.

We calculate and compare these parameters for a spin-entangled state in an ion trap. The state in question is generated by transferring squeezing from the motional to the spin degree of freedom. This is achieved by applying the Tavis-Cummings Hamiltonian for a particular time and results in a nonclassical spin state [1].

We compare the parameters $\xi^2$ and $\chi^2$ as a function of the squeezing parameter $r$ and the number of ions $N$ by simulating the system's evolution using the QuTip library. We identify the oversqueezed regime and the range of operation of the aforementioned procedure.

[1] R. J. Lewis-Swan, J. C. Zu*niga Castro, D. Barberena, and A. M. Rey. Exploiting nonclassical motion of a trapped ion crystal for quantum-enhanced metrology of global and differential spin rotations. Phys. Rev. Lett.
[2] L. Pezzé and A. Smerzi. Entanglement, nonlinear dynamics, and the Heisenberg limit. Phys. Rev. Lett.

QI 36.38 Thu 17:00 Tent

**Consistent Strong-Coupling Quantum Master Equations from Dynamical Maps** — •Anton Braun, André Eckardt, and Alexander Schnell — Technische Universität Berlin, Institut für Theoretische Physik

One of the most basic quantum master equations describing the interaction between a quantum system and its environment is the Redfield equation. It is, however, well known that it violates complete positivity and leads to incorrect steady states for non-weak coupling. Following up on work by Becker et al. [1], modifications to the Redfield equation are investigated that combat these issues by introducing a correction term that steers the dynamics towards the correct steady state. To this end, we study the exact solution of the Caldeira-Leggett model and show that the corresponding dynamical map can be obtained by combining Redfield theory with ideas from the formalism of periodically refreshed baths. In this way, divergence of the Redfield dynamical map for long times is cured by instead recursively evolving to a shorter time. Finally, the correction term of Ref. [1] can then be recovered from the so-obtained dynamical map. This gives a completely novel perspective on the long-standing issues of the Born-Markov approximation.

[1] Phys. Rev. Lett. 129, 200403 (2022)

QI 36.39 Thu 17:00 Tent

**Quantum algorithms to solve partial differential equations in battery modelling** — •David Steffen[1,2], Albert Pool[1,2], Michael Schelling[1,2], and Birger Horstmann[1,2,3] — [1]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Wilhelm-Runge-Str. 10, 89081 Ulm — [2]Helmholtz Institute Ulm, Helmholtzstr. 11, 89081 Ulm — [3]Department of Physics, Ulm University, Albert-Einstein-Allee 11, 89081 Ulm

Mathematical models of electrochemical systems as batteries or fuel cells consist of sets of coupled nonlinear partial differential equations. We present variational quantum algorithms to simulate these systems on a quantum computer. The spacetime solution can be obtained as the ground state of a Feynman-Kitaev Hamiltonian evaluated via quantum nonlinear processing units (QNPUs) [1] or the system is encoded through feature maps and solved with Differentiable Quantum Circuits (DQC) [2].

These algorithms can be used on different scales from continuum modelling on cell level to molecular dynamics and thus bridging the gap to quantum chemistry which is another promising field of quantum computing in battery research.

[1] Pool, A.J. et al, Phys. Rev. Res. 2024, 6, 033257
[2] Kyriienko, O. et al., Phys. Rev. A 2021, 103, 052416

QI 36.40 Thu 17:00 Tent

**The role of the zero mode on the entanglement dynamics of harmonic chains** — •Stefan Aimet[1] and Spyros Sotiriadis[2] — [1]Freie Universität Berlin, Berlin, Germany — [2]University of Crete, Heraklion, Greece

In this submission, we investigate the role of a special zero mode feature on the evolution of entanglement under global quench dynamics of harmonic chains.

QI 36.41 Thu 17:00 Tent

**Quantum robustness of the toric code in a parallel field on the honeycomb lattice** — •Viktor Kott, Matthias Mühlhauser, Jan Alexander Koziol, and Kai Phillip Schmidt — Chair of Theoretical Physics V, Friedrich-Alexander-Universität, Erlangen, Germany

We study the quantum robustness of topological order in the toric code on a honeycomb lattice under a uniform parallel field. For a field in the z-direction, the system maps to the transverse-field Ising model on the honeycomb lattice, showing a second-order quantum phase transition in the 3D Ising* universality class. A positive x-field similarly maps to a ferromagnetic transverse-field Ising model on the triangular lattice, with the same phase transition. In contrast, a negative x-field maps to a frustrated antiferromagnetic model, leading to a 3D XY* transition and a first-order transition to a polarized phase at higher field values. These findings, confirmed by quantum Monte Carlo and series expansions, apply to both honeycomb and triangular lattices, revealing critical behaviors and potential multi-critical points.

QI 36.42 Thu 17:00 Tent

**Householder reflections in the Hilbert space of ions trapped in Paul trap** — •Vasil Vasilev and Nikolay Vitanov — Department of Physics, Sofia University, James Bourchier 5 boulevard, 1164 Sofia, Bulgaria

This work investigates the ways of generating Householder reflections in the Hilbert space of ions trapped in Paul trap. The Householder reflection is a powerful approach for matrix manipulation in classical data analysis. Here we explore its use in quantum information processing for the creation of arbitrary unitary matrices. In previous publications, an arbitrary Householder transformation is produced either by using different couplings in an N-pod system, for which, however, the Hilbert space is non-scalable [1], or in a scalable Hilbert space but for equal couplings [2,3]. Here we discuss the more general situation of constructing Householder reflections with different couplings in a scalable Hilbert space. The ultimate objective is to construct C^n-phase gates which can be used as native implementations of Householder reflections and hence for efficient decomposition of unitary matrices. The proposed concept can also be used for physical synthesis of arbitrary random matrices. We explore their Haar measures and present a comparison with the Givens rotations method.

[1] Peter A. Ivanov and Nikolay V. Vitanov Phys. Rev. A 77, 012335
[2] Peter A. Ivanov, Nikolay V. Vitanov and Martin B. Plenio Phys. Rev. A 78, 012323
[3] S. S. Ivanov, P. A. Ivanov, I. E. Linington, and N. V. Vitanov Phys. Rev. A 81, 042328

QI 36.43 Thu 17:00 Tent

**Onset of Quantum Thermalization in Jahn-Teller model. Stochasticity in ergodic quantum systems.** — •Yoana Chorbadzhiyska and Peter Ivanov — Sofia University, Sofia, Bulgaria

In the present work, we investigate the onset of quantum thermalization in a system governed by the Jahn-Teller Hamiltonian which describes the interaction between a single spin and two bosonic modes. We find that the Jahn-Teller model exhibits a finite-size quantum phase transition between the normal phase and two types of super-radiant phase when the ratios of spin-level splitting to each of the two bosonic frequencies grow to infinity. We test the prediction of the eigenstate thermalization hypothesis (ETH) in the Jahn-Teller model. We validate the diagonal part of the hypothesis utilizing various measures. Further, we focus on the statistical properties of the off-diagonal matrix elements and consider an alternative indicator for the validity of this aspect of the ETH. We discuss briefly the theory behind the derivation of the indicator and comment on the application of this theory to the quantum parameter estimation in ergodic systems.

QI 36.44 Thu 17:00 Tent

**Characterization and mitigation of optical side-channels in QKD** — •Evelyn Edel[1], Moritz Birkhold[1,2], Lukas Knips[1,2,3], Sebastian Melik[4], and Harald Weinfurter[1,2,3] — [1]Ludwig Maximilian University, Munich, Germany — [2]Munich Center for Quantum Science and Technology, Munich, Germany — [3]Max Planck Institute of Quantum Optics, Garching, Germany — [4]University of Gdańsk, Gdańsk, Poland

Unlike classical key distribution methods reliant on computationally hard problems, quantum key distribution (QKD) achieves information-theoretic security by the principles of quantum mechanics. The decoy-state BB84 protocol offers a practical scheme for realizing free-space QKD sender modules, allowing the use of highly attenuated laser pulses as a photon source. Yet, device imperfections could make side channel attacks by an eavesdropper possible. This work presents a characterization of spectral side channels in our sender module, arising from imperfect spectral overlap. For pulse generation, the module under investigation hosts four vertical-cavity surface-emitting lasers (VCSELs) in a monolithic array, one for each polarization state. Using a spectrometer also in combination with a streak camera, we analyze the spectral behavior and time-dependent variations of these diodes for different bias and modulation currents. To minimize the resulting side channels, Peltier modules are tested for cooling individual diodes. This setup will allow us to identify VCSEL arrays with the best spectral overlaps and quantize the information leaked to an eavesdropper, facilitating the future optimization of our modules.

QI 36.45 Thu 17:00 Tent

**Quantum search with resetting** — •Sayan Roy, Emma King, and Giovanna Morigi — Theoretische Physik, Universität des Saarlandes, D- 66123 Saarbrücken, Germany

Search problems are prevalent in science and nature. Algorithms incorporating resetting mechanisms, where the system randomly or periodically resets to its initial state, have demonstrated improved efficiency in search tasks within both classical and quantum domains [1]. In this contribution, we consider resetting protocols for quantum walks in one dimension with nearest-neighbor hopping and determine the time the walker needs to reach a given target for different implementations of the resetting procedure. We then discuss how the results may be generalized to lattices of higher dimensions and different site connectivity.

[1]. M.R. Evans, S.N. Majumdar and G. Schehr, J. Phys. A: Math. Theor. **53**, 193001.

QI 36.46 Thu 17:00 Tent

**Off-resonant dipole-phonon interaction for quantum information processing with molecular rotors** — •Leonel O. Stenkhoff, Monika Leibscher, and Christiane P. Koch — Freie Universität Berlin

Encoding quantum information in molecular ions requires a mechanism allowing for cooling and control of rotational quantum states. To this end, the dipole-phonon interaction of molecular and atomic ions co-trapped in a linear Paul trap is utilized. Resonant dipole interaction occurs when the rotational energy splitting is comparable to the eigenfrequency of a normal mode of the trap. Off-resonant dipole-phonon coupling scales with the trap frequency and the dipole moment of the molecule and can become the dominant part of the interaction if the molecule has a particular large dipole moment, as we demonstrate for the example of a trapped cytochrome complex. The prospects of cooling rotational quantum states via off-resonant dipole coupling are also discussed, which is particularly interesting for systems, where no resonant dipole-phonon interaction is observed in the range of achievable trap frequencies.

QI 36.47 Thu 17:00 Tent

**Pulse shaping strategies: smooth sine-based pulses for enhanced stability and super power broadening with two tunable types of pulses** — •Ivo Mihov and Nikolay Vitanov — Center for Quantum Technologies, Department of Physics, Sofia University, 5 James Bourchier blvd, 1164 Sofia, Bulgaria

This study explores two approaches to pulse shaping for qubit dynamics. First, smooth sine pulses are investigated as alternatives to rectangular pulses, minimizing power broadening, reducing sidebands, and avoiding truncation issues. Two analytic solutions, based on Weber's parabolic cylinder functions and a simplified asymptotic approach, are derived and validated on IBM Quantum processors, confirming the predicted effects.

In contrast, the study also examines two novel pulse families designed to enhance power broadening, creating "super power broadening." These pulse shapes – quadratic and even-power pulses – amplify non-adiabaticity at the pulse edges, enabling more sensitive interactions for applications such as EIT, quantum tomography, and nonlinear optics. These pulse shaping strategies, tested on IBM Quantum processors, offer new tools for optimizing quantum state manipulation, broadening interaction frequencies, and improving spectroscopy techniques.

QI 36.48 Thu 17:00 Tent

**Simulating Chemistry with Fermionic Optical Superlattices** — •Jin Zhang[1], Fotios Gkritsis[2], Daniel Dux[3], Naman Jain[1], Christian Gogolin[2], and Philipp Preiss[1,4] — [1]Max Planck Institute for Quantum Optics, Garching — [2]Covestro Deutschland AG, Leverkusen — [3]Physikalisches Institut der Universitat Heidelberg — [4]Munich Center for Quantum Science and Technology, Munich

Computational chemistry requires finding the ground states of strongly correlated electrons in molecular orbitals. Quantum algorithms and computers promise to provide such ground state energies for molecular systems whose size is beyond the reach of classical numerical methods. One approach is to translate molecular structure problems to fermionic quantum simulators, which naturally obey the fermionic exchange symmetries found in nature. We show that quantum number preserving Ansatze for variational optimization in quantum chemistry find an elegant mapping to ultracold fermions in optical superlattices. Using native Hubbard dynamics, trial ground states of molecular Hamiltonians can be prepared and their molecular energies measured in the lattice. The scheme requires local control over interactions and chemical potentials and global control over tunneling dynamics, but foregoes the need for shuttling operations or long-range interactions. Our work enables the application of recent quantum algorithmic techniques, such as Double Factorization and quantum Tailored Coupled Cluster, to present-day fermionic optical lattice systems with significant improvements in the required number of experimental repetitions. We provide detailed quantum resource estimates for hardware experiments.

QI 36.49 Thu 17:00 Tent

**Sparse Optimization of Quantum Fourier Transform Spectroscopy** — •Chinmay Sangavadekar[1], Zhengjun Wang[1,2], and Frank Schlawin[1,2,3] — [1]University of Hamburg, Luruper Chaussee 149, Hamburg, Germany — [2]Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany — [3]The Hamburg Centre for Ultrafast Imaging, Hamburg, Germany

Nonlinear interferometers are of fundamental importance for quantum-enhanced photonic sensing. They enable sensing in the infrared regime at low photon flux and without the need of detecting infrared photons. Here we present a theoretical model for quantum Fourier transform spectroscopy with nonlinear interferometers. We further explore how sparse optimization may reduce the necessary number of measurements and thereby speed up data acquisition.

QI 36.50 Thu 17:00 Tent

**Modeling spin initialization in highly strained silicon-vacancy centers** — •Michael Gstaltmeyr, Marco Klotz, Andreas Tangemann, and Alexander Kubanek — Institute for Quantum Optics, University Ulm, Germany

Spin qubits in solid state hosts are, due to their promise of scalability, candidates for the realization of quantum networks. The good spin properties of diamond paired with the optical properties of group-IV defects make them of special interest. We are using highly strained Silicon-Vacancy centers in nanodiamonds to mitigate phonon induced electron spin dephasing at liquid helium temperature. However, high strain introduces challenges in optical spin initialization, as additional transitions closely interact with the initialization pathway, complicating the traditional three-level pump model. This work explores these interactions and proposes improved methods to characterize the system.

QI 36.51 Thu 17:00 Tent

**Quantum Generative Modelling with Conservation Law based Pretraining** — •Akash Malemath[1,2], Yannick Werner[3], Paul Lukowicz[1,3], and Maximilian Kiefer-Emmanouilidis[1,2,3] — [1]Department of Computer Science and Research Initiative QCAI, RPTU, Kaiserslautern-Landau — [2]Department of Physics, RPTU, Kaiserslautern-Landau — [3]DFKI Kaiserslautern

Abstract:

Compared to the recent advancements in classical generative AI, quantum generative models still lack the capability to generate complex data effectively. One of the greatest challenges in classical AI is developing systems that extract fundamental relationships from large datasets and encode them into suitable embeddings. In quantum generative AI, these concepts are still in early stages and are mostly learned using classical methods.

In this work, we evaluate embeddings inspired by conservation laws as a pretraining step, applying them to simple quantum generative models like the Quantum Circuit Born Machine (QCBM). This implicit generative model is well-suited for reproducing target distributions and is simple enough to demonstrate the benefits of pretraining. Specifically, we explore pretraining using the particle number distribution and system Hamiltonian within the QCBM, aiming to model target distributions with reduced effort. Our analysis of pretraining in QCBM focuses on its impact on model convergence and accuracy, using metrics such as Kullback-Leibler (KL) divergence, and compares pretrained models with those trained normally.

QI 36.52 Thu 17:00 Tent

**Cluster-additivity of perturbative discrete product of unitaries and applications to the variational quantum eigensolver** — •Max Hörmann, Harald Leiser, Sumeet Sumeet, and Kai Phillip Schmidt — Chair for Theoretical Physics V, FAU Erlangen-Nürnberg, Germany

We explore the cluster-additivity properties of a perturbatively defined unitary transformation $U = U_1 \cdot \ldots \cdot U_n$, where each successive order in perturbation theory introduces an additional unitary operator $U_n$ [1]. We establish connections to continuous unitary transformations and compare this approach with globally defined transformations, such as the projective cluster-additive transformation [2]. Furthermore, we emphasize the striking parallels between this transformation and ansätze commonly employed in the variational quantum eigensolver algorithm. Building on this, we propose a variational extension of the transformation, expanding its applicability beyond the perturbative framework. Finally, we assess whether this transformation can effectively construct good initial guesses for larger systems by leveraging information from smaller subsystems.

[1] N. Datta, J. Fröhlich, L. Rey-Bellet and R. Fernández, Low-temperature phase diagrams of quantum lattice systems. II. Convergent perturbation expansions and stability in systems with infinite degeneracy, Helv. Phys. Acta 69(5-6), 752 (1996).

[2] M. Hörmann and K. P. Schmidt, Projective cluster-additive transformation for quantum lattice models, SciPost Phys. 15, 097 (2023).

QI 36.53 Thu 17:00 Tent

**Employing Two-Photon Interference to Secure QKD Against Optical Side Channels** — •Franziska Divkovic[1], Moritz Birkhold[1,2], Harald Weinfurter[1,2,3], and Lukas Knips[1,2,3] — [1]Ludwig Maximilian University, Munich, Germany — [2]Munich Center for Quantum Science and Technology, Munich, Germany — [3]Max Planck Institute of Quantum Optics, Garching, Germany

Quantum Key Distribution (QKD) provides a key advantage over classical cryptography by enabling secure communication without the risk of unnoticed eavesdropping on the quantum channel. However, in real devices, side channels - additional degrees of freedom (DOFs) correlated with the one used to encode the key - can allow eavesdroppers to extract information. If not quantified, these side channels can compromise the security of the QKD scheme.

A key assumption in the security proof is the phase randomization of consecutive pulses representing the same symbol. Indistinguishable pulses, which are phase-randomized, prevent attacks by ensuring no information can be extracted from alternate DOFs. To verify whether this criterion is met, the interference of these pulses is investigated. Additionally, the interference of pulses representing different symbols is analyzed to assess their indistinguishability across all except polarization. The visibility of the interference pattern serves as a key metric for quantifying pulse indistinguishability and security. This is achieved using a fiber-based interferometer with a delay line in one arm and a polarization-cleaning mechanism. This research provides insights for defining specifications and developing tests to secure against attacks.

QI 36.54 Thu 17:00 Tent

**Robust VECSEL for Controlling trapped Magnesium Ions** — •Tobias Spanke, Lennart Guth, Philip Kiefer, Lucas Eisenhart, Deviprasath Palani, Apurba Das, Florian Hasse, Jörn Denter, Mario Niebuhr, Ulrich Warring, and Tobias Schätz — Physikalisches Institut, Albert-Ludwigs-Universität, Freiburg

Trapped ions present a promising platform for quantum simulations and quantum sensing. Versatile and robust laser systems with narrow bandwidth and high power and intensity stability are required at UV range of 280 nm to reliably load and control this platform. The latest systems for $Mg^+$, $Be^+$ ions are based on vertical external cavity surface-emitting lasers (VECSEL) [1] in the near-infrared. A new generation of air-cooled systems is proposed to decrease bandwidth and increase stability while mitigating expensive temperature control systems. With the goal of measuring magnesium ions at a frequency stability of 200 kHz ($\lambda \approx 1120$ nm, P = 2 W with $\lambda \approx 280$ nm at the experiment) with high accuracy. We aim at further development of the VECSEL into a compact, stable, and user-friendly "turnkey" system.

[1] Burd, S. et al.(2016), VECSEL systems for generation and manipulation of trapped magnesium ions, Optica Vol. 3, Issue 12, pp. 1294-1299 (2016)

QI 36.55 Thu 17:00 Tent

**Complexity: chaos, regular, and complex** — •Adisorn Panasawatwong, Jan-Michael Rost, and Ulf Saalmann — MPI-PKS

We are developing a machine learning-based approach to extract meaningful information from noisy physical observables. Distinguishing signal from noise in chaotic systems is a significant challenge. Our primary goal is to introduce a novel method for quantifying the inherent complexity of these signals, similar to resolution functions used in standard data analysis. A key aspect of our approach is to assign zero complexity to systems that exhibit either extreme regularity or extreme chaos. We designed machine learning networks specifically tailored to uncover hidden patterns within these noisy observables. This approach aims to enhance our ability to extract critical information from a wide range of applications, from classical noise to the complex quantum systems that produce noisy, intricate data sets.

QI 36.56 Thu 17:00 Tent

**Efficient quantum control by composite ultrastrong field** — •Kremena Parashkevova and Nikolay Vitanov — Center for Quantum Technologies, Faculty of Physics, Sofia University, James Bourchier 5 blvd., 1164 Sofia, Bulgaria

We present a study on coherent quantum control of a qubit by an ultrastrong driving field in the regime where the rotating-wave approximation cannot be applied. The resulting counter-rotating term makes traditional quantum control methods, such as resonant, adiabatic and shortcut techniques, unable to achieve high control accuracy. We identify the recently developed universal composite pulses as the only quantum control method which successfully maintains very high accuracy even in this ultrastrong coupling regime.

QI 36.57 Thu 17:00 Tent

**Towards Scalable Quantum Computing with Trapped Ions: Single-Ion Addressing and Efficient Cooling** — •Robin Strohmaier, Daniel Wessel, Alexander Müller, Jonas Vogel, Björn Lekitsch, and Ferdinand Schmidt-Kaler — QUANTUM, Institut für Physik, Johannes Gutenberg-Universität Mainz

Trapped ions are a leading platform for scalable and fault-tolerant quantum computing. In this work, we present two critical advancements toward realizing scalable quantum computing with linear crystals of ions: precise single-ion addressing and efficient near-ground-state cooling of ion crystals.

Single ion addressing of the spin qubit in $^{40}Ca^+$ is achieved using a crossed acousto-optic deflector (AOD) setup. This system utilizes a tightly focused 400 nm laser beam to drive stimulated Raman transitions between spin states. We demonstrate a beam focus of 1 $\mu$m, enabling low crosstalk between neighboring ions. Additionally, we implement several ground state cooling schemes which can be used within sequences as well. This enables longer gate sequences and hence deeper algorithms. Combined with our new developed, SLE fabricated, glass trap and its low heating rates, these advancements support the handling of ion crystals with tens of ions, paving the way for operations involving multiple logical qubits. These results mark significant progress toward scalable quantum computation with trapped ions.

QI 36.58 Thu 17:00 Tent

**Noisy Rydberg Quantum Gates** — •Santiago Higuera Quintero[1], Sebastian Weber[1], Katharina Brechtelsbauer[1], Nicolai Lang[1], Tilman Pfau[2], Florian Meinert[2], and Hans Peter Büchler[1] — [1]Institute for Theoretical Physics III and IQST, University of Stuttgart, 70550 Stuttgart, Germany — [2]Institute of Physics and IQST, University of Stuttgart, 70550 Stuttgart, Germany

Modelling noise processes in noisy intermediate-scale quantum (NISQ) devices plays an important role in designing hardware and algorithms in the journey for scalable quantum computers. In this era, classical emulators of quantum systems can help to better understand typical errors in quantum information processing which arise from coupling to the environment and experimental limitations. We present a noise analysis of our gate protocols and determine relevant Kraus maps under typical noise sources to Rydberg-based platforms, such as: photon recoil, laser and thermal noise. Finally, we provide an overview of our online platform that provides users the opportunity to try out our gate-based emulator of the Rydberg quantum computer of the QRydDemo project and get familiar with its native gate operations.

QI 36.59 Thu 17:00 Tent

**Quantum systems driven by nonclassical light treated using the hierarchy of pure states** — •Vladislav Sukharnikov[1], Stasis Chuchurka[1], and Frank Schlawin[2] — [1]Department of Physics, Universität Hamburg, 22761 Hamburg, Germany — [2]Max Planck Institute for the Structure and Dynamics of Matter, 22761 Hamburg, Germany

Quantum systems driven by nonclassical light fields have garnered significant attention, particularly in light of recent breakthroughs in high-harmonic generation using nonclassical light sources. Developing a comprehensive theoretical framework for these systems would be highly beneficial. However, the inherent complexity of the problem limits a fully general treatment. In this work, we investigate the interaction between an atomic system and nonclassical light, such as squeezed light, examining the dynamic evolution of both the atomic system and the field. To tackle this challenging problem, we employ a hierarchy of pure states to model the coupling to the field, which is treated as a non-Markovian bath. This method allows for parallelization and effectively treats multimode structure of the field, providing deeper insights into the underlying dynamics and expanding our understanding of these complex systems.

QI 36.60 Thu 17:00 Tent

**Exploring Long-Range Interactions in Quantum Many-Body Systems** — •Antonia Duft, Patrick Adelhardt, and Kai Phillip Schmidt — Friedrich-Alexander Universität Erlangen-Nürnberg

Long-range interactions play a crucial role in many quantum many-body systems and might influence their dynamics, critical behavior, and phases of matter. Experimentally, algebraically decaying long-range interactions $\sim r^{-(d+\sigma)}$ are relevant in various quantum-optical platforms, including ultracold atoms, trapped ions, and Rydberg atom arrays which can also serve as analogue quantum simulators. However, their theoretical treatment poses challenges compared to short-ranged systems. To address these, we utilize the method of perturbative Continuous Unitary Transformations (pCUT)combined with classical Monte Carlo (MC) techniques. A linked-cluster expansion is set up for long-range interactions using white graphs and the embedding is handled in a MC algorithm. This approach enables the extraction of high-order series expansions of physical quantities in the thermodynamic limit. The pCUT+MC approach can be employed to tackle a multitude of systems, including paradigmatic models like the spin-1/2 transverse field Ising model, XY model, and Heisenberg model. We further apply the method to spin-1 Heisenberg systems.

QI 36.61 Thu 17:00 Tent

**Is Localization a security threat in Quantum Machine Learning?** — •Yannick Werner[1], Nikolaos Palaiodimopoulos[1,2], Omid Faizy[2,3], Nico Piatkowski[4], Paul Lukowicz[1,2], and Maximilian Kiefer-Emmanouilidis[1,2] — [1]DFKI Kaiserslautern — [2]RPTU Kaiserslautern-Landau — [3]Sorbonne Université, Paris — [4]Fraunhofer IAIS, Sankt Augustin

As Quantum Machine Learning (QML) becomes more developed and widely used in commercial applications, addressing its security risks is essential. We examine Quantum Neural Networks (QNNs) as disordered quantum systems to explore whether effects like Many-Body Localization (MBL) could impact QNN tasks such as classifying or generating data. It has been shown, that applying a simple cyclic permutation after embedding the data and before readout can recover complex classical data from the measurements of a single disorder realization [1]. This suggests that a trained QNN, which effectively represents such a single disorder realization, could be vulnerable to exposing sensitive data it is supposed to classify. For instance, an eavesdropper might recover sensitive input data from stolen measurement results, a risk that is non-existent with classical classifiers. To address this, we analyse shallow variational quantum circuits with nearest-neighbour interactions and strongly varying weights, where MBL dynamics are expected. We assess their vulnerability to data recovery and examine the balance between expressibility, trainability, and security risks in QNN designs.

[1]arXiv:2409.16180v1 (2024).

QI 36.62 Thu 17:00 Tent

**Gradient magnetometry with atomic ensembles** — •Iagoba Apellaniz[1], Iñigo Urizar-Lanz[1], Zóltan Zimborás[1,2,3], Philipp Hyllus[1], and Géza Tóth[1,3,4] — [1]Department of Theoretical Physics, University of the Basque Country UPV/EHU, P. O. Box 644, ES-48080 Bilbao, Spain — [2]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, DE-14195 Berlin, Germany — [3]Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, HU-1525 Budapest, Hungary — [4]IKERBASQUE, Basque Foundation for Science, ES-48013 Bilbao, Spain

We study gradient magnetometry with an ensemble of atoms with arbitrary spin. We calculate precision bounds for estimating the gradient of the magnetic field based on the quantum Fisher information. For quantum states that are invariant under homogeneous magnetic fields, we need to measure a single observable to estimate the gradient. On the other hand, for states that are sensitive to homogeneous fields, a simultaneous measurement is needed. We present a method to calculate precision bounds for gradient estimation with a chain of atoms or with two spatially separated atomic ensembles. We also consider a single atomic ensemble with an arbitrary density profile, where the atoms cannot be addressed individually, and which is a very relevant case for experiments. Our model can take into account even correlations between particle positions. While in most of the discussion we consider an ensemble of localized particles that are classical with respect to their spatial degree of freedom, we also discuss the case of gradient metrology with a single Bose-Einstein condensate.

QI 36.63 Thu 17:00 Tent

**A Weak Measurement Based Toy Model to Probe Quantum Properties in a Cosmological Setting** — •Joel Huber[1,2,3], Časlav Brukner[3], and Igor Pikovski[4] — [1]Universität Siegen — [2]ETH Zurich — [3]IQOQI Vienna — [4]Stevens Institute of Technology

Probing quantum properties in cosmology could offer profound insights into the fundamental nature of the universe. We present a novel perspective on the detectability of quantum properties in cosmology. Firstly, we motivate a set of fundamental limitations inherent to observational cosmology and translate them into operational constraints for a general quantum system. We then propose a toy model and show how the limitations can be successfully circumvented by studying weakly coupled pointer degrees of freedom. We find that the noncommutativity of observables can be inferred by comparing measurement statistics, even though limited by the weakness of the measurements. This result can provide a hint but not conclusive evidence, for the quantum nature of the system. Finally, we investigate generalised Leggett-Garg inequalities, which separate classical from non-classical temporal correlations. We demonstrate that they cannot be violated using three consecutive weak measurements while remaining agnostic about the underlying interactions.

QI 36.64 Thu 17:00 Tent

**Towards a quantum processor with non-local interactions and programmable connectivity.** — •Franz von Silva-Tarouca[1], Stephan Roschinski[1], Johannes Schabbauer[1], and Julian Léonard[1,2] — [1]TU Wien, Atominstitut, Vienna Center for Quantum Science and Technology (VCQ), Austria — [2]Institute of Science and Technology Austria (ISTA), Am Campus 1, 3400 Klosterneuburg, Austria

Quantum computers and simulators are especially promising for tackling problems that require a high degree of entanglement. However, the efficient and deterministic generation of many-body entanglement still poses a challenge.

We report on progress towards building a quantum processor based on an array of single atoms trapped in optical tweezers and strongly coupled to a high-finesse fiber cavity. The cavity enables non-local interactions, mediated by the joint coupling of the atoms to the cavity mode. Microscopic addressing via the optical tweezers allows for tuning this coupling for each atom, enabling programmable connectivity. This, combined with other established techniques in cavity quantum information processing, provides us with an extensive experimental toolkit for generating many-body entanglement and a variety of quantum computation and simulation experiments.

QI 36.65 Thu 17:00 Tent

**Quantum simulator with 40 nuclear spins in diamond** — •Christina Ioannou — Qutech, TuDelft, Netherlands

Individually controllable $^{13}C$ nuclear spins in diamond, associated with a single NV-center, can be used to realise a quantum simulator for the observation of many-body quantum phenomena. On this poster I will discuss the capabilities of the platform such as collective initialisation with dynamic nuclear polarisation, individual spin control and readout as well as global pulses, which make up a comprehensive toolbox for studying many-body phenomena under a range of tunable Floquet Hamiltonians. Applications of this quantum simulator include observing novel phases of matter such as discrete time crystals, studying the thermalisation a many-body 3D-coupled spin system under Floquet driving, Hamiltonian engineering and estimating entanglement entropies with randomised measurements.

QI 36.66 Thu 17:00 Tent

**Quantum strategies for rendezvous and domination tasks on graphs with mobile agents** — •Giuseppe Viola[1] and Piotr Mironowicz[2,3,4] — [1]University of Siegen, Siegen, Germany — [2]University of Gdansk, Gdansk, Poland — [3]Stockholm University, Stockholm, Sweden — [4]Gdansk University of Technology, Gdansk, Poland

This work explores the application of quantum non-locality, a renowned and unique phenomenon acknowledged as a valuable resource. Focusing on a novel application, we demonstrate its quantum advantage for mobile agents engaged in specific distributed tasks without communication. The research addresses the significant challenge of rendezvous on graphs and introduces a new distributed task for mobile agents grounded in the graph domination problem. Through an investigation across various graph scenarios, we showcase the quantum advantage. Additionally, we scrutinize deterministic strategies, highlighting their comparatively lower efficiency compared to quantum strategies. The work concludes with a numerical analysis, providing further insights into our findings.

QI 36.67 Thu 17:00 Tent

**Optimal control of arbitrary perfectly entangling gates for open quantum systems** — •Adrian Romer, Daniel Reich, and Christiane P. Koch — Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Berlin, Germany

Perfectly entangling gates (PE) are crucial for various applications in quantum information. One method to realize these gates is with the help of an external control field, whose concrete shape is found using optimal control theory. Instead of optimizing the shape that realizes a specific gate, the optimization target can be extended to the full set of PE. This increases the flexibility of optimization and allows to find the best PE from the set of all PE. First, we show that it is possible to construct the unitary part of an unknown coherent evolution by propagating specifically talilored density matrices. We then extend this construction method to approximate the unitary part of a non-unitary evolution. Lastly, we employ this method to superconducting qubits, where we numerically find optimized control fields that generate maximally entangled states for a desired gate duration, even if dissipation is present in the system.

QI 36.68 Thu 17:00 Tent

**Phase Space Dynamics of Continuous-Variable, Open Bosonic Systems with Generative Neural Quantum States** — •Ege Görgün — Institut für Festkörpertheorie und Optik, Jena, Deutschland

Simulating the dynamics of interacting many-body quantum systems poses a significant challenge due to the exponential complexity scaling with system size. In this work, we derive the quantum master equation for phase space quasi-probability distributions across a diverse set of open bosonic systems, providing an analytical foundation for tracking their dynamics. We then present a neural quantum state (NQS) ansatz based on an invertible neural network (INN) trained within a time-dependent variational principle (TDVP) framework, offering a versatile approach for modelling the phase space dynamics of a broad class of continuous-variable systems. Leveraging the inherent invertibility of INNs, our model provides a robust architecture that can serve not only as a Monte Carlo sampler but also enable direct access to probability distributions over time through latent space dynamics.

QI 36.69 Thu 17:00 Tent

**Correlations in non Markovian Open Quantum System Dynamics** — •Isabelle McEntee, Adrian Romer, and Christiane P. Koch — Freie Universität Berlin, Berlin, Germany

Open quantum systems are complex and not easily described. To simulate these dynamics with an equation of motion, we must make many assumptions, in particular weak system bath coupling and Markovianity. This work focuses on two methods that do not make these assumptions and allow for the simulation of correlations that occur in non Markovian dynamics. The first is called the Surrogate Hamiltonian method (Baer & Kosloff, 1997, The Journal of Chemical Physics), here the number of bath modes that interact with our system is limited to create a smaller, finite surrogate bath. This method treats correlations through different configurations of bath excitations. The second method (Chin et al., 2010, Journal of Mathematical Physics), involves mapping system and bath onto a semi-infinite chain which is evaluated using the Density Matrix Renormalization Group (DMRG) technique. This technique allows for correlations to be treated through tensor decomposition. Both methods truncate the bath and thus the system-bath correlations. We study and compare how correlations are built in these two approaches.

## QI 37: Poster – Quantum Information Technologies (joint session Q/QI)

Time: Thursday 17:00–19:00 Location: Tent

QI 37.1 Thu 17:00 Tent

**Design of a tweezer setup for rearrangement and addressing of single atoms in an optical cavity** — •Micha Kappel, Raphael Benz, Sebastián Alejandro Morales Ramirez, Vincent Beguin, Krishna Relekar, and Stephan Welte — 5. Physikalisches Institut, Center for Integrated Quantum Science and Technology and CZS Center QPhoton, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

Neutral atoms coupled to an optical cavity are a promising platform for implementing quantum network nodes. To realize network nodes with multiple stationary atomic qubits, it is crucial to position and address the atoms precisely within the cavity mode. We present an optical design utilizing two two-dimensional acousto-optical deflectors to create optical tweezers capable of trapping arrays of Rubidium atoms inside the cavity. This setup not only facilitates precise atom trapping but also enables individual addressing and rearrangement of the atoms.

To mitigate the inevitable atom losses during operation, we propose the inclusion of a reservoir containing additional atoms in a tweezer array outside the cavity mode. These extra atoms can be used to replenish lost atoms within the cavity. We describe our optical setup and discuss experimental techniques and challenges.

QI 37.2 Thu 17:00 Tent

**Characterization and development of the Saarbrücken fiber link for memory-based quantum communication protocols** — •Christian Haen[1], Max Bergerhoff[1], Jonas Meiers[1], Stephan Kucera[2], and Jürgen Eschner[1] — [1]Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken — [2]Luxembourg Institute of Science and Technology (LIST), Belveaux, Luxembourg

Deployed telecom glass fiber networks offer a basis for the wide-scale development of quantum networks, but characteristics of existing fibers, such as large loss and arrival time or polarization drifts through environmental exposure, must be addressed.

Previously, we demonstrated and characterized quantum network protocols on a 14-km long urban dark fiber link in Saarbrücken by transmitting photons from an SPDC source [1]. Now, we report on characterizing and developing the fiber link to allow for quantum network protocols using photons emitted by a $^{40}Ca^{+}$ single-ion quantum memory, in order to demonstrate atom-photon entanglement and, based on this, device-independent quantum key distribution under realistic conditions.

[1] S.Kucera et al., npj Quantum Inf 10, 88 (2024)

QI 37.3 Thu 17:00 Tent

**Two-cavity-mediated photon-pair emission by one atom** — •Tobias Frank, Gianvito Chiarella, Pau Farrera, and Gerhard Rempe — Max Planck Institute for Quantum Optics, Hans-Kopfermann-Straße 1, 85748 Garching bei München

Single atoms coupled to high-finesse Fabry-Perot cavities provide a versatile quantum network node, enabling efficient generation, storage, and manipulation of photonic qubits with high fidelity. A key focus of ongoing research is to scale either the number of atoms coupled to the cavity or the number of cavity modes interacting with each atom. Our group achieved the latter by using two optical fiber based cavities which couple independently to a single atom in the high atom-photon cooperativity regime. This enables new quantum communication schemes, in which photonic qubits are either tracked by nondestructive qubit detection or received by an heralded quantum memory. In our recent work, we demonstrate an on-demand photon pair generation scheme [1] in which a single atom with three energy levels in a ladder configuration couples to two optical fiber cavities, generating photon pairs with an in-fiber emission efficiency of $\eta_{pair} = 16(1)\%$. We study the correlation properties of the emitted light and simulate the regime of strong atom-photon coupling, in which the atom emits photon pairs without populating the intermediate state. We propose a scenario to observe such a double-vacuum-stimulated effect experimentally.

[1] G Chiarella, T Frank, P Farrera, G Rempe. Optica Quantum Vol. 2, Issue 5, pp. 346-350 (2024)

QI 37.4 Thu 17:00 Tent

**Device-independent quantum key distribution with atom-photon entanglement for an urban fiber link** — •Jonas Meiers, Christian Haen, Max Bergerhoff, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken

Quantum cryptographic protocols offer physical security through no-cloning or entanglement. Following the entanglement-based quantum key distribution protocol of [1], we present our device-independent implementation with a $^{40}Ca^{+}$-ion as quantum memory. The protocol requires four atomic bases and two photonic bases and allows us to create a quantum key with security verification via the Bell parameter. We employ polarization entanglement between a single trapped $^{40}Ca^{+}$ ion and an emitted photon at 854 nm, generated via the $P_{3/2} \rightarrow D_{5/2}$ transition [2]. The photon is frequency-converted to the telecom band, enabling its transmission over our 15-km-long urban fiber link across Saarbrücken [3]. The fiber link has been characterized and stabilized for the transmission of polarization-encoded qubits. The projected qubits are error-corrected via a cascade algorithm to create the secure key and enable secure communication between the two nodes.

[1] R. Schwonnek et al., Nat. Commun. 12, 2880 (2021)
[2] M. Bock et al., Nat. Commun. 9, 1998 (2018)
[3] S.Kucera et al., npj Quantum Inf. 10, 88 (2024)

QI 37.5 Thu 17:00 Tent

**Quantum Network Nodes with Cold Atoms in Optical Cavities** — •Raphael Benz, Sebastián Alejandro Morales Ramírez, Micha Kappel, Vincent Beguin, Krishna Relekar, and Stephan Welte — 5. Physikalisches Institut, Center for Integrated Quantum Science and Technology and CZS Center QPhoton, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany.

The practical implementation of a quantum network remains an outstanding challenge pursued across various hardware platforms. Cold neutral atoms trapped in a high-finesse optical cavity have proven to be a promising platform due to the strong atom-light interaction and the controllability of the system. However, current implementations are limited to a few atoms in the cavity. The ability to position and individually control an array of atoms using optical tweezers opens the possibility of extending this platform to multi-qubit quantum network nodes. We present the plans of our group in Stuttgart to realize such a multi-qubit quantum network node. Several experiments are envisioned with this system, including photon-mediated quantum information processing between intra-cavity atoms, the generation of highly entangled photonic cluster states, and the creation of optical Gottesman-Kitaev-Preskill states.

QI 37.6 Thu 17:00 Tent

**Setup and calibration of a single-photon spectrometer** — •Jannis Sode, David Lindler, Marlon Schäfer, Tobias Bauer, and Christoph Becher — Universität des Saarlandes, Fachrichtung Physik, Campus E2 6, 66123 Saarbrücken

Fiber-based quantum networks consist of spin-photon interfaced quantum memory nodes utilizing flying qubits with wavelengths in the low-loss telecom bands. These photons are either directly generated via optical transitions or transducted using quantum frequency conversion. This enables communication and transfer of quantum states via preexisting optical fiber infrastructure. Due to the small signal level of the transmitted quantum states of light, it is mandatory to explore and control the noise sources in the transmission channels.
To this end, an exact spectral analysis of signals on the single-photon level is necessary to determine the spectral noise distribution. However, commercially available spectrometers typically have a small detection efficiency at infrared wavelengths.
In this contribution, we present the setup of a spectrometer able to measure single-photon signals in the telecom wavelength range (1500-1600 nm) using superconducting nanowire single photon detectors with high detection efficiency. We discuss the overall efficiency as well as the accuracy of the spectrometer.

QI 37.7 Thu 17:00 Tent

**Towards fiber-integrated quantum frequency conversion in PPLN waveguides** — •Felix Rohe, Marlon Schäfer, Tobias Bauer, David Lindler, and Christoph Becher — Universität des Saarlandes, Fachrichtung Physik, Campus E2 6, 66123 Saarbrücken

Quantum frequency conversion to the low-loss telecom bands is a key enabling technology for long-range fiber-based quantum networks. While many state-of-the-art conversion devices use free-space coupling to nonlinear waveguides, for applications outside of a controlled lab environment, a more robust and compact design is desirable. One approach would be to substitute the free-space optics in favor of a fiber-based coupling scheme.

Here, we present the coupling of a solid-core photonic crystal fiber (PCF) to a periodically-poled lithium niobate (PPLN) waveguide. PCF are promising candidates for a fiber-integrated design because of their ability to simultaneously guide waves with a large difference in wavelength in the fundamental mode. We show coupling efficiencies of 637 nm signal and 2162 nm pump fields, as well as conversion efficiency and pump-induced noise rate for the difference frequency generation 637 nm - 2162 nm = 903 nm.
As an outlook, we present a concept for an "all-fiber" two-stage quantum frequency converter for NV-resonant photons, that does not use free-space optics. A two-stage conversion scheme was shown to yield very low noise rates in the conversion of SiV-resonant photons [1].

[1] Schäfer, M. et al., Adv Quantum Technol. 2023, 2300228

QI 37.8 Thu 17:00 Tent

**Fabricating Tapered Optical Fibres for Quantum Networks** — •Lasse Jens Irrgang[1], Timo Eikelmann[1], Mara Brinkmann[1], Tuncay Ulas[1], Donika Imeri[1,2], Konstantin Beck[1], Sunil Kumar Mahato[1], Rikhav Shah[1,2], and Ralf Riedinger[1,2] — [1]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany — [2]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg, Germany

On the journey towards a quantum internet, the development of reliable quantum repeaters and quantum end-nodes is essential. Particularly well suited for usage as quantum bits for storing and processing quantum information in these applications are silicon vacancies in diamond. Crucial for this approach is a coupling of photonic quantum channels to the diamond, where the latter serves as a waveguide.

A recent solution for this challenge, outshining traditional methods, is the so-called adiabatic mode coupling using optical fibres. In this technique, a tapered optical fibre is positioned in contact with the top surface of the diamond waveguide, enabling highly efficient adiabatic coupling of light between the two waveguides. Presented here, is an automated etching setup for the fabrication of these tapered fibres. The silica glass etching process is based on hydrofluoric acid solution. The developed automated etching setup evidentially facilitates the fabrication of linearly tapered fibres with smooth etched surfaces. The customizable taper extends up to a few millimetres, corresponding to an angle of less than one degree between the fibre's centre axis and the tapered surface.

QI 37.9 Thu 17:00 Tent

**Setup of a rack-mounted ion trap with integrated cavity** — •Lara Becker[1], Jolan Costard[1], Stephan Kucera[1,2], and Jürgen Eschner[1] — [1]Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken — [2]Luxembourg Institute of Science and Technology, Belveaux, Luxembourg

For the realization of quantum networks, quantum repeaters [1] overcome the distance limitations due to propagation loss in direct transmission. Interfaces between single trapped ions and single photons [2] are promising building blocks for implementing a quantum repeater.

We are setting up a multi-segment Paul trap for $^{40}Ca^{+}$ ions with an integrated fiber cavity to increase the photon collection and generation efficiency of the interface. The trap consists of two laser-machined and metal-coated ceramic ferrules, into which the fiber cavity with sub-mm spacing is integrated. With its compact design, the trap-cavity system including the vacuum chamber, control electronics, ablation laser and photo-ionization laser will be stored in a single transportable rack. Its future implementation will enable quantum repeater protocols [3] over the Saarbrücken fiber link [4].

[1] H.-J. Briegel, et al., Phys. Rev. Lett. 81, 5932 (1998)
[2] M. Bock et al., Nat. Commun. 9, 1998 (2018)
[3] M. Bergerhoff, et al., Phys. Rev. A 110, 032603 (2024)
[4] S. Kucera, et al., npj Quantum Inf. 10, 88 (2024)

QI 37.10 Thu 17:00 Tent

**AlGaAs Bragg Reflection Waveguides as Single and Entangled Photon Pair Source** — •Akriti Raj[1], Tobias Bauer[1], David Lindler[1], Quankui Yang[2], Thorsten Passow[2], and Christoph Becher[1] — [1]Universität des Saarlandes, FR Physik, Campus E2.6, 66123 Saarbrücken — [2]Fraunhofer-Institut für Angewandte Festkörperphysik IAF, Tullastr. 72, 79108 Freiburg

True single and entangled photon pair sources are crucial elements for applications in quantum technologies. Such sources may be realized by AlGaAs Bragg reflection waveguides, generating correlated single photon pairs through the process of spontaneous parametric down conversion (SPDC) [1]. The material AlGaAs is our preferred choice as the nonlinear medium because it features a high nonlinear coefficient, allows for room temperature operation and has the advantage of being a non-birefringent material. By using a type II SPDC process where the downconverted photons are orthogonally polarised to each other, the produced photons are inherently polarisation entangled eliminating the need for any additional entanglement setup [2]. We here present photon generation rates of $4 \times 10^7$ pairs/s/mW from these waveguides. The purity of the produced single photons is quantified by measuring the heralded $g^{(2)}(0) = 0.0017$ at $\approx 0.28$ mW pump power. The photons show 91.9% entanglement fidelity with the $|\psi^+>$ Bell state and 90% purity. We thus realize a room temperature entangled pair photon source at 1546 nm that is already coupled in a standard single-mode telecom fiber for further applications. [1] F. Appas et al., J. Light. Technol. 40 (2022). [2] R. T. Horn et al., Sci. Rep. 3.1 (2013).

QI 37.11 Thu 17:00 Tent

**Low Noise Quantum Frequency Conversion of Telecom Photons to SnV-Resonant Wavelengths** — •David Lindler, Tobias Bauer, Marlon Schäfer, and Christoph Becher — Universität des Saarlandes, FR Physik, Campus E2.6, 66123 Saarbrücken

Tin-Vacancy-Centers (SnV) in diamond represent a promising candidate for quantum nodes in quantum communication networks, featuring excellent optical and spin coherence [1,2]. To exchange the information between these nodes over long distances through optical fiber links, the spin state of the SnV-Center is transfered onto single photons. These photons are then converted into the low-loss telecom bands via quantum frequency down-conversion, to avoid the problem of high loss in fibers in the visible wavelength regime. After travelling trough the fiber, the reverse process, converting telecom photons back to the SnV-resonant wavelength, allows the photons to interact with another SnV-based quantum node once again.

We here present a two-stage low noise scheme for quantum frequency conversion of the telecom photons back to the SnV-resonant wavelength based on difference frequency generation in PPLN waveguides. The two step process drastically reduces noise at the target wavelength compared to the single step process [3]. We will present initial results on the conversion efficiency, conversion-induced noise count rates and the frequency stabilization of the mixing laser.

[1] J. Görlitz et al., npj Quant. Inf. 8, 45 (2022).
[2] I. Karapatzakis et al., Phys. Rev. X 14, 031036 (2024).
[3] M. Schäfer et al., Adv Quantum Technol. 2300228 (2023).

QI 37.12 Thu 17:00 Tent

**Phase as the Measurement Quantity in Optically Detected Magnetic Resonance Setups With NV Centers** — •Ludwig Horsthemke[1], Jonas Homrighausen[2], Ann-Sophie Bülter[1], Jens Pogorzelski[1], Dennis Stiegekötter[1], Frederik Hoffmann[1], Markus Gregor[2], and Peter Glösekötter[1] — [1]Department of Electrical Engineering and Computer Science, FH Münster — [2]Department of Engineering Physics, FH Münster

Measurements of optically detected magnetic resonance (ODMR) with nitrogen-vacancy (NV) centers usually observe the fluorescence intensity while applying a microwave radiation of varying frequency. We propose the phase between the excitation and the fluorescence as an alternative measurement quantity, offering a higher immunity to intensity fluctuations.

The fluorescence decay dynamics of NV centers act as a low pass filter in the frequency domain which changes its frequency response at the application of a resonant MW radiation. Upon intensity modulation of the excitation light at a frequency around 13 MHz we observe a contrast in the phase between excitation and fluorescence. We have previously shown that the phase has a high immunity to intensity fluctuations in all-optical magnetometry setups since we avoid the misinterpretation of changes in fluorescence intensity as changing magnetic fields [1]. In this work, we show the application of the phase measurement in a continuous wave ODMR setup.

[1] Horsthemke, L., et al. Excited-State Lifetime of NV Centers for All-Optical Magnetic Field Sensing. Sensors 24, 2093 (2024).

QI 37.13 Thu 17:00 Tent

**Sol-gel process for bonding thin-film diamond** — •Nick Brinkmann[1,2], Sunil Mahato[1,2], Rikhav Shah[1], Donika Imeri[1,2], Leonie Eggers[1,2], Konstantin Beck[1], Lasse Irrgang[1], and Ralf Riedinger[1,2] — [1]University of Hamburg, Faculty of Mathematics, Informatics and Natural Sciences, Department of Physics, Institute for Quantum Physics, Luruper Chaussee 149, 22761 Hamburg — [2]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg, Germany

Diamond nanophotonic structures hold immense potential for breakthroughs in quantum infomations technologies and are a leading platform for developing quantum memory chips.

One challenge in the development of nanophotonic structures lies in the reliable transfer and bonding of single crystal diamond thin-films onto suitable substrates.

Here we present an innovative and scalable method that utilizes a sol-gel process, which holds promise for efficiently and securely managing the transfer of these thin-film diamonds.

This method can elevate the fabrication of nanophotonic structures on diamonds, which can serve as interfaces between the spins of color centers, such as SiV, and photons.

Thus, it contributes to a new possibility for integrating such structures into photonic networks, promising significant advances in quantum optics and communication.

QI 37.14 Thu 17:00 Tent

**Nanophotonic Quantum Network Nodes - Imaging of cryogenic Nanophotonics** — •Leonie Eggers[1,2], Timo Eikelmann[1], Donika Imeri[1,2], Caius Niemann[1], Konstantin Beck[1], Rikhav Shah[1], Mara Brinkmann[1], Lasse Irrgang[1], Nick Brinkmann[1,2], Sunil Mahato[1,2], and Ralf Riedinger[1,2] — [1]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg — [2]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg, Germany

Silicon vacancies (SiV) in diamond combined with nanophotonic cavities are a promising platform for network-based quantum solid-state processors, due to their optically addressable spin transition and high noise tolerance. Paired with a fiber network this can enable efficient long-distance quantum communication and a modular approach to building larger quantum processors.

As temperature below 300 mK are needed for the SiV to have long-lived spin degrees of freedom, we show a high- resolution confocal imaging system that can image the nanophotonics on the diamond samples inside a cryostat. This improves our ability to couple optical fibers to the nanophotonics in-situ while operating the cryostat, enabling our research on building nanophotonic quantum network.

QI 37.15 Thu 17:00 Tent

**Resolving the Low-Field Ambiguity in All-Optical Magnetometry in Resource Constrained Devices** — •Ann-Sophie Bülter[1], Ludwig Horsthemke[1], Jens Pogorzelski[1], Dennis Stiegekötter[1], Frederik Hoffmann[1], Sarah Kirschke[2], Markus Gregor[2], and Peter Glösekötter[1] — [1]Department of Electrical Engineering and Computer Science, FH Münster — [2]Department of Engineering Physics, FH Münster

Machine learning algorithms offer a promising solution for unambiguous magnetic field determination in all-optical fluorescene intensity measurements with nitrogen-vacancy (NV) centers, addressing the ambiguity below 8 mT [1].

To continue this work, we exploit the dependency of the phase and the magnitude of the fluorescence on both the magnetic field and frequency, applying advanced regression techniques. The primary focus of our study is to investigate the effect of feature engineering to enhance the accuracy of magnetic field determination. By comparing the results of feature-engineering approaches with those using raw data alone, we demonstrate the potential of machine learning for precise and reliable magnetic field measurements in all-optical magnetic field sensing. Additionally, we assess the resource efficiency of these methods to ensure their feasibility for the implementation on a microcontroller.

[1] Horsthemke, L., et al. Towards Resolving the Ambiguity in Low-Field, All-Optical Magnetic Field Sensing with High NV-Density Diamonds. Engineering Proceedings 68, 8 (2024).

QI 37.16 Thu 17:00 Tent

**Diamond Membrane with Strained SiV Color Centers Coupled to a Fabry-Perot Microcavity** — •Robert Berghaus[1], Florian Feuchtmayr[1], Selene Sachero[1], Gregor Bayer[1], Julia Heupel[2], Tobias Herzig[3], Jan Meijer[3], Cyril Popov[2], and Alexander Kubanek[1] — [1]Institut für Quantenoptik, Universität Ulm — [2]Institute of Nanostructure Technologies and Analytics, University of Kassel — [3]Felix Bloch Institute for Solid State Physics, University Leipzig

Group IV color centers in diamond, such as silicon vacancy (SiV), are promising for quantum optics because of their optical transitions, spin access, and good coherence properties. SiV centers typically require millikelvin temperatures, but increasing the ground state splitting improves coherence, allowing operation at higher temperatures. Here, we demonstrate the integration of a single-crystal diamond membrane into a high-finesse microcavity (F = 3000), achieving significant lifetime shortening with a Purcell factor of 2.2 in a liquid helium atmosphere. Absorption and strain spectroscopy confirm enhanced ground-state splitting, paving the way for a spin-photon interface.

QI 37.17 Thu 17:00 Tent

**Flex-PCB Integrated Quantum Sensor With NV Centers in Diamond (FleQS)** — •Jens Pogorzelski[1], Jonas Homrighausen[2], Ludwig Horsthemke[1], Ann-Sophie Bülter[1], Frederik Hoffmann[1], Dennis Stiegekötter[1], Markus Gregor[2], and Peter Glösekötter[2] — [1]Department of Electrical Engineering and Computer Science, FH Münster — [2]Department of Engineering Physics, FH Münster

The utilisation of nitrogen-vacancy (NV) centers in diamond microcrystals for quantum magnetometry represents a promising approach for the development of sensitive, integrated magnetic field sensors [1]. Nevertheless, the cost and complexity of the technology have thus far limited its application. This study presents the most compact, fully integrated quantum sensor based on LED excitation, which represents an evolution of previous designs [2]. The sensor integrates all essential components, including a pump light source, photodiode, microwave antenna, optical filters and fluorescence detection, in a compact system that requires no external optical adjustments. The assembly is constructed on a flexible, foldable printed circuit board with surface-mounted components and a laser-cut optical filter. The PCB is folded and moulded. Furthermore, the random alignment of the NV axes is determined. The result is a 3.8x3.1 mm sensor head with a sensitivity of 68 nT/Hz^1/2, representing a miniaturization of quantum magnetometers.

[1] Stürner, F.M. et al., 2021. Advanced Quantum Technologies 4.
[2] Pogorzelski, J. et al., 2024. Sensors 24, 743.

QI 37.18 Thu 17:00 Tent

**Quantum frequency conversion device for single photons from SnV centers in diamond** — •Marlon Schäfer, David Lindler, Tobias Bauer, and Christoph Becher — Universität des Saarlandes, Fachrichtung Physik, Campus E2 6, 66123 Saarbrücken

Most quantum emitters exhibit optical transitions in the visible to near-infrared spectral region. In fiber-linked quantum networks, these photons need to be converted to low-loss telecom bands at 1550 nm through nonlinear three-wave mixing in periodically-poled lithium niobate waveguides to minimize transmission losses.

To make this technology viable for real-world applications, quantum frequency converters must operate robustly outside laboratory conditions without human intervention. Here, we explore automatic beam alignment and path stabilization for a device that converts single photons from tin-vacancy (SnV) centers in diamond using a two-stage scheme. Such a two-stage scheme was recently shown to successfully circumvent pump-induced noise for the conversion of single photons from silicon-vacancy centers in diamond [1].

[1] Schäfer, M. et al., Adv. Quantum Technol. 2023, 2300228.

QI 37.19 Thu 17:00 Tent

**Towards a spin-exchange collision-based optical quantum memory in noble-gas spins** — •Alexander Erl[1,2], Norman Vincenz Ewald[1,2], Andrés Medina Herrera[2], Denis Uhland[3], Wolfgang Kilian[2], Jens Voigt[2], Ilja Gerhardt[3], and Janik Wolters[1,4] — [1]DLR, Institute of Optical Sensor Systems, Berlin — [2]PTB, 8.2 Biosignals, Berlin — [3]LUH, Institute of Solid State Physics, Hannover — [4]TUB, Institute of Optics and Atomic Physics, Berlin

A critical limitation on current room-temperature quantum memory systems [1] is the maximum achievable storage time on the order of a few $\mu$s, which must be extended for various quantum communication applications, such as unforgeable quantum tokens for authentication. We report on our first steps towards a long-lived quantum memory with an all-optical interface based on a mixture of $^{129}$Xe noble gas and $^{133}$Cs alkali metal vapor, both confined in a glass cell at near room temperature. The interface relies on EIT, implemented through a $\Lambda$-scheme in the Zeeman sublevels of the long-lived hyperfine ground states of $^{133}$Cs, coupled to an excited state via the $D_1$ line at 895 nm [2]. Spin-exchange collisions in the strong coupling regime are envisioned to transfer the stored information from the alkali vapor to the noble gas [3]. The coherence time of $^{129}$Xe, which can extend up to several hours [4], offers the potential for long-term storage of quantum information in collective atomic excitations. [1] M. Jutisz et al., arXiv:2410.21209 (2024) [2] G. Buser et al., PRX, 020349 (2022) [3] O. Katz et al., PRA 105, 042606 (2022) [4] C. Gemmel et al., EPJ D 57, 303-320 (2010)

QI 37.20 Thu 17:00 Tent

**Optimal control solutions for nuclear spin polarization of nitrogen-vacancy (NV) centers in diamond** — •René Wolters[1], Matthias Müller[1], Felix Motzoi[1], and Tommaso Calarco[1,2] — [1]Forschungszentrum Jülich GmbH, Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, Germany

The topic of nuclear spin polarization in colour center platforms, including NV centers in a diamond lattice or silicon carbide, has attracted considerable interest in recent years. This is due to the favourable conditions for quantum sensory devices and the storage of quantum states that are enabled by the long coherence time of the nuclear spins and their operability at room temperature. The defining characteristic of colour centers is that the electronic spin state of the center can be both initialized and read out via laser irradiation in the visible wavelength spectrum. Dynamical nuclear polarization (DNP) techniques are employed with the objective of transferring the spin polarization from the electronic to the surrounding nuclear spins. We employ quantum optimal control to optimize DNP pulses in terms of both time and error resilience, with regard to the polarization of single or few well-defined nuclear spins in a weak magnetic field which can be addressed and controlled individually. The weak magnetic field permits longer coherence times and simpler implementation with fewer errors. Furthermore, we investigate how to polarize the nuclear spins with the minimal possible number of initializations of the electron spin, to reduce disruption of the laser irradiation.

QI 37.21 Thu 17:00 Tent

**Frequency Stabilization of a Hybrid SnV-$^{40}$Ca$^{+}$ Interface at Telecom Wavelengths** — •Tobias Bauer, David Lindler, Max Bergerhoff, Jürgen Eschner, and Christoph Becher — Universität des Saarlandes, FR Physik, Campus E2.6, 66123 Saarbrücken

In quantum networks, the synchronization of dissimilar quantum nodes requires precise frequency control and efficient wavelength conversion. We demonstrate a platform combining optical frequency comb technology with quantum frequency conversion to integrate SnV color centers in diamond and trapped $^{40}$Ca$^{+}$ ions into a common telecom-wavelength framework.

Our setup employs two mutually stabilized frequency combs as precise frequency references for all system lasers at each node. We characterize the system with classical light by stabilizing the excitation lasers at the SnV (619 nm) and $^{40}$Ca$^{+}$ (854 nm) system wavelengths to their respective frequency combs. These lasers are then frequency-converted to a common telecom wavelength (1550 nm) using pump lasers that are likewise referenced to the combs. The successful operation of our complete stabilization scheme is demonstrated through beat note measurements between the converted lasers at the telecom wavelength, verifying the frequency precision required for future quantum network applications.

QI 37.22 Thu 17:00 Tent

**Automated Electrode Routing Routine for Surface Electrode Paul Traps for Quantum Computing** — •Axel Hoffmann[1], Florian Ungerechts[2], Rodrigo Munoz[2], Janina Bätge[2], Masum Billah[2], Maximilian Kanz[1], Dirk Manteuffel[1], and Christian Ospelkaus[2,3] — [1]Institut für Hochfrequenztechnik und Funksysteme, Leibniz Universität Hannover, Appelstr. 9A, 30167 Hannover, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — [3]Physikalisch-Technische Bundesanstalt, Bundesallee 100,38116 Braunschweig, Germany

Trapped-ion quantum processors based on surface electrode Paul traps with integrated microwave conductors for near-field quantum control are a promising approach for scalable quantum computers. Due to increasing complexity of the processor chip models numerical analysis of the cause-effect relationship becomes challenging. In a complex multi-zone processor chip architecture, it is known that the electrode routing affects the ion transport, trapping and state control. To overcome these challenges already in the first design step, an automated electrode routing routine is proposed. Applying an iterative Method of Moments simulation process, cross-talk can be avoided while keeping the computational costs feasible. Challenges and benefits compared to straight forward approaches are discussed.

QI 37.23 Thu 17:00 Tent

**Towards quantum computation with Sr atom arrays** — •Eran Reches[1,3], Kevin Mours[1,3], Robin Eberhard[1,3], Dimitrios Tsevas[1,3], Zhao Zhang[1,3], Lorenzo Festa[1,3], Max Melchner[1,2,3], Andrea Alberti[1,2,3], Sebastian Blatt[1,2,3], Johannes Zeiher[1,2,3], and Immanuel Bloch[1,2,3] — [1]Max-Planck Institut für Quantenoptik, 85748 Garching, Germany — [2]Fakultät für Physik, Ludwig-Maximilians-Universität München, 80799 Munich, Germany — [3]Munich Center for Quantum Science and Technology, 80977 Munich, Germany

We report on the recent progress of the MQV quantum computing demonstrator based on neutral Sr atoms trapped in arrays of optical tweezers. We have shown high-fidelity detection, single- and two-qubit operations as well as state-of-the-art vacuum-limited lifetime in a non-cryogenic platform. We further present our ongoing work on the realization of highly parallel atom moves, setting the stage for future implementations of brickwall-type digital circuits.

QI 37.24 Thu 17:00 Tent

**Towards fully chip-integrated optical and near-field microwave control of trapped-ion qubits** — •Mohammad Masum Billah[1,2], Florian Ungerechts[1], Rodrigo Munoz[1], Janina Bätge[1], Axel Hoffmann[1,4], Giorgio Zarantonello[1,3], Christopher Reiche[1,2], and Christian Ospelkaus[1,2,5] — [1]Institut für Quantenoptik, Leibniz Universität Hannover — [2]Laboratorium für Nano- und Quantenengineering, Leibniz Universität Hannover — [3]QUDORA Technologies GmbH — [4]Institut für Hochfrequenztechnik und Funksysteme, Leibniz Universität Hannover — [5]Physikalisch-Technische Bundesanstalt

To fully harness the capabilities of surface-electrode trapped ion quantum computers, a large number of qubits is essential. Scalable ion traps are critical for accommodating these qubits, but also require a significant number of free-space lasers for qubit state preparation as well as for readout, cooling and optical quantum gates. While microwave near-field gate operations can reduce the need for the latter lasers, achieving full scalability necessitates the integration of optical waveguides and grating couplers within the trap chip for effective qubit control. This integration poses novel challenges in ion trap design and the microfabrication processes used to create the corresponding chips. Our study addresses key issues such as the impact of optical windows in the chip on trapping potentials, DC shuttling operations, and specifically, the effects on microwave near-field interactions. We further explore the implications of these integrations and discuss the increasing complexity in fabricating such highly integrated ion traps.

QI 37.25 Thu 17:00 Tent

**Hybrid Quantum Photonics With One Dimensional Photonic Crystal Cavities and Silicon Vacancy Centers In Nanodiamonds** — Lukas Antoniuk[1], Niklas Lettner[1,2], •Tim Mülleneisen[1], Anna P. Ovvyan[3,5], Daniel Wendland[3], Viatcheslav N. Agafonov[4], Wolfram H.P. Pernice[3,5], and Alexander Kubanek[1,2] — [1]Institute for Quantum Optics, Ulm University, Germany — [2]Center for Integrated Quantum Science and Technology (IQst), Ulm University, Germany — [3]Institute of Physics and Center for Nanotechnology, University of Münster, Germany — [4]Universite F. Rabelais, 37200 Tours, France — [5]Heidelberg University, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany

Scaling up current quantum hardware to large numbers of their qubit building blocks is the one of the most pressing challenges in modern quantum technologies. To achieve this, one could separate qubits physically and mediate interaction between them by flying qubits. However, therefore one requires high interaction strength between the stationary and flying qubits. Here, we summarize our efforts to combine silicon nitride photonics and negatively charged silicon vacancy centers hosted in nanodiamonds to achieve this and build up a scalable interface between light and matter on the basis of this hybrid approach.

QI 37.26 Thu 17:00 Tent

**Progress towards a novel apparatus for unit testing of ion transport and quantum logic protocols in context of QVLS-Q1** — Christian Joohs[1,2], Markus Duwe[1,2], •Alexander Onkes[1,2], Hardik Mendpara[1,2], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]PTB, Bundesallee 100, 38116 Braunschweig

We report on the progress of the QVLS-Q1 supporting experiment. It is being developed to test and characterize ion transport and EIT cooling. The trap is a surface electrode Paul trap, which means that the trapped ions have two-dimensional freedom of movement above the trap. It comprises a register-like design with different zones for trapping, storage, readout and quantum logic operations (termed QCCD architecture [1,2]). Here we report on updates of the experimental setup, specifically on progress of the optical and vacuum setup. Furthermore, we present the first steps towards a cloud interface to allow easy access for future collaborations.

[1] D.J. Wineland et al., J. Res. Natl. Inst. Stand. Technol. 103, 259 (1998)

[2] D. Kielpinski et al., Nature 417, 709 (2002)

QI 37.27 Thu 17:00 Tent

**Fermionic State Preparation and Imaging in Tweezer Arrays** — •Kirill Khoruzhii[1,3], Naman Jain[1], Marcus Culemann[1], Jin Zhang[1], Xinyi Huang[1], Pragya Sharma[1], Jun Ong[1], and Philipp Preiss[1,2] — [1]Max Planck Institute of Quantum Optics, Garching — [2]Ludwig-Maximilians-Universität, Munich — [3]Munich Center for Quantum Science and Technology

We demonstrate a platform for deterministic preparation of ultracold fermionic lithium-6 atoms in a tweezer array, combined with rapid and high-fidelity free-space spin-resolved imaging. This system enables programmable initialization of atomic arrays, providing a foundation for hybrid tweezer/lattice experiments and quantum simulation. Atoms are loaded into a tweezer array generated by two orthogonally oriented acousto-optic deflectors (AODs). Using magnetic field gradients for controlled atom spilling, we prepare pairs of spin-up and spin-down atoms in the ground state of each tweezer with over 90% success rate. The entire experiment cycle is completed in under 2 seconds. Uniformity of the AOD-generated tweezer array is ensured through model-based optimization, achieving intensity homogeneity to within 1% for arrays up to 10x10 tweezers. This consistency is crucial for reliable state preparation. For imaging, counter-propagating resonant beams illuminate the atoms for 20 $\mu$s and enable free-space single atom detection with a fidelity exceeding 95%. Spin states are distinguished by polarization-dependent fluorescence, with photons spatially separated and directed to the camera. This platform will be used to realize a fermionic many-body interferometer.

QI 37.28 Thu 17:00 Tent

**Developing a photon-pair source for quantum repeaters** — •Henning Mollenhauer — DLR Berlin-Adlershof, Berlin — TU-Berlin, Berlin

We are reporting on the development of a photon-pair source for signal and idler photons at 894nm and 1550nm. The underlying process is spontaneous parametric down-conversion (SPDC) inside a periodically poled KTP crystal. To achieve spectrally pure and narrow-band characteristics for signal and idler photons our ppKTP crystal is designed as a monolithic cavity [1]. Pulsed pump light at 567nm for the SPDC process is produced in sum frequency generation from the target wavelengths. For the future we plan to interface our photon source with a single-photon quantum memory [2], to build a demonstrator of a quantum repeater. [1] Mottola et al. (2020) [2] Jutisz et al. (2024)

QI 37.29 Thu 17:00 Tent

**Tin-vacancy centers in photonic crystal cavities in diamond** — •Daniel Bedialauneta Rodriguez, Tim Turan, Nina Codreanu, and Ronald Hanson — Delft University of Technology

Color centers in diamond are a promising platform for realizing quantum networks as a spin-photon interface that also gives access to naturally occurring 13C memory qubits. The nitrogen-vacancy (NV) center has been successfully used to realize a three-node quantum network. However, its low emission rate of coherent photons and sensitivity to surface charges makes scaling to more nodes difficult.

The tin-vacancy (SnV) center has emerged as a compelling alternative due to its favorable optical properties and compatibility with nanophotonic structures. Here, we present the integration of SnV centers into photonic crystal cavities. These cavities promise to enhance the light-matter interaction, ultimately boosting the rate of entanglement between nodes. We measure cavity properties at cryogenic temperatures and demonstrate in-situ frequency tuning through gas desorption. We use this technique to probe the cavity-SnV system.

QI 37.30 Thu 17:00 Tent

**Neutral Ca fluorescence during ablation loading for surface ion traps** — •David C Stuhrmann[1], Radhika Goyal[1], Tobias Pootz[1], Sascha Agne[2], Celeste Torkzaban[1], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — [2]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Surface electrode ion traps are well suited for building a scalable quantum computer because ions trapped in a Paul trap can have long coherence times combined with high fidelities. For trapping 40Ca+ ions I need to generate a stream of individual ions reaching the trap center. This is achieved by a laser ablation process together with a two step photo-ionization which uses a resonant 423nm laser and free-running 375nm laser. As a measure of the amount of released Ca atoms from ablation I study neutral Ca fluorescence with the 423nm resonant transition. The time resolved fluorescence signal is used to scan the laser powers and positions. A frequency scan of the 423nm beam shows how many atoms of a certain velocity class get released and that a detuning of 500 MHz or less are desirable. The signal strength is also used for finding the optimal horizontal and vertical position of ablation laser as well as determining the ablation threshold. The results show that our ablation setup is suited for generating Ca+ ions and that we can adjust our various laser parameters.

QI 37.31 Thu 17:00 Tent

**Transport through a 1D channel with an epitaxial GaAs quantum dot in its vicinity** — •Selma Delić[1,2], Paola Atkinson[3], Xuelin Jin[1,2], Nataliya Demarina[1], Detlev Grützmacher[1,2], and Beata Kardynał[1,2] — [1]PGI, Forschungszentrum Jülich, 52428 Jülich, Germany — [2]2 Department of Physics, RWTH, 52074 Aachen, Germany — [3]Institut des Nano Sciences de Paris, CNRS UMR 7588, Sorbonne Université, 75005 Paris, France

Gate-defined quantum dots (GDQD) in GaAs/AlGaAs heterostructures host spin qubits which are potentially scalable and which, thanks to the direct bandgap of GaAs, may be addressable optically. High fidelity transfer of quantum information from a photon to the electron spin in the gated qubit can be mediated by photon absorption in a self-assembled GaAs quantum dot (SAQD) [1] followed by adiabatic transfer of the photo-generated electron into the GDQD [2].

In this contribution, we present the results of our studies of the transport and optical properties of nanostructures defined by gates in GaAs/AlGaAs heterostructures with embedded SAQDs. SAQDs are tunnel coupled to the gated nanostructures. We study the effect of the quantum states in the SAQD on the electron transport characteristics of a 1D channel. Further, we discuss the impact of the lateral alignment of the gates relative to the SAQD on the device characteristics. Based on our findings, we present a potential design of the heterostructures for the spin-photon interface and the design of the devices.

[1] P. Atkinson et al., Jrn. Appl. Phys. 112, 054303 (2012)
[2] B. Joecker et al., Phys. Rev. B 99, 205415 (2019)

QI 37.32 Thu 17:00 Tent

**Fabrication and Characterization of Photonic Nanostructures in Diamond for Quantum Applications** — •Jonathan Ensslin, Colin Sauerzapf, Oliver von Berg, Rainer Stöhr, and Jörg Wrachtrup — 3rd Institute of Physics, University of Stuttgart

The unique optical properties and long-lived spin coherence times of color centers in diamond make them a promising platform for quantum technologies [1]. This work focuses on the fabrication and characterization of photonic nanostructures, such as free-standing optical waveguides, capable to enhance collection efficiency [2] and spin-photon interaction [3]. Fabrication techniques, including anisotropic reactive ion beam etching (RIBE), were optimized to achieve precise control over waveguide dimensions and etch profiles, highlighting the advances of RIBE over inductively coupled plasma etching [4, 5]. By tailoring etching parameters, stable processes for both straight and angled etches were developed, improving reproducibility and selectivity. We investigated etch rates, angular dependencies, and mask material selectivity. These developments pave the way for creating diamond nanostructures capable of hosting color centers, ultimately facilitating their integration with optical cavities. Future work includes optical characterization of the structures and the fabrication of defect-hosting waveguides for scalable quantum devices. [1] M. Pompili et al., Science 372, 259-264, (2021) [2] M. Krumrein et al., ACS Photonics 11 (6), 2160-2170, (2024) [3] L. Childress et al., Science Advances, vol. 4, no. 1, pp. 12-18, (2021) [4] H. A. Atikian et al., APL Photonics 2 (5), 051301, (2017) [5] C. Chia et al., Opt. Express 30, 14189-14201 (2022)

QI 37.33 Thu 17:00 Tent

**Towards experimental implementation of a free-space continuous-variable quantum key distribution scheme with unidirectional modulation of squeezed states** — •Jan Schreck[1,2], Thomas Dirmeier[1,2], Kevin Jaksch[1,2], and Christoph Marquardt[2,1] — [1]Max Planck Insitute for the Science of Light, Erlangen, Germany — [2]Chair of Optical Quantum Technologies, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

Continuous-variable quantum key distribution (CV-QKD) offers a chance to create quantum-safe cryptography. Polarization is a promising degree of freedom to encode QKD signals in free-space optical (FSO) links. Furthermore, a experimental CV-QKD implementation by unidirectional modulation of polarization squeezed states of light can increase CV-QKD's resilience to channel noise and finite post-processing efficiency. In addition, supression of information leakage to potential eavesdroppers is possible. This work presents our idea of a quantum signal source generating squeezed states of light and the concept of the optical sender and receiver.

QI 37.34 Thu 17:00 Tent

**Multiplexing and Signal Optimization in Surface-Electrode Ion Trap Quantum Processors** — •Janina Bätge[1], Florian Ungerechts[1], Rodrigo Munoz[1], Mohammad Masum Billah[1], Axel Hoffmann[1,2], Giorgio Zarantonello[1,3], and Christian Ospelkaus[1,4] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Germany — [2]Institut für Hochfrequenztechnik und Funksysteme, Leibniz Universität Hannover, Germany — [3]QUDORA Technologies GmbH, Braunschweig, Germany — [4]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Scaling up ion trap quantum processors requires efficient management of control signals for the increasing number of control electrodes. We present three methods to minimize the number of signals by controlling multiple electrodes with shared inputs. The first method uses a bucket brigade for ion storage. The second employs switching electronics to sequentially charge multiple electrodes with a single signal. The final method uses switches to multiplex the control signals for ion transport through an X-junction. In this approach, it is crucial to optimize the assignment of electrodes to signals and determine the minimal number of signals needed for efficient shuttling.

QI 37.35 Thu 17:00 Tent

**Efficient simulation workflow for designing micro-structured planar Paul traps** — •Kais Rejaibi, Dorna Niroomand, Patrick Huber, Rodolfo Muñoz Rodriguez, and Christof Wunderlich — Department of Physics, School of Science and Technology University of Siegen, 57068 Siegen, Gemany

When developing novel micro-structured traps for quantum science with trapped ions, design considerations include, for instance, precise ion shuttling, suppressing micromotion, and ensuring robust quantum state control in quantum experiments. To be able to efficiently design novel traps, we have developed a simulation workflow that uses the Boundary Element Method (BEM) to accurately model electric fields from complex electrode geometries such as microfabricated surface ion traps incorporating the Magnetic Gradient Induced Coupling (MAGIC) scheme and effectively handling open boundary conditions with low computational overhead.

By applying solid harmonics decomposition to the simulated fields, we identify and mitigate higher-order multipole components that lead to residual micromotion and other effects. This process allows us to iteratively refine electrode designs and generate precise voltage control configurations, optimizing micromotion compensation and improving ion transport. Our approach focuses on simulation and analytical techniques for designing ion traps capable of reliable shuttling through varying magnetic fields. By streamlining the development process, we enhance the performance of traps, contributing to more robust and scalable implementations in quantum computing applications.

QI 37.36 Thu 17:00 Tent

**Single qubit addressing in a 2D array of neutral Ytterbium atoms** — •Clara Schellong[1], Tobias Petersen[1], Nejira Pintul[1], Jonas Rauchfuss[1], Jan Deppe[1], Carina Hansen[1], Till Schacht[1], Frederik Mrozek[1], Koen Sponselee[1], Alexander Ilin[1], Klaus Sengstock[1,2], and Christoph Becker[1,2] — [1]Center of Optical Quantum Technologies University of Hamburg, Luruper Chaussee 149, 22761 Hamburg — [2]Institute for Quantum Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg

Neutral atoms have shown to be a promising candidate for building large scale quantum computers and quantum simulators, with fast high-fidelity single and two-qubit gates as well as flexible initialisation and readout. Recently, alkaline earth (-like) atoms such as Ytterbium (Yb) have shown to offer promising ways to overcome some of the main challenges on the road to scalable and flexible quantum simulators with decent effective circuit depth. Additionally, an optical coherent qubit mapping scheme enables mid-circuit measurements and advanced error correction techniques.

We will present different manipulation and addressing techniques for optimised and spatially resolved single- and two-qubit operations in a two-dimensional array of neutral Yb atoms.

QI 37.37 Thu 17:00 Tent

**Real-time QKD with a deterministic sub-poissonian Source on an Intercity Scale** — •Joscha Hanel[1], Jingzhong Yang[1], Jipeng Wang[1], Vincent Rehlinger[1], Zenghui Jiang[1], Frederik Benthin[1], Tom Fandrich[1], Jialiang Wang[1], Fabian Klingmann[2], Raphael Joos[3], Stephanie Bauer[3], Sascha Kolatschek[3], Ali Hreibi[4], Eddy Rugeramigabo[1], Michael Jetter[3], Simone Portalupi[3], Michael Zopf[1,5], Peter Michler[3], Stefan Kück[4], and Fei Ding[1,5] — [1]Institut für Festkörperphysik, Leibniz Universität Hannover — [2]Fraunhofer-Institut für Photonische Mikrosysteme, Dresden — [3]Institut für Halbleiteroptik und Funktionelle Grenzflächen, IQST and SCoPE, University of Stuttgart — [4]Physikalisch-Technische Bundesanstalt, Braunschweig — [5]Laboratorium für Nano- und Quantenengineering, Leibniz Universität Hannover

While quantum key distribution (QKD) is among the most mature quantum technologies today, it remains a considerable challenge to achieve practical transmission rates over long distances with sub-poissonian photon sources. However, use of such sources is desirable in the long run, as they facilitate integration into future receiver-based networks.

We present a polarization-based BB84-QKD system using a quantum dot (QD) as a bright, pure, and deterministic single photon source that emits into the telecom C-band. We employ active polarization stabilization and both spectral and temporal filtering to demonstrate positive secure key rates in the kbit/s range for transmission distances on the intercity scale.

QI 37.38 Thu 17:00 Tent

**Sparse Optimization of Two-Dimensional Terahertz Spectroscopy** — •zhengjun wang — University of Hamburg Institute for Quantum Physics Luruper Chaussee 149 22761 Hamburg

two-dimensional terahertz spectroscopy (2DTS) is a low-frequency analogue of two-dimensional optical spectroscopy that is rapidly maturing as a probe of a wide variety of condensed matter systems. However, a persistent problem of 2DTS is the long experimental acquisition times, preventing its broader adoption. A potential solution, requiring no increase in experimental complexity, is signal reconstruction via compressive sensing. In this work, we apply the sparse exponential mode analysis (SEMA) technique to 2DTS of a cuprate superconductor. We benchmark the performance of the algorithm in reconstructing the terahertz nonlinearities and find that SEMA reproduces the asymmetric photon echo lineshapes with as low as a 10

QI 37.39 Thu 17:00 Tent

**Simulating a Many-Body System with Waveguide Arrays** — •Florian Huber[1,2,3], Benedikt Braumandl[1,2,3,4], Carlotta Versmold[1,2,3], Jan Dziewior[1,2,3], Robert Jonsson[5], Johannes Knörzer[6], Alexander Szameit[7], and Jasmin Meinecke[1,2,3,8] — [1]Max-Planck-Institut für Quantenoptik, Germany — [2]Ludwig-Maximilians-Universität, Germany — [3]Munich Center for Quantum Science and Technology, Germany — [4]Technische Universität München, Germany — [5]Nordita, KTH Royal Institute of Technology and Stockholm University, Sweden — [6]ETH Zurich, Switzerland — [7]Universität Rostock, Germany — [8]Technische Universität Berlin, Germany

Waveguide arrays, femtosecond laser-written into fused silica, are a versatile, still well-controllable simulation platform. If the distance between the laser written channels is large compared to the transversal mode size of each waveguide the system can be described by a nearest neighbor coupling Hamiltonian. The possibility to change the propagation and coupling constants in the manufacturing process allows the simulation of a large class of tridiagonal Hamiltonians. In our case the coupling and propagation constants of the waveguide array describing a giant atom system can be found by applying a Lanczos transformation to its interaction Hamiltonian. We report on the current progress of the simulation of oscillating bound states of a giant atom coupled to a waveguide using waveguide arrays as a simulation platform.

QI 37.40 Thu 17:00 Tent

**A Photonic-Integrated Quantum-Random Number Generator** — •Ömer Bayraktar[1,2], Jonas Pudelko[1,2], Laurenz Ottmann[1,2], Christoph Pacher[3], Winfried Boxleitner[3], and Christoph Marquardt[1,2] — [1]Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany — [2]Max Planck Insitute for the Science of Light, Erlangen, Germany — [3]AIT Austrian Institute of Technology GmbH, Center for Digital Safety & Security, Vienna, Austria

Quantum-random number generators (QRNG) are key componenents for quantum-key distribution systems. In addition, compared to conventional true-random number generators, they offer advantages in generation rate and modelling of the entropy source.

We present an experimental QRNG based on balanced homodyne detection of the quantum-optical vacuum state. This QRNG is designed for operations under the restrictive requirements of a 3U CubeSat.

The optical part of the QRNG is monolithically integrated on an Indium-Phosphide photonic-integrated circuit and is placed on a 10x10 $cm^2$ printed-circuit board accomodating necessary electronics. We show first conclusive results obtained with this system and discuss its operation in space.

QI 37.41 Thu 17:00 Tent

**SiV assisted photonic quantum computing** — •Konstantin Beck[1], Donika Imeri[1,2], Lasse Irrgang[1,2], Leonie Eggers[1,2], Nick Brinkmann[1,2], Sunil Kumar Mahato[1,2], Rikhav Shah[1], Roman Schnabel[1,2], and Ralf Riedinger[1,2] — [1]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany — [2]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg, Germany

Silicon vacancy centers in diamond (SiV) have shown great potential for applications in quantum sensing and quantum communication, due to their optically addressable spin transitions and stability against noise. At temperatures below 300 mK, the SiV has a long-lived spin degree of freedom that enables its use as a qubit for quantum information applications. By efficiently interfacing squeezed photons to the SiV, error-resilient optical Gottesman-Kitaev-Preskill (GKP) states can be created, which enable fault-tolerant continuous variable (CV) quantum computation.

We present a conceptual framework for an efficient telecom squeezed light interface for SiV and the subsequent creation of optical GKP cluster states. Key aspects, such as quantum frequency conversion of squeezed states and spin dependent reflection off the SiV as well as the theoretical implications of using optical GKP qubits in 2D-cluster states for CV quantum computing are highlighted.

QI 37.42 Thu 17:00 Tent

**Towards the scale-up of a large-scale quantum computer**

**based on Yb-ions** — •Saptarshi Biswas[1], Ivan Boldin[1], Benjamin Bürger[1], Nora Daria Stahr[2,4], Radhika Goyal[2], Patrick Huber[1], Eike Iseke[3,4], Friederike J. Giebel[3,4], Lukas Kilzer[2], Nila Krishnakumar[3,4], Rodolfo Muñoz Rodriguez[1], Tobias Pootz[2], Kais Rejaibi[1], David Stuhrmann[2], Jacob Stupp[2,4], Konstantin Thronberens[3,4], Celeste Torkzaban[2], Pedram Yaghoubi[1], Christian Ospelkaus[2,3,4], and Christof Wunderlich[1] — [1]Department of Physics, School of Science and Technology University of Siegen, 57068 Siegen, Gemany — [2]Gottfried Wilhelm Leibniz Universität, Hannover, Germany — [3]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [4]Laboratory of Nano and Quantum-Engineering, Hannover, Germany

We present the status of a cryogenic (4K) experimental set-up for quantum computing with radio frequency (RF)-controlled trapped ions. It incorporates a novel micro-structured planar Paul trap with integrated micromagnets and we report on the characterization of the first trap generation to be used in this set-up. Also, progress in developing laser cooling techniques for mixed $Yb^+$-$Ba^+$ crystals is reported.

QI 37.43 Thu 17:00 Tent

**A cryogenic apparatus for scalable quantum computation with surface ion traps** — •Marco Schmauser[1], Marco Valentini[1], Michael Pasquini[1], Jakob Wahl[1,2], Eric Kopp[1], Philipp Schindler[1], Thomas Monz[1], and Rainer Blatt[1] — [1]Universität Innsbruck, Innsbruck, Austria — [2]Infineon Technologies Austria AG, Villach, Austria

Trapped-ion quantum systems are promising candidates for future quantum computing applications. Current trapped ion quantum computing systems in the quantum optics group in Innsbruck are built on a macroscopic linear trap and thus are limited to a maximal number of about 20 ions. Microfabricated surface traps are a popular approach to achieve scalability since they allow for a modular design in which one quantum computing processor consists of many microtraps. We built a cryogenic apparatus to realize fast testing and characterization of such microfabricated traps. The cryostat cools down the trap to a temperature of around 5K within several hours which allows the integration of superconducting materials, for example in the context of superconducting photon detectors, into the trap. Additionally, the integration of the trap via a standardized socket significantly reduces the time to exchange the chips. The setup features 100 DC electrodes and 6 RF electrodes with two independent resonators to enable axial and radial shuttling operations and 21 in-vacuum fibers for all wavelengths of 40Ca+ ions which pave the way for integrating optics into the trap chips. For our first experiments we glue a block of borofloat glass with an inscribed waveguide for 729nm light on top of a surface trap.

QI 37.44 Thu 17:00 Tent

**A rack-mounted narrow-band photon pair-source for interfacing with an atomic quantum memory** — •Leon Messner[1,2], Mathilde Kakuschke[1,3], Benjamin Maass[2,3], Helen Chrzanowski[4], and Janik Wolters[2,3,1] — [1]Advanced Quantum Light Sources UG, Berlin, Germany — [2]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institute of Optical Sensor Systems, Berlin, Germany — [3]Technische Universität Berlin, Institut für Optik und Atomare Physik, Berlin, Germany — [4]Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany

We present the implementation and performance analysis of a portable, rack-mounted photon-pair source for coupling to a ladder-type quantum memory in room-temperature Cesium vapor

The photon source [1] is generating photon-pairs with a bandwidth of 250 MHz, compatible to the linewidth and frequency needs of the atomic storage media. It has high coupling and heralding efficiencies up to 45%.

This allows research into crucial applications and fundamental questions of photon synchronization and shaping using a ladder-type quantum memory in warm alkali vapor [2]. Their fast and noise-free operation make them an ideal component for on-demand storage and retrieval of quantum information in photonic infrastructures.

[1] Mottola, R. et al., Optics Express **28**, 3159-3170 (2020)
[2] Maaß, B. et al., Phys. Rev. Applied **22**, 044050 (2024)

QI 37.45 Thu 17:00 Tent

**Studying multifrequency optical lattices for quantum simulation** — •Jonathan Bracker[1], Luca Asteria[1,2,5], Marcel Nathanael Kosch[1], Klaus Sengstock[1,2,3], and Christof Weitenberg[1,2,4] — [1]Institut für Quantenphysik, Universität Hamburg, 22761 Hamburg, Germany — [2]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg, Germany — [3]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany — [4]Department of Physics, TU Dortmund University, 44227 Dortmund, Germany — [5]University of Kyoto, Kyoto, Japan

The multifrequency scheme for optical lattices [1] offers a stable and highly tunable approach for generating complex lattice geometries. Here I present some results of my master's thesis, where I performed numerical simulations of the eigenspectrum and Kapitza-Dirac dynamics for a 5-fold symmetric quasiperiodic optical lattice, revealing localization properties and spectral features. Additional Kapitza-Dirac simulations and preliminary absorption images for a non-separable 3D multifrequency lattice are presented as a first step toward exploring these lattice configurations.

[1] M. Kosch et al., Phys. Rev. Research 4, 043083 (2022)

## QI 38: Quantum Thermodynamics

Time: Friday 11:00–13:15 Location: HS IX

QI 38.1 Fri 11:00 HS IX

**Understanding System-Meter Correlation Time in Quantum Information Engines** — •Rasmus Hagman, Janine Splettstösser, and Henning Kirchberg — Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, S-412 96 Göteborg, Sweden

We examine a quantum information engine (QIE) with a finite cycle time, operating between two thermal reservoirs. The engine utilizes information transfer between a working system, modeled as a quantum two-level system, and a meter, modeled as a quantum harmonic oscillator, to convert heat into work.The time-dependent information transfer is linked to the correlation time between the system and meter, which is a crucial resource for the QIE, as the cycle time is lower bounded by this correlation time. Our study accounts for the energetic costs of quantum measurement and the information acquisition process in a comprehensive framework that includes finite-time operations. In this framework, the QIE can reach a Zeno limit at very short correlation times, enabling the extraction of net positive work from a single heat bath where the acquired information needs to be considered to fulfill the second law. We also analyze work and heat as functions of the system's and meter's temperatures, and find that the QIE work in different regimes: as heat engine, heat pump or refrigerator, as well as a "true" information engine, producing net positive work by extracting heat from the colder bath. We optimize power output at given efficiency by analyzing Pareto fronts. Our QIE model could be tested in cavity quantum electrodynamics experiments for empirical validation.

QI 38.2 Fri 11:15 HS IX

**The laws of thermodynamics in a 3D scattering environment** — •Michael Gaida, Giulio Gasbarri, and Stefan Nimmrichter — Universität Siegen, Deutschland

The laws of thermodynamics, fundamental to physics, are well-established for macroscopic systems but need to be refined in the microscopic and quantum regimes, where the dynamics exhibits strong fluctuations out of equilibrium. In such cases, stochastic models are used, but their thermodynamic consistency must be scrutinized. Collision models for example, which treat the environment as a sequence of unitarily interacting ancillae, rely on precise timing, tailored ancilla resonances, or external work sources to maintain consistency [1]. In contrast, a dilute thermal gas environment gives rise to random, off-resonant scattering events that exchange energy between internal and motional degrees of freedom. Here we consider the dynamics and equilibration of an open system with both motional and internal degrees of freedom of a gas, extending previous results in one dimension [2]. We consider the case of a thermal reservoir and of a non equilibrium work reservoir in which the external and internal temperature of the gas particles differs.

[1] P. Strasberg, G. Schaller, T. Brandes, and M. Esposito, Quan-

tum and information thermodynamics: A uni- fying framework based on repeated interactions, Phys. Rev. X 7, 021003 (2017). [2] S. L. Jacob, M. Esposito, J. M. Parrondo, and F. Barra, Thermalization induced by quantum scattering, PRX Quantum 2, 020312 (2021).

QI 38.3 Fri 11:30 HS IX

**An autonomous engine converting particle-exchange to mechanical motion** — •Sofia Sevitz[1], Federico Cerisola[2], and Janet Anders[1,2] — [1]University of Potsdam, Institute of Physics and Astronomy, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany — [2]Physics and Astronomy, University of Exeter, Exeter EX4 4QL, United Kingdom

We study the platform consisting of a quantum dot coupled to a mechanical resonator. By coupling the dot (medium of the particle-exchange engine) to the resonator (work load), the produced work is stored in the displacement (which functions as a battery) and can be directly measured. We develop a thermodynamics framework to quantify heat and particle flows between system and reservoirs. In this way, we are able to estimate the mechanical energy stored in the displacement of the resonator. By computing the Husimi distribution we show that as the energy transfer increases, the state of the resonator approaches a coherent state, resulting in the emergence of measurable self-sustained oscillations. The device considered here provides a promising platform for the study of work extraction and storage in the nanoscale with experimentally feasible capabilities.

QI 38.4 Fri 11:45 HS IX

**Consistent Clausius inequality and its typical positivity for pure states** — •Philipp Strasberg — Instituto de Física de Cantabria (IFCA), Santander, Spain

I show how to consistently derive Clausius inequality, in unison with textbook thermodynamics but in conflict with some recent suggestions in quantum thermodynamics, using a microscopic notion of entropy and temperature. While its strict non-negativity can only be established for a specific initial ensemble, I also show how dynamical typicality ensures that the overwhelming majority of pure states behaves like said ensemble. While the talk focuses on the archetypal example of two systems exchanging heat, the results are general and applicable to a much wider range of scenarios.

QI 38.5 Fri 12:00 HS IX

**Boyle's Law in Single-Particle Quantum Systems** — •Anton Kantz, Jonathan Brugger, Anja Kuhnhold, and Andreas Buchleitner — Physikalisches Institut der Albert-Ludwigs-Unversität Freiburg, Hermann-Herder-Str. 3, D-79014 Freiburg

We examine properties of statistically defined pressure in a single-particle quantum system. Previous work [1] has shown that isotropic pressure can be achieved if the corresponding classical system is chaotic, or through averaging over many high-energy quantum states of an integrable system.

An important property of a classical gas is Boyle's law, which states that pressure is inversely proportional to volume. We investigate Boyle's law for a single quantum particle moving in a two-dimensional domain. In analogy to the ideal gas law, we aim to define a temperature using the product of pressure - derived directly from the microscopic spectral structure - and volume.

We first consider a two-dimensional rectangular box, which exhibits integrable dynamics, and investigate Boyle's law under various microscopic definitions of pressure. We then transition to a Sinai billiard, which generates classically chaotic dynamics, and investigate to which extent the structure of the billiard's eigenstates makes Boyle's law emerge.

[1] C. Wulf, Microscopic Models of Pressure, Bachelor thesis, Albert-Ludwigs-Universität Freiburg, 2024

QI 38.6 Fri 12:15 HS IX

**Non-Markovian Noise Driving a Single-Atom Heat Engine** — •Moritz Göb[1], Bo Deng[1,2], Milton Aguilar[3], Max Masuhr[1,2], Daqing Wang[1,2], Eric Lutz[3], and Kilian Singer[1] — [1]Experimental Physics I, Institute of Physics, University of Kassel, Heinrich-Plett-Straße 40, 34132 Kassel — [2]Institute of Applied Physics, University of Bonn, Wegelerstraße 8, 53115 Bonn — [3]Institute for Theoretical Physics I, University of Stuttgart, Pfaffenwaldring 57, 70550 Stuttgart

We present a Paul trap with a tapered geometry [1]. The radio frequency electrodes are angled in axial direction. This configuration yields a coupling of the motional radial and axial degrees of freedom, allowing for the implementation of a single-atom heat engine [2] and duffing-like oscillator [3]. In this contribution, we present the design, implementation, and characterization of such an ion trap. Furthermore, we present first results of using non-Markovian noise to drive a heat engine.

[1] B. Deng, M. Göb, M. Masuhr, J. Roßnagel, G. Jacob, D. Wang and K. Singer, Quantum Sci. Technol. 10 015017 (2025).
[2] J. Roßnagel, S. T. Dawkins, K. N. Tolazzi, O. Abah, E. Lutz, F. Schmidt-Kaler, and K. Singer, Science 352, 325 (2016).
[3] B. Deng, M. Göb, B. A. Stickler, M. Masuhr, K. Singer and D. Wang, PRL 131, 153601 (2023).

QI 38.7 Fri 12:30 HS IX

**Nonequilibrium quantum thermodynamics without detailed balance** — •Irene Ada Picatoste[1] and Heinz-Peter Breuer[1,2] — [1]Physikalisches Institut, Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, University of Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany

We study quantum Brownian motion through the paradigmatic Caldeira-Leggett model describing a central mode coupled to a thermal bath of modes. Starting from the microscopic solution, we construct an exact, time-convolutionless master equation for the reduced state of the central mode [1] and, using a recently developed approach to nonequilibrium quantum thermodynamics [2], we find an effective energy operator using the principle of minimal dissipation. We then examine the instantaneous fixed point of the dynamics and use its jump operators to understand the mechanisms governing the dynamics. We identify two different processes: a particle exchange generator in the detailed balance form that drives the system towards a Gibbs state [3] and, due to the absence of the rotating wave approximation, an additional squeezing generator.

[1] I. A. Picatoste, A. Colla, and H.-P. Breuer, Phys. Rev. Research 6, 013258 (2024).
[2] A. Colla and H.-P. Breuer, Phys. Rev. A 105, 052216 (2022).
[3] A. Colla and H.-P. Breuer, arXiv preprint 2408.00649 (2024).

QI 38.8 Fri 12:45 HS IX

**Quantum Thermodynamics in Strongly Coupled Open Systems: Additivity of Multiple Baths Scenarios** — •Tim Alhäuser[1] and Heinz-Peter Breuer[1,2] — [1]Institute of Physics, University of Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, University of Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany

Employing the framework of Dynamically Emergent Quantum Thermodynamics [1], an open system approach to non-equilibrium quantum thermodynamics, we discuss the definitions of heat, work and renormalized temperature in strongly coupled and structured environments beyond the Born approximation. Using the Fano-Anderson model [2] we investigate heat and energy transfer in quantum systems. A comparison is made between exact solutions of this model [3] and those obtained through the expansion of the time-convolutionless (TCL) master equation at second and fourth order in both single- and multi-baths cases, demonstrating the performance of the TCL approach. This leads to a unique splitting of the master equation's dissipator into contributions from individual baths, based on appropriate conditions for the heat currents and bath temperatures.

[1] A. Colla and H.-P. Breuer, Phys. Rev. A **105**, 052216 (2022).
[2] A. Colla and H.-P. Breuer, arXiv: 2408.00649 [quant-ph](2024).
[3] I. A. Picatoste, A. Colla, and H.-P. Breuer, Phys. Rev. Res. **6**, 013258 (2024).

QI 38.9 Fri 13:00 HS IX

**Coherence Manipulation in Asymmetry and Thermodynamics** — •Tulja Varun Kondra — Heinrich Heine University Dusseldorf

In the classical regime, thermodynamic state transformations are governed by the free energy. This is also called as the second law of thermodynamics. Previous works showed that, access to a catalytic system allows us to restore the second law in the quantum regime when we ignore coherence. However, in the quantum regime, coherence and free energy are two independent resources. Therefore, coherence places additional nontrivial restrictions on the state transformations that remain elusive. In order to close this gap, we isolate and study the nature of coherence, i.e., we assume access to a source of free energy. We show that allowing catalysis along with a source of free energy allows us to amplify any quantum coherence present in the quantum state arbitrarily. Additionally, any correlations between the system and the catalyst can be suppressed arbitrarily. Therefore, our results provide a key step in formulating a fully general law of quantum thermodynamics.

## QI 39: Quantum Foundations

Time: Friday 11:00–13:00 Location: HS VIII

QI 39.1 Fri 11:00 HS VIII

**Discovering Local Hidden-Variable Models for Arbitrary Multipartite Entangled States and Arbitrary Measurements** — •Nick von Selzam[1] and Florian Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, Erlangen — [2]Friedrich-Alexander-Universität Erlangen-Nürnberg

Measurement correlations in quantum systems can exhibit non-local behaviour, a fundamental aspect of quantum mechanics with applications such as device-independent quantum information processing. However, it is in general not known which states are local and which ones are not. In particular, it remains an outstanding challenge to explicitly construct local hidden-variable (LHV) models for arbitrary multipartite entangled states. To address this, we use gradient-descent algorithms from machine learning to find LHV models which reproduce the statistics of arbitrary measurements for quantum many-body states. In contrast to previous approaches, our method employs a general ansatz, enabling it to discover LHV models for all local states. Therefore, it for example provides actual estimates for the critical noise levels at which two-qubit Werner states and three-qubit GHZ and W states become local. Furthermore, we find evidence suggesting that two-spin subsystems in the ground states of translationally invariant Hamiltonians are genuinely local, while bigger subsystems are in general not. Our method now offers a quantitative tool for determining the regimes of non-locality in any given physical context, such as non-equilibrium, decoherence or disorder.

ArXiv: 2407.04673

QI 39.2 Fri 11:15 HS VIII

**Generalizing the Mermin inequality to larger numbers of measurement settings** — •Fynn Otto, Carlos de Gois, and Otfried Gühne — Universität Siegen, Germany

Multipartite Bell nonlocality is an important resource for quantum information processing. It is detected by the violation of Bell inequalities and gap between the classical bound and the quantum bound grows exponentially with the number of parties for the Mermin inequality. This inequality is limited to two measurement settings per party. Nevertheless, advantages arise by increasing the number of settings. We present a new class of symmetric Bell inequalities generalizing the Mermin inequality to an arbitrary number of measurement settings. They are maximally violated by the Greenberger-Horne-Zeilinger (GHZ) state and provide a significantly higher noise robustness. We investigate improvements in the required detection efficiency for loophole-free Bell tests and advantages for self-testing the GHZ state. Our results decrease current experimental requirements, e.g. for secure quantum communication and state verification.

QI 39.3 Fri 11:30 HS VIII

**Nature cannot be described by any causal theory with a finite number of measurements** — •Lucas Tendick — Inria Paris-Saclay, Bâtiment Alan Turing, FRA, 91120 Palaiseau

We show, for any $n \geq 2$, that there exists quantum correlations obtained from performing n dichotomic quantum measurements in a bipartite Bell scenario, which cannot be reproduced by $n-1$ measurements in any causal theory. That is, it requires any no-signaling theory an unbounded number of measurements to reproduce the predictions of quantum theory. We prove our results by showing that there exists Bell inequalities that have to be obeyed by any no-signaling theory involving only $n-1$ measurements and show explicitly how these can be violated in quantum theory. Finally, we discuss the relation of our work to previous works ruling out alternatives to quantum theory with some kind of bounded degree of freedom and consider the experimental verifiability of our results.

QI 39.4 Fri 11:45 HS VIII

**Causal structure of quantum black-boxes** — •Leonardo Silva Vieira Santos — Universität Siegen

The relationship between causality and quantum measurements is central to many of the foundational challenges in quantum theory. Key examples of this tension include Bell's theorem, the concept of "impossible measurements" in quantum field theory, and the "multi-agent paradoxes," such as Wigner's friend and its generalizations. In this work, we systematically explore how causality constrains the implementation of quantum operations and the insights it offers. We introduce a framework for causal modeling in quantum operations, deriving a range of results, including the connection between commutation and factorization (Tsirelson's problem) and information causality.

QI 39.5 Fri 12:00 HS VIII

**Multi-Path and Multi-Particle Tests of Complex versus Hyper-Complex Quantum Theory** — Ece Ipek Saruhan[1,2], Joachim von Zanthier[2], and •Marc-Oliver Pleinert[2] — [1]Institute for Quantum Optics and Quantum Information (IQOQI) Vienna, Boltzmanngasse 3, A-1090 Vienna — [2]Quantum Optics and Quantum Information Group, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 1, 91058 Erlangen, Germany

The axioms of quantum mechanics provide limited information regarding the structure of the Hilbert space, such as the underlying number system. The latter is generally regarded as complex, but generalizations of complex numbers, so-called hyper-complex numbers, cannot be ruled out in theory. Therefore, specialized experiments to test for hyper-complex quantum mechanics are needed. To date, experimental tests are limited to single-particle interference exploiting a closed phase relation in a three-path interferometer called the Peres test. The latter distinguishes complex quantum mechanics from quaternionic quantum mechanics. Here, we propose a general matrix formalism putting the Peres test on a solid mathematical ground. On this basis, we introduce multi-path and multi-particle interference tests, which provide a direct probe for any dimension of the number system of quantum mechanics.

QI 39.6 Fri 12:15 HS VIII

**Witnesses for non-projectively simulable POVMs** — •Raphael Brinster, Nikolai Wyderka, Hermann Kampermann, and Dagmar Bruss — Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf

Quantum measurements are an indispensable tool in quantum information tasks like quantum computing and quantum cryptography. Usually, one distinguishes between projective measurements and generalised measurements (POVMs), where the latter perform better in certain tasks like unambiguous state discrimination. POVMs, that can be simulated by projective measurements acting on the same Hilbert space are called projectively simulable POVMs. In general, determining whether a given POVM is projectively simulable or not is a hard problem. Analogously to entanglement witnesses, we construct non-simulability witnesses from a hierarchy of semidefinite programs. These witnesses are linear maps, which can be evaluated using measurement statistics. A negative outcome certifies non-simulability. Using this tool we calculate upper bounds on the minimum amount of white noise one has to add to make every POVM in d dimensions simulable.

QI 39.7 Fri 12:30 HS VIII

**Correlations and quantum circuits with dynamical causal order** — •Raphaël Mothe[1,2,3], Alastair Abbott[3], and Cyril Branciard[1] — [1]Institut Néel, CNRS, Grenoble, France — [2]University of Siegen, Siegen, Germany — [3]Inria, Grenoble, France

Requiring that the causal structure between different parties is well-defined imposes constraints on the correlations they can establish, which define so-called causal correlations. Some of these are known to be dynamical in that their causal structure is not fixed a priori but is instead established on the fly, with for instance the causal order between future parties depending on some choice of parties in the past. Here we identify a new way that the causal order between the parties can be dynamical: with at least four parties, there can be some dynamical order, which can nevertheless not be influenced by the choice of past parties. This leads us to introduce an intermediate class of correlations with what we call non-influenceable causal order, in between the set of non-dynamical correlations and the set of general causal correlations. We then define analogous classes of processes, considering the recently introduced classes of quantum circuits with classical or quantum control of causal order the latter being the largest class within the process matrix formalism known to have a clear interpretation in terms of coherent superpositions of causal orders. This allows us to formalise precisely in which sense certain quantum processes can have both indefinite and dynamical causal orders.

QI 39.8 Fri 12:45 HS VIII

**Quantum-error-correction assisted test of quantum aspects of gravity** — •Yixuan Wang, Julen Simon Pedernales, and Martin Bodo Plenio — Institut für Theoretische Physik, Universität Ulm, Ulm, Germany

The detection of gravitationally induced entanglement (GIE) offers a promising avenue to experimentally test those hybrid quantum-classical models of gravity that can be represented as non-LOCC (local operations and classical communication) maps. However, practical observation of such entanglement may be hindered by environmental decoherence or fundamental decoherence mechanisms, such as those postulated in wavefunction collapse models. To address these challenges, quantum error correction can play a pivotal role. In my talk, I demonstrate that local quantum error-correcting codes without introducing external entanglement enable the observation of entanglement in models of linearized gravitational interactions, even under the influence of collapse noise from models like Ghirardi-Rimini-Weber (GRW), Continuous Spontaneous Localization (CSL), or the Anastopoulos-Hu gravitational decoherence framework. Furthermore, the recovery of entanglement using local operations provides direct evidence that these combined models (linearized gravity + collapse models) deviate fundamentally from LOCC behavior.

## QI 40: Quantum Control II (joint session QI/Q)

Time: Friday 11:00–13:00 Location: HS II

QI 40.1 Fri 11:00 HS II

**Optimally Controlled NMR in Electrochemistry: Overcoming Challenges and Turning Them into Opportunities** — •Armin J. Römer[1,2], Johannes F. Kochs[1,2], Michael Schatz[1], Matthias Streun[1], Simone S. Köcher[1,3], and Josef Granwehr[1,2] — [1]Forschungszentrum Jülich GmbH, Institute of Energy Technologies, Fundamental Electrochemistry (IET-1), Jülich, Germany — [2]RWTH Aachen University, Aachen, Germany — [3]Fritz Haber Institute of the Max Planck Society, Berlin, Germany

Quantum optimal control is a versatile, powerful method to tailor nuclear magnetic resonance (NMR) experiments. With the growing importance of NMR on electrochemical systems, we present how optimal control can be used to address experimental challenges in complex setups, such as *operando* electrolysis. Particularly, conductive cell components cause magnetic field distortions due to shielding and eddy current effects, leading to reduced resolution, non-quantitative results, and possible artifacts. In a complementary approach, we combine ensemble optimal control with finite element method (FEM) simulations. We show how NMR setups are accurately modeled in FEM and how this knowledge is used to improve NMR measurements on an *operando* electrolysis setup. Furthermore, we demonstrate how an NMR measurement can be turned surface selective by exploiting the characteristic near-surface magnetic field distortions. We demonstrate how quantum optimal control enables new experiments, which provide additional information and insights of unparalleled detail into complex systems.

QI 40.2 Fri 11:15 HS II

**Comparison of Gate-set evaluation metrics for closed-loop optimal control on nitrogen-vacancy center ensembles in diamond** — •Thomas Reisser[3,4], Philipp J. Vetter[1,2], Maximilian G. Hirsch[1,2,5], Tommaso Calarco[3,4,6], Felix Motzoi[3,4], Fedor Jelezko[1,2], and Matthias M. Müller[3] — [1]Institute for Quantum Optics, Ulm University, 89081 Germany — [2]Center for Integrated Quantum Science and Technology (IQST), 89081 Germany — [3]Institute for Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, 52425 Germany — [4]Institute for Theoretical Physics, University of Cologne, 50937 Germany — [5]NVision Imaging Technologies GmbH, 89081 Germany — [6]Dipartimento di Fisica e Astronomia, Università di Bologna, 40127 Italy

Precise control of a quantum system is a prerequisite for quantum information, quantum computing, and quantum metrology. Quantum gates on ensembles of nitrogen vacancy centers usually suffer from decoherence, large amplitude errors, imperfect state preparation and therefore limited total operation fidelity. Large state preparation and measurement errors can cause the typically used quantum process tomography to fail. We investigate the applicability of quantum process tomography, linear inversion gate-set tomography, randomized linear gate-set tomography, and randomized benchmarking as measures for closed-loop quantum optimal control experiments. Closed-loop optimizations are performed and evaluated with all measures to find a gate-set with universally improved performance and demonstrate the relative trade-offs between the methods.

QI 40.3 Fri 11:30 HS II

**Spin control of highly-strained silicon-vacancy centers in nanodiamonds** — •Andreas Tangemann, Marco Klotz, and Alexander Kubanek — Institute for Quantum Optics, University Ulm, Germany

Spin qubits in solid state hosts are, due to their promise of scalability, candidates for the realization of quantum networks. The good spin properties of diamond paired with the optical properties of group-IV defects make them of special interest. We are using highly-strained silicon vacancy centers in nanodiamonds to mitigate phonon induced dephasing of the spin qubit at liquid Helium temperature, due to orbital ground state splittings exceeding 1THz. Here we show coherent control of the electron spin, access to a 13C nuclear spin via indirect control and nuclear spin single-shot readout, as well as coherent control over the optical dipole of the SiV centers. These techniques lay the foundation for future quantum network experiments with SiV centers at liquid Helium temperatures.

QI 40.4 Fri 11:45 HS II

**Nuclear spin control with highly strained silicon-vacancy centers** — •Marco Klotz, Andreas Tangemann, and Alexander Kubanek — nstitute for Quantum Optics, University Ulm, Germany

Spin qubits in solid state hosts are due to their promise of scalability candidates for the realization of quantum networks. The good spin properties of diamond paired with the optical properties of group-IV defects make them of special interest. We are using highly strained silicon vacancy centers to mitigate phonon induced electron spin dephasing at liquid Helium temperature. Here we show our current results on electron spin characterization. Furthermore, we use highly efficient electron spin driving to access, control and characterize coupled C13 nuclear spins. This paves the way for nuclear spin assisted quantum error correction and networking with group IV defects.

QI 40.5 Fri 12:00 HS II

**Cryogenic microwave generator for quantum information processing with trapped ions** — •Sebastian Halama[1], Peter Toth[2], Marco Bonkowski[1], and Christian Ospelkaus[1,3] — [1]Leibniz Universität Hannover, Institut für Quantenoptik, Welfengarten 1, 30167 Hannover, Germany — [2]Technische Universität Braunschweig, Institut für CMOS Design, Hans-Sommer-Str. 66, 38106 Braunschweig — [3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig

Scaling up quantum computers to a higher number of qubits while maintaining control of all qubit states is still a major challenge. Surface-electrode ion traps are a promising platform for such a large-scale quantum computer. With the microwave near-field approach [1], qubit control realized by microwave conductors that are integrated into the ion trap naturally scale with the trap itself. However, the microwave signal generation currently takes place outside of the vacuum chamber in which the ion trap is located. Here we report on the design of a cryogenic three-channel microwave generator with amplitude modulation capabilities and its co-integrating with a surface-electrode ion

trap on a common chip carrier. We present first measurements taken with the cryogenic microwave generator and discuss further steps of the experiment.

[1] Ospelkaus et. al, Phys. Rev. Lett. **101**, 090502 (2008)

QI 40.6 Fri 12:15 HS II

**Optimizing Rydberg Ensemble Dynamics: Double Excitation Suppression** — •Vidisha Aggarwal[1,2], Boxi Li[1], Eloisa Cuestas[1], Robert Zeier[1], Felix Motzoi[1,2], and Tommaso Calarco[1,2,3] — [1]Peter Grünberg Institute-Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, 52425 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, 50937 Koln, Germany — [3]Dipartimento di Fisica e Astronomia, Università di Bologna, 40127 Bologna, Italy

We propose an optimization strategy for Rydberg ensemble dynamics to suppress double excitations and enhance single-photon emission, crucial for quantum technologies like optical communication. Using a Rydberg 'superatom'-an ensemble of Rubidium-87 atoms in an optical cavity-we encode its internal state into an optical qubit [1]. While the Rydberg blockade ideally ensures single-photon emission, imperfections lead to double excitations, hindering controlled retrieval.

To address this, we use the Derivative Removal by Adiabatic Gate (DRAG) method, which introduces an auxiliary pulse to suppress unwanted transitions [2,3]. Though typically used with superconducting qubits, applying DRAG to neutral atoms demonstrates the versatility of quantum control techniques. This approach significantly improves the probability of obtaining just a single Rydberg excitation compared to the experimental pulse.

[1] V. Magro, A. Ourjoumtsev, et al. Nat. Photonics 17, 688*693 (2023). [2] F. Motzoi and F. K. Wilhelm, Phys. Rev. A 88, 062318 (2013). [3] B. Li, F. Motzoi et al., PRX Quantum 3, 030313 (2022).

QI 40.7 Fri 12:30 HS II

**Motion-Insensitive Time-Optimal Control of Optical Qubits** — •Léo Van Damme[1], Zhao Zhang[2], Amit Devra[1], Steffen J. Glaser[1], and Andrea Alberti[2] — [1]School of Natural Sciences, Technical University of Munich, Lichtenbergstrasse 4, D-85747 Garching, Germany — [2]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Ultranarrow optical transitions, widely used in modern atomic clocks, are gaining significant attention for quantum computing applications. However, optical qubits are highly susceptible to motion-induced decoherence and photon-recoil heating, which, if unaddressed, pose critical barriers to the realization of large-scale quantum circuits.

In this work, we demonstrate that these effects can be controlled by modulating the phase of the driving laser field over time, for general quantum gates and arbitrary initial atomic states.

We have developed a method that reduces the problem of infinite motional states to a set of constraints on a two-level system. This dramatic simplification, combined with optimal control techniques, reveals that optimal solutions not only substantially improve gate fidelity and speed but are also feasible for practical implementation.

QI 40.8 Fri 12:45 HS II

**Accelerated creation of NOON states with ultracold atoms via counterdiabatic driving** — •Simon Dengis[1], Sandro Wimberger[2,3], and Peter Schlagheck[1] — [1]CESAM Research Unit, University of Liege, 4000 Liege, Belgium — [2]Istituto Nazionale di Fisica Nucleare (INFN), Sezione Milano Bicocca, Gruppo collegato di Parma, Italy — [3]Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, Parco Area delle Scienze 7/A, 43124 Parma, Italy

A quantum control protocol is proposed for the creation of NOON states with $N$ ultracold bosonic atoms on two modes, corresponding to the coherent superposition $|N,0\rangle + |0,N\rangle$. This state can be prepared by using a third mode where all bosons are initially placed and which is symmetrically coupled to the two other modes. Tuning the energy of this third mode across the energy level of the other modes allows the adiabatic creation of the NOON state. While this process normally takes too much time to be of practical usefulness, due to the smallness of the involved spectral gap, it can be drastically boosted through counterdiabatic driving which allows for efficient gap engineering. We demonstrate that this process can be implemented in terms of static parameter adaptations that are experimentally feasible with ultracold quantum gases. Gain factors in the required protocol speed are obtained that increase exponentially with the number of involved atoms and thus counterbalance the exponentially slow collective tunneling process underlying this adiabatic transition. arXiv:2406.17545.

## QI 41: Quantum Computing and Simulation II (joint session Q/QI)

Time: Friday 11:00–13:00 Location: AP-HS

**Invited Talk** QI 41.1 Fri 11:00 AP-HS

**Towards Quantum Simulation with Qudits** — •Martin Ringbauer — Universität Innsbruck, Institut für Experimentalphysik, Technikerstraße 25, 6020 Innsbruck

Current quantum computers and simulators are almost exclusively built for binary information processing, yet, nature rarely gives us two-level systems. This is true for our quantum information carriers, as well as for the systems we want to simulate with our quantum devices. I will discuss the opportunities and challenges of using the inherent multilevel Hilbert space of trapped ions for quantum computing information processing. This will be exemplified by recent experimental results for qudit-enhanced QIP, as well as native qudit quantum simulations.

QI 41.2 Fri 11:30 AP-HS

**Tuning the qubit-qubit interaction for multi-qubit quantum gates** — •Patrick H. Huber, Dorna Niroomand, Markus Nünnerich, Patrick Barthel, and Christof Wunderlich — Walter-Flex-Straße 3, 57072 Siegen

Internal hyperfine states of ions trapped in a common potential provide long-lived qubits that can be coupled via the ions' Coulomb interaction. A set of such qubits, analogous to a classical register, can be referred to as a quantum register. The Magnetic Gradient Induced Coupling (MAGIC) approach to quantum computing with trapped ions can provide an always-on, all-to-all Ising-type interaction between radio frequency-controlled qubits in such a quantum register [1,2]. The interaction strength is determined by the trapping potential and the applied magnetic field gradient. Here we present a novel method that allows for the tuning of the qubits' interaction without changing the trapping potential nor the magnetic field while simultaneously preserving the qubits' coherence. This method uses pulsed dynamical decoupling and is demonstrated experimentally in a quantum register of four laser-cooled $^{171}Yb^{+}$ qubits. It is used to synthesize an arbitrary coupling matrix within a quantum register and to generate non-interacting subregisters. Thus, this method opens up novel ways for efficiently synthesizing quantum algorithms on a trapped ion quantum computer. [1] A. Khromova *et al.*, Phys. Rev. Lett. 108, 220502 (2012). [2] P. Baßler *et al.*, Quantum 7, 984 (2023).

QI 41.3 Fri 11:45 AP-HS

**Fast radio frequency-driven entangling gates for trapped ions** — •Markus Nünnerich, Patrick Huber, Dorna Niroomand, and Christof Wunderlich — Department of Physics, School of Science and Technology, University of Siegen, 57068 Siegen, Gemany

Entangling gates are a fundamental component of any quantum processor, ideally operating at high speeds in a robust and scalable manner. Here, we experimentally investigate a novel radio frequency (RF)-driven two-qubit gate with trapped and laser cooled $^{171}Yb^{+}$ ions exposed to a static magnetic gradient field of 19 T/m that induces an effective qubit-qubit interaction (Magnetic Gradient Induced Coupling, MAGIC). The hyperfine states $|0\rangle \equiv |^2S_{1/2}, F=0, m_F=0\rangle$ and $|1\rangle \equiv |^2S_{1/2}, F=1, m_F=-1\rangle$ are used as qubits. We generate Bell states by applying continuously two RF driving fields, each one of them on resonance to one of the two qubit transitions. The phase of these driving fields is varied periodically yielding effectively a sequence of back-to back dynamical decoupling pulses. By adjusting the Rabi frequency induced by the driving fields, the effective coupling of the qubits to the ions' motional state is changed, and the entangling gate speed can be varied between $\approx 4$ ms and $\approx 300\mu s$. Higher gate speeds are advantageous for achieving faster and deeper quantum algorithms. In currently used micro-structured traps with larger magnetic field gradients, gate speeds on par with laser-driven gates in trapped ions are expected.

QI 41.4 Fri 12:00 AP-HS

**Coherent control of trapped-ion qubits and qumodes via phase-stable optical addressing** — •Kai Shinbrough[1], Donovan J. Webb[1], Iver R. Øvergaard[1], Oana Băzăvan[1], Sebastian Saner[1], Gabriel Araneda[1], Raghavendra Srinivas[1,2], and Christopher J. Ballance[1,2] — [1]University of Oxford, Oxford, UK — [2]Oxford Ionics, Oxford, UK

Control over the phase of optical addressing beams in the trapped-ion platform allows for precise control of the coupling between spin and motional states of the ion. This control serves as a resource for fast, high-fidelity multi-qubit entangling gates, as well as for continuous variable quantum information processing using the motional state qumodes of single ions and ion chains. Here we report on a suite of qubit-qubit, qubit-qumode, and qumode-qumode interactions enabled by this phase control, including two-qubit gates faster than the speed limit imposed by off-resonant carrier coupling [1], non-Gaussian operations performed on the ion motional state [2,3] (which, along with a complete set of Gaussian operations, satisfy the Lloyd-Braunstein criterion for universal quantum computation [4]), and progress toward a linear chain of $^{40}$Ca$^{+}$ ions with individually addressed standing waves.

[1] S. Saner, O. Băzăvan, *et al.*, Phys. Rev. Lett. **131**, 220601 (2023).
[2] O. Băzăvan, S. Saner, *et al.*, arXiv:2403.05471 (2024).
[3] S. Saner, O. Băzăvan, *et al.*, arXiv:2409.03482 (2024).
[4] S. Lloyd, S. L. Braunstein, Phys. Rev. Lett. **82**, 1784 (1999).

QI 41.5 Fri 12:15 AP-HS

**Integrated micromagnets for trapped ion quantum science** — •Benjamin Bürger, Patrick Huber, and Christof Wunderlich — Universität Siegen, Walter-Flex-Straße 3, 57072 Siegen

We present the design and implementation of quasi-two-dimensional (2D) micromagnets tailored to generate an inhomogeneous static magnetic field. This field, when integegrated into a micro-structured ion trap, enables frequency-selective addressing of ions through radio frequency radiation (RF) and conditional quantum dynamics with trapped ions. We will integrate the magnet design into a planar Paul trap that is split into two types of regions: An interaction zone and a cooling/readout zone. The micromagnets are meticulously designed to produce high field gradients while maintaining a low absolute field strength, effectively minimizing decoherence induced by magnetic field noise within the qubit interaction zones. In the cooling/readout zones, the magnets are designed to generate a small homogeneous magnetic field to facilitate efficient Doppler cooling on larger strings. Furthermore, the magnetic field orientation is optimized to support both $\sigma$ and $\pi$ polarized RF-driven transitions in $^{171}$Yb$^{+}$ ions facilitating efficient cooling on the magnetic-field-insensitive $\pi$ transition and utilizing the $\sigma$ transition for gate operations.

QI 41.6 Fri 12:30 AP-HS

**Towards a cryogenic trapped ion quantum demonstrator using cryogenic control electronics** — •Dorna Niroomand[1], Daniel Busch[1], Kais Rejaibi[1], Ernst A Hackler[1], Rodolfo M Rodriguez[1], Patrick Huber[1], Garima Saraswat[2], Michael Johanning[2], and Christof Wunderlich[1] — [1]Department of Physics, School of Science and Technology University of Siegen, 57068 Siegen, Gemany — [2]eleQtron, 57072 Siegen, Germany

Trapped ion quantum computing platforms in cryogenic vacuum have the advantage of rapidly achieving ultra-high vacuum. This allows long ion storage times even in the relatively shallow trapping potential of surface-electrode Paul traps. In addition, it offers more flexibility in exchanging trap chips, making it feasible to study multiple generations of traps with different structure and experimental specifications. Here, I will discuss the progress towards building and operating a cryogenic (4 K) quantum demonstrator that includes low-noise cryogenic electronics to precisely control trapping potentials and enable shuttling of ions (BMBF-funded project ATIQ). En route towards scalable trapped ion quantum processors, multiple generations of microfabricated surface-electrode traps with integrated magnets and cryogenic control electronics will be investigated in this platform.

QI 41.7 Fri 12:45 AP-HS

**Cooling a quantum annealer with a quantum field** — •Raphael Menu and Giovanna Morigi — Universität des Saarlandes, Saarbrücken

We analyse the Landau-Zener dynamics of a qubit, which is simultaneously coupled to a dissipative auxiliary system. By tuning the coupling, the qubit dynamics ranges from a dephasing master equation to a strongly coupled qubit-auxiliary system, which is effectively a non-Markovian reservoir for the qubit. We determine the quantum trajectories in the different regimes and analyse the distribution of each trajectory in terms of the time-dependent probability of a diabatic transition. Depending on the strength of the coupling, we observe multipeaked configurations, which undergo transitions to narrow distributions. These transitions are signaled by a higher probability that a jump occurs. The behavior of the probability of a quantum jump as a function of the coupling and of the time of the sweep, in turn, allows us to shed light on the stages of the dynamics when the environment is detrimental and when instead it corrects diabatic transition. It shows, in particular, that memory effects can be beneficial in cooling a quantum system.

## QI 42: Quantum Technologies (Color Centers and Ion Traps) II (joint session Q/QI)

Time: Friday 11:00–13:00 Location: HS Botanik

**Invited Talk** QI 42.1 Fri 11:00 HS Botanik

**Multi-color excitation of quantum emitters** — •Thomas Bracht — TU Dortmund, 44227 Dortmund, Germany

On-demand photon generation is essential for reliable quantum communication. Solid state quantum emitters have emerged as a promising platform, offering excellent photon properties and controllability.

In this talk, I introduce the Swing-UP of quantum EmitteR (SUPER) scheme, which enables excitation of a quantum emitter using two pulses of different colors, allowing for completely off-resonant, red-detuned excitation. This novel multi-color approach is advantageous as spectral filtering can be used to suppress the excitation laser, boosting the total photon yield. In a completely quantized picture, it corresponds to a two-photon process [1]. After its theoretical prediction [2], the SUPER scheme has been experimentally demonstrated in quantum dots [3] and other systems.

As an outlook, I show how this technique can be used to generate highly entangled photon pairs, which are an important building block in quantum information technology.

[1] Richter et al., arXiv:2405.20095 (2024) [2] Bracht et al., PRX Quantum 2, 040354 (2021) [3] Karli et al., Nano Lett. 22, 6567 (2022)

QI 42.2 Fri 11:30 HS Botanik

**Measuring MHz charge dynamics in diamond with a tin-vacancy color center** — •Charlotta Gurr[1], Cem Güney Torun[1], Gregor Pieplow[1], and Tim Schröder[1,2] — [1]Humboldt-Universität zu Berlin, Germany — [2]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, Berlin, Germany

Color centers in diamond are influenced by electric noise from their diamond host material [1]. Free charge carriers being trapped and released from charge traps in the diamond lattice create a fluctuating electric field environment, shifting the color center's energy levels. The optical transitions are therefore rendered unstable, to the detriment of applications that require a source of indistinguishable photons. Little is known about the nature of the charge traps. Here, we develop a technique to investigate the charge process dynamics of single charges in diamond with MHz resolution, using a tin-vacancy color center. We find charge capture and release rates spanning two orders of magnitude within Hz and kHz, possibly revealing two different effects influencing the charge processes. Furthermore, we find that 520 nm illumination of the diamond sample influences the charge release rates more strongly than more energetic 445 nm illumination. We believe this to be caused by a two-step process leading to the release of charges from charge traps. These findings expand our understanding of charge traps in diamond as well as the processes responsible for capturing and releasing single charges.

[1] Pieplow, Torun et al., *Quantum Electrometer for Time-resolved Material Science at the Atomic Lattice Scale*, arXiv:2401.14290, 2024

QI 42.3 Fri 11:45 HS Botanik

**Integration of group IV color centers in nanodiamonds in a tunable Fabry-Perot microcavity** — •Selene Sachero, Robert Berghaus, Florian Feuchtmayr, and Alexander Kubanek — Institute for Quantum Optics, Ulm University, 89081 Ulm, Germany

Quantum repeater are essential building block to create a large scale quantum communication network. An ideal quantum repeater nodes efficiently link a quantum memory with photons serving as flying qubits. By coupling group IV vacancy defect centers in nanodiamonds (NDs) to an open Fabry-Perot cavity, such an interface can be created. As such a platform, we propose a fully tunable cavity composed by two Bragg mirrors which allows short cavity lengths down to $\approx 1\ /mu$m, and provides efficient coupling of the quantum emitter at liquid helium temperatures.

Here, we show the good optical properties of a single group IV emitter and its transfer, via nanomanipulation, to a Fabry-Perot cavity. The coupling of the emitter into the resonator is achieved maintaining an high finesse.

Moreover, we perform PL measurement at cryogenic temperatures and observe a lifetime reduction due to the Purcell factor.

QI 42.4 Fri 12:00 HS Botanik

**Entanglement by path identity based on engineered photon pairs** — •Richard Bernecker[1,2], Baghdasar Baghdasaryan[3], and Stephan Fritzsche[1,2] — [1]Institute for Theoretical Physics, Friedrich Schiller University Jena, 07743 Jena, Germany — [2]Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany — [3]Institute of Applied Physics, Friedrich Schiller University Jena, Albert-Einstein-Str. 6, 07745 Jena, Germany

Entangled photon pairs are essential for applications in quantum communication and distributed quantum computing. A convenient approach for entanglement generation is to coherently superimpose photon pairs created in multiple nonlinear crystals via spontaneous parametric down-conversion (SPDC). The entanglement emerges because no information is available about which crystal created the pair, provided the propagation paths of the photon pairs are overlapped. This path identity approach was experimentally demonstrated by overlapping separable orbital angular momentum modes using three nonlinear crystals and spiral phase plates. However, the number of nonlinear crystals governs the dimensionality of the entangled state, posing challenges for generating entanglement in large Hilbert spaces. Recently, we explored the direct generation of maximally entangled states via pump and crystal shaping in SPDC. In this contribution, we combine pump shaping techniques with the path identity approach to engineer high-dimensional entangled states. A key advantage of this method is the potential for increasing the scalability of the entanglement dimensionality without requiring additional crystals in the setup.

QI 42.5 Fri 12:15 HS Botanik

**Enhanced atom-photon interactions based on integrated waveguides immersed in hot atomic vapor** — •Annika Belz[1], Benyamin Shnirman[1,2], Xiaoyu Cheng[1], Harald Kübler[1], Hadiseh Alaeian[3], Robert Löw[1], and Tilman Pfau[1] — [1]5. Physikalisches Institut, Universität Stuttgart, Germany — [2]Institut für Mikroelektronik Stuttgart (IMS-Chips), Stuttgart, Germany — [3]Departments of Electrical & Computer Engineering and Physics & Astronomy, Purdue University, West Lafayette, USA

The combination of thermal atomic vapor with nanophotonic structures provides a unique platform for the manipulation of atom-photon and light induced atom-atom interactions and can exhibit large optical non-linearities, even at the few photon level.

We can further enhance these non-linearities via an enlarged Purcell factor using slot waveguides. We observe saturable repulsive interactions of the atoms within the slot as an intensity dependent blue shift. In order to verify the nature of the non-linearity in more detail we incorporate an integrated Mach-Zehnder interferometer to access also the non-linear phase shift.

QI 42.6 Fri 12:30 HS Botanik

**Cavity-Enhanced Spin-Photon Interface for Single Tin-Vacancy Centers in Diamond** — •Andras Lauko[1], Kerim Köster[1], Julia Heupel[2], Philipp Fuchs[3], Michael Kieschnick[4], Michael Förg[5], Thomas Hümmer[5], Cyril Popov[2], Jan Meijer[4], Christoph Becher[3], and David Hunger[1] — [1]Karlsruher Institut für Technologie — [2]Universität Kassel — [3]Universität des Saarlandes — [4]Universität Leipzig — [5]Qlibri GmbH

Building a long-distance quantum network is one of the big challenges in the field of quantum communication, which requires the development of a quantum repeater.

Tin-vacancy centers in diamond are a rising candidate among color centers in diamond, having higher operating temperatures than silicon-vacancy centers and less prone to phonon-coupling relative to nitrogen-vacancy centers.

In our experiment, we integrate a diamond membrane into an open access fiber-based Fabry-Perot microcavity to attain emission enhancement in a single well-collectable mode. We present our fully tunable, cryogenic cavity platform operating in a tabletop dilution cryostat, and we achieve a picometer mechanical stability. The platform also allows for integration of a superconducting DC magnet and microwave antenna for spin manipulation.

We observe cavity-enhanced fluorescence signal of single, shallow-implanted tin-vacancy centers in diamond, showing Purcell-enhancement and thus higher emission rates and reduced excited state lifetimes.

QI 42.7 Fri 12:45 HS Botanik

**Optimal Control for Quantum Technology with NV-Centers in Diamond** — •Matthias Müller — Peter-Grünberg-Institute of Quantum Control (PGI-8), Forschungszentrum Jülich GmbH

Diamond-based quantum technology is a fast-emerging field with both scientific and technological importance. The performance relies on unique features like superposition and entanglement and depends on sophisticated mechanisms of control to perform the desired tasks. Quantum Optimal Control (QOC) has proven to be a powerful tool to accomplish this task. I will give a brief overview on the use of QOC for NV-centers in diamond [1], the CRAB algorithm for Optimal Control [2], the optimal-control software QuOCS [3] and report on recent applications toward quantum sensing and quantum computing [4,5,6].

[1] P. Rembold et al., AVS Quantum Sci. 2, 024701 (2020) [2] M. M. Müller et al., Rep. Prog. Phys. 85 076001 (2022) [3] M. Rossignolo et al. Comp. Phys. Comm. 291, 108782 (2023) [4] N. Oshnik et al., Phys. Rev. A 106, 013107 (2022) [5] N. Grimm et al., arXiv:2409.06313 (2024) [6] P. Vetter et al., npj Quantum Information 10 (1), 96 (2024)

## QI 43: Open Quantum Systems II (joint session Q/QI)

Time: Friday 11:00–13:00 Location: HS I

QI 43.1 Fri 11:00 HS I

**Controlling matter phases beyond Markov** — •Baptiste Debecker, John Martin, and François Damanet — University of Liège, Liège, Belgium

Controlling phase transitions in quantum systems via coupling to reservoirs has been mostly studied for idealized memory-less environments under the so-called Markov approximation. Yet, most quantum materials and experiments in the solid state, atomic, molecular and optical physics are coupled to reservoirs with finite memory times. Here, using the spectral theory of non-Markovian dissipative phase transitions developed in the companion paper [Debecker, Martin, and Damanet (to be published)], we show that memory effects can be leveraged to reshape matter phase boundaries, but also reveal the existence of dissipative phase transitions genuinely triggered by non-Markovian effects.

QI 43.2 Fri 11:15 HS I

**Markovianity in Quantum Thermodynamics: Principles and Practice** — •Thomas Schulte-Herbrüggen[1], Emanuel Malvetti[1], Frederik vom Ende[2], and Gunther Dirr[3] — [1]Technical University of Munich (TUM) — [2]FU Berlin — [3]University of Würzburg

We connect quantum control theory with quantum thermodynamics for open Markovian systems. We sketch a *Markovianity Filter*, i.e. how to construct the Markovian counterparts of several types of quantum Thermal Operations (via Lie semigroups). By way of example, we parameterise the Markovian subset of maps within the set of all Thermal Operations.

As an application, we give inclusions in terms of $d$-majorisation for reachable sets of bilinear control systems, where coherent controls are complemented by switchable couplings to a thermal bath as additional resource.

QI 43.3 Fri 11:30 HS I

**The quantum harmonic oscillator in a dissipative bath of anyon pairs** — •Nils-Henrik Meyer[1], Michael Thorwart[1], and Axel Pelster[2] — [1]I. Institute of Theoretical Physics, University of Hamburg, Germany — [2]Physics Department and Research Center OPTIMAS, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Germany

We determine the quantum statistical dynamics of a quantum mechanical harmonic oscillator coupled to a heat bath constructed of 1D anyons. For that, we use the quantum mechanical path integral of anyon pairs in one dimension introduced by Grundberg and Hansson [1]. These anyons are characterized by one statistical parameter entering in the dispersion relation of the heat bath. By this, we formally obtain a heat bath of free bosons which, however, couple nonlinearly to the system. By utilizing the smearing formula of Ref. [2], we find a direct nontrivial influence of the anyons on the spectral density and therefore the dynamics of the system up to second order in a perturbative approach. We show that the relaxation properties of the system are directly determined by the anyonic statistical parameter of the bath.

[1] J. Grundberg and T. H. Hansson. Mod. Phys. Lett. A **10**, 985 (1995).
[2] H. Kleinert, W. Kürzinger, and A. Pelster. J. Phys. A **31**, 8307 (1998).

QI 43.4 Fri 11:45 HS I

**Microscopic model for a nonliner dissipative dielectric medium** — •Nils Berhausen, Sascha Lang, and Stefan Yoshi Buhmann — Institut für Physik, Universität Kassel, Heinrich-Plett-Straße 40, 34132 Kassel, Germany

Through nonlinear optical effects, such as the Kerr effect, it is experimentally possible to artificially generate spacetimedependent refractive index modulations via strong electric fields. Suitable experimental setups allow for generating backgrounds which affect the field dynamics similarly to nontrivial curved spacetimes. For instance, tabletop setups with refractive index modulations can give rise to photon pair creation that can be observed by the technique of electro-optic sampling in certain nonlinear crystals. In existing theoretical works, the dynamics of nonlinear optical media is usually described in a phenomenologically motivated extension of linear macroscopic electrodynamics, which does not necessarily cover the full quantum vacuum dynamics. In this talk, I will present first results on an alternative microscopic approach for nonlinear optical media. To incorporate nonlinearities, we describe the medium with anharmonic oscillators and allow those oscillators to nonlinearly couple to the electric field. The resulting model takes into account a number of nonlinear optical effects, including second-harmonic generation.

QI 43.5 Fri 12:00 HS I

**Calculating two-time correlations for dissipative, interacting spin systems with phase space methods** — •Jens Hartmann and Michael Fleischhauer — RPTU Kaiserslautern, Kaiserslautern, Germany

The recently developed Truncated Wigner Approximation (TWA) for spins [1,2] is a powerful technique to simulate dissipative, interacting spin systems with a large number of spins taking into account leading-order quantum effects. However, determining two-time correlations within phase space approaches is notoriously difficult. We here developed an efficient method to numerically calculate multi-time-correlations of strongly coupled spins and demonstrate its accuracy for different benchmark problems. Furthermore of special interest is the superradiant emission from atoms coupled to a waveguide, which can be described very well with our method [3]. We compute the second order correlation function of the emitted light for different times and see a good agreement between the theoretical and experimental data for the superradiant bursts and the corresponding behavior of the correlation function.

[1,2] C. Mink et al., 10.21468/SciPostPhys.15.6.233, PhysRevResearch.4.043136
[3] F. Tebbenjohanns et al., PhysRevA.110.043713

QI 43.6 Fri 12:15 HS I

**Exploring non-Markovian dynamics in microwave spin control of group-IV color centers coupled to a phononic bath** — •Mohamed Belhassen[1], Gregor Pieplow[1], and Tim Schröder[1,2] — [1]Humboldt-Universität zu Berlin, Berlin, Germany — [2]Ferdinand-Braun-Institut, Berlin, Germany

Microwave control is a well-established technique for driving the electronic spin of diamond color centers. In our earlier work [1], we demonstrated that optimizing the orientation of the static magnetic field lifting the spin degeneracy and the polarization of the microwave field driving the spin, is essential for achieving efficient control conditions in a low strain environment. Expanding on this, we now incorporate the phononic bath, which introduces decay and decoherence to the qubit's quantum state. We examine the system dynamics using both Markovian and non-Markovian master equations, revisiting the interplay between magnetic and microwave field orientations and applied strain, with a focus on their impact on the qubit decay and decoherence times. We interpret our simulation results and compare them with the most recent experimental results. Finally, we assess the validity of the Born-Markov approximation and investigate how bath memory effects impact quantum state evolution.

[1] G. Pieplow, M. Belhassen, T. Schröder, Phys. Rev. B 109, 115409

QI 43.7 Fri 12:30 HS I

**Non-Markovian dynamics of giant atificial atoms at finite temperature** — •Mei Yu[1], Hai Chau Nguyen[1], Walter Strunz[2], Valentin Link[2], and Stefan Nimmrichter[1] — [1]University of Siegen, Siegen, Germany — [2]Dresden University of Technology, Dresden, Germany

Superconducting qubits, when coupled to either a meandering transmission line or to surface acoustic waves, enable the creation of giant artificial atoms. These atoms interact with the waveguide through two or more spatially separated contact points, providing a tunable platform to explore non-Markovian dynamics with significant memory effects beyond the atomic lifetime. Thus far, the non-Markovian characteristics of this system have been analyzed at zero temperature and validated experimentally [1]. In this work, we examine the influence of finite temperature on the non-Markovian behavior of giant atom dynamics. Contrary to intuitive expectations, we find that thermal effects can suppress the spontaneous emission decay rate rather than enhancing it.

[1] G. Andersson, B. Suri, L. Guo, T. Aref, and P. Delsing, Non-exponential decay of a giant artificial atom, Nature Physics 15, 1123 (2019).

QI 43.8 Fri 12:45 HS I

**On the foundation of quantum physics** — •Hans-Otto Carmesin — Gymnasium Athenaeum, Harsefelder Straße 40, 21680 Stade — Studienseminar Stade, Bahnhofstr. 5, 21682 Stade — Universität Bremen, Fachbereich 1, Postfach 330440, 28334 Bremen

Quantum physics, QP, is a mystery, described by unexplained postulates (Hilbert et al., 1928). However, evident properties of volume in nature, corresponding to space and vacuum, provide the volume dynamics, VD (Carmesin 2023, 2024) - and the VD implies the postulates of QP. Moreover, the VD provides and explains the wave function as well as the Schrödinger equation, including generalizations. Naturally, the VD provides the value of the dark energy, properties of space and of vacuum, as well as the solution of the Hubble tension.

Furthermore, the VD implies many fundamental physical results.

Literature

Hilbert, D.; Nordheim, L.; Neumann, J v. (1928): Über die Grundlagen der Quantenmechanik. Mathematische Annalen, pp. 395-407.

Carmesin, H.-O. (2023): Geometrical and Exact Unification of Spacetime, Gravity and Quanta. Berlin: Verlag Dr. Köster.

Carmesin, H.-O. (2024): How Volume Portions Form and Found Light, Gravity and Quanta. Berlin: Verlag Dr. Köster.

More info: https://www.researchgate.net/profile/Hans-Otto-Carmesin

## QI 44: Quantum Technologies (Detectors and Photon Sources) (joint session Q/QI)

Time: Friday 14:30–16:15 Location: AP-HS

QI 44.1 Fri 14:30 AP-HS

**Niobium-based plasmonic superconducting photodetectors for IR** — •Sandra Mennle[1], Philipp Karl[1], Monika Ubl[1], Pavel Ruchka[1], Heidemarie Schmidt[2], and Harald Giessen[1] — [1]4th Physics Institute, Research Center SCoPE, and IQST, University of Stuttgart, Germany — [2]Leibniz Institute of Photonic Technology, Albert-Einstein-Str. 9, 07745 Jena, Germany

In the last decade photon-based quantum technologies have become a fast-growing field of research, which requires fast and reliable detectors. Moreover, applications in the mid-IR like spectroscopy or astronomic photography are in need for highly efficient photodetection. For these applications superconducting nanowire photon detectors feature a great potential due to their high efficiency and sensitivity.

To enhance the absorption at larger wavelengths in the IR spectral range, we are using a plasmonic perfect absorber geometry to match the optical impedance of the detector to the incident light and to suppress any reflection. By design plasmonic resonances feature a large bandwidth, polarization sensitivity and can easily be spectrally tuned.

We present detectors which reach an absorption of over 95% for wavelengths up to 4 $\mu$m and demonstrate nanostructures with 90% absorption in 8-12 $\mu$m spectral range. This concept than can be extended to use not only one, but multiple detectors which then form a detector array i.e. a highly sensitive camera with plasmonically enhanced efficiency.

QI 44.2 Fri 14:45 AP-HS

**Deep ultraviolet laser light for cluster interferometry** — •Hannah Foltas, Richard Ferstl, Severin Sindelar, Bruno Ramírez-Galindo, Stefan Gerlich, Sebastian Pedalino, and Markus Arndt — University of Vienna, Faculty of Physics, Boltzmanngasse 5, Vienna, Austria

Matter-wave interferometry with massive nanoparticles may contribute to the understanding of the quantum-classical interface, and it can open new avenues for materials science or lithography at the nanoscale. Here we discuss the need for and recent progress in realizing a light source that can fulfill the requirements for photodepletion gratings for cluster matter-waves: A standing deep ultraviolet (DUV) light wave shall ionize metallic or dielectric nanoparticles in its antinodes by absorption of a single photon and thus form a measurement-induced diffraction grating. Ionization can be achieved if the photon energy exceeds the cluster ionization energy, which depends on the material, size and charge state of the particle. We target a wavelength below 230 nm and a photon energy of 5.4-5.5 eV, which will be sufficient to ionize clusters of vastly different density, such as sodium or gold and even insulating nanoparticles such as silicon. Starting from a TiSa laser beam at 900 - 920 nm (ca. 6 W) we first generate blue light with a power of $>$ 2.5 W behind an external cavity using an LBO crystal and a circular laser beam profile. This light is further doubled to $<$ 230 nm light in a second cavity with elliptical mode profile and using a BBO crystal. We demonstrate the usefulness of this light source in absorption tests on cluster beams.

QI 44.3 Fri 15:00 AP-HS

**Ultra-small Nb-based plasmonic superconducting photodetectors arrays** — •Philipp Karl[1], Sandra Mennle[1], Monika Ubl[1], Ksenia Weber[1], Pavel Ruchka[1], Mario Hentschel[1], Philipp Flad[1], Detlef Born[2], Heidemarie Schmidt[2], and Harald Giessen[1] — [1]4th Physics Institute, Research Center SCoPE, and IQST, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany — [2]Leibniz Institute of Photonic Technology, Albert-Einstein-Str. 9, 07745 Jena, Germany

Applications based on quantum technologies, such as quantum computing and quantum cryptography, require precise and highly efficient photodetection. We present a superconducting plasmonic perfect absorber detector.

The absorption of our plasmonic structures can be increased by utilizing the plasmonic perfect absorber principle, to achieve up to almost 100% absorption over a wide spectral range.

In addition, our concept is compatible with meander patterns to create scalable pixelated detector arrays. We demonstrate up to 64x64 pixel designs whose spectral range can be tuned from 1 $\mu$m up to 11 $\mu$m.

QI 44.4 Fri 15:15 AP-HS

**Micro-Integrated ECDL-MOPA Laser Modules for Quantum Technology Applications** — •Janpeter Hirsch, Martin Gärtner, Stephanie Gerken, Nora Goossen-Schmidt, Simon Kubitza, Norbert Müller, Max Schiemangk, Dian Zou, and Andreas Wicht — Ferdinand-Braun-Institut (FBH), Berlin, Germany

We present our next generation of micro-integrated ECDL-MOPA laser modules, each operating at a specific wavelength of 689, 767, 780, 794, and 922 nm, with adaptability to other wavelengths. The 767 nm module exemplifies their performance, delivering over 350 mW of fiber-coupled output power, a FWHM linewidth below 200 kHz at 1 ms timescales, and an extended mode-hop-free tuning range exceeding 100 GHz [1].

These modules are further designed with enhanced robustness to facilitate operation on mobile platforms and in space environments [2]. We will present results of preliminary mechanical stress testing, including shock tests at accelerations beyond 1000 $g$, to demonstrate their resilience and reliability under extreme conditions.

We acknowledge funding from Federal Ministry of Education and Research within the funding program "Quantum technologies - from basic research to market" under grant number 13N15724 and from DLR Space Administration / Federal Ministry for Economic Affairs and Climate Action under grant numbers 50WM2152, 50WM2176, 50WM2164, 50WM21694.

[1] J. Hirsch et al., in Proc. of SPIE Vol. 12912, 129120B (2024)
[2] D. Zou et al., in CLEO 2023, JTh2A.70 (2023)

QI 44.5 Fri 15:30 AP-HS

**Superconducting nanowire detection of neutral atoms & molecules via their internal and kinetic energy in the eV range, Adv. Phys. Res. DOI: 10.1002/apxr.202400133** — Marcel Strauss[1], Ronan Gourges[3], Martin F. X. Mauser[1], •Linus Kulman[1], Mario Castaneda[3], Andreas Fognini[3], Armin Shayeghi[2], Philipp Geyer[1], and Markus Arndt[1] — [1]University of Vienna, Faculty of Physics & VDSP & VCQ, Boltzmanngasse 5, A-1090 Vienna — [2]University of Vienna, Faculty of Physics & VCQ, Boltzmanngasse 5, A-1090 Vienna and Institute for Quantum Optics and Quantum Information (IQOQI) Vienna, Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 — [3]Single Quantum, Rotterdamseweg 394, 2629 HH, Delft, The Netherlands

Superconducting nanowires have found many applications in photonics as single photon detectors. Here we explore their potential as quantum sensors for neutral matter at low energy. We find that they exhibit outstanding sensitivity both with regard to the detection of internal atomic excitations as well as to the impact of neutral molecules, here demonstrated for metastable atoms as well as supersonic beams of perfluorodecalin. For metastable atoms, the quantum yield of SNWDs compares well with that of secondary electron multipliers and they outperform secondary electron multipliers by orders of magnitude in the detection of neutral molecules at impact energies as low as 2 eV.

QI 44.6 Fri 15:45 AP-HS

**A narrowband, decorrelated photon pair source based on a Ti:LiNbO$_3$ waveguide cavity** — •Jasmin Sommer, Michelle Kirsch, Kai Hong Luo, Christof Eigner, Harald Herrmann, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn, Germany

Many applications in quantum information processing require narrowband and spectrally pure photon pairs at telecom wavelength. We developed a source for such photon pairs exploiting cavity-enhanced parametric down conversion (PDC) in a periodically poled LiNbO$_3$ waveguide. With coated end-faces of the waveguide, a cavity is formed. The clustering due to different free spectral ranges for TE- and TM-modes leads to spectrally narrowband photon pair generation of the type II phase-matched PDC-process. To obtain decorrelated pairs, it is furthermore necessary to pump the PDC source with tailored pulses of around 775 nm wavelength with an adaptable pulse width in the nanosecond range. We designed a suitable pump source using an electro-optic modulator for pulse carving, fiber amplifiers to boost the signal and a second harmonic stage for conversion to the pump wavelength. Details on the design of the pump source as well as initial results obtained with the photon pair source will be presented.

QI 44.7 Fri 16:00 AP-HS

**Investigation of AM-PM conversion noise in nonlinear extensions of a frequency comb** — •Angelina Jaros[1], Mattias Misera[1], Thomas Puppe[2], Uwe Sterr[1], and Erik Benkler[1] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig — [2]TOPTICA Photonics AG, Lochhamer Schlag 19, 82166 Gräfelfing

An application of optical frequency combs is the transfer of frequency stability from an ultra-stable laser to the interrogation laser of an optical atomic clock. The stability transfer is limited by noise added onto the frequency comb. Its source could be the conversion of amplitude modulation (AM) of the seed comb light to phase modulation (PM) noise during the nonlinear processes employed for spectral broadening of the comb spectrum to cover the desired target wavelengths.
We investigate this AM-PM conversion in an Er:fiber fs-laser with two identical nonlinear extension branches. Single-frequency cw lasers at the fundamental and target wavelengths are employed for the generation of RF beats containing the PM. A modulator is employed to introduce AM in one branch before its nonlinear conversion stage, and the differential PM between the two wavelengths is measured after the nonlinear conversion to suppress phase noise due to path-length variations. By comparing to the second, unmodulated branch seeded by the same fundamental comb, phase noise in the seed comb and frequency noise of the cw lasers are suppressed.
The results may lead to further reduction of phase noise added by the nonlinear conversion steps in optical frequency combs.

## QI 45: Quantum Technologies (Solid State Systems) (joint session Q/QI)

Time: Friday 14:30–16:30 Location: HS I

QI 45.1 Fri 14:30 HS I

**Low Temperature Spectroscopy of hBN Quantum Emitters** — •Mouli Hazra[1], Manuel Rieger[2], Anand Kumar[1], Mohammad Nasimuzzaman Mishuk[1], Tjorben Matthes[1], Viviana Villafane[2,3], Jonathan J. Finely[2], and Tobias Vogl[1] — [1]Department of Computer Engineering, TUM School of Computation Information and Technology, Technical University of Munich, 80333 Munich, Germany — [2]Walter Schottky institute, School of Natural Sciences and MQST, Technical University of Munich, 85748 Garching, Germany. — [3]Walter Schottky Institute, School of Computation, Information and Technology and MQST, Technical University of Munich, 85748 Garching, Germany

Hexagonal boron nitride (hBN) hosts a large range of high quality single-photon emitters (SPEs) making it promising candidate for quantum technology applications. The practical integration of these emitters requires precise control of emission wavelengths, spatial localization, and directionality of those emitters. In this work, we have created localized, spectrally stable SPEs using electron beam irradiation without any pre- or post-treatment. To understand their chemical nature, we performed cryogenic experiments to minimize thermal broadening and gain insights into their optical and structural characteristics. We studied how excitation wavelength and temperature influence the emission. This work marks a significant step toward deterministic, high-quality SPEs in hBN, advancing integrated quantum photonic technologies.

QI 45.2 Fri 14:45 HS I

**Towards on-chip microwave to telecom transduction using erbium doped silicon** — •Daniele Lopriore and Andreas Reiserer — Technical University of Munich, TUM School of Natural Sciences and Munich Center for Quantum Science and Technology, 85748 Garching

The development of a device that converts microwave to optical photons at telecommunication wavelengths would be a key enabler for communication between remote quantum computers and would pave the way for the entanglement of distant superconducting qubits. We investigate ensembles of erbium dopants that exhibit coherent microwave [1] and optical transitions [2]. They can be used as a nonlinear medium mediating an efficient Raman conversion process [3]. High efficiencies require enhancing both the microwave and the telecom transitions with high quality factor resonators. We will present our progress towards low-loss manufacturing and measurements of the spin properties in erbium-doped silicon waveguides, and give an outlook towards the transduction efficiencies achievable with our approach. [1] A. Gritsch, et al. arXiv:2405.05351 (2024). [2] A. Gritsch, et al. Phys.Rev.X 12, 041009 (2022). [3] C. O'Brien, et al. Phys.Rev.Lett. 113, 063603 (2014).

QI 45.3 Fri 15:00 HS I

**Hybrid Nanophotonic Spin-Photon Interface of $Si_3N_4$ Photonics and Silicon Vacancy Centers in Nanodiamonds** — •Lukas Antoniuk[1], Niklas Lettner[1,2], Anna P. Ovvyan[3,5], Daniel Wendland[3], Viatcheslav N. Agafonov[4], Wolfram H.P. Pernice[3,5], and Alexander Kubanek[1,2] — [1]Institute for Quantum Optics, Ulm University, Germany — [2]Center for Integrated Quantum Science and Technology (IQst), Ulm University, Germany — [3]Institute of Physics and Center for Nanotechnology, University of Münster, Germany — [4]Universite F. Rabelais, 37200 Tours, France — [5]Heidelberg University, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany

Color centers in diamond have shown promising internal properties to be harnessed for quantum networks, secure quantum communication and distributed quantum computing. These applications require exchanging quantum information between stationary qubits and flying qubits, thus an efficient interface between them is needed. We base such an interface on negatively charged silicon vacancy centers ($SiV^-$) in nanodiamonds [1] and one-dimensional silicon nitride photonic crystal cavities. We present our progress on this hybrid platform which are access to the $SiV^-$ qubit space [2] and control of optical coupling via nanomanipulation [3].

[1] Klotz et al., arXiv:2409.12645 [2] Lettner et al., ACS Photonics, 11(2):696-702 [3] Antoniuk et al., Physical Review Applied, 21(5):054032

QI 45.4 Fri 15:15 HS I

**Deterministic preparation and retrieval of the dark state population in a quantum dot** — •René Schwarz[1], Florian Kappe[1], Yusuf Karli[1], Thomas Bracht[2], Saimon Covre da Silva[3], Armando Rastelli[3], Vikas Remesh[1], Doris Reiter[2], and Gregor Weihs[1] — [1]Institute of Experimental Physics, University of Innsbruck, Innsbruck, Austria — [2]Condensed Matter Theory, Department of Physics, TU Dortmund, Dortmund, Germany — [3]Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Linz, Austria

Semiconductor quantum dots are arguably the most promising platform for future quantum technologies. Due to the confinement of charge carriers, a variety of photon states can be generated, making them a highly adaptable quantum platform. While state-of-the-art optical excitation methods target the so-called bright excitons or biexcitons, quantum dots also accommodate optically dark excitons, which are not directly accessible via optical excitation methods. The dark exciton states exhibit significantly slower decay rates compared to their bright counterparts, making them potential candidates for application in quantum information protocols that require control of quantum coherence over long time scales [1]. In this work, we perform a full magneto-optical characterization (in-plane magnetic field) as well as a deterministic preparation and retrieval of the dark exciton state population in a single GaAs/AlGaAs quantum dot emitting at ~ 800 nm using a combination of a magnetic field and chirped laser pulses [2]. [1] Phys. Rev. Lett. 94, 030502 (2005). [2] arXiv, 2404.10708 (2024)

QI 45.5 Fri 15:30 HS I

**Spectroscopy and coherent manipulation of REI-based organic molecular systems for quantum information applications.** — •Vishnu Unni C.[1], Evgenij Vasilenko[1], Nicholas Jobbitt[1], Xiaoyu Yang[1], Barbora Brachnakova[1], Senthil Kuppusamy[1], Timo Neumann[2], Mario Ruben[1], Michael Seitz[2], and David Hunger[1] — [1]Karlsruher Institut für Technologie, Karlsruhe, Germany — [2]University of Tübingen, Tübingen, Germany

A europium-based molecular complex has recently shown [1] competing optical coherence time as that of europium-doped crystals. This opens the possibility of tailoring ligand fields to improve optical and spin properties to realize optically addressed spin qubits. We measure an improved photon echo coherence time of 3 $\mu$s at 4K, a narrow optical linewidth of 120 kHz, and a spin lifetime longer than an hour at 150 mK using spectral hole burning (SHB) in the complex reported in [1]. We measure spin inhomogeneous lines of the hyperfine transitions of the ground states. Simultaneously, we screen many organic complexes with improved branching ratios of up to 1.3% and characterize their hyperfine splittings of ground and excited states and optical coherence times. The self-assembly of molecular complexes into high-quality crystals is exploited to integrate them into fiber-based microcavities[2] which enhances emission rates by the Purcell effect. These results are important steps towards single ion experiments to realize optically addressable spin qubits.

[1] Serrano et al., Nature, 603, 241-246 (2022)
[2] Hunger et al., New J. Phys 12, 065038 (2010)

QI 45.6 Fri 15:45 HS I

**Hybrid integration of silicon carbide color centers into photonic integrated circuitry** — •Jan Riegelmeyer, Gerben Timmer, Keyuan Fang, Maurice van der Maas, Elena Volkova, Kees Koot, Ryoichi Ishihara, Tim Taminiau, and Carlos Errando Herranz — QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft 2628 CJ, Netherlands

Color centers in the solid-state are promising qubit candidates for quantum information processing, but scaling to practical systems requires significantly increasing the number of qubits within a single processing unit. A solution to this challenge is integrating color centers into photonic integrated circuits (PICs) for efficient and miniaturized photon collection, manipulation, and detection. However, traditional color center host materials like silicon carbide (SiC), lack well-established PIC technology, limiting scalability. Here, we address this limitation via the hybrid integration of SiC chiplets into silicon nitride (SiN) PICs using micro transfer printing. The chiplets are suspended structures fabricated from 4H-SiC-on-insulator containing photonic waveguides and cavities designed for the V2 color center. We optimized the geometry of chiplet and PIC to ensure reliable transfer printing and efficient optical transmission and demonstrate successful hybrid integration. While optimized for SiC color centers, our approach applies to other color center host materials.

QI 45.7 Fri 16:00 HS I

**Building a weakly coupled nuclear spin register using the V2 color center in Silicon Carbide** — •Pierre Kuna[1], Erik Hesselmeier-Hüttmann[1], Wolfgang Knolle[2], Florian Kaiser[3,4], Nguyen Tien Son[5], Misagh Ghezellou[5], Jawad Ul-Hassan[5], Vadim Vorobyov[1], and Jörg Wrachtrup[1,6] — [1]3rd Institute of Physics, IQST, and Research Center SCoPE, University of Stuttgart, Stuttgart, Germany — [2]Department of Sensoric Surfaces and Functional Interfaces, Leibniz-Institute of Surface Engineering (IOM), Leipzig, Germany — [3]Materials Research and Technology (MRT) Department, Luxembourg Institute of Science and Technology (LIST), 4422 Belvaux, Luxembourg — [4]University of Luxembourg, 41 rue du Brill, L-4422 Belvaux, Luxembourg — [5]Department of Physics, Chemistry and Biology, Linköping University, Linköping, Sweden — [6]Max Planck Institute for solid state physics, Stuttgart, Germany

The V2 color center in Silicon Carbide is a promissing candidate for scalable quantum networks due to its long coherence time, electrical compatibility, hosting two different and individually addressable nuclear spin baths[1].

In this work, we resolve the nuclear spin environment of a single color center using Electron DOuble Nuclear Spin Resonnance (ENDOR) spectroscopy showing over ten addressable nuclear spins and demonstrate their individual initialisation and control. We furthermore show first results on the entanglement of two weakly coupled nuclear spins.

[1] Erik Hesselmeier et al. Phys. Rev. Lett. 132, 180804-May, 2024

QI 45.8 Fri 16:15 HS I

**Purcell enhancement of single defects in silicon carbide coupled to a a fiber-based Fabry-Pérot microcavity** — •Jannis Hessenauer[1], Jonathan Körber[2], Jawad Ul-Hassan[3], Georgy Astakhov[4], Wolfgang Knolle[5], Jörg Wrachtrup[2], and David Hunger[1] — [1]Physikalisches Institut, Karlsruhe Institute of Technology (KIT), Germany — [2]3rd Institute of Physics, University of Stuttgart, Germany. — [3]Department of Physics, Chemistry and Biology, Linköping University, Sweden. — [4]Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, Germany. — [5]Leibniz-Institute of Surface Engineering (IOM), Germany.

The negatively charged silicon vacancy center (V2) in silicon carbide (SiC) has recently emerged as a promising realization of a solid-state spin-photon interface. Remarkably, it exhibits narrow optical linewidths, even when integrated into nanostructures, and at temperatures up to 20 K. However, only a small fraction of the light is emitted into the coherent zero-phonon line. An optical microcavity can be used to enhance this fraction via the Purcell effect. In this work, we integrate a three micron thin membrane of SiC containing color centers into a cryogenic fiber-based Fabry-Pérot-resonator. We study the cavity-membrane system and find excellent agreement with our model and minimal losses introduced by the membrane. We observe Purcell enhancement of the zero-phonon line, manifesting itself in a lifetime shortening and a strong zero-phonon line emission. Utilizing the spectral selectively of the cavity allows us to address individual defects in a spatially dense sample, which results in a high single photon purity.