# Quantum Information Division
# Fachverband Quanteninformation (QI)

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## Overview of Invited Talks and Sessions

(Lecture halls HFT-FT 101, HFT-FT 131, and HFT-TA 441; Poster A and B)

### Invited Talks

| | | | | |
|---|---|---|---|---|
| QI 1.1 | Mon | 9:30–10:00 | HFT-FT 101 | **Quantum causal structure and quantum memory** — •Fabio Costa |
| QI 2.1 | Mon | 9:30–10:00 | HFT-FT 131 | **Spin circuit-QED in the time-domain** — •Jurgen Dijkema, Xiao Xue, Patrick Harvey-Collard, Maximilian Rimbach-Russ, Sander L. de Snoo, Guoji Zheng, Amir Sammak, Giordano Scappucci, Lieven M.K. Vandersypen |
| QI 2.4 | Mon | 10:30–11:00 | HFT-FT 131 | **Gate defined electron and hole quantum dots in bilayer graphene** — •Luca Banszerus |
| QI 5.1 | Mon | 15:00–15:30 | HFT-FT 101 | **Multi-copy activation of genuine multipartite entanglement in continuous-variable systems** — Klára Baksová, Olga Leskovjanová, Ladislav Mišta, •Elizabeth Agudelo, Nicolai Friis |
| QI 6.1 | Mon | 15:00–15:30 | HFT-FT 131 | **Heat engine and force sensing with trapped ions** — •Kilian Singer, Bo Deng, Moritz Göb, Max Masuhr, Daqing Wang |
| QI 8.1 | Mon | 16:30–17:00 | HFT-FT 131 | **Quantum Simulations in Integrated Waveguide Arrays** — •Jasmin D. A. Meinecke, Florian Huber, Benedikt Braumandl, Sholeh Razavian, Jan Dziewior, Robert Jonsson, Johannes Knörzer, Harald Weinfurter, Alexander Szameit |
| QI 9.1 | Tue | 9:30–10:00 | HFT-FT 101 | **Does provable absence of barren plateaus imply classical simulability? Or, why we might need to rethink variational quantum computing** — •Zoe Holmes |
| QI 10.1 | Tue | 9:30–10:00 | HFT-FT 131 | **Loophole-free Bell Inequality Violation with Superconducting Circuits** — •Andreas Wallraff |
| QI 10.2 | Tue | 10:00–10:30 | HFT-FT 131 | **Microwave quantum networks** — •Kirill G. Fedorov |
| QI 10.6 | Tue | 11:30–12:00 | HFT-FT 131 | **Quantum sensing of axionic dark matter with a phase resolved haloscope** — •Audrey Cottet |
| QI 10.7 | Tue | 12:00–12:30 | HFT-FT 131 | **Demonstration of Quantum Advantage in Microwave Quantum Radar** — Réouven Assouly, Rémy Dassonneville, Théau Péronnin, •Audrey Bienfait, Benjamin Huard |
| QI 15.1 | Wed | 9:30–10:00 | HFT-FT 101 | **Computationally Universal Phases of Quantum Matter** — •Robert Raussendorf, Cihan Okay, Dongsheng Wang, David Stephen, Hendrik P Nautrup |
| QI 22.1 | Thu | 9:30–10:00 | HFT-FT 101 | **Quantum computing for chemistry - recent results and an industry perspective** — •Christian Gogolin |
| QI 24.1 | Thu | 9:30–10:00 | HFT-TA 441 | **Verification of quantum measurements via self-testing** — •Laura Mančinska |
| QI 28.1 | Thu | 15:00–15:30 | HFT-FT 131 | **An atomic scale multi-qubit platform** — •Hong Thi Bui, Yu Wang, Yi Chen, Christoph Wolf, Yujeong Bae, Andreas J. Heinrich, Soo-hyon Phark |
| QI 32.1 | Fri | 9:30–10:00 | HFT-FT 131 | **Quantum levitodynamics: Harnessing quantum motion of levitated particles for fundamental and applied quantum research** — •Sungkun Hong |

## Invited Talks of the joint Symposium Entanglement in Quantum Information, Condensed Matter and Gravity (SYQI)

See SYQI for the full program of the symposium.

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| SYQI 1.1 | Wed | 15:00–15:30 | H 0105 | **The Quantum Internet: Concepts, Challenges and Progress** — •Ronald Hanson |
| SYQI 1.2 | Wed | 15:30–16:00 | H 0105 | **Strange metals - A platform to study entanglement in condensed matter?** — •Silke Paschen |
| SYQI 1.3 | Wed | 16:00–16:30 | H 0105 | **Quantum black holes may not have interiors** — •Vijay Balasubramanian |
| SYQI 1.4 | Wed | 16:30–17:00 | H 0105 | **Gauge Symmetry-Resolved Entanglement in Lattice Gauge Theories: A Tensor Network Approach** — Noa Feldman, Johannes Knaute, Erez Zohar, •Moshe Goldstein |
| SYQI 1.5 | Wed | 17:00–17:30 | H 0105 | **Parameter estimation of gravitational waves with a quantum metropolis algorithm** — •Miguel Angel Martin - Delgado |

## Invited Talks of the joint Symposium Quantum Communication: Promises or Reality? (SYQC)

See SYQC for the full program of the symposium.

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| SYQC 1.1 | Fri | 9:30–10:00 | H 0105 | **Efficient Quantum Dot Micropillars for Quantum Networks** — David Dlaka, Petros Androvitsaneas, Andrew Young, Qirui Ma, Edmund Harbord, •Ruth Oulton |
| SYQC 1.2 | Fri | 10:00–10:30 | H 0105 | **Superconducting Single Photon Detectors - Limited only by the laws of physics** — •Andreas Fognini |
| SYQC 1.3 | Fri | 10:45–11:15 | H 0105 | **Laser triggering of quantum light sources using engineered optical pulses** — •Kimberley Hall |
| SYQC 1.4 | Fri | 11:15–11:45 | H 0105 | **Quantum Networks and Technologies** — •Rob Thew |

## Sessions

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| QI 1.1–1.12 | Mon | 9:30–13:00 | HFT-FT 101 | **Quantum Foundations** |
| QI 2.1–2.10 | Mon | 9:30–12:45 | HFT-FT 131 | **Semiconductor Qubits (joint session QI/HL)** |
| QI 3.1–3.14 | Mon | 9:30–13:15 | HFT-TA 441 | **Quantum Communication** |
| QI 4.1–4.10 | Mon | 15:00–18:00 | EW 203 | **Materials and Devices for Quantum Technology I (joint session HL/QI)** |
| QI 5.1–5.10 | Mon | 15:00–18:00 | HFT-FT 101 | **Entanglement Theory** |
| QI 6.1–6.4 | Mon | 15:00–16:15 | HFT-FT 131 | **Trapped Ion and Atom Qubits** |
| QI 7.1–7.11 | Mon | 15:00–18:00 | HFT-TA 441 | **Quantum Error Correction** |
| QI 8.1–8.7 | Mon | 16:30–18:30 | HFT-FT 131 | **Photons and Photonic Quantum Processors** |
| QI 9.1–9.13 | Tue | 9:30–13:15 | HFT-FT 101 | **Quantum Machine Learning and Classical Simulability** |
| QI 10.1–10.11 | Tue | 9:30–13:30 | HFT-FT 131 | **Focus Session: Exploring Quantum Entanglement with Superconducting Qubits and Resonators (joint session QI/TT)** |
| QI 11.1–11.8 | Tue | 9:30–11:45 | HFT-TA 441 | **Quantum Thermodynamics** |
| QI 12.1–12.23 | Tue | 11:00–14:30 | Poster B | **Poster I** |
| QI 13.1–13.15 | Tue | 11:00–13:00 | Poster B | **Poster MP (joint session MP/QI)** |
| QI 14.1–14.5 | Tue | 11:45–13:00 | H 3007 | **Focus Session: Nanomechanical Systems for Classical and Quantum Sensing I (joint session TT/DY/HL/QI)** |
| QI 15.1–15.12 | Wed | 9:30–13:00 | HFT-FT 101 | **Quantum Computing Theory** |
| QI 16.1–16.14 | Wed | 9:30–13:15 | HFT-FT 131 | **Superconducting Qubits (joint session QI/TT)** |
| QI 17.1–17.7 | Wed | 9:30–11:15 | HFT-TA 441 | **Quantum Information: Concept and Methods I** |
| QI 18.1–18.39 | Wed | 11:00–14:30 | Poster A | **Poster II** |
| QI 19.1–19.13 | Wed | 15:00–18:15 | H 0104 | **Superconducting Electronics: Qubits I (joint session TT/QI)** |
| QI 20.1–20.10 | Wed | 15:00–17:45 | EW 202 | **Focus Session: Nanomechanical Systems for Classical and Quantum Sensing II (joint session HL/DY/TT/QI)** |
| QI 21.1–21.8 | Thu | 9:30–13:00 | EW 202 | **Focus Session: Nanomechanical Systems for Classical and Quantum Sensing III (joint session HL/DY/TT/QI)** |
| QI 22.1–22.13 | Thu | 9:30–13:15 | HFT-FT 101 | **Quantum Simulation I** |

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| QI 23.1–23.13 | Thu | 9:30–13:00 | HFT-FT 131 | **Quantum Control** |
| QI 24.1–24.14 | Thu | 9:30–13:30 | HFT-TA 441 | **Verification and Benchmarking of Quantum Systems** |
| QI 25.1–25.9 | Thu | 14:00–16:45 | EW 203 | **Materials and Devices for Quantum Technology II (joint session HL/QI)** |
| QI 26.1–26.5 | Thu | 15:00–16:15 | H 2053 | **Superconducting Electronics: Qubits II (joint session TT/QI)** |
| QI 27.1–27.10 | Thu | 15:00–17:45 | HFT-FT 101 | **Quantum Simulation II** |
| QI 28.1–28.10 | Thu | 15:00–18:00 | HFT-FT 131 | **Surface Atom and Color Center Spin Qubits** |
| QI 29.1–29.10 | Thu | 15:00–17:45 | HFT-TA 441 | **Quantum Information: Concept and Methods II** |
| QI 30 | Thu | 18:00–19:00 | HFT-TA 441 | **Members' Assembly** |
| QI 31.1–31.11 | Fri | 9:30–12:30 | HFT-FT 101 | **Decoherence and Open Quantum Systems** |
| QI 32.1–32.14 | Fri | 9:30–13:30 | HFT-FT 131 | **Quantum Sensing and Metrology** |
| QI 33.1–33.9 | Fri | 9:30–12:00 | HFT-TA 441 | **Quantum Materials and Many-Body Systems** |

## Members' Assembly of the Quantum Information Division

Thursday 18:00–19:00 HFT-TA 441
An invitation including the agenda will be sent by email.

# QI 1: Quantum Foundations

Time: Monday 9:30–13:00 Location: HFT-FT 101

**Invited Talk** QI 1.1 Mon 9:30 HFT-FT 101

**Quantum causal structure and quantum memory** — •Fabio Costa — Nordita, Stockholm University and KTH Royal Institute of Technology, Stockholm, Sweden

In recent years, a new formalism has been proposed to describe quantum processes where causal relations between events can be unknown or indefinite. The same formalism has been shown to be useful to describe multi-time memory in causally ordered, non-Markovian open quantum systems. Here I will review the approach and some of the most recent developments, with a focus on the definition and characterisation of non-classical memory and its relation to entanglement characterisation.

QI 1.2 Mon 10:00 HFT-FT 101

**Causal modeling quantum non-Markovianity** — •Leonardo Silva Vieira Santos and Otfried Gühne — University of Siegen

The interaction of every quantum system with its surrounding environment introduces deviations in its temporal evolution from the reversible trajectory predicted by the Schrödinger equation. When one can access the system on a timescale comparable to the characteristic decay time of correlations and excitations in the environment, memory effects (i.e., non-Markovianity) become significant. The question arises: Is there anything inherently non-classical about the evolution of non-Markovian open quantum systems? This question is somewhat non-trivial, as defining what is truly "non-classical" involves subtle considerations. In the realm of quantum correlations, Bell's theorem stands out as arguably the strongest notion of non-classicality ever discovered and experimentally tested. In this work, we take steps toward establishing Bell-type theorems for the multi-time statistics of non-Markovian open quantum systems. We derive a scalable family of Bell-type inequalities designed to detect the non-classicality of quantum stochastic processes. Our findings demonstrate that the violation of these inequalities serves as a device-independent test for quantum memory – the environment's memory that cannot be classically simulated.

QI 1.3 Mon 10:15 HFT-FT 101

**Towards exact factorization of quantum dynamics via Lie algebras** — •David Edward Bruschi[1], André Xuereb[2], and Robert Zeier[3] — [1]Institue for Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich, Jülich, Germany — [2]Department of Physics, University of Malta, Malta — [3]Quantum Control (PGI-8), 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 lay the foundations for an approach to determine the dimensionality of a Hamiltonian Lie algebra by appropriately characterizing its generating terms. This requires us to develop a new tool to construct sequences of operators that determine the final dimension of the algebra itself. Our work is exact and fully general, therefore providing statements on the ultimate ability to exactly control the dynamics or simulate specific classes of physical systems. 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 1.4 Mon 10:30 HFT-FT 101

**State reachability in isolated systems with 2-body Hamiltonians** — •Konrad Szymanski — Universität Siegen, Siegen, Germany

In the most basic physical systems, the dynamics is governed by time-independent 2-body interactions. A natural question arises: is the entire set of states explored if an arbitrary classical initial state and interaction pattern can be chosen? Different definitions are possible: for qubits, the pure product states are evolved with Hamiltonians composed by combinations of length-2 and 1 Pauli strings.

Only trivial conserved quantities exist in the general case, which limits the available approaches to investigate this reachability problem. Nevertheless, we show that unreachable states exist for a sufficiently complex model system. However, the problem for the most general models remains unsolved, and we present related open questions.

QI 1.5 Mon 10:45 HFT-FT 101

**New Partial Trace Inequalities and Distillability of Werner States** — •Pablo Costa Rico — TUM, Mϋchen, Deutschland

We present a new characterization for the $n$-distillability of Werner states and classify some of them according to their 2-distillability. This result brings out new inequalities with respect to partial traces with bound on the dimension of the system and also the rank of the matrix. For an $n$-partite system we prove that there are $2^n - 1$ partial trace inequalities using the dimension of the systems, and for the bounds with respect to the rank, for the case $n = 2$ we prove

$$\|tr_1 C\|_2^2 + \|tr_2 C\|_2^2 \le r\|C\|_2^2 + \frac{1}{r}|trC|^2$$

for matrices, which can be written as a rank 1 plus a normal matrix, and

$$\big|\|tr_1 C\|_2^2 - \|tr_2 C\|_2^2\big| \le r\|C\|_2^2 - \frac{1}{r}|trC|^2$$

for any matrix. Here we also present the proofs for many other inequalities in bipartite systems, and for tripartite systems we also obtain some results for positive matrices. Finally, we show numerical results indicating that this results could also be generalized to more families of inequalities depending on more parameters, such as the norm or exponents.

**15 min. break**

QI 1.6 Mon 11:15 HFT-FT 101

**Contextuality, Coherences, and Quantum Cheshire Cats** — •Jonte Hance[1,2], Ming Ji[1], and Holger Hofmann[1] — [1]Department of Quantum Matter, Graduate School of Advanced Science and Engineering, Hiroshima University, Kagamiyama 1-3-1, Higashi Hiroshima 739-8530, Japan — [2]Quantum Engineering Technology Laboratories, Department of Electrical and Electronic Engineering, University of Bristol, Woodland Road, Bristol, BS8 1US, UK

We analyse the quantum Cheshire cat using contextuality theory, to see if this can tell us anything about how best to interpret this paradox. We show that this scenario can be analysed using the relation between three different measurements, which seem to result in a logical contradiction. We discuss how this contextual behaviour links to weak values, and coherences between prohibited states. Rather than showing a property of the particle is disembodied, the quantum Cheshire cat instead demonstrates the effects of these coherences, which are typically found in pre- and postselected systems. See https://iopscience.iop.org/article/10.1088/1367-2630/ad0bd4 for more details.

QI 1.7 Mon 11:30 HFT-FT 101

**Quantum incompatibility of multipartite measurements** — •Lucas Tendick — Inria Paris-Saclay, Bâtiment Alan Turing, FRA 91120 Palaiseau

The incompatibility of quantum measurements, i.e., the effect that certain observable quantities cannot be measured simultaneously has traditionally and extensively been studied for measurements on a single system. Here, we introduce the notion of incompatibility for distributed measurements acting on multiple systems. We define and study the basic notions of incompatibility in this setting and show how to characterize and witness different locality constraints. Furthermore, we draw connections between the incompatibility of distributed measurements and multipartite quantum correlations. Finally, we discuss more generally the resources for potential applications that are provided by these type of incompatible measurements.

QI 1.8 Mon 11:45 HFT-FT 101

**On the 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[1,2,3,5] — [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 — [5]Univ. Gdansk, Inst. of Physics, Sobieskiego 18, PL-80-216 Gdansk-Wrzeszcz, Poland

The weak value of an operator, as put forth by Aharonov, Albert, and Vaidman, is a property of a pre- and post-selected quantum system and, in general, a complex entity. It is observed by weakly coupling a system of interest to a pointer system and manifests as a change in the state of the pointer. Contrary to the eigenvalue of an operator, the weak value can exceed its eigenspectrum resulting in 'weak value amplification' [1,2]. By pre- and post-selecting on the path *and* polarisation degrees of freedom of an optical Mach-Zehnder interferometer, the weak values of the path-projection and polarisation operators as well as that of their product are observed, with the transverse mode of the beam being the pointer. This effect is state sensitive, as introducing correlations between path and polarisation in the pre- or post-selected states prevents the observation of the product of the weak values [3,4].

[1] Y. Aharonov et al, PRL. **60**, 1351 (1988) [2] L. Vaidman et al, Phys. Rev. A **96**, 032114 (2017) [3] X. Xu et al, Opt. Lett **45**, 1715 (2020) [4] X. Xu et al, PRL. **122**, 100405 (2019)

QI 1.9 Mon 12:00 HFT-FT 101

**Attempting to Simplify the Search for SIC-POVMs** — •Ghislaine Coulter-de Wit[1,2], David Llamas[1], Matt Weiss[1], and Christopher Fuchs[1] — [1]University of Massachusettes Boston, Boston, USA — [2]Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Deutschland

Symmetric informationally complete quantum measurements or SIC-POVMs are interesting from a number of perspectives. For example in QBism, SIC-POVMs give a way of representing the Born Rule such that the form minimizes the distinction between it and the classical law of total probability [DeBrota, Fuchs, and Stacey, Phys. Rev. Res. 2, 013074 (2020)]. However, it is unclear whether they exist in all dimensions. In the search for SIC-POVMs, we are most interested in the group covariant case, where the problem boils down to finding a single fiducial vector for generating the whole structure. For finite dimensions $d$, this amounts to finding a solution to $d^2$ simultaneous fourth-order polynomial equations generated by the discrete Weyl-Heisenberg group. However, it has been conjectured that it is already enough to satisfy only $3d/2$ of the defining equations to find a solution [Appleby, Dang, and Fuchs, Entropy 16, 1484 (2014)]. Using techniques of gradient descent we find strong correlations in the solutions between the conjecture and full $d^2$ equations. These numerical results imply that the conjecture is true, dropping the complexity of numerically searching for SICs from a quadratic to a linear number of equations in $d$.

QI 1.10 Mon 12:15 HFT-FT 101

**Classical phase-space model for gravity-mediated entanglement** — Marta Marchese, •Martin Plávala, Matthias Kleinmann, and Stefan Nimmrichter — Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Strasse 3, 57068 Siegen, Germany

Whether gravity is fundamentally quantum or not is still a debated question. On one side, there are several well-established quantum-gravity theories, on the other, there are semi-classical descriptions that treat the gravity field as a classical measurement-feedback channel. The lack of experimental evidence leaves the problem still unresolved, but experiments with massive interference particles have been proposed: witnessing entanglement generated by the gravitational interaction between two masses in a matter-wave interferometer is claimed to probe the quantum nature of the gravitational field. Here, we argue that such a scheme is not sufficient to rule out all possible classical descriptions of gravity. Indeed, one can achieve the same entanglement built up through a classical evolution of the Wigner function of the two gravitationally interacting masses, making use of a second-order approximation of the Newtonian potential. This suggests that alternative experimental schemes be developed to test the quantum nature of gravity.

QI 1.11 Mon 12:30 HFT-FT 101

**Measurement in the complex SYK thermofield double and its holographic dual** — Stefan Forste[1], Saurabh Natu[1], Yannic Kruse[1], and •Raphael Brinster[1,2] — [1]Bethe Center for Theoretical Physics and Physikalisches Institut der Universität Bonn,Germany — [2]Faculty of Mathematics and Natural Sciences, Heinrich Heine University Düsseldorf, Germany

In this talk, I will briefly introduce the concepts of holography and the AdS/CFT correspondence. Then, I will explain how to calculate the entropy of the thermofield double State (TFD) in the complex SYK model (two non-interacting copies of systems describing $N$ Dirac fermions with an all-to-all coupling) after a $U(1)$-charge measurement was applied and relate it to the von-Neumann entropy of some space-time region in a black hole background. By introducing a specific decoding operator, a quantum teleportation protocol can be realised, sending information from one side of the TFD to the other. By the correspondence, this is related to a traversable wormhole. In contrast to similar work that has been done in the Majorana SYK model, the results are measurement-dependent, i.e. they depend on the total charge of the system.

QI 1.12 Mon 12:45 HFT-FT 101

**Critical models and discrete holography** — •Dimitris Saraidaris and Alexander Jahn — Freie Universität Berlin, Germany

Tensor networks on hyperbolic lattices have been recently studied as prominent models of discrete holography. In particular, by filling the bulk of a hyperbolic lattice with matchgate tensors, following the inflation rules imposed by its geometry, the disordered states appearing on the boundary are related to critical models. We use the Multi-scale Quasicrystal Ansatz to translate these boundary states into coupling constants for the disordered XY and XXZ Heisenberg model with periodic boundary conditions. Firstly, we observe that there is a range of disorder strengths, that show entanglement entropy scaling similar to the uniform critical model. Generalizing to the non-Gaussian model, we observe that the criticality of the disordered boundary states does not depend on the choice of the tensors in the bulk, but on the geometry of the tiling. Finally, we study the same models with open boundary conditions. Here, we can find disordered models whose entanglement entropy exceeds the excepted value for the uniform critical model, with a correction term that grows linearly with subsystem size.

# QI 2: Semiconductor Qubits (joint session QI/HL)

Time: Monday 9:30–12:45 Location: HFT-FT 131

**Invited Talk** QI 2.1 Mon 9:30 HFT-FT 131

**Spin circuit-QED in the time-domain** — •Jurgen Dijkema[1], Xiao Xue[1], Patrick Harvey-Collard[1], Maximilian Rimbach-Russ[1], Sander L. de Snoo[1], Guoji Zheng[1], Amir Sammak[2], Giordano Scappucci[1], and Lieven M.K. Vandersypen[1] — [1]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands — [2]QuTech and Netherlands Organization for Applied Scientific Research, Delft University of Technology, Delft, The Netherlands

Semiconductor spin qubits hold promise for quantum computation due to their long coherence times and potential for scaling. So far, interactions between spin qubits are limited to spins a few hundreds of nanometers apart. A distributed architecture with local registers and long-range couplers will be needed to scale up to millions of qubits. Circuit quantum electrodynamics can provide a pathway to realize interactions between distant spins. Here, we report long-range spin-spin interactions using an on-chip superconducting resonator in two regimes. First with two spins detuned from the resonator frequency, allowing the demonstration of two-qubit iSWAP logic via virtual photons. Next, we tune the two spin frequencies to match the resonator frequency and demonstrate spin state-transfer using real resonator photons.

QI 2.2 Mon 10:00 HFT-FT 131

**Optimal electron trajectories improving the spin-shuttling fidelity beyond the adiabatic limit** — •Alessandro David[1], Lars R. Schreiber[2], Hendrik Bluhm[2], Tommaso Calarco[1], and Felix Motzoi[1] — [1]Institute of Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, Jülich, Germany — [2]JARA-FIT Institute for Quantum Information, Forschungszentrum Jülich GmbH and RWTH Aachen University, Aachen, Germany

Spin-qubit quantum computers are currently limited by a connectivity problem. A promising solution is the use of conveyor-mode shuttling architectures [1] where the qubit encoded in the spin of an electron is reliably transported by a moving quantum dot [2]. During this process the spin experiences decoherence from uncontrollable features of the device heterostructure such as interface roughness, valley degree of freedom and spin-orbit coupling [3]. In this work we compute the energy splitting of the valley with the help of an alloy-disorder model [4] and we focus on the dephasing interaction between spin and valley. Using quantum optimal control techniques we find electron trajectories that improve the spin-shuttling fidelity by reducing the valley excitation even at higher speeds than the adiabatic limit. The experimental adequacy of our results is inspected through statistical sampling of different devices and bandwidth limitation of the electron trajectories.

[1] Künne and Willmes et al., arXiv:2306.16348 (2023) [2] Struck et al., arXiv:2307.04897 (2023) [3] Langrock and Krzywda et al., PRX Quantum 4, 020305 (2023) [4] Wuetz, et al., Nat. Comm. 13, 7730 (2022)

QI 2.3 Mon 10:15 HFT-FT 131

**Counteracting decoherence induced by spin-valley coupling in single-qubit manipulation zones via quantum optimal control** — •Akshay Menon Pazhedath[1], Alessandro David[1], Lars R. Schreiber[2], Tommaso Calarco[1], Matthias M. Müller[1], Hendrik Bluhm[2], and Felix Motzoi[1] — [1]Peter Grünberg Institute-Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany — [2]JARA-FIT Institute for Quantum Information, Forschungszentrum Jülich GmbH and RWTH Aachen University, Aachen, Germany

Quantum bus architectures based on electron spin shuttling in a Si/SiGe heterostructure are promising candidates for scalable quantum computing. Electrically controlled single qubit gates are achieved with a carefully placed micro-magnet that provides a synthetic spin-orbit coupling in the designated manipulation zones [Künne et al. arXiv:2306.16348 (2023)]. The presence of spin-valley mediated decoherence hotspots at the vicinity of the micro-magnet can cause spin decoherence, limiting the capability to achieve fault tolerant gates. Using quantum optimal control techniques, we obtain new electron trajectories leading to significant improvements to the gate fidelity. The influence of valley splitting and the distance from decoherence hotspots are also investigated, based on statistical sampling of prototypical device configurations. For increasing values of spin-valley coupling, 99.12% of the samples converged below the required fault tolerant gate fidelity threshold, where all of the under- performing samples are due to a high value of spin-valley coupling.

**Invited Talk** QI 2.4 Mon 10:30 HFT-FT 131

**Gate defined electron and hole quantum dots in bilayer graphene** — •Luca Banszerus — Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark — JARA-FIT and 2nd Institute of Physics A, RWTH Aachen University, Aachen, Germany

Bilayer graphene (BLG) quantum dots (QDs) have long been regarded as an attractive platform for hosting spin qubits since the low nuclear spin densities and weak spin-orbit interaction in BLG promise long spin coherence times. In addition to the spin, BLG exhibits a tunable valley degree of freedom, which is associated with a strong out-of-plane magnetic moment with opposite signs for the K- and K'-valley. This allows controlling the valley splitting in BLG and to use valley space as an additional qubit platform.

In contrast to conventional semiconductors, the band structure of BLG is (almost) perfectly electron/hole symmetric and exhibits an electrically tuneable band gap, which we use to form ambipolar electron/hole double QDs. We observe the creation of single electron-hole pairs with opposite quantum numbers and use the electron-hole symmetry to achieve a protected spin-valley blockade in electron-hole double quantum dots. The latter allows for spin-to-charge conversion and valley-to-charge conversion, which is essential for the operation of spin and valley qubits.

QI 2.5 Mon 11:00 HFT-FT 131

**Spin and valley relaxation in a single-electron bilayer graphene quantum dot** — •Lin Wang and Guido Burkard — Department of Physics, University of Konstanz, D-78457, Germany

Bernal-stacked bilayer graphene (BLG) has a tunable gap controlled by an out-of-plane electric field. This makes BLG a possible candidate to form quantum dots (QDs). Spin-based qubits in BLG QDs have received great attention due to the low spin-orbit interaction and low hyperfine coupling. Long spin relaxation times of a single-electron state in BLG QDs was recently reported [1,2]. In addition to spin, valley pseudospin is another degree of freedom in BLG. The two valleys experience opposite Berry curvatures and associated magnetic moments via an out-of-plane electric field. This provides a promising way towards controlling valleys and further establish valley-based electronics and qubits. The valley relaxation time between triplets and singlets was reported to be remarkably long in BLG double QDs [3]. To assess the potential of spin/valley qubits, the spin/valley relaxation time is a crucial parameter since it directly limits the lifetime of encoded information. Here, we theoretically investigate the spin/valley relaxation in a single-electron BLG QD due to spin-orbit/intervalley coupling assisted by (i) 1/f charge noise and (ii) electron-phonon couplings arising from the deformation potential and the bond-length change. Detailed comparisons with the existing experiments on both spin and valley relaxation times are shown. [1]L. Banszerus et al., Nat. Commun. 13, 3637 (2022). [2]L. M. Gächter et al., PRX Quantum 3, 020343 (2022). [3]R. Garreis et al., arXiv:2304.00980.

**15 min. break**

QI 2.6 Mon 11:30 HFT-FT 131

**Classification and magic magnetic field directions for spin-orbit-coupled double quantum dots** — •Aritra Sen[1], Gyorgy Frank[1], Baksa Kolok[1], Jeroen Danon[2], and Andras Palyi[1] — [1]Budapest University of Technology and Economics, Budapest, Hungary — [2]Norwegian University of Science and Technology, Trondheim, Norway

Fundamental building blocks of spin-based quantum computing have been demonstrated in semiconductor double quantum dots with significant spin-orbit coupling. Here, we show that spin-orbit-coupled double quantum dots can be categorized in six classes, according to a partitioning of the multidimensional space of their $g$ tensors. The class determines physical characteristics of the double dot, i.e., features in transport, spectroscopy, and coherence measurements, as well as qubit control, shuttling, and readout experiments. In particular, we predict that the spin physics is highly simplified due to pseudospin conservation, whenever the external magnetic field is pointing to special directions ('magic directions'), where the number of special directions is determined by the class. We also analyze the existence and relevance of magic loops in the space of magnetic-field directions, corresponding to equal local Zeeman splittings. These results present an important step toward precise interpretation and efficient design of spin-based quantum computing experiments in materials with strong spin-orbit coupling.

QI 2.7 Mon 11:45 HFT-FT 131

**Dynamical sweetspots in driven germanium double quantum dot spin qubits** — •Yaser Hajati and Guido Burkard — Konstanz University, Konstanz, Germany

In recent years, significant strides have been made in advancing hole-spin qubits based on semiconductor quantum dots, particularly in germanium (Ge). Hole spins in Ge quantum dots can leverage the strong spin-orbit coupling compared to silicon, potentially enabling fast and reliable qubit operations. Our study focuses on exploring the use of a periodic drive field to engineer the properties of Ge quantum-dot based qubits amidst charge noise. Specifically, we investigated the Rabi frequency of a hole qubit experiencing detuning driving in a planar Ge double quantum dot, focusing on the single-hole flopping mode with spin-orbit interaction. Our findings indicate that the Rabi frequency linked to a hole within a planar double quantum dot, driven on resonance, exhibits an inverse correlation with detuning energy while demonstrating a positive correlation with driving frequency, Zeeman field strength, and spin-orbit coupling. Furthermore, through strategic modulation of the drive frequencies slightly off resonance, we effectively mitigated the impact of charge noise. This modulation significantly boosted the fidelity of quantum gates when manipulating the qubit within specific ranges of drive frequencies and detuning. Importantly, our study shows that fidelity improvements at dynamic sweet spots exceed those achievable by solely adjusting drive frequency and detuning. Discovering these spots holds potential for enhancing quantum gate reliability in Ge quantum dot-based computing.

QI 2.8 Mon 12:00 HFT-FT 131

**Floquet Quantum Processors** — •Giovanni Francesco Diotallevi and Monica Benito — Universität Augsburg, Augsburg, Germany

Quantum dot confined hole spin qubits posses a variety of properties that render them highly attractive candidates for the development of quantum computing platforms [1]. However, using these to construct functioning large quantum processors still faces major challenges. Among these, being able to simultaneously control distant qubits with minimal cross-talk between untargetted qubits remains a goal to be achieved in the field. In this direction recent studies proposed to mediate the coupling between two distant qubits by means of superconducting quantum resonators [2].

In this research we intend to explore techniques involving external periodic drives to better control the coupling of these hole spin qubits to the interaction-mediating resonators. In particular, we envision an ensemble of periodic fields used to control the individual coupling of a series of hole spin qubits to a single resonator. Using Floquet-based theory it is indeed possible to tune the spin-orbit interaction of these qubit systems [3], thus allowing us to selectively choose which qubits to couple in order to perform desired quantum gates.

References: [1] Y. Fang et Al., *Recent advances in hole-spin qubits,* Materials for Quantum Technology, vol. 3, no. 1, p. 012003, 2023. [2] J. Dijkema et Al., *Two-qubit logic between distant spins in silicon,* 2023. [3] O. V. Kibis et Al., *Floquet engineering of the luttinger hamiltonian,* Phys. Rev. B, vol. 102, p. 035301, Jul 2020.

QI 2.9 Mon 12:15 HFT-FT 131

**Quantum Gates with Oscillating Exchange Interaction** — •Daniel Nguyen, Irina Heinz, and Guido Burkard — Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

Two-qubit gates between spin qubits are often performed using a rectangular or an adiabatic exchange interaction pulse resulting in a CZ gate. An oscillating exchange pulse not only performs a CZ gate, but also enables the iSWAP gate, which offers more flexibility to perform quantum algorithms. We provide a detailed description for two-qubit gates using resonant and off-resonant exchange pulses, give conditions for performing the respective gates, and compare their performance to the state-of-the-art static counterpart. We find that for relatively low charge noise the gates still perform reliably and compare to the conventional CZ gate.

D. Q. L. Nguyen, I. Heinz, and G. Burkard, Quantum gates with oscillating exchange interaction (2023), arXiv:2303.18015 [quant-ph].

QI 2.10 Mon 12:30 HFT-FT 131

**Gate operations on Exchange-Only spin qubits with oscillating drive** — •Tobias Heinz, Stephen R. McMillan, and Guido Burkard — Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

A major obstacle on the path towards large-scale quantum computing lies in achieving high fidelities for gate operations. Spin qubits using exchange interaction alone have emerged as promising candidates [1] due to their resistance to certain types of decoherence [2]. Motivated by the proposed gate of Doherty and Wardrop [3], this work focuses on the application of an oscillating drive field to facilitate an entangling two qubit operation between two local Resonant-Exchange qubits. By driving the exchange interaction belonging to one qubit, we propose a CNOT gate for universal quantum computing, with gate times in the range of a hundred nanoseconds. We analyze the impact of the drive amplitude on gate fidelity and gate time, providing insights into the optimal parameter regimes. Through numerical simulations, we determine the impacts of leakage and off-resonant processes on the fidelity. For context, we compare our results to a static gate obtained through a dc pulse of the interqubit exchange coupling. Our proposal contributes to the understanding of the implementation of spin qubits and paves the way for the development of robust and scalable quantum computers. [1] G. Burkard et al. Rev. Mod. Phys. 95, 025003 (2023). [2] J. M. Taylor et al. Phys. Rev. Lett. 111, 050502 (2013). [3] A. C. Doherty et al. Phys. Rev. Lett. 111, 050503 (2013).

# QI 3: Quantum Communication

Time: Monday 9:30–13:15 Location: HFT-TA 441

QI 3.1 Mon 9:30 HFT-TA 441

**Quantum Frequency Conversion for Entanglement Distribution** — •Tommy Block[1,2], Yuya Maeda[3], Pooja Malik[1,2], Yiru Zhou[1,2], Florian Fertig[1,2], Chengfeng Xu[1,2], Tim van Leent[1,2], and Harald Weinfurter[1,2,4] — [1]Ludwig-Maximilians-Universität, Fakultät für Physik, Schellingstr. 4, 80799 München — [2]Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, 80799 München — [3]Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan — [4]Max-Planck-Institut für Quantenoptik, 85748 Garching

Entanglement distribution between distant quantum nodes is one of the most crucial tasks for a future quantum network. In our experiment we utilize optical fibers as quantum channels to distribute the entanglement between two Rubidium-87 atom-based quantum memories via entanglement swapping. Since the emission wavelength of our Rb atoms is 780 nm, the photons would suffer high attenuation losses in optical fibers, limiting the maximum achievable distance for entanglement distribution. Here we describe how to convert the 780 nm photons to 1514nm (telecom S-band) with a second generation quantum frequency converter (QFC) with higher stability and signal to noise ratio, while preserving the quantum information encoded in the polarization state of photon. This QFC device will enable distribution of entanglement over suburban distances.

QI 3.2 Mon 9:45 HFT-TA 441

**A highly compact and robust QKD sender unit for satellite applications** — •Moritz Birkhold[1,2], Michael Auer[1,2,3], Adomas Baliuka[1,2], Peter Freiwang[1,2], Lukas Knips[1,2,4], and Harald Weinfurter[1,2,4,5] — [1]Ludwig Maximilian University, Munich, Germany — [2]Munich Center for Quantum Science and Technology, Munich, Germany — [3]Universität der Bundeswehr, Neubiberg, Germany — [4]Max Planck Institute of Quantum Optics, Garching, Germany — [5]University of Gdańsk, Poland

Quantum key distribution (QKD) offers fundamental advantages over classical distribution of secret keys. If done correctly, any eavesdropping attack will be detected, allowing to exchange a perfectly private key between two parties. The BB84 protocol with decoy state analysis enabeling use of highly attenuated laser pulses as a photon source is very promising for bringing QKD out of laboratories into the real world. Furthermore, provided the device is robust and efficient with space and energy consumption, deploying QKD sender units on satellites and transmitting the keys in free space can accelerate the creation of a global QKD network.

In this talk, we show our advances in creating such a compact and low-power sender unit using vertical cavity surface emitting lasers, micro optics and waveguide chips. This unit is tested for possible side channels and, together with an equally compact and low-power processing and control board handling the full QKD protocol including error correction, privacy amplification and authentication, is about to fly on the QUBE-II satellite mission.

QI 3.3 Mon 10:00 HFT-TA 441

**Towards a Compact Quantum Key Distribution Receiver** — •Michael Steinberger[1,2], Moritz Birkhold[1,2], Michael Auer[1,2,3], Adomas Baliuka[1,2], Lukas Knips[1,2,4], and Harald Weinfurter[1,2,4,5] — [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 — [5]Institute of Theoretical Physics and Astrophysics, Faculty of Mathematics, Physics, and Informatics, University of Gdańsk, Gdańsk, Poland

Quantum Key Distribution (QKD) provides a method to exchange a key between two parties that is secure of any eavesdropping attempts. Since it relies on single to few photons as information carriers, technical realizations often include complex and big detection systems. This talk focusses on the development of a compact receiver for implementing polarization-based decoy-state BB84 QKD. We choose CMOS-based single photon detectors (SPADs) to enable a high degree of integration, due to their small size and on-chip evaluation of the detections. The Technical University of Vienna provides us with diverse SPADs, that enable various very compact optical systems with improved detection efficiencies. These concepts will enable a new range of versatile and mobile QKD receiver devices.

QI 3.4 Mon 10:15 HFT-TA 441

**QKD Post-Processing in Space** — •Adomas Baliuka[1,2], Michael Auer[1,2,3], Moritz Birkhold[1,2], Lukas Knips[1,2,4], and Harald Weinfurter[1,2,4,5] — [1]Ludwig-Maximilian-University, Munich, Germany — [2]Munich Center for Quantum Science and Technology, Munich, Germany — [3]Universität der Bundeswehr München, Neubiberg, Germany — [4]Max Planck Institute of Quantum Optics, Garching, Germany — [5]Institute of Theoretical Physics and Astrophysics, University of Gdańsk, 80-308 Gdańsk, Poland

Classical post-processing is an essential part of all quantum key distribution (QKD) protocols. For satellite-based QKD, additional challenges arise from the harsh conditions in earth's orbit, where classical communication throughput is scarce and available computational capabilities are limited by a tight power budget and the need for radiation-resistant components. At the same time, this high-loss QKD scenario leaves no room for compromises concerning, e.g., the efficiency of error correction, or the use of viable satellite overpasses for demanding computations and classical communication.

To meet these challenges, we minimize the amount of data transmitted for post-processing by dedicated compression methods. We further perform error correction using irregular quasi-cyclic (QC) low density parity check (LDPC) codes and state-of-the-art rate adaption techniques. Despite our large block sizes, this allows our QKD post-processing to stay within tight memory and time constraints without compromising on efficiency, and offloads demanding computations to the receiver on ground.

QI 3.5 Mon 10:30 HFT-TA 441

**Limits on the repeater rate in multipartite quantum routers with quantum memories** — •Julia Alina Kunzelmann, Nikolai Wyderka, Hermann Kampermann, and Dagmar Bruss — Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf

Quantum routers play an important role in quantum communication networks, enabling the transmission of quantum information over longer distances. To increase the repeater rate in multipartite networks, multiplexing between quantum memories can be used. In our work, we investigate the limitations of repeater rates in quantum networks with $N$ parties, each equipped with $m$ memories. Based on our generalized multiplexing scheme for $N$ parties we analyze the relation between the maximally achievable repeater rate and the number of parties and memories included in the network. We present both, numerical and analytical results.

QI 3.6 Mon 10:45 HFT-TA 441

**Quantum conference key agreement in networks with bipartite entanglement sources** — •Anton Trushechkin, Giacomo Carrara, Justus Neumann, Hermann Kampermann, and Dagmar Bruss — Heinrich Heine University Düsseldorf, Faculty of Mathematics and Natural Sciences, Institute for Theoretical Physics III, Universitätsstr. 1, Düsseldorf 40225

We analyze quantum conference key agreement (QCKA) in networks with arbitrary topology and focus on decentralized networks with bipartite entanglement sources (rather than sources of multipartite entangled states like GHZ-states or W-states). Various strategies of QCKA are discussed. In particular, we compare the performance of genuine QCKA with parallel bipartite quantum key distribution (QKD) and derive the secret key rates based on the properties of the network. Also we show that QCKA on multipartite 2-entangled states cannot exceed the rates achievable by parallel bipartite QKD protocols.

**15 min. break**

QI 3.7 Mon 11:15 HFT-TA 441

**Experimental anonymous quantum conferencing** — Jonathan W. Webb[1], Joseph Ho[1], •Federico Grasselli[2,3], Gláucia Murta[2], Alexander Pickston[1], Andres Ulibarrena[1], and Alessandro Fedrizzi[1] — [1]Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh, United Kingdom — [2]HHU Düsseldorf — [3]Institut de Physique Théorique, CEA Paris Saclay

Anonymous quantum conference key agreement (AQCKA) allows a group of users within a network to establish a shared cryptographic key without revealing their participation. Although this can be achieved using bipartite primitives alone, it is costly in the number of network rounds required. By allowing the use of multipartite entanglement, there is a substantial efficiency improvement. We experimentally implement the AQCKA task in a six-user quantum network using Greenberger-Horne-Zeilinger (GHZ)-state entanglement and obtain a significant resource cost reduction in line with theory when compared to a bipartite-only approach. We also demonstrate that the protocol retains an advantage in a four-user scenario with finite-key effects taken into account.

QI 3.8 Mon 11:30 HFT-TA 441

**Towards High Throughput Quantum Key Distribution with Quantum Dots** — •Koray Kaymazlar, Martin von Helversen, Timm Gao, Lucas Rickert, Daniel Vajner, and Tobias Heindel — Institute of Solid State Physics, Technical University of Berlin

Quantum key distribution (QKD) systems using polarization encoding require fast modulation of the polarization states of single-photon pulses. Here, we present a prototype for a QKD system based on the BB84 protocol which aims for secure key generation at high rates. The setup consists of electronics based on a field programmable gate array (FPGA) and a digital to analog converter (DAC) driving a fiber-based electro optic modulator for quantum light from a cavity-enhanced semiconductor quantum dot emitting in the spectral range around 900 nm or 1550 nm. We characterize and optimize the performance of this setup in terms of secure key rate.

We also considered practical issues which are synchronization of sender (Alice) and receiver (Bob) side of the system, alongside random bit handling in the sender*s end. Various solutions were implemented to address these practical challenges, followed by an evaluation to discern their impact on the system*s functionality.

QI 3.9 Mon 11:45 HFT-TA 441

**Microwave quantum tokens with time multiplexing** — •Florian Fesquet[1,2], Valentin Weidemann[1,2], Fabian Kronowetter[1,2,3], Michael Renger[1,2], Wun K. Yam[1,2], Simon Gandorfer[1,2], Achim Marx[1], Rudolf Gross[1,2,4], and Kirill G. Fedorov[1,2,4] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]School of Natural Sciences, Technische Universität München, 85748 Garching, Germany — [3]Rohde & Schwarz GmbH & Co. KG, 81671 Munich, Germany — [4]Munich Center for Quantum Science and Technology, 80799 Munich, Germany

Quantum key distribution (QKD) holds the promise of delivering unconditionally secure distribution of classical keys between remote parties. So far, its implementation in the microwave regime, frequency-compatible with superconducting quantum circuits, has been missing. Here, we present a realization of a continuous-variable (CV) QKD protocol using propagating displaced squeezed microwave states and demonstrate an experimental unconditional security. We show that secret key rates can be increased by adding finite trusted noise to the preparation side and by exploiting the time multiplexing approach. Our results indicate feasibility of secure microwave quantum communication under cryogenic (up to 1200 meters) and open-air (up to 80 meters) conditions. Finally, we discuss coupling of the squeezed microwave states to spin ensembles, enabling long-term quantum memories for resulting quantum tokens.

QI 3.10 Mon 12:00 HFT-TA 441

**Microwave quantum teleportation in a thermal environment** — •Wun Kwan Yam[1,2], Simon Gandorfer[1,2], Florian Fesquet[1,2], Kedar E. Honasoge[1,2], Maria-Teresa Handschuh[1,2], Fabian Kronowetter[1,2,3], Achim Marx[1], Rudolf Gross[1,2,4], and Kirill G. Fedorov[1,2,4] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]School of Natural Sciences, Technische Universität München, 85748 Garching, Germany — [3]Rohde & Schwarz GmbH Co. KG, 81671 Munich, Germany — [4]Munich Center for Quantum Science and Technology, 80799 Munich, Germany

Microwave quantum teleportation enables efficient and unconditionally secure exchange of quantum states. It also paves the way towards distributed quantum computing based on superconducting qubits with natural frequency in the microwave regime. We perform quantum teleportation of microwave coherent states between spatially separated cryostats by exploiting two-mode squeezed states propagating over a cryogenic link between those fridges. We study the influence of the cryolink's temperature on the fidelity of teleported states and experimentally demonstrate robustness of our teleportation protocol. Finally, we analyze ultimate limits of this approach and discuss it in the context of microwave quantum local area networks.

QI 3.11 Mon 12:15 HFT-TA 441

**Where are the photons in a transmission-line pulse?** — •Evangelos Varvelis[1,2], Debjyoti Biswas[3], and David P. DiVincenzo[1,2,4] — [1]Institute for Quantum Information, RWTH Aachen University, 52056 Aachen, Germany — [2]Jülich-Aachen Research Alliance (JARA), Fundamentals of Future Information Technologies, 52425 Jülich, Germany — [3]Department of Physics, IIT Madras, Chennai 600036, India — [4]Peter Grünberg Institute, Theoretical Nanoelectronics, Forschungszentrum Jülich, 52425 Jülich, Germany

It is now common to say that photons can be transmitted along optical fibers or transmission lines. But in many cases the transmission pulse is defined by a time-profile of the field strength, i.e., the electric field or voltage V(t), at the transmission point. How does this turn into a precise description of the arrival profile of the photons in the pulse? We show that there is a highly nontrivial mathematical relation between the function V(t) and the arrival function of the photons. Paradoxically, even if V(t) is strictly limited in time, the photon arrival profile cannot be. This, and the counterintuitive relation between V(t) and the expected number of arriving photons, has consequences for the security of quantum cryptography.

QI 3.12 Mon 12:30 HFT-TA 441

**Ultrafast quantum state transfer and the speed limit of quantum communication** — •Przemyslaw Zielinski[1,2,3], Iñigo Arrazola[4], and Peter Rabl[1,2,3] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, 85748 Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany — [4]Instituto de Física Teórica, UAM-CSIC, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain

We investigate the controlled transfer of quantum states between two nodes of a quantum network with tunable couplings to a common waveguide. Specifically, we are interested in the performance of the state transfer protocol when the coupling is pushed into the ultrastrong coupling regime and the usual rotating wave approximation does no longer apply. In this regime we use optimal control theory to evaluate the minimal time for which a nearly perfect state transfer fidelity can still be achieved. We discuss the implications of these general findings for quantum communication strategies in superconducting quantum networks, where tunable ultrastrong couplers can be realized with flux-biased Josephson circuits.

QI 3.13 Mon 12:45 HFT-TA 441

**Bounds on Conference Key Agreement in LOSR-Networks** — •Justus Neumann, Giacomo Carrara, Anton Trushechkin, Hermann Kampermann, and Dagmar Bruss — Heinrich Heine Universität, Düsseldorf, Deutschland

Conference key agreement is the extension of quantum key distribution from two to arbitrary many participants. Typically, the parties need to prepare multipartite entangled states to establish a secret key. However, generating highly multipartite entangled quantum states can be challenging in practice. We consider networks with bipartite sources, where each party is allowed to perform local operations. In addition, all parties share a classical random variable indicating the operation the parties have to perform. In this scenario the parties are not allowed to communicate classically during the prepare and measure phase. Although this limits the parties' abilities to generate a high key rate, it has advantages for practical implementations because no memories are needed. We discuss how such networks can be used to establish a secret bit string shared by all parties. Through inflation techniques, we derive upper bounds on the asymptotic multipartite key rate and we show that in a BB84- multipartite protocol the states that can be prepared in these networks do not outperform biseparable states.

QI 3.14 Mon 13:00 HFT-TA 441

**Entanglement-based free-space links for quantum networks** — •Antonio Gallego Barrio[1,2], Jan Tepper[1], Michael Auer[2,3,4], Alberto Comin[1], and Harald Weinfurter[2,4,5] — [1]Airbus Central R&T, Munich, Germany — [2]Ludwig-Maximilians-Universität, Munich, Germany — [3]Universität de Bundeswehr München, Neubiberg, Germany — [4]Munich Center for Quantum Science and Technology, Munich, Germany — [5]Max-Planck-Institut für Quantenoptik, Garching, Germany

Quantum key distribution (QKD) protocols can be implemented with different technologies and means. For a future practical quantum network it will be valuable to combine them wisely and exploit the relative strengths of fiber based and free-space links.

Here we present some of the approaches and the main challenges which need to be overcome when implementing the links of a quantum network. The key topics are photon detection, time-correlated single photon counting and verification and use of entanglement.

There will also be a brief review about the limitations of the commercially available technologies and some of the implementation details of the QKD links, which will have a deep impact on the development of near-term QKD networks.

## QI 4: Materials and Devices for Quantum Technology I (joint session HL/QI)

Time: Monday 15:00–18:00 Location: EW 203

QI 4.1 Mon 15:00 EW 203

**A Quantum Polyspectra Approach to the Analysis of Quantum Emitter Blinking Dynamics at Low Photon Rates Without Binning** — •M. Sifft[1], A. Kurzmann[2], J. Kerski[4], R. Schott[3], A. Ludwig[1], A. D. Wieck[1], A. Lorke[4], M. Geller[4], and D. Hägele[1] — [1]Ruhr Uni., DE — [2]RWTH Aachen, DE — [3]ETH Zürich, CH — [4]Uni. Duisburg-Essen, DE

The statistical analysis of quantum emitters becomes hard or even impossible for traditional methods like the full counting statistics in cases of decreasing light levels. We propose a polyspectra approach that prevails even in scenarios of high photon losses or low photon rates. A minimum photon flux and binning of photon-events is no longer required [1]. By comparing theoretical polyspectra (higher-order generalizations of the usual power spectrum) with those calculated directly from the detector output, we can identify the emitter's Liouvillian or transition matrix.

We analyze quantum dot fluorescence data and determine on-off switching rates at average photon rates much lower than the system dynamics. Our Python libraries, SignalSnap and QuantumCatch, are freely available for computing polyspectra on GPUs and for their subsequent analysis [2,3]. The libraries allow for an advanced analysis of general continuous quantum measurements yielding the systems Liouvillian or its underlying hidden Markov model.

[1] Sifft et al., arXiv:2310.10464,
[2] github.com/markussifft/signalsnap,
[3] github.com/markussifft/quantumcatch

QI 4.2 Mon 15:15 EW 203

**A type-IV gatemon qubit based on Ge/Si core-shell nanowires** — Han Zheng[1], Luk Yi Cheung[1], Nikunj Sangwan[1], Roy Haller[1], Carlo Ciaccia[1], Artem Kononov[1], Erik P. A. M. Bakkers[2], Joost Ridderbos[3], Andreas Baumgarner[1,4], and •Christian Schönenberger[1,4] — [1]Dep. Physics, Univ. of Basel, Basel, Switzerland — [2]Dep. of Appl. Phys., Eindhoven Univ. of Technology, Eindhoven, The Netherlands — [3]MESA+ Inst. of Nanotechnology, Univ. of Twente, Enschede, The Netherlands — [4]Swiss Nanoscience Institute, Univ. of Basel, Basel, Switzerland

Transmon qubits are currently the most popular solid-state platform for small and intermediate scale quantum technology applications. However, there are several challenges, such as the large size and hence the difficulty in scaling to many qubits, the sensitivity to flux noise and the associated power load for driving qubits through flux lines.

A possible solution are semiconductor-superconductor hybrid systems called gatemon qubits where the Josephson junction is realized by a gate-tunable weak link. Such gatemons have intensively been studied in III-V semiconductor 2D and 1D platforms. But only recently work has been started on using type-IV semiconductors to realize gatemons. Here, we present a gatemon qubit based on a Ge/Si core-shell nanowire Josephson junction. On this new platform we demonstrate the electrical tunability and coherent manipulation, with coherence times on par with other gatemon platforms. We also demonstrate that these junctions are highly transmissive opening a way to realize parity protected 4e gatemon devices.

QI 4.3 Mon 15:30 EW 203

**Real-Time Processing of Quantum Measurements: Quantum Polyspectra Approach to the Weak, Strong, and Single Photon Regime** — •Armin Ghorbanietemad, Markus Sifft, and Daniel Hägele — Ruhr University Bochum, Faculty of Physics and Astronomy, Experimental Physics VI, Germany

Quantum polyspectra have recently been successfully utilized in the evaluation of continuous quantum measurement records across weak, strong, and single photon regimes. This analysis is conducted by comparing experimental quantum polyspectra with their theoretical counterparts [1]. Our freely accessible Python library, SignalSnap [2], offers an efficient GPU-based method for calculating the polyspectra. Expanding on this groundwork, we introduce new software for the real-time evaluation of quantum measurement data with MHz bandwidth using polyspectra. This approach enables immediate processing and interpretation of quantum measurements. The goal is to achieve real-time characterization of quantum systems by estimating their Liouvillians. This capability is crucial for deepening our understanding of quantum dynamics. Real-time evaluation of measurements allows experimentalist to find interesting parameter settings already in the lab or to identify obvious errors in the experiment, like drift, missalignment, or unwanted external noise.

[1] Sifft et al., Phys. Rev. Research 3, 033123 (2021).
[2] https://github.com/MarkusSifft/SignalSnap

QI 4.4 Mon 15:45 EW 203

**Multiband $k \cdot p$ theory for hexagonal germanium** — •Yetkin Pulcu[1], Janos Koltai[2], Andor Kormanyos[3], and Guido Burkard[1] — [1]Department of Physics, University of Konstanz, D-78457 Konstanz, Germany — [2]Department of Biological Physics, Eötvös Loránd University, Budapest, Hungary — [3]Department of Physics of Complex Systems, Eötvös Loránd University, Budapest, Hungary

The direct bandgap found in hexagonal germanium and some of its alloys with silicon allows for an optically active material within the group-IV semiconductor family with various potential technological applications. However, there remain some unanswered questions regarding several aspects of the band structure, including the strength of the electric dipole transitions at the center of the BZ. In this work [2], using 10 band $\mathbf{k} \cdot \mathbf{p}$ Hamiltonian with SOC near the $\Gamma$ point, we obtain a self-consistent model that describes 2H-Ge via fitting to *ab initio* data. To understand the weak dipole coupling between the lowest conduction band and the top valance band, we start from a spinless 12-band model and show that when adding spin-orbit coupling, the lowest conduction band hybridizes with a higher-lying conduction band. Additionally, we derive the effective low-energy Hamiltonian for the conduction bands for the possible spin dynamics and nanostructure studies. Finally, we include the effects of a magnetic field and predict the electron and hole g-factor of the conduction and valence bands.

[1] Pulcu, Yetkin, et al. "Multiband $k \cdot p$ theory for hexagonal germanium." arXiv preprint arXiv:2310.17366 (2023).

QI 4.5 Mon 16:00 EW 203

**Spin-orbit coupling of color centers for quantum applications** — •Mirjam Neubauer, Maximilian Schober, Witold Dobersberger, and Michel Bockstedte — Institute for Theoretical Physics, Johannes Kepler University Linz, Altenbergerstr. 69, A-4040 Linz, Austria

Color centers in semiconductors, such as the NV-center in diamond, the silicon vacancy ($V_{Si}^-$), and the di-vacancy ($V_C V_{Si}$) in 4H-silicon carbide (4H-SiC), are potential candidates for quantum bits (qubits). Manipulating the spin optically involves exciting the fundamental high-spin multiplet and intersystem crossing (ISC), which includes spin-orbit, spin-spin, and spin-phonon couplings. These interactions, together with the zero-field splitting of ground and excited states, enable diverse spin-photon protocols. To optimize the engineering of such interfaces, a comprehensive understanding of spin-selective interactions and resulting spin-relaxation pathways is crucial. Recent experiments regarding the $V_{Si}^-$ in SiC have revealed spin-dependent lifetimes and intercrossing rates using an effective model that considers only one or two out of the five predicted intermediate states [1]. Here we address this issue. We employ our extended CI-cRPA approach for correlated defect states [2] to calculate the spin-orbit and spin-spin coupling. We present a fine structure of the quartet states of $V_{Si}^-$ consistent with existing literature. Based on our calculations, we discuss the ISC and spin-relaxation paths.

[1] N. Morioka et al.Phys. Rev. Appl. **17** 054005 (2022).
[2] M. Bockstedte, et al., npj Quant Mater **3**, 31 (2018).

QI 4.6 Mon 16:15 EW 203

**Protocols to measure the non-Abelian Berry phase by pumping a spin qubit through a quantum-dot loop** — •Baksa Kolok[1] and Andras Palyi[1,2] — [1]Department of Theoretical Physics, Institute of Physics, Budapest University of Technology and Economics, Muegyetem rkp. 3., H-1111 Budapest, Hungary — [2]MTA-BME Quantum Dynamics and Correlations Research Group, Muegyetem rkp. 3., H-1111 Budapest, Hungary

A quantum system constrained to a degenerate energy eigenspace can undergo a nontrival time evolution upon adiabatic driving, described by a non-Abelian Berry phase. This type of dynamics may provide logical gates in quantum computing that are robust against timing errors. A strong candidate to realize such holonomic quantum gates is an electron or hole spin qubit trapped in a spin-orbit-coupled semiconductor, whose twofold Kramers degeneracy is protected by time-reversal symmetry. Here, we propose and quantitatively analyze protocols to measure the non-Abelian Berry phase by pumping a spin qubit through a loop of quantum dots. One of these protocols allows to characterize the local internal Zeeman field directions in the dots of the loop. We expect a nearterm realisation of these protocols, as all key elements have been already demonstrated in spin-qubit experiments. These experiments would be important to assess the potential of holonomic quantum gates for spin-based quantum information processing.

**15 min. break**

**Invited Talk** QI 4.7 Mon 16:45 EW 203

**Strategic wafer-scale creation of telecom single-photon emitters in silicon for large-scale quantum photonic integrated circuits** — •Yonder Berencen — Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, 01328, Dresden, Germany

Indistinguishable single-photon sources at telecom wavelengths are crucial for transmitting quantum information over long distances with minimal losses, facilitating secure quantum communication and a modular approach to quantum computing. Monolithic integration of these sources with reconfigurable photonic elements and single-photon detectors in a silicon chip is vital for scalable quantum hardware, such as quantum photonic integrated circuits (QPICs). While many necessary components for QPICs are available, the lack of on-chip single-photon emitters in silicon has hindered practical implementation on the nanoscale. This study presents two wafer-scale protocols, demonstrating quasi-deterministic creation of single G and W telecom-wavelength color centers in silicon with over 50% probability. Both protocols are compatible with current silicon technology, enabling fabrication of single telecom quantum emitters at desired nanoscale positions on a silicon chip. These results offer a clear pathway for industrial-scale photonic quantum processors with technology nodes below 100 nm, overcoming a critical obstacle in the development of scalable quantum photonic hardware.

QI 4.8 Mon 17:15 EW 203

**Color centers in hexagonal boron nitride for quantum memories.** — •Chanaprom Cholsuk[1], Asli Cakan[2], Sujin Suwanna[3], and Tobias Vogl[1,2] — [1]Abbe Center of Photonics, Institute of Applied Physics, Friedrich Schiller University Jena, 07745 Jena, Germany — [2]Department of Computer Engineering, School of Computation, Information and Technology, Technical University of Munich, 80333 Munich, Germany — [3]Optical and Quantum Physics Laboratory, Department of Physics, Faculty of Science, Mahidol University, Bangkok 10400, Thailand

A quantum memory is essential for large-scale quantum networks. While several quantum memories have been developed so far, many cases remain unable to meet all requirements entirely i.e. long storage time, selective compatibility, and high memory efficiency. This work therefore proposes a quantum memory from color centers in hexagonal boron nitride in a cavity based on the Raman scheme with Lambda-type ($\Lambda$) energy levels. 257 triplet and 211 singlet spin electronic transitions have been characterized by density functional theory and classified with quantum applications. The result suggests that some defects inherit the $\Lambda$ electronic structures under neutral charge, whereas some require charge-state manipulation. Further, the required quality factor and bandwidth provide a reasonable range for achieving a 95% writing efficiency. Consequently, this work contributes to realizing hBN as a quantum memory for future quantum networks.

QI 4.9 Mon 17:30 EW 203

**Coherence properties of exciton-polariton condensates in a long lifetime microcavity** — •Yannik Brune[1], Elena Rozas[1], Kirk Baldwin[2], Loren Pfeiffer[2], David Snoke[3], and Marc Assmann[1] — [1]Department of Physics, Technische Universität Dortmund, Dortmund 44227, Germany — [2]Department of Electrical Engineering, Princeton University, New Jersey 08544, USA — [3]Department of Physics & Astronomy, University of Pittsburgh, Pittsburgh 15260, USA

The coherence properties of all-optically excited polariton condensates are typically hindered by the interactions with the concurrently excited incoherent background. We circumvent this restriction by using an annular shaped CW excitation beam, acting as a trapping potential in combination with long lifetime polaritons in a high Q-factor microcavity. Our approach enables the separation of the condensation area from the excitation area. The condensate properties are then examined using two-channel homodyne detection. This allows us not only to determine $g^2(0)$ but also access its Husimi-Q distribution and further properties like quantum coherence. These results provide a deeper understanding of the polariton condensate behavior beyond the condensation threshold. Our findings offer new insights into the use of CW pumped polariton condensates as ultralow threshold coherent light source.

QI 4.10 Mon 17:45 EW 203

**Theory of valley physics in SiGe quantum dots** — •Jonas de Lima and Guido Burkard — Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

The weak spin-orbit coupling and the nuclear zero-spin isotopes of silicon and germanium make Si/Ge quantum dots an ideal host for semiconductor spin qubits. However, the degeneracy of the conduction band minima of bulk silicon, known as valleys, limits the performance and scalability of quantum information processing, because the valley degree of freedom competes with the spin as a low-energy two-level system. The valley degeneracy is lifted in quantum dots in Si/SiGe heterostructures due to biaxial strain and a sharp interface potential, but the reported valley splittings are often uncontrolled and can be as low as 10 to 100 $\mu$eV. This presentation will discuss in detail the main challenges for the enhancement and control of the valley splitting in silicon quantum dots. In addition, it will describe a new three-dimensional model within the effective mass theory for the calculation of the valley splitting in Si/SiGe heterostructures, which takes into account concentration fluctuations at the interface and the lateral confinement. With this model, we predicted the valley splitting as a function of various parameters, such as, the width of the interface, the electric field and the size and location of the quantum dot.

# QI 5: Entanglement Theory

Time: Monday 15:00–18:00 Location: HFT-FT 101

**Invited Talk** QI 5.1 Mon 15:00 HFT-FT 101

**Multi-copy activation of genuine multipartite entanglement in continuous-variable systems** — Klára Baksová[1], Olga Leskovjanová[2], Ladislav Mišta[2], •Elizabeth Agudelo[1], and Nicolai Friis[1] — [1]Atominstitut, Technische Universität Wien, Stadionallee 2, 1020 Vienna, Austria — [2]Department of Optics, Palacký University, 17. Listopadu 12, 771˜46 Olomouc, Czech Republic

In multipartite systems, entanglement takes various forms. Some mixed states show entanglement across every possible cut of a multipartite system, though they originate from separable states in different partitions. Genuine multipartite entangled (GME) states, not formed by mixing partition-separable states, are intriguing. Advances in quantum tech raise questions about this framework when multiple state copies are accessible. States in finite dimensions are GME-activatable if they are not partially separable across any one bipartition, likely true for infinite dimensions too. We explore this in the continuous-variable context, providing GME-activatable non-Gaussian state examples. For Gaussian states, using a biseparability criterion for the covariance matrix, we find it fails to detect GME activation. We find fully inseparable Gaussian states that meet this criterion but can still be GME, showing the criterion's insufficiency for Gaussian states. To the best of our knowledge, there is no documented instance of a Gaussian state that is both fully inseparable and definitively biseparable, highlighting a gap in our current understanding of these particular quantum systems.

QI 5.2 Mon 15:30 HFT-FT 101

**General class of continuous variable entanglement criteria** — Martin Gärttner[1,2,3,4], •Tobias Haas[5], and Johannes Noll[3] — [1]Institut für Theoretische Physik, Universität Heidelberg, Germany — [2]Physikalisches Institut, Universität Heidelberg, Germany — [3]Kirchhoff-Institut für Physik, Universität Heidelberg, Germany — [4]Institute of Condensed Matter Theory and Optics, Friedrich-Schiller-University Jena, Jena — [5]Centre for Quantum Information and Communication, Université libre de Bruxelles, Belgium

We present a general class of entanglement criteria for continuous variable systems. Our criteria are based on the Husimi Q-distribution and allow for optimization over the set of all concave functions rendering them extremely general and versatile. We show that several entropic criteria and second moment criteria are obtained as special cases. Our criteria reveal entanglement of families of states undetected by any commonly used criteria and provide clear advantages under typical experimental constraints such as finite detector resolution and measurement statistics.

Based on PRL 131, 150201 and PRA 108, 042410.

QI 5.3 Mon 15:45 HFT-FT 101

**Concurrence of entangled states in $d \times d$ dimensions with relaxed axisymmetry** — •Juan Arnaudas[1] and Jens Siewert[2,3] — [1]BCAM - Basque Center for Applied Mathematics, E-48009 Bilbao, Spain — [2]University of the Basque Country UPV/EHU, E-48080 Bilbao, Spain — [3]Ikerbasque, Basque Foundation for Science, E-48013 Bilbao, Spain

Families of highly symmetric states are an interesting playground for entanglement theory, because sometimes an exact solution to the entanglement problem is possible for them. This way they reveal the structure of the space of entangled states and may serve as a benchmark for other methods, e.g., for entanglement witnesses. An interesting example of such a family are the bipartite states with relaxed axisymmetry, in particular, because a fraction of them are entangled with a positive partial transpose (PPT). For a facet of this family the separability problem could be solved for any finite dimension $d$ [1], and for $d = 3$ a numerically exact solution for the concurrence was presented [2], thereby exactly quantifying also the PPT entanglement. In this work we explore the possibility of analytically proving the $d = 3$ result and to extend it to higher dimensions.

[1] M. Seelbach Benkner *et al.*, Phys. Rev. A **106**, 022415 (2022).

[2] G. Sentís *et al.*, Phys. Rev. A **94**, 020302(R) (2016).

QI 5.4 Mon 16:00 HFT-FT 101

**Alternatives of entanglement depth and metrological bounds** — •Szilárd Szalay[1] and Géza Tóth[1,2] — [1]Wigner Research Centre for Physics, Budapest, Hungary — [2]UPV/EHU, Bilbao, Spain

We work out the general theory of one-parameter families of partial entanglement properties, and the resulting entanglement depth like quantities. Special cases of these are the depth of partitionability, the depth of producibility (or simply entanglement depth) and the depth of stretchability, based on one-parameter families of partial entanglement properties known earlier. We also construct some further, physically meaningful cases, for instance the squareability, the toughness, and the degree of freedom. Metrological bounds on multipartite entanglement in terms of the quantum Fischer information fit naturally into this framework. Here we formulate these in terms of the depth of squareability, which therefore turns out to be the natural choice, leading to stronger bounds than the usual entanglement depth. We also formulate convex roof bounds for both cases, being much stronger than the direct ones.

QI 5.5 Mon 16:15 HFT-FT 101

**Multipartite entanglement and the structure constants of Lie algebras** — Satoya Imai[1,2], •Sophia Denker[1], 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

Entanglement is an important resource in quantum information processing. Therefore, its detection and investigation are crucial tasks, too. In this contribution we present traceless operators based on the symmetric and antisymmetric structure constants of Lie algebras and explore their relation to trace polynomials. It turns out that these observables are useful for multipartite entanglement detection and, moreover, are linked to permutation-based entanglement witnesses. Further, we find that they are connected to projectors on highly entangled sub-spaces, which makes them strong entanglement criteria for high-dimensional tripartite systems.

**15 min. break**

QI 5.6 Mon 16:45 HFT-FT 101

**Multiplexing and Information Transport in Quantum Networks** — •Julia Freund, Alexander Pirker, and Wolfgang Dür — Insitute for Theoretical Physics, Innsbruck, Austria

The concepts of multiplexing and transport of quantum data are vital in quantum information such as quantum networks, distributed quantum metrology and computing. We focus on graph states due to their key role as multipartite-entangled resource states for example in measurement-based quantum computation or entanglement-based quantum networks. To manipulate the resource state for data transport and multiplexing, we utilize local Clifford operations, Pauli measurements and classical communication. The manipulation strategies we provide allow to extract and transport multiplexed Bell pairs, GHZ states and one-dimensional cluster states within a two-dimensional cluster state resource. Furthermore, our strategies maintain connectivity in the remaining graph state while being efficient in terms of required manipulations.

QI 5.7 Mon 17:00 HFT-FT 101

**Absolute separability witnesses for symmetric multiqubit states** — •Eduardo Serrano Ensástiga, Jérôme Denis, and John Martin — Institut de Physique Nucléaire, Atomique et de Spectroscopie, CESAM, University of Liège, B-4000 Liège, Belgium

Entanglement is a valuable resource for quantum applications, and a well-established method for creating entangled multiqubit symmetric states in a controlled manner is the application of a global unitary operation. However, certain states, called symmetric absolutely separable (SAS), remain unentangled after any unitary gate preserving permutation invariance in the constituents of the system. In this work, we develop criteria for detecting SAS states of any number of qubits [1,2]. Our approach is based on the Glauber-Sudarshan P representation for finite-dimensional quantum systems. We introduce families of linear and non-linear SAS witnesses formulated respectively as algebraic inequalities or a quadratic optimization problem. These witnesses are capable of identifying more SAS states than previously known counterparts [3].

[1] E. Serrano-Ensástiga, and J. Martin, Maximum entanglement of

mixed symmetric states under unitary transformations, SciPost Phys. 15, 120 (2023).
[2] E. Serrano-Ensástiga, J. Denis and J. Martin, Absolute separability witnesses for symmetric multiqubit states, too appear on arXiv soon.
[3] F. Bohnet-Waldraff, O. Giraud, and D. Braun, Absolutely classical spin states, Phys. Rev. A 95, 012318 (2017).

QI 5.8 Mon 17:15 HFT-FT 101

**Number-phase uncertainty relations and bipartite entanglement detection in spin ensembles** — •Giuseppe Vitagliano[1], Matteo Fadel[9], Iagoba Apellaniz[2], Matthias Kleinmann[3], Bernd Lücke[4], Carsten Klempt[4,5], and Geza Toth[2,6,7,8] — [1]Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Vienna 1020, Austria — [2]UPV/EHU, ES-48080 Bilbao, Spain — [3]Universität Siegen, DE-57068 Siegen, Germany — [4]Leibniz Universität Hannover, DE-30167 Hannover, Germany — [5]DLR-SI, DE-30167 Hannover, Germany — [6]DIPC, ES-20080 San Sebastian, Spain — [7]IKERBASQUE, ES-48011 Bilbao, Spain — [8]Wigner Research Centre for Physics, HU-1525 Budapest, Hungary — [9]ETH Zürich, CH-8093 Zürich, Switzerland

We present a method to detect bipartite entanglement and EPR steering based on number-phase-like uncertainty relations in split spin ensembles. In particular, we show how to detect bipartite entanglement in an unpolarized Dicke state of many spin-1/2 particles. We demonstrate the utility of the criteria by applying them to a recent experiment given in K. Lange et al. [Science 360, 416 (2018)]. Our methods also work well if split spin-squeezed states are considered. We discuss how to handle experimental imperfections.

[1] G. Vitagliano et al., Quantum 7, 914 (2023)

QI 5.9 Mon 17:30 HFT-FT 101

**Sequential Weak Measurements for Generating Multipartite Entangled States** — •Trinidad B. Lantaño, Dayou Yang, Koenraad Audenaert, Susana Huelga, and Martin Plenio — Institut für Theoretische Physik, Albert-Einstein-Allee 11, Universität Ulm 89069, Germany

We propose a state preparation protocol based on sequential measurements of a central spin coupled with a spin ensemble, and investigate the usefulness of the generated multi-spin states for quantum enhanced metrology. Remarkably, our protocol allows for the generation of highly entangled spin states, devoid of the necessity for non-linear spin interactions. The metrological sensitivity of the resulting state surpasses the standard quantum limit, reaching the coveted Heisenberg limit under symmetric coupling strength conditions. Additionally, we study the relevant case where coupling strengths are not symmetric, obtaining a specific time length for the preparation protocol where optimal sensitivity is achieved. Our results establish a new approach for the generation of large-scale, entangled states for quantum enhanced metrology within current experimental capabilities.

QI 5.10 Mon 17:45 HFT-FT 101

**Topological entanglement duality in magnon systems** — •Vahid Azimi Mousolou — Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden.

Recent progress has demonstrated that magnons provide a promising platform for quantum information processing technologies, offering potential energy efficiency compared to other counterparts. One notable advantage is the strong and intrinsic entangling property of magnons in magnetic materials [1-5]. Here, we present a topological duality in magnetic materials based on magnon entanglement.

[1] V. Azimi-Mousolou et al., Phys. Rev. B 108, 094430 (2023). [2] Y. Liu et al., New J. Phys. 25, 113032 (2023). [3] V. Azimi-Mousolou et al, Phys. Rev. A 106, 032407 (2022). [4] V. Azimi-Mousolou et al, Phys. Rev. B 104, 224302 (2021). [5] V. Azimi-Mousolou at al, Phys. Rev. B 102, 224418 (2020).

# QI 6: Trapped Ion and Atom Qubits

Time: Monday 15:00–16:15 Location: HFT-FT 131

**Invited Talk** QI 6.1 Mon 15:00 HFT-FT 131

**Heat engine and force sensing with trapped ions** — •Kilian Singer[1], Bo Deng[1], Moritz Göb[1], Max Masuhr[2], and Daqing Wang[2] — [1]Institute of Physics, University of Kassel, Heinrich-Plett-Straße 40, 34132 Kassel, Germany — [2]Institut für Angewandte Physik, University of Bonn, Wegelerstr. 8, 53115 Bonn, Germany

Thermodynamic machines can be reduced to the ultimate atomic limit [1], using a single ion as a working agent. The confinement in a linear Paul trap with tapered geometry allows for coupling axial and radial modes of oscillation. The heat-engine is driven thermally by coupling it alternately to hot and cold reservoirs, using the output power of the engine to drive a harmonic oscillation. From direct measurements of the ion dynamics, the thermodynamic cycles for various temperature differences of the reservoirs can be determined and the efficiency compared with analytical estimates. I will describe how the engine principle can be exploited to implement a differential probe for non-classical baths [2] and to amplify zeptonewton forces [3] using non-linear features of the tapered trap design.

[1] J. Rossnagel et al., "A single-atom heat engine", Science 352, 325 (2016).
[2] A. Levy, M. Göb, B. Deng, K. Singer, E. Torrontegui and D.Wang "Single-atom heat engine as a sensitive thermal probe." New Journal of Physics, 22, 093020 (2020).
[3] B. Deng, M. Göb, B. Stickler, M. Masuhr, K. Singer, and D. Wang Phys. Rev. Lett. 131, 153601 (2023).

QI 6.2 Mon 15:30 HFT-FT 131

**Simulation and optimization methods for collision gates with ultra-cold atoms** — •Jan Reuter[1,2], Tommaso Calarco[1,2,3], Felix Motzoi[1,2], and Robert Zeier[1] — [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

Atoms in an optical lattice can be used for various applications of quantum technologies, including quantum simulators or quantum computers. In our study, we simulate fermionic $^6$Li atoms in an optical lattice using a split-step method to solve the Schrödinger equation in up to three dimensions. We analyze the behavior of one, two or three atoms in a double-well potential in a 1D-confinement under the influence of a SWAP- or $\sqrt{\text{SWAP}}$-gate. For this task, we optimize our time-dependent controls by simulating the gradient and the Hessian matrix of the quantum state with respect to these controls. Furthermore, we can verify our results by showing that the simulation of a two-atom collision in a 1D-confinement agrees with the result of a corresponding simulation assuming a 2D-confinement with a tight potential in one of these dimensions.

QI 6.3 Mon 15:45 HFT-FT 131

**Atom transport optimization: theoretical frameworks, control algorithms, and experimental integration.** — •Cristina Cicali[1,2], Robert Zeier[1], Felix Motzoi[1,2], and Tommaso Calarco[1,2,3] — [1]Forschungszentrum Jülich,Peter Grünberg Institute, Quantum Control (PGI-8), 52425 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, 50937 Köln, Germany — [3]Dipartimento di Fisica e Astronomia, Università di Bologna, 40127 Bologna, Italy

Ultracold atoms constitute a promising platform for quantum computing and quantum simulation. We study the transport of individual atoms in optical tweezers using methods of optimal control. As part of the BMBF project FemiQP, we are developing a theoretical framework for numerically optimizing atom transport trajectories, including strategies aimed at maximizing the transport fidelity, velocity, and robustness against experimental imperfections. Quantum control algorithms such as the dressed-CRAB (d-CRAB) and Gradient Ascent Pulse Engineering (GRAPE) are compared with regard to their utility to effectively optimize the atom transport. In collaboration with the group Christian Groß, optimized control protocols are adapted to the experimental platform in Tübingen.

QI 6.4 Mon 16:00 HFT-FT 131

**Fiber cavities for enhancement of comb-assisted microscopy and spectroscopy** — •Stephan Fraundienst[1,2], Franziska Haslinger[1,2], Maerpreet Arora[1,2], Tom Schubert[1,2], Bingxin Xu[3], Thomas Udem[1,3], Thomas Hümmer[1,2], Nathalie Picqué[3], and Michael Förg[1,2] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität Munich, Germany — [2]Qlibri GmbH, Munich, Germany — [3]Max-Planck-Institut für Quantenoptik, Garching, Germany

Tunable, open, scanning fiber-based microcavities spanning 100 $\mu$m and longer offer a compelling platform for light-matter interactions, such as single trapped ion coupling or frequency comb enhanced spectroscopy and microscopy. However, fabricating the concave mirrors at the tip of an optical fiber for long microcavities proves challenging. We provide a method for fabricating fiber mirrors with high finesse and sufficient free spectral range to couple a frequency comb into a microcavity.

## QI 7: Quantum Error Correction

Time: Monday 15:00–18:00 Location: HFT-TA 441

QI 7.1 Mon 15:00 HFT-TA 441

**Outperforming Gottesman-Kitaev-Preskill quantum error correction via feedback with memory** — •Matteo Puviani[1], Sangkha Borah[1,2], Remmy Zen[1], Jan Olle[1], and Florian Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, 91058 Erlangen, Germany — [2]Friedrich-Alexander Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

Bosonic codes allow the encoding of a logical qubit in a single component device, utilizing the infinitely large Hilbert space of an harmonic oscillator. In particular, the Gottesman-Kitaev-Preskill code has recently been demonstrated to be correctable well beyond the break-even point of the best passive encoding in the same system. However, the current approaches to quantum error correction (QEC) are based on protocols that only implement immediate measurement-based feedback. In our work, we train a recurrent neural network using the recently proposed Feedback GRAPE (Gradient Ascent Pulse Engineering with Feedback) method to develop a time-dependent QEC scheme based on feedback memory that outperforms current strategies and paves the way for novel measurement-based QEC.

QI 7.2 Mon 15:15 HFT-TA 441

**Discovering Compact Quantum Circuits for Fault-Tolerant Logical State Preparation with Reinforcement Learning** — •Remmy Zen[1], Jan Olle[1], Luis Colmenarez[2,3], Matteo Puviani[1], Markus Müller[2,3], and Florian Marquardt[1,4] — [1]Max Planck Institute for the Science of Light, Staudtstrasse 2, 91058 Erlangen, Germany — [2]Institute for Quantum Information, RWTH Aachen University, 52056 Aachen, Germany — [3]Peter Grünberg Institute, Theoretical Nanoelectronics, Forschungszentrum Jülich, 52425 Jülich, Germany — [4]Department of Physics, Friedrich-Alexander Universität Erlangen-Nürnberg, Staudtstrasse 5, 91058 Erlangen, Germany

One of the key aspects in realizing large-scale fault-tolerant quantum computers is quantum error correction (QEC). The first essential step of QEC is to encode the logical state into physical qubits. However, there is no unique recipe for finding a compact quantum circuit that encodes or prepares the logical state in a fault-tolerant way, especially under hardware constraints such as qubit connectivity and gate set. In this work, we use reinforcement learning (RL) to automatically discover compact quantum circuits that prepare the logical state of a QEC code fault-tolerantly with the flag-based protocol for a given qubit connectivity and gate set. We first demonstrate that an RL agent can fault-tolerantly prepare logical states of a code with up to 15 physical qubits without any hardware constraints. We then show RL-discovered compact circuits for fault-tolerant logical state preparation on a 2D grid.

QI 7.3 Mon 15:30 HFT-TA 441

**Coherent errors and readout errors in the surface code** — •Aron Marton[1] and Janos Asboth[1,2] — [1]Institute of Physics, Budapest University of Technology and Economics, Budapest, Hungary — [2]Wigner Research Centre for Physics, Budapest, Hungary

We consider the combined effect of readout errors and coherent errors, i.e., deterministic phase rotations, on the surface code. We use a recently developed numerical approach, via a mapping of the physical qubits to Majorana fermions. We show how to use this approach in the presence of readout errors, treated on the phenomenological level: perfect projective measurements with potentially incorrectly recorded outcomes, and multiple repeated measurement rounds. We find a threshold for this combination of errors, with an error rate close to the threshold of the corresponding incoherent error channel (random Pauli-Z and readout errors). The value of the threshold error rate, using the worst case fidelity as the measure of logical errors, is 2.6%. Below the threshold, scaling up the code leads to the rapid loss of coherence in the logical-level errors, but error rates that are greater than those of the corresponding incoherent error channel. We also vary the coherent and readout error rates independently, and find that the surface code is more sensitive to coherent errors than to readout errors. Our work extends the recent results on coherent errors with perfect readout to the experimentally more realistic situation where readout errors also occur.

QI 7.4 Mon 15:45 HFT-TA 441

**Coherent error threshold for surface codes from Majorana delocalization** — Florian Venn[1], •Jan Behrends[2], and Benjamin Béri[1,2] — [1]DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK — [2]T.C.M. Group, Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge, CB3 0HE, UK

Statistical mechanics mappings provide key insights on quantum error correction. However, existing mappings assume incoherent noise, thus ignoring coherent errors due to, e.g., spurious gate rotations. We map the surface code with coherent errors, taken as $X$- or $Z$-rotations (replacing bit or phase flips), to a two-dimensional (2D) Ising model with complex couplings, and further to a 2D Majorana scattering network. Our mappings reveal both commonalities and qualitative differences in correcting coherent and incoherent errors. For both, the error-correcting phase maps, as we explicitly show by linking 2D networks to 1D fermions, to a $\mathbb{Z}_2$-nontrivial 2D insulator. However, beyond a rotation angle $\phi_{\mathrm{th}}$, instead of a $\mathbb{Z}_2$-trivial insulator as for incoherent errors, coherent errors map to a Majorana metal. This $\phi_{\mathrm{th}}$ is the theoretically achievable storage threshold. We numerically find $\phi_{\mathrm{th}} \approx 0.14\pi$. The corresponding bit-flip rate $\sin^2(\phi_{\mathrm{th}}) \approx 0.18$ exceeds the known incoherent threshold $p_{\mathrm{th}} \approx 0.11$.

QI 7.5 Mon 16:00 HFT-TA 441

**Accurate optimal quantum error correction thresholds from coherent information** — •Luis Colmenarez[1,2], Ze-min Huang[3], Sebastian Diehl[4], and Markus Mueller[1,2] — [1]Institute for Quantum Information, RWTH Aachen University, Aachen, Germany — [2]Institute for Theoretical Nanoelectronics (PGI-2), Forschungszentrum Juelich, Juelich, Germany — [3]Department of Physics and Institute for Condensed Matter Theory, University of Illinois at Urbana-Champaign, Illinois, USA — [4]Institute for Theoretical Physics, University of Cologne, Cologne, Germany

In general, obtaining optimal thresholds of quantum error correcting codes (QEC) implies simulating QEC using complicated and, often, sub-optimal decoding strategies. In a few cases, optimal decoding can be framed as a phase transition in disordered classical spin models. In both situations, accurate estimation of thresholds demands intensive computational resources. In this work we use the coherent information of noisy mixed states, to accurately estimate optimal QEC thresholds already from small-distance codes at moderate computational cost. We show the effectiveness and versatility of our method by applying it first to the topological surface and color code under bit-flip and depolarizing noise, and then extend the coherent information based methodology for phenomenological and circuit level noise. For all examples we obtain optimal error thresholds from small instances of the codes with 1% difference compared to known values. We establish the coherent information as a reliable competitive practical tool for the calculation of optimal thresholds under realistic noise models.

**15 min. break**

QI 7.6 Mon 16:30 HFT-TA 441

**Coherent errors in stabilizer codes caused by quasi-static phase damping** — •David Pataki[1], Aron Marton[1], Janos Asboth[1,2], and Andras Palyi[1,3] — [1]Department of Theoretical Physics, Institute of Physics, Budapest University of Technology and Economics, Muegyetem rkp. 3., H-1111 Budapest, Hungary — [2]Wigner Research Centre for Physics, H-1525 Budapest, P.O. Box 49., Hungary — [3]HUN-REN–BME Quantum Dynamics and Correlations Research Group, Muegyetem rkp. 3., H-1111 Budapest, Hungary

Quantum error correction is a key challenge for the development of practical quantum computers, a direction in which significant experimental progress has been made in recent years. In solid-state qubits, one of the leading information loss mechanisms is dephasing, usually modelled by phase flip errors.

In this talk, I will introduce quasi-static phase damping, a more subtle error model which describes the effect of Larmor frequency fluctuations due to 1/f noise. I will show how this model is different from a simple phase flip error model, in terms of repeated syndrome measurements.

Considering the surface code, I will provide numerical evidence for an error threshold, in the presence of quasi-static phase damping and readout errors. I will also discuss the implications of our results for spin qubits and superconducting qubits.

QI 7.7 Mon 16:45 HFT-TA 441

**Simultaneous Discovery of Quantum Error Correction Codes and Encoders with a Noise-Aware Reinforcement Learning Agent** — •Jan Olle[1], Remmy Zen[1], Matteo Puviani[1], and Florian Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany — [2]Department of Physics, Friedrich-Alexander Universität Erlangen-Nürnberg, Staudtstraße 5, 91058 Erlangen, Germany

Finding optimal ways to protect quantum states from noise remains an outstanding challenge across all quantum technologies, and quantum error correction (QEC) is the most promising strategy to address this issue. In the context of real-world scenarios there are two challenges: codes have typically been categorized only for their performance under an idealized noise model and the implementation-specific optimal encoding circuit is not known. In this work, we train a Reinforcement Learning agent that automatically discovers both QEC codes and their encoding circuits for a given gate set, qubit connectivity, and error model. The agent is noise-aware, meaning that it learns to produce encoding strategies simultaneously for a range of noise models, thus leveraging transfer of insights between different situations. Moreover, by developing a vectorized Clifford simulator, our RL implementation is extremely efficient, allowing us to produce many codes and their encoders from scratch within seconds, with code distances varying from 3 to 5 and with up to 20 physical qubits. Our approach opens the door towards hardware-adapted accelerated discovery of QEC approaches across the full spectrum of quantum hardware platforms of interest.

QI 7.8 Mon 17:00 HFT-TA 441

**Hardware-Tailored Logical Gates for Quantum Error-Correcting Codes** — •Eric Kuehnke[1], Kyano Levi[2,1], Jens Eisert[1], and Daniel Miller[1] — [1]Freie Universität Berlin — [2]Technische Universität Berlin

Quantum error-correcting codes play a key role in fault-tolerant quantum computing. Due to the encoding of logical information into higher-dimensional and abstract Hilbert spaces of quantum error-correcting codes, however, the transformation of said logical information poses a difficult challenge. We use the representation of Clifford gates as symplectic binary matrices to construct hardware-tailored logical circuits for quantum error-correcting codes. We achieve this by translating the problem of circuit compilation into a binary optimization problem, which we solve with the help of Gurobi, a professional tool for mathematical optimization.

We apply our newly developed method to construct hardware-tailored logical gates for specific quantum error-correcting codes. One of these is the twisted toric-24 code, a quantum error-correcting code that encodes two logical qubits into twelve physical qubits.

QI 7.9 Mon 17:15 HFT-TA 441

**Scaling Hardware-Based Quantum Error Correction via a Multi-Context Approach** — •Jan-Erik Reinhard Wichmann, Maximilian Jakob Heer, and Kentaro Sano — RIKEN Center for Computational Science, Kobe, Japan

The theory of quantum error correction is generally well understood, though its practical implementation remains challenging. This is due to the low-latency requirements for the classical computations that are required to carry out the quantum error correction. Recent advancements have shown that it is possible to meet these latency requirements for surface codes using algorithms implemented in FPGA hardware, but the issue of growing hardware resource consumption persists.

A commonly suggested approach is to distribute the error correction algorithm across multiple FPGA chips. However, the incurred communication overhead runs counter to the latency requirements and will cause the so-called exponential backlog problem.

Here we thus present a different way to reduce hardware resource consumption by using a multi-context approach, trading hardware resources for execution time. By repeatedly saving and loading parts of the error decoder in memory, we can overcome the size limits of a single FPGA. This allows for the simultaneous treatment of larger qubit numbers for higher code distances and even lattice surgery operations, which has remained a difficult challenge so far. The technique we are presenting is developed with our own variant of the Union-Find algorithm in mind but is sufficiently general to be used with all algorithms which work on decoder graphs with limited connectivity.

QI 7.10 Mon 17:30 HFT-TA 441

**Fermionic Tetrahedron: Test-Bed for Error Analysis on NISQ** — •Daniel F. Urban[1,2], Jannis Ehrlich[1], and Christian Elsässer[1,2] — [1]Fraunhofer-Institut für Werkstoffmechanik IWM, Freiburg, Germany — [2]Freiburger Materialforschungszentrum, Universität Freiburg, Germany

Current noisy intermediate-scale quantum computers (NISQ) are error-prone, such that the results are not reliable. We employ small Fermionic clusters as test models to investigate the influence of different kinds of hardware errors on the calculation of the electronic energy spectrum. For the Fermionic tetrahedron, four pair-wise coupled electronic orbitals, we analyze the measured expectation values and the quality of states obtained by variational optimization algorithms. We identify the challenges of ad-hoc QC calculations starting from a basis of atomic orbitals opposed to those that make use of a better preconditioned basis, e.g. orbitals of a self-consistent Hartree-Fock solution. We observe significant errors in the computed expectation values on real hardware, while the optimization itself gives states that have high fidelities when compared to the exact solution. We trace back the origin of the high errors in energies to the way the expectation value is calculated on the QC hardware, and we demonstrate to which extent Zero Noise Extrapolation (ZNE) can improve the results.

QI 7.11 Mon 17:45 HFT-TA 441

**Distributed quantum codes as the sensor for chip-level catastrophic errors** — •Song Zhang[1,2], Xiuhao Deng[1,3], Guixu Xie[1,2], and Jinghan Lu[1,2] — [1]International Quantum Academy (SIQA), Shenzhen, P. R. China — [2]Shenzhen Institute for Quantum Science and Engineering (SIQSE), Southern University of Science and Technology, Shenzhen, P. R. China — [3]Shenzhen Institute for Quantum Science and Engineering (SIQSE), and Department of Physics, Southern University of Science and Technology, Shenzhen, P. R. China

Superconducting qubits are a key platform for quantum computing, but recent studies have revealed a critical challenge: ionizing radiation like cosmic rays can trigger correlated errors across all qubits on a chip, leading to catastrophic errors. This issue presents a significant obstacle for fault-tolerant quantum computing, as it defies the conventional assumption of short-range or uncorrelated errors in error correction strategies. To overcome this issue, we propose novel cross-chip schemes that function as a distributed quantum sensor, specifically designed to detect these chip-level correlated errors. Our sensor is particularly practical for real-world applications due to its reliance on quantum non-demolition measurements, which reduces unnecessary resets, and its ability to detect and differentiate errors with various types and correlation ranges. This approach is a crucial step towards enabling large-scale, fault-tolerant quantum architectures by tackling the problem of chip-level catastrophic errors.

# QI 8: Photons and Photonic Quantum Processors

Time: Monday 16:30–18:30 Location: HFT-FT 131

**Invited Talk** QI 8.1 Mon 16:30 HFT-FT 131
**Quantum Simulations in Integrated Waveguide Arrays** — •Jasmin D. A. Meinecke[1,2,3,4], Florian Huber[1,2,3], Benedikt Braumandl[1,2,3], Sholeh Razavian[1,2,3], Jan Dziewior[1,2,3], Robert Jonsson[5], Johannes Knörzer[6], Harald Weinfurter[1,2,3], and Alexander Szameit[7] — [1]Department für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Max-Planck-Institut für Quantenoptik, Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [4]Institut für Festkörperphysik, Technische Universität Berlin, Hardenbergstr. 36, 10623 Berlin, Germany — [5]Nordita, KTH Royal Institute of Technology and Stockholm University, Hannes Alfvens vag 12, SE-106 91 Stockholm, Sweden — [6]Institute for Theoretical Studies, ETH Zurich, 8092 Zurich, Switzerla — [7]Institut für Physik, Universität Rostock, Albert-Einstein-Straße 23, 18059 Rostock, Germany

Photons exhibit low decoherence and fast transmission, making them promising for emerging quantum technologies. In particular, integrated circuits provide stable structures for quantum computation and simulation. One example are integrated waveguide arrays for simulations based on quantum walk models. Especially the precise control of path as well as polarization degree of freedom allows the simulation of Markovian as well as non-Markovian dynamics as found in open quantum systems. We analyse information as well as energy flow in quantum systems revealing insights into time evolution and dynamics also of many-body systems.

QI 8.2 Mon 17:00 HFT-FT 131
**Rigorous treatment of photon propagation between quantized quasinormal mode cavities** — •Robert Fuchs[1], Juanjuan Ren[2], Sebastian Franke[1], Stephen Hughes[2], and Marten Richter[1] — [1]Nichtlineare Optik und Quantenelektronik, Institut für Theoretische Physik, TU Berlin, Berlin, Germany — [2]Department of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, Ontario K7L 3N6, Canada

Spatially extended systems consisting of separated quantum emitters or resonators that couple via propagating photons are key to implementations of many quantum technologies, including quantum communication and quantum computing applications. Quasinormal modes (QNMs) are solutions to a Helmholtz equation with open boundary conditions. Hence, QNMs are a powerful tool for calculating the resonances of open optical cavities including dispersive plasmonic nanoparticles.

However, the focus of study so far has mostly been on single cavities or coupled resonators with small spatial separation. We extend the quantized QNM theory to the case of multiple, distant cavities and define parameters to determine when a separate treatment of the individual systems is possible. We also include quantum emitters in the theory. Using a bath of propagating photons, we derive system-bath correlation functions to rigorously describe the time delayed interactions between the QNM cavities and quantum emitters that give rise to feedback-induced phenomena.

QI 8.3 Mon 17:15 HFT-FT 131
**Towards Photon-Number-Entanglement from a Sequentially Excited Quantum Three-Level System** — •Daniel A. Vajner[1], Nils Kewitz[1], Carlos Anton-Solanas[2], Stephen C. Wein[3], Martin von Helversen[1], Yusuf Karli[4], Vikas Remesh[4], Saimon F. Covre da Silva[5], Armando Rastelli[5], Gregor Weihs[4], and Tobias Heindel[1] — [1]Technical University of Berlin, Berlin, Germany — [2]Universidad Autónoma de Madrid, Madrid, Spain — [3]Quandela, Massy, France — [4]Universität Innsbruck, Innsbruck, Austria — [5]Johannes Kepler University Linz, Linz, Austria

As recently demonstrated, the sequential resonant excitation of 2-level quantum systems leads to the generation of time bin modes that are entangled in the photon-number-basis [1]. Here, we extend this notion to 3-level quantum systems, realized by a biexciton in a semiconductor quantum dot that is subject to sequential pulses that are resonant with the two-photon transition. The different decay rates of the exciton and biexciton, in combination with the cascaded emission, lead to the creation of a complex multi-dimensional entangled state which could be used in quantum information applications [2]. By performing energy- and time-resolved correlation experiments, in combination with extensive theoretical modelling and simulations, we analyze the generated state and confirm its high-dimensional structure. This represents a scalable way towards complex and on-demand entangled photonic states.

[1] Wein, Stephen C., et al. Nature Photonics 16.5 (2022): 374-379.
[2] Santos, Alan C., et al. arXiv:2304.08896 (2023).

QI 8.4 Mon 17:30 HFT-FT 131
**Investigation of the degree of sequential indistinguishability of ZnSe-based single-photon sources** — •Christine Falter[1,3], Yurii Kutovyi[1,3], Nils von den Driesch[2,3], Detlev Grützmacher[1], and Alexander Pawlis[1,2,3] — [1]Peter Grünberg Institute PGI-9, Forschungszentrum Jülich GmbH — [2]Peter Grünberg Institute PGI-10, Forschungszentrum Jülich GmbH — [3]JARA-Fundamentals of Future Information Technology, Jülich Aachen Research Alliance

The realization of secure quantum communication networks requires the development of efficient and scalable sources of single, indistinguishable photons. We recently demonstrated highly efficient and spectrally tunable single photon emission from spatially isolated Cl donors in ZnSe/ZnMgSe quantum well nanopillar structures covered with a resist mask. Photoluminescence measurements reveal a high photon extraction efficiency (PEE) of 16%. Utilizing 2D ray-tracing simulations, we estimate the internal quantum efficiency to be close to unity, which is confirmed by the short radiative lifetime of our emitters. Finally, we investigate the degree of indistinguishability using Hong-Ou-Mandel-type experiments. We employ Monte Carlo simulations to replicate the experimental signatures and to investigate the influence of various experimental factors on the measurements. We estimate the degree of sequential indistinguishability to be as high as 90%. This result paves the way for Cl-doped ZnSe/ZnMgSe nanopillars to serve as highly efficient SPSs in future quantum communication networks.

QI 8.5 Mon 17:45 HFT-FT 131
**Single erbium emitters in nanophotonic silicon resonators** — •Jakob Pforr[1,2], Andreas Gritsch[1,2], Alexander Ulanowski[1,2], Stephan Rinner[1,2], Johannes Früh[1,2], Florian Burger[1,2], Jonas Schmitt[1,2], Kilian Sandholzer[1,2], Adrian Holzäpfel[1,2], and Andreas Reiserer[1,2] — [1]Max-Planck-Institut für Quantuenoptik, 85748 Garching, Germany — [2]TU München and Munich Center for Quantum Science and Technology, 85748 Garching, Germany

Erbium is a promising candidate for quantum networks, because it offers coherent optical transitions in the minimal-loss window of optical fibers. Integrating it in silicon allows for CMOS compatible fabrication and scalability. Previous work showed narrow inhomogeneous broadening ($\sim$1 GHz) and narrow homogeneous linewidth (<0.01 MHz) in erbium ensembles [1]. We demonstrate that this can also be achieved in samples that were fabricated in a commercial nanophotonic foundry [2]. In addition, by integrating the dopants into suited resonators with $Q \sim 10^5$ and $V \sim \lambda^3$, the optical lifetime is reduced 60-fold via Purcell-enhancement and single dopants can be observed [3]. We present our recent advances towards spin control, which demonstrate that Er:Si is a suitable spin-photon interface for quantum networks in the telecom C band.

References:
[1] Gritsch et. al. 2021. PRX 12(4): 041009.
[2] Rinner et. al. 2023. Nanophotonics 12(17): 3455-3462.
[3] Gritsch et. al. 2023. Optica 10: 783-789

QI 8.6 Mon 18:00 HFT-FT 131
**Squeezed light source on lithium niobate on insulator for quantum computing without periodic poling** — •Tummas Napoleon Arge[1], Seongmin Su[2], Francesco Lenzini[3], Jonas Schou Neergaard-Nielsen[1], Tobias Gehring[1], and Ulrik Lund Andersen[1] — [1]Technical University of Denmark, Fysikvej 311, 2800 Kgs. Lyngby, Denmark — [2]University of Heidelberg, Grabengasse 1 69117 Heidelberg — [3]University of Munster, Schlossplatz 2 48149 Münster

Squeezed quantum states combined with a linear beamsplitter network and photon number resolving detectors can produce the holy grail in continuous-variable quantum computing, GKP states. Lithium niobate on insulator (LNOI) is an emerging platform suitable for producing squeezed states of light due to its ultra-low propagation loss and high non-linear $\chi^(2)$ coefficient. A squeezing source for a circuit generating GKP states must obey two conditions: 1) a high amount of squeezing and 2) high purity.

This work presents a design for a squeezer on an LNOI platform without using periodic poling. Perfect phase matching in a type-I OPO is achieved using a higher-order transversal mode TM2 as the pump field, producing a signal/idler pair in the TE0 mode. Preliminary experiments show a parametric gain of 3, which will lead to -0.5 dB of squeezing off chip. The nature of the phasematching suppresses unwanted modes, fulfilling condition 2).

In conclusion, further work is needed to demonstrate efficient squeezing on this platform fulfilling the two conditions.

QI 8.7 Mon 18:15 HFT-FT 131

**Deterministic creation of isolated and ultra-bright quantum emitters in hexagonal boron nitride** — •Safa L. Ahmed[1,2], Ioannis Karapatzakis[2], Luis Kussi[2], Marcel Schrodin[2], Rainer Kraft[2], Christoph Sürgers[2], and Wolfgang Wernsdorfer[1,2] — [1]IQMT, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany — [2]PHI, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Single-photon emitters (SPEs) in hexagonal boron nitride (hBN) show fascinating applications in quantum information processing and quantum sensing. In order to utilize quantum emitters as sensors it is crucial to have stable SPEs. We create defects via AFM nanoindentation [1] on multilayer hBN flakes followed by high temperature annealing in Ar environment. This produces ultra-bright SPEs which do not photobleach due to charge build-up, and are both spatially and spectrally deterministic. A high yield of single isolated emitters is observed. Their second order correlation measurements and Debye-Waller factors show a high quantum yield. In addition, low temperature measurements were carried out that show spectral changes and emitter robustness to thermal cycles. Such deterministic surface quantum emitters could be incorporated into quantum sensing devices with enhanced spatial resolution and sensitivity.

## QI 9: Quantum Machine Learning and Classical Simulability

Time: Tuesday 9:30–13:15 Location: HFT-FT 101

**Invited Talk** QI 9.1 Tue 9:30 HFT-FT 101

**Does provable absence of barren plateaus imply classical simulability? Or, why we might need to rethink variational quantum computing** — •Zoe Holmes — EPFL, Lausanne, Switzerland

A large amount of effort has recently been put into understanding the barren plateau phenomenon. Here we face the increasingly loud elephant in the room and ask a question that has been hinted at by many but not explicitly addressed: Can the structure that allows one to avoid barren plateaus also be leveraged to efficiently simulate the loss classically? We present strong evidence that commonly used models with provable absence of barren plateaus are also in a sense classically simulable, provided that one can collect some classical data from quantum devices during an initial data acquisition phase. This follows from the observation that barren plateaus result from a curse of dimensionality, and that current approaches for solving them end up encoding the problem into some small, classically simulable, subspaces. This sheds serious doubt on the non-classicality of the information processing capabilities of parametrized quantum circuits for barren plateau-free landscapes and on the possibility of superpolynomial advantages from running them on quantum hardware. We end by discussing caveats in our arguments, the role of smart initializations, and by highlighting new opportunities that our perspective raises.

QI 9.2 Tue 10:00 HFT-FT 101

**Can a neural network fake a Boson Sampler?** — •Martina Jung[1], Martin Gärttner[1], and Moritz Reh[1,2] — [1]Friedrich-Schiller-Universität, Jena, Deutschland — [2]Universität Heidelberg, Heidelberg, Deutschland

Originally defined to demonstrate quantum supremacy, Boson Sampling and its simulation have become an own field of research. The simulation of a Boson Sampler is an - per-construction - classically intractable problem due to the computational complexity of its distribution. A statistics-based approach to learn the probability distribution of a sampling process faces issues like sparse data and highly correlated output configurations. These problems are reminiscent of natural language processing (NLP) tasks where a neural network is trained to respond to a query. Indeed, NLP models like a recurrent neural network (RNN) decompose the task by learning to sequentially predict the next word based on the preceding sequence of words. Transferring this concept to the bosonic Fock space, we train a RNN to simulate a Boson Sampler by predicting the conditional probabilities related to input-output configurations. The model's ability to extrapolate is tested on input sequences of lengths beyond the ones seen during the training.

QI 9.3 Tue 10:15 HFT-FT 101

**Parametrized Quantum Circuits and their approximation capacities in the context of quantum machine learning** — Alberto Manzano[1], •David Dechant[2,3], Jordi Tura[2,3], and Vedran Dunjko[2,3,4] — [1]Department of Mathematics and CITIC, Universidade da Coruña, Campus de Elviña s/n, A Coruña, Spain — [2]Applied Quantum Algorithms Leiden, The Netherlands — [3]Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands — [4]LIACS, Universiteit Leiden, P.O. Box 9512, 2300 RA Leiden, Netherlands

Parametrized quantum circuits (PQC) are used in recent approaches to quantum machine learning to learn various types of data, with an underlying expectation that if the PQC is made sufficiently deep, and the data plentiful, the generalization error will vanish, and the model will capture the essential features of the distribution. While there exist results proving the approximability of square-integrable functions by PQCs under the $L^2$ distance, the approximation for other function spaces and under other distances has been less explored. In this work we show that PQCs can approximate the space of continuous functions, $p$-integrable functions and the $H^k$ Sobolev spaces under specific distances. Moreover, we develop generalization bounds that connect different function spaces and distances. These results provide a theoretical basis for different applications of PQCs, for example for solving differential equations. Furthermore, they provide us with new insight on how to design PQCs and loss functions which better suit the specific needs of the users.

QI 9.4 Tue 10:30 HFT-FT 101

**Unifying (Quantum) Statistical and Parametrized (Quantum) Algorithms** — •Alexander Nietner — FU-Berlin

Kearns SQ oracle lends a unifying perspective for most classical machine learning algorithms. This no longer holds in case of quantum learning and with respect to the SQ or QSQ oracle. In this work we explore the problem of learning from an evaluation oracle, which provides an estimate of function values. We introduce an intuitive framework that yields unconditional lower bounds for learning from evaluation queries and characterizes the query complexity for learning linear function classes. The framework is directly applicable to the QSQ setting and virtually all algorithms based on loss function optimization.

We first apply this formalism to the QSQ setting studying the learnability of unitary and Clifford quantum circuit states at different depth regimes and prove exponential separations of learning stabilizer states from QSQs versus from quantum copy access.

Our second application is to analyze popular QML settings and to develop an intuitive picture that goes beyond that of barren plateaus. This enables us to show how the implications of a barren plateau depend on the particular setting, which gives new and valuable insights into variational algorithms.

QI 9.5 Tue 10:45 HFT-FT 101

**Information-theoretic generalization bounds for learning from quantum data** — •Matthias C. Caro[1,2], Tom Gur[3], Cambyse Rouzé[4,5], Daniel Stilck França[6], and Sathyawageeswar Subramanian[3,7] — [1]Dahlem Center for Complex Quantum Systems, FU Berlin — [2]IQIM, Caltech — [3]Department of Computer Science and Technology, University of Cambridge — [4]Inria, Télécom Paris - LTCI, Institut Polytechnique de Paris, Palaiseau, France — [5]Zentrum Mathematik, TU München — [6]Univ Lyon, ENS Lyon, UCBL, CNRS, Inria, LIP, F-69342, Lyon Cedex 07, France — [7]Department of Computer Science, University of Warwick

Learning tasks play an increasingly prominent role in quantum information and computation. However, the many directions of quantum learning theory have so far evolved separately. We propose a general mathematical formalism for describing quantum learning by training on classical-quantum data and then testing how well the learned hypothesis generalizes to new data. In this framework, we prove bounds on the expected generalization error of a quantum learner in terms of classical and quantum information-theoretic quantities measuring how strongly the learner's hypothesis depends on the specific data seen during training. To achieve this, we use tools from quantum optimal transport and quantum concentration inequalities. Our framework encompasses and gives intuitively accessible generalization bounds for a variety of quantum learning scenarios. Thereby, our work lays a foundation for a unifying quantum information-theoretic perspective on quantum learning.

QI 9.6 Tue 11:00 HFT-FT 101

**Efficient classical surrogate simulation of quantum circuits** — •Manuel S. Rudolph[1,5], Enrico Fontana[2,3,4], Ross Duncan[3], Ivan Rungger[4], Zoë Holmes[1], Lukasz Cincio[5], and Cristina Cîrstoiu[3] — [1]EPFL, Lausanne, Schweiz — [2]University of Strathclyde, Glasgow, UK — [3]Quantinuum, Cambridge, UK — [4]National Physical Laboratory, Teddington, UK — [5]Los Alamos National Lab, Los Alamos, USA

Performant classical simulation of quantum systems is crucial for benchmarking quantum algorithms and verifying potential quantum advantages. Here, we provide two results. First, we prove that there exists a polynomial-time algorithm for simulating quantum circuits affected by constant local Pauli noise with bounded average error as the number of qubits or circuit depth increases. This highlights that, on average, there cannot be an exponential quantum-classical separation in observable estimation tasks when the quantum hardware is affected by such noise. Second, we turn our Theorems into a full-fledged high-performance simulation algorithm called "LOWESA" for noisy and noise-free quantum circuits. LOWESA can be understood as a classical surrogate for expectation landscapes with fast re-evaluation at different circuit parameters. We show that we can scale our simulations to the 127-qubit examples presented in Nature 618, 500-505 (2023), where we produce near-exact expectation values and highlight the strengths of LOWESA compared to other established simulation methods.

**15 min. break**

QI 9.7 Tue 11:30 HFT-FT 101

**Exponential concentration in quantum kernel methods** — •Supanut Thanasilp[1], Samson Wang[2], Marco Cerezo[3], and Zoe Holmes[1] — [1]EPFL, Lausanne, Switzerland — [2]Imperial college London, London, UK — [3]Los Alamos National Laboratory, New Mexico, US

Kernel methods in Quantum Machine Learning have recently gained significant attention as a candidate for achieving a quantum advantage. Among attractive properties, when training a kernel-based model one is guaranteed to find the optimal models parameters due to the convexity of the landscape. However, this is based on the assumption that the kernel can be efficiently obtained from quantum hardware. In this work we study the performance of quantum kernel models from the perspective of the resources needed to accurately estimate kernel values. We show that, under certain conditions, values of quantum kernels over different input data can be exponentially concentrated (in the number of qubits) towards some fixed value. Thus on training with a polynomial number of measurements, one ends up with a trivial model where the predictions on unseen inputs are independent of the training data. We identify four sources that can lead to concentration including expressivity of data embedding, global measurements, entanglement and noise. For each source, an associated concentration bound of quantum kernels is analytically derived. Lastly, we show that when dealing with classical data, training a parametrized data embedding with a kernel alignment method is also susceptible to exponential concentration.

QI 9.8 Tue 11:45 HFT-FT 101

**On the expressivity of embedding quantum kernels** — •Elies Gil-Fuster[1,2], Jens Eisert[1,2,3], and Vedran Dunjko[4,5] — [1]Dahlem Center for Complex Quantum Systems, Freie Universitat Berlin — [2]Fraunhofer Heinrich Hertz Institute, Berlin — [3]Helmholtz-Zentrum Berlin fur Materialien und Energie — [4]Applied Quantum Algorithms, Universiteit Leiden, Netherlands — [5]LIACS, Universiteit Leiden, Netherlands

One of the most natural connections between quantum and classical machine learning has been established in the context of kernel methods. Quantum kernels are typically evaluated by explicitly constructing quantum feature states and then taking their inner product, here called embedding quantum kernels. Since classical kernels are usually evaluated without using the feature vectors explicitly, we wonder how expressive embedding quantum kernels are. In this work, we raise the question: can all quantum kernels be expressed as the inner product of quantum feature states? Our first result is positive: for any kernel function there always exists a corresponding quantum feature map and an embedding quantum kernel. In a second part, we formalize the question of universality of efficient embedding quantum kernels. We show that efficient embedding quantum kernels are universal within a broad class of shift invariant kernels. We then extend this result to a new class of so-called composition kernels, which we show also contains projected quantum kernels introduced in recent works. We finally identify the directions towards new, more exotic, and unexplored quantum kernel families.

QI 9.9 Tue 12:00 HFT-FT 101

**A Multi-Excitation Projective Simulation Learning Agent** — •Philip LeMaitre, Marius Krumm, and Hans Briegel — Universität Innsbruck, Institut für Theoretische Physik, Innsbruck, Austria

The rapid integration of artificial intelligence (AI) into daily life, driven by advanced large language models such as ChatGPT, highlights a critical question in AI research: how can we comprehend an AI's decision-making process that leads to specific outcomes? To address this question, the field of explainable AI emerges as vital, with the projective simulation reinforcement learning framework being a notable component. An extension of this framework is considered to enable the AI agent to process multiple variables concurrently, enhancing its ability to discern complex correlations within its environment. Additionally, an inductive bias inspired from quantum many-body expansions of the Hamiltonian is introduced. This bias focuses on smaller clusters of memory states during decision-making, balancing the increased complexity inherent in the extended model. The enhanced framework is then applied to two distinct learning scenarios: a simple defence game featuring deceptive strategies by the attacker, and a more complex scenario mimicking computer diagnostics and maintenance tasks. In both contexts, the agent successfully learns optimal policies by leveraging higher-order correlations. Furthermore, a preliminary overview of the quantum variant of the model is provided, offering a more realistic model for future explorations in explainable quantum AI.

QI 9.10 Tue 12:15 HFT-FT 101

**On the average-case complexity of learning output distributions of quantum circuits** — Alexander Nietner[1], Marios Ioannou[1], Ryan Sweke[1,3], Richard Kueng[2], Jens Eisert[1], •Marcel Hinsche[1], and Jonas Haferkamp[1,4] — [1]FU Berlin — [2]JKU Linz — [3]IBM Quantum — [4]Harvard University

In this work, we show that learning the output distributions of brickwork random quantum circuits is average-case hard in the statistical query model, which models most practical algorithms. Our main results are:

- At super logarithmic circuit depth $d = \omega(\log(n))$, any learning algorithm requires super polynomially many queries to achieve a constant probability of success over the randomly drawn instance.
- There exists a $d = O(n)$, such that any learning algorithm requires $\Omega(2^n)$ queries to achieve a $\Omega(2^{-n})$ probability of success over the randomly drawn instance.
- At infinite circuit depth $d \to \infty$, any learning algorithm requires $2^{2^{\Omega(n)}}$ many queries to achieve a $2^{-2^{O(n)}}$ probability of success over the randomly drawn instance.

Moreover, we confirm a variant of a conjecture by Aaronson and Chen and show that the output distribution of a brickwork random quantum circuit is constantly far from any fixed distribution in total variation distance with probability $1 - O(2^{-n})$.

QI 9.11 Tue 12:30 HFT-FT 101

**Understanding quantum machine learning also requires rethinking generalization** — •Elies Gil-Fuster[1,2], Jens Eisert[1,2,3], and Carlos Bravo-Prieto[1] — [1]Dahlem Center for Complex Quantum Systems, Freie Universitat Berlin — [2]Fraunhofer Heinrich Hertz Institute, Berlin — [3]Helmholtz-Zentrum Berlin fur Materialien und Energie

Quantum machine learning models have shown successful generalization performance even when trained with few data. In this work, through systematic randomization experiments, we show that traditional approaches to understanding generalization fail to explain the behavior of such quantum models. Our experiments reveal that state-of-the-art quantum neural networks accurately fit random states and random labeling of training data. This ability to memorize random data defies current notions of small generalization error, problematizing approaches that build on complexity measures such as the VC dimension, the Rademacher complexity, and all their uniform relatives. We complement our empirical results with a theoretical construction showing that quantum neural networks can fit arbitrary labels to quantum states, hinting at their memorization ability. Our results do not preclude the possibility of good generalization with few training data but rather rule out any possible guarantees based only on the properties of the model family. These findings expose a fundamental challenge in the conventional understanding of generalization in quantum machine learning and highlight the need for a paradigm shift in the design of quantum models for machine learning tasks.

QI 9.12 Tue 12:45 HFT-FT 101

**More efficient exchange-only quantum gates via reinforcement learning** — •Violeta N. Ivanova-Rohling[1,2,3], Niklas Rohling[1], and Guido Burkard[1] — [1]Department of Physics, University of Konstanz — [2]Zukunftskolleg, University of Konstanz — [3]Department of Mathematical Foundations of Computer Sciences, IMI, Bulgarian Academy of Sciences

There has recently been rapid progress in the research of spin qubits [1], including the realization of exchange-only qubits [2,3]. Here, we use reinforcement learning to optimize the efficiency of exchange-based pulse sequences that encode the universal two-qubit gates CNOT and CZ with nearest-neighbor interaction for quantum dot arrangements in a chain and in a 2 by 3 grid. We improve on gate sequences currently known in the literature. Specifically, with our reinforcement learning framework, we manage to find a gate sequence encoding CNOT with a shorter total time than the Fong-Wandzura sequence [4] which is currently state of the art. Moreover, the flexibility of our approach makes it applicable for gate-sequence optimization for a variety of desired quantum gates and a variety of different connection topologies.

[1] Burkard, Ladd, Pan, Nichol, Petta, Rev. Mod. Phys. **95**, 025003 (2023)
[2] DiVincenzo, Bacon, Kempe, Burkard, Whaley, Nature **408**, 339 (2000)
[3] Weinstein et al., Nature **615**, 817 (2023)
[4] Fong, Wandzura, Quantum Info. Comput. **11**, 1003 (2011)

QI 9.13 Tue 13:00 HFT-FT 101

**The Mean King's Problem as a learning task** — •Niklas Rohling — Department of Physics, University of Konstanz

The Mean King's Problem [1-5] is an early example of an advantage due to the availability of additional quantum resources. This original version of the problem is a single-shot measurement where Alice has to determine correctly the outcome of a measurement which was performed previously by the king's men. The difficulty comes from the fact that the measurement basis used by the king's men is revealed only after Alice has completed her measurement. The striking result is that Alice can find the correct answer with certainty if she is allowed to entangle the state initially with an additional quantum system. Here, we formulate the Mean King's Problem as a learning task where several copies of the state after the king's men's measurement, sorted by their outcome, are available. We investigate how the number of copies required to determine the measurement outcome of the king's men within desired error bounds $\varepsilon$ and success probability $1-\delta$ scales with system size when additional quantum resources are (or are not) allowed to be used. We compare to the exponential advantage of quantum-enhanced learning found recently for measurements in product bases [6].

[1] Vaidman, Aharonov, Albert, PRL **58**, 1385 (1987)
[2] Aharonov, Englert, Z. Naturforsch. **56a**, 16 (2001)
[3] Englert, Aharonov, Physics Letters A **84**, 1 (2001)
[4] Aravind, Z. Naturforsch. **58a**, 682 (2003)
[5] Durt, Int. J. Mod. Phys. B **20**, 1742 (2006)
[6] Huang et al., Science **376**, 1182 (2022)

## QI 10: Focus Session: Exploring Quantum Entanglement with Superconducting Qubits and Resonators (joint session QI/TT)

Harnessing quantum entanglement is crucial for advancing quantum technologies, and superconducting qubits and resonators have shown great promise in this regard. Impressive progress is contemporarily made in generating access to intermediate-scale quantum circuits, for the exploration of applications. These advancements highlight the progress and potential of superconducting qubits in harnessing quantum entanglement, paving the way for further progress in quantum communication, computation, and sensing. Organized by Oded Zilberberg.

Time: Tuesday 9:30–13:30 Location: HFT-FT 131

**Invited Talk** QI 10.1 Tue 9:30 HFT-FT 131

**Loophole-free Bell Inequality Violation with Superconducting Circuits** — •Andreas Wallraff — Department of Physics, ETH Zurich, Switzerland

Superposition, entanglement, and non-locality constitute fundamental features of quantum physics. Remarkably, the fact that quantum physics does not follow the principle of locality can be experimentally demonstrated in Bell tests performed on pairs of spatially separated, entangled quantum systems. While Bell tests were explored over the past 50 years, only relatively recently experiments free of so-called loopholes succeeded. Here, we demonstrate a loophole-free violation of Bell's inequality with superconducting circuits [1]. To evaluate a CHSH-type Bell inequality, we deterministically entangle a pair of qubits and perform fast, and high-fidelity measurements along randomly chosen bases on the qubits connected through a cryogenic link spanning 30 meters. Evaluating more than one million experimental trials, we find an average S-value of 2.0747 * 0.0033, violating Bell's inequality by more than 22 standard deviations. Our work demonstrates that non-locality is a viable new resource in quantum information technology realized with superconducting circuits with applications in quantum communication, quantum computing and fundamental physics.

[1] S. Storz, J. Schär, A. Kulikov, P. Magnard, P. Kurpiers, J. Lütolf, T. Walter, A. Copetudo, K. Reuer, A. Akin, J-C. Besse, M. Gabureac, G. J. Norris, A. Rosario, F. Martin, J. Martinez, W. Amaya, M. W. Mitchell, C. Abellán, J-D. Bancal, N. Sangouard, B. Royer, A. Blais, and A. Wallraff, Nature 617, 265-270 (2023).

Work done in collaboration with Simon Storz, Josua Schaer, Anatoly Kulikov, Paul Magnard, Philipp Kurpiers, Janis Luetolf, Theo Walter, Adrian Copetudo, Kevin Reuer, Abdulkadir Akin, Jean-Claude Besse, Mihai Gabureac, Graham J. Norris, Andres Rosario, Ferran Martin, Jose Martinez, Waldimar Amaya, Morgan W. Mitchell, Carlos Abellan, Jean-Daniel Bancal, Nicolas Sangouard, Baptiste Royer, Alexandre Blais, and Andreas Wallraff

**Invited Talk** QI 10.2 Tue 10:00 HFT-FT 131

**Microwave quantum networks** — •Kirill G. Fedorov — Walther-Meißner-Institut, 85748 Garching, Germany — School of Natural Sciences, Technische Universität München, 85748 Garching, Germany — Munich Center for Quantum Science and Technology (MC-

QST), 80799 München, Germany

Distributing quantum entanglement between distant nodes of a large-scale network is a fundamentally important milestone for many applications in the field of quantum information processing. Here, entanglement in the form of two-mode squeezed light can be employed as a resource for various nonclassical communication protocols, such as quantum teleportation or remote qubit entanglement. Motivated by the recent breakthroughs in quantum computation & simulation with superconducting circuits operated at microwave frequencies, we demonstrate distribution of two-mode squeezed states at carrier frequencies around 5.5 GHz across a local area cryogenic quantum network. We present the experimental evidence for robustness of the microwave entanglement distribution against noise and losses in superconducting channels. Furthermore, we utilize this entanglement resource to perform a coherent state teleportation between distant cryostats with fidelities exceeding the no-cloning limit. Finally, by relying on the same technology and frequency range, we discuss remote entanglement of superconducting qubits with two-mode squeezed microwave light. Our results highlight feasibility of microwave quantum communication and pave the road towards distributed quantum computing with superconducting circuits.

QI 10.3 Tue 10:30 HFT-FT 131

**Investigation of hybrid CV-DV entanglement in the microwave regime** — •Simon Gandorfer[1,2], Yuki Nojiri[1,2], Fabian Kronowetter[1,2], Kedar E. Honasoge[1,2], Maria-Teresa Handschuh[1,2], Joan Agustí[1,2], Peter Rabl[1,2,3], Rudolf Gross[1,2,3], and Kirill G. Fedorov[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]School of Natural Sciences, Technische Universität München, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany

Distributing entanglement between spatially separated nodes of a large-scale quantum network is a fundamentally important milestone for many applications. It also provides the quantum resource for various quantum protocols, such as quantum teleportation or remote qubit gate operations. In our experiment, we employ a superconducting transmon qubit in a superconducting 3D aluminium cavity illuminated by one mode of a microwave two-mode squeezed (TMS) state. Here, the TMS state acts as a quantum-correlated reservoir. By choosing an appropriate set of observables, we identify a joint measurement between the qubit and the second mode of the TMS state that allows us to observe a hybrid, discrete-continuous variable, entanglement. We experimentally investigate the entanglement conversion process in this novel hybrid regime and discuss its possible extensions and applications for distributed quantum computing.

QI 10.4 Tue 10:45 HFT-FT 131

**Parametric coupler architecture for on-demand reset, readout and leakage recovery of superconducting qubits** — •Gerhard Huber[1,2], Federico Roy[2,3], Joao Romeiro[1,2], Leon Koch[1,2], Niklas Bruckmoser[1,2], Niklas Glaser[1,2], Ivan Tsitsilin[1,2], Max Werninghaus[1,2], and Stefan Filipp[1,2] — [1]Technical University of Munich, Physics Department, 85748 Garching, Germany — [2]Walther-Meißner-Institut, 85748 Garching, Germany — [3]Theoretical Physics, Saarland University, 66123 Saarbrücken, Germany

When using superconducting qubits thermal excitations of the initial state, leakage into non-computational states during gate operations and unwanted decoherence due to coupling to a readout mode are, however, major sources of errors. Here, we present a superconducting qubit architecture with tunable qubit-resonator coupling. This architecture allows for the efficient preparation of the qubit ground state, the recovery of leakage from higher states and for on-demand qubit readout activated by a single parametric coupler. We experimentally demonstrate a reset operation that unconditionally prepares the qubit ground state with a fidelity of $99.8 \pm 0.02$ % and a leakage recovery operation with a $98.5 \pm 0.3$ % success probability. Furthermore, we implement a coupler-driven readout with a single-shot assignment fidelity of $88 \pm 0.4$ %. Completing this set of elementary operations with qubit-qubit gates using the same coupling element, reduces the system complexity and facilitates the implementation of scalable quantum processors.

QI 10.5 Tue 11:00 HFT-FT 131

**Novel 3D circuit QED architecture for quantum information processing** — •Desislava Atanasova[1,2], Ian Yang[1,2], Teresa Hönigl-Decrinis[1,2], Daria Gusenkova[3], Ioan Pop[3], and Gerhard Kirchmair[1,2] — [1]Institute for Quantum Optics and Quantum Information, A-6020 Innsbruck, Austria — [2]Institute for Experimental Physics, University of Innsbruck, A-6020 Innsbruck, Austria — [3]Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Superconducting circuits based on 3D architectures offer a way for hardware-efficient quantum information processing. Combined with nonlinearity, a single bosonic mode can replace a multi-qubit register, thus significantly reducing the required control electronics. Compared to their purely planar counterpart, 3D circuits possess longer lifetimes and a straightforward design that eases engineering the interactions in composite systems.

In this work, a superconducting coaxial cavity is coupled to a fluxonium qubit via a readout resonator. The tunability of the qubit, provided by a magnetic flux hose, is used to adjust the cavity-qubit interaction in situ. Combined with an element for two-photon dissipation, this setup could be utilized as an improved building block for a fully protected logical qubit.

**15 min. break**

**Invited Talk** QI 10.6 Tue 11:30 HFT-FT 131

**Quantum sensing of axionic dark matter with a phase resolved haloscope** — •Audrey Cottet — LPEM, ESPCI Paris — LPENS, Ecole Normale Supérieure de Paris

There is a general consensus that a large part of the matter and energy in the Universe is unknown. Well established candidates for dark matter are axions or axion-like particles. Their interaction with particles of the standard model is expected to be very weak. Hence, their detection requires ultimate amplification and measurement techniques. Quantum sensing is appealing in that context. We propose a new type of detector based on a non-linear quantum cavity coupled to a tunable magnetic mode. In order to circumvent the standard quantum limit of detection, we propose to exploit the phase-number variables of the electromagnetic field. The sensitivity of the detector can be pushed further by exploiting interference fringes in a cavity Schrödinger cat state. We expect a figure of merit exceeding by several orders of magnitude that of current detectors. This opens the way to real-time detection of possible axion signals. I will present how these ideas are being implemented experimentally using a hybrid cavity/magnon/superconducting circuit platform.

**Invited Talk** QI 10.7 Tue 12:00 HFT-FT 131

**Demonstration of Quantum Advantage in Microwave Quantum Radar** — Réouven Assouly, Rémy Dassonneville, Théau Péronnin, •Audrey Bienfait, and Benjamin Huard — Laboratoire de Physique à l'ENS Lyon, Lyon, France

The quantum radar promises to improve the speed of detection of a target placed in a noisy background by a factor of up to 4 in the low power regime compared to best possible classical radar. Observing this quantum advantage requires exploiting the quantum correlations through a joint measurement of the initially entangled probe and the idler which has never been performed in the previous microwave quantum radar attempts. Following a proposal by Guha and Erkmen [1], we demonstrate a quantum advantage of up to 1.2+/-0.1 in a proof-of-principle quantum radar operating at microwave frequencies.

Using a dual-purpose quantum emitter/receiver based on a Josephson ring modulator, we are able to generate two-mode squeezed states as well as perform the required joint measurement between the idler and the noisy reflected signal. After generation, the idler is stored in a memory mode while the signal half is emitted into a transmission line, goes through a tunable target after which it comes back to the quantum transceiver where it can be jointly measured with the idler using a two-mode squeezing operation followed by a photon-counting measurement via an auxiliary transmon qubit.

[1] Guha, S., Erkmen, B.I., Phys. Rev. A 80, 052310 (2009)

QI 10.8 Tue 12:30 HFT-FT 131

**Hot Schrodinger Cat States in a High Coherence Niobium Cavity Coupled to a Superconducting Qubit** — •Ian Yang[1,2], Thomas Agrenius[2,3], Vasilisa Usova[1,2], Oriol Romero-Isart[2,3], and Gerhard Kirchmair[1,2] — [1]Institute for Experimental Physics, University of Innsbruck, 6020 Innsbruck, Austria — [2]Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, 6020 Innsbruck, Austria — [3]Institute for Theoretical Physics, University of Innsbruck, Innsbruck 6020, Austria

The observation of quantum phenomena often necessitates sufficiently pure states. The standard paradigm for creating pure states has been to cool the system of interest to the ground state or decouple it sufficiently from any hot thermal bath. This requirement can be challenging to achieve.

In this study, we prepare a non-classical state originating from a mixed state, utilising dynamics that preserve the initial purity of the state. We generate a Schrodinger cat state within a high-coherence microwave cavity, operating at a mode temperature of up to two Kelvin, which is one hundred times hotter than its environment.

Our experimental findings have implications in generating nonclassical states for other bosonic degrees of freedom such as in the motion of a massive particle. Furthermore, they reduce the purity requirements of the initial state.

QI 10.9 Tue 12:45 HFT-FT 131

**Material losses characterization in superconducting resonators based on $\alpha$ and $\beta$ Tantalum** — •Ritika Dhundhwal[1], Haoran Duan[2], Lucas Brauch[1], Soroush Arabi[1], Qili Li[3], Sudip Pal[6], Jose Palomo[5], Dirk Fuchs[1], Alexander Welle[4], Mark Scheffler[6], Zaki Leghtas[5], Jasmin Aghassi-Hagmann[2], Christian Kübel[2], Wulf Wulfhekel[1], Ioan M. Pop[1,3,6], and Thomas Reisinger[1] — [1]IQMT, KIT — [2]INT, KIT — [3]PHI, KIT — [4]IFG, KIT — [5]ENS, Paris — [6]Uni Stuttgart

Implementation of tantalum as a new material platform in transmon qubit has shown promising results with coherence time exceeding 0.3 ms[1]. To understand the underlying cause for record breaking coherence times, the main focus has been on use of alpha phase tantalum to achieve high quality qubits and resonators whereas the beta phase remains largely unexplored. In this work, we compare internal quality factor in lumped element resonators as a function of photon number and temperature. We use various material characterization tools to investigate surface and bulk properties of tantalum. Further, we vary the energy participation ratio in tantalum metal-substrate and metal-air interfaces to estimate the loss tangent and get insight into dominant loss mechanism. [1] Place, A.P.M., Rodgers, L.V.H., Mundada, P. et al. Nat Commun 12, 1779 (2021).

QI 10.10 Tue 13:00 HFT-FT 131

**Quantum phases in frustrated arrays of Josephson junctions: Effective $XY$ spin models** — •Benedikt Pernack, Mikhail V. Fistul, and Ilya M. Eremin — Theoretische Physik III, Ruhr-Universität Bochum, Bochum, Germany

Motivated by experiments on superconducting qubit networks [1,2], we present here a detailed analysis of collective quantum phases occurring in *frustrated* quasi-$1D$ saw-tooth arrays of small (quantum) Josephson junctions ($f$-$JJA$s). Frustration is introduced through the periodic arrangement of 0- and $\pi$-Josephson junctions with the Josephson coupling energies of different signs. In the frustrated regime the classical ground state is highly degenerate and formed by various patterns of vortex/antivortex penetrating each basic cell of an $f$-$JJA$.

In the quantum frustrated regime using the variational approach we derive an effective $XY$ spin Hamiltonian. Depending on the length $L$ of an $f$-$JJA$ we obtain two very different regimes: a) $L \ll L_{cr} = \sqrt{C/C_0}$, where $C$ and $C_0$ are a 0-Josephson junction and superconducting island capacitances, accordingly, the quantum superposition of vortex and antivortex in a single cell dominates; b) $L \gg L_{cr} = \sqrt{C/C_0}$, the quantum superposition of vortex and antivortex is strongly suppressed, and a long (short) exchange interaction is established. In latter case using mean-field analysis and numerical diagonalization of the effective $XY$ spin model, we characterize quantum phases in various $f$-$JJA$s.

QI 10.11 Tue 13:15 HFT-FT 131

**Frustrated $2D$-Josephson junction arrays with topological constraints** — •Oliver Neyenhuys, Mikhail V. Fistul, and Ilya M. Eremin — Theoretische Physik III, Ruhr-Universität Bochum, Bochum 44801, Germany

Geometrical frustration in correlated systems can give rise to a plethora of ordered states and intriguing phases. We theoretically analyze a subset of vertex-sharing frustrated lattices, built up by corner sharing superconducting triangles interrupted by 0-Josephson junctions on two edges and a $\pi$-Josephson junction on the third edge. Such lattices have multiple degenerate free energy minima composed of different patterns of vortices/antivortices ($V/AV$) penetrating each triangle. Exemplary for the Kagome lattices with periodically arranged 0- and $\pi$-Josephson junctions, we identify various classical and quantum phases. We derive an effective Ising-type spin Hamiltonian, describing the interaction between $V/AV$s. Strongly anisotropic long-range interactions between well separated $V/AV$s emerge from the constraints due to flux quantization in any hexagon loop. In the classically frustrated regime, we calculate the temperature-dependent spatially averaged spin polarization $m(T)$ characterizing the crossover between the ordered and disordered $V/AV$ states. In the coherent quantum regime, we analyze the lifting of the degeneracy of the ground state and the appearance of the highly entangled states[1].

[1] O. Neyenhuys, M. Fistul and I. Eremin, Long-range Ising spins models emerging from frustrated Josephson junctions arrays with topological constraints, PhysRevB.108.165413 (2023)

## QI 11: Quantum Thermodynamics

Time: Tuesday 9:30–11:45 Location: HFT-TA 441

QI 11.1 Tue 9:30 HFT-TA 441

**Fermionic one-body entanglement as a thermodynamic resource** — •Krzysztof Ptaszyński[1,2] and Massimiliano Esposito[1] — [1]Complex Systems and Statistical Mechanics, Department of Physics and Materials Science, University of Luxembourg, L-1511 Luxembourg, Luxembourg — [2]Institute of Molecular Physics, Polish Academy of Sciences, Mariana Smoluchowskiego 17, 60-179 Poznań, Poland

There is a controversy about whether a pure state of a single fermion delocalized between two modes (e.g., quantum dots) should be regarded entangled or not, that is, whether the quantum correlations encoded in such a state are operationally accessible and useful as a resource. This has been questioned on the basis that such an entanglement cannot be accessed by local operations on individual modes due to the parity superselection rule which constrains the set of physical observables. In other words, one cannot observe violations of Bell's inequality.

Here we approach this issue from the perspective of quantum thermodynamics [1]. We show that a single-particle fermionic state can be used in open-system thermodynamic processes, enabling one to perform tasks forbidden for separable (non-entangled) states. Therefore, its entanglement is a genuine quantum resource with a clear physical manifestation. Our work thus shows that quantum thermodynamics may be a useful theoretical framework to shed light on unsolved problems of quantum information theory.

[1] Phys. Rev. Lett. 130, 150201 (2023)

QI 11.2 Tue 9:45 HFT-TA 441

**Role of nonequilibrium fluctuations and feedback in a quantum dot thermal machine** — •Juliette Monsel[1], Nicolas Chiabrando[1,2], Matteo Acciai[1], Robert Whitney[3], Rafael Sánchez[4], and Janine Splettstoesser[1] — [1]Dept. of Microtechnology and Nanoscience, Chalmers University of Technology, Göteborg, Sweden — [2]École Normale Supérieure de Lyon, Lyon, France — [3]Université Grenoble Alpes, CNRS, LPMMC, Grenoble, France — [4]Universidad Autónoma de Madrid, Madrid, Spain

Steady-state thermoelectric engines can be operated using various resources, including information and nonequilibrium resources, even without any average particle or energy flow from the resource into the working substance. In those cases, fluctuations in the currents clearly play a key role in the performance of the engine. We study a three-quantum dot setup in which one dot is coupled to two electronic reservoirs at different chemical potentials (the working substance) while the other two dots are in contact with a hot reservoir and a cold reservoir respectively (the resource). The temperature difference between these two reservoirs creates nonequilibrium conditions in the resource allowing for work production in the form of a steady-state current against the potential bias in the working substance. Simultaneously, the capacitive coupling between the dots creates an autonomous feedback mechanism which can participate in the work extraction and be interpreted as an autonomous Maxwell demon scheme. We investigate the respective roles of the information flow and nonthermal fluctuations in the performance of this engine.

QI 11.3 Tue 10:00 HFT-TA 441

**Coherent effects in the path integral formulation of quantum work.** — Nicolás Torres-Domínguez and •Carlos Viviescas — Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia

A proper definition of work and heat remains a relevant issue in the framework of quantum thermodynamics. The usual approach to this problem is through the two-point measurement (TPM) scheme, which, despite its relevant role in the development of the actual understanding of work statistics in the quantum regime, has a fundamental limitation: Due to energy projective measurements it involves, the effects that the initial coherences may have on the energetics of the system are lost. The Margenau-Hill (MH) is an alternative scheme that offers a bypass to this problem and retains the coherences in the initial state. In this work we introduce a path integral formulation for work in the MH scheme, which provides further insight on the role of initial coherences in quantum thermodynamic setups, and paves the way for a semiclassical study of the quantum work distribution.

QI 11.4 Tue 10:15 HFT-TA 441

**The Thermomajorization Polytope and its Degeneracies** — Frederik vom Ende[1] and •Emanuel Malvetti[2,3] — [1]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — [2]School of Natural Sciences, Technische Universität München, 85737 Garching, Germany — [3]Munich Center for Quantum Science and Technology & Munich Quantum Valley, 80799 München, Germany

In quantum thermodynamics thermal operations are considered free. Our goal is to understand which states are reachable from a given initial state using thermal operations. In the quasi-classical case of diagonal states the problem reduces to understanding the thermomajorization polytope. By drawing a connection between the polytope of Gibbs-stochastic matrices and transportation polytopes we study the degeneracies of the thermomajorization polytope and as a consequence we can characterize in which cases cyclic state transfers are possible.

**15 min. break**

QI 11.5 Tue 10:45 HFT-TA 441

**Thermodynamic concepts in autonomous quantum systems** — •Anja Seegebrecht and Tanja Schilling — University Freiburg, Freiburg, Germany

Physically sound definitions of thermodynamic quantities for open quantum systems pose a challenge. They are at best available for the weak coupling regime where the reduced dynamics can be described by Markov master equations. To extend concepts like internal energy, work and heat to processes with strong interactions and memory effects, the canonical form of the time-convolutionless master equation offers a promising possibility. This unique time-local representation has Lindblad-like structure with a Hamiltonian and a dissipator. It is obtained by minimisation of the dissipative part of the dynamics. Accordingly, it characterizes the dissipation and non-Markovianity. The identification of thermodynamic energies follows the typical method that internal energy is the expectation value of the effective Hamiltonian of the system. Changes of this local energy can be split into a part that relates to entropy variation and a part that does not, namely heat and work contributions. We contrast the minimal dissipation definition with three different approaches for autonomous systems. They are also based on this strategy but propose different decompositions of the dynamics. The comparison highlights the benefits of the canonical form.

QI 11.6 Tue 11:00 HFT-TA 441

**Complexity-constrained quantum thermodynamics** — Anthony Munson[1,2], Naga Teja Bhavya Kothakonda[3,4], Jonas Haferkamp[5], Nicole Yunger Halpern[1,2], Jens Eisert[4], and •Philippe Faist[4] — [1]Joint Center for Quantum Information and Computer Science, NIST and University of Maryland, College Park, MD 20742, USA — [2]Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742, USA — [3]Physics Department, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain — [4]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — [5]School of Engineering and Applied Sciences, Harvard University, MA 02134, USA

Complexity measures the difficulty of realizing a quantum process, such as preparing a state or implementing a unitary. We present an approach to quantifying the thermodynamic resources required to implement a process if the process's complexity is restricted. reset to the all-zero state. We show that the minimal thermodynamic work required to reset an arbitrary state to the all-zero state (Landauer erasure), if the process cannot exceed some complexity threshold, is quantified by the state's *complexity entropy*. We prove elementary properties of the complexity (relative) entropy and determine the complexity entropy's behavior under random circuits. Also, we identify information-theoretic applications of the complexity entropy. Overall, our approach extends the resource-theoretic approach to thermodynamics to integrate a notion of *time*, as quantified by *complexity*.

QI 11.7 Tue 11:15 HFT-TA 441

**Storing work in thermal equilibrium: ergotropy of mean-force Gibbs states** — •Karen Hovhannisyan[1] and Janet Anders[1,2] — [1]University of Potsdam, Institute of Physics and Astronomy, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany — [2]Department of Physics and Astronomy, University of Exeter, Stocker Road, Exeter EX4 4QL, UK

Subsystems of a strongly-interacting many-body system are not in Gibbs states when the system is in thermal equilibrium as a whole. Such non-Gibbsian states can store work in the form of ergotropy. We use this observation to devise a quantum battery that is simply a detachable subsystem of a many-body lattice. The charging cycle consists of connecting the subsystem, letting it equilibrate, and then disconnecting and extracting work from it. This cycle requires very little external control and the charged state of the battery, being a part of global thermal equilibrium, can be maintained indefinitely and for free. As out system we use 1D and 2D harmonic lattices with strong long-range interactions. We show that the stored work, quantified by the Gaussian ergotropy, can increase polynomially with the size of the subsystem, showing that this setup can be potentially useful in practical implementations of noise-robust quantum batteries.

QI 11.8 Tue 11:30 HFT-TA 441

**Towards a local version of the second law of thermodynamics** — •Ahana Ghoshal[1,2] and Ujjwal Sen[2] — [1]University of Siegen, Germany — [2]Harish-Chandra Research Institute, India

A local version of the second law of thermodynamics is undoubtedly a fundamentally important area of research, and is all the more important with the advent of quantum devices and networks. Here we intend to provide two investigations in this direction. In the first part, we define and study two thermodynamical quantities: the heat current deficit and the entropy production rate deficit, which are differences between the global and local versions of the corresponding quantities. The investigation leads, in certain cases, to a complementarity of the time-integrated heat current deficit and the relative entropy of entanglement between the two systems. In the second part, we obtain the Gorini-Kossakowski-Sudarshan-Lindblad master equation for two or more quantum systems connected locally to a combination of Markovian and non-Markovian heat baths. We analyze the thermodynamic quantities for such a mixed set of local environments, and derive a modified form of the Spohn's theorem for that setup. The modification of the theorem naturally leads to a witness as well as an easily computable quantifier of non-Markovianity.

# QI 12: Poster I

Time: Tuesday 11:00–14:30 Location: Poster B

QI 12.1 Tue 11:00 Poster B

**Entanglement informed construction of variational quantum circuits in the context of circuit cutting** — •Alina Joch[1,2] and Benedikt Fauseweh[1,2] — [1]DLR, Cologne, Germany — [2]TU Dortmund, Dortmund, Germany

Circuit cutting is a method to divide a quantum circuit into smaller parts and solve these parts separately. The method is only reasonable for few cuts due to the exponential overhead in classical information exchange between the different parts. We look at two spin chain models, both with an additional impurity at the central spin of the chain, forming an entanglement barrier. We then benchmark the accuracy of the ground state energy of these models obtained by a variational quantum eigensolver with finite-depth quantum circuit with varying number of entanglement gates with the central spin. After a certain number of layers, plateaus are formed whose values only depend on the absolute number of entanglement gates with the central spin. We analyze the dependence of the achieved accuracy on the number and localization of entangling gates. We identify model parameters in which a low number of entangling gates is sufficient to achieve high accuracy, allowing for efficient circuit cutting.

QI 12.2 Tue 11:00 Poster B

**Kibble-Zurek scaling in the presence of quantum many body scar states** — •Lukas Windgätter[1] and Benedikt Fauseweh[1,2] — [1]Deutsches Zentrum für Luft und Raumfahrt, Linder Höhe, 51147 Köln, Germany — [2]TU Dortmund, Fakultät für Physik, Otto-Hahn-Straße 4, 44227 Dortmund, Germany

The Kibble-Zurek (KZ) mechanism describes the formation of topological defects in a physical system that is driven across a continuous phase transition. These topological defects arise due to the diverging correlation length and relaxation time at the critical point and their number scales with the rate at which the system is driven across its transition. Due to its nature, the KZ mechanism provides an excellent test for quantum annealing simulations. Indeed it has recently been shown via the KZ scaling, that the newest generation of quantum annealers are capable of coherently simulating spin systems such as the one dimensional Ising chain. A fundamental question concerns the interplay of the KZ mechanism with non-ergodic systems, such as quantum many-body scar states. In our work we are investigating the KZ-mechanism in the presence of such quantum many body scar states in the one dimensional Ising ladder. We present results how the scar states alter the KZ effect and the onset of decoherence using both classical simulations employing matrix product states and coherent quantum annealing simulations.

QI 12.3 Tue 11:00 Poster B

**Scalable and Exponential Quantum Error Mitigation of BQP Computations using Verification** — Joseph Harris[1] and •Elham Kashefi[2] — [1]German Aerospace Center, Cologne, Germany — [2]School of Informatics, University of Edinburgh, Scotland

We present a scalable and modular error mitigation protocol for running BQP computations on a quantum computer with time-dependent noise. Utilising existing tools from quantum verification, our framework interleaves standard computation rounds alongside test rounds for error-detection and inherits a local-correctness guarantee which exponentially bounds (in the number of circuit runs) the probability that a returned classical output is correct. On top of the verification work, we introduce a post-selection technique we call basketing to address time-dependent noise behaviours and reduce overhead. The result is a first-of-its-kind error mitigation protocol which is exponentially effective and requires minimal noise assumptions, making it straightforwardly implementable on existing, NISQ devices and scalable to future, larger ones.

QI 12.4 Tue 11:00 Poster B

**Simulating the critical ground state of spin chains: An ansatz study on accuracy scaling and efficacy of the Variational Quantum Eigensolver** — •Bavithra Govintharajah[1,3] and Benedikt Fauseweh[1,2] — [1]German Aerospace Center (DLR), Institute for Software Technology, Linder Höhe, 51147 Köln — [2]TU Dortmund University, Department of Physics, Otto-Hahn-Str 4, 44227 Dortmund — [3]RWTH Aachen University, Department of Physics, Otto-Blumenthal-Straße, 52074 Aachen

Where the limits of variational quantum algorithms lie is a crucial question that needs to be answered in the Noisy Intermediate Scale Quantum (NISQ) era. The simulation of quantum-integrable models is a great tool to not only find an answer to this question but also to benchmark current hardware platforms to steer the research forward. The success of such simulations using the Variational Quantum Eigensolver (VQE) relies heavily on the choice of the parameterized quantum circuit used as the ansatz to estimate expectation values. We study this aspect by comparing various heuristic ansaetze with a theoretically motivated model aware ansatz. We analyze the ansatz dependent accuracy of critical ground state energy calculations by applying it to the Transverse Field Ising and the Heisenberg spin chain hamiltonians.

QI 12.5 Tue 11:00 Poster B

**Coherence as a resource for phase estimation** — •Felix Ahnefeld[1], Thomas Theurer[2], and Martin B. Plenio[1] — [1]Institut für Theoretische Physik, Universität Ulm — [2]Department of Mathematics and Statistics, Institute for Quantum Science and Technology, University of Calgary

Quantum phase estimation is a vital subroutine for several quantum algorithms that promise super-polynomial speedups compared to the best-known classical algorithm. Given a fixed number of copies of a black box unitary, the goal is to estimate an eigenvalue of the unitary, i.e., a phase factor, as precisely as possible. Quantum mechanical strategies can outperform classical estimation strategies and the question arises which resources allow for such an advantage. We address this question by investigating a family of constrained phase estimation protocols whose performance is measured with respect to the average cost of a generic cost function that penalizes deviations of the phase estimates to the true value. We quantitatively link the performance of the protocol with so-called measures of quantum coherence that are rigorously defined within the framework of a quantum resource theory. We show that for every non-trivial cost function, which one can think of as the specific task phase estimation should solve, coherence grants an operational advantage compared to classical strategies. Lastly, we provide universal bounds on the average cost in terms of the number of the query size and the provided coherence.

QI 12.6 Tue 11:00 Poster B

**Quantum Simulation of Quantum Link Model on Ladder Geometry** — •Sabhyata Gupta, Younes Javanmard, Luis Santos, and Tobias Osborne — Institut für Theoretische Physik - Leibniz Universität Hannover

Lattice Gauge Theory (LGT) stands as a cornerstone in the edifice of theoretical physics. LGTs, however, present a formidable computational challenge due to their intricate nature, requiring substantial computational resources. This work underscores the profound potential of quantum simulation as a transformative tool within the domain of lattice gauge theory. Using physical constraints on the Hilbert space enforced by Gauss law in U(1) (2+1)-d LGT, we formulate the problem efficiently to study its dynamics on a NISQ device. We employ state of the art techniques like fast-forwarding, and scaled quantum gates to achieve longer simulation of a large system.

QI 12.7 Tue 11:00 Poster B

**Quantum processors for reinforcement learning** — •edison argüello and sabine wölk — DLR (Deutsches Zentrum für Luft- und Raumfahrt)

Many quantum algorithms, such as e.g. the implementation of the hybrid learning agent described by Hamann and Wölk,[1] require conditional multiqubit gates such as the Toffoli gate. A standard implementation of the Toffoli gate can be constructed from single qubit T- and Hadamard-gates and a minimum of 6 CNOT gates. However, in present quantum computer hardware, CNOT-gates are one of the main sources of errors prohibiting conditional quantum gates with a large number of control-qubits. In this poster, we present our investigation about a more direct implementation of a Toffoli gate in a fully coupled 3-qubit system with a Ising-like interaction. We expect that this new approach will reduce the Toffoli gate time and thus the resulting error compared to an implementation based on CNOT-gates.

**References**
1. Hamann A., Wölk S. (2022). Performance analysis of a hybrid agent for quantum-accessible reinforcement learning. New Journal of Physics 24(3), 033044.

QI 12.8 Tue 11:00 Poster B

**Noise-protected quantum state transfer between distant nodes in a quantum network** — •Syeda Aliya Batool[1,2,3] and Peter Rabl[1,2,3] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, 85748 Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany

We propose and analyze the implementation of a noise-resilient qubit-photon interface for advancing long-distance quantum communication. The considered network consists of two unidirectionally coupled quantum nodes, where each node comprises of qubit coupled to an optical cavity. The transmission protocol is implemented by generating time-symmetric pulses on both nodes under ideal conditions. In this way, the state of the qubit coupled to the input node is mapped onto the time-symmetric photon wave packet that propagates through the channel and can then be absorbed by the qubit coupled to the output node. To address the detrimental effect of low-frequency noise on this protocol, we employ a continuous dynamical decoupling process by strongly driving the qubit with an external dressing field. This technique implements a continuous spins-echo effect, while still permitting a faithful mapping of the qubit state onto a propagating photonic qubit. This research contributes valuable insights into the development of noise-protected qubit-photon interfaces. The results provide the path for robust quantum communication protocols, establishing a foundation for secure quantum information transfer across extended distances.

QI 12.9 Tue 11:00 Poster B

**On the generalisation of dynamic decoupling sequences for quantum systems** — •Colin Read[1] and John Martin[2] — [1]Institut de Physique Nucléaire, Atomique et de Spectroscopie, CESAM, Université de Liège, Belgium — [2]Institut de Physique Nucléaire, Atomique et de Spectroscopie, CESAM, Université de Liège, Belgium

Although qubits are the most common elementary quantum systems for storing and processing quantum information, current efforts aim at using quantum systems with more than two levels (qudits) to enhance the performance of certain quantum technologies. The main challenge to the realisation of most quantum technologies (both qubit and qudit-based) is decoherence, that is the loss of information in the environment generated by an unwanted interaction of the system with its environment. While many schemes have been developed to correct or mitigate errors in qubit systems due to decoherence, similar schemes for qudits are still very little explored. One such scheme, named Dynamical Decoupling (DD), aims at periodically interacting with the quantum system by means of a carefully designed sequence of pulses in order to average out this interaction. In this work, we present some results on the qudit generalization of qubit-DD. Using several different numerical methods, we construct some qudit pulse sequences and compare them with their qubit counterpart. We also show that, by using balanced multiple driving pulses, we can directly apply known results for pulse placement optimisation to achieve a higher order of decoherence suppression using a smaller number of pulses.

QI 12.10 Tue 11:00 Poster B

**Adaptive and provably accurate estimation of quantum expectation values using the empirical Bernstein stopping rule** — •Uğur Tepe[1], Alexander Gresch[1,2], and Martin Kliesch[1,2] — [1]Faculty of Mathematics and Natural Sciences, Heinrich Heine University Düsseldorf — [2]Hamburg University of Technology, Institute for Quantum Inspired and Quantum Optimization, Germany

Quantum computing promises exponential speed-ups across several tasks. However, a *practical* quantum advantage over classical computing is yet to be sought. Potential candidate problems stem, among others, from quantum chemistry, in which a certifiably accurate result is paramount. This, in turn, already results in a massive measurement effort due to many required measurement settings and shot noise.

In this work, we utilize an adaptive stopping algorithm, the so-called empirical Bernstein stopping (EBS) algorithm in the context of the variational quantum eigensolver (VQE). EBS provides provably accurate estimates while exploiting the empirical variance information to reduce the measurement effort required to do so. We numerically benchmark EBS against non-adaptive alternatives such as Hoeffding's inequality by setting up a VQE for the dissociation curve of the hydrogen molecule, resulting in a massively reduced measurement effort.

QI 12.11 Tue 11:00 Poster B

**Evaluating Ground State Energy with Low-Depth Quantum Circuit and High Accuracy** — Shuo Sun[1], Chandan Kumar[2], Elvira Shishenina[2], Edwin Knobbe[2], and •Christian B. Mendl[2] — [1]Technical University of Munich, Munich, Germany — [2]BMW Group, Munich, Germany

Solving electronic structure problems is widely recognized as one of the most promising applications of quantum computing. However, due to limitations imposed by the coherence time of qubits in the NISQ (Noisy Intermediate Scale Quantum) era, it's vital to design algorithms with shallow circuits.

In this project, we develop a novel Variational Quantum Eigensolver (VQE) ansatz based on the Qubit Coupled Cluster (QCC) approach, which demands optimization over only $n$ parameters rather than the usual $n+2m$ parameters, where $n$ represents the number of Pauli word time evolution gates $e^{-itP}$, and $m$ is the number of qubits involved.

We evaluate the ground state energy of $O_3$, $Li_4$ and $Cr_2$, using active space CAS(2,2), CAS(4,4) and CAS(6,6) in conjunction with the enhanced QCC ansatz, UCCSD (Unitary Coupled Cluster Single-Double) ansatz, or FCI (Full Configuration Interaction) method as the active space solver. Furthermore, we assess our enhanced QCC ansatz on two distinct quantum hardware platforms, one superconducting-based and one trapped-ion-based, and conclude with a gate count analysis on both setups.

QI 12.12 Tue 11:00 Poster B

**Upscaling quantum simulation of materials using VQE-based methods** — •Max Haas and Daniel Barragan-Yani — DLR, Cologne, Germany

Variational quantum eigensolvers (VQEs) are a promising class of algorithms to achieve quantum advantage on noisy hardware. Because of the limited circuit depth that is viable with the current hardware, improving the scalability of these algorithms is an ongoing research effort. We utilize point group symmetries that are inherent to molecules and materials in order to reduce the complexity of the simulated Hamiltonians. Furthermore we combine different state-of-the-art error mitigation techniques in order to reduce the error rates and thus increase the maximum circuit depth.

QI 12.13 Tue 11:00 Poster B

**Hybrid classical-quantum text search based on hashing** — •Farid Ablayev, Marat Ablayev, and Nailya Salikhova — Kazan, Russian Federation

We consider the problem of finding occurrences of a given substring $w$ (of length $m$) in a text *string* (of length $n$).

We propose a hybrid classical - quantum algorithm **A**, that implements Grover's search to find a given substring in a text.

What's new is that our algorithm uses the hashing technique.

- The **A** algorithm produces a result with a high probability of obtaining the correct answer.
- The **A** algorithm is based on Grover's search. This search is presented in the paper as an auxiliary algorithm **A**1 and requires $O(\sqrt{n})$ query steps.
- The **A** algorithm exponentially saves the number of qubits relative to the parameter $m$ – the length of the substring. Namely, the algorithm requires $O(\log n + \log m)$ qubits for his work.

The main idea of the paper is the use of the uniform hash family functions technique to save space complexity in quantum search. The **A** algorithm is based on a certain universal family of hash functions. The arXiv version of the article was published in November 2024 https://arxiv.org/abs/2311.01213.

QI 12.14 Tue 11:00 Poster B

**Fast Hamiltonian Learning using the Bayesian parameter shift rule** — •Jonathan Schluck[1], Lennart Bittel[2], and Martin Kliesch[3] — [1]Heinrich-Heine University, Duesseldorf, Germany — [2]Freie Universität, Berlin, Germany — [3]Hamburg University of Technology, Institute for Quantum Inspired and Quantum Optimization, Germany

Hamiltonian learning commonly refers to determining unknown parameters of a Hamiltonian from measurement data. Andi Gu et al.

have proposed an efficient protocol for the estimation of its coefficients in the Pauli basis. The measurements are given by time derivatives of certain expectation values. Such estimation problems can be solved using the parameter shift rule known in the context of variational quantum algorithms. In this work, we use an extension of the parameter shift rule based on Bayesian estimation to estimate the time derivatives from fewer measurements. We demonstrate numerically that this leads to a reduction of the total measurement effort of the Hamiltonian learning protocol.

QI 12.15 Tue 11:00 Poster B

**Relating CP divisibility of dynamical maps with compatibility of channels** — •Arindam Mitra[1,2,3], Debashis Saha[4], Samyadeb Bhattacharya[5], and Archan S. Majumdar[6] — [1]The Institute of Mathematical Sciences, Chennai, India. — [2]Homi Bhabha National Institute, Mumbai, India. — [3]Indian Institute of Technology Bombay, Mumbai, India. — [4]Indian Institute of Science Education and Research Thiruvananthapuram, Kerala, India — [5]International Institute of Information Technology-Hyderabad, Gachibowli, Hyderabad, India. — [6]S. N. Bose National Centre for Basic Sciences, Kolkata, India

The role of CP-indivisibility and incompatibility as valuable resources for various information-theoretic tasks is widely acknowledged. This study delves into the intricate relationship between CP-divisibility and channel compatibility. Our investigation focuses on the behaviour of incompatibility robustness of quantum channels for a pair of generic dynamical maps. We show that the incompatibility robustness of channels is monotonically non-increasing for a pair of generic CP-divisible dynamical maps. Further, our explicit study of the behaviour of incompatibility robustness with time for some specific dynamical maps reveals non-monotonic behaviour in the CP-indivisible regime. Additionally, we propose a measure of CP-indivisibility based on the incompatibility robustness of quantum channels. Our investigation provides valuable insights into the nature of quantum dynamical maps and their relevance in information-theoretic applications. Ref.- arXiv:2309.10806 [quant-ph]

QI 12.16 Tue 11:00 Poster B

**Symmetry-enriched measurement-only quantum circuits on a Kitaev honeycomb lattice** — •Daniel Simm, Guo-Yi Zhu, and Simon Trebst — Institute for Theoretical Physics, University of Cologne, Zülpicher Straße 77, 50937 Cologne, Germany

Quantum circuits offer unprecedented dynamical control of many-body entanglement, attracting significant attention from quantum information theorists and many-body physicists alike. Even in circuits that are built exclusively from measurements, long-range entanglement can be created through the competition of different, non-commuting measurement operators as shown in a wide variety of models. Previous work, however, primarily focused on measurement-only circuit dynamics with little to no structure. Here we investigate such symmetry-enriched quantum circuits derived from the Kitaev honeycomb model [1, 2, 3] with distinct structures in space and time and characterize the emerging, dynamically created quantum states by their entanglement structure. In doing so, we also study the analytical tractability of random Clifford circuits and discuss a possible computational complexity transition.

[1] Lavasani et al., Phys. Rev. B 108, 115135 (2023)
[2] Sriram et al., Phys. Rev. B 108, 094304 (2023)
[3] Zhu et al., arXiv:2303.17627 (2023)

QI 12.17 Tue 11:00 Poster B

**Bohmian Trajectories of Quantum Walks** — •Florian Huber[1,2,3], Carlotta Versmold[1,2,3], Jan Dziewior[1,2,3], Lukas Knips[1,2,3], Eric Meyer[4], Alexander Szameit[4], and Jasmin D. A. Meinecke[1,2,3,5] — [1]Department für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Max-Planck-Institut für Quantenoptik, Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [4]Institute of Physics, University of Rostock, Germany — [5]Institute of Solid State Physics, Technische Universität Berlin, Germany

Classical random walks as well as quantum random walks are an important tool to describe the information and energy flow inside of a physical system. While in classical mechanics each particle follows a definite trajectory, in standard quantum mechanics (QM) no such description of the coherent propagation of the quantum walker is possible. However, certain interpretations of QM, as for example Bohmian mechanics, a non-local hidden variable theory, attribute definite positions and momenta to particles and therefore allow to visualize particle trajectories. We simulate the quantum random walk of a particle in a multi-well potential with photons propagating in an integrated waveguide array written into fused silica substrate. In this case the Bohmian velocity correspond to the the Poynting vector in classical electrodynamics and can be reconstructed from weak measurements. By analyzing numerous time steps of the evolution we can reconstruct the energy flow lines which correspond to the Bohmian trajectories.

QI 12.18 Tue 11:00 Poster B

**Quantum measurement tomography** — •Juan Manuel Henning[1], Christopher Cedzich[2], and Martin Kliesch[1] — [1]TUHH, Hamburg, Germany — [2]HHU, Düsseldorf, Germany

Measuring quantum systems is essential for obtaining the result of any quantum computation or simulation. Thus, obtaining a mathematical description of the measurement process, with as much information as possible, is highly desirable.

Quantum measurement tomography protocols are expensive and high-information-gain tools that intend to infer a full mathematical description of an unknown measurement device from experimental data. Inspired by quantum state and process tomography, we find and investigate the performance guarantee of a projected least squares protocol. We bound the estimation error of the obtained quantum measurement description in an operationally justified metric, which is given by the diamond norm. Our bounds feature a better scaling than the ones inherited from optimal quantum process tomography and provide the best available guarantees for this metric.

QI 12.19 Tue 11:00 Poster B

**Continuous Variable Conference Key Agreement** — •Monika Mothsara[1], Elizabeth Agudelo[2], Hermann Kampermann[1], Dagmar Bruss[1], and Gláucia Murta[1] — [1]Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, D-40225 Düsseldorf, Germany — [2]Atominstitut, Technische Universität Wien, 1020 Vienna, Austria

In contrast to discrete-variable quantum key distribution (QKD) protocols, quantum key distribution protocols based on continuous variable (CV) degrees of freedom offer low-cost implementation and are compatible with current communication technologies. However, their security proofs are harder and therefore the existing literature for continuous-variable quantum key distribution (CV-QKD) has very few complete security proofs. The majority of previous investigations into the security proofs of CV-QKD have been restricted to asymptotic regime and collective attacks. Only recently, Ref. [1] extended the analysis of a practical protocol to the finite-size regime against coherent attacks using the entropy accumulation theorem (EAT) [2]. In this work, we investigate continuous-variable conference key agreement (CV-CKA) protocols based on multipartite entangled states. We aim to provide a complete security analysis of CV-CKA and compare the performance with a concatenation of bipartite protocols.

[1] S. Bäuml et al., arXiv preprint arXiv:2303.09255 (2023)
[2] F. Dupuis et al., Commun. Math. Phys. 379, 867-913 (2020)

QI 12.20 Tue 11:00 Poster B

**Refining classical protocols for transmitting quantum systems** — •Sebastian Schlösser and Matthias Kleinmann — Universität Siegen, Siegen, Germany

We study a scenario in which Alice transmits a quantum state to Bob, who then performs a quantum measurement. Here, the state is not known to Bob and the measurement is not known to Alice. A classical simulation of this scenario requires communication of at least one bit, but the quantitative advantage of quantum systems is an open question. The problem was addressed by Toner and Bacon and the most recent results establish that two bits of communication and shared randomness are sufficient for the case of one qubit and generalized measurements. We refine this recent protocol and show that a perfect simulation for a single round can be achieved by transmitting only 1.89 bits on average. The reduction in communication cost raises the question of whether a further reduction is possible in the qubit case. Importantly, for a qutrit, it is not even known whether a finite amount of communication is sufficient to simulate the quantum statistics. We investigate other state spaces to gain a comprehensive understanding of the problem and aim to extend the protocol to the qutrit case.

QI 12.21 Tue 11:00 Poster B

**Trainability barriers and opportunities in quantum generative modeling** — •Sacha Lerch[1], Manuel Rudolph[1], Supanut

Thanasilp[1], Oriel Kiss[2,3], Sofia Vallecorsa[2], Michele Grossi[2], and Zoe Holmes[1] — [1]EPFL — [2]CERN — [3]UNIGE

Quantum generative models have the potential to provide a quantum advantage, but their scalability is still in question. We investigate the barriers to training quantum generative models, focusing on exponential loss concentration. The interplay between explicit and implicit models and losses is explored, leading to untrainability of explicit losses (e.g., KL-divergence). Maximum Mean Discrepancy, a commonly-used implicit loss, can be trainable with the appropriate kernel choice. However, the trainability comes with spurious minima due to indistinguishability of high-order correlations. We also propose to leverage quantum computers leading to a quantum fidelity-type loss. Lastly, data from high-energy experiments is used to compare the performance of different loss functions.

QI 12.22 Tue 11:00 Poster B

**Exact circuit implementation of S^2-conserving fermionic UCCSD-singlet excitations** — •Felix Rupprecht and Sabine Wölk — Institute for Quantum Technologies, German Aerospace Center, Ulm, Germany

Finding groundstates of chemical systems is considered to be one of the most promising tasks to be solved on quantum computers. Most of the quantum algorithms proposed for solving this problem either try to prepare the groundstate directly, e.g. via variational methods like (Adapt-)VQE, or at least require a good initial guess of a groundstate candidate (QPE).

In the context of (Adapt-)VQE it was observed [Bertels et. al, J. Chem. Theory Comput. 18, 11 (2022)] that the use of non-S^2-conserving excitations and low order trotterization leads to spin contamination, i.e. the state leaving the spin sector in which the algorithm started in, resulting in slower convergence.

We investigate S^2-conserving fermionic UCCSD-singlet excitations and observe that the space on which the excitations act may be decomposed into a direct sum of invariant subspaces. Within those subspaces we then find exact quantum circuits implementing the excitation.

We compare the S^2-conserving excitations to other excitations in terms of convergence rate and resources required when used as the excitation pool for the Adapt-VQE algorithm.

This work is part of the QuEST+ project funded by the Baden-Württemberg Ministry of Economic Affairs, Labour and Housing.

QI 12.23 Tue 11:00 Poster B

**Hybrid quantum-classical algorithm for ground state and excitations of the transverse-field Ising model in the thermodynamic limit** — •Sumeet Sumeet, Max Hörmann, and Kai P. Schmidt — Department of Physics, Staudtstraße 7, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germany

We describe a hybrid quantum-classical approach to treat quantum many-body systems in the thermodynamic limit by combining numerical linked-cluster expansions (NLCE) with the variational quantum eigensolver (VQE). Here, the VQE algorithm is used as a cluster solver within the NLCE. We test our hybrid quantum-classical algorithm (NLCE+VQE) for the ferromagnetic transverse-field Ising model (TFIM) on the one-dimensional chain and the two-dimensional square lattice [1]. The calculation of ground-state energies on each open cluster demands a modified Hamiltonian variational ansatz for the VQE. One major finding is convergence of NLCE+VQE to the conventional NLCE result in the thermodynamic limit when at least $N/2$ layers are used in the VQE ansatz for each cluster with $N$ sites. We further extend this approach for calculation of excited states for the TFIM. We further extend NLCE+VQE to determine the one quasi-particle dispersion and energy gap of the TFIM in the polarized phase. To this end we determine we developed a new variational cost function based on the projective cluster-additive transformation [2].

*[1] Sumeet, M. Hörmann, K.P. Schmidt, arXiv:2310.07600*
*[2] M. Hörmann and K.P. Schmidt. SciPost Phys., 15:097, 2023.*

## QI 13: Poster MP (joint session MP/QI)

Time: Tuesday 11:00–13:00 Location: Poster B

QI 13.1 Tue 11:00 Poster B

**Machine Learning Quantum Mechanical Ground States based on Stochastic Mechanics** — •Kai-Hendrik Henk and Wolfgang Paul — Martin-Luther-University, Halle(Saale), Germany

The Rayleigh-Ritz variation principle is a proven way to find ground states and energies for bound quantum systems in the Schrödinger picture. Advances in machine learning and neural networks make it possible to extend it from an analytical search from a subspace of the complete Hilbert space to the a numerical search in the almost complete Hilbert space. In this paper, we extend the Rayleigh-Ritz principle to Nelson's stochastic mechanics formulation of non-relativistic quantum mechanics, and propose a new algorithm to find the osmotic velocities $u(x)$, which contain the information of a quantum systems in this picture. As a proof of concept, we calculated $u(x)$ for one dimensional systems, the harmonic oscillator, the double well and the Pöschl-Teller potential. To obtain exited states, we calculate ground states of super symmetrical partner Hamiltonians for each of these potentials. We will show that this method is more efficient than the stochastic optimal control algorithm, that was the usual method to obtain osmotic velocities without going back to the Schrödinger equation.

QI 13.2 Tue 11:00 Poster B

**Quantum Dynamics on a Two-dimensional Comb: A Numerical Investigation** — •Ognen Kapetanoski and Irina Petreska — Ss. Cyril and Methodius University in Skopje, Faculty of Natural Sciences and Mathematics, Institute of Physics, Skopje, Macedonia

This study explores the quantum dynamics in anisotropic and heterogeneous media, using the comb model - a unique branched structure characterized by a backbone and lateral fingers. The focus is on the two-dimensional comb, which constitutes a simplified yet comprehensive model for theoretical investigation of the quantum motion under geometric constraints. The comb-like constraints are achieved by incorporating the Dirac delta function into the kinetic energy operator of the Schrödinger equation. Employing the finite difference approximation and the fourth-order Runge-Kutta method, the time-dependent Schrödinger equation is numerically solved. This enables the calculation of the wave functions and analysis of the probability density function. From the obtained results, localization of the wave packet due to the comb-like geometric constraints is evident. We also recall the previously derived analytical solutions on an infinite domain, expressed in terms of the Fox H-function. The comparative analysis between the analytical and numerical solution highlights the complexity of quantum transport phenomena, underscoring the challenges and potential of theoretical and computational approaches in quantum mechanics.

[1] T. Sandev, I. Petreska, E.K. Lenzi, *J. Math. Phys.* **59**, 012104 (2018).

QI 13.3 Tue 11:00 Poster B

**How to model an EUV-polariton?** — •Fridtjof Kerker[1,2], Christina Bömer[1,3], and Dietrich Krebs[1,2,3] — [1]The Hamburg Centre for Ultrafast Imaging, Hamburg, Germany — [2]Department of Physics - Universität Hamburg, Germany — [3]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

In recent studies of x-ray parametric down-conversion (XPDC), unexpected imprints of a polaritonic excitation in the extreme ultraviolet (EUV) regime have been revealed. While polaritons, i.e., hybridized states of light and matter, exist in numerous contexts, they are largely unexplored at short wavelengths, such as the EUV spectral range. Under these conditions, new theoretical approaches are necessary to understand the phenomenon.

In this poster presentation, we introduce a first model of the EUV-polariton, which allows us to simulate its generation inside a diamond sample during XPDC. We derive the full scattering signal according to our model and find good agreement with the experimental XPDC data. We further employ our model to analyze the coupling strength of the observed EUV-polariton and discover it to reach up to the strong-coupling regime - notably without requiring an external enhancement-cavity. Our results provide first theoretical insights into this new kind of polariton and constitute a basis for future investigations into strong EUV-light-matter coupling.

QI 13.4 Tue 11:00 Poster B

**Driving chiral matter by chiral light** — •Alexandra Schrader, Benjamin Schwager, Christian Bohley, and Jamal Berakdar — Martin-Luther-Universität Halle-Wittenberg

Many chiral materials display a magneto-electric response which, in lowest order, can be expressed by a complex cross-coupling of the electric (magnetic) dipole moments to the magnetic (electric) fields. A number of physical properties depend on the material's chirality state and hence it is important to find ways to drive and separate objects according to their chirality. E.g., chiral molecules, which are crucial in drug manufacturing, can be chirality-specific separated by optical forces which act differently on different types of enantiomer. This theory contribution discusses how engineering the chiral characteristics of light through structuring both the spatial polarization and orbital phase allow to optimize the chiral forces and torques to steer chiral matter.

QI 13.5 Tue 11:00 Poster B

**Particle dynamics on quantum membranes** — •Lars Meschede, Benjamin Schwager, and Jamal Berakdar — Martin-Luther-Universität Halle-Wittenberg

We are working on an approach for an effective description of particles confined to a thin tubular neighborhood of a curved, dynamical, lower-dimensional submanifold (e.g. membranes). In addition to the well-known geometric potential due to confinement to a static submanifold, the dynamical degrees of freedom give rise to new effective, dynamical scalar and vector potentials. The coupling of the particles to the underlying space itself allows the transfer of energy and momentum to the manifold. In the case of membranes, the coupled dynamics of the particles and the membrane can be described by a (quantum) field theory of two interacting fields, which also yields an equation governing the membrane dynamics in the presence of particles confined to it. This setup can be seen as an elastic field analog of an electromagnetic cavity. If one considers the non-relativistic case, the Lagrangian and the necessity of the existence of a new effective vector potential follow from the invariance requirement under Galilean transformations. An additional coupling of the particles to the external electromagnetic field allows radiative excitations of vibrational modes of the membrane. This approach could be of interest for the description of the long-wavelength coupled electron-membrane dynamics on flexible 2D structures.

QI 13.6 Tue 11:00 Poster B

**Electron-phonon and Coulomb intercation in twisted bilayer graphene aligned on $\mathbf{WSe_2}$** — •Sonia Haddad[1,2] and Jihang Zhu[3] — [1]Laboratoire de Physique de la Matière Condensée, Faculté des Sciences de Tunis, Université Tunis El Manar, Campus Universitaire 1060 Tunis, Tunisia — [2]Institute for Theoretical Solid State Physics, IFW Dresden, Helmholtzstr. 20, 01069 Dresden, Germany — [3]Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Strasse 38, Dresden 01187, Germany

The origin of the superconducting state, emerging at the so-called magic-angle (MA), in twisted bilayer graphene (TBG) is still an open question. However, there is a general consensus on the key role of the flat electronic bands occuring at the MA. Recently, a stable superconducting state has been observed in TBG aligned on $WSe_2$ at small twist angles compared to MA, which calls into question the relevance of the flat bands. Here we address the role of SOC induced in TBG by its proximity to $WSe_2$. Based on the continuum model, we study the effect of the SOC on the electron-phonon interaction and on the screened Coulomb potential. Our results show that the latter is the key factor for the stability of the superconducting phase, which is expected to be due to a Kohn-Luttinger mechanism.

QI 13.7 Tue 11:00 Poster B

**Microscopic mechanism of photo-induced tip-surface currents driven by near-infrared pulses** — •Carlos Bustamante[1], Franco Bonafé[1], Simon Maier[2], Rupert Huber[2], and Angel Rubio[1] — [1]Max Planck Institute for the Structure an Dynamics of Matter, Hamburg, Germany. — [2]Department of Physics, University of Regensburg, Regensburg, Germany.

The control of photo-induced currents from a tip using terahertz laser pulses, when combined with electronic microscopy, has allowed the study of ultrafast dynamics at the atomic scale. Although the charge transfer process has been described by simplified models, further improvement of this technique to achieve shorter time scales and better resolution at the atomic scale requires an ab initio framework. In this work, we have studied the electron dynamics of a tip-surface arrangement described atomistically, when interacting with near-infrared single-cycle laser pulses using TDDFT. Our results provide further insight into the nature of the photo-current induced by the laser pulse, its dependence on the electric field amplitude of the laser and the role of multiphoton absorption.

QI 13.8 Tue 11:00 Poster B

**Slow Modes in Dissipatively Stabilized Superconductors** — •Tom Zander and Sebastian Diehl — Universität zu Köln, D-50937 Cologne, Germany

Topological states of fermionic matter can be induced by purely dissipative dynamics. Other interesting states can exhibit superfluidity or superconductivity. The states which are cooled into, irregardless of the initial state, are called 'dark states'.

We construct an interacting field theory using the Keldysh formalism to investigate a system of 1d fermions cooling into a superconducting dark state. Using the Hubbard-Stratonovich transformation, as well as other tools of quantum field theory, we derive, in the long wavelength limit, the effective slow mode action for the Goldstone and hydrodynamic modes.

QI 13.9 Tue 11:00 Poster B

**Energy conserving adaptive QM/MM method using an extended Hamiltonian approach** — •Marvin Nyenhuis and Nikos Doltsinis — Institute for Solid State Theory, University of Münster, Wilhelm-Klemm-Straße 10, 48149 Münster

We present an extended Hamiltonian formalism that introduces a fictitious switching particle with mass $\mu_k$ which propagates a system between two different potential energy surfaces ($V_{k-1} \to V_k$) during a hybrid ab initio (QM) and classical force field (MM) molecular dynamics simulation by mixing both potentials via a switching function $g(\lambda_k) \in [0, 1]$.

$$\mathcal{H} = \sum_{I=1}^{N} \frac{\mathbf{P}_I^2}{2M_I} + \sum_{j=1}^{k} \frac{\Delta V_j}{|\Delta V_j|} \frac{1}{2} \mu_j \dot{\lambda}_j^2 + \underbrace{g\left(\lambda_k\right) V_{k-1}\left(\mathbf{R}\right) + \left\{1 - g\left(\lambda_k\right)\right\} V_k\left(\mathbf{R}\right)}_{V_{\mathrm{mix}}}$$

The Hamiltonian consists of the kinetic energy of all nuclei $I \in \{1, \ldots, N\}$ with mass $M_I$, kinetic energy of all completed $\lambda_j$, $j \in \{1, \ldots, (k-1)\}$ and running switching procedures ($\lambda_k$) as well as the mixed potential energy $V_{\mathrm{mix}}$ depending on all nuclear positions $\mathbf{R}$. Each $\lambda_k$ is propagated from 0→1 and describes the progress of switching.

QI 13.10 Tue 11:00 Poster B

**Numerical simulations of stochastic optimal control model for navigation of finite size microswimmers** — •Malte Thumann — Institut für Numerische und Angewandte Mathematik, Universität Göttingen

Using stochastic optimal control theory, we study the optimal navigation of finite size microswimmers in the presence of a fluid flow and thermal fluctuations in two-dimensional space. The resulting Hamilton-Jacobi-Bellmann (HJB) equation is a nonlinear convection-diffusion type partial differential equation (PDE) that describes the optimal torque an active swimmer must satisfy to navigate towards a desired target. This equation is numerically solvable in a three-dimensional phase space (position and orientation) for a given set of initial conditions. We discretise the HJB equation in a finite element framework known as the discontinuous Galerkin method, which operates over a trial space of functions that are only piecewise continuous. This allows for a more stable and flexible discretisation scheme, in particular to cope with the challenging task of implementing singular boundary conditions arising from the stochastic optimal control approach. Using the optimal torque solution, we perform stochastic simulations to determine the optimal mean microswimmer path. Our work emphasises that finite element methods are a suitable discretisation technique to handle PDEs arising in theoretical biophysics in a non-trivial setting with complex geometries, singularities, or higher order local approximations.

QI 13.11 Tue 11:00 Poster B

**Perturbative Series Expansions for Two-Particle Bound-State Energies in the Thermodynamic Limit: A Green's Function Approach** — •Maximilian Bayer, Patrick Adelhardt, and Kai Phillip Schmidt — Friedrich-Alexander-Universität Erlangen-

Nürnberg (FAU), Staudtstr. 7, 91058 Erlangen, Germany

The investigation of (quasi-)particle bound states has been a focal point in quantum mechanics research, tracing its roots back to the solutions of the Hydrogen atom. In the realm of solid-state systems, the emergence of two-quasi-particle bound-states, such as excitons, Cooper pairs or magnon-magnon bound-states in spin systems, gives rise to unique material properties. Our interest lies in developing general techniques for systematically computing the energies associated with such bound-states on lattice systems in a perturbative manner.

We introduce an approach based on zero-temperature Green's functions (Resolvents), capable of generating series expansions for these energies in the thermodynamic limit, eliminating the need for exact diagonalization and Rayleigh-Schrödinger perturbation theory on finite systems. This technique is universal in the dimensionality of the system and accommodates fermionic, bosonic, and hard-core bosonic particles, only requiring finite-range interactions.

By reducing the eigenvalue equation into the determinant of a finite matrix we obtain a finite expression even for infinite systems. This expression allows for the extraction of bound-state energies either exactly for fixed perturbation parameters or in the form of a power series, if such a series exists.

QI 13.12 Tue 11:00 Poster B

**Comparison the determination techniques of the effective refractive index of all-dielectric metasurface as a graphene layer substrate using finite-element electromagnetic simulations** — •Zoya Eremenko and Aliaksei Charnukha — Leibniz Institute for Solid State and Materials Research

We proposed the use of the resonant all-dielectric metasurface as a graphene layer substrate. The task is to define the effective refractive index of such a metasurface to have the possibility to control the surface plasmon polariton propagation length. We studied some techniques to define the effective refractive index of the metasurface. The first one is determining the band structure of a two-dimensional photonic crystal with a square lattice of the defined metasurface structure and obtained the eigen frequencies at definite relation between metasurface unit cell parameters. The second one is retrieval of the effective parameter technique from S-parameters defined from simulations results. Thus, such techniques give the opportunity to use any structure configuration of the resonant all-dielectric metasurfaces.

QI 13.13 Tue 11:00 Poster B

**Thermalization of black holes and the SYK model** — •Zhuo-Yu Xian[1], Yuxuan Liu[2], Shao-Kai Jian[3], Yi Ling[4], and Jiasheng Liu[5] — [1]Julius-Maximilians-Universität Würzburg, 97074 Würzburg, Germany — [2]Institute of Quantum Physics, School of Physics, Central South University, Changsha 418003, China — [3]Department of Physics and Engineering Physics, Tulane University, New Orleans, Louisiana, 70118, USA — [4]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China — [5]Ludwig-Maximilians-Universität München, Geschwister-Scholl-Platz, 1 D-80539 München

We investigate the evolution of entanglement and Heisenberg operators within open and strongly coupled systems interacting with its environment, in the frameworks of both the doubly holographic model and the Sachdev-Ye-Kitaev (SYK) model. In both cases, the entanglement within the system initially increases as a result of internal interactions; however, it eventually dissipates into the environment. We also study the operator size growth in the Lindbladian SYK model and analytically obtain the suppression of the growth due to the dissipation. The dynamic behaviors of the entanglement and the opeartor size observed in these two models are attributable to the competition between the internal interaction of the system and the external interaction with the environment.

QI 13.14 Tue 11:00 Poster B

**Conceptual-Mathematical Approach for the Derivation of Effective Field Theories from QCD- & Gauge Theories (Large 48x48 matrices in QCD from Hubbard-Stratonovich transformations)** — •Bernhard Mieck — Keine Institution

An effective field theory of BCS quark pairs is derived from an ordinary QCD-type path integral with SUc(Nc=3) non-Abelian gauge fields. We consider the BCS quark pairs as constituents of nuclei and as the remaining degrees of freedom in a coset decomposition SO(N,N) /U(N) x U(N) of a corresponding total self-energy matrix taking values as generator within the so(N,N) Lie algebra. The underlying dimension (N = Nf x 4 x Nc) is determined by the product of isospin- 'Nf = 2' (flavour- 'Nf = 3') degrees of freedom, by the 4x4 Dirac gamma matrices with factor '4' and the colour degrees of freedom 'Nc = 3'; therefore, the smallest, total self-energy generator has Lie algebra so(N,N) with N = 24. We distinguish between a total unitary sub-symmetry U(N) for purely density related parts of the quarks, which are taken into account as background fields and as invariant vacuum states in a SSB, and between the BCS terms of quarks as coset elements so(N,N) / u(N). These HST's are sufficient to achieve a path integral entirely determined by self-energy matrices for the coset decomposition. Concerning homotopies, we attain the nontrivial Hopf mapping Π_{3}(S^2)=Z from consideration of Fujikawa-anomalies and would like to point again the possibility for further nontrivial homotopies, as e.g. Π_{7}(S^4) = Z or Π_{2^n -1}( S^( 2^(n-1) ) ) = Z.

QI 13.15 Tue 11:00 Poster B

**Wave function of the universe in the presence of trans-Planckian censorship** — •Vikramaditya Mondal — School of Physical Sciences, Indian Association for the Cultivation of Science, Kolkata 700032, India

The wave function for a closed de Sitter universe has been computed, demanding consistency with the recently proposed Trans-Planckian Censorship Conjecture (TCC). We extend the Einstein-Hilbert action to contain a complex-valued term that provides an exponentially decaying weight for the geometries violating TCC in the Lorentzian path integral sum while working in the minisuperspace approach to quantum cosmology. This postulated modification suppresses the probability of the evolution of the universe into configurations that violate TCC. We show that due to the presence of this suppression factor, the Hubble rate of the universe at the end of the inflation gets subdued and assumes a value less than what is expected classically. Moreover, the consequences of this quantum gravity-motivated correction in the primordial power spectrum are discussed as well.

# QI 14: Focus Session: Nanomechanical Systems for Classical and Quantum Sensing I (joint session TT/DY/HL/QI)

Nanomechanical and cavity-optomechanical systems have been recently established as a controllable and configurable platform that can be engineered to tackle outstanding sensing challenges both in the classical and in the quantum regime. With this focus session, experts from different but synergetically overlapping fields of nanomechanical sensing pursuing classical, non-linear and quantum approaches are brought together. The session shall provide an overview over the recent exciting developments of the techniques explored in micro- and nanomechanical systems and sensing concepts exploring quantum measurement schemes.
This joint session will be continued Wednesday afternoon (TT53) and Thursday morning (TT70). Organized by Eva Weig, Hubert Krenner, and Hans Hübl.

Time: Tuesday 11:45–13:00 Location: H 3007

QI 14.1 Tue 11:45 H 3007

**Josephson Optomechanics** — •Surangana Sengupta[1], Bjoern Kubala[1,2], Joachim Ankerhold[1], and Ciprian Padurariu[1] — [1]ICQ and IQST, Ulm University, Germany — [2]DLR-QT, German Aerospace Center, Ulm, Germany

In recent years, optomechanical cooling using microwave radiation has been realized in various superconducting circuits with a microwave cavity comprising a mechanical element. Circuits provide an opportunity to engineer nonlinear cavities, by using Josephson junctions, thereby generating quantum states of light for optomechanics experiments.
Here, we will theoretically describe an optomechanical setup where the cavity is realized by an LC circuit driven by a dc-biased Josephson junction. By engineering the nonlinearity, such a cavity becomes an effective N-level system, with $N = 2, 3, ...$, where the access to Fock states $N$ and above is blocked. Consequently, the cavity emission spectrum shows Mollow-type side peaks, analogous to an optical cavity interacting with an atom. We show that at these Mollow side peaks, the system exhibits a new, nonlinear type of optomechanical cooling. We calculate the cooling rate using the spectral density of noise due to the radiation pressure [1] and highlight how its unusual features compared to conventional optomechanics, can be explained in a dressed state picture.
[1] F. Marquardt *et.al.*, Phys. Rev. Lett. **99** (2007) 093902

QI 14.2 Tue 12:00 H 3007

**Logarithmic susceptibility of a quantum parametrically modulated oscillator** — •Daniel Boness[1], Wolfgang Belzig[1], and Mark Dykman[2] — [1]Department of Physics, University of Konstanz, 78457 Konstanz, Germany — [2]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA

A weakly damped nonlinear oscillator modulated close to twice its eigenfrequency has two stable states, which have the same vibration amplitudes but opposite phases. The states are equally populated due to classical or quantum fluctuations.

An extra force at half the modulation frequency lifts the symmetry of the states. Even a weak force can result in a significant change of the populations, as it beats against the intensity of quantum and classical fluctuations. We develop an approach that allows us to find this population change.

We also study the effect of the extra force with frequency slightly detuned away from half the modulation frequency. For a detuning that is small compared to the switching rate the force leads to the imbalance of populations that is modulated at the frequency of the detuning. For larger detuning, the adiabatic picture breaks down and the wells are again equally populated. However, the rates of switching between the wells is exponentially increased. We calculate the change of the logarithm of the switching rate, termed logarithmic susceptibility, using the real-time instanton method. The results are relevant for controlling parametric oscillators and their application in quantum information systems.

QI 14.3 Tue 12:15 H 3007

**Cavity optomechanics with carbon nanotube quantum dots** — •Akong N. Loh, Furkan Özyigit, Fabian Stadler, Niklas Hüttner, and Andreas K. Hüttel — Institute for Experimental and Applied Physics, University of Regensburg, 93040 Regensburg, Germany

Carbon nanotubes (CNTs) are the smallest and lightest nanomechanical beam resonators. When suspended transversally between two electrodes (Ti/Au for example) and then gated, they can act as mechanical beam resonators with large quality factors and also as quantum dots. The motion of a CNT is coupled to other degrees of freedom, such as photons, spins, and electrons. The optomechanical coupling of a single wall carbon nanotube nanomechanical resonator to a microwave cavity has been realized and quantified through optomechanically induced transparency measurements [1]. The quantum dot properties of the CNT were exploited (specifically the nonlinearity of the coulomb blockade) to significantly enhance the coupling strength [1,2]. Current work is directed towards achieving even stronger coupling and possibly groundstate cooling of the nanomechanical resonator through anti-Stokes processes. This requires significant improvement of the microwave cavity, CNT growth and transfer. All measurements are done at ∼10 mK in a dilution refrigerator.
[1] S. Blien *et al.*, Nat. Comm. **11** (2020) 1636
[2] N. Hüttner et al., Phys. Rev. Applied, in press (2023), arXiv:2304.02748

QI 14.4 Tue 12:30 H 3007

**Signatures of Josephson force in a vibrating carbon nanotube junction** — •Andreas K. Hüttel[1,2], Jukka-Pekka Kaikkonen[2], Keijo Korhonen[2], and Pertti Hakonen[2] — [1]Institute for Experimental and Applied Physics, Universität Regensburg, Regensburg, Germany — [2]Low Temperature Laboratory, Dept. of Applied Physics, Aalto University, Espoo, Finland

A carbon nanotube suspended between superconducting electrodes acts simultaneously as nanomechanical resonator and as a Josephson junction. Its energy-dependent density of states and with that displacement-dependent critical current further adds to the complexity of the system, as does both mechanical and electronic nonlinearity. Measurements on such a system display complex behaviour of the vibrational resonance with respect to junction biasing. Strikingly, the resonance frequency appears to decrease in a distinct parameter region where the biasing is similar in size to the junction switching current.

Using highly parallelized Julia code, we numerically solve the coupled differential equation system of the driven (via an ac gate voltage and ac current or voltage bias) system for realistic device parameters and characterize the evolving steady state. Specific attention is given to the impact of the Josephson junction behaviour on the mechanical resonance frequency and the vibration amplitude, and on the ac signal simultaneously acting on gate and bias.

QI 14.5 Tue 12:45 H 3007

**Optimization of Flux-Tunable Microwave Resonators for Strong Single-Photon Optomechanics in Nano-Electromechanical Systems** — •Korbinian Rubenbauer[1,2], Thomas Luschmann[1,2], Kedar Honasoge[1,2], Achim Marx[1,2], Kirill G. Fedorov[1,2,3], Rudolf Gross[1,2,3], and Hans Huebl[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [2]School of Natural Sciences, Technical University of Munich, Garching, Germany — [3]Munich Center for Quantum Science and Technologies, Munich, Germany

Quantum sensing leverages quantum properties to enhance the precision of sensing applications. One promising implementation for the detection of forces or accelerations are optomechanical systems which encode the displacement of a low-frequency mechanical element onto the properties of a high-frequency optical or electromagnetic resonator. We present a flux-tunable superconducting quantum circuit with an integrated superconducting quantum interference device (SQUID), where the mechanical element is embedded in the SQUID structure. This implements a magnetic field and flux tunable optomechanical interaction with the prospect of reaching the strong single-photon coupling regime. We discuss the design concept of the device and detail its optimization. We corroborate the conceptual improvements with experimental data demonstrating the performance improvements of the microwave resonator, the optomechanical coupling and the mechanical element.

## QI 15: Quantum Computing Theory

Time: Wednesday 9:30–13:00 Location: HFT-FT 101

**Invited Talk** QI 15.1 Wed 9:30 HFT-FT 101

**Computationally Universal Phases of Quantum Matter** — •Robert Raussendorf[1], Cihan Okay[2], Dongsheng Wang[3], David Stephen[4], and Hendrik P Nautrup[5] — [1]Leibniz Universtät Hannover — [2]Bilkent University Ankara, Turkey — [3]Chinese Academy of Sciences, China — [4]University of Colorado, Boulder, USA — [5]University of Innsbruck

In measurement based quantum computation, the computational power hinges on the resource quantum state. Some states give universal computational power, but most states provide no computational power at all [1]. This picture changes in the presence of symmetry. Namely, for phases of ground states of symmetric Hamiltonians, i.e., symmetry-protected topological (SPT) phases, it has been found that computational power is uniform across those phases. This observation gave rise to the term 'computational phases of quantum matter* [2,3]. In my talk, I give a short history of this line of research, and then present examples of symmetry protected quantum phases that have universal computational power [4 - 6].

[1] D. Gross, S. T. Flammia, and J. Eisert, PRL 102, 190501 (2009).
[2] A. C. Doherty and S. D. Bartlett, PRL 103, 020506 (2009).
[3] A. Miyake, Phys. Rev. Lett. 105, 040501 (2010).
[4] R. Raussendorf et al., Phys. Rev. Lett. 122, 090501 (2019).
[5] D.T. Stephen et al., Quantum 3, 142 (2019).
[6] A.K. Daniel, R.N. Alexander, A. Miyake, Quantum 4, 228 (2020).

QI 15.2 Wed 10:00 HFT-FT 101

**Mapping quantum circuits to shallow-depth measurement patterns based on graph states** — •Thierry Nicolas Kaldenbach[1] and Matthias Heller[2] — [1]German Aerospace Center (DLR), Institute of Materials Research, Cologne, Germany — [2]Fraunhofer Institute for Computer Graphics Research IGD, Darmstadt, Germany

The paradigm of measurement-based quantum computing (MBQC) starts from a highly entangled resource state on which unitary operations are executed through adaptive measurements and corrections ensuring determinism. This is set in contrast to the more common quantum circuit model, in which unitary operations are directly implemented through quantum gates prior to final measurements. In this work, we incorporate concepts from MBQC into the circuit model to create a hybrid simulation technique, permitting us to split any quantum circuit into a classically efficiently simulatable Clifford-part and a second part consisting of a stabilizer state and local (adaptive) measurement instructions, a so-called standard form, which is executed on a quantum computer. We further process the stabilizer state with the graph state formalism, thus enabling a significant decrease in circuit depth for certain applications. We show that groups of fully commuting operators can be implemented using fully-parallel, i.e., non-adaptive, measurements within our protocol. Finally, we demonstrate the utility of our technique on two examples of high practical relevance: the Quantum Approximate Optimization Algorithm (QAOA) and the Variational Quantum Eigensolver (VQE).

QI 15.3 Wed 10:15 HFT-FT 101

**Quantum state preparation via engineered ancilla resetting** — •Daniel Alcalde Puente[1,2], Felix Motzoi[1], Tommaso Calarco[1,2,3], Giovanna Morigi[4], and Matteo Rizzi[1,2] — [1]Forschungszentrum Julich - Institute of Quantum Control, Peter Grünberg Institut (PGI-8), Jülich, Germany — [2]Institute for Theoretical Physics-University of Cologne, Köln, Germany — [3]Dipartimento di Fisica e Astronomia - Universita di Bologna, Bologna, Italy — [4]Theoretical Physics- Department of Physics- Saarland University, Saarbrucken, Germany

In this study, we investigate a quantum resetting protocol for preparing ground states of frustration-free Hamiltonians. The protocol uses a steering Hamiltonian for local coupling to ancillary degrees of freedom, which are periodically reset. For short reset times, the dynamics resemble a Lindbladian with the target state as its steady state. We use Matrix Product State simulations and quantum trajectory methods to assess the protocol's efficiency in preparing the spin-1 Affleck-Kennedy-Lieb-Tasaki state, focusing on convergence time, fidelity, and energy evolution at various reset intervals. Our findings indicate that entanglement with the ancillary system is crucial for rapid convergence, with an optimal reset time for peak performance. The protocol also demonstrates robustness against small deviations in reset time and dephasing noise. Our results suggest that quantum resetting could be more advantageous than other methods like quantum reservoir engineering in certain contexts.

QI 15.4 Wed 10:30 HFT-FT 101

**Shot noise reduction by problem-tailored measurements** — •Timo Eckstein[1,2], Refik Mansuroglu[1], Martin Kliesch[3], and Michael J. Hartmann[1,2] — [1]FAU Erlangen-Nürnberg, Germany — [2]MPI for the Science of Light, Germany — [3]TU Hamburg, Germany

The preparation and measurements of low-energy eigenstates of strongly correlated many-body systems are considered an auspicious real-world use case of near-term quantum computers. Such quantum states feature nontrivial long-range entanglement, which cannot be efficiently described using classical methods but may still be prepared on quantum devices.

Here, we address the challenge of efficiently extracting information from the quantum device in such applications. Naive measurement schemes, like estimating eigenvalues of Pauli strings can require excessive amounts of measurements. These requirements are significantly reduced by our strategy.

In contrast to observable agnostic methods like shadow tomography, we focus on observable specific ones. Specifically, starting from tractable subsystems, we constructed measurements that are tailored for energy estimation of interacting quantum systems with local Hamiltonians. This construction leads to estimators with smaller variances compared to local Pauli bases. Indeed, in our numerical studies, we find linear variance improvements which translate to quadratic savings in the required number of measurements. We show this to hold analytically if constrained to positively correlated splitting or alternatively to Pauli-bipartitions.

QI 15.5 Wed 10:45 HFT-FT 101

**Polynomial pre-processing for quantum singular value transformations** — •Shawn Skelton and Tobias Osbourne — Leibniz Universität Hannover

Quantum signal processing (QSP), and its extension quantum singular value transformation (QSVT), are increasingly popular frameworks for developing fault-tolerant quantum algorithms. Despite their recent prominence in the literature, QSP implementations still struggle to complete a costly classical pre-processing step. Namely, one must select a set of $SU(2)$ rotation matrices for a given polynomial $P(x)$ using algorithms which rely upon either optimization or polynomial root-finding subroutines. These techniques either introduce undesirable constraints on the input polynomials or struggle with high-degree polynomials. Furthermore, this pre-processing can depend on how users design their problem, and notably on whether one works in the variable domain $z \in U(1)$ or $x \in [-1, 1]$. We introduce a new method for computing rotation matrices for the complex-variable case and compare the run-time and reliability of our technique to existing methods. Our benchmark functions are selected for their ubiquity in the literature - functional approximations used to implement matrix inversion, Hamiltonian simulation, and unstructured search with QSP. Because QSP/QSVT techniques are relatively new to the literature, we also consider the *ease of application* of each method and suggest best practices for new users.

**15 min. break**

QI 15.6 Wed 11:15 HFT-FT 101

**Squeezing and quantum approximate optimization** — •Gopal Chandra Santra[1,2], Fred Jendrzejewski[1,3], Philipp Hauke[2,4], and Daniel J. Egger[5] — [1]Universität Heidelberg, Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany — [2]Pitaevskii BEC Center and Department of Physics, University of Trento, Via Sommarive 14, I-38123 Trento, Italy — [3]Alqor UG (haftungsbeschränkt), Marquardstrasse 46, 60489 Frankfurt am Main, Germany — [4]INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Trento, Italy — [5]IBM Quantum, IBM Research Europe - Zurich, Säumerstrasse 4, CH-8803 Rüschlikon, Switzerland

Although variational quantum algorithms provide fascinating prospects in combinatorial optimization, the achievable performance and the role of quantum correlations therein remain unclear. We shed light on this open issue by establishing a tight connection between the quantum approximate optimization algorithm (QAOA) and the seemingly unrelated field of quantum metrology via generating squeezed states both numerically and on an IBM quantum chip while QAOA is tasked to solve MaxCut problems with increased precision. Such QAOA-tailored squeezing relates to quantum correlation in the form of entanglement; it permits us to propose a figure of merit for future hardware benchmarks, and it can resource-effectively boost the averaged final energy of QAOA optimization obtained in MaxCut of random graph instances. Further exploiting this connection between metrology and optimization may uncover solutions to prevailing problems and push the scope of precision in both fields.

QI 15.7 Wed 11:30 HFT-FT 101

**Overlap Gap Property limits limit swaping in QAOA** — •Mark Goh — Institute of Material Physics in Space, German Aerospace Center, Cologne, Germany — Institute for Theoretical Physics, University of Cologne, Cologne, Germany

The Quantum Approximate Optimization Algorithm (QAOA) is a quantum algorithm designed for finding approximate solutions to combinatorial optimization problem. Recent works on evaluating the performance of QAOA for $q$-spin glass models have been found to to beat semi-definite programming at layer $p = 11$ for the Sherrington–Kirkpatrick model (2-spin glass). In addition, the algorithm to evaluate the expectation value has time complexity $\mathcal{O}(p^2 4^p)$, independent of the input size in the large $n$ limit.

We show that under the likely conjecture that Max-$q$-XORSAT on large-girth regular hypergraph exhibit the Overlap Gap Property (OGP), the swapping of limits in QAOA leads to suboptimal results. Numerical simulations of Max-q-XORSAT on large-girth regular hypergraph supports the conjecture as OGP is observed when the degree of a vertex is greater than $q$.

Furthermore, since the performance of QAOA for the pure $q$-spin model matches asymptotically for Max-$q$-XORSAT on large-girth regular hypergraph, we show that the average-case value obtained by QAOA for the pure $q$-spin model for even $q \geq 4$ is bounded away from optimality even when the algorithm runs indefinitely if the conjecture is true. This suggests that a necessary condition for the validity of limit swapping in QAOA is the absence of OGP.

QI 15.8 Wed 11:45 HFT-FT 101

**Symmetry obstructions to the quantum approximate optimization algorithm** — Sujay Kazi[1,2,3], Martin Larocca[2,4], Marco Farinati[5], Patrick J. Coles[6], Marco Cerezo[7], and •Robert Zeier[8] — [1]Courant Institute of Mathematical Sciences, New York University, New York, New York 10012, USA — [2]Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA — [3]Department of Electrical and Computer Engineering, Duke University, Durham, NC 27708, USA — [4]Center for Nonlinear Studies, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA — [5]Departamento de Matemática, FCEN, UBA - IMAS CONICET — [6]Normal Computing Corporation, New York, New York, USA — [7]Information Sciences, Los Alamos National Laboratory, Los Alamos, NM 87545, USA — [8]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), 54245 Jülich, Germany

The quantum approximate optimization algorithm (QAOA) approximates ground states related to the maximum-cut graph problem. We study symmetries and algebraic properties of QAOA ansätze. For the free (or multi-angle) ansatz, the Lie algebras observed for any connected graph split into six classes corresponding to path, cycle, bipartite, and remaining graphs. We predict that polynomially and exponentially deep quantum circuits will suffer from barren plateaus when the free ansatz is applied to the remaining graphs. But shallow circuits of logarithmic depth will likely lack the resources to approximately reach the ground state. Even for the so-called standard ansatz, we indicate why the effectiveness of QAOA might be negatively affected.

QI 15.9 Wed 12:00 HFT-FT 101

**Discrete adiabatic quantum optimization** — •Vanessa Dehn and Thomas Wellens — Fraunhofer Institut für Angewandte Festkörperphysik IAF, Freiburg, Deutschland

The Quantum Approximate Optimization Algorithm (QAOA) is a well-known candidate for solving combinatorial optimization problems more efficiently than classical computers in the current noisy intermediate-scale quantum (NISQ) era. The form of the QAOA circuit is inspired by adiabatic quantum computing (AQC) in terms of starting in the ground state of the mixing Hamiltonian, which is then gradually transferred to the ground state of the cost Hamiltonian by approximating the adiabatic annealing path via Trotterization for an increasing and very large iteration depth p. Therefore, the performance of QAOA is expected to improve with increasing p. However, recent studies [1] showed, that QAOA can exhibit a poor performance for large circuit parameters, even in the adiabatic limit.

To explain this behavior, a modification of the continous adiabatic theorem, namely the discrete adiabatic theorem, is applied, where the state evolves by applying a product of gradually varying unitaries. To understand the decrease of the ground state population, we track the population and population changes of each state throughout the whole protocol for different sets of parameters. Furthermore, we explore how these insights may be used in order to find optimized schedules for the QAOA angles.

[1] V. Kremenetski et al., arXiv:2305.04455 (2023).

QI 15.10 Wed 12:15 HFT-FT 101

**Quantum optimization with quantum circuits** — •Francesco Preti and Felix Motzoi — Forschungszentrum Jülich, Wilhelm-Jonen Strasse, Jülich

We study the possibility of sampling different types of gradients for NISQ optimization from quantum circuits. We show that in certain contexts, e.g. for certain numbers of parameters, we can obtain a faster sampling of gradient guesses that, although they lack the precision of standard gradients, still lead to fast, reliable optimization. We then apply our method to different types of cost functions to evaluate the quality of the optimization.

QI 15.11 Wed 12:30 HFT-FT 101

**Efficient Amplitude Encoding of Classical Data** — •Vittorio Pagni — Deutsches Zentrum für Luft - und Raumfahrt (Dlr), Deutschland

Although the theoretical advantages associated to quantum computers have been proved, whenever we want to apply the most efficient quantum algorithms to classical data or initialize our quantum circuit in a specific state, an efficient state preparation algorithm can prevent us from wasting the quantum speed up because of a computational bottleneck effect, especially for large classical vectors.

We present an improved version of a pre-existing (PhysRevResearch.4.013091) quantum amplitude encoding procedure that encodes the real or complex entries of a properly normalized classical vector $\vec{v} = (v_1, .., v_N)$ of length N into the amplitudes of a quantum state. Our approach generalizes the protocol to complex entries and it shows a quadratic time speed up with respect to the original. Furthermore, the procedure also allows for some flexibility in the way the intermediate operations are performed, so that it is possible to customize the balance between memory and time cost for the specific application. Depending on the data density $\rho(\vec{v}) = \sum_{i=0}^{N-1} \| \frac{v_i}{v_{max}} \|^2$, $\frac{1}{N} \leq \rho \leq 1$ of the classical input vector of length N and on the parallelization parameter M, $1 \leq M \leq N$, the number of qubits scales as $O(M \log_2 N)$ while the time cost increases as $O(\frac{1}{\sqrt{\rho}} \frac{N}{M} \log_2 \log_2 N)$, which has an upper bound of $O(\sqrt{N} \log_2 \log_2 N)$ in the worst case scenario.

QI 15.12 Wed 12:45 HFT-FT 101

**Holonomic quantum computation: a scalable adiabatic architecture** — Jose Carrasco, Tommaso Guaita, and •Clara Wassner — Dahlem Center for Complex Quantum Systems, Freie Universitat Berlin, 14195 Berlin, Germany

Holonomic quantum computation is a framework that exploits the geometric evolution within specific eigenspaces of a degenerate Hamiltonian to enact the unitary evolution of computational states. In this study, we present a scalable architecture consisting of a universal set of fully holonomic gates, specifically designed for quantum computations on contemporary experimental platforms. Notably, our proposal offers a straightforward implementation in Rydberg array experiments, capitalizing on the capability to manipulate atoms using tweezers. This renders the experimental realization of large-scale holonomic implementations feasible for the first time. Owing to their geometric nature, our gates exhibit promising resistance against certain faults. We conduct a comprehensive analysis of the geometric properties of these gates, giving systematic insight on the mechanisms of their noise robustness. To demonstrate the resistance of our gates, we conduct a range of simulations under various coherent and incoherent error models.

## QI 16: Superconducting Qubits (joint session QI/TT)

Time: Wednesday 9:30–13:15 Location: HFT-FT 131

QI 16.1 Wed 9:30 HFT-FT 131

**Improving Fabrication Methods for High Coherence Superconducting Qubits** — •Niklas Bruckmoser[1,2], Leon Koch[1,2], David Bunch[1,2], Ivan Tsitsilin[1,2], Kedar E. Honasoge[1,2], Thomas Luschmann[1,2], Lasse Södergren[1,2], Christian Schneider[1,2], Max Werninghaus[1,2], and Stefan Filipp[1,2] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [2]Technical University of Munich, TUM School of Natural Sciences, Physics Department, 85748 Garching, Germany

The development of superconducting qubits and resonators with long coherence times and high quality factors is an essential milestone on the way towards useful quantum applications. While significant improvements in coherence time have been achieved over the last years, reaching qubit lifetimes well beyond 0.1 ms involves careful investigation of all fabrication processes. In this talk, we show that achieving such high-quality devices becomes possible through a combination of substrate cleaning, etching optimization, and post-process sample cleaning. By using resonator measurements as a figure of merit to minimize TLS loss, we achieve internal quality factors of more than $Q_{\text{int}} = 1 \times 10^7$ for thin-film niobium coplanar waveguide resonators in the single-photon regime and observe transmon qubits with single-shot lifetimes as high as $T_1 = 0.7$ ms. Additionally, we exploit the high quality of the niobium resonators as sensors to investigate losses arising from different types of silicon substrates.

QI 16.2 Wed 9:45 HFT-FT 131

**Enhanced parameter targeting in flip-chip geometry for large-scale superconducting quantum computing** — •Léa Richard[1,2], Agata Skoczylas[1,2], Franziska Wilfinger[1], Niklas Bruckmoser[1,2], Leon Koch[1,2], David Bunch[1,2], Lasse Södergren[1,2], and Stefan Filipp[1,2] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, 85748 Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany

In order to use quantum computing to tackle classically intractable problems, quantum processors must grow to larger scales. However, routing multiple control lines to an increasing number of qubits is not feasible in current superconducting planar architectures.

Using 3D-integration techniques, such as flip-chip bonding, plays a crucial role in mitigating this problem. A challenge arising from this new technology is the precise control of the vertical placement of the chips. In quantum circuits, capacitances and inductances are determined by the geometry of the electrodes. Hence, in a flip-chip assembly, it depends on the gap separating the two bonded chips. During the bonding process, variations may occur, preventing an accurate parameter targeting.

In this talk, we discuss the fabrication of thermally evaporated indium bumps and review the development of an optimized flip-chip bonding process. Moreover, we present a method for improved interchip spacing control and parameter targeting through the use of polymer spacers.

QI 16.3 Wed 10:00 HFT-FT 131

**Frequency tuning of superconducting qubits by junction annealing** — •Julius Feigl[1,2], Leon Koch[1,2], Florian Wallner[1,2], Niklas Bruckmoser[1,2], David Bunch[1,2], Lasse Södergren[1,2], Christian Schneider[1,2], and Stefan Filipp[1,2] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany

When scaling superconducting quantum processors beyond a couple of qubits, frequency collisions can become a limiting factor for gate fidelities. These collisions arise from parameter variations in the fabrication process, resulting in imprecise frequency targeting. A solution to enhance frequency targeting of individual superconducting qubits is the controlled annealing of the Josephson junction. In fact, Josephson junction resistance can be increased by local heating via a tightly focused laser beam. This leads to a modified Josephson inductance. In our work, we investigate wafer-scale laser annealing of fixed-frequency transmons with Al/AlOx/Al junctions. We explore the influence of annealing parameters on the resistance change for various junction sizes. The observed variations of the junction resistance after the annealing step reveal different temperature regimes for annealing. Temperatures exceeding 200 °C induce a reduction of up to 35 % in resistance, while temperatures below lead to an increase of up to 5 % in resistance. Consequently, we present a prospective approach to bi-directional annealing.

QI 16.4 Wed 10:15 HFT-FT 131

**All-nitride superconducting devices for quantum computing** — •Thomas Smart, Roudy Hanna, Michael Schleenvoigt, Albert Hertel, Abdur Rehman Jalil, Detlev Grützmacher, and Peter Schüffelgen — Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Strasse, Jülich, 52425, Germany

The ongoing search for better superconducting devices for quantum computing has led to many proposals on how these devices can be improved to yield longer coherence times. Nitride based superconducting devices have been proposed as a potential platform for the next generation of quantum computing due to their stability and desirable superconducting properties. Here, we present the fabrication of all-nitride superconducting devices via molecular beam epitaxy on c-plane sapphire. These devices exhibit high crystalline quality and desirable superconducting properties. We explore the advantages of these devices compared to commonly used alternatives and how the use of reconstructed sapphire yields ideal growth qualities.

QI 16.5 Wed 10:30 HFT-FT 131

**Magnetic field dependence of a Josephson travelling wave parametric amplifier** — •Lucas Janssen[1], Christian Dickel[1], Guilliam Butseraen[2], Jonas Krause[1], Alexis Coissard[3], Luca Planat[3], Gianluigi Catelani[4], Nicolas Roch[2], and Yoichi Ando[1] — [1]University of Cologne, Cologne, Germany — [2]Institut Néel, Grenoble, France — [3]Silent Waves, Grenoble, France — [4]Technology Innovation Institute, Abu Dhabi, United Arab Emirates

We investigate the magnetic field dependence of a Josephson travelling-wave parametric amplifier (TWPA) that is designed as a version of photonic crystal. We show that the change in photonic bandgap and plasma frequency of the TWPA can be modelled by considering the suppression of the critical current in the Josephson junctions (JJs) of the TWPA due to the Fraunhofer effect and closing of the superconducting gap in magnetic fields. These dependencies allow us to tune the operation of the TWPA by magnetic fields in a wide range of frequencies without using SQUIDs. The JJ geometry is found to be crucial for the magnetic-field dependences: for example, the TWPA bandgap can be widely shifted without losing gain or bandwidth by an in-plane magnetic field in one direction, while in the other in-plane direction the TWPA performance is severely compromised already at 2mT. With out-of-plane field, the TWPA's response is hysteretic, and it is severely compromised at 5mT. We also show that we can use magnetic shielding to use the TWPA in experiments where high fields are required.

QI 16.6 Wed 10:45 HFT-FT 131

**Embedded Amplifier for Efficient Superconducting Qubit**

**Readout** — •Lindsay Orr[1,2], Benton Miller[3,4], Florent Lecocq[3,5], and Anja Metelmann[1] — [1]Institute for Theory of Condensed Matter, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany — [2]Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, 14195 Berlin, Germany — [3]National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA — [4]Department of Physics, University of Colorado, Boulder, Colorado 80309, USA — [5]Department of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, Colorado 80309, USA

High fidelity qubit readout is a cornerstone of quantum computing. In superconducting architecture, this is typically achieved by routing signals from a readout cavity to a parametric amplifier via microwave circulators. The use of these off-chip components enables the independent design and optimization of the readout cavity and parametric amplifier. However, the intrinsic losses and large magnetic fields of these circulators reduces measurement efficiency and inhibits scalability. Our strategy to circumvent this is to perform the amplification and signal routing directly on-chip, by coupling a transmon qubit to a nonreciprocal multimode parametric system. As a consequence of this, the qubit and amplifier become a single open quantum system with a large Hilbert space. In this talk, we will discuss the theoretical challenges in understanding the quantum dynamics, focusing on extracting qubit measurement and dephasing rates.

QI 16.7 Wed 11:00 HFT-FT 131

**Three wave mixing with a dimer Josephson junction array amplifier** — •Mitchell Field[1], Nicolas Zapata[1], and Ioan M. Pop[1,2,3] — [1]Institute of Quantum Materials and Technology, Karlsruhe Institute of Technology — [2]Physikalisches Institut, Karlsruhe Institute of Technology — [3]1. Physikalisches Institut, University of Stuttgart

Superconducting Josephson junction parametric amplifiers are robust, low noise amplifiers used to improve the signal to noise ratio of microwave quantum measurements. A common way to generate amplification is with the intrinsic non-linearity of superconducting quantum interference devices (SQUIDs), which sustain four wave mixing processes. In this work we re-engineer an established optical lithography design for dimer Josephson junction array amplifiers [1] by replacing SQUIDs with superconducting non-linear asymmetric inductive elements (SNAILs) [2] which we use to introduce a three wave mixing process. The asymmetric Josephson potential of SNAILs induces a so-called Kerr-free point [3], which we use to improve the dynamic range [4] and increase the signal-pump detuning to several gigahertz.

1. Winkel, P. et al. Phys. Rev. Applied 13, 024015 (2020).
2. Frattini, N. E. et al. Applied Physics Letters 110, 222603 (2017).
3. Sivak, V. V., Shankar, S., Liu, G., Aumentado, J. & Devoret, Phys. Rev. Appl. 13, 024014 (2020).
4. Eichler, C. & Wallraff, A. EPJ Quantum Technol. 1, 119 (2014).

**15 min. break**

QI 16.8 Wed 11:30 HFT-FT 131

**Single-qubit gates on Fluxonium qubits with a sub-harmonic drive** — •Johannes Schirk[1,2], Florian Wallner[1,2], Niklas Bruckmoser[1,2], Leon Koch[1,2], Ivan Tsitsilin[1,2], Niklas Glaser[1,2], Vincent Koch[1,2], Longxiang Huang[1,2], Klaus Liegener[1,2], Max Werninghaus[1,2], Etienne Denois[3], Dominique Sugny[3], Christian Schneider[1,2], and Stefan Filipp[1,2] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [3]Laboratoire Interdisciplinaire Carnot de Bourgogne, CNRS-Université de Bourgogne, Dijon, France

Current implementations of superconducting quantum processors rely on microwave drive lines and flux bias lines to control qubits. To ensure fast and high-fidelity operations, the coupling between the qubit and the control lines must be sufficiently large, which in turn increases energy relaxation of the qubits. In this talk, we present a new approach to control Fluxonium qubits. We experimentally realize high-fidelity single-qubit gates by applying a parametric drive to the qubit's flux line, eliminating the need for an additional charge line. Moreover, we demonstrate the ability to drive the qubit with a sub-harmonic drive frequency at a fraction of its resonance frequency, using a multi-photon process to excite the qubit. This allows us to place a low-pass filter on the flux line below the qubit's resonance frequency, thereby suppressing energy relaxation into this single remaining control line.

QI 16.9 Wed 11:45 HFT-FT 131

**High-Fidelity Readout of Fluxonium Qubits** — •Florian Wallner[1,2], Johannes Schirk[1,2], Niklas Bruckmoser[1,2], Leon Koch[1,2], Ivan Tsitsilin[1,2], Niklas Glaser[1,2], Vincent Koch[1,2], Longxiang Huang[1,2], Klaus Liegener[1,2], Max Werninghaus[1,2], Christian Schneider[1,2], and Stefan Filipp[1,2] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany

Fast and high-fidelity qubit readout is one of the fundamental operations for quantum computation. A higher readout fidelity significantly reduces the number of experiments needed to reach the specified accuracy. Recently, the use of measurements in a mid-circuit fashion with classical feedback became an important resource for efficient quantum circuits. Here the performance of the readout is even more critical for the resulting circuit fidelity. In this talk we report on our recent advances to improve the readout of superconducting Fluxonium qubits. We demonstrate dispersive readout within $1.2\,\mu$s with assiment fidelities higher than 98.3 % and a QNDness of up to 98.0 %. These high numbers enable us to use an active feedback based reset that outperforms passive methods to initialize the qubit. Due to our high readout photon number of $\bar{n} > 50$ we can mitigate the use of a parametric amplifier. Moreover, through dedicated flux pulses we can utilize the dispersive shift landscape of the qubits. With this, we can protect the qubit during idling times and significantly enhance the resonator shift during readout improving the readout fidelity even further.

QI 16.10 Wed 12:00 HFT-FT 131

**Improving Transmon Qudit Measurement on IBM Quantum Hardware** — •Tobias Kehrer, Tobias Nadolny, and Christoph Bruder — Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

The Hilbert space of a physical qubit typically features more than two energy levels. Using states outside the qubit subspace can provide advantages in quantum computation. To benefit from these advantages, individual states of the d-dimensional qudit Hilbert space have to be discriminated properly during readout. In this contribution (arXiv:2307.13504), we propose and analyze two measurement strategies that improve the distinguishability of transmon qudit states. Both strategies aim to minimize drive-frequency dependent assignment errors of qudit states. Based on a model describing the readout of IBM Quantum devices, these strategies are compared to the default measurement. In addition, we employ higher-order X-gates that make use of two-photon transitions for qudit state preparation.

QI 16.11 Wed 12:15 HFT-FT 131

**Automated Characterization of Superconducting Quantum Processors** — •Konstantin Lehmann, Adam Lawrence, Timo van Abswoude, Thorsten Last, and Adriaan Rol — Orange Quantum Systems B.V., Elektronicaweg 10, 2628 XG Delft, NL

The qubit count of transmon-based quantum processors is steadily increasing. Some processors are already beyond the 100-qubit scale [1]. In order to keep the development cadence of those quantum processors high, the test time per qubit need to be strongly reduced from days to hours. Therefore, we developed the library SCQT and its accompanied automation framework GRACE.

SCQT is based on the open-source measurement framework Quantify [2]. It supports adaptive measurements to reduce the size and duration of large experiments. SCQT is designed with processor-scaling in mind and is equipped for features like tuneable couplers, leakage correction and cross-talk correction.

GRACE extracts the quantities of interest from the calibration protocols and transitions smoothly to the next protocol. This level of automation allows to take longer measurements without supervision, thereby reducing significantly the effort to characterize transmon-based quantum processors.

[1] https://www.ibm.com/quantum/roadmap
[2] https://quantify-os.org/

QI 16.12 Wed 12:30 HFT-FT 131

**Suppression of coherent errors in Cross-Resonance gates via recursive DRAG** — •Boxi Li[1,2], Tommaso Calarco[1,2,3], and Felix Motzoi[1] — [1]Forschungszentrum Jülich, Institute of Quantum Control (PGI-8), D-52425 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, D-50937 Cologne, Germany —

[3]Dipartimento di Fisica e Astronomia, Università di Bologna, 40127 Bologna, Italy

The high-precision control of quantum logical operations is a prerequisite to increasing circuit depths in quantum processors, implementing useful quantum algorithms, and reaching fault-tolerant scalable architectures. A ubiquitous approach used for entangling gates has been all-microwave control of superconducting qubits, primarily using the Cross-Resonance two-qubit gate; however, fidelities are still limited by control imperfections. Here, we derive a universal analytical pulse shape that significantly improves fidelities in Cross-Resonance gates, suppressing both the three off-resonant transitions on the control qubit and unwanted two-qubit rotation operators. Experimentally tested on the IBM Quantum Platform, our proposed drive pulse demonstrates successful suppression of coherent errors, allowing for much faster gates than the current state-of-the-art. Despite limited remote access, across multiple qubit pairs, we achieve a notable two to threefold reduction in error for the CNOT gate, resulting in coherence-limited gates with fidelities in the 99.7% range, higher than any publicly accessible CNOT gate on the IBM Quantum Platform.

QI 16.13 Wed 12:45 HFT-FT 131

**Superconducting Qubit reset using Demolition Measurement** — •Ashutosh Mishra[1], Frank Wilhelm-Mauch[1], and Shai Machnes[1,2] — [1]Peter Grünberg Institute - Quantum computing Analytics (PGI-12) Forschungszentrum Jülich, Jülich, Germany — [2]Qruise GmbH, Saarbrücken, Germany

Superconducting qubits have been a popular choice for quantum computing, but still are noisy and have been plagued with errors. The error budget of surface code as presented by Google Quantum AI [1] had almost half the errors due to measurement, leakage and qubit idle during measurement and reset. Measurement and reset of the qubits also constitute a large fraction of the time between two experiments. Since algorithms like VQE, QEC rely on multiple measurements to either estimate better parameters for the anstaz or to detect errors, reducing the time taken to measure and reset the qubit can significantly increase the data taking rate and at the same time reduce qubit idling errors. In this project we look for a scheme for combining the measurement and reset processes of the qubit and the readout resonator using optimal control tools. We demonstrate that one can perform a qubit readout, clear leakage population of the qubit and then empty the resonator and reset the qubit to the ground state within $1\mu s$.

[1] "Suppressing quantum errors by scaling a surface code logical qubit." Nature 614, no. 7949 (2023): 676-681.

QI 16.14 Wed 13:00 HFT-FT 131

**Renormalization effects in driven quantum phase slip junctions** — •Christina Koliofoti and Roman-Pascal Riwar — Forschungszentrum Jülich, Peter Grünberg Institut (PGI-2), 52425 Jülich, Deutschland

Quantum circuit theory is a powerful tool to describe superconducting circuits. In its language, quantum phase slips (QPSs) are considered to be the exact dual to the Josephson effect. This duality renders the integration of QPS junctions into a unified theoretical framework challenging. As we argue, different existing formalisms may be inconsistent, and the correct inclusion of time-dependent flux driving requires introducing a large number of auxiliary, nonphysical degrees of freedom. We resolve these issues by describing QPS junctions as inductive rather than capacitive elements, and reducing the Hilbert space to account for a compact superconducting phase. Our treatment provides an approach to circuit quantization exclusively in terms of node-flux-node variables, and eliminates spurious degrees of freedom. In this talk we present in particular the possibility of a voltage-dependent renormalization of the QPS amplitude, by accounting for spatial variations of the electric field built up across the junction.

## QI 17: Quantum Information: Concept and Methods I

Time: Wednesday 9:30–11:15 Location: HFT-TA 441

QI 17.1 Wed 9:30 HFT-TA 441

**Noisy Stabilizer Formalism** — •Maria Flors Mor Ruiz and Wolfgang Dür — Universität Innsbruck, Institut für Theoretische Physik, Technikerstraße 21a, 6020 Innsbruck, Austria

Despite the exponential overhead to describe general multi-qubit quantum states and processes, efficient methods for certain state families and operations have been developed and utilized. The stabilizer formalism and the Gottesman-Knill theorem, where pure stabilizer or graph states are manipulated by Clifford operations and Pauli measurements, are prominent examples, and these states play a major role in many applications in quantum technologies. This talk presents the developed noisy stabilizer formalism, i.e., a method that allows one to efficiently describe and follow not only pure states under Clifford operations and Pauli measurements but also Pauli noise processes acting on such stabilizer states, including uncorrelated and correlated dephasing and single- or multiple-qubit depolarizing noise. The method scales linearly in the number of qubits of the initial state, but exponentially in the size of the target state. Thus, whenever a noisy stabilizer state is manipulated by means of local Pauli measurements such that a multipartite entangled state of a few qubits is generated, one can efficiently describe the resulting state.

QI 17.2 Wed 9:45 HFT-TA 441

**Wilsonian Renormalization as a Quantum Channel** — •Matheus Henrique Martins Costa[1], Jeroen van den Brink[1,2], Flávio de Souza Nogueira[1], and Gastao Inácio Krein[3] — [1]IFW Dresden, Dresden, Germany — [2]Würzburg-Dresden Cluster of Excellence, Dresden, Germany — [3]Instituto de Física Teórica - UNESP, Sao Paulo, Brazil

We show that the Wilsonian formulation of the renormalization group (RG) defines a quantum channel acting on the momentum-space density matrices of a quantum field theory. This information-theoretical property of the RG allows us to derive a remarkable consequence for the vacuum of theories at a fixed point: they have no entanglement between momentum scales.

With this result we also begin an investigation of behavior of momentum-space entanglement across the phase transition in the Sine-Gordon model and, more generally, we derive constraints on the form of the ground state of fixed-point theories, possibly being useful for the development of numerical techniques.

QI 17.3 Wed 10:00 HFT-TA 441

**Achievable state transformations under rotational invariance** — •Fynn Otto and Konrad Szymański — Universität Siegen, Germany

Rotational invariance is a fundamental characteristic of physical interactions, naturally leading to rotationally covariant dynamics. In communication between distant parties, the lack of a common reference frame imposes similar constraints on the effective transformations: they must be independent of the unknown reference, and thus are rotationally covariant as well. This feature is captured by the formalism of $SU(2)$-covariant operations: those that commute with the actions of all group elements. We present an analytical characterization of covariant transformations and introduce semidefinite programs to examine which states are reachable from a given input using $SU(2)$-covariant channels. Our results improve our understanding of the transformations of directional information carriers and showcase the mechanisms of quantum operations lacking a reference frame.

QI 17.4 Wed 10:15 HFT-TA 441

**Cost-efficient readout error mitigation** — •Ákos Budai[1,2], Zoltán Zimborás[2], and András Pályi[1] — [1]Budapest University of Technology and Economics — [2]Wigner RCP, Hungarian Academy of Sciences

Readout error mitigation (REM) is an efficient tool to improve the functionality of Noisy Intermediate-Scale Quantum (NISQ) devices. In most superconducting prototype quantum computers, the readout error dominates the errors of individual gates. The level of improvement gained by REM depends on the error probabilities and number of shots available. In this work, we quantify the efficiency of REM in quantum state tomography. We derive approximate analytical results for the mean squared error of the estimation. We start by introducing the measurement protocol for the case of single-qubit tomography, then we generalize to the N-qubit case and derive the scaling properties of the calculation with the number of qubits and the order of the Taylor expansion.

QI 17.5 Wed 10:30 HFT-TA 441

**Imaginary Time Evolution: A Lie-theoretic study with applications to Quantum Algorithms and Statistical Physics** — •Roberto Gargiulo[1], Matteo Rizzi[1,2], and Robert Zeier[1] — [1]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), Jülich 52425, Germany — [2]University of Cologne, Institute for theoretical physics (THP), 50937 Cologne, Germany

The imaginary time evolution has long been used in physics to relate dynamical and equilibrium properties. We discuss this duality in the case of variational quantum algorithms, where a systematic study of symmetries via Lie theory can be used to relate compact real Lie algebras (such as $\mathfrak{su}(n), \mathfrak{so}(n), \mathfrak{sp}(n)$) to the their noncompact "imaginary-time" counterparts.

This connection is exemplified for the transfer-matrix method in classical spin systems, especially for the two-dimensional Ising model. This is also related to the standard ansatz for the quantum approximate optimization algorithm aimed at solving the maximum-cut graph problem. By leveraging this Lie-theoretic approach, we study similarities and differences between the two counterparts and explore potential applications.

QI 17.6 Wed 10:45 HFT-TA 441

**Graphical Calculus for Non-Gaussian Quantum States** — •Lina Vandré[1,2], Boxuan Jing[2], Yu Xiang[2], Otfried Gühne[1], and Qiongyi He[2] — [1]University of Siegen — [2]School of Physics, Peking Universit

Multipartite entangled states are an important resource for quantum computing, quantum communications, and quantum metrology. The multi-mode complex entangled quantum states prepared in experiments are classified into continuous variable (CV) and discrete variable (DV) systems according to the type of variables.

When analysing multiparticle entanglement, the exponentially increasing dimension of the Hilbert space is a challenging factor. It is a natural approach to consider specific families of states that enable a simple description and useful properties. Graph and hypergraph states form such families of multi-qubit quantum states, as they can be described by a graphical formalism. They have applications in various contexts, for example, measurement-based quantum computation or self-testing. The graphical formalism of graph and hypergraph states can be generalised to CV systems. While CV graph states are Gaussian, general hypergraph states are non-Gaussian. There are already several works about CV graph states, but there is very little exploration of CV hypergraph states.

In this talk, I introduce graphical rules for Gaussian operations applied to non-Gaussian hypergraph states. I show how these rules help to prepare complex non-Gaussian states as well as how the formalism can be used for characterizing non-Gaussian states.

QI 17.7 Wed 11:00 HFT-TA 441

**What connects entangled photons?** — •Eugen Muchowski — Primelstrasse 10, 85591 Vaterstetten

A local realistic model is presented which reproduces the quantum mechanical predictions for expectation values with polarization measurements, but is not based on shared statistical parameters. Instead, the coupling of the entangled particles is based on initial conditions and conservation of spin angular momentum. The model refutes Bell's theorem and also explains teleportation and entanglement swapping in a local way. It is also shown which error in Bell's derivation leads to Bell's inequality failing to correctly describe the relationships between expectation values from quantum mechanics. The consequences for quantum computing are discussed.

## QI 18: Poster II

Time: Wednesday 11:00–14:30 Location: Poster A

QI 18.1 Wed 11:00 Poster A

**Scaling of the quantum approximate optimization algorithm on superconducting qubit based hardware** — Johannes Weidenfeller[1,2], •Lucia Valor[1], Julien Gacon[1,3], Caroline Tornow[1,2], Luciano Bello[1], Stefan Woerner[1], and Daniel Egger[1] — [1]IBM Quantum, IBM Research Europe, Zurich, Switzerland — [2]ETH, Zurich, Switzerland — [3]EPFL, Lausanne, Switzerland

Quantum computers may provide good solutions to combinatorial optimization problems by leveraging the Quantum Approximate Optimization Algorithm (QAOA). The QAOA is often presented as an algorithm for noisy hardware. However, hardware constraints limit its applicability to problem instances that closely match the connectivity of the qubits. Furthermore, the QAOA must outpace classical solvers. In our work, we investigate and benchmark swap strategies used to map dense problems into linear, grid and heavy-hex coupling maps. Using known entropic arguments, we find that the required gate fidelity for dense problems lies deep below the fault tolerant threshold. We also provide a methodology to reason about the execution-time of QAOA. Finally, we execute the closed-loop optimization on cloud-based quantum computers, using Qiskit Runtime, with transpiler settings optimized for QAOA. This work highlights some obstacles to improve to make QAOA competitive, such as gate fidelity, gate speed, and the large number of shots needed. The QAOA Qiskit Runtime program used acts as a tool to investigate such issues at scale on noisy superconducting qubit hardware.

QI 18.2 Wed 11:00 Poster A

**Simulating Many-Body Systems using Waveguide Arrays** — •Benedikt K. Braumandl[1,2,3,4], Johannes Knörzer[5], Robert H. Jonsson[6], Alexander Szameit[7], and Jasmin D. A. Meinecke[1,2,4,8] — [1]MPI für Quantenoptik, Germany — [2]Fakultät für Physik, LMU München, Germany — [3]Fakultät für Physik, TU München, Munich, Germany — [4]Munich Center for Quantum Science and Technology, Germany — [5]ITS, ETH Zürich, Switzerland — [6]Nordita, KTH Stockholm, Sweden — [7]Institut für Physik, Universität Rostock, Germany — [8]Institut für Festkörperphysik, TU Berlin, Germany

The study of quantum many-body systems poses an interesting yet difficult task of current research. Often, these complex systems cannot directly be implemented experimentally, even when using state of the art technology. Nevertheless, for some systems, this problem can be evaded by employing mathematical mappings to simpler geometries. The modified version can then be easily implemented in more accessible platforms such as waveguide arrays. Our research focuses on the design and experimental implementation of such arrays for the simulation of complex many-body systems. Using this platform, we can exploit the beneficial properties of photons such as long coherence times and high controllability. In particular, we simulate the dynamics of a giant atom coupled to a waveguide at various coupling points – a system that exhibits a phenomenon known as *oscillating bound states* [1].

[1] D. Noachtar et al. "Nonperturbative treatment of giant atoms using chain transformations". In *Phys. Rev. A* 106.1 (2022).

QI 18.3 Wed 11:00 Poster A

**Quantum acoustics for high frequency gravitational wave sensing** — •Marius Bild, Andraz Omahen, Dario Scheiwiller, Matteo Fadel, and Yiwen Chu — ETH Zürich, Labor für Festkörperphysik, Otto-Stern-Weg 1, 8093 Zürich

Mechanical resonators are emerging as an important new platform for quantum science and technologies. In particular, interfacing a bulk acoustic resonator with a superconducting qubit enables the creation and control of quantum states of mechanical motion that can be assigned macroscopic masses, useful for tests of fundamental quantum mechanics as well as in quantum sensing experiments. For example, the high intrinsic sensitivity to metric perturbations of space time, makes bulk acoustic resonators prime candidates for compact sensors of high frequency gravitational waves. Here we show how gravitational wave amplitudes can be bound by precise temperature measurements of the phonon modes in our devices, as well as how quantum states with high Fisher information can achieve quantum enhanced sensitivities.

QI 18.4 Wed 11:00 Poster A

**Transmon qubit as an absolute power sensor at milli-Kelvin**

**temperatures** — •Asen Lyubenov Georgiev, Fabian Kaap, Thomas Weimann, Alexander Fernández Scarioni, Victor Gaydamachenko, Christoph Kissling, Bhoomika Ravi Bhat, Mark Bieler, and Lukas Grünhaupt — Physikalisch-Technische Bundesanstalt

Superconducting quantum bits (qubits) are the basic elements of quantum computational devices. When operating qubits at milli-Kelvin temperatures with a series of cryogenic components on the electrical lines the exact attenuation is not known. Therefore, the resulting microwave power in the cryogenic environment is not predictable a priori. However, qubits can be used as very sensitive power sensors in the 3 to 8 GHz range, and we can measure the microwave power without the need for further dedicated devices. Here, we present a transmon-based circuit, a specific realization of superconducting qubit, which allows us to harness their power sensing capabilities. Finally, we measure and evaluate the absolute power sensing capabilities of the fabricated devices.

QI 18.5 Wed 11:00 Poster A

**Germanium quantum wells as a novel material platform for spin qubits** — •Niels Focke[1], Lino Visser[1], Spandan Anupam[1], Alberto Mistroni[2], Yuji Yamamoto[2], Giovanni Capellini[2,3], Felix Reichmann[2], and Vincent Mourik[1] — [1]JARA-FIT Institute for Quantum Information, Forschungszentrum Jülich GmbH and RWTH Aachen University, Campus Boulevard 79, 52074 Aachen, Germany — [2]IHP, Leibniz-Institut für Innovative Mikroelektronik, D-15236 Frankfurt (Oder), Germany — [3]Dipartimento di Scienze, Universita Roma Tre, Roma 00146, Italy

Germanium quantum wells emerged in recent years as a promising platform for gate-defined spin qubits. The unique properties of a two-dimensional hole gas in strained Ge, with exceptional carrier mobility, compatibility with silicon-based technologies, intrinsic spin-orbit-coupling, and anisotropic g-tensor are key to this promise. Particularly, the last two properties allow fast all-electrical qubit driving and enable novel approaches for spin qubit control. Additionally, the low effective mass and Fermi level pinning to the valence band simplifies the fabrication requirements of these devices. These considerations make Germanium quantum wells an excellent material choice for spin qubits. However, many of the platform*s physical properties are yet to be understood in depth. Our measurements aim to uncover the microscopic behavior of the quantum well stack. The initial focus is on one and two qubit devices, to explore and understand the anisotropy of spin-orbit interaction and g-factor tensor. We report the current progress of our studies regarding these devices.

QI 18.6 Wed 11:00 Poster A

**Critically coupled qubit-photon interfaces in waveguide QED** — •Nicolas Jungwirth[1,2,3] and Peter Rabl[1,2,3] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, 85748 Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany

The development of large-scale quantum processors relies on the effective implementation of quantum networks. Chiral interfaces constitute a novel approach in this context. To this end, interfaces that feature giant atoms coupled to a waveguide at two spatially separated points have already been introduced. In these systems, the directional emission of a photon is based on interference effects [1]. We propose an extended configuration for a more efficient transfer between nodes. By studying the non-Markovian dynamics of the giant atom, we ascertain critical coupling conditions under which the shape of the spontaneously emitted photons becomes almost fully symmetric.

[1] C. Joshi *et al.*, Phys. Rev. X **13**, 021039 (2023).

QI 18.7 Wed 11:00 Poster A

**Ideal Single Photon Sources at Telecom Wavelengths** — •Jonas Grammel[1], Julian Maisch[2], Nam Tran[2], Simone Luca Portalupi[2], Peter Michler[2], and David Hunger[1] — [1]Physikalisches Institut, Karlsruher Institut für Technologie — [2]Institut für Halbleiteroptik und Funktionelle Grenzflächen, Universität Stuttgart

Semiconductor single photon sources are fundamental building blocks for quantum information applications. The current limitations of such quantum dot sources are the emitting wavelength and insufficient collection efficiency in fiber-based implementations. In the project *Telecom Single Photon Sources* we aim to realize high brightness, fiber coupled sources of single and indistinguishable photons at the telecom wavelength for the upcoming realization of fiber-based quantum networks. We employ open cavities realized with fiber-based mirrors, in combination with InGaAs quantum dots emitting in the telecom O-band and C-band. We improve the photon indistinguishability, with prospect to achieve the limit of Fourier-limited photons, by utilizing the lifetime reduction of the emitters via the Purcell effect.

QI 18.8 Wed 11:00 Poster A

**A model for energy conversion in photovoltaic systems from quantum resource theories of thermodynamics** — •Nicolas Schubel, Giovanni Spaventa, Susana F. Huelga, and Martin B. Plenio — Institute of Theoretical Physics, Ulm University, Ulm, Germany

Quantum Resource Theories have proven themselves to be a useful tool to analyse problems from a information-theoretic perspective. Here this formalism gets used to analyse Shockley and Queisser's well known result on the efficiency of solar cells. A model will be presented which recovers this limit in the framework of the resource theory of athermality and which subsequently is expanded to hot carrier solar cells. To that end, the initial model will be broken down to its core components, thus rendering it suitable for a resource-theoretical analysis. The applied method excels at predicting bounds based on fundamental limitations, which will then be exploited in calculating the maximum efficiency over a family of possible density of states.

QI 18.9 Wed 11:00 Poster A

**Quantum-computing study of the electronic structure of 3D crystals: the case study of silicon** — Michal Ďuriška[1,2], Ivana Miháliková[1,2], and •Martin Friák[1] — [1]Institute of Physics of Materials, Czech Academy of Sciences, Brno, Czech Republic — [2]Masaryk University, Brno, Czech Republic

Building upon our previous experience with quantum computing of small molecular systems (see, e.g., I. Miháliková et al., https://doi.org/10.3390/molecules27030597, and I. Miháliková et al., https://doi.org/10.3390/nano12020243), we newly focus on computing the electronic structure of crystals. Being inspired by the work of Cerasoli et al. (Phys. Chem. Chem. Phys., 2020, 22, 21816), we have used hybride variational quantum eigensolver (VQE) algorithm, which combined classical and quantum information processing. Employing tight-binding type of crystal description, we present our results for crystalline diamond-structure silicon. In particular, we focus on the states along the eight lowest bands within the electronic structure of Si and compare the results with values obtained by classical means. While we demonstrate an excellence agreement between classical and quantum-computer results for the lowest-energy band even for relatively small number of optimization-procedure iterations, higher-energy bands require much higher numbers of iterations, several thousands of them, i.e. dozens of millions of quantum-unit calls. Several results were obtained also using quantum processors provided by the IBM. We gratefully acknowledge the financial support from the Czech Academy of Sciences (the Praemium Academiae of M.F.).

QI 18.10 Wed 11:00 Poster A

**Creating NOON states with ultracold bosonic 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 Matematica, Fisica e Informatica, Università di Parma, Parco Area delle Scienze 7/A, 43124 Parma, Italy

We theoretically investigate quantum control protocols for the creation of NOON states using ultracold bosonic atoms on two modes, corresponding to the coherent superposition $|N,0\rangle + |0,N\rangle$, for a small number N of bosons. One possible method to create this state is to consider a third mode where all bosons are initially placed, which is symmetrically coupled to the two other modes. Tuning the energy of this third mode across the energy level of the other two modes allows the adiabatic creation of the NOON state. The main issue with this method is that it requires a large amount of time to reach the NOON state. However, this problem can be addressed by the application of a counterdiabatic Hamiltonian, which allows one to significantly reduce the time required to achieve these entangled states. We demonstrate that such a counterdiabatic protocol is feasible and effective for a single particle, and then discuss how to extend its application to a larger number of bosons.

QI 18.11 Wed 11:00 Poster A

**A simple demonstration experiment of entanglement using the nuclear and electron spin of nitrogen vacancy centers in diamond** — •Tim Duka, Lina M. Todenhagen, and Martin S. Brandt — Walter Schottky Institut and School of Natural Sciences, Technische Universität München, Am Coulombwall 4, 85748 Garching, Germany

Entanglement is the key resource that distinguishes quantum from classical technology and allows for example quantum computation to gain advantages over classical computation. On the other hand, entanglement is not a phenomenon that we can observe in our everyday lives, which makes experiments that demonstrate this phenomenon important for educational purposes. The nitrogen vacancy (NV) center in diamond is one of the most promising platforms for quantum applications in solid state systems at room temperature. Its electron spin can be read out and initialized with the use of its spin-dependent photoluminescence and optical spin pumping, respectively. Furthermore, driving a microwave field at the resonance frequency of the electron spin transition allows for optically detected magnetic resonance (ODMR) experiments that can be sensitive to the hyperfine splitting caused by the state of the nitrogen nuclear spin. This enables the application of electron spin rotations conditioned on the nuclear spin as well as single spin rotations. Here, we present a fairly simple demonstration of entanglement between the electron spin and the nitrogen nuclear spin of a NV center in diamond that can be performed by students, at room temperature, and on a typical confocal microscopy setup.

QI 18.12 Wed 11:00 Poster A

**Faithful extraction of internal quality factors in overcoupled tunable superconducting resonators** — •Kedar E. Honasoge[1,2], Yuki Nojiri[1,2], Maria-Teresa Handschuh[1,2], Daniil E. Bazulin[1,2], Leon Koch[1,2], Thomas Luschmann[1,2], Niklas Bruckmoser[1,2], Florian Fesquet[1,2], Achim Marx[1], Rudolf Gross[1,2,3], and Kirill G. Fedorov[1,2,3] — [1]Walther-Meißner-Institut, 85748 Garching, Germany — [2]School of Natural Sciences, Technische Universität München, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), 80799 München, Germany

In quantum information processing, advancing superconducting circuits to reach ever-higher coherence times and internal quality factors has been a key focus. However, the faithful extraction of internal quality factors from reflection measurements of overcoupled resonators represents a long-standing problem due to its large intrinsic, Fano-type, uncertainty in the fitting procedures. Here, we develop a particular solution for this problem by considering a typical tunable superconducting resonator weakly coupled to an antenna circuit, which allows for additional transmission measurements. We develop an input-output model for this case and apply it to our experimental data by simultaneously fitting both the reflection and transmission data. We demonstrate that this approach significantly increases accuracy of the extracted internal quality factors. Finally, we discuss extensions of our method to other types of superconducting quantum circuits.

QI 18.13 Wed 11:00 Poster A

**Concatenated Continuous Dynamic Decoupling of Ensemble NV Centers in Diamond for GHz-range AC magnetometry** — •Takuya Kitamura[1,2], Hitoshi Sumiya[3], Shinobu Onoda[4], Junichi Isoya[5], and Fedor Jelezko[1,2] — [1]Institute for Quantum Optics, Ulm Univesity, Ulm, Germany — [2]Center for Integrated Quantum Science and Technology(IQST), Germany — [3]Sumitomo Electric Industries Ltd., Itami, Japan — [4]National Institutes for Quantum Science and Technology, Takasaki, Japan — [5]Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

GHz-range AC magnetometry with microwave dressed states are well studied for single Nitrogen-Vacancy(NV) centers in diamond. To increase its sensitivity, use of ensemble NVs is essential. Increase of the sensor spins means increase of the spins to be controlled. In particular, this is critical for the dressed-based magnetometer because the quality of the dressed states is affected by the homogeneity of the control fields.

Here, concatenated continuous dynamical decoupling (CCDD) is applied to 500 micrometer thick NV diamond. Prolongation of the coherence time is observed, but it is still not good enough for sensing because of the huge inhomogeneity in the microwave control fields. In order to understand the effect of inhomogeneity on the CCDD, we quantatively characterize the inhomogeneity of the fields by analyzing the decay of Rabi oscillations. This makes a important step toward sensitive GHz-range AC magnetometry with ensemble NV centers.

QI 18.14 Wed 11:00 Poster A

**Microfluidic quantum sensing platform for lab-on-a-chip applications** — •Robin D. Allert, Fleming Bruckmaier, Nick R. Neuling, Karl D. Briegel, and Dominik B. Bucher — Department of Chemistry, Technical University of Munich, 85748 Garching, Germany

Lab-on-a-chip (LOC) applications have emerged as invaluable physical and life sciences tools. The advantages stem from the advanced system miniaturization of microfluidics, requiring far less sample volume while allowing for complex functionality, increased reproducibility, and higher throughput. However, LOC applications require extensive sensor miniaturization to leverage these inherent advantages fully. Atom-sized quantum sensors, such as the nitrogen-vacancy (NV) center in diamond, promise to bridge this gap, enabling sensing of temperature, electric and magnetic fields on the nano- to microscale. Nevertheless, the technical complexity of both disciplines has so far impeded an uncompromising combination of LOC systems and quantum sensors. Here, we present a fully integrated microfluidic platform for NV centers in diamond, enabling full quantum sensing capabilities while being biocompatible and easily adaptable to arbitrary channel and chip geometries. To illustrate the potential of quantum sensors in LOC systems, we demonstrate various NV center-based sensing modalities for chemical analysis in our microfluidic platform, ranging from paramagnetic ion detection to high-resolution NMR spectroscopy. Consequently, our work opens the door for novel chemical analysis capabilities within LOC devices with applications in electrochemistry, or bioanalytics.

QI 18.15 Wed 11:00 Poster A

**Quantum Reservoir Computing in coupled cavities with weak measurements** — •Lara Anna Giebeler, Niclas Götting, Frederik Lohof, and Christopher Gies — Institute for Theoretical Physics, University of Bremen, 28359 Bremen, Germany

Quantum Reservoir Computing (QRC) has emerged as a new quantum machine learning approach to process time-series information by utilizing the coherent dynamics inherent to quantum systems. A possible experimental realization of QRC could be achieved by using semiconductor quantum dots embedded in coupled-cavitiy-arrays as a reservoir.

Early implementations for QRC propose the use of projective (strong) measurements, but these projective measurements induce a back-action on the system, disturbing the dynamics of the reservoir and prohibiting online time-series processing. In the context of actual physical implementations, it has been proposed to use weak measurements [1]. Although these weak measurements provide only reduced information about the system, they also result in little back-action on the reservoir and retain its properties. This work considers the usage of these weak measurements in coupled-cavity QRC to enable online time-series processing.

[1] Mujal, P., Martínez-Peña, R., Giorgi, G.L. et al. npj Quantum Inf 9, 16 (2023). https://doi.org/10.1038/s41534-023-00682-z

QI 18.16 Wed 11:00 Poster A

**Optical reservoir computing with non-classical states of light** — •Lukas Porstendorfer, Steffen Wilksen, Frederik Lohof, and Christopher Gies — Institute for Theoretical Physics, University of Bremen, 28359 Bremen, Germany

Optical reservoir computers (ORC) are physical computational networks that use a complex dynamical system to map inputs into higher dimensional spaces using a large number of optical modes. The ORC has a low computational learning cost, as only the output weights of the network are trained, while still being able to solve tasks such as pattern recognition or chaotic time series prediction. While recent experimental implementations of ORC often used inputs of light in the classical regime, we aim to study the influence of non-classical inputs on the computational efficiency of the ORC to harness the indistinguishability of the quantum particles. With this we aim to explore how quantum effects, such as two-photon interference, influence or even improve the performance of the reservoir.

QI 18.17 Wed 11:00 Poster A

**A Superconducting Platform for Quantum Information Processing** — •Lucien Québaud[1,2], Ian Yang[1,2], Desislava

Atanasova[1,2], Teresa Hoenigl-Decrinis[1,2], and Gerhard Kirchmair[1,2] — [1]Institute for Quantum Optics and Quantum Information, A-6020 Innsbruck, Austria — [2]Institute for Experimental Physics, University of Innsbruck, A-6020 Innsbruck, Austria

In the pursuit of advancing quantum information processing, high-Q coaxial cavities have emergred as a potential avenue to realize interactions in multi-qubit systems. In this work, we present such a platform involving transmon qubits coupled to a high-purity niobium $\lambda/4$ coaxial seamless design.

A modular magnetic hose is introduced for implementing fast magnetic flux control within the superconducting cavity, crucial for fast frequency changes of tunable transmon qubits. The magnetic hose offers a solution to the longstanding challenge of achieving high-coherence 3D cQED systems with fast magnetic flux control.

In order to achieve fast and accurate qubit readout, which is typically limited by the Purcell effect in the dispersive regime, we propose a novel Purcell filter design replacing the conventional readout pin. This design incorporates a modular band-pass filter centred at the resonator frequency, allowing fast qubit measurements while mitigating the impact of the Purcell effect on qubit lifetime.

All these quantum engineering tools enable the construction of a robust superconducting platform for quantum information processing applications.

QI 18.18 Wed 11:00 Poster A

**Broadband impedance-matched Josephson parametric amplifier** — •Diego E. Contreras[1,2], Kedar E. Honasoge[1,2], Maria-Teresa Handschuh[1], Daniil E. Bazulin[1,2], Achim Marx[1], Rudolf Gross[1,2,3], and Kirill G. Fedorov[1,2,3] — [1]Walther-Meißner-Institut, 85748 Garching, Germany — [2]School of Natural Sciences, Technische Universität München, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany

In the field of quantum information processing with superconducting circuits the development of robust quantum-limited parametric amplifiers attracts increasing interest. Such amplifiers are used in various applications, ranging from single-shot qubit readout to generation of non-classical states of light. Unfortunately, conventional Josephson parametric amplifiers are usually narrow band, while broadband traveling wave parametric amplifiers require rather complex fabrication and design routines. Here, we investigate a compromise solution in the form of impedance-matched Josephson parametric amplifiers (IMJPAs). These devices promise simple fabrication, quantum-limited noise performance, and reasonably broadband amplification. Our IMJPA consists of an impedance-modulated, tapered transmission line coupled to a dc-SQUID. We discuss optimization and fabrication of this device and provide results of basic characterization measurements in terms of IMJPA's gain, bandwidth, and dynamic range.

QI 18.19 Wed 11:00 Poster A

**Learning the Ground Energy Profile of $H_2$ Using Variational Quantum Circuits** — Sergio Cotrino and •Carlos Viviescas — Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia

Leveraging Machine Learning techniques with quantum data enables both information processing and learning on quantum systems. We applied Meta-Variational Quantum Eigensolver (meta-VQE) to learn a molecule's ground energy profile using a set of training points. We trained an ansatz quantum circuit using a non-linear Gaussian encoding for circuit parameters, with the interatomic distance as a free variable. This approach delivers a reliable approximation of the ground energy across a specific interatomic distance range. Furthermore, it generates effective initial parameters for standard VQE training, yielding superior results (opt-meta-VQE). We implemented Meta-VQE using both analytic noise-free simulations and 10,000-shots simulations in PennyLane's quantum computing framework. The analytic simulation accurately models the potential energy surface for an $H_2$ molecule within chemical accuracy, employing a hardware-inspired ansatz and the ADAM optimizer. The 10,000-shots simulation approximates the energy profile but is less precise due to sample variability. Meta-VQE introduces an innovative method for information extraction and production by learning from quantum data within variational quantum circuits.

QI 18.20 Wed 11:00 Poster A

**NV-centre Spectroscopy on Magnetic Films on Diamond Membranes** — •Luis Kussi[1], Marcel Schrodin[1], Ioannis Karapatzakis[1], Safa L. Ahmed[2], Christoph Sürgers[1], and Wolfgang Wernsdorfer[1,2] — [1]Physikalisches Institut, Karlsruhe Institute of Technology, Karlsruhe, Germany — [2]Institute of Quantum Materials and Technologies, Karlsruhe Institute of Technology, Karlsruhe, Germany

The NV colour centre in diamond consists of a substituted nitrogen atom and an adjacent vacancy along one of the four crystallographic axes. It has been extensively studied in recent years due to its unique and fascinating spin and optical properties. The ground state and excited state energy levels are accessible via optically detected magnetic resonance (ODMR) and are sensitive to external magnetic and electric fields as well as strain. We investigate thin metallic films deposited on thin diamond membranes containing ensembles of NV-centres by ODMR to measure the strain of the film. Specifically, we use $Mn_3AN$ ($A = Ga, Ag$) antiperovskite films with antiferromagnetic order below a Néel temperature $T_N$ in the range $100-300$ K. The magnetic phase transition is accompanied by a sudden change in the lattice parameters, which generates strain near the diamond/film interface. We report on the experimental setup at low temperatures and present first results obtained using confocal microscopy or widefield imaging with a CCD camera to create a strain map of the film.

QI 18.21 Wed 11:00 Poster A

**Navigating Quantum Circuit Implementation: Quantum Error-Correction on the Qiskit Noisy Simulator** — •Yunos El Kaderi[1,2], Andreas Honecker[1], and Iryna Andriyanova[2] — [1]Laboratoire de Physique Theorique et Modelisation, CNRS UMR 8089, CY Cergy Paris University, France — [2]Laboratoire Traitement de l'Information et des Systèmes, CNRS UMR 8051, CY Cergy Paris University, France

Quantum computing's promise lies in its potential for exponential speedup, yet this potential can be limited by errors arising from various sources of noise. In this contribution, we dig into the practical implementation of quantum circuits on the Qiskit simulator, both in the ideal realm of noise-free operations and the challenging landscape of noisy simulators. To mitigate errors that are led by noise, we'll introduce the concept of Quantum Error-Correcting Codes. We'll demonstrate an example of [5,1,3] stabilizer code, exploring how it enables the encoding of a single logical qubit into a quantum state distributed across five physical qubits, how it can detect, and how we may correct the errors.

QI 18.22 Wed 11:00 Poster A

**Variational Quantum Quasi-Particle Operators** — •Gary Schmiedinghoff[1] and Benedikt Fauseweh[2] — [1]German Aerospace Center, Cologne — [2]TU Dortmund, Dortmund

Quantum simulations are the most promising area for finding quantum advantage on near-term devices. Variational methods are powerful tools to approximate the ground state of a quantum system, but finding excited states, such as done in quantum deflation algorithms, is costly due to the repetitive optimization and accumulation of errors. We propose an ansatz for excitation operators on periodic systems that are optimized once to create a single excitation of tunable momentum. This operator can then be used to prepare various excited states by being applied to the, for instance variationally obtained, ground state. The ansatz is constructed perturbatively, such that the accuracy can be improved depending on the computational capacities, while fulfilling fundamental commutation conditions.

QI 18.23 Wed 11:00 Poster A

**Microwave-shielding of ultracold polar molecules - from evaporation to field-linked tetramers** — •Sebastian Eppelt[1], Shrestha Biswas[1], Xingyan Chen[1], Xinyu Luo[1], Timon Hilker[1], and Immanuel Bloch[1,2] — [1]Max-Planck-Institute of Quantum Optics, Garching, Germany — [2]Ludwig-Maximilans-University, Munich, Germany

Thanks to their strong electric dipole moments and rich internal structure, ultracold polar molecules are a promising platform for realizing exotic quantum matter, for implementing quantum information schemes and for performing precision measurements. In many of these applications, samples of interacting molecular need to be prepared in the quantum-degenerate regime. For a long time, employing evaporative cooling via elastic collisions has been prevented by intrinsically unstable two-body collisions at short range. Protecting molecules against such collisions can be achieved by engineering a repulsive barrier using a blue-detuned, circularly polarized microwave field which couples two rotational states. Here, we demonstrate how microwave shielding can be employed to evaporatively cool a fermionic, 3D gas of $^{23}Na^{40}K$ well below $T_F$. Furthermore, we show how to realize a novel kind of scattering resonances which can be used to tune the interactions between molecules by manipulating the microwave field. These universal field-linked resonances arise due to the existence of long-lived, tetratomic bound states in the intermolecular potential. Lastly, we present our advances in creating and observing these bound states, whose properties agree very well with parameter-free theory calculations.

QI 18.24 Wed 11:00 Poster A

**Continuous-Wave, Room-Temperature Masers, using NV-Centers in Diamond** — •Christoph W. Zollitsch[1,2], Stefan Ruloff[1], Yan Fett[1], Haakon T. A. Wiedemann[1], Rudolf Richter[1], Jonathan D. Breeze[1,2], and Christopher W. M. Kay[1,3] — [1]Department of Chemistry, Saarland University, Saarbrücken, Germany — [2]Department of Physics & Astronomy, University College London, London, UK — [3]London Centre for Nanotechnology, University College London, London, UK

The concepts of microwave amplification by stimulated emission of radiation (MASER) were developed in the late 1950s, in conjunction with its optical counterpart the laser. While lasers found applications in many fields the applications of masers were highly specialized. This was due to the extreme operating conditions of the first masers, requiring cryogenic temperatures and high vacuum environments. However, the maser*s excellent low-noise microwave amplification as well as its ultra narrow linewidth make it an attractive candidate for a broad range of microwave applications. Here, we characterize the operating space of a diamond NV-center maser system. Key for the continuous emission of microwave photons is a level inversion, in addition to a high-quality, low mode-volume microwave resonator to enhance the spontaneous emission of the NV-centers. We investigate the performance of the maser system as a function of level inversion and resonator quality-factor and construct a phase diagram, identifying the parameter space of operation and discuss the optimal working points and pathways for optimization.

QI 18.25 Wed 11:00 Poster A

**Optimizing Diamond Substrates for Electrical Readout of Nitrogen-Vacancy Centers** — •Jonas Wiebe, Lina Maria Todenhagen, and Martin S. Brandt — Walter Schottky Institut and School of Natural Sciences, Technische Universität München, Am Coulombwall 4, 85748 Garching, Germany

Due to its remarkable room temperature properties, the nitrogen-vacancy (NV) center in diamond is a highly interesting quantum system for practical applications, particularly in the field of quantum sensing. The spin state of the NV center can be read out by either optically or electrically detected magnetic resonance (ODMR or EDMR, respectively), with EDMR offering specific advantages for miniaturization and device integration. However, the much less investigated electrical readout encounters very different challenges than its optical counterpart. Notably, the presence of a spin-independent background current from other defects, such as the nitrogen donor $N_s^0$, represents a critical and unique aspect in EDMR. In this study, we use helium ion irradiation on different diamond materials to specifically tune the NV to $N_s^0$ concentration and investigate the EDMR and ODMR performance of these samples across different irradiation doses.

QI 18.26 Wed 11:00 Poster A

**Programmable cooling on noisy quantum computers: Optimization and error mitigation** — •Imane El Achchi, Achim Rosch, and Anne Matthies — Institute for Theoretical Physics,University of Cologne,50937 Cologne,Germany

Recent advances in quantum computing provide a vast playground for the application of quantum algorithms on noisy intermediate-scale quantum devices. Here, we test the performance of the programmable adiabatic demagnetization protocol proposed in Ref. [1] on IBM's quantum devices. The noise resilient cooling protocol is a promising application for near-term quantum computers that promises the preparation of interesting quantum many-body ground states regardless of the system's initial state. We explore the implementation of the cooling protocol using the transverse field Ising model for the available small system size and limited gate depth on IBM's quantum devices, as well as on simulators of Qiskit. Moreover, we enhance the performance for a given noise level through optimizing the protocol parameters. We also explore mitigating the effect of noise using different error mitigation techniques.

Reference: [1] Anne Matthies, Mark Rudner, Achim Rosch, and Erez Berg. Programmable adiabatic demagnetization for systems with trivial and topological excitations, 2022.

QI 18.27 Wed 11:00 Poster A

**Characterization of Paramagnetic States in Substrates for Transmon Qubits** — •Michael Göldl[1,3], Niklas Bruckmoser[2,3], Leon Koch[2,3], Stefan Filipp[2,3], and Martin S. Brandt[1,3] — [1]Walter Schottky Institut, Technische Universität München, Am Coulombwall 4, 85748 Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Walther-Meißner-Straße 8, 85748 Garching, Germany — [3]School of Natural Science, Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany

Electrically Detected Magnetic Resonance (EDMR) is a highly sensitive technique to detect paramagnetic impurities and defects in semiconductors. Defects like the $P_{b0}$ defect at the $Si/SiO_2$ interface are such paramagnetic states and act as recombination centers for excess charge carriers which can be detected as a decrease in photoconductivity. Since both $P_{b0}$ and charge carriers such as electrons in the conduction band have spin, this recombination is governed by the Pauli exclusion principle. Using magnetic resonance, the spin signature of the defects as well as their concentration can be determined. Here, we present a study where we quantify the $P_{b0}$ defect densities in Si substrates used for for the manufacturing of superconducting transmon qubits and compare the EDMR results obtained after varying interface treatments of the substrate to coherence times observed for transmon qubits fabricated on similarly treated wafers.

QI 18.28 Wed 11:00 Poster A

**High-Coherence Fluxonium Qubits Using Dolan Bridge Junction Arrays** — •Vincent Koch[1,2], Johannes Schirk[1,2], Florian Wallner[1,2], Niklas Bruckmoser[1,2], Leon Koch[1,2], Ivan Tsitsilin[1,2], Niklas Glaser[1,2], Longxiang Huang[1,2], Klaus Liegener[1,2], Christian Schneider[1,2], and Stefan Filipp[1,2] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany

Fluxonium qubits have experienced increasing interest in recent years as they exhibit large anharmonicity and high coherence times without sacrificing controlability, which makes them a very well-suited platform for high-fidelity super-conducting quantum computation. In the pursuit of designing and fabricating high coherence fluxonium qubits we investigate the implementation of Josephson junction arrays using different fabrication techniques to improve on junction density and yield. We start by examining the limits posed on the bridge dimensions by fabricating test structures and performing DC and AC measurements to determine yield and fidelity. Afterwards, we integrate the junction arrays into single fluxonium qubit designs and measure the coherence time. Additionally, we discuss and simulate the dominating loss channels of fluxoniums, such as dielectric and quasiparticle losses.

QI 18.29 Wed 11:00 Poster A

**Fabrication of 3D-integrated superconducting quantum circuits in flip-chip geometry** — •Agata Skoczylas[1,2], Léa Richard[1,2], Niklas Bruckmoser[1,2], Leon Koch[1,2], David Bunch[1,2], Lasse Södergren[1,2], and Stefan Filipp[1,2] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, 85748 Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany

To address traditionally challenging problems using quantum computing, it is essential for quantum processors to scale up significantly. However, the current superconducting planar geometry makes it impossible to route the numerous control and readout lines required for a larger number of qubits.

Employing techniques from 3D-integration, such as flip-chip bump bonding, is needed to overcome this issue. However, implementing such technology for superconducting quantum circuits while preserving high coherence times introduces new challenges during fabrication. Indeed, to enable flip-chip bump bonding, essential components, such as indium bumps and spacers, must be added to standard circuit elements. Additionally, achieving precise horizontal and vertical alignment while bonding is essential to maintain accurate parameter targeting.

Here, we present the fabrication processes of thermally evaporated indium bumps and polymer spacers. Moreover, we review the fabrication of superconducting coplanar waveguide resonators in a flip-chip geometry and discuss the impact of 3D-integration on resonators quality factors and frequency targeting.

QI 18.30 Wed 11:00 Poster A

**Quantum noise can enhance algorithmic cooling** — Zahra Farahmand, •Reyhaneh Aghaei Saem, and Sadegh Raeisi — Department of Physics, Sharif University of Technology, Tehran, Iran

Heat-bath algorithmic cooling (HBAC) techniques are techniques that are used to purify a target element in a quantum system. These methods compress and transfer entropy away from the target element into auxiliary elements of the system. The performance of algorithmic cooling has been investigated under ideal noiseless conditions. However, realistic implementations are imperfect, and for practical purposes, noise should be taken into account. Here we analyze HBAC techniques under realistic noise models. Surprisingly, we find that noise can, in some cases, enhance the performance and improve the cooling limit of HBAC techniques. We numerically simulate the noisy algorithmic cooling for the two optimal strategies, partner-pairing and two-sort algorithms. We find that for both of them, in the presence of the generalized amplitude damping noise, the process converges, and the asymptotic purity can be higher than the noiseless process. This opens up new avenues for increasing the purity beyond heat-bath algorithmic cooling.

QI 18.31 Wed 11:00 Poster A

**Optimization of Niobium Film Stress for Superconducting Quantum Circuits** — •David Bunch[1,2], Leon Koch[1,2], Niklas Bruckmoser[1,2], Lasse Södergren[1,2], and Stefan Filipp[1,2] — [1]Walther Meißner Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [2]Technical University of Munich, TUM School of Natural Sciences, Physics Department, Garching, Germany

High quality superconducting films are important for high coherence superconducting quantum processors. Past studies have shown that intrinsic stress effects the superconducting critical temperature and amount of bulk oxidation of sputtered thin films. Two level systems hosted in film oxides are a major contributor to losses in superconducting circuits, so film stress should controlled during sputtering via the argon gas pressure. In this work, we sputter niobium thin films with a wide range of stresses, from compressive to tensile. We evaluate the films' suitability for quantum circuits by performing thin film measurements such as critical temperature and residual resistivity ratio measurements. Eventually we test the quality of the thin films by measuring the internal quality factor of coplanar waveguide resonators as a function of photon number.

QI 18.32 Wed 11:00 Poster A

**Analytical approximations to single fluxonium circuits** — •Longxiang Huang, Johannes Schirk, Florian Wallner, Ivan Tsitsilin, Christian Schneider, Klaus Liegener, and Stefan Filipp — Walther-Meißner-Institut, Garching, Germany

In the ongoing effort of realizing quantum computers based on superconducting circuits, fluxonium qubits have recently emerged as a promising architecture, which show high coherence times and high anharmonicity compared to transmon qubits[1]. However, the eigensystem of fluxonium still deserves further investigation due to the difficulties of solving the double well potential. Previous efforts focused on numerical diagonalizations of the fluxonium Hamiltonian on harmonic oscillator basis[2]. Here, we present an alternative way to solve the double well potentials analytically with the help of a hyperbolic quasi-exactly solvable Generalized Manning potential. An analytical exact solution to certain eigenfunctions has been shown to terminate as confluent Heun's polynomials and associated eigenenergies could be determined by Wronskians[3]. We develop an analytical method to determine an approximation to the wavefunctions with above 99.9% fidelity and energies with 1% error rates in the light fluxonium regime.

[1] Nguyen, L. B. et al. Blueprint for a High-Performance Fluxonium Quantum Processor. PRX Quantum 3, 037001 (2022).

[2] Zhu, G. et al. Circuit QED with fluxonium qubits: Theory of the dispersive regime. Phys. Rev. B 87, 024510 (2013).

[3] Xie, Q.-T. New quasi-exactly solvable double-well potentials. J. Phys. A: Math. Theor. 45, 175302 (2012).

QI 18.33 Wed 11:00 Poster A

**Extending the Hybrid Agent for Reinforcement Learning Beyond Fixed-Length Scenarios** — •Oliver Sefrin and Sabine Wölk — Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Quantentechnologien, 89081 Ulm

In Quantum Reinforcement Learning, the "hybrid agent for quantum-accessible reinforcement learning" (Hamann and Wölk, 2022) provides a quadratic speed-up in terms of sample complexity over classical algorithms. This hybrid agent may be used in deterministic and strictly episodic environments, for which the maze problem is a standard example.

With the current algorithm, however, the episode length (i.e., the number of actions to be played in an episode) is a hyperparameter which needs to be set. For scenarios such as mazes with an unknown distance towards the goal, this poses a problem, since a feasible episode length value is not known initially.

In this work, we propose an adaption to the hybrid algorithm that uses a variable episode length selection strategy, allowing its usage in a wider range of maze problem scenarios. We test our novel approach against classical agents in various maze scenarios. Finally, we reason about conditions for which a quantum advantage persists.

QI 18.34 Wed 11:00 Poster A

**Quantum error correction for quantum registers based on color centers** — •Daniel Dulog and Martin Plenio — Universität Ulm, Institut für Theoretische Physik, Ulm, Germany

Among many quantum technologies, color centers in diamond provide a possible hardware basis for quantum computation, where a typical information processing unit might contain several nitrogen-vacancy (NV) centers in contact with adjacent carbon-13 nuclear spins. With specifically tailored dynamical decoupling sequences (PRL 117, 130502) it is possible to execute selective, high-fidelity two-body gates between the electron spin of the NV center and a targeted nuclear spin. We present a protocol that uses speed-optimized gates of that kind to utilize the nuclear spin environment as code space for quantum error correction within the NV center qubit register.

QI 18.35 Wed 11:00 Poster A

**Spin-up tunnelling detection in noisy readout for SiMOS qubit** — •Noah Gläser[1], Viktor Adam[2], Clément Godfrin[3], and Wolfgang Wernsdorfer[1,2] — [1]PHI (KIT), Wolfgang- Gaede-Str. 1, 76131 Karlsruhe — [2]IQMT (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen — [3]imec, Remisebosweg 1, 3001 Leuven

We present an algorithm for binarisation of noisy binary data in the limit of low signal-to-noise ratio (SNR). The algorithm was initially developed for readout of a SiMOS qubit featuring a Single Electron Transistor (SET) to sense charge in a close-by quantum dot. Each measured SET current stems from one of two distinct levels, representing the absence/presence of a single electron in the quantum dot. The challenge is to revert the current back to the binary signal, in order to decide if level jumps occurred during the measurement. For sufficiently large SNR ($\gtrsim 3$), this can be done with a threshold filter, but fails if the standard deviation of the noise exceeds the difference between the two levels. Our algorithm extracts the qubit's spin-up fraction reliably in three steps, even at SNR $\lesssim 1$. First, it automatically identifies the two current levels. In a second step, we adapt *total variation denoising* to our binary case to obtain the underlying sequence of presence/absence of the electron. A maximum likelihood estimator then utilises the time-resolved signal edges to deduce the obtained spin-up fraction, which is the main quantity of interest for the qubit readout. Finally, we demonstrate the algorithm's performance compared to the threshold method on experimental data.

QI 18.36 Wed 11:00 Poster A

**Photonic Integration of Diamond Qubits into Hybrid Circuits** — •Maarten H. van der Hoeven[1], Julian M. Bopp[1,2], Tommaso Pregnolato[1,2], Marco Stucki[1,2], Alok Gokhale[1], Lea M. Rektorschek[1], Sinan Gündoğdu[1,2], and Tim Schröder[1,2] — [1]Humboldt-Universität zu Berlin, Department of Physics, Berlin, Germany — [2]Ferdinand-Braun-Institute, Berlin, Germany

Quantum photonic circuits are fundamental building blocks for quantum information applications, like secure communication or quantum computing. Hybrid photonic systems combine different materials to leverage their individual strengths. Our devices are based on color centers in diamond nanocavities coupled to an AlGaN/AlN guiding layer on a sapphire substrate.

Here we report on the characterization of recently fabricated "Sawfish" cavities [1]. These cavities show high quality factors and mode resonances that precisely follow the behavior expected from the corresponding design parameters [2]. For the scalable fabrication of "Sawfish" cavities coupled to single color centers we are working on the development of a deterministic coupling method. This method is based on the localization of color centers and subsequent fabrication of nanocavities around them. Furthermore, we numerically optimized the photon transfer between diamond and AlGaN/AlN waveguides by using tapered regions in both materials. Combining these methods facilitates the assembly of fully integrated quantum photonic circuits.

[1] J. M. Bopp et al., arXiv:2210.04702 (2022).
[2] T. Pregnolato et al., arXiv:2311.03618 (2023).

QI 18.37 Wed 11:00 Poster A

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

A multi-node quantum network will be a platform for distributed quantum computing and secure quantum communication. Heralded entanglement between the distant nodes is the first step towards this grand goal. To this end, we present the plan to entangle two Rubidium atom-based nodes. At node 1, the atom is trapped in a red detuned optical light field [1] while at node 2, the atom is trapped at the crossing point of the cavity modes inside a 3D optical lattice [2]. These nodes will be separated by 13 km line-of-sight and connected by optical fibers. To entangle these atoms, we will start with entangling the spin state of the atom with the polarization state of a photon at node 1. This entangled photon on absorption by the atom at node 2 changes the atomic state accordingly and leads to vacuum-stimulated emission of a herald photon. The emission of the herald photon will signal the successful entanglement of the two atoms. In this talk, I will present the progress of this project and give first estimates of the fidelity and possible entanglement generation rates. [1] Y. Zhou et al., arXiv:2308.08892 [2] M. Brekenfeld et al., Nat. Physics 16 647-651 (2020).

QI 18.38 Wed 11:00 Poster A

**Controlled coupling between bulk acoustic wave resonator modes and spin states in silicon-vacancy centers** — •Stefan Pfleging[1,2], Arianne Brooks[1,2], and Yiwen Chu[1,2] — [1]Department of Physics, ETH Zürich — [2]Quantum Center, ETH Zürich

Hybrid quantum devices making use of a high-overtone bulk acoustic wave resonator (HBAR) are useful for storing and manipulating quantum information. By interfacing HBARs with superconducting circuits, quantum states of motion have been successfully created and manipulated [1, 2]. To enhance the coherence properties of hybrid quantum devices and thus their applicability as a quantum memory, we propose coupling HBARs coherently to the spin states of a negatively charged silicon vacancy color center ($SiV^-$) in diamond, which exhibits coherence times in the order of 10 ms at cryogenic temperatures [3]. We aim to show that the spin qubit, which can be realized within the level scheme of the $SiV^-$ in presence of a magnetic field, can be manipulated by acoustic modes of the HBAR. In order to demonstrate the use of the $SiV^-$ coupled to the HBAR as a quantum memory, the initial goal is to couple a classically driven acoustic mode to the spin of the $SiV^-$. As a longer-term goal, we can further incorporate a superconducting qubit coupled to the acoustic resonator, forming a coherent interface between microwave circuits and spin qubits.

[1] Y. Chu, *et al.*, *Nature* **563**, 666-670 (2018)
[2] M. Bild, M. Fadel, Y. Yang, *et al.*, *Science* **380**, 274-278 (2023)
[3] S. Meesala, *et al.*, *Phys. Rev. B* **97**, 205444 (2018)

QI 18.39 Wed 11:00 Poster A

**Relativistic study of the two photon ionization by entangled photon** — •Valeriia Kosheleva[1], Shahram Panahiyan[1,2,3], Angel Rubio[1,4,5], and Frank Schlawin[1,2,3] — [1]Max Planck Institute for the Structure and Dynamics of Matter, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, Hamburg D-22761, Germany — [3]University of Hamburg, Luruper Chaussee 149, Hamburg, Germany — [4]Center for Computational Quantum Physics (CCQ), The Flatiron Institute, 162 Fifth Avenue, New York, New York 10010, USA — [5]Nano-Bio Spectroscopy Group, Departamento de Física de Materiales, Universidad del País Vasco, 20018 San Sebastian, Spain

The phenomenon of two-photon ionization (TPI), a pivotal nonlinear process in the interaction between light and matter, involves the absorption of two photons by an atom, resulting in the emission of a photoelectron. Previous research has extensively examined the angular distribution of photoelectrons in response to incident radiation [1,2]. The availability of entangled photon states has recently opened avenues for exploring nonlinear processes with nonclassical light [3].

In this study, we employ a fully relativistic Scattering S-matrix formalism to scrutinize TPI in alkali-like atoms utilizing entangled photon states. Our findings contribute to advancing the comprehension and potential manipulation of TPI through non-classical light sources.

[1] G. De Ninno, et al., Nature Photonics 14, 554558 (2020). [2] V. P. Kosheleva, et al., Phys. Rev. A 102, 063115 (2020). [3] B. Dayan, et al., Phys. Rev. Lett. 94, 043602 (2005).

## QI 19: Superconducting Electronics: Qubits I (joint session TT/QI)

Time: Wednesday 15:00–18:15 Location: H 0104

QI 19.1 Wed 15:00 H 0104

**Simultaneous flux-locking of gradiometric fluxonium qubits** — •Denis Bénâtre[1], Mathieu Féchant[1], Nicolas Zapata[1], Patrick Paluch[1], Nicolas Gosling[1], and Ioan Pop[1,2] — [1]IQMT, Karlsruhe Institute of Technology, Eggenstein-Leopoldshafen, Germany — [2]PHI, Karlsruhe Institute of Technology, Karlsruhe, Germany

Gradiometric fluxoniums are a novel type of fluxonium qubits introduced by Gusenkova et al. (Appl. Phys. Lett. 120, 2022). Benefiting from their double-loop geometry, gradiometric fluxoniums are substantially less sensitive to global magnetic fields, while retaining all regular fluxonium properties. Going further, we propose to show the simultaneous locking of a handful of gradiometric fluxoniums at a flux point corresponding to the so-called sweet spot of operation, allowing them to be used without the need for external flux biasing after locking. This is done by trapping a fluxon in the most external loop of each device with an external magnetic field while crossing the metal-to-superconductor transition.

QI 19.2 Wed 15:15 H 0104

**Superconducting flux qubits with stacked Josephson junctions** — •Alex Kreuzer[1], Hossam Tohamy[1], Thilo Krumrey[1], Alexandru Ionita[1], Hannes Rotzinger[1,2], and Alexey V. Ustinov[1,2] — [1]Physikalisches Institut (PHI), Karlsruher Institut für Technologie (KIT) — [2]Institut für Quantenmaterialien und -technologien (IQMT), Karlsruher Institut für Technologie (KIT)

Josephson junctions are commonly employed as nonlinear inductive components in superconducting qubits, allowing to tailor specific circuit properties. The promising flux qubit types like fluxonium or quarton qubits require compact inductances, often implemented as arrays of Josephson junctions. Challenges arise due to stray capacitance, originating from the capacitive coupling of an array island to the ground, leading to parasitic resonances at GHz frequencies that can degrade or compromise qubit performance. To address this limitation, we investigate an alternative approach: implementing qubit inductances by stacking Josephson junctions vertically. Junction stacks help to minimize the parasitic capacitance of their electrodes to the ground. We present transport characteristics of the stacks as well as microwave loss measurement data using a quarton-type flux qubit with stacked Josephson junctions. The experimental data are compared to results of numerical simulations.

QI 19.3 Wed 15:30 H 0104

**Pure kinetic inductance coupling between generalized flux qubits and their readout** — •Soeren Ihssen[1], Simon Geisert[1], Patrick Winkel[1,2], Martin Spiecker[1], Mathieu Fechant[1], Patrick Paluch[1,2], Nicolas Gosling[1], Nicolas Zapata[1], Thomas Reisinger[1], Wolfgang Wernsdorfer[1], and Ioan M. Pop[1,2,3] — [1]IQMT, Karlsruhe Institute of Technology, Germany — [2]PHI, Karlsruhe Institute of Technology, Germany — [3]Physics Institute 1, Stuttgart University, Germany

We develop a qubit-readout circuit coupled through the kinetic inductance of superconducting granular aluminum (grAl). Utilizing the material properties of grAl to implement the dispersive shift removes the need for electromagnetic coupling. This enables a localized tuning knob to engineer the readout independent of the capacitance matrix. If the capacitance matrix is designed to be symmetric, the qubit-readout coupling is entirely mediated by the grAl kinetic inductance. We validate the pure kinetic coupling concept and demonstrate various generalized flux qubit regimes from plasmon to fluxon, with dispersive shifts ranging from 30 kHz to 7 MHz at the half-flux quantum sweet spot. Using purely kinetic coupling, we achieve readout performance comparable to standard electromagnetic coupling, with quantum state preparation fidelity of 99.7 % and 92.7 % for the ground and excited states, respectively, and below 0.1 % leakage to non-computational states. The excited state fidelity is limited by qubit relaxation to the ground state with quantum demolishing effects below 1%.

QI 19.4 Wed 15:45 H 0104

**Fully tunable Flux Qubits for TLS Research** — •Benedikt Berlitz, Alexey V. Ustinov, and Jürgen Lisenfeld — Physikalisches Institut, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Material defects forming two-level-systems (TLS) present a source of decoherence and unwanted degrees of freedom in superconducting quantum systems. The qubits in turn can be used as a tool to study the properties of TLS. We fabricated superconducting flux qubits specifically to be used as TLS detectors, aiming for good coherence in a large frequency range. The goal is to gather comparable data of many defects located within the same device. We will describe design, fabrication and measurements of the fabricated samples. Studying TLS with these tools will enhance our understanding of the underlying physics of TLS in amorphous materials and hopefully reveal a path to achieving higher coherence with superconducting qubits.

QI 19.5 Wed 16:00 H 0104

**Mapping the lateral positions of individual material defects in superconducting transmon qubits** — •Alexander K. Händel, Alexey V. Ustinov, and Jürgen Lisenfeld — Physikalisches Institut, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Material defects are limiting the coherence of superconducting circuits and mitigating their effects is vital in the realization of functional quantum devices. With transmon qubits, the spatial distribution of most coherence breaking defects is likely to be inhomogeneous, due to the qubit's electric field strength varying greatly with position, affecting a defects participation ratio. By tuning the resonance frequency of individual defects with static electric fields induced by on-chip electrodes we are able to resolve their positions on the qubit chip. We present first results of mapping the positions of defects in a transmon qubit, distinguishing defects on the qubit capacitor from those residing on the leads of Josephson junctions. Our results identify critical circuit components which contain major defects detrimental for the qubit performance and provide valuable information to improve qubit design and fabrication methods.

QI 19.6 Wed 16:15 H 0104

**Experiments on the Influence of Infrared Photons on Superconducting Qubits** — •Markus Griedel[1,2], Sebastian Koch[2], Hannes Rotzinger[1,2], and Alexey V. Ustinov[1,2] — [1]Institut für Quanten Materialien und Technologien (IQMT) — [2]Physikalisches Institut (PHI) - KIT, 76131 Karlsruhe, Germany

The energy gap of superconductors allows for a large variety of ultralow noise applications, as for instance, for using them to construct qubits. At sufficiently low temperatures, the number of excitations above the gap is generally low but not zero. Such excitations can be created by numerous external influences, including absorption of high energy particles from radioactive decay or extraterrestrial space. Also stray infrared photons play a role, since their energy is larger than the energy gap of conventional superconductors used for making qubit. One external leakage pathway is the dielectric of a coaxial cable used to manipulate and read out the qubit which connects to room temperature electronics. Here, the combination of the dielectric's transparency to infrared photons and the high infrared photon flux from elevated cryogenic temperature stages make the insertion of a low-pass filter with a sharp cutoff well below the superconducting gap frequency an important requirement.

In this contribution, we present experimental investigation of the influence of infrared photons on superconducting qubits. We have measured the dephasing and decay times as well as the qubit temperature in response to incident photon flux. We explore usage of various materials for making infrared filters.

QI 19.7 Wed 16:30 H 0104

**Measuring and understanding quasiparticle effects in magnetic-field-resilient 3D transmons (Experiment)** — •Jonas Krause[1], Christian Dickel[1], Giampiero Marchegiani[2], Lucas Janssen[1], Gianluigi Catelani[2,3], and Yoichi Ando[1] — [1]University of Cologne — [2]Technology Innovation Institute Abu Dhabi — [3]Forschungszentrum Juelich

Recent research shows quasiparticle-induced decoherence of superconducting qubits depends on the superconducting gap asymmetry due to the different thickness of the top and bottom films in Al-AlOx-Al junctions [1]. With magnetic-field-resilient transmons [2] we investigate this from a new angle. We present spectroscopy and parity-switching-time ($\tau_p$) measurements of a 3D transmon up to 400 mT in-plane field. The magnetic field tunes the transmon frequency $f_{01}$ without a strong reduction in $T_2^*$. The gap asymmetry, initially close to $hf_{01}$, causes a non-monotonic evolution of $\tau_p$. After an increase with in-plane field up to 150 mT, $\tau_p$ decreases at higher fields. Higher Josephson harmonics are needed to accurately model the spectrum [3]. At low fields, small parity splitting requires qutrit pulse sequences for parity measurements. Magnetic fields are an interesting tuning knob to study quasiparticle loss and gap engineering because they allow changing both the gap and gap difference. Charge-parity measurements are also a readout mechanism for topological qubits which often require high fields.

[1] G. Marchegiani et al., RX Quantum 3 (2022) 040338
[2] J. Krause et al., Phys. Rev. Applied 17 (2022) 034032
[3] D. Willsch et al., arXiv:2302.0919

QI 19.8 Wed 16:45 H 0104

**Measuring and understanding quasiparticle effects in magnetic-field-resilient 3D transmons (Theory)** — Jonas Krause[1], Christian Dickel[1], Giampiero Marchegiani[2], Luc Janssen[1], •Gianluigi Catelani[2,3], and Yoichi Ando[1] — [1]Physics Institute II, University of Cologne, Germany — [2]Quantum Research Center, Technology Innovation Institute, UAE — [3]JARA Institute for Quantum Information (PGI-11), Forschungszentrum Juelich, Germany

In this talk, we present the modeling of the charge-parity lifetime ($\tau_p$) of a magnetic-field resilient 3D transmon [1]. Experimentally, the lifetime $\tau_p$ depends non-monotonically on the in-plane magnetic field. We explain this unexpected behavior within a generalized approach to quasiparticle decoherence. The model accounts for the transmon being a SQUID measured mainly at the bottom sweet spot and for the magnetic field tuning (Fraunhofer effect). It also incorporates effects of temperatures on the order of the transmon frequency. At zero field, the qubit frequency $f_{01}$ is nearly resonant with the superconducting gap difference [2], so quasiparticle tunneling gives a sizable contribution to the parity-switching rate $1/\tau_p$. Increasing the in-plane field, $f_{01}$ decreases and becomes detuned from the gap difference, causing the initial growth in $\tau_p$, while photon-assisted qubit transitions increase producing the subsequent decay at higher fields. We show that $\tau_p$ and the qubit lifetime $T_1$ can be consistently described by the model.

[1] J. Krause et al., Phys. Rev. Appl. 17 (2022) 034032
[2] G. Marchegiani et al., PRX Quantum 3 (2022) 040338

QI 19.9 Wed 17:00 H 0104

**Near quantum-limited amplification up to 1 T using granular aluminum** — •Nicolas Zapata[1], Ivan Takmakov[1,2], Dennis Rieger[1,2], Simon Günzler[1,2], Ameya Nambisan[1], Thomas Reisinger[1], Wolfgang Wernsdorfer[1,2], and Ioan Pop[1,2] — [1]IQMT, Karlsruhe Institute of Technology, 76131 Karslruhe, Germany — [2]PHI, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Josephson Junction based amplifiers have become essential components for the readout of microwave quantum circuits. Despite the advances made over the last decade, they still have limited applicability in systems that require high magnetic fields. The use of high kinetic inductance materials like granular Aluminum (grAl), opens the path for low noise amplification in Tesla fields thanks to their in-plane resilience [1] and negligible high order non-linearities [2], which is particularly attractive for the readout of semiconducting spin-qubits [3] and single molecular magnet qubits [4]. Here we present a non-degenerate parametric amplifier made of two coupled grAl resonators forming a Bose-Hubbard dimer [5, 6]. We report near quantum-limited 20 dB amplification, with an instantaneous bandwidth of few MHz and signal-to-pump detuning above 100 MHz, which was stable up to 1 T.

[1] K. Borisov et al., Appl. Phys. Lett. 117 (2020) 120502
[2] N. Maleeva et al., Nat. Commun. 9 (2018) 3889
[3] J. Stehlik et al., Phys. Rev. Appl. 4 (2015) 014018
[4] C. Godfrin et al., Phys. Rev. Lett. 119 (2017) 187702
[5] C. Eichler et al., Phys. Rev. Lett. 113 (2014) 110502
[6] P. Winkel, I. Takmakov et al., Phys. Rev. Appl. 13 (2020) 024015

QI 19.10 Wed 17:15 H 0104

**Phase-flux symmetries in three-wave mixing Josephson travelling wave parametric amplifiers** — •Daniil E. Bazulin[1,2], Kedar E. Honasoge[1,2], Niklas Bruckmoser[1,2], Leon Koch[1,2], Thomas Luschmann[1,2], Achim Marx[2], Stefan Filipp[1,2,3], and Kirill G. Fedorov[1,2,3] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, 85748 Garching, Germany — [2]Walther-Meißner-Institut, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany

Enabling the three-wave mixing process in Josephson Travelling Wave Parametric Amplifiers (JTWPAs) requires inversion symmetry breaking of an effective potential. This task can be achieved in various ways by exploiting either flux- or phase-bias regimes. Moreover, common JTWPA coupling schemes additionally introduces two distinct possibilities of flux or phase pumping. As the result, we identify four interrelated bias and pump schemes, which we theoretically and experimentally analyze in our samples based on Superconducting Nonlinear Asymmetric Inductive Elements (SNAILs). We show that the nonlinear behavior of such a JTWPA strongly depends on the chosen bias-pumping scheme, unraveling novel experimental control schemes for optimal JTWPA performance.

QI 19.11 Wed 17:30 H 0104

**rf-SQUID-based three-wave-mixing traveling-wave parametric amplifier** — •Victor Gaydamachenko, Christoph Kissling, Marat Khabipov, Fabian Kaap, Sergey Lotkhov, Ralf Dolata, Alexander B. Zorin, and Lukas Grünhaupt — Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Traveling-wave parametric amplifiers (TWPAs) are one of the most promising devices for the improvement of the readout efficiency of fW-range microwave signals at a bandwidth of several GHz. By adding only a minimal amount of noise close to the absolute limit allowed by quantum mechanics, quantum technologies and other applications benefit from their usage. We realize a TWPA based on an array of 2000 rf-SQUIDs with phase-matching achieved by periodic capacitance loading, which we optimized by time-domain circuit simulations. Our TWPA is fabricated using Nb/Al-Al$O_x$/Nb trilayer technology. In the three-wave mixing regime the device provides an average gain of 18 dB between 3 and 7 GHz and exhibits a saturation power of approximately -90 dBm. Here, we present the design and experimental results including noise characterization of the device.

QI 19.12 Wed 17:45 H 0104

**Frequency targeting and geometric effects in fabrication of superconducting tunable resonators** — •Maria-Teresa Handschuh[1,2], Kedar E. Honasoge[1,2], Wun Yam[1,2], Florian Fesquet[1,2], Achim Marx[1], Rudolf Gross[1,2,3], and Kirill G. Fedorov[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]School of Natural Sciences, Technical University of Munich, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology, 80799 Munich, Germany

Achieving a high-volume and high-quality fabrication process of uniform nonlinear resonators based on Josephson junctions is one of the central challenges in applied quantum information processing with superconductors. Here, we report on the realization of a reliable fabrication process for Nb resonators with Al/AlOx/Al Josephson junctions and circuits on 4-inch high-resistivity silicon wafers, ensuring precise control over relevant parameters. We address the challenges associated with the large-scale fabrication by investigating the impact of geometric irregularities on device performance, including finite-size geometry effects and center-to-edge effects. Undesired frequency shifts can arise from variations in device dimensions and inhomogeneous oxidation techniques. We overcome these challenges by a systematic analysis, allowing us to improve the controllability and accuracy of resonator frequency tuning. This enables the reproducible fabrication of low-loss tunable resonators for quantum information processing applications.

QI 19.13 Wed 18:00 H 0104

**Characterizing the origin of non-Markovian noise in superconducting qubits and its effect on quantum algorithms** — •Ivan Rungger, Abhishek Agarwal, Lachlan Lindoy, Deep Lall, and Francois Jamet — National Physical Laboratory, Teddington TW11 0LW, United Kingdom

Non-Markovian noise can be a significant source of errors in superconducting qubits. It is caused by ubiquitous effects such as quasiparticle induced charge parity fluctuations, as well as frequency fluctuations induced by two level systems or other defects. We develop a method based on mirrored pseudo-identity gates to characterise the non-Markovian noise in qubits [1]. We show that Markovian noise models fail to capture the experimental behaviour, and that only by including the non-Markovian components one can describe the experiments. We further present fast time-resolved characterization techniques that allow us to identify the physical origin of the non-Markovian noise. We find large changes of the dominating noise contributions, such as qubit frequency fluctuations, over both long time-scales of hours and days, and also over very short micro-seconds time-scales. We show that the developed noise model allows us to predict and then mitigate the effects of noise in quantum computing applications.

[1] A. Agarwal, L. P. Lindoy, D. Lall, F. Jamet, I. Rungger, arXiv:2306.13021 (2023)

## QI 20: Focus Session: Nanomechanical Systems for Classical and Quantum Sensing II (joint session HL/DY/TT/QI)

Nanomechanical and cavity-optomechanical systems have been recently established as a controllable and configurable platform that can be engineered to tackle outstanding sensing challenges both in the classical and in the quantum regime. With this focus session, experts from different but synergetically overlapping fields of nanomechanical sensing pursuing classical, non-linear and quantum approaches are brought together. The session shall provide an overview over the recent exciting developments of the techniques explored in micro- and nanomechanical systems and sensing concepts exploring quantum measurement schemes.

Organized by Eva Weig, Hubert Krenner, and Hans Hübl.

Time: Wednesday 15:00–17:45 Location: EW 202

QI 20.1 Wed 15:00 EW 202

**Quantum backaction evasion in cavity magnomechanics** — •Victor Augusto Sant Anna V Bittencourt[1], Clinton A. Potts[2], John P. Davis[3], and Anja Metelmann[1,4,5] — [1]ISIS (UMR 7006), Universite de Strasbourg, 67000 Strasbourg, France — [2]Kavli Institute of NanoScience, Delft University of Technology, PO Box 5046, 2600 GA Delft, Netherlands — [3]Department of Physics, University of Alberta, Edmonton, Alberta T6G 2E9, Canada — [4]Institute for Theory of Condensed Matter, Karlsruhe Institute of Technology, 76131, Karlsruhe, Germany — [5]Institute for Quantum Materials and Technology, Karlsruhe Institute of Technology, 76344, Eggenstein-Leopoldshafen, Germany

Magnetic excitations (magnons) hosted in a solid can couple to mechanical vibrations of the material (phonons) via a radiation-pressure like interaction due to magneto-elastic effects. When the magnet is loaded on a microwave cavity, phonons can be driven and measured via the microwave while having the tunability of the magnetic excitations. Nevertheless, the noise added to mechanics can hinders both potential applications of the system at the quantum level and measurements of the phonon mode. Here, we propose a scheme to evade quantum backaction on a phonon mode of a cavity magnomechanical system by using a two-tone microwave drive. We study the robustness of the different possible backaction evading schemes, and show that measurements of the phonon mode can be performed with added noise below the standard quantum limit.

QI 20.2 Wed 15:15 EW 202

**Optical detection of guided GHz acoustic phonons in a semiconductor hybrid microcavity** — •Mingyun Yuan[1], Antonio Crespo-Poveda[1], Alexander S. Kuznetsov[1], Klaus Biermann[1], Alexander Poshakinskiy[2], and Paulo V. Santos[1] — [1]Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., Hausvogteiplatz 5, 10117 Berlin, Germany — [2]ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Spain

The interaction between acoustic phonons and optical quasiparticles has profound implication in both understanding of light-matter interaction and acousto-optical applications. We report on the optical detection of phonon echos resulting from the interaction between acoustic phonons and exciton polaritons in a hybrid (Al,Ga)As microcavity grown by molecular beam epitaxy. The microcavity spacer embedding multiple quantum wells is surrounded by Bragg mirrors designed to enable polariton formation. Simultaneously, the spacer-quantum wells and the Bragg reflectors act as the core and cladding regions, respectively, of an acoustic waveguide sustaining GHz acoustic phonons propagating along [110], excited by side bulk-acoustic-wave transducers. The acoustic modulation gives rise to an optical comb in the polariton photoluminescence, in which both the guided phonon modes and the substrate phonon modes are identified via Fourier transform. Our results demonstrate the robust generation of guided acoustic phonons above 6 GHz as well as their effective coupling to the polaritons, and showcase the sensitive optical detection of acoustic modes.

QI 20.3 Wed 15:30 EW 202

**Topological phononic waveguides with ultralow loss** — •Ilia Chernobrovkin[1], Xiang Xi[1], Jan Kosâta[2], Oded Zilberberg[3], Anders Sørensen[1], and Albert Schliesser[1] — [1]Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark — [2]Institute for Theoretical Physics, ETH Zürich, 8093 Zürich, Switzerland — [3]Department of Physics, University of Konstanz, 78464 Konstanz, Germany

Topological insulators have long intrigued researchers in terms of fundamental physical properties as well as potential applications. The advantages of topological insulators have been extended to the realm of bosonic defects or waveguiding systems and overturned some of conventional views of photonic or phononic wave manipulation. However, the existing topological phononic waveguides still have large transportation loss, which limits its applications.

In our work, we combine the so-called soft-clamping technique - which can dramatically suppress mechanical losses - with non-trivial topology, designed to enable valley-locked propagation along a topological edge. Our systems are based on sub-100 nm thin, highly stressed membrane made of silicon nitride membranes. Our preliminary experimental results show a measured Q-factor above 1 million for whispering-galley megahertz-frequency elastic modes along a closed triangular path of length of ~10 mm, which corresponds to a classical coherent length of tens of meters. Our system can be considered promising for use in phononic circuits for coherent microwave signal processing or interconnection.

QI 20.4 Wed 15:45 EW 202

**Dry processing of high Q 3C-silicon carbide nanostring resonators** — •Felix David, Philipp Bredol, and Eva Weig — Technical University of Munich - Chair of Nano and Quantum Sensors, Garching, Germany

We fabricate string resonators from strongly stressed 3C-silicon carbide (SiC) grown on a silicon substrate. The conventional fabrication process involves electron-beam lithography with PMMA to define a metallic hard mask for the subsequent dry-etching step via a liftoff process. This requires some wet-chemical process steps, which can destroy our samples. Here we describe an alternative process, which avoids all wet-chemical process steps to enable superior quality. It involves the use of a negative electron-beam resist as an etch mask, as well as the completely reactive-ion etching-based release of the nanostrings. The dry-processed nanostrings can be fabricated with a high yield and exhibit high mechanical quality factors at room temperature. Due to the high reliability combined with the high process speed, it also allows us to investigate material-intensive questions, such as the influence of etching depth and undercut on the mechanical quality factor.

QI 20.5 Wed 16:00 EW 202

**Spatial Mode Mapping of 2D Mechanical Resonators** — •Lukas Schleicher, Leonard Geilen, Alexander Holleitner, and Eva Weig — TU München, Garching, Deutschland

We present studies on the spatial mapping of mechanical modes of 2D resonators based on monolayer transition-metal dichalcogenides. A spatially resolved mode mapping allows us to investigate non-isotropic pre-strain and other transfer-related artefacts, such as cracks and surface contaminations, which may result from the fabrication process. We compare the mechanical properties of drums with various sizes and fabrication methods of the 2D resonators.

**15 min. break**

QI 20.6 Wed 16:30 EW 202

**Electrochemical etching strategy for shaping monolithic 3D structures from 4H SiC wafers** — •André Hochreiter, Fabian Gross, Morris Niklas Möller, Michael Krieger, and Heiko Weber — Lehrstuhl für Angewandte Physik Universität Erlangen-Nürnberg, Germany

Silicon Carbide's (SiC) as wide bandgap semiconductor has outstanding material properties, which enable applications like already available commercial power-electric devices, and applications in quantum sensing. For mechanical applications of SiC, extremely high quality factors are predicted, but on-chip 3D shaping of SiC is difficult due to its chemical robustness. We report on an electrochemical etching (ECE) strategy, which solely relies on a doping contrast introduced by targeted ion-implantation of p-dopants on n-type material. With such a dopant-selective etching, n-doped regions remain inert and p-type regions are removed. We present devices as diverse as monolithic cantilevers, membranes and disk-shaped optical resonators etched out a single crystal wafer. The electrochemically etching process leaves the etched surface with low roughness, which can even be improved by annealing.

QI 20.7 Wed 16:45 EW 202

**Probing the Mechanical Loss of Individual Surfaces of a Nanomechanical String Resonator** — •Philipp Bredol, Felix David, and Eva Weig — Technical University of Munich, Chair of Nano and Quantum Sensors, 85748 Munich, Germany

Stressed nanostring resonators are a promising platform for sensing applications and quantum technologies because of their small footprint and high mechanical quality factors. In this contribution we show that the dissipation caused by sidewall surfaces and the dissipation caused by bottom and top surfaces can be individually determined from the mechanical response spectrum. This information helps to evaluate and adjust fabrication parameters such as etchant chemistry, etch mask materials and possible annealing steps. Being able to characterize the mechanical loss mechanisms that limit a given device is important for integration with other structures and to further push the performance of nanostring resonators.

QI 20.8 Wed 17:00 EW 202

**Parametric normal mode splitting for coupling strength estimation** — •Ahmed A. Barakat, Avishek Chowdhury, Anh Tuan Le, and Eva M. Weig — Technical University of Munich, Munich, Germany

The experimental estimation of the linear coupling strength between two nanomechanical modes is a challenging task. For dielectrically actuated nano-string resonators, the coupling strength between in-plane and out-of-plane modes is usually estimated by tuning the modal eigenfrequencies using a bias voltage up to the occurrence of the avoided crossing. In this contribution, we introduce a novel approach using parametric excitation to estimate the linear coupling strength at any bias voltage.

In addition to a broadband noise excitation, the proposed approach involves parametrically driving in the direction of at least one of the eigenmodes with a frequency that resonates with the difference between both eigenfrequencies causing a parametric normal mode splitting. Using the dependence of the splitting width on the coupling strength, a mathematical model is introduced and perturbed around the parametric excitation frequency using the multiple scales method. The locus of the splitting is derived analytically and agrees well with the experimental results, leading to an accurate estimation of the coupling strength.

QI 20.9 Wed 17:15 EW 202

**Tunable near-infrared exciton-polariton optomechanical GHz rulers of light** — •Alexander Kuznetsov, Klaus Biermann, and Paulo V. Santos — Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., Hausvogteiplatz 5-7, 10117 Berlin, Germany

Frequency combs, which consist of many equidistant optical lines, are photonic analogues of spatial rulers. Such rulers of light can be used for high-resolution spectroscopy, ranging, optical and atomic clocks, and for large-scale quantum systems. On-chip miniaturized and low-power comb-sources are, therefore, of great importance. Here, we demonstrate generation of tunable combs using spatially confined light-matter quasiparticles – exciton-polaritons – coherently modulated by GHz phonons inside a hybrid photon-phonon (Al,Ga)As patterned microcavity. Using non-resonant optical excitation, we create polariton Bose-Einstein-like condensates (BEC) with long temporal coherence reaching $\tau_{BEC} \approx 2$ ns. The BEC is modulated by piezoelectrically generated strain of bulk acoustic wave (BAW) phonons with frequency $f_{BAW} = 7$ GHz and RF-tunable amplitude. Since $\tau_{BEC} \gg 1/f_{BAW}$, the modulation is coherent and leads to the emergence of well-resolved phonon sidebands, separated by $f_{BAW}$, in the polariton emission spectrum. For large BAW amplitudes, the comb contains up to 50 well-resolved lines with nearly-flat profile. The demonstrated RF-induced comb functionality may be useful for the realization of on-chip arrays of tunable GHz optical combs as well as coherent optical-to-microwave bi-directional conversion.

QI 20.10 Wed 17:30 EW 202

**Imaging acoustic fields on metasurfaces** — •Alessandro Pitanti[1,2,3], Mingyun Yuan[1], Simone Zanotto[3], and Paulo Ventura Santos[1] — [1]Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., 5-7 Hausvogteiplatz, Berlin 10117, Germany — [2]Dipartimento di Fisica E. Fermi, Università di Pisa, Largo B. Pontecorvo 3, Pisa 56127, Italy — [3]NEST, CNR Istituto Nanoscienze and Scuola Normale Superiore, piazza San Silvestro 12, Pisa 56127, Italy

The last decades have witnessed a rich activity towards the integration of acoustic technologies within electro-optical circuits in high-frequency hybrid devices. The main role in this trend has been played by surface acoustic waves (SAW), easily integrable in several material platforms via piezoelectricity. Given their high frequency and quality factors, simple SAW delay-line resonators have found application as sensors, filters, and oscillators for telecommunication applications. More complex manipulation of acoustic waves would boost SAW-based technologies, becoming a key for the transition to 6G; complete wave manipulation and control in the GHz range would offer the most promise for integration with modern communication technologies.

In this context, we illustrate the use of light-interferometry and atomic force microscopy based scanning probe techniques for a fine investigation of GHz acoustic fields in mechanical metasurfaces. Focusing on the role of symmetries in wave scattering, we show complex wave manipulation, leading to asymmetric negative refraction and anisotropic transmission of mechanical waves.

## QI 21: Focus Session: Nanomechanical Systems for Classical and Quantum Sensing III (joint session HL/DY/TT/QI)

Nanomechanical and cavity-optomechanical systems have been recently established as a controllable and configurable platform that can be engineered to tackle outstanding sensing challenges both in the classical and in the quantum regime. With this focus session, experts from different but synergetically overlapping fields of nanomechanical sensing pursuing classical, non-linear and quantum approaches are brought together. The session shall provide an overview over the recent exciting developments of the techniques explored in micro- and nanomechanical systems and sensing concepts exploring quantum measurement schemes.

Organized by Eva Weig, Hubert Krenner, and Hans Hübl.

Time: Thursday 9:30–13:00 Location: EW 202

**Invited Talk** QI 21.1 Thu 9:30 EW 202

**Quantum sensors and memories based on soft-clamped phononic membrane resonators** — •Albert Schliesser — Niels Bohr Institute, Copenhagen University, Denmark

Soft-clamping of membrane resonators using a phononic pattern enables Q-factors above 1 billion and coherence times exceeding 100 ms at low temperature. We monitor the motion of such membranes with optical interferometry. This allows us to measure force and displacement at and beyond the standard quantum limit, and control the motional quantum state, even at room temperature. This platform lends itself for sensing applications; as an example, we image individual viruses and nanoparticles using the membrane as a force sensor. In a different set of experiments, we demonstrate mechanical storage and subsequent retrieval of optical pulses with an efficiency of 40%, suggesting applications as quantum memory for light.

**Invited Talk** QI 21.2 Thu 10:00 EW 202

**Quantum mechanics-free subsystem with mechanical oscillators** — •Laure Mercier de Lepinay[1], Caspar Ockeloen-Korppi[1], Matthew Woolley[2], and Mika Sillanpää[1] — [1]Department of Applied Physics, Aalto University, P.O. Box 15100, FI-00076 Aalto, Finland — [2]School of Engineering and Information Technology, UNSW Canberra, ACT, 2600, Australia

Quantum mechanics sets a limit on the precision of the continuous measurement of an oscillator's position. However, with an adequate coupling configuration of two oscillators, it is possible to build an oscillator-like subsystem of quadratures isolated from quantum and classical backaction which therefore does not suffer from this limit. We realize such a quantum mechanics-free subsystem using two micromechanical drumheads coupled to microwave cavities. Multitone phase-stable microwave pumping of the system allows to implement the necessary effective coupling configuration. We first demonstrate the measurement of two collective quadratures, evading backaction simultaneously on both of them, obtaining a total noise within a factor of 2 of the full quantum limit. Secondly, this measurement technique is directly adapted to the detection of continuous variable entanglement which is based, according to the Duan criterion, on variance estimates of two collective quadratures. We therefore verify the stabilized quantum entanglement of the two oscillators deeper than had been possible before for macroscopic mechanical oscillators.

**Invited Talk** QI 21.3 Thu 10:30 EW 202

**Electrothermally tunable metal-graphene-siliconnitride membrane mechanical device** — •Elke Scheer, Mengqi Fu, and Fan Yang — Department of Physics, University of Konstanz, 78457 Konstanz

Controlling the properties of mechanical devices over a wide range is important for applications as well as for fundamental research. In this work, we demonstrate an on-chip tunable device composed of a suspended siliconnitride (SiN) membrane with a graphene (G) layer on top which is connected to Au electrodes. Taking advantage of the electrical and thermal conductance properties of G and the difference in the thermal expansion coefficients of SiN and Au, we developed a device in which the G-Au interface serves as local heater by injecting a dc current. The force induced by the thermal expansion difference tunes the residual stress in the SiN membrane and deflects the membrane when the loading power overcomes the threshold to the buckling transition. With this device we realize an extreme large eigenfrequency tuning (more than 50 %) of the vibration mode. By injecting an ac voltage instead, and thus applying a periodic force to the membrane, we achieve strong excitation of the membrane resonator into the nonlinear vibration. This device may act as proof-of-principle for a compact on-chip excitation scheme for multidimensional and composite nanomechanical resonators.

**15 min. break**

**Invited Talk** QI 21.4 Thu 11:15 EW 202

**From Nanomechanics to Spins** — •Christian Degen — ETH Zurich, Switzerland

Nanomechanical resonators are exquisite sensors for weak magnetic forces, with exciting prospects in nanoscale detection and imaging of nuclear and electronic spins. In this talk, I will give an overview of our laboratory's activities in this field, including force detection with optomechanical membranes and strings, and nuclear spin imaging with the technique of magnetic resonance force microscopy.

**Invited Talk** QI 21.5 Thu 11:45 EW 202

**Enhanced cooling efficiency in nonlinear cavity optomechanics** — •Anja Metelmann[1], Nicolas Diaz-Naufal[2], David Zoepfl[3], Lukas Deeg[3], Christian Schneider[3], Mathieu Juan[4], and Gerhard Kirchmaier[3] — [1]Karlsruhe Institute of Technology, Karlsruhe, Germany — [2]Free University Berlin, Berlin, Germany — [3]University of Innsbruck, Innsbruck, Austria — [4]Universite de Sherbrooke, Sherbrooke, Canada

Unlocking the quantum potential of mechanical resonators hinges on achieving ground state cooling, a key milestone for quantum information processing and ultra-precise quantum measurements. In the vibrant field of cavity optomechanics, dynamical backaction cooling and feedback protocols have successfully nudged macroscopic mechanical elements toward the quantum ground state. While linear regime cooling is well-explored, recent theoretical insights suggest that a nonlinear cavity could amplify cooling efficiency. We explore this intriguing nonlinear regime, focusing on the cooling dynamics of a mechanical resonator coupled to a nonlinear cavity, embodying the characteristics of a high-Q Duffing oscillator. In this talk we present a comparative analysis between theoretical predictions and experimental results from a magnetomechanical platform. The findings unveil a captivating enhancement in cooling efficiency attributed to the Duffing nonlinearity. This breakthrough not only enriches our understanding of optomechanical interactions but also holds promise for advancing cooling strategies in quantum technologies.

QI 21.6 Thu 12:15 EW 202

**Brillouin scattering selection rules in elliptical optophononic resonators** — •Anne Rodriguez[1,2], Priya Priya[1], Edson Cardozo de Oliveira[1], Abdelmounaim Harouri[1], Isabelle Sagnes[1], Florian Pastier[3], Martina Morassi[1], Aristide Lemaître[1], Loic Lanco[1], Martin Esmann[1], and Daniel Lanzillotti-Kimura[1,4] — [1]Centre de Nanosciences et de Nanotechnologies, Université Paris-Saclay, CNRS, Palaiseau, France — [2]present address: Chair for Nano and Quantum Sensors, Technische Universität München, Garching, Germany — [3]Quandela SAS, Palaiseau, France — [4]Institut für Physik, Universität Oldenburg, Germany

The selection rules of spontaneous Brillouin scattering in bulk crystalline solids are intrinsic material properties that formally constrain the energy, direction and polarization of the scattered photons for a given input state. In this work, we manipulate the polarization states of the input laser and Brillouin signal independently using polarization-sensitive optical micropillar cavities. The ellipticity of the micropillars lifts the degeneracy of the optical cavity modes, and induces a wavelength-dependent rotation of polarization [1,2], altering the Brillouin scattering selection rules. We developed a Brillouin spectroscopy scheme based on polarization filtering, allowing to measure acoustic phonon resonances with frequencies in the range of 20-100 GHz [3], with background-free spontaneous Brillouin scattering spectra.

[1] H. Wang et al., Nat. Phot. 13, 770 (2019). [2] B. Gayral et al., APL 72, 1421 (1998). [3] A. Rodriguez et al., ACS Photonics 10, 1687 (2023).

QI 21.7 Thu 12:30 EW 202

**3D Microwave Cavity-Assisted Detection of High-Q Silicon Nitride Nanomechanical String Resonators** — •Run Fa Jonny Qiu, Anh Tuan Le, Avishek Chowdhury, and Eva Weig — Technical University of Munich, Chair of Nano- and Quantum Sensors, Hans-Piloty Str. 1, 87548 Munich, Germany

Amorphous, low-pressure chemical vapor deposition (LPCVD)-grown silicon nitride (Si3N4) is a highly pre-stressed material due to its thermal-coefficient mismatch and is exploited in our fabrication of doubly-clamped freely suspended nanomechanical string resonators with superjacent electrodes for dielectric drive and detection. High-quality factor (Q-factor) nanomechanical string resonators with a Q-factor of roughly 300000 were fabricated. Two large gold-coated antennas connected to the electrodes are deposited on-chip which permits for a direct coupling of the mechanical displacement-induced change of the capacitance between the electrodes to the electric field of the three-dimensional (3D) rectangular cavity. Research on the quarter-wave coaxial cavity together with a capacitive loop and disk coupling revealed the possibility of both coupling schemes for the detection of mechanical modes. Applying direct current (DC) voltage to the electrodes allows for a frequency tuning of the mechanical flexural modes in the opposite direction, which due to the inherent coupling of the two in-plane (ip) and out-of-plane (oop) modes leads to an avoided crossing.

QI 21.8 Thu 12:45 EW 202

**Optomechanical acceleration beats in confined polariton condensates** — Alexander Kuznetsov, Klaus Biermann, and •Paulo Ventura Santos — Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e. V., Hausvogteiplatz 5-7, 10117 Berlin, Germany

High-frequency optomechanics involving optoelectronic systems with long temporal coherences enable access to the regime of non-adiabatic modulation, where the optomechanical modulation quantum $\hbar\Omega_M$ exceeds the typical energy decoherence rate of the optoelectronic resonances. Characteristic for this regime is the appearance of modulation sidebands around the optoelectronic resonance line displaced by energy multiples $m\Omega_M$,$(m = 0, \pm1, \dots)$ with amplitude and number determined by the energy modulation amplitude $\Delta E_M$. Here, we experimentally demonstrate a novel regime of temporal coherence invoked by the harmonic modulation of an optomechanical resonance at extreme energy modulation amplitudes $\Delta E_M/(\hbar\Omega_M) > 150$. We show that the resonance energy of a confined exciton-polariton Bose-Einstein condensate harmonically driven at these high relative modulation amplitudes exhibit temporal correlations with time-scales much shorter than the modulation period [Kuznetsov et al., DOI:10.21203/rs.3.rs-3197243/v1]. These correlations manifest themselves as comb of spectral resonances with energy scale determined by the ratio $\Delta E_M/(\hbar\Omega_M)$. We show that they arise from accelerated rates of energy change during the harmonic cycle and are, thus, termed the acceleration beats.

# QI 22: Quantum Simulation I

Time: Thursday 9:30–13:15 Location: HFT-FT 101

**Invited Talk** QI 22.1 Thu 9:30 HFT-FT 101

**Quantum computing for chemistry - recent results and an industry perspective** — •Christian Gogolin — Covestro Deutschland AG, 51373 Leverkusen, Germany

In this talk I give an overview of recent research in the area of quantum computing for the simulation of chemistry that my group as Covestro has carried out and published with our research partners at Google and QC Ware. In particular I will cover large scale experiments to benchmark error mitigation techniques and proposals to drastically reduce the number of repetitions/shots needed to measure molecular Hamiltonians, including ways to obtain a balanced treatment of dynamic and static correlation.

QI 22.2 Thu 10:00 HFT-FT 101

**Drug design on quantum computers** — •Nikolaj Moll[1], Gian-Luca R. Anselmetti[1], Matthias Degroote[1], Thomas Fox[2], Elica Kyoseva[1], Raffaele Santagati[1], Michael Streif[1], and Christofer S. Tautermann[2] — [1]Quantum Lab, Boehringer Ingelheim, 55218 Ingelheim, Germany — [2]Medicinal Chemistry, Boehringer Ingelheim Pharma GmbH & Co. KG, 88397 Biberach, Germany

The current limitations of classical computing methods in accurately describing quantum systems hinder the application of quantum chemistry to drug design. More precise computations replace many labor-intensive experiments, provided the computational cost is lower. Quantum computations could offer key insights into chemical systems, justifying high computational costs in an industrial setting. To significantly impact the pharmaceutical industry, quantum computers must address a broader set of problems, including those involving large protein structures. New methods that balance accuracy and time on quantum computers could be beneficial. Significant advancements in hardware and quantum algorithms have reduced computational costs over the years, sparking optimism for the future use of quantum computing in quantum chemistry. However, harnessing the full potential of quantum computing in the pharmaceutical industry requires further improvements in hardware, error correction codes, and novel algorithms. Several routes exist to achieve these goals and progress these challenges. Open research integrating academia and industry will help make quantum computing an essential tool for designing better drugs faster.

QI 22.3 Thu 10:15 HFT-FT 101

**Strong error bounds for Trotter & Strang Splittings and their implications to Quantum Chemistry** — •Daniel Burgarth[1], Paolo Facchi[2], Alexander Hahn[3], Mattias Johnsson[4], and Kazuya Yuasa[4] — [1]FAU Erlangen-Nürnberg — [2]University of Bari — [3]Macqaurie University — [4]Waseda University

Efficient error estimates for the Trotter product formula are central in quantum computing, mathematical physics and numerical simulations (strang-splitting and split-step algorithms). However, the dependency of the Trotter error on the actual input state is not properly understood and not much is known for the important case of unbounded operators. Here, we develop such a general theory of error estimation for the Trotter product formula and higher-order product formulas with an explicit dependency on the input state. These bounds have two crucial advantages over the operator norm estimates in the literature: First, previous bounds are too pessimistic as they quantify the worst-case scenario. Second, previous bounds become trivial for unbounded operators. Therefore, they cannot be applied to a wide class of Trotter scenarios, including atomic and molecular Hamiltonians considered in chemistry simulations. By providing state-dependent bounds, we overcome both problems and are able to treat errors in chemistry simulations from an analytical perspective.

QI 22.4 Thu 10:30 HFT-FT 101

**Digital quantum simulation of thermal observables using a global quench** — Hugo Perrin[1], Thibault Scoquart[1], Nikolay Gnezdilov[2], and •Andrei Pavlov[1] — [1]KIT, Karlsruhe, Germany — [2]Dartmouth College, Hanover, USA

Thermal state preparation is essential for quantum simulation since it describes the natural equilibrium states of matter. We discuss the thermalization protocol based on a global quench that induces all-to-all random interaction within a few-qubit system. The interaction constants are drawn from complex Gaussian distribution. Running the protocol multiple times and averaging the results over realizations of the interaction constants leads to thermal observables. We implement our protocol on the IBM quantum computer for a four-qubit system. Using circuit recompilation, we restore the thermal observables predicted by the exact dynamics evaluated on a classical computer. We show thermal occupation probabilities for the sixteen states with temperature controlled by the variance of the interaction constants and duration of the quench protocol.

QI 22.5 Thu 10:45 HFT-FT 101

**Noise-assisted digital quantum simulation of open systems** — •José Guimarães[1,2,3], Jaemin Lim[1], Mikhail Vasilevskiy[2,3], Susana Huelga[1], and Martin Plenio[1] — [1]Institute of Theoretical Physics at Ulm University, Ulm, Germany — [2]Center of Physics of University of Minho and Porto, Braga, Portugal — [3]International Iberian Nanotechnology Laboratory, Braga, Portugal

In the current developmental phase of quantum computing, noise is generally considered a limiting factor. However, our recent research demonstrates that the intrinsic noise can be strategically utilized to efficiently simulate open quantum systems within the framework of Markovian approximations. This approach distinguishes itself from earlier methodologies by requiring solely the characterisation of device-specific noise and the implementation of partial quantum error mitigation techniques. As a result, it opens the door for a potential exponential speedup in the simulation of open quantum systems when compared to traditional closed-system quantum simulations that require full error mitigation in current noisy quantum devices. Moreover, we present a new methodology for simulating (generalised) amplitude damping in near-term quantum computers. This later approach eliminates the dependence on resource-intensive ancillary qubits or mid-circuit measurements. Our approach holds the potential to unlock new simulation techniques in Noisy Intermediate-Scale Quantum (NISQ) devices, harnessing their intrinsic noise to enhance quantum computations.

**15 min. break**

QI 22.6 Thu 11:15 HFT-FT 101

**Quantum computing Floquet energy spectra** — •Benedikt Fauseweh[1,2] and Jian-Xin Zhu[3] — [1]TU Dortmund University, Germany — [2]German Aerospace Center (DLR), Germany — [3]Los Alamos National Laboratory, USA

The classical computational framework for describing Floquet systems is challenging. The prevalent method involves simple time evolution for a set of initial states, providing limited insights. The Floquet formalism, which offers information about the entire eigenvalue spectrum, is of theoretical interest. However, its computational complexity is even greater than that of simple time evolution methods.

To address this, we present two quantum algorithms tailored for NISQ devices. Utilizing parameterized quantum circuits, these algorithms are designed to variationally approximate Floquet eigenstates in both time and frequency domains. The accuracy of the first algorithm is dependent on the depth of the quantum circuit, whereas the second focuses on frequency truncation and the width of the parameterized quantum circuit. Notably, as the system size increases, the algorithms exhibit complementary requirements in terms of qubit count and circuit depth.

Additionally, our work underscores a connection between the ability of variational methods to approximate ground states of quantum critical systems and Floquet modes. This observation suggests potential avenues for further research in the behavior and characteristics of driven quantum systems.

Reference: B. Fauseweh and J.-X. Zhu, Quantum 7, 1063 (2023)

QI 22.7 Thu 11:30 HFT-FT 101

**Prolonging a discrete time crystal by quantum-classical feedback** — •Gonzalo Camacho[1] and Benedikt Fauseweh[1,2] — [1]German Aerospace Center (DLR), Institute für Softwaretechnologie, Rathausalle 12, 53757, Sankt Augustin, Germany — [2]TU Dortmund, Department of Physics, Otto-Hahn-Str 4, 44227 Dortmund, Germany

The realization of quantum time crystals on noisy intermediate-scale quantum (NISQ) devices has verified further the potential of employing quantum computers to study non-equilibrium phases of quantum matter. While ideal quantum time crystals exhibit collective sub-harmonic oscillations and spatio-temporal long-range order persisting for infinite times, the decoherence time of current NISQ devices sets a natural limit to the survival of these phases, restricting their observation to a shallow quantum circuit. In this work, we propose a time-periodic scheme that leverages quantum-classical feedback protocols in sub-regions of the system to enhance a time crystal signal significantly exceeding the decoherence time of the device. As a case of study, we focus on the survival of the many-body localized discrete time crystal phase (MBL-DTC) in the one dimensional periodically kicked Ising model, accounting for decoherence of the system with an environment. Based on classical simulation of quantum circuit realizations using tensor networks, we find that this approach is suitable for implementation on existing quantum hardware and presents a prospective path to simulate complex quantum many-body dynamics that transcend the low depth limit of current digital quantum computers.

QI 22.8 Thu 11:45 HFT-FT 101

**Detecting Entanglement Phase Transitions in Monitored U(1)-Symmetric Quantum Circuits** — •Ali G. Moghaddam[1,2], Kim Pöyhönen[1], and Teemu Ojanen[1] — [1]Faculty of Engineering and Natural Sciences, Tampere University, FI-33014 Tampere, Finland — [2]Department of Physics, Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan 45137-66731, Iran

Recently discovered measurement-induced entanglement phase transitions in monitored quantum circuits provide a novel example of far-from-equilibrium quantum criticality. Here we introduce an efficient strategy that bypasses the need for direct measurements of entanglement entropy - requiring an exponential number of measurements relative to subsystem size. Our proposed method offers a scalable approach to capturing entanglement transitions in symmetric monitored quantum circuits. Drawing parallels to entanglement entropy and mutual information, we demonstrate the utility of both bipartite and multipartite fluctuations in analyzing measurement-induced criticality. Remarkably, the phase transition can be revealed by measuring fluctuations of only a handful of qubits.

QI 22.9 Thu 12:00 HFT-FT 101

**Maximizing quantum expectation values over time is NEXP-har** — •Lennart Bittel[1], Sevag Gharibian[2], and Martin Kliesch[3] — [1]Freie Universität Berlin, Germany — [2]Universität Paderborn, Germany — [3]Technische Universität Hamburg, Germany

Understanding equilibration behavior of closed systems is an important but difficult problem. Intuitively, after some equilibration time, many-body systems typically transition to a steady state, in which expectation values become stationary. Sometimes, after long evolution times, however, a system can *exit* an equilibrium state again. Thus, a natural question is to ask how far out of equilibrium the long-term expectation value of an observable can be, i.e., to find the extremal value $\sup_{t\in\mathbb{R}} \langle O(t)\rangle$. We first show that even for $k$-local Hamiltonians, approximating this quantity is NEXP-hard. Thus, no polynomial-time classical algorithm exists (unconditionally), and understanding equilibration behavior of closed systems can be extremely computationally difficult. We then show a similar result for estimating the ansatz error for a VQA setup, in which one can potentially reuse gate generators a superpolynomial number of times. This yields two arguably rare examples of physically motivated NEXP-hard problems. Finally, in terms of upper bounds, we show both problems are in EXPSPACE, i.e. solvable in exponential space, but potentially double-exponential time.

QI 22.10 Thu 12:15 HFT-FT 101

**Quantum simulation of thermodynamics in an integrated quantum photonic processor** — Frank Somhorst[1], Reineer van der Meer[1], Malaquias Correa Anguita[1], Riko Schadow[2], Henk Snijders[3], Michiel de Goede[3], Ben Kassenberg[3], Pim Venderbosch[3], Caterina Taballione[3], Jorn Epping[3], Hans van der Vlekkert[3], Jardi Timmerhuis[3], Jacob Bulmer[4], Jasleen Lugani[5], Ian Walmsley[6,7], Pepijn Pinske[1], Jens Eisert[2,8,9], •Nathan Walk[2], and Jelmer Renema[1] — [1]University of Twente — [2]Freie Universität Berlin — [3]QuiX Quantum B.V. — [4]University of Bristol — [5]IIT Delhi — [6]Imperial College London — [7]University of Oxford — [8]Helmholtz-Zentrum Berlin für Materialien und Energie — [9]Fraunhofer Heinrich Hertz Institute

A core questions of quantum physics is how to reconcile the unitary evolution, which is information-preserving and time-reversible, with evolution following the second law of thermodynamics, which, in general, is neither. The resolution is to recognize that global unitary evolution of a multi-partite quantum state can generate entanglement and cause the local subsystems to evolve towards maximum-entropy states. We experimentally demonstrate this effect in linear quantum optics by simultaneously showing the convergence of local quantum states to a generalized Gibbs ensemble, while introducing an efficient certification method to show that the state retains global purity. Our quantum states are manipulated by a programmable integrated quantum photonic processor, which simulates arbitrary non-interacting Hamiltonians, demonstrating the universality of this phenomenon.

QI 22.11 Thu 12:30 HFT-FT 101

**Soliton versus single-photon quantum dynamics in arrays of superconducting qubits** — •Ben Blain[1], Giampiero Marchegiani[1], Juan Polo[1], Gianluigi Catelani[2,1], and Luigi Amico[1,3,4,5] — [1]Quantum Research Center, Technology Innovation Institute, Abu Dhabi 9639, United Arab Emirates — [2]JARA Institute for Quantum Information (PGI-11), Forschungszentrum Jülich, 52425 Jülich, Germany — [3]Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543 — [4]INFN-Sezione di Catania, Via S. Sofia 64, 95127 Catania, Italy — [5]MajuLab, CNRS-UNS-NUS-NTU International Joint Research Unit, UMI 3654, Singapore

Superconducting junctions constitute a promising platform for both future implementation of quantum processors and for quantum simulation. Arrays of Transmon qubits naturally implement the Bose-Hubbard model, with negative (attractive) on-site interaction[1]. In this work[2], we demonstrate that the transport near the ground state of such systems occurs as transmissions of a bright quantum soliton[3]. We analyse how the transport involves specific collective bosonic excitations.

[1] O. Mansikkamäki, S. Laine, A. Piltonen, and M. Silveri, PRX Quantum **3**, 040314 (2022).

[2] B. Blain, G. Marchegiani, G. Catelani, J. Polo, and L. Amico, Phys. Rev. Research **5**, 033130 (2023).

[3] A. Scott, J.C. Eilbeck, H. Gilhoj, Phys. D: Nonlinear Phenom. **78**, 194 (1994).

QI 22.12 Thu 12:45 HFT-FT 101

**Perspectives of running self-consistent DMFT calculations for strongly correlated electron systems on noisy quantum computing hardware** — •Jannis Ehrlich[1], Daniel F. Urban[1,2], and Christian Elsässer[1,2] — [1]Fraunhofer-Institut für Werkstoffmechanik IWM, Freiburg, Germany — [2]Freiburger Materialforschungszentrum, Universität 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 exponential growth of the many-particle Hilbert space with the number of considered electronic orbitals. 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. 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. [arXiv: 2311.10402]

QI 22.13 Thu 13:00 HFT-FT 101

**Low-depth simulations of fermionic systems on realistic quantum hardware** — •Manuel Algaba, P V Sriluckshmy, Martin Leib, and Fedor Šimkovic — IQM Quantum Computers, Georg-Brauchle-Ring 23-25, 80992 Munich, Germany

We introduce a general strategy for mapping fermionic systems to quantum hardware with realistic qubit connectivity which results in low-depth quantum circuits as counted by the number of native two-qubit gates. We achieve this by leveraging novel operator decomposition and circuit compression techniques paired with specifically chosen fermion-to-qubit mappings that allow for a high degree of gate cancellations and parallelism. Our mappings retain the flexibility to simultaneously optimise for qubit counts or qubit operator weights and can be applied to the investigation of arbitrary fermionic lattice geometries.

We showcase our approach by investigating the Fermi-Hubbard model as well as more complex multi-orbital models and report unprecedentedly low circuit depths per Trotter layer.

# QI 23: Quantum Control

Time: Thursday 9:30–13:00 Location: HFT-FT 131

QI 23.1 Thu 9:30 HFT-FT 131

**Neural-network-supported preparation of cat states in Jaynes-Cummings model** — •Pavlo Bilous[1], Hector Hutin[2], Benjamin Huard[2], and Florian Marquardt[1,3] — [1]Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany — [2]Ecole Normale Supérieure de Lyon, CNRS, Laboratoire de Physique, 69342 Lyon, France — [3]Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

We present a neural-network (NN) based approach for control optimization in the Jaynes-Cummings model allowing for high-fidelity preparation of cat states $\psi_{\rm cat}(\alpha)$ in the cavity. The NN is first trained on a random selection of $\alpha$-values sampled from a region of interest and can be afterwards applied to *any* $\alpha$ from this region for construction of the $\psi_{\rm cat}(\alpha)$ state. The data processing pipeline consisting of the NN and a Schrödinger equation solver ensures the construction of the proper fields driving the qubit and the cavity at the training stage. For each training point $\alpha$, the controls are optimized to minimize the loss function defined as the infidelity of the resulting state $\psi(\alpha)$ with respect to the target state $\psi_{\rm cat}(\alpha)$. We search for the control fields as an expansion in a so called B-spline basis used extensively in computational atomic physics. This approach reduces significantly the number of parameters needed to characterize the driving signals and ensures their well-behaved shape feasible for experimental implementation. We generalize our approach for the construction of other quantum states described by one or a few parameters.

QI 23.2 Thu 9:45 HFT-FT 131

**Modelling two-qubit gates of superconducting transmon processors** — Michael Krebsbach, •Martin Koppenhöfer, and Thomas Wellens — Fraunhofer-Institut für Angewandte Festkörperphysik IAF, Tullastraße 72, 79108 Freiburg, Deutschland

Two-qubit gate errors remain one of the biggest obstacles on the road towards scalable quantum processors and circuits. In fixed-coupling superconducting transmon qubits, crosstalk effects can cause a significant degradation of two-qubit gate fidelities [1]. A precise understanding of these errors and their origin is an important step for error mitigation and thus crucial for the implementation of deeper circuits. We develop a noise model based on Hamiltonian simulation of coupled three-level systems, taking into account higher transmon levels and their anharmonicities. By comparing simulation results with experiments on IBM hardware, we identify important error mechanisms such as frequency collisions and investigate their impact on gate fidelities. [1] A. Ketterer and T. Wellens, Phys. Rev. Applied 20, 034065 (2023)

QI 23.3 Thu 10:00 HFT-FT 131

**Qunatum Information Storage in Cavity Coupled Spin Ensembles** — •Michael Schilling and Jószef Zsolt Bernád — Forschungszentrum Jülich, Jülich, Deutschland

Recent investigations have highlighted the potential of spin ensembles coupled to a cavity as a robust platform for quantum information storage, demonstrating remarkable coherence times of 500ms. A primary challenge in this context is the efficient absorption of photons by the spin ensemble from external sources. We have developed a semi-analytical framework to significantly enhance this absorption process, achieving an 1.7-fold speedup compared to existing methodologies. Additionally, to maintain the integrity of quantum information stored within the ensemble, we optimize quantum operations, facilitating the implementation of dynamical decoupling sequences. To this end we expanded upon the Hierarchical Equations of Motion (HEOM) method, enabling its application to quasi-continuous distributions of spins.

QI 23.4 Thu 10:15 HFT-FT 131

**Quantum Circuits Noise Tailoring from a Geometric Perspective** — •Junkai Zeng[1,2], Yong-Ju Hai[2], Hao Liang[1,2], and Xiu-Hao Deng[1,2] — [1]Shenzhen Institute for Quantum Science and Engineering (SIQSE), Southern University of Science and Technology, Shenzhen, P. R. China — [2]nternational Quantum Academy (SIQA), and Shenzhen Branch, Hefei National Laboratory, Futian District, Shenzhen, P. R. China

Quantum errors resulting from unwanted interactions with noisy environments pose a significant challenge to the advancement of quantum information technology. It is well known that quantum gates can resist noise by optimizing control pulse waveforms. On the other hand, despite using noisy individual gate operations, high-fidelity quantum circuit output can still be achieved through optimized, noise-aware circuit compilation. We show that a recently developed geometric tool for controlling and analyzing continuous noisy qubit dynamics, termed Quantum Erroneous Evolution Diagram (QEED), can be extended to study quantum errors at the circuit level. We show how introducing twirling operations can create equivalent quantum circuits with altered evolution diagrams that exhibit reduced error, and randomized compiling is essentially analogous to averaging over an ensemble of random walk trajectories from this viewpoint. We further show how combining randomized compiling with robust quantum control at the gate level can significantly enhance circuit fidelity.

QI 23.5 Thu 10:30 HFT-FT 131

**Universal readout error mitigation** — •Adrian S. Aasen[1,2], Andras Di Giovanni[3], Hannes Rotzinger[3,4], Alexey V. Ustinov[3,4], and Martin Gärttner[1,2] — [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 — [4]Institut für QuantenMaterialien und Technologien, Karlsruher Institut für Technologie, Karlsruhe, Germany

Quantum technologies rely heavily on accurate control and reliable readout of quantum systems. Current experiments are limited by numerous sources of noise that can only be partially captured by simple analytical models and additional characterization of the noise sources is required. To overcome this challenge, we designed a universal readout error mitigation protocol. This protocol is based on quantum state tomography (QST), which estimates the density matrix of a quantum system, and quantum detector tomography (QDT), which characterizes the measurement procedure. By treating readout error mitigation in the context of state tomography the method becomes largely device-, architecture-, noise source-, and quantum state-independent.

QI 23.6 Thu 10:45 HFT-FT 131

**Benchmarking a readout noise mitigation method on a superconducting qubit** — •Andras Di Giovanni[1], Adrian S. Aasen[3,4], Hannes Rotzinger[1,2], Martin Gärttner[3,4], and Alexey V. Ustinov[1,2] — [1]Physikalisches Institut, — [2]Institut für QuantenMaterialien und Technologien, Karlsruher Institut für Technologie, Karlsruhe, Germany — [3]Kirchhoff-Institut für Physik, Universität Heidelberg, Heidelberg, German — [4]Institut für Festkörpertheorie und -optik, Friedrich-Schiller-Universität, Jena, Germany

Quantum technologies rely both on precise control and accurate readout of quantum systems. Current experiments are limited by numerous sources of noise that can only be partially captured by analytical models and therefore additional characterization of the noise sources is required. We benchmark a device tomography based method for readout error mitigation on a superconducting qubit. For this, we implement an experiment on a transmon with the goal of increasing its readout fidelity. In this talk, we present experimental results obtained by characterizing the performance of the method by carrying out a systematic sweep of noise sources on a superconducting qubit chip: suboptimal readout signal amplification and resonator photon population, off-resonant qubit drive, and effectively increased decoherence. Overall, a significant improvement of the infidelity up to a factor of 30 is observed, enabling the reliable readout of very noisy quantum systems.

**15 min. break**

QI 23.7 Thu 11:15 HFT-FT 131

**Quantum gate design with machine learning** — •Bijita Sarma and Michael Hartmann — Friedrich-Alexander Universität Erlangen-Nürnberg (FAU), Erlangen, 91058, Germany

Designing of fast and high fidelity quantum gates is crucial for getting the most out of current quantum hardware since detrimental effects of decoherence can in this way be minimised during the operation of the gates. However, achieving fast gates with high-fidelity and desirable efficiency on the state-of-the-art physical hardware platforms remains a formidable task owing to the presence of hardware level errors and crosstalk. In recent years, machine learning (ML)-based methods have found widespread applications in different domains of science and technology for nontrivial tasks. In this work, we exploit the power of ML to design quantum gates that uses the hardware-level leakage errors to one's advantage. These gates are found to exhibit controlled leakage dynamics in and out of the computational states at appropriate times during the course of the gate that makes these extremely fast.

QI 23.8 Thu 11:30 HFT-FT 131

**Robust quantum gates for dynamical correction of coherent errors** — •Xiu-Hao Deng[1,2], Yong-Ju Hai[1], Yuanzhen Chen[1,2], and Kangyuan Yi[1] — [1]Shenzhen Institute for Quantum Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China — [2]Guangdong Provincial Key Laboratory of Quantum Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China

In this talk, I will present our theory and experimental results. As quantum circuits become more integrated and complex, additional error sources that were previously insignificant start to emerge. Consequently, the fidelity of quantum gates benchmarked under pristine conditions falls short of predicting their performance in realistic circuits. To overcome this problem, we must evaluate their robustness against pertinent error models beyond isolated fidelity. Here we will report the theory of a geometric framework for diagnosing and correcting various errors and the experimental realization of robust quantum gates in superconducting quantum circuits based on this approach. Using quantum process tomography and randomized benchmarking, we demonstrate robust single-qubit gates against a quasi-static noise in a broad range of strengths, which is a common source of correlated errors. We also apply our method to non-static noises and to realize robust two-qubit gates. Our work provides a versatile toolbox for achieving noise-resilient complex quantum circuits.

QI 23.9 Thu 11:45 HFT-FT 131

**Accurate Quantum Feedback Control via Conditional State Tomography with Reinforcement Learning** — •Sangkha Borah[1,2] and Bijita Sarma[2] — [1]Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany — [2]Friedrich-Alexander-Universitat Erlangen-Nurnberg, Staudtstraße 7, 91058 Erlangen, Germany

The efficacy of measurement-based feedback control (MBFC) protocols faces challenges due to the presence of measurement noise, impacting the accurate inference of the underlying dynamics of a quantum system from noisy continuous measurement records. This, in turn, hinders the determination of precise control strategies. To address these limitations, this study investigates a real-time stochastic state estimation approach facilitating noise-free monitoring of conditional dynamics, encompassing the complete density matrix of the quantum system. Referred to as 'conditional state tomography,' this method allows for leveraging noisy measurement records within a single quantum trajectory. Consequently, it empowers the development of refined MBFC strategies, effectively overcoming the constraints posed by measurement noise. The proposed approach holds promise for diverse feedback quantum control scenarios and proves particularly advantageous for reinforcement-learning (RL)-based control. In RL applications, the agent can be trained using arbitrary conditional averages of observables or the full density matrix as input, enabling the rapid and accurate learning of control strategies.

QI 23.10 Thu 12:00 HFT-FT 131

**Quantum control landscapes of piecewise-constant pulses** — •Martino Calzavara[1,2] and Felix Motzoi[1] — [1]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), Jülich 52425, Germany — [2]Institute for Theoretical Physics, Universität zu Köln, Cologne 50937, Germany

Since the introduction of the GRAPE algorithm for the efficient computation of 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 through a parametrized quantum circuit, allowing us to analyze the properties of fidelity as a function of the control pulses - the so-called control landscape - by employing concepts and techniques from the fields of Variational Quantum Circuits and Quantum Machine Learning. Among these techniques, Fourier spectrum analysis has proven valuable in gaining insights into the representational power of these quantum circuits.

In this study, we present a Fourier representation of GRAPE landscapes that enables us to numerically and analytically investigate relevant landscape properties. Notably, these properties are found to depend on a non-dimensional parameter that expresses the time-energy budget of the time evolution.

QI 23.11 Thu 12:15 HFT-FT 131

**Deciding Observability in Quantum Dynamics Easily** — Markus Wiener and •Thomas Schulte-Herbrüggen — Technical University of Munich (TUM)

Among the questions arising in quantum engineering there is a practical yet fundamental one: given a controlled quantum dynamical system, for which observables can measurements give full information for system identification?

In finite-dimensional closed systems, a unified (Lie) frame of quantum systems theory settles this observability problem—as will be illustrated in paradigmatic $n$-qubit systems. Implications and generalisations will be outlined as well.

QI 23.12 Thu 12:30 HFT-FT 131

**Reinforcement learning entangling operations for spin qubits** — •Mohammad Abedi — Forschungszentrum Jülich. Germany

Traditional methods of optimising control pulses rely on the ability to compute gradients of a model of the system dynamics. We investigate reinforcement learning (RL) is a model-free alternative, which optimises entangling operations directly from experience by interacting with a quantum dot spin qubit system. While employing a detailed numerical model of the quantum chip at this point, we explore how the realistically limited observation on quantum systems can be augmented via sequential autoregressive learning with transformer models.

QI 23.13 Thu 12:45 HFT-FT 131

**Improving robustness of quantum feedback control with reinforcement learning** — •Manuel Guatto, Francesco Ticozzi und Gian Antonio Susto — Università degli studi di Padova, 35131 Padova, via Gradenigo 6B

Different reinforcement learning techniques are used to derive a feedback law for state preparation of a target state for a test system undergoing varying amounts of noise that is not included in the system model. Comparing the results indicates that the learned controls are more robust to unmodeled perturbations with respect to simple feedback strategy based on optimized population transfer, and that training on simulated nominal model retain the same advantages displayed by controllers trained on real data. The possibility of effective off-line training of robust controllers promises significant advantages towards practical implementation.

# QI 24: Verification and Benchmarking of Quantum Systems

Time: Thursday 9:30–13:30 Location: HFT-TA 441

**Invited Talk** QI 24.1 Thu 9:30 HFT-TA 441
**Verification of quantum measurements via self-testing** — •Laura Mančinska — QMATH, Department of Mathematical Sciences, University of Copenhagen, Denmark

Self-testing is the strongest form of quantum functionality verification which allows a classical user to deduce the quantum state and measurements used to produce measurement statistics. While self-testing of quantum states is well-understood, self-testing of measurements, especially in high dimensions, has remained more elusive. We demonstrate the first general result in this direction by showing that every real projective measurement can be self-tested in the 2-party Bell scenario. The standard definition of self-testing only allows for the certification of real measurements. Therefore, our work effectively broadens the scope of self-testable projective measurements to their full potential. To reach this result, we employ the idea that existing self-tests can be extended to verify additional untrusted measurements. This is known as 'post-hoc self-testing'. We formalize the method of post-hoc self-testing and establish a sufficient condition for its application.

We develop a new technique of iterative self-testing, which involves using post-hoc self-testing in a sequential manner. Starting from any established self-test, we fully characterize the set of measurements that can be verified via iterative self-testing. This provides a clear methodology for constructing new self-tests from pre-existing ones.

This talk is based on a joint work with Ranyiliu Chen and Jurij Volčič.

QI 24.2 Thu 10:00 HFT-TA 441
**Verification-Inspired Quantum Benchmarking** — •Johannes Frank[1,4], Elham Kashefi[2,3,4], Dominik Leichtle[4], and Michael Oliveira[4,5] — [1]Technical University of Munich, Germany — [2]School of Informatics, University of Edinburgh, 10 Crichton Street, EH8 9AB Edinburgh, United Kingdom — [3]National Quantum Computing Centre, Didcot, OX11 0QX, United Kingdom — [4]Laboratoire d'Informatique de Paris 6, CNRS, Sorbonne Université, 4 Place Jussieu, 75005 Paris, France — [5]International Iberian Nanotechnology Laboratory, Portugal

Currently available quantum devices suffer from significant noise and are limited in size which restricts their computational power. For this reason, quantum benchmarking, the task to judge and compare the usefulness of quantum hardware, is both important and nontrivial. Previously proposed benchmarking protocols and metrics however rely on heuristics or require strong assumptions on the behavior of the analyzed device. In this paper, we introduce a new approach to quantum benchmarking, inspired by quantum verification. As opposed to other benchmarking protocols, our proposal uses cryptographic tools to eliminate the reliance on heuristics and allow for provable statements about a device's computational power. It crucially offers scalability, customizability, and universality for quantum computation. Our work uncovers a deep connection between the fields of quantum verification and benchmarking. We give a concrete construction of a readily employable benchmarking protocol, and show that it achieves our improved standards for quantum benchmarking.

QI 24.3 Thu 10:15 HFT-TA 441
**Collective operations can exponentially enhance quantum state verification** — •Ferran Riera Sabat, Jorge Miguel-Ramiro, and Wolfgang Dür — Institut für Theoretische Physik, Universität Innsbruck, Technikerstraße 21a, 6020 Innsbruck, Austria

Maximally entangled states are a key resource in many quantum communication and computation tasks, and their certification is a crucial element to guarantee the desired functionality. Collective strategies for the efficient local verification of ensembles of Bell pairs that make use of initial information and noise transfer to a few copies prior to their measurement are introduced. In this way the number of entangled pairs that need to be measured and hence destroyed is significantly reduced as compared to previous, even optimal, approaches that operate on individual copies. Moreover, the remaining states are directly certified. We show that our tools can be extended to other problems and larger classes of multipartite states.

QI 24.4 Thu 10:30 HFT-TA 441
**Certifying the topology of quantum networks: theory and experiment** — •Lisa T. Weinbrenner[1], Nidhin Prasannan[2], Kiara Hansenne[1], Sophia Denker[1], Jan Sperling[3], Benjamin Brecht[2], Christine Silberhorn[2], and Otfried Gühne[1] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany — [2]Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS), Germany — [3]Paderborn University, Theoretical Quantum Science, Institute for Photonic Quantum Systems (PhoQS), Germany

Distributed quantum information in networks is paramount for global secure quantum communication. Moreover, it finds applications as a resource for relevant tasks, such as clock synchronization, magnetic field sensing, and blind quantum computation. For quantum network analysis and benchmarking of implementations, however, it is crucial to characterize the topology of networks in a way that reveals the nodes between which entanglement can reliably be distributed. Here, we demonstrate an efficient scheme for this topology certification. Our scheme allows for distinguishing, in a scalable manner, different networks consisting of bipartite and multipartite entanglement sources, for different levels of trust in the measurement devices and network nodes. We experimentally demonstrate our approach by certifying the topology of different six-qubit networks generated with polarized photons, employing active feed-forward and time multiplexing. Our methods can be used for general simultaneous tests of multiple hypotheses with few measurements, being useful for other certification scenarios.

QI 24.5 Thu 10:45 HFT-TA 441
**Verification of quantum memory in non-Markovian processes based on local information** — •Charlotte Bäcker[1], Konstantin Beyer[1,2], and Walter Strunz[1] — [1]TUD Dresden University of Technology, 01062, Dresden, Germany — [2]Stevens Institute of Technology, Hoboken, New Jersey, 07030, USA

Non-Markovian processes in quantum physics may be the result of the environmental degrees of freedom acting as a memory. It is an ongoing debate whether the memory effects can be modeled by a classical memory or whether their origin is inherently quantum. We propose a witness based only on local information of the system dynamics, which allows to verify the quantum nature of the memory. Using physically motivated examples, we show that both classical and quantum memory can occur in non-Markovian dynamics and establish the link between classical memory and a physically measurable quantum trajectory representation.

QI 24.6 Thu 11:00 HFT-TA 441
**Overlapping tomography: Reducing the number of measurement settings** — •Kiara Hansenne, Lisa Weinbrenner, Carlos de Gois, and Otfried Gühne — Universität Siegen, Germany

Quantum state tomography aims at reconstructing the density operator of a quantum system using data acquired from measurements on several copies of the system's state. While the conventional approach demands an exponential increase in measurement settings with the growth of particle numbers, certain situations only necessitate access to the density operators of k-body reduced states. Notably, for n-qubit systems, prior studies have shown that the number of Pauli measurement settings scales as e^O(k) log^2(n). In this work, we present insights from a one-to-one correspondence with a well-studied problem in combinatorics, and show how to explicitly obtain optimal measurement settings. Furthermore, by dropping the Pauli measurement assumption, we demonstrate the feasibility of marginal tomography with 3^k measurement settings, independently of the number of qubits.

**15 min. break**

QI 24.7 Thu 11:30 HFT-TA 441
**Parameterizing Pauli noise to capture crosstalk in quantum devices** — •Matthias Zipper[1], Christopher Cedzich[2], and Martin Kliesch[1] — [1]Hamburg University of Technology, Germany — [2]Heinrich-Heine-Universität Düsseldorf, Universitätsstr. 1, 40225 Düsseldorf, Germany

Physically meaningful and efficient noise models are important for the development of reliable quantum devices. We propose a parameterization of Pauli noise that arises naturally from intuitive axioms and combines the following desirable properties: (i) Each parameter is associated with a subset of qubits, and hence is interpreted as describing regional noise. (ii) While a priori capable of representing any Pauli noise channel, the parameterization becomes efficient under physically motivated locality assumptions. (iii) Our approach is compatible with a wide range of SPAM-robust protocols from the RB family, which facilitates its practical use in quantum system characterization. Our model thus resolves the spatial structure of Pauli noise and addresses the topic of "crosstalk" for quantum gates and circuits.

QI 24.8 Thu 11:45 HFT-TA 441

**ACES on correlated noise - promises and challenges of frontend noise metrology** — •Michael Ronen, Joris Kattemölle, and Guido Burkard — Universität Konstanz, Konstanz, Deutschland

Correlated noise poses a severe challenge to the advantage of many practical quantum algorithms. Error mitigation is indispensable for achieving a quantum advantage with noisy intermediate-scale quantum technology. It relies heavily on our ability to measure and quantify the noise affecting the circuits in quantum computers. Averaged circuit eigenvalue sampling (ACES) promises to be an effective frontend method of noise metrology that can compete with randomized benchmarking and noise tomography. We mark out the capabilities of ACES in measuring spatially and temporally correlated noise. We demonstrate that it can meet expectations when estimating spatially correlated errors but find limits in characterizing their temporally correlated counterparts. These difficulties arise since the error models' complexity grows exponentially with the depth of the circuit while the amount of extractable information stays constant with the number of qubits. By shining a light on ACES' capabilities, we better understand the promises and challenges of frontend noise metrology. Thereby, we point to future lines of inquiry that will improve the accuracy of correlated error model estimation. This will ultimately move us closer to achieving a practical quantum advantage.

QI 24.9 Thu 12:00 HFT-TA 441

**Stability of classical shadows under gate-dependent noise** — •Raphael Brieger[1,3], Markus Heinrich[1], Ingo Roth[2], and Martin Kliesch[1,3] — [1]Heinrich Heine University Düsseldorf, Faculty of Mathematics and Natural Sciences, Germany — [2]Quantum Research Center, Technology Innovation Institute, Abu Dhabi, UAE — [3]Hamburg University of Technology, Institute for Quantum Inspired and Quantum Optimization, Germany

Expectation values of observables are routinely estimated using so-called classical shadows—the outcomes of randomized bases measurements on a repeatedly prepared quantum state. In order to trust the accuracy of shadow estimation in practice, it is crucial to understand the behavior of the estimators under realistic noise. In this work, we prove that any shadow estimation proto- col involving Clifford unitaries is stable under gate-dependent noise for observables with bounded stabilizer norm—originally introduced in the context of simulating Clifford circuits. For these ob- servables, we also show that the protocol's sample complexity is essentially identical to the noiseless case. In contrast, we demonstrate that estimation of "magic" observables can suffer from a bias that scales exponentially in the system size. We further find that so-called robust shadows, aiming at mitigating noise, can introduce a large bias in the presence of gate-dependent noise compared to unmitigated classical shadows. On a technical level, we identify average noise channels that affect shadow estimators and allow for a more fine-grained control of noise-induced biases.

QI 24.10 Thu 12:15 HFT-TA 441

**Shadow tomography with noisy readouts** — •Hai-Chau Nguyen — University of Siegen

Shadow tomography emerges as a scalable technique to characterise the quantum state of a quantum computer or quantum simulator. Unfortunately, shadow tomography is by construction intrinsically sensitive to readout noise. In fact, the complicated structure of the readout noise due to crosstalk appears to be detrimental to the scalability of the most practical shadow tomography scheme. We show that shadow tomography accepts much more flexible constructions beyond the standard ones, which can eventually be made conformable with readout noise. With this construction, we show that readout errors in shadow tomography with randomised qubit measurements can be efficiently mitigated simply by randomly flipping the qubit before, and the classical outcome bit after the measurement. That a single X-gate is sufficient for mitigating readout noise for classical shadows is in contrast to Clifford-twirling, where the implementation of random Clifford gates is required.

QI 24.11 Thu 12:30 HFT-TA 441

**User-friendly confidence regions for quantum state tomography** — •Carlos de Gois and Matthias Kleinmann — Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany

Quantum state tomography is the standard technique for reconstructing a quantum state from measurement data. In practice, only a finite number of copies of the unknown state can be measured, thus the estimated state will almost surely diverge from the true state. A common way to express this limited knowledge about the true state is by providing confidence regions that contain the true state with high probability. Although some methods to construct such confidence regions already exist, they all have drawbacks such as requiring too many samples, not generalizing to arbitrary measurements, or being difficult to describe. In this talk, I will discuss a new construction that overcomes these issues. The resulting regions are described by ellipsoids in the space of Hermitian operators, have an asymptotically optimal sample cost, and can be straightforwardly applied to any measurement scheme. To investigate their performance in practice, I will use simulated tomography experiments to compare the sample costs with respect to previous proposals, and show that our construction leads to tighter regions, especially for high-dimensional systems.

QI 24.12 Thu 12:45 HFT-TA 441

**Pathological Behavior of Point Estimators with Minimum Bias (in Quantum Tomography, etc.)** — •Yien Liang[1,2,3] and Matthias Kleinmann[1] — [1]Universität Siegen, Walter-Flex-Straße 3, D-57068 Siegen, Germany — [2]Peking University, Beijing 100871, China — [3]Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstr. 1, D-40225 Düsseldorf, Germany

Being unbiased can be a desirable property for a statistical point estimator, that is, that the mean estimated value of a parameter coincides with the actual value of the parameter. While this property can be traded for other desiderata, it has been noted that in quantum physics, specifically in quantum state tomography, any estimator that always yields a physical estimate is necessarily biased. This affects the possible meaning of a state estimator, however, only if this effect is sizable enough to warrant a discussion. So far, no quantitative account of this effect was given and it could be possible that the bias of such an estimator is arbitrary small. Here we ask a more general question concerning the quantitative account of the minimum bias in situations where no unbiased estimator is available. For the example of Bernoulli trails with a constrained parameter space, we find that the least biased estimator is unique, but also pathological, in a certain sense.

QI 24.13 Thu 13:00 HFT-TA 441

**Overcoming scalability bottlenecks of detecting quantum entanglement** — •Daniel Miller[1], Lukas Postler[2], Antonio Anna Mele[1], Kyano Levi[1], Christian Marciniak[2], Ivan Pogorelov[2], Milena Guevara-Bertsch[2], Alex Steiner[2], Robert Freund[2], Rainer Blatt[2,3], Philipp Schindler[2], Jose Carrasco[2], Martin Ringbauer[2], Thomas Monz[2,4], and Jens Eisert[1] — [1]Freie Universität Berlin — [2]Universität Innsbruck — [3]IQOQI — [4]AQT

Concomitant with the rapid development of architectures in quantum technologies, increasingly sophisticated methods of quantum system identification are being developed. Mature schemes of quantum system identification should be (i) sample efficient in the system size, including an (ii) efficient classical post-processing, must be (iii) provably robust under realistic error models for a large class of states and (iv) should solely rely on experimentally feasible capabilities when resorting to quantum data processing. In this work, we identify sufficient requirements on the quality of a quantum device to permit provably scalable entanglement detection. Our proof is enabled by novel techniques that further strengthen the already deep connection between the theories of quantum entanglement and quantum error correction.

QI 24.14 Thu 13:15 HFT-TA 441

**Proposed method to produce large multipartite nonlocality and to benchmark quantum computers** — •Jan Lennart Bönsel[1], Otfried Gühne[1], and Adán Cabello[2] — [1]Universität Siegen, Germany — [2]Universidad de Sevilla, Spain

Nonlocality is a characteristic of quantum mechanics that does not occur in local realistic models. The violation of a Bell inequality can thus be used to verify nonclassicality.

In this contribution, we address the problem of producing $n$-partite Bell nonlocality with a very large number of qubits $n$. The main limiting factors are: (i) A restricted connectivity of the quantum computer might not allow an easy preparation of arbitrary entangled states. (ii) Noise limits the observable violation, and (iii) the number of different combinations of local measurements grows exponentially with $n$. Here, we point out that, for a given two-qubit connectivity, there is a particular entangled state that can be efficiently prepared, effectively overcoming (i). For the extreme cases of connectivity, we consider the GHZ and the linear cluster state. For these states, there exist $n$-partite Bell inequalities for which the resistance to white noise increases exponentially with $n$, which limits the impact of (ii). Finally, we introduce a method to address (iii). As a result, we show how to produce $n$-partite Bell nonlocality with unprecedented large $n$ using quantum computers under the assumption that there is no qubit communication after the local measurements. The $n$-partite nonlocality allows to quantify the nonclassicality and thus benchmark quantum computers. We test our approach on the IBM Quantum platform.

## QI 25: Materials and Devices for Quantum Technology II (joint session HL/QI)

Time: Thursday 14:00–16:45 Location: EW 203

**Invited Talk** QI 25.1 Thu 14:00 EW 203

**Compact, plug-and-play module to generate high-quality photon states from quantum dots** — •Vikas Remesh — Institute für Experimentalphysik, Universität Innsbruck, Innsbruck, Austria

As the quantum revolution gathers pace, there is a constant need to develop novel architectures to control quantum systems. Semiconductor quantum dots (QD) are regarded as the most promising sources of quantum light, due to their wavelength-tunability, high purity, high degrees of entanglement, and scalability. To realize a resource-efficient and scalable platform, it is desirable to have an ensemble of quantum dots that can be collectively excited with high efficiency. Shaped laser pulses have been remarkably effective in the development of controllable quantum systems. The most efficient optical excitation method of quantum dots relies on chirped laser pulses, as it offers robustness against spectral and intensity fluctuations. Yet, the existing methods to generate chirped laser pulses coupled to a quantum emitter are lossy and mechanically unstable, severely hampering the prospects of a practical quantum dot device. In this talk, I will briefly navigate through the impact of pulse-shaping schemes in advancing quantum dot control. Subsequently, I will present a compact, robust, and plug-and-play architecture for chirped pulse excitation of quantum dots, and demonstrate high-quality photon generation. Our method is a significant milestone in realizing a direct fiber-coupled, multipurpose quantum dot photon source.

QI 25.2 Thu 14:30 EW 203

**Light-matter correlations in Quantum Floquet Engineering** — •Beatriz Pérez-González[1], Gloria Platero[1], and Álvaro Gómez-León[2] — [1]Instituto de Ciencia de Materiales de Madrid (ICMM-CSIC), Madrid, Spanien — [2]Instituto de Física Fundamental (IFF-CSIC), Madrid, Spanien

Quantum Floquet engineering requires a proper gauge-invariant description of light-matter interaction to correctly capture the physics of the system beyond the strong-coupling regime. This means that such models typically involve a highly non-linear dependence on the photonic operators which makes their analysis and simulation complex.

In this talk, we present a non-perturbative truncation scheme for the light-matter Hamiltonian, which is valid for arbitrary coupling strength. This method can successfully capture the physics of both, fermions and photons, in agreement with the predictions of gauge-invariant models. Importantly, it also keeps track of the role of light-matter correlations, which are essential to correctly predict the properties of the many-body system.

We find that, even in the high-frequency regime, light-matter correlations can spontaneously break key symmetries. We focus on the implications this has when the electronic system has topological properties, since the breaking of a certain symmetry can jeopardize topological properties and their robustness. We exemplify our findings with the SSH chain, and show that a topological phase transition can be induced by coupling to a cavity and that the critical point can be predicted from the spectral function.

QI 25.3 Thu 14:45 EW 203

**Near-Ideal Room Temperature Single Photon Emitters hosted in hexagonal Boron Nitride for Quantum Optics Application** — •Tjorben Matthes[1,2], Anand Kumar[2], Chanaprom Cholsuk[1,2], Mohammad Nasimuzzaman Mishuk[2], Josefine Krause[2], Mouli Hazra[2], Kabilan Sripathy[2], and Tobias Vogl[1,2] — [1]Technical University of Munich, TUM School of Computation, Information and Technology, Arcisstraße 21, 80333 München — [2]Friedrich Schiller University Jena, Institute of Applied Physics, Albert-Einstein-Straße 15, 07745 Jena

In this talk, we will give an insight into our work done on single photon emitters hosted in hexagonal Boron Nitride (hBN) and the integration of those emitters into integrated photonics chips that have laser-written waveguides with controllable crosslinks at their heart.

We recently demonstrated the deterministic creation of identical single-photon emitters in hexagonal Boron Nitride that show exceptional characteristics regarding purity, stability, and brightness. In a follow-up work, we determined additional optical characteristics and carefully compared them to those predicted for numerous defect complexes by density functional theory (DFT) calculations. Currently, we are extending this work, bringing us closer to understanding the actual nature of the defect creation.

Furthermore, we are working on the technical utilisation of single photon emitters for quantum communication and optical circuits. In particular, we focus on laser-written waveguides that can be used for numerous applications having crosslinks with tunable splitting ratios.

QI 25.4 Thu 15:00 EW 203

**Theory of optical ionization of Silicon Vacancies in 4H-SiC** — •Maximilian Schober and Michel Bockstedte — Institute for Theoretical Physics, Johannes Kepler University Linz, Altenbergerstr. 69, A-4040 Linz, Austria

The Silicon Vacancy ($V_{Si}$) in 4H-SiC represents a quantum bit with advantageous properties for applications like quantum sensing and as a single-photon emitter. Optical readout of its spin state is achieved via a spin-selective optical cycle enabled by coupled defect electron spins and associated spin-dependent interactions. An alternative readout method involves spin-to-charge conversion through optical ionization [1] of the qubit, followed by the electrical detection of the resulting spin-sensitive photocurrents. Relatively little is known, however, regarding the photophysics of the optically silent charge states of $V_{Si}$ created throughout this process. To tackle this issue, we investigate such systems with a combined ab initio framework of density functional theory and CI-cRPA [2] capable of including the crucial multiplet physics of such qubit centers. We discuss the relevant single and two-photon processes for optical charge state switching and electrical detection of the spin states. Furthermore, we shine light on the nominally "dark" neutral and doubly negatively charged centers as potential infrared emitters.

[1] M. Niethammer et al., Nat Commun 10, 5569 (2019).
[2] M. Bockstedte et al., npj Quant Mater 3, 31 (2018).

**15 min. break**

QI 25.5 Thu 15:30 EW 203

**Inhomogenous broadening of donor bound exciton transitions in ultra-pure 28-Si:P** — •Nico Eggeling[1], Finja Tadge[1], Dolores García de Viedma[1], N.V. Abrosimov[2], Jens Hübner[1], and Michael Oestreich[1] — [1]Leibniz Universität Hannover, Germany — [2]IKZ Berlin, Germany

Donor-bound excitons in ultra-pure silicon offer distinct characteristics which qualify them as well-suited candidates for applications in the field of quantum computing [1]. Using a combination of numerical and analytical calculations, we analyze the influence of statistical electric field fluctuations on donor-bound excitonic transitions in ultra-pure 28-Si:P. Our results show good agreement with current measurements of the inhomogeneously broadened excitonic linewidth. Employing approximations concerning screening effects and Monte-Carlo-type simulations, linewidth predictions are made and confirmed. The inhomogeneous nature of the excitonic complex is shown using spectral hole burning [2]. The next steps include measurements and discussion of temporal broadening of the hole-burning linewidth due to donor-acceptor recombination.

[1] Sauter, et al. Phys. Rev. Lett. **126**, 137402, (2021).
[2] Yang, et al. Appl. Phy. Lett. **95**, 122113, (2009).

QI 25.6 Thu 15:45 EW 203

**All-dry Pick-Up and Transfer Method for Quantum Emitters in hBN** — •Mohammad Nasimuzzaman Mishuk[1,2], Mouli Hazra[2], Anand Kumar[1,2], and Tobias Vogl[1,2] — [1]Department of Computer Engineering, School of Computation, Information and Technology, Technical University of Munich, 80333 Munich, Germany — [2]Abbe Center of Photonics, Institute of Applied Physics, Friedrich Schiller University Jena, 07745 Jena, Germany

Quantum emitters (QE) hosted by defects in hexagonal Boron Nitride (hBN) can operate at room temperature, serving as stable single photon emitters. They can also be integrated into various materials and devices, making them highly versatile in quantum technologies and photonic integrated circuits. However, creating these quantum emitters directly on different surfaces is challenging. That's why more often they are created on standard silicon chip coated with thin silicon dioxide layer. Owing to this difficulty, various transfer processes are developed which are mostly wet. In this study, we present an all-dry transfer method for transferring quantum emitters onto arbitrary substrates. Using our pick-up and transfer method, we have achieved a success probability of 1 in 4 for any single photon emitter. The validity of our results has been confirmed through second-order correlation measurements. We are actively working on improving its quality, quantity, and accuracy.

QI 25.7 Thu 16:00 EW 203

**Plug-and-play quantum light from semiconductor quantum dots in fiber-pigtailed hybrid circular Bragg Gratings** — •Lucas Rickert[1], Kinga Zolnacz[2], Daniel Vajner[1], Martin v. Helversen[1], Johannes Schall[1], Shulun Li[1,4], Sven Rodt[1], Anna Musial[3], Grzegorz Sek[3], Zhichuan Niu[4], Stephan Reitzenstein[1], and Tobias Heindel[1] — [1]Institute of Solid State Physics, Technical University Berlin, Berlin, Germany — [2]Department of Optics and Photonics, Wroclaw University of Science and Technology, Wroclaw, Poland — [3]Department of Experimental Physics, Wroclaw University of Science and Technology, Wroclaw, Poland — [4]Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

We report on the fabrication of hybrid circular Bragg gratings (hCBGs) with deterministically integrated semiconductor quantum dots (QDs), and discuss in detail the fabrication methods to deterministically match the emitter spatially and spectrally to the cavity mode. The devices exhibit bright, pure and indistinguishable single photon emission with experimentally measured Purcell enhancement >15 with high reproducibility.

Finally, we show how these high-performance hCBGs can be combined with directly attached single-mode fibers to harness the high quality quantum light in a plug-and-play fashion, and discuss excitation schemes suitable for optimum performance of these fiber-coupled systems.

QI 25.8 Thu 16:15 EW 203

**Optical dipole orientation of single photon emitters in $MoS_2$** — •Katja Barthelmi[1,2], Lukas Sigl[1], Tomer Amit[3], Mirco Troue[1], Thomas Klokkers[1], Anna Herrmann[1], Takashi Taniguchi[4], Kenji Watanabe[4], Sivan Refaely-Abramson[3], and Alexander Holleitner[1,2] — [1]Walter Schottky Institut and Physik Department, Technical University of Munich, Garching, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Weizmann Institute of Science, Revohot, Israel — [4]National Institute for Materials Science, Tsukuba, Japan

Single photon emitters in monolayer $MoS_2$ can be formed by helium ion irradiation. The irradiation results in defects with an emission energy of 1.75 eV and a high position accuracy [1-3]. To further understand the microscopic structure of the defects, we study their emission dipole orientation by back focal plane imaging. We find that the optical dipole of the quantum emitters is in-plane orientated. Additionally, we resolve the far-field emission pattern spectrally through back focal plane spectroscopy. The novel method allows us to also study emission lines of low intensity.

[1] K. Barthelmi et al., in: Applied Physics Letters 117, 070501 (2020). [2] J. Klein et al., in: Nature Communications 10, 2755 (2019). [3] J. Klein and L. Sigl., in: ACS Photonics 8, 669-677 (2021). [4] K. Barthelmi et al., (2024).

QI 25.9 Thu 16:30 EW 203

**Optimization of Circular Bragg Grating Resonators for Quantum Dot Photonic Cluster State Sources in the Telecom C-Band** — •Yorick Reum, Jochen Kaupp, Simon Betzold, Felix Kohr, Tobias Huber-Loyola, Sven Höfling, and Andreas Pfenning — Technische Physik, Julius-Maximilians-Universität Würzburg, Germany

A major technological bottleneck for the realization of measurement-based optical quantum computing is the production of strings of highly-entangled photons, *photonic cluster states*. Semiconductor quantum dots (QDs) were shown to be promising candidates for cluster state sources, but spin-decoherence and non-negligible excitonic lifetimes currently limit fidelity and length of the emitted states [1]. This challenge can be tackled by embedding the QD into a cavity with high Purcell enhancement, inducing faster recombination times. We show Purcell-enhanced single-photon emission in the *telecom C-band* from InAs quantum dots inside *circular Bragg grating ("bullseye")* cavities, with excitonic decay times of down to $\tau = (180 \pm 3)$ ps, corresponding to a Purcell factor of $F_P = (6.7{\pm}0.6)$ [2]. To further optimize these resonators, we develop *best-fitting cavities* with 3D finite-difference time-domain simulations and discuss novel strategies for *post-fabrication tuning* via atomic layer deposition.

[1] Cogan, D., et al., Deterministic generation of indistinguishable photons in a cluster state. Nat. Photon. 17, 324-329 (2023).
[2] Kaupp, J., et al., Purcell-Enhanced Single-Photon Emission in the Telecom C-Band. Adv Quantum Technol. 2023, 2300242.

## QI 26: Superconducting Electronics: Qubits II (joint session TT/QI)

Time: Thursday 15:00–16:15 Location: H 2053

QI 26.1 Thu 15:00 H 2053

**Frequency-conversion loss in three-wave-mixing traveling-wave parametric amplifiers** — •Christoph Kissling, Victor Gaydamachenko, Marat Khabipov, Alexander B. Zorin, and Lukas Grünhaupt — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Traveling-Wave Parametric Amplifiers (TWPAs) enable near-quantum-limited amplification of weak microwave signals with several GHz bandwidths and saturation powers above -100 dBm. One aspect of current research is the reduction of microwave loss in TWPAs, which is seen as one reason why the added noise of TWPAs stays repeatedly above the quantum limit. Typically, most of the microwave loss is attributed to lossy dielectric layers. However, in this talk we address another loss mechanism which can occur in three-wave-mixing TWPAs. We discuss how frequency-conversion of a probe tone by the presence of noise in the kHz to MHz range can dominate the insertion loss. This potentially-overlooked nonlinear loss mechanism appears like linear loss and can therefore lead to false conclusions in the characterization and optimization of TWPAs.

QI 26.2 Thu 15:15 H 2053

**Generating on-chip ac radiation for high impedance electronics** — •David Scheer and Fabian Hassler — Institute for Quantum Information, RWTH Aachen University, 52056 Aachen, Germany

Superconducting circuits with high impedances have promising applications in qubit design and quantum metrology. It is however difficult to supply external ac signals to a high impedance environment due to impedance mismatching and parasitic capacitances. The ac Josephson effect can provide a solution to this problem since it generates oscillating currents from an external dc bias. Here we present the use of Josephson junctions as an on chip radiation source as a way to avoid external driving of high impedance circuits.

QI 26.3 Thu 15:30 H 2053

**High-impedance resonators based on granular aluminum** — •Mahya Khorramshahi, Martin Spiecker, Patrick Paluch, Ritika Dhundhwal, Nicolas Zapata, Ioan M. Pop, and Thomas Reisinger — Karlsruhe Institute of Technology, Karlsruhe, Germany

High-impedance resonators in superconducting quantum circuits are important in the advancement of quantum computing technologies. In particular, impedances surpassing the resistance quantum can be realized, enabling the development of protected qubits and strong coupling to small-dipole-moment systems with exciting prospects for interfacing to spin qubits or donor spins. Utilizing granular aluminum (GrAl), we have developed compact resonators operating in the few GHz regime and characteristic impedances as high as 80 kOhm. We characterized the resonators, with GrAl resistivity increasingly close to the superconducting to insulating transition, and report on single photon quality factors, non-linearity, and noise-spectral density.

QI 26.4 Thu 15:45 H 2053

**Longitudinal coupling between a molecular spin ensemble and a superconducting resonator** — •Simon Günzler[1,2], Dennis Rieger[2], Thomas Koch[2], Kiril Borisov[2], Patrick Winkel[2], Grigore Timco[3], Richard E.P. Winpenny[3], Ioan M. Pop[1,2], and Wolfgang Wernsdorfer[1,2] — [1]IQMT, Karlsruhe Institute of Technology, Germany — [2]PHI, Karlsruhe Institute of Technology, Germany — [3]PSI and School of Chemistry, The University of Manchester, UK

Hybrid quantum architectures coupling electronic spin ensembles to superconducting circuits have advanced remarkably in the past decade. So far, however, they rely on transverse coupling schemes, tuning the spin transition in close proximity to the circuit's frequency. Here, we demonstrate longitudinal coupling between spins in a microcrystal of $Cr_7Ni$ and the kinetic inductance of a granular aluminum superconducting microwave resonator. Remarkably, this enables the measurement of the crystal's magnetization independent of the detuning between the spin and resonator mode. Separate resonators fabricated from niobium on the same chip allow us to excite and measure the relaxation of the spins more than 2 GHz detuned from the readout resonator.

QI 26.5 Thu 16:00 H 2053

**Fermionic quantum computation with Cooper pair splitters** — Kostas Vilkelis[1,2], •Antonio Manesco[2], Juan Daniel Torres Luna[1,2], Sebastian Miles[1,2], Michael Wimmer[1,2], and Anton Akhmerov[2] — [1]Qutech, Delft University of Technology, Delft 2600 GA, The Netherlands — [2]Kavli Institute of Nanoscience, Delft University of Technology, Delft 2600 GA, The Netherlands

We propose a practical implementation of a universal quantum computer that uses local fermionic modes (LFM) rather than qubits. Our design consists of quantum dots tunnel coupled by a hybrid superconducting island together with a tunable capacitive coupling between the dots. We show that coherent control of Cooper pair splitting, elastic cotunneling, and Coulomb interactions allows us to implement the universal set of quantum gates defined by Bravyi and Kitaev. Finally, we discuss possible limitations of the device and list necessary experimental efforts to overcome them.

## QI 27: Quantum Simulation II

Time: Thursday 15:00–17:45 Location: HFT-FT 101

QI 27.1 Thu 15:00 HFT-FT 101

**Digital Simulations of Fermion-Boson Models on a Quantum Computer** — •Riccardo Roma[1,2], Tim Bode[1], Alessandro Ciani[1], Dmitry Bagrets[1,3], and Frank Wilhelm-Mauch[1,2] — [1]Institute for Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich, 52425 Jülich, Germany — [2]Theoretical Physics, Saarland University, 66123 Saarbrücken, Germany — [3]Institute for Theoretical Physics, University of Cologne, 50937 Cologne, Germany

Performing simulations of many-body correlated systems formed both by fermions and bosons on quantum computers is a demanding challenge. Current techniques based on digital approaches to encode all degrees of freedom into qubits and to simulate, for instance, the time evolution of the system have been proven to be extremely inefficient. We propose an alternative architecture to solve this problem which is based on a superconducting platform with transmons coupled to additional resonators used for the quantum information storage. This architecture expands the native set of gates of the quantum processor by adding an entangling gate between the transmons, which encode the fermions, and the resonators, which store the bosons without any need for approximations related to the truncation of the bosonic Fock space. We illustrate the potential of our approach by presenting a number of examples for the Trotterized time evolution algorithm applied to models from solid-state physics and quantum optics.

QI 27.2 Thu 15:15 HFT-FT 101

**Mitigating crosstalk errors by randomized compiling: simulation of the BCS model on a superconducting quantum computer** — •Thibault Scoquart[1], Hugo Perrin[1], Kyrylo Snizkho[2], Alexander Shnirman[1], and Jörg Schmalian[1] — [1]Karlsruhe Institute of Technology, Institut für Theorie der Kondensierten Materie, TKM, 76049, Karlsruhe, Germany — [2]CEA Grenoble, France

In this presentation, I give an overview of our work on 3-qubit simulations of the out-of-equilibrium dynamics of the BCS model, performed on IBMQ quantum computers. In these devices, most errors occur during the application of the 2-qubit CNOT gates. These faulty operations may affect neighboring qubits as well, producing Crosstalk errors, which are believed to be one of the main error source on these devices, and remain challenging to model. As a starting point to mitigate noise, one typically uses Randomized Compiling, a quantum circuit sampling technique which maps unknown noise into a simpler Pauli noise channel. In our work, we have extended this technique to neighboring qubits, and shown that Crosstalk noise can be turned into a simple depolarising noise channel, maximizing the efficiency of existing error mitigation schemes. We illustrate this by combining crosstalk RC with the Noise Estimation Circuit (NEC) error mitigation scheme for our BCS simulations. We show that using crosstalk RC indeed dramatically improves the quality of our results, which can in turn be used as an indirect measure of the impact of crosstalk on a given device.

Preprint: arXiv :2305.02345 (2023)

QI 27.3 Thu 15:30 HFT-FT 101

**Robust Experimental Signatures of Phase Transitions in the Variational Quantum Eigensolver** — •Kevin Lively[1], Tim Bode[2], Jochen Szangolies[1], Jian-Xin Zhu[3], and Benedikt Fauseweh[4] — [1]Deutsches Zentrum für Luft- und Raumfahrt — [2]Forschungszentrum Jülich — [3]Los Alamos National Laboratory — [4]Technische Universität Dortmund

The Variational Quantum Eigensolver (VQE) is widely considered to be a promising candidate for a quantum-classical algorithm which could achieve near-term quantum advantage. However, current levels of hardware noise can require extensive application of error mitigation techniques in order for the results of calculations to be meaningful. In this work we use several IBM devices to explore a finite size spin model with multiple 'phase-like' regions characterized by distinct ground state configurations. Using pre-optimized VQE solutions, we demonstrate that in contrast to calculating the energy, where zero noise extrapolation is required in order to obtain qualitatively accurate results, calculation of the two site spin correlation functions and fidelity susceptibility yields accurate behavior across multiple regions. Taken together, these two sets of observables could be used to identify level crossing in VQE solutions in a simple and noise robust manner, with potential near-term application to identifying avoided crossings and non-adiabatic conical intersections in electronic structure calculations.

QI 27.4 Thu 15:45 HFT-FT 101

**Quantum circuits to measure scalar spin chirality** — •Leander Reascos[1,2], Bruno Murta[1,3], Ernesto Galvão[3,4], and Joaquín Fernández-Rossier[3] — [1]Centro de Física das Universidades do Minho e do Porto, Universidade do Minho, Campus de Gualtar, 4710-057 Braga, Portugal — [2]Institute of Physics, University of Augsburg, 86159 Augsburg, Germany — [3]International Iberian Nanotechnology Laboratory (INL), Av. Mestre José Veiga, 4715-330 Braga, Portugal — [4]Instituto de Física, Universidade Federal Fluminense, Av. Gal. Milton Tavares de Souza s/n, Niterói, RJ, 24210-340, Brazil

The scalar spin chirality is a three-body physical observable that plays an outstanding role both in classical magnetism, characterizing noncoplanar spin textures, and in quantum magnetism, as an order parameter for chiral spin liquids. In quantum information, the scalar spin chirality is a witness of genuine tripartite entanglement. Here we propose an indirect measurement scheme, based on the Hadamard test, to estimate the scalar spin chirality for general quantum states. We apply our method to study chirality in two types of quantum states: generic one-magnon states of a ferromagnet, and the ground state of a model with competing symmetric and antisymmetric exchange. We show a single-shot determination of the scalar chirality is possible for chirality eigenstates, via quantum phase estimation with a single auxiliary qutrit. Our approach provides a unified theory of chirality in classical and quantum magnetism.

QI 27.5 Thu 16:00 HFT-FT 101

**MC-PDFT embedding scheme for electronic structure Quantum Algorithms** — •Luca Righetti[1], Pauline Ollitrault[2,3], and Ivano Tavernelli[2] — [1]École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland — [2]IBM Quantum, IBM Research Zurich, Rüschlikon, Switzerland — [3]QC Ware, Palo Alto,CA,USA

In this work we propose a new hybrid quantum algorithm combining the Variational Quantum Eigensolver (VQE) algorithm with a classical embedding method. The embedding consists in employing Multiconfiguration Pair Density Functional Theory (MC-PDFT) theory as a post-processing method for calculating the final energy of the system. The hybrid algorithm is motivated by the need of properly treating electron correlation in strongly correlated systems. We also propose a self-consistently optimized version of VQE, where molecular coefficient are re-optimized after every iteration until convergence. By comparing the performance of our algorithm with classical methods having similar computational costs, we observe an improvement in the accuracy of dissociation energies and ground state energies of different molecules. We test our embedding method with $H_2$, $H_2O$ and $N_2$. Our aim is not only to enhance the precision of VQE in predicting molecular energies, but also to reduce the depth and the width of the quantum circuit. Overall, this algorithm is able to achieve, in most cases, an accuracy comparable to more computationally expensive classical methods and to reduce quantum resources. We believe that this method can pave the way toward the simulation of larger molecular systems with current quantum devices.

**15 min. break**

QI 27.6 Thu 16:30 HFT-FT 101

**Towards scalable simulations of correlated materials via hybrid quantum-classical algorithms** — •Yannic Rath, Francois Jamet, Connor Lenihan, Lachlan P. Lindoy, Abhishek Agarwal, and Ivan Rungger — National Physical Laboratory, Teddington, TW11 0LW, United Kingdom

Dynamical mean-field theory (DMFT) has emerged as one of the main workhorses for the accurate numerical simulation of materials from first principles in regimes of strong correlation. In this talk, we discuss novel routes towards enhancing the predictive abilities of DMFT by integrating quantum algorithms into its pipeline in a hybrid quantum-classical approach [arXiv:2304.06587] and point out algorithmic advancements which are necessary to bring down the overall complexity of the method.

We leverage the representational power of tensor networks as a classical description of the Hamiltonian's ground state. To extract dynamical properties, we employ a quantum algorithm simulating a real-time evolution of the state [arXiv:2205.00094], which naturally increases the entanglement and limits the applicability of classical wavefunction methods. We discuss optimizations of the tensor network representation, as well as improvements to its compilation into a shallow quantum circuit, which tailors the approach for applications in practically relevant scenarios and increases its potential to eventually enable simulations that are out of reach of classical techniques.

QI 27.7 Thu 16:45 HFT-FT 101

**Hybrid quantum-classical algorithm for ground state and excitations of the transverse-field Ising model in the thermodynamic limit** — •Sumeet Sumeet, Max Hörmann, and Kai P. Schmidt — Department of Physics, Staudtstraße 7, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germany

We describe a hybrid quantum-classical approach to treat quantum many-body systems in the thermodynamic limit by combining numerical linked-cluster expansions (NLCE) with the variational quantum eigensolver (VQE). Here, the VQE algorithm is used as a cluster solver within the NLCE. We test our hybrid quantum-classical algorithm (NLCE+VQE) for the ferromagnetic transverse-field Ising model (TFIM) on the one-dimensional chain and the two-dimensional square lattice [1]. The calculation of ground-state energies on each open cluster demands a modified Hamiltonian variational ansatz for the VQE. One major finding is convergence of NLCE+VQE to the conventional NLCE result in the thermodynamic limit when at least $N/2$ layers are used in the VQE ansatz for each cluster with $N$ sites. We further extend this approach for calculation of excited states for the TFIM. We further extend NLCE+VQE to determine the one quasi-particle dispersion and energy gap of the TFIM in the polarized phase. To this end we determine we developed a new variational cost function based on the projective cluster-additive transformation [2].

*[1] Sumeet, M. Hörmann, K.P. Schmidt, arXiv:2310.07600*
*[2] M. Hörmann and K.P. Schmidt. SciPost Phys., 15:097, 2023.*

QI 27.8 Thu 17:00 HFT-FT 101

**Simulation of the Dissipative Dynamics of Strongly Interacting NV Centers with Tensor Networks** — •Jirawat Saiphet and Daniel Braun — Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14-D, 72076 Tübingen

NV centers in diamond are a promising platform for high-sensitivity quantum sensing. The successful creation of nanometer-separated double and triple NVs in a quantum register paves the way for enhancing sensitivity through NV-NV dipolar coupling. Hence, controlling these strongly interacting NVs becomes essential. However, simulating the dynamics of a many-body system, even for a few bodies, is a challenging task due to exponential scaling of the dimension of Hilbert space. To circumvent this problem, we employ the tensor network technique, representing the many-body state in the forms of a Matrix Product State (MPS) and a Matrix Product Density Operator (MPDO).

We address the issue of simulating the real-time evolution of a finite number of NVs with strong and long-range coupling via dipole-dipole interaction. Initially, we benchmark tensor network algorithms for time-evolution in terms of numerical accuracy and stability. Subsequently, we simulate the dynamics of the mixed state with and without dissipation. Finally, we implement an optimization algorithm to find optimal controls for preparing a highly entangled state.

QI 27.9 Thu 17:15 HFT-FT 101

**Electronic structure calculations of GaAs employing a quantum computer simulator** — •Ivana Miháliková[1,2], Michal Ďuriška[1,2], and Martin Friák[1] — [1]Institute of Physics of Materials, Czech Academy of Sciences, Brno, Czech Republic — [2]Department of Condensed Matter Physics, Faculty of Science, Masaryk University, Brno, Czech Republic

The simulation and characterization of physical systems stand out as one of the most promising applications of quantum computers. In our research, we focused on performing electronic structure calculations of GaAs through the utilization of quantum computer simulators. While the Variational Quantum Eigensolver (VQE) was used for calculating ground state energies, we employed the Variational Quantum Deflation (VQD) algorithm to access higher energy levels. Using a tight-binding Hamiltonian, we examined the influence of various computational settings including the choice of the optimization methods and the architecture of the quantum circuit. Our results indicate that the number of iterations necessary for an accurate evaluation is higher for higher-energy levels. In this context, the optimization method, Constrained Optimization BY Linear Approximation (COBYLA), emerges as the most advantageous choice.

QI 27.10 Thu 17:30 HFT-FT 101

**Nonlinear dynamics as a ground-state solution on quantum computers** — •Albert Pool[1,2], Alejandro Somoza[1,2], Michael Lubasch[3], Conor Mc Keever[3], and Birger Horstmann[1,2,4] — [1]Institute of Engineering Thermodynamics, German Aerospace Center (DLR), Ulm, Germany — [2]Helmholtz Institute Ulm, Ulm, Germany — [3]Quantinuum, London, UK — [4]Department of Physics, Ulm University, Ulm, Germany

For the solution of time-dependent nonlinear differential equations, we present variational quantum algorithms (VQAs) that encode both space and time in qubit registers. The spacetime encoding enables us to obtain the entire time evolution from a single ground-state computation. We describe a general procedure to construct efficient quantum circuits for the cost function evaluation required by VQAs. To mitigate the barren plateau problem during the optimization, we propose an adaptive strategy. The approach is illustrated for the nonlinear Burgers equation. We classically optimize quantum circuits to represent the desired ground-state solutions, run them on IBM Q System One, and demonstrate that current quantum computers are capable of accurately reproducing the exact results.

## QI 28: Surface Atom and Color Center Spin Qubits

Time: Thursday 15:00–18:00 Location: HFT-FT 131

**Invited Talk** QI 28.1 Thu 15:00 HFT-FT 131

**An atomic scale multi-qubit platform** — •Hong Thi Bui[1,2], Yu Wang[1,2], Yi Chen[3], Christoph Wolf[1,2], Yujeong Bae[1,2], Andreas J. Heinrich[1,2], and Soo-hyon Phark[1,2] — [1]Center for Quantum Nanoscience, Institute for Basic Science (IBS), Seoul, Korea — [2]Ewha Womans University, Seoul, Korea — [3]International Center for Quantum Materials, Peking University, Beijing, China

Individual electron spins in solids present promising prospects as qubits in quantum science and technology. Nevertheless, scaling up their utilization has posed a longstanding challenge. The use of a scanning tunneling microscope (STM) for individual atom addressability and precise atom-by-atom positioning allows for a bottom-up design of functional quantum devices. In this work, we successfully achieved the atom-by-atom construction, coherent manipulation, and readout of coupled electron-spin qubits using an STM. To facilitate coherent control of "remote" qubits that are outside of the tunnel junction, we complemented each electron spin with a local magnetic field gradient generated by a nearby single-atom magnet [1]. The readout process was accomplished by using a sensor qubit within the tunnel junction and implementing pulsed double electron spin resonance [2]. This approach allowed for the demonstration of fast single-, two-, and three-qubit operations in an all-electrical fashion [2]. Our qubit platform at the Angstrom scale exemplifies quantum functionalities utilizing electron spin arrays assembled atom by atom on a surface.

References: [1] S. Phark et al. Adv. Sci. 10, 2302033 (2023). [3] Y. Wang et al. Science 382, 87-92 (2023).

QI 28.2 Thu 15:30 HFT-FT 131

**Theoretical study of entangled-state generation and coherence in atomic spins using electron spin resonance with the scanning tunneling microscope.** — Eric Switzer[1,2], Jose Reina-Gálvez[3], Géza Giedke[2], Talat Rahman[1], Christoph Wolf[3], and •Nicolas Lorente[4] — [1]University Central Florida, Orlando, Florida — [2]DIPC, San Sebastian, Spain — [3]QNS, Ewha Womans University, Seoul, Republic of Korea — [4]CFM (CSIC-EHU), San Sebastian, Spain

Experimental techniques using pulsed electron spin resonance (ESR) with scanning tunneling microscopy (STM) have uncovered a new method to generate entangled spin states using atomic sites prepared on a substrate [1]. In this work, we demonstrate the use of a newly developed NEGF-derived quantum master equation software [2-5] to model ESR-STM for realistic experimental conditions relevant to atomic-scale qubit systems. We predict changes in measured current on the STM tip within the time domain and correlate patterns in the current with the generation of a non-trivial entangled spin state. We also demonstrate the role of electron dynamics in the sequential regime on the coherence of the entangled state as a function of time. [1] Yu Wang et al. Science 382, 87 (2023) [2] J. Reina-Gálvez et al. Phys. Rev. B 100, 035411 (2019) [3] J. Reina-Gálvez et al. Phys. Rev. B 104, 245435 (2021) [4] J. Reina-Gálvez et al. Phys. Rev. B 107, 235404 (2023) [5] https://github.com/qphensurf/

QI 28.3 Thu 15:45 HFT-FT 131

**Demonstration of coherent excitation in a tin-vacancy color center in diamond with the SUPER scheme** — •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], Gregor Pieplow[1], Tommaso Pregnolato[1,3], Joseph H.D. Munns[1], Doris E. Reiter[4], and Tim Schröder[1,3] — [1]Institute of Physics, Humboldt University of Berlin, Berlin, Germany — [2]Institute of Solid State Theory, University of Münster, Münster, Germany — [3]Ferdinand-Braun-Institute, Berlin, Germany — [4]Faculty of Physics, Technical University Dortmund, Dortmund, Germany

We present a new approach to generate coherent single photons using a technique named SUPER (Swing-UP of the quantum EmitteR population) on a tin-vacancy color center in diamond. Traditional methods rely on resonant excitation but face a major challenge in separating the excitation laser from emitted photons due to spectral overlap. SUPER, however, employs two-color nonresonant pulses to achieve full inversion to the excited state allowing effective spectral filtering.

The implementation of SUPER involves a specially designed spectral pulse engineering setup. This setup generates pulses with specific spectral shapes directed to a tin-vacancy center within a diamond nanopillar. This study marks the first application of SUPER to a color center in diamond, demonstrating coherent single photon emission with nonresonant pulses. The results, consistent with theoretical models, show promise for the exploration of ultrafast processes using these methods.

QI 28.4 Thu 16:00 HFT-FT 131

**Scaling-up of NV Quantum Information Processors** — •Jonas Breustedt and Martin Plenio — Institut für Theoretische Physik, Universität Ulm

Finding a working and scaleable quantum computation architecture is an important topic in current quantum information. Here, quantum information processors based on nitrogen-vacancy (NV) centers in diamond constitute one such possible architecture. One particular advantage is their compactness: At distances between NV centers of ∼10nm, even micrometer sized diamond arrays could host on the order of millions of NVs. However, this close proximity is also required for efficient inter-NV coupling and consequently poses a problem when combined with the optical readout schemes for NVs: Selective addressability of individual NVs becomes a challenging affair, due to readout pulses performing the same external perturbation on multiple NVs.

In this work, we study the effect of optical driving of a coupled 2-NV system. We then quantify how differences in local, i.e. NV specific, parameters can be employed to obtain selective addressability of NV centers even though both centers experience the same optical driving. Our goal is to derive parameter regimes for, in particular, NV distances and lattice strain in which NVs can still be accessed individually. Identifying these regimes would be an important step to scale-up NV quantum information processing platforms.

QI 28.5 Thu 16:15 HFT-FT 131

**Quantum Optimal Circuit Compilation Algorithm for NV Centers** — •Yaqing Xy Wang[1], Mees Hendriks[3], Felix Motzoi[1], Tommaso Calarco[1,2], and Matthias M. Müller[1] — [1]Peter Grünberg Institute,Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, D-52425 Germany — [2]Dipartimento di Fisica e Astronomia "Augusto Righi" Viale Berti Pichat 6/2, Bologna, Italy — [3]CHARM Therapeutics Ltd., The Stanley Building, 7 St. Pancras Square, London, N1C 4AG, UK

This talk illustrates an approach to circuit compilation that is applicable to centrally coupled qubit network. The method serves as an end-to-end mapping between a desired unitary to control pulse on the physical platform. The decomposition of circuit unitary to sequence of gates originating in native terms of the platform Hamiltonian is achieved by a modified recursive Cartan Decomposition of the unitary. Moreover, A quasi-analytic pulse generation method is proposed for achieving native basis gates that bypasses the costly matrix exponentiation involved in numerical pulse optimization algorithms. The method is expected to demonstrate its time optimality on larger Hilbert spaces with a high level of qubit connectivity as well as for more arbitrary unitary objectives that arise in quantum simulation tasks, nonetheless on smaller systems it provides mathematically elegant solutions. In both scenarios, the proposed method is robust against the short dephasing time of the central ancilla qubit(NV center).

**15 min. break**

QI 28.6 Thu 16:45 HFT-FT 131

**Continuous-Wave, Room-Temperature Masers, using NV-Centers in Diamond** — •Christoph W. Zollitsch[1,2], Stefan Ruloff[1], Yan Fett[1], Haakon T. A. Wiedemann[1], Rudolf Richter[1], Jonathan D. Breeze[1,2], and Christopher W. M. Kay[1,3] — [1]Department of Chemistry, Saarland University, Saarbrücken, Germany — [2]Department of Physics \& Astronomy, University College London, London, UK — [3]London Centre for Nanotechnology, University College London, London, UK

The concepts of microwave amplification by stimulated emission of radiation (MASER) were developed in the late 1950s, in conjunction with its optical counterpart the laser. While lasers found applications in many fields the applications of masers were highly specialized. This was due to the extreme operating conditions of the first masers, requiring cryogenic temperatures and high vacuum environments. However, the maser*s excellent low-noise microwave amplification as well as its ultra narrow linewidth make it an attractive candidate for a broad range of microwave applications. Here, we characterize the operating space of a diamond NV-center maser system. Key for the continuous emission of microwave photons is a level inversion, in addition to a high-quality, low mode-volume microwave resonator to enhance the spontaneous emission of the NV-centers. We investigate the performance of the maser system as a function of level inversion and resonator quality-factor and construct a phase diagram, identifying the parameter space of operation and discuss the optimal working points and pathways for optimization.

QI 28.7 Thu 17:00 HFT-FT 131

**Strain Engineering for Transition Metal Defects in SiC** — •Benedikt Tissot[1], Péter Udvarhelyi[2,3], Adam Gali[2,3], and Guido Burkard[1] — [1]Department of Physics, University of Konstanz, D-78457 Konstanz, Germany — [2]HUN-REN Wigner Research Centre for Physics, P.O. Box 49, H-1525 Budapest, Hungary — [3]Budapest University of Technology and Economics, Institute of Physics, Department of Atomic Physics, Műegyetem rakpart 3., 1111 Budapest, Hungary

Transition metal (TM) defects in silicon carbide (SiC) are a promising platform for applications in quantum technology as some of these defects, e.g. vanadium (V), allow for optical emission in one of the telecom bands. For other defects it was shown that straining the crystal can lead to beneficial effects regarding the emission properties. Motivated by this, we theoretically study the main effects of strain on the electronic level structure and optical electric-dipole transitions of the V defect in SiC. In particular we show how strain can be used to engineer the g-tensor, electronic selection rules, and the hyperfine interaction. Based on these insights we discuss optical Lambda systems and a path forward to initializing the quantum state of strained TM defects in SiC.

QI 28.8 Thu 17:15 HFT-FT 131

**Coherence properties of NV-center ensembles coupled to an electron-spin bath in diamond** — Reyhaneh Ghassemizadeh, Wolfgang Körner, •Daniel F. Urban, and Christian Elsässer — Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany

Nitrogen-vacancy (NV) centers in diamond are one of the promising solid-state-based qubit platforms. Quantum-technology applications in general require long coherence times for the qubit. However, the coherence time of NV centers is limited due to their coupling to the surrounding fluctuating environmental electronic and nuclear spins. In this study we use the cluster-correlation expansion (CCE) method to study the decoherence of ensembles of NV centers in a range of electron-spin bath-concentrations $\rho$ of 0.1 - 100 ppm. We demonstrate the statistical ensemble averaging and compute the Hahn-echo coherence time ($T_2$) and the stretched exponential parameter as a function of $\rho$. Moreover, we perform a geometrical analysis in order to determine the effective dipolar interaction length depending on the bath concentrations. Our results provide a quantified description of the decoherence behaviour of NV ensembles as well as individual electron-spin bath-configurations that lead to a prolonged coherency of the NV center.

QI 28.9 Thu 17:30 HFT-FT 131

**Performance of quantum registers in diamond in the presence of spin impurities** — •Dominik Maile and Joachim Ankerhold — Institute for Complex Quantum Systems, Ulm University

The Nitrogen Vacancy Center in diamond coupled to addressable surrounding nuclear spins forms a versatile building block for future quantum technologies. While previous activities focused on sensing with only a single or very few spins in operation, recently multi-qubit registers have been successfully implemented for quantum information processing. Further progress requires a detailed understanding of the performance of quantum protocols for consecutive gate operations and thus, beyond established treatments for relaxation and dephasing. In this talk, we provide such a theoretical analysis for a small spin registers with up to four spins built out of NV and environmental constituents in presence of ensembles of impurity spins. Thereby, we discuss the tradeoff between fast control of the full register and the leakage of entanglement to unwanted spins in the environment. We also show perspectives on how to overcome present limitations.

[1] D.Maile and J.Ankerhold, arXiv:2211.06234 (2023)

QI 28.10 Thu 17:45 HFT-FT 131

**Fidelity of photon-mediated entanglement between remote nuclear-spin multi-qubit registers** — •Wolf-Rüdiger Hannes, Regina Finsterhoelzl, and Guido Burkard — Department of Physics, University of Konstanz, 78457 Konstanz, Germany

The nuclear spin environment of NV centers can be used to realize a multiqubit register, for which long-lived single-qubit states and high-fidelity electron-nuclear gates have been demonstrated [1]. For scalable quantum networking applications, linking registers in a photonic network is important, but has so far been realized with one nuclear spin per node only [2,3]. We theoretically analyze the requirements to extend the photonic architecture proposed by Nemoto et al. [4], which makes use of the intrinsic nitrogen spin, to multiple $^{13}C$ spins per node. In particular we analyze the case where decoherence-protected gates suggested in Ref. [1] are applied consecutively and estimate a fidelity for creating multiple remote Bell pairs between two nodes. One requirement is the correction of unconditional phases acquired by unaddressed nuclear spins during a decoupling sequence. Even though the currently achieved degree of control of $^{13}$C spins might not be sufficient for large-scale devices, the two schemes are compatible in principle.

[1] C. E. Bradley, J. Randall, M. H. Abobeih et al., Phys. Rev. X 9, 031045 (2019). [2] N. Kalb, A. A. Reiserer, P. C. Humphreys et al., Science 356, 928 (2017). [3] E. Bersin, M. Sutula, Y. Q. Huan et al., arXiv:2307.08619 (2023). [4] K. Nemoto, M. Trupke, S. J. Devitt et al., Phys. Rev. X 4, 031022 (2014).

## QI 29: Quantum Information: Concept and Methods II

Time: Thursday 15:00–17:45 Location: HFT-TA 441

QI 29.1 Thu 15:00 HFT-TA 441

**Information and uncertainty in the fermionic phase space** — Nicolas Cerf and •Tobias Haas — Centre for Quantum Information and Communication, Université libre de Bruxelles, Belgium

We put forward several information-theoretic measures for the information encoded in phase-space distributions of a single fermion using the theory of supernumbers. In contrast to the bosonic case, the anti-commuting nature of Grassmann variables allow us to provide simple expressions for the phase-space distributions of arbitrary physical states. We show that all physical states are Gaussian and thus can be described by positive (negative) thermal Wigner W-distributions of positive (negative) temperature. We prove uncertainty relations for general measures of disorder, including, e.g. the fermionic analogs of the unproven phase-space majorization and Wigner entropy conjectures as well as the Lieb-Solovej theorem and the Wehrl-Lieb inequality.

QI 29.2 Thu 15:15 HFT-TA 441

**Experiments to refute real quantum mechanics suffer from the entanglement loophole** — •Pedro Barrios[1,2], Michael Epping[1], Dagmar Bruss[2], and Hermann Kampermann[2] — [1]Institute for Software Technology, German Aerospace Center (DLR), Cologne, Germany — [2]Heinrich-Heine Universität Düsseldorf, Germany

Complex numbers are used extensively in quantum mechanics. The question of whether they are merely helpful or indeed necessary in the formalism is still unresolved. There have been many successful attempts of formulations using real numbers only [PRL 102 020505 (2009)]. Nevertheless, a particular Bell-type experiment has been proposed [Nature 600, 625 (2021)], where a certain class of theories of real quantum mechanics fails to reproduce the predictions of standard quantum theory, thereby falsifying these theories. However, we show that this result suffers from the following loophole, which cannot be closed in practice: If the involved parties initially share entanglement, then the experiment can be explained with real numbers only. Therefore, experimentally, both formulations are still undistinguishable.

QI 29.3 Thu 15:30 HFT-TA 441

**Time-optimal multi-qubit gates: Complexity, efficient heuristic and gate-time bounds** — •Pascal Bassler[1], Markus Heinrich[1], and Martin Kliesch[2] — [1]Institute for Theoretical Physics, Heinrich Heine University Düsseldorf, Germany — [2]Institute for Quantum Inspired and Quantum Optimization, Hamburg University of Technology, Germany

Multi-qubit entangling interactions arise naturally in several quantum computing platforms and promise advantages over traditional two-qubit gates. In particular, a fixed multi-qubit Ising-type interaction together with single-qubit X-gates can be used to synthesize global ZZ-gates (GZZ gates). We develop a method to synthesize such global ZZ-gate with optimal gate time. First, we show that the synthesis of such quantum gates that are time-optimal is NP-hard. Second, we develop a heuristic algorithm with polynomial runtime for synthesizing fast multi-qubit gates. Third, we derive lower and upper bounds on the optimal GZZ gate-time. Based on explicit constructions of GZZ gates and numerical studies, we conjecture that any GZZ gate can be executed in a time O(n) for n qubits. We expect that our efficient synthesis of fast multi-qubit gates allows for faster and, hence, also more error-robust execution of quantum algorithms.

QI 29.4 Thu 15:45 HFT-TA 441

**Virtual subsystems under pseudo-Hermitian evolution** — •Himanshu Badhani — The Institute of Mathematical Sciences, Chennai

Given a bipartite system undergoing evolution under a pseudo-Hermitian Hamiltonian, its evolution is unitary in the appropriately chosen metric Hilbert space. If the metric operator does not have a tensor product decomposition (even if the underlying vector space has a tensor product structure), then the Hilbert space does not have a tensor product structure. It is therefore not clear how one should define a subsystem in such Hilbert spaces. In our work, we establish a general prescription to define the "subsystems" in such scenarios. We propose two different methods of partially tracing out the degrees of freedom: one of the methods exploits the equivalence of the pseudo-Hermiticity and Hermiticity. The other method considers a purely geometric approach wherein the Hilbert space is given a vector bundle structure over a base space. Partial tracing is then defined as the sum of the parallel transported states to any one of the fibers of the vector bundle. We show that these two methods of "partial trace" are equivalent. While the choice of the metric has no bearing on the system's properties, these subsystems can depend on the chosen metric since they correspond to the virtual subsystems of the original system. We prove this statement by establishing the C *-algebra in the non-trivial Hilbert space and its *-isomorphism to the algebra of the virtual bi-partition.

arXiv:2309.03042v1 and arXiv:2109.10682v2

QI 29.5 Thu 16:00 HFT-TA 441

**Construction of perfect tensors using biunimodular vectors** — •suhail rather — Max Planck Institute for the Physics of Complex Systems Dresden, Germany

Dual unitary gates are highly non-local bipartite unitary gates that have been studied extensively in quantum many-body physics and quantum information in the recent past. A special subset of dual unitary gates consists of rank-four perfect tensors, which are equivalent to highly entangled multipartite pure states called absolutely maximally entangled (AME) states. In this work, numerical and analytical constructions of dual unitary gates and perfect tensors that are diagonal in a special maximally entangled basis are presented. The main ingredient in our construction is a phase-valued (unimodular) two-dimensional array whose discrete Fourier transform is also unimodular. We obtain perfect tensors for several local Hilbert space dimensions, particularly, in dimension six. A perfect tensor in local dimension six is equivalent to an AME state of four qudits, denoted as AME(4,6), and such a state cannot be constructed from existing constructions of AME states based on error-correcting codes and graph states. The existence of AME(4,6) states featured in well-known open problem lists in quantum information, and was settled positively in Phys. Rev. Lett. 128 080507 (2022). We provide an explicit construction of perfect tensors in local dimension six that can be written in terms of controlled unitary gates in the computational basis, making them amenable for quantum circuit implementations.

QI 29.6 Thu 16:15 HFT-TA 441

**Entropy constraints from the spectral quantum marginal problem** — Felix Huber[1,2] and •Nikolai Wyderka[3] — [1]Faculty of Physics, Astronomy and Applied Computer Science, Institute of Theoretical Physics, Jagiellonian University, ul. Lojasiewicza 11, 30-348 Krakow, Poland — [2]NAQUIDIS Center, Talence, France — [3]Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, 40225 Düsseldorf, Germany

Deciding whether given eigenvalues of reduced density matrices are compatible with a joint state is known as the spectral quantum marginal problem. Its applications range from the sums of Hermitian matrices problem to optimizing trace polynomials on the positive cone and deciding the compatibility of local invariants. Even though the problem is hard to decide in general, we show how to formulate a complete hierarchy of semidefinite programs that is able to generate dimension-free certificates of spectral incompatibility in some cases. Consequently, we apply this hierarchy to derive stronger entropy inequalities that bound entropies of a quantum system and it parts.

**15 min. break**

QI 29.7 Thu 16:45 HFT-TA 441

**Measuring beam deflections via weak measurements** — •Carlotta Versmold[1,2,3], Elina Köster[1], Florian Huber[1,2,3], Lev Vaidman[4], Harald Weinfurter[1,2,3], and Jan Dziewior[1,2,3] — [1]Department für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Max-Planck-Institut für Quantenoptik, Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [4]Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv, Israel

The technique of weak value amplification makes it possible to measure small angular and spatial displacements of a laser beam precisely by using an interferometric measurement device. So far, weak value amplification setups could only measure displacements occurring due to an interaction inside the measurement device. Here, we present an interferometric weak measurement setup able to measure displacements of a light beam that occur outside of the device. For this, we implement a Sagnac-type interferometer with a dove prism in one of its arms. The dove prism mirrors the displacements, which occurred outside the interferometer, and introduces a relative deflection between the light beams in the two interferometer arms. Then, the center of mass of the resulting interference pattern will shift depending on the initial displacement times the weak amplification factor of the pre- and postselected interferometer states. In this experiment we demonstrate how tuning the interferometer to a large amplification factor allows a clear increase in the resolution for both external beam deflections and displacements.

QI 29.8 Thu 17:00 HFT-TA 441

**The Min-Entropy of Classical-Quantum Combs for Measurement-Based Applications** — •Isaac D. Smith, Marius Krumm, Lukas J. Fiderer, Hendrik Poulsen Nautrup, and Hans J. Briegel — Institute for Theoretical Physics, UIBK, 6020 Innsbruck, Austria

Learning a hidden property of a quantum system typically requires a series of interactions. In this work, we formalise such multi-round learning processes using a generalisation of classical-quantum states, called classical-quantum combs. Here, 'classical' refers to a random variable encoding the hidden property to be learnt, and 'quantum' refers to the quantum comb describing the behaviour of the system. The optimal strategy for learning the hidden property can be quantified by applying the comb min-entropy to classical-quantum combs. To demonstrate the power of this approach, we focus attention on an array of problems derived from measurement-based quantum computation (MBQC) and related applications. Specifically, we describe a known blind quantum computation (BQC) protocol using the combs formalism and thereby leverage the min-entropy to provide a proof of single-shot security for multiple rounds of the protocol, extending the existing result in the literature. Furthermore, we consider a range of operationally motivated examples related to the verification of a partially unknown MBQC device. These examples involve learning the features of the device necessary for its correct use, including learning its internal reference frame for measurement calibration.

QI 29.9 Thu 17:15 HFT-TA 441

**Hardware-Tailored Mutually Unbiased Bases** — •Kyano Levi[1,2], Eric Kuehnke[2], Daniel Miller[2], and Jens Eisert[2] — [1]Technische Universität Berlin — [2]Freie Universität Berlin

Gathering sufficient statistics for quantum state tomography poses a bottleneck for applications on current quantum hardware. In our work, we address this bottleneck by constructing hardware-tailored and near-optimal quantum circuits for diagonalizing entire stabilizer groups on $n \leq 6$ qubits.

We use the new circuits to craft sets of mutually unbiased bases that are tailored to important hardware connectivities. Our results allow for an exponential reduction of the sample complexity when performing full-state tomography on up to $n = 12$ qubits, as verified by theory, simulations, and experiments on quantum hardware. Specifically, we achieve a 1.8x shot reduction over state-of-the-art tensor product bases for three-qubit full-state tomography with a cloud-based quantum computer. With classical simulations, we demonstrate a theoretical shot reduction of 11.4x for $n = 11$ qubits.

Our circuits feature a two-qubit gate depth that is within reach for present-day, erroneous quantum hardware, rendering them a versatile building block for meaningful applications on existing devices.

QI 29.10 Thu 17:30 HFT-TA 441

**Quantum Wasserstein distance based on an optimization over subsets of physical quantum states** — •Géza Tóth[1,2,3,4] and József Pitrik[4,5,6] — [1]Theoretical Physics and EHU Quantum Center, University of the Basque Country UPV/EHU, ES-48080 Bilbao, Spain — [2]Donostia International Physics Center (DIPC), ES-20080 San Sebastián, Spain — [3]IKERBASQUE, Basque Foundation for Science, ES-48011 Bilbao, Spain — [4]Wigner Research Centre for Physics, HU-1525 Budapest, Hungary — [5]Alfréd Rényi Institute of Mathematics, HU-1053 Budapest, Hungary — [6]Department of Analysis, Institute of Mathematics, Budapest University of Technology and Economics, HU-1111 Budapest, Hungary

We define the quantum Wasserstein distance such that the optimization of the coupling is carried out over bipartite separable states rather than bipartite quantum states in general, and examine its properties. Surprisingly, we find that the self-distance is related to the quantum Fisher information. We present a transport map corresponding to an optimal bipartite separable state. We discuss how the quantum Wasserstein distance introduced is connected to criteria detecting quantum entanglement. We define variance-like quantities that can be obtained from the quantum Wasserstein distance by replacing the minimization over quantum states by a maximization. Besides separable states, we consider other relevant subsets of physical quantum states. We extend our results to a family of generalized quantum Fisher information quantities.

[1] G. Tóth and J. Pitrik, Quantum 7, 1143 (2023); arXiv:2209.09925.

## QI 30: Members' Assembly

Time: Thursday 18:00–19:00 Location: HFT-TA 441

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

# QI 31: Decoherence and Open Quantum Systems

Time: Friday 9:30–12:30 Location: HFT-FT 101

QI 31.1 Fri 9:30 HFT-FT 101

**Do Quantum Dynamics Admit Dynamic Kraus Operators?** — •Frederik vom Ende — Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany

We tackle the - curiously, still open - question of whether any quantum dynamics admit dynamic Kraus operators that are continuous in time. Our contribution is a result which states that all Lipschitz-continuous dynamics can be approximated arbitrarily well using analytic Kraus operators; equivalently, the partial trace over analytic paths of unitaries can approximate all quantum dynamics. This generalizes a recent result stating that analytic quantum dynamics can be represented exactly as the reduction of unitary dynamics generated by a time-dependent Hamiltonian. This talk is based on arXiv:2306.03667

QI 31.2 Fri 9:45 HFT-FT 101

**Wave-particle correlations in multiphoton resonances of coherent light-matter interaction** — •Themistoklis Mavrogordatos — ICFO - The Institute of Photonic Sciences, Castelldefels (Barcelona), Spain

We discuss the conditional measurement of field amplitudes by a nonclassical photon sequence in the Jaynes-Cummings (JC) model under multiphoton operation. We do so by employing a correlator of immediate experimental relevance to reveal a distinct quantum evolution in the spirit of [G. T. Foster *et al.*, Phys. Rev. Lett. **85**, 3149 (2000)], relying on the complementary nature of the pictures obtained from different unravelings of the JC master equation. We demonstrate that direct photodetection entails a conditioned separation of timescales, a quantum beat and a semiclassical oscillation, produced by the coherent light-matter interaction in its strong-coupling limit. We single the quantum beat out in the analytical expression for the waiting-time distribution, pertaining to the particle nature of the scattered light, and find a negative spectrum of quadrature amplitude squeezing, characteristic of its wave nature. Finally, we jointly detect the dual aspects of the emitted radiation via the wave-particle correlator, showing an asymmetric regression of fluctuations to the steady state which depends on the quadrature amplitude being measured. The individual realizations thus obtained allow the experimenter to access the distribution and statistics of the light field in a regime where photon blockade persists [H. J. Carmichael, Phys. Rev. X. **5**, 031028 (2015)].

QI 31.3 Fri 10:00 HFT-FT 101

**Synchronization of Cascaded Quantum Oscillators** — •Florian Höhe[1], Johannes Richter[1], Lukas Danner[1,2], Ciprian Padurariu[1], Björn Kubala[1,2], and Joachim Ankerhold[1] — [1]ICQ and IQST, Ulm University, Ulm, Germany — [2]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany

Systems performing self-oscillations occur both in natural and engineered systems. The nonlinearity of these oscillators yields limit cycle with stable amplitude but free phase, allowing them synchronize their frequency and phase to other oscillators. Synchronization of quantum self-sustained oscillators, realizable in experiments on trapped ions or superconducting circuits, has been explored in two geometries: First, injecting a classical signal lets the quantum oscillator adjust its dynamics to the signal and can compensate for the diffusive effects of quantum noise. On the other hand, one can couple two or more quantum oscillators symmetrically which then collectively synchronize to a single frequency.

In this work we want to investigate an alternative geometry: We keep the asymmetry of injection locking but replace the classical source by a quantum oscillator, by feeding the emission of one quantum oscillator into the other one. We model the quantum oscillators by van der Pol oscillators and use the input-output formalism yielding a description of the full system in terms of a master-equation. Numerical simulations of the system show one sided frequency pulling, synchronization in the relative phase and correlations in the quantum noise.

QI 31.4 Fri 10:15 HFT-FT 101

**Systematic coarse-graining of environments for the non-perturbative simulation of open quantum systems** — •Nicola Lorenzoni[1], Namgee Cho[1], James Lim[1], Dario Tamascelli[1,2], Susana F. Huelga[1], and Martin B. Plenio[1] — [1]Institut für Theoretische Physik und IQST, Albert-Einstein-Allee 11, Universität Ulm, D-89081 Ulm, Germany — [2]Dipartimento di Fisica "Aldo Pontremoli", Università degli Studi di Milano, Via Celoria 16, 20133 Milano-Italy

Conducting precise electronic-vibrational dynamics simulations of molecular systems poses significant challenges when dealing with an environment composed of numerous vibrational modes. Here, we introduce novel techniques for the construction of effective phonon spectral densities that capture accurately open system dynamics over a finite time interval of interest. When combined with existing non-perturbative simulation tools, our approach can reduce significantly the computational costs associated with many-body open system dynamics.

QI 31.5 Fri 10:30 HFT-FT 101

**Minimising entanglement in tensor-network quantum trajectories** — •Tatiana Vovk[1,2] and Hannes Pichler[1,2] — [1]Institute for Quantum Optics and Quantum Information, Innsbruck, Austria — [2]University of Innsbruck, Innsbruck, Austria

We introduce a way to directly leverage noise in trajectory-based stochastic methods to simulate open quantum many-body systems. Our key proposition revolves around the insight that the same system dynamics can be obtained by different stochastic propagators, which give distinct ensembles of pure-state trajectories. Specifically, we introduce an adaptive optimisation strategy for selecting the stochastic propagator with the objective of minimising the entanglement, which serves as a proxy of the expected cost of classically representing various trajectories. The physical mechanism underlying this idea is reminiscent of the phenomenon of measurement-induced phase transitions. We complement our discussion with explicit examples of one-dimensional open quantum dynamics, demonstrating that optimised trajectory-based methods employing matrix product states (MPSs) can yield an exponential reduction in classical computational cost compared to other MPS-trajectory-based methods or compared to conventional matrix product density operator technique. We note that our findings are interesting also from a fundamental quantum-information-theoretic perspective, since they give rise to heuristic algorithms for finding upper bounds on mixed-state entanglement measures, such as the entanglement of formation, a task that holds an independent and intrinsic interest.

QI 31.6 Fri 10:45 HFT-FT 101

**Schrieffer-Wolff transformation for non-Hermitian systems** — •Grigory A. Starkov[1], Mikhail V. Fistul[2], and Ilya M. Eremin[2] — [1]Theoretische Physik IV, Universität Würzburg, Würzburg, Germany — [2]Institut für Theoretische Physik III, Ruhr-Universität Bochum, Bochum, Germany

Non-Hermitian Hamiltonians arise ubiquitously as the effective description of dissipative systems. Their important feature is the presence of the special type of degeneracies called Exceptional Points (EP), where not only the eigenvalues but the corresponding eigenvectors coalesce. The properties of EPs have interesting applications, e.g., for increasing the sensitivity of quantum sensors or for adiabatic state switching.

The structure of EPs of order n is typically studied by employing the effective local n x n Hamiltonian without specifying the means to obtain it. Here, we establish the Schrieffer-Wolff transformation for non-Hermitian systems as a way to systematically derive such effective Hamiltonians in a perturbative manner. We show that under certain conditions the transformation preserves the PT-symmetry or the pseudo-Hermitian symmetry of the original Hamiltonian. Finally, we briefly mention the PT-symmetric circuit QED with two qubits as an example of the application of the approach.

[1] G. A. Starkov, M. V. Fistul, and I. M. Eremin, arXiv:2309.09829 (2023).

[2] G. A. Starkov, M. V. Fistul, and I. M. Eremin, Phys. Rev. A 108, 022206 (2023).

**15 min. break**

QI 31.7 Fri 11:15 HFT-FT 101

**Developing efficient open quantum systems methods for time-dependent Hamiltonians** — •Steffen Wilksen, Frederik Lo-

hof, and Christopher Gies — Institute for Theoretical Physics, University of Bremen, Bremen, Germany

In various quantum technological applications, the fidelity of quantum gates realized by switching operations is fundamentally limited by both the switching speed and the energy separation of the corresponding states, as stated by the adiabatic theorem. While analytic solutions exist for simplified, isolated systems, like the Landau-Zener problem, various open-quantum-system methods need to be employed to investigate the effects of dissipation and dephasing to enable quantitative predictions. The purpose of this talk is to review established methods from open quantum systems and discuss their applicability and limitations in the context of quantum technology applications. The Landau-Zener problem will be extended to coupling to an external reservoir using a modified Bloch-Redfield approach. We compare this to numerically exact treatments and discuss the role of the Born-Markov approximation in the context of quantum repeater protocol simulations.

QI 31.8 Fri 11:30 HFT-FT 101

**Fast and robust cat state preparation utilizing higher order nonlinearities** — •Suocheng Zhao[1,2], Matthias Krauss[2], Tom Bienaimé[3], Shannon Whitlock[3], Christiane Koch[2,4], Sofia Qvarfort[5], and Anja Metelmann[6,1,3] — [1]IQMT, KIT, Eggenstein-Leopoldshafen, Germany — [2]Freie Universität, Berlin, Germany — [3]ISIS, University of Strasbourg and CNRS — [4]Dahlem Center for Complex Quantum Systems and Fachbereich Physik — [5]Nordita and Department of Physics, KTH Royal Institute of Technology and Stockholm University, Stockholm, Sweden — [6]TKM, KIT, Karlsruhe, Germany

Cat states are a valuable resource for quantum metrology applications, promising to enable sensitivity down to the Heisenberg limit. Moreover, Schrödinger cat states, based on a coherent superposition of coherent states, show robustness against phase-flip errors making them a promising candidate for bosonic quantum codes. Despite its applications, cat states are difficult to generate. A coherent state can evolve into a cat state under a single Kerr-type anharmonicity as found in superconducting devices as well as Rydberg atoms. Such platforms nevertheless exhibit only the second order anharmonicity, which limits the time it takes for a cat state to be prepared. In this talk, we will show how proper tuning of higher order nonlinearities leads to shorter cat preparation time. We will also discuss practical aspects including optimal control schemes and ways to mitigate decoherence. Lastly, we propose an ensemble of Rydberg atoms that exhibits higher order nonlinearities as a platform to prepare cat states in the laboratory.

QI 31.9 Fri 11:45 HFT-FT 101

**The role of nonsecular terms in vibrational polaritons** — •R. Kevin Kessing, Marcos S. Tacca, James Lim, Susana F. Huelga, and Martin B. Plenio — Institut für Theoretische Physik und IQST, Albert-Einstein-Allee 11, Universität Ulm, D-89081 Ulm, Germany

In what is commonly known as the rotating-wave approximation, the nonsecular terms $a^\dagger b^\dagger + ab$ are often disregarded in the theoretical modeling of strongly coupled light-matter systems. Part of the justification for this process is that these terms, when considered individually, appear to be "non-energy-conserving". Though this is often an acceptable approximation, depending on the system setup, it may lead to qualitatively incorrect predictions. We investigate the contribution of such nonsecular terms to polariton physics on both the intra-system level (e.g., comparing Rabi/Dicke vs. Jaynes–Cummings/Tavis–Cummings models) as well as on the system-environment level (e.g., GKSL vs. Redfield equations).

QI 31.10 Fri 12:00 HFT-FT 101

**Telling different unravelings apart via nonlinear quantum-trajectory averages** — Eloy Piñol[1], Themistoklis K. Mavrogordatos[1], Dustin Keys[2], •Romain Veyron[1], Piotr Sierant[1], Miguel Angel García-March[3], Samuele Grandi[1], Morgan W. Mitchell[1,4], Jan Wehr[2], and Maciej Lewenstein[1,4] — [1]ICFO – Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain — [2]Department of Mathematics, The University of Arizona Tucson, AZ 85721-0089 USA — [3]Instituto Universitario de Matemática Pura y Aplicada, Universitat Politècnica de València, Camino de Vera, s/n, 46022 Valencia, Spain — [4]ICREA – Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain

We propose a way to experimentally distinguish different unravelings of the Gorini-Kossakowski-Sudarshan-Lindblad master equation appealing to stochastic conditional dynamics via quantum trajectories. Our proposal is based on performing a nonlinear operation on single-trajectory quantum mechanical averages and subsequently averaging over all different realizations comprising the ensemble. We focus on the paradigmatic quantum nonlinear system of resonance fluorescence for the two most popular unravelings: the Poisson-type, corresponding to direct detection of the photons scattered from the two-level emitter, and the Wiener-type, revealing complementary attributes of the scattered field such as the wave amplitude and the spectrum. Our proposal is tested against commonly met limitations in current experimental setups.

QI 31.11 Fri 12:15 HFT-FT 101

**Multi-photon realization of open quantum systems in integrated waveguide arrays** — •Sholeh Razavian[1,2,3], Jasmin Meinecke[1,2,4], and Harald Weinfurter[1,2,3] — [1]Department fur Physik, Ludwig-Maximilians-Universitat, Munich, Germany — [2]Max-Planck-Institute for quantum optics, Garching, Germany — [3]Munich Center for Quantum Science and Technology, München, Germany — [4]Institut für Festkörperphysik, Technische Universität Berlin, Germany

It is important to thoroughly examine the interaction between a quantum system and its surroundings, as understanding the stability of such systems will foster their applicability for extending previous studies toward the investigation of decoherence in multi-party quantum systems. Evanescently coupled, photonic waveguides with birefringent properties turned out to enable the simulation of open quantum systems and decoherence effects.

A quantum simulation of single and two-photon coupling to a low dimensional discrete environment by sending into the arrays of waveguides on a chip has been studied. This allows us to explicitly observe the amount of information stored in the polarization degrees of freedom as a system and the path degrees of freedom as an environment. This interaction creates quantum correlation at various times during non-Markovian evolution and causes polarization decoherence along the waveguide arrays.

# QI 32: Quantum Sensing and Metrology

Time: Friday 9:30–13:30 Location: HFT-FT 131

**Invited Talk** QI 32.1 Fri 9:30 HFT-FT 131
**Quantum levitodynamics: Harnessing quantum motion of levitated particles for fundamental and applied quantum research** — •Sungkun Hong — Institute for Functional Matter and Quantum Technologies, University of Stuttgart, 70569 Stuttgart — Center for Integrated Quantum Science and Technology (IQST), University of Stuttgart, 70569 Stuttgart, Germany

Quantum levitodynamics is a thriving new field in quantum science that aims to control the quantum motion of micro- and nanoparticles levitated, for example, in optical traps. In recent years, researchers have made rapid progress in achieving quantum control of optically levitated dielectric nanoparticles. This progress opens up exciting possibilities for the development of new quantum technologies and for testing quantum physics beyond the microscopic world. In this talk, I will give a brief overview of the field and discuss my group's research activities, in particular, our efforts to develop a novel nanophotonic platform for levitodynamics with ultrastrong quantum cooperativity.

QI 32.2 Fri 10:00 HFT-FT 131
**Squeezed Superradiance Enables Robust Entanglement-Enhanced Metrology Even with Highly Imperfect Readout** — •Martin Koppenhöfer[1,3], Peter Groszkowski[1,2], and Aashish A. Clerk[1] — [1]Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637, USA — [2]National Center for Computational Sciences, Oak Ridge National Laboratory, Tennessee 37831, USA — [3]Fraunhofer-Institut für Angewandte Festkörperphysik IAF, Tullastraße 72, 79108 Freiburg, Deutschland

Quantum metrology protocols using entangled states of large spin ensembles attempt to achieve measurement sensitivities surpassing the standard quantum limit (SQL), but in many cases they are severely limited by even small amounts of technical noise associated with imperfect sensor readout. Amplification strategies based on time-reversed coherent spin-squeezing dynamics have been devised to mitigate this issue, but are unfortunately very sensitive to dissipation, requiring a large single-spin cooperativity to be effective. Here, we propose a new dissipative protocol that combines amplification and squeezed fluctuations. It enables the use of entangled spin states for sensing well beyond the SQL even in the presence of significant readout noise. Further, it has a strong resilience against undesired single-spin dissipation, requiring only a large collective cooperativity to be effective.

QI 32.3 Fri 10:15 HFT-FT 131
**Ennhanced Raman Scattering with squeezed states of light** — •Shahram Panahiyan[1,2] and Frank Schlawin[1,2] — [1]Max Planck Institute for the Structure and Dynamics of Matter, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

Quantum sources of light are unique tools in metrology enabling pushing the limitations of the utilization of the classical light fields [1]. In our theoretical studies, we employ the squeezed state of light to improve the precision of multiphoton absorption [2,3] and stimulated Raman measurements. We derive bounds on the sensitivity that can be obtained for such measurements and propose optimal experimental setups. We compare our results with measurements using classical light and highlight the advantages of quantum light in nonlinear spectroscopy and imaging.

[1] M. Barbieri, PRX Quantum 3, 010202 (2022). [2] S. Panahiyan et al., Phys. Rev. Lett. 130, 203604 (2023). [3] S. Panahiyan et al., Phys. Rev. A 106, 043706 (2023).

QI 32.4 Fri 10:30 HFT-FT 131
**Achieving heisenberg scaling via interacting many body dynamics** — •Ricard Puig i Valls[1], Paolo Andrea Erdman[2], Pavel Sekatski[3], Paolo Abiuso[4], John Calsamiglia[5], and Martí Perarnau-Llobet[3] — [1]EPFL, Lausanne, Switzerland — [2]FU, Berlin, Germany — [3]UNIGE, Geneva, Switzerland — [4]IQOQI, Vienna, Austria — [5]GIQ, Barcelona, Spain

Theoretical models describing quantum metrology schemes and the corresponding experimental demonstrations have so far mainly described protocols that involve the preparation of the sensor into a carefully engineered quantum state; interaction of the sensor with an external (unknown) field and measurement of the sensor to retrieve information. However, the process of preparation can sometimes be lengthy, require fine tuning and be sensible to noise. The main goal of this project is to use many-body interactions to entangle the state while the field encodes information into it. Thus, we eliminate the preparation process and we add some dynamics that might counter the noise effect.

In this setting, we consider the estimation of a magnetic field by N spins whose interactions can be externally controlled. We derive an analytic expression for the Quantum Fisher Information and we show an idealized protocol that achieves Heisenberg Scaling via a N-body interaction. We achieve a quantum advantage by using 2-body interactions (numerically we can approach HS) and show that measuring the spin of the probe state suffices to saturate the QFI. Finally, preliminary results show that the noise resilience might be higher.

QI 32.5 Fri 10:45 HFT-FT 131
**Activation of metrologically useful genuine multipartite entanglement** — •Róbert Trényi[1,2,3], Árpád Lukács[1,4,3], Paweł Horodecki[5,6], Ryszard Horodecki[5], Tamás Vértesi[7], and Géza Tóth[1,2,8,3] — [1]Dept. of Th. Phys., UPV, Bilbao, Spain — [2]DIPC, San Sebastián, Spain — [3]Wigner RCP, Budapest, Hungary — [4]Dept. of Math. Sci., Durh. Univ., UK — [5]Int. Cnt. for Theory of Quant. Tech., UG, Gdansk, Poland — [6]Fac. of Appl. Phys. and Math., Nat. Quant. Inf. Cnt., GUT, Gdansk, Poland — [7]Inst. for Nucl. Research, Debrecen, Hungary — [8]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. Moreover, the maximal metrological usefulness is reached exponentially fast with the number of copies and the necessary measurements are just simple correlation observables. We also provide examples of states not living in the above mentioned class that improve their usefulness. Our scheme can also be used to protect certain quantum states against certain types of errors without the use of full-fledged quantum error correction techniques.

**15 min. break**

QI 32.6 Fri 11:15 HFT-FT 131
**Quantum metrology in the finite-sample regime** — •Johannes Jakob Meyer[1], Sumeet Khatri[1], Daniel Stilck França[1,2,3], Jens Eisert[1,4,5], and Philippe Faist[1] — [1]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Berlin, Germany — [2]Department of Mathematical Sciences, University of Copenhagen, Copenhagen, Denmark — [3]Ecole Normale Superieure de Lyon, Lyon, France — [4]Helmholtz-Zentrum für Materialien und Energie, Berlin, Germany — [5]Fraunhofer Heinrich Hertz Institut, Berlin, Germany

In quantum metrology, the ultimate precision of estimating an unknown parameter is often stated in terms of the Cramér-Rao bound. Yet, the latter is no longer guaranteed to carry operational meaning in the regime of few measurement samples. We instead propose to quantify the quality of a metrology protocol by the probability of obtaining an estimate with a given accuracy. This approach, which we refer to as probably approximately correct (PAC) metrology, ensures operational significance in the finite-sample regime. The accuracy guarantees hold for any value of the unknown parameter, unlike the Cramér-Rao bound which assumes it is approximately known. We establish a strong connection to multi-hypothesis testing with quantum states, which allows us to derive an analogue of the Cramér-Rao bound which contains explicit corrections relevant to the finite-sample regime and apply our framework to phase estimation with an ensemble of spin-1/2 particles. Our operational approach allows the study of quantum metrology in the finite-sample regime and opens up new avenues for research at the interface of quantum information theory and quantum metrology.

QI 32.7 Fri 11:30 HFT-FT 131
**Magnetometry with Driven Spin Systems** — •Dhruv Desh-

mukh and Joachim Ankerhold — Institute for complex quantum systems, Ulm University, Germany

The dynamics of time-dependent two-level system is a well addressed problem in quantum physics that has spurred the development of many novel techniques and technologies due to its widespread applicability. Here, we focus on the problem of a two-level system driven linearly over the entire parameter space of amplitude and frequency of the classical drive. This problem does not have analytical solutions and has only been solved approximately, near resonance for a weak drive and, for high-frequency drives. Employing Floquet formalism, we have found special manifolds on the parameter space for which the entire Bloch Sphere exhibits period multiplicity. This treatment allows for a deeper understanding of the approximate solutions obtained before.

Understanding the Floquet dynamics has proved to be vital for applications in magnetometry. We found that setting drive parameters at the quasi-energy crossing manifolds in the parameter space, yields the highest quantum fisher information (QFI) for magnetic field oriented parallel to the drive. The Floquet dynamics of periodically driven multi-spin clusters, and spin-chains, were also investigated. In regard to magnetometry, we found (for some simple cases) that the QFI scales linearly with the number of spins (Heisenberg scaling) for suitable parameter choices.

QI 32.8 Fri 11:45 HFT-FT 131

**Quantum sensing of RF signals with spin defects in a 2D material** — •Roberto Rizzato[1,2], Martin Schalk[2,3], Stephan Mohr[1], Jens Hermann[1,2], Joachim Leibold[1], Fleming Bruckmaier[1], Giovanna Salvitti[1], Chenjiang Qian[3], Peirui Ji[3], Georgy Astakhov[4], Ulrich Kentsch[4], Manfred Helm[4], Andreas Stier[2,3], Jonathan Finley[2,3], and Dominik Bucher[1,2] — [1]Technical University of Munich, TUM School of Natural Sciences, Department of Chemistry, 85748 Garching, Germany. — [2]Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany. — [3]Technical University of Munich, Walter Schottky Institut, 85748 Garching, Germany — [4]Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, Bautzner Landstraße 400, Dresden, 01328, Germany

Negatively-charged Boron Vacancy centers (VB-) in hexagonal Boron Nitride (hBN) are attracting increasing interest since they represent optically-addressable qubits in a 2D material. In particular, these spin defects have shown promise as sensors for temperature, pressure, and static magnetic fields. However, their short spin coherence time limits their scope for quantum technology. Here, we apply dynamical decoupling techniques to suppress magnetic noise and extend the spin coherence time by two orders of magnitude, approaching the fundamental T1 relaxation limit. Based on this, we demonstrate a set of quantum sensing protocols to detect RF signals with sub-Hz resolution. This work opens a promising path to the development of quantum technology integrated into ultra-thin structures.

QI 32.9 Fri 12:00 HFT-FT 131

**Optimal Control for Quantum Technology with NV-Centers in Diamond** — •Matthias Müller — Forschungszentrum Jülich GmbH, Institute for Quantum Control (PGI-8)

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.

[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] A. Marshall et al., Phys. Rev. Res. 4, 043179 (2022)

QI 32.10 Fri 12:15 HFT-FT 131

**Toward probing thin films with quantum sensors in diamonds** — •Martin Wanckel[1,2,3], Verena Streibel[2,3], Fabian Freire[1], Ian D. Sharp[2,3], and Dominik Bucher[1] — [1]Department of Chemistry ,TUM School of Natural Sciences, Technische Universität München, 85748, Garching, Germany — [2]Walter Schottky Institute, Am Coulombwall 4, 85748, Garching, Germany — [3]Department of Physics,TUM School of Natural Sciences, Technische Universität München, 85748, Garching, Germany

Nuclear magnetic resonance (NMR), one of the most powerful analytical techniques in chemistry and the life sciences, is typically limited to macroscopic volumes due to its inherently low sensitivity. This limitation excludes NMR spectroscopy from the analysis of planar surfaces or interfaces. In recent years, it has been shown that NMR signals can be detected from nanoscale volumes by a new sensor class - quantum sensors based on defects in the diamond lattice - nitrogen-vacancy (NV) centers [1]. In this contribution, we will present our recent results, where we used an ensemble of NV centers to detect the NMR signal of a self-assembled monolayer on an aluminum oxide layer. This discussion includes the detection of spatially resolved NMR signals and the monitoring of the layer formation in real-time at the solid-liquid interface. In the outlook, we will discuss possible further applications, such as probing thin film materials in catalysis and energy science. Reference: 1.Liu, Kristina S., et al. Surface NMR using quantum sensors in diamond. PNAS 2022 Vol. 119 No. 5 e2111607119.

QI 32.11 Fri 12:30 HFT-FT 131

**Investigation of exotic phases in low-dimensional systems using nanoscale NMR with NV centres in diamond** — •Marcel Martin[1], Yash Nitin Palan[2], Falko Pientka[2], and Nabeel Aslam[1] — [1]Felix-Bloch-Institut für Festkörperphysik, Universität Leipzig — [2]Institut für Theoretische Physik, Goethe-Universität Frankfurt am Main

Understanding exotic phases of matter such as unconventional superconductors, quantum spin liquids and topological insulators promises a deeper understanding of fundamental physics or even a new approach to technological challenges of our time. Especially in low dimensional systems, strong quantum effects can promote the occurrence of such phases. Conventional nuclear magnetic resonance (NMR) has proven to be a reliable and powerful method in the study of many such exotic phases in different materials but is limited to bulk samples.

Here, we present the novel approach of applying nanoscale NMR to low-dimensional solids and surfaces. Using nitrogen vacancy (NV) centres in diamond as local probes, we harness their ability to detect an NMR signal from thin layers even down to a single monolayer as well as from surfaces of bulk materials. This opens the door to the investigation of exotic phases in truly low-dimensional systems using NMR. In this talk, we will show first calculations for the study of induced superconductivity in one- and two-dimensional semiconductors. Other material classes of interest will also be discussed.

QI 32.12 Fri 12:45 HFT-FT 131

**Measuring nuclear spin qubits by qudit-based spectroscopy in Silicon Carbide** — •Erik Hesselmeier[1], Pierre Kuna[1], Istvan Takacs[2], Viktor Ivady[2,4], Wolfgang Knolle[3], Nguyen Tien Son[4], Misagh Ghezellou[4], Jawad Ul-Hassan[4], Durga Dasari[1], Florian Kaiser[5], Vadim Vorobyov[1], and Jörg Wrachtrup[1] — [1]3rd Institute of Physics, University of Stuttgart, Stuttgart, Germany — [2]Eötvös Loránd , Egyetem tér 1University-3, H-1053 Budapest, Hungary — [3]Department of Sensoric Surfaces and Functional Interfaces, Leibniz-Institute of Surface Engineering (IOM), Leipzig, Germany — [4]Department of Physics, Chemistry and Biology, Linköping University, Linköping, Sweden — [5]Materials Research and Technology (MRT) Department, LIST, 4422 Belvaux, Luxembourg

Nuclear spins with hyperfine coupling to single electron spins are highly valuable quantum bits. In this work [1] we probe and characterise the particularly rich nuclear spin environment around single silicon vacancy color-centers (V2) in 4H-SiC. By using the electron spin-3/2 qudit as a 4 level sensor, we identify several sets of 29Si and 13C nuclear spins through their hyperfine interaction. We extract the major components of their hyperfine coupling via optical detected nuclear resonance, and assign them to shells in the crystal via the DFT simulations. We utilise the ground state level anti-crossing of the electron spin for dynamic nuclear polarization and achieve a nuclear spin polarization of up to 98(6)%. We show that this scheme can be used to detect the nuclear magnetic resonance signal of individual spins and demonstrate their coherent control. [1] Preprint Arxiv: 2310.15557

QI 32.13 Fri 13:00 HFT-FT 131

**Wavelength Dependence of the Electrical and Optical Readout of NV Centers in Diamond** — •Lina Maria Todenhagen[1,2] and Martin S. Brandt[1,2] — [1]Walter Schottky Institut, Technische Universität München, Am Coulombwall 4, 85748 Garching, Germany — [2]Physik-Department, School of Natural Sciences, Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany

The nitrogen-vacancy (NV) center in diamond is one of the most attractive quantum systems used in practical applications, especially for quantum sensing. However, the miniaturization and integration of NV-based quantum technology is still challenging, as the conventional optical spin readout (optically detected magnetic resonance, ODMR) requires an extensive optical setup and is often limited by the inefficient outcoupling of photons. Alternatively, we can read out the spin state purely electrically by generating a spin-dependent photocurrent (electrically detected magnetic resonance, EDMR). To maximize the achievable spin contrast in both readout techniques, we investigate the influence of different optical excitation wavelengths and identify different spectral regimes that drive different excitation processes in both stable charge states of the NV center, $NV^0$ and $NV^-$. While ODMR works efficiently between 480 and 580 nm, we find that EDMR shows an additional strong dependence on the excitation dynamics, and is significantly enhanced by resonantly exciting the zero-phonon line of the NV neutral charge state.

QI 32.14 Fri 13:15 HFT-FT 131

**Gradient Magnetometry with Bose-Einstein Condensates** — •Iagoba Apellaniz[1,2,3] and Géza Tóth[1,2,4,5,6] — [1]Department of Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spain — [2]EHU Quantum Center, University of the Basque Country UPV/EHU, Leioa, Spain — [3]Department of Applied Mathematics, University of the Basque Country UPV/EHU, E-48013 Bilbao, Spain — [4]Donostia International Physics Center (DIPC), P.O. Box 1072, E-20080 San Sebastián, Spain — [5]IKERBASQUE, Basque Foundation for Science, E-48013 Bilbao, Spain — [6]Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary

We study gradient magnetometry with BECs. We obtain the precision bounds for estimating the gradient of the magnetic field based on the quantum Fisher information [1]. For a single BEC the precision bound cannot surpass the so called shot noise limit. On the other hand, if one considers two spatially separated ensembles [2], the Heisenberg scaling can be achieved. We present a method to quantify these precision bounds based on the quantum states.

[1] I. Apellaniz et al., Phys. Rev. A, 97 053603 (2018)
[2] G. Vitagliano et al., Quantum 7, 914 (2023)

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

Time: Friday 9:30–12:00 Location: HFT-TA 441

QI 33.1 Fri 9:30 HFT-TA 441

**Classification of Phases of Matrix Product States with Symmetric Quantum Circuits, and Symmetric Measurements with Feedforward** — •David Gunn[1], Tristan Kraft[1], Georgios Styliaris[2], and Barbara Kraus[1,3] — [1]University of Innsbruck — [2]Max-Planck-Institut für Quantenoptik — [3]Technical University of Munich

We consider how symmetry-preserving measurements with feedforward alter the phase classification of matrix product states (MPS) in the presence of global on-site symmetries. We demonstrate that, for all finite abelian symmetries, by including symmetry-preserving measurements, any two symmetric MPS belong to the same phase. We give an explicit protocol to achieve a transformation between any two phases that uses only a depth-two circuit, two rounds of symmetric measurements, and a constant number of auxiliary systems per site. In the case of non-abelian symmetries, symmetry protection prevents one from deterministically transforming states to product states directly via measurements. Nonetheless, we provide an asymptotically deterministic, symmetry-preserving protocol, using a log-depth circuit and measurements, that demonstrates certain non-abelian, symmetry-protected topological (SPT) phases also trivialize.

QI 33.2 Fri 9:45 HFT-TA 441

**Deterministic generation of qudit photonic graph states from quantum emitters** — •Zahra Raissi[1,2], Edwin Barnes[2], and Sophia E. Economou[2] — [1]Paderborn University, Paderborn, Germany — [2]Virginia Tech, Virginia, USA

We propose and analyze deterministic protocols to generate qudit photonic graph states from quantum emitters. We show that our approach can be applied to generate any qudit graph state, and we exemplify it by constructing protocols to generate one- and two-dimensional qudit cluster states, absolutely maximally entangled states, and logical states of quantum error correcting codes. Some of these protocols make use of time-delayed feedback, while others do not. The only additional resource requirement compared to the qubit case is the ability to control multi-level emitters. These results significantly broaden the range of multi-photon entangled states that can be produced deterministically from quantum emitters and open up new possibilities for quantum information processing.

QI 33.3 Fri 10:00 HFT-TA 441

**Closed-form expressions for graph states** — •Hrachya Zakaryan, Konstantinos Rafail Revis, and Zahra Raissi — Department of Computer Science, Paderborn University, Germany

Two-colorable graphs states are multipartite entangled states, which can be represented by two-coloarble graphs. These are graphs where the vertices can be divided into two disjoint sets, such that no vertices in each set are connected by an edge. These graphs give rise to important graph states such as the cluster and GHZ states, which are vital quantum resources. We consider qudit systems, and therefore examine unweighted and weighted graphs, in two cases: Controlled-Z (CZ) edges and Controlled-Phase (CP) edges. Closed forms for their corresponding Local-Unitary (LU) equivalent states are obtained. Additionally, setups with specific phases and experimental interest, are examined. An extension of the stabilizer formalism to CP based graphs as well as multi-colorable graphs is considered.

QI 33.4 Fri 10:15 HFT-TA 441

**Renormalisation Through The Lens Of Quantum Convolutional Neural Networks** — •Nathan A. McMahon[1], Petr Zapel[2], and Michael J. Hartmann[1] — [1]Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) — [2]University of Basel, Switzerland.

A quantum convolutional neural network (QCNN) can be used to perform quantum phase recognition for the cluster-Ising model. This circuit outputs $+1$ if the input state is in the symmetry protected topological (SPT) phase, called the target phase, and 0 if it is in either of the other phases. This observation has been shown numerically and experimentally, but much less is known analytically. In this talk we first introduce a set of conditions on a QCNN that describes success at the phase recognition task restricted to a subset of possible input quantum states and proceed to show the cluster-Ising QCNN satisfies these conditions via random circuit analysis. When averaged over random circuits, if the QCNN outputs can distinguish between phases, some input states must be non-typical. In contrast, the rate of change of the QCNN outputs with respect to perturbations of the input state also has an operator representation, where all input states we consider are typical and converge to zero with QCNN depth. Since all input states can be generated from a reference state under these perturbations, this explains how the QCNN performs phase recognition and extends to incoherent perturbations.This suggests QCNNs may provide insight in how to extend the corresponding SPT phase to mixed states.

**15 min. break**

QI 33.5 Fri 10:45 HFT-TA 441

**Magnon-magnon quantum entanglement and the phonon effects in antiferromagnetic structure** — •Yuefei Liu[1], Anna Delin[1], Erik Sjöqvist[2], and Olle Eriksson[2] — [1]Department of Applied Physics, School of Engineering Sciences, KTH Royal Institute of Technology, AlbaNova University Center, SE-10691 Stockholm, Sweden — [2]Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden

Quantum correlation, such as entanglement, is a central resource in many quantum information protocols that naturally comes about in any study toward quantum technologies. This applies also to quantum magnonics. First, we investigate antiferromagnets in which sublattices with ferromagnetic interactions can have two different magnon modes, and we show how this may lead to experimentally detectable bipartite continuous variable magnon-magnon entanglement. Our current study and result not only provide original evidence for creation and observation of tunable and robust entangled quantum states of magnons in a wide range of temperature including room temperature, but also expands the magnon applications from spintronics and quantum information processing to biomedical applications. The ability to produce quantum states with tunable and robust entanglement in ambient conditions has significant implications as it would avoid costly cooling procedures, reduce the effect of thermal noise, simplify the experimental setups, and widen the range of quantum applications.

QI 33.6 Fri 11:00 HFT-TA 441

**Measurement induced phase transition with an extended log-law phase in an integrability-broken transverse field Ising model** — •Monalisa Singh Roy, Jonathan Ruhman, Emanuele G. Dalla Torre, and Efrat Shimshoni — Bar-Ilan University, Ramat Gan, 52900 Israel.

Measurement induced entanglement phase transitions in many-body quantum systems are a fundamental obstacle for any quantum computing platform. The unitary dynamics of these many-body systems competes against the localization of the wavefunction due to repeated measurements, resulting in a transition from the quantum entangled (volume-law) phase into a disentangled Zeno-like (area-law) phase at strong measurements, that's unsuitable for further quantum operations. Recently an extended critical phase with a logarithmic scaling of the entanglement entropy has been identified in a class of integrable models with dissipative dynamics. We extend this and study the critical transition in a non-integrable system - a one dimensional transverse field Ising model, in presence of an integrability-breaking field and no-click dissipation. First, we show that the measurement induced transitions in this system is qualitatively different from the trivial volume-law to area-law transition of the entanglement entropy in integrable systems. Then we show how these transitions can be connected via the integrability breaking field. We also identify the same phase transitions from the correlation function exponents and calculation of mutual information in each phase, and present the complete phase diagram for this non-integrable system.

QI 33.7 Fri 11:15 HFT-TA 441

**Visualizing the localized electrons of a kagome flat band** — •Caiyun Chen[1,2], Jiangchang Zheng[1], Ruopeng Yu[1], Soumya Sankar[1], Hoi Chun Po[1], Kam Tuen Law[1], and Berthold Jäck[1] — [1]Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong SAR, China — [2]Institute for Advanced Study, HKUST Jockey Club, Clear Water Bay, Kowloon, Hong Kong SAR, China

Destructive interference between electron wavefunctions on the two-dimensional kagome lattice induces an electronic flat band, which could host a variety of interesting quantum states. Key to realize these proposals is to demonstrate the real space localization of kagome flat band electrons. The extent to which the complex structure of realistic materials counteracts the localizing effect of destructive interference is hitherto unknown. We used scanning tunneling microscopy (STM) to visualize the non-trivial Wannier states of a kagome flat band at the surface of CoSn, a kagome metal. We find that the local density of states associated with the flat bands of CoSn is localized at the kagome lattice center, consistent with theoretical predictions. Our results show that these states exhibit an extremely small localization length of two to three angstroms concomitant with a strongly renormalized quasiparticle velocity, comparable to that of moire superlattices. Our findings provide fundamental insight into the electronic properties of kagome metals and present a key step for future research on emergent many-body states in these systems.

QI 33.8 Fri 11:30 HFT-TA 441

**Entanglement spectrum and multifractality in monitored free fermions in two dimensions** — •Karim Chahine and Michael Buchhold — Institut für Theoretische Physik, Universität zu Köln, D-50937 Cologne, Germany

We investigate the entanglement structure and wave function characteristics of continuously monitored free fermions with $U(1)$-symmetry in 2D. Using exact numerical simulations, we establish the phenomenology of the entanglement transition and explore the similarities and differences with Anderson-type localization transitions. At weak monitoring, we observe characteristic $L \log L$ entanglement growth and multifractal dimension $D_q = 2$, resembling a metallic Fermi liquid. Furthermore, excellent agreement is found with a Wigner-Dyson distribution for the entanglement spectrum statistics. At strong monitoring, exponentially localized wave functions lead to saturation, following an area law for entanglement and a Poissonian distribution for the entanglement spectrum is seen. In between, the critical point exhibits entanglement scaling consistent with emergent conformal invariance and strong multifractality. Furthermore, we numerically reveal a close link between the multifractal exponent $D_q$ and the purification decay rate and find another witness of multifractality in the spectral form factor. Our results shape the understanding of a monitoring-induced metal-to-insulator transition in entanglement content. This establishes 2D monitored fermions as a unique platform to explore the connection between non-unitary quantum dynamics in $D$ dimensions and quantum statistical mechanics in $D+1$ dimensions.

QI 33.9 Fri 11:45 HFT-TA 441

**Orbital and electronic entanglement in quantum teleportation schemes** — •Anna Galler[1,2] and Patrik Thunström[3] — [1]Graz University of Technology, 8010 Graz, Austria — [2]Max Planck Institute for the Structure and Dynamics of Matter, 22761 Hamburg, Germany — [3]Uppsala University, 75120 Uppsala, Sweden

With progress towards more compact quantum computing architectures, fundamental questions regarding the entanglement of indistinguishable particles need to be addressed. In a solid state device, this quest is naturally connected to the quantum correlations of electrons. In this talk, I analyse the formation of orbital (mode) and particle entanglement in strongly correlated materials due to the Coulomb interaction between the electrons. To study the role of the different forms of electronic entanglement, I propose and analyse three different electronic teleportation schemes: quantum teleportation within a molecule on graphene, a nitrogen-vacancy center, and a quantum dot array.

[Galler and Thunström, Phys. Rev. Res. 3, 033120 (2021)]