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 Josepshon 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).