QI 1: Implementations: Spin Qubits, Atoms, and Photons

Time: Monday 9:30–12:45 Location: H8

Invited Talk QI 1.1 Mon 9:30 H8

Coherence of spin qubits in planar germanium — •Nico Willem Hendrickx — IBM Research Zurich, Switzerland

The prospect of building quantum circuits using advanced semiconductor manufacturing techniques position quantum dots as an attractive platform for quantum information processing. Initial demonstrations of one and two-qubit logic have been performed in gallium arsenide and later silicon. However, until recently, interconnecting larger spin qubit systems has remained a challenge.

Over the past years, hole states in strained germanium quantum wells have emerged as a host for spin qubits. These states have favourable properties for defining extended spin qubit arrays. The small effective mass relaxes constraints on lithography, the low degree of disorder enables reproducible quantum dots, the lack of a valley degeneracy ensures an well-defined qubit state and the strong spin-orbit coupling allows for local and electrical qubit control.

Over the past years, this platform has rapidly evolved from materials growth to supporting multi-qubit logic. I will first give an overview of the development of this system, starting from material growth to recent results on operating a highly-connected two-dimensional qubit array. Next, we will discuss the impact of noise on the qubit coherence, as well as strategies to mitigate this. We study the magnetic field dependence of various qubit properties in order to find sweet spots for operation. Finally, we will discuss strategies, challenges, and opportunities in scaling these systems up as a step towards the realisation of scalable qubit tiles for fault-tolerant quantum processors.

QI 1.2 Mon 10:00 H8

Spin relaxation times of single-electrons in bilayer graphene quantum dots — •Katrin Hecker[1,2], Luca Banszerus[1,2], Samuel Möller[1,2], Eike Icking[1,2], Kenji Watanabe[3], Takashi Taniguchi[3], Christian Volk[1,2], and Christoph Stampfer[1,2] — [1]2nd Institute of Physics, RWTH Aachen University, Germany — [2]Peter Grünberg Institute (PGI-9), Forschungszentrum Jülich, Germany — [3]National Institute for Materials Science, Japan

Thanks to its weak spin-orbit coupling and low nuclear spin density, bilayer graphene (BLG) promises long spin relaxation and coherence times, making this material a potentially interesting platform for spin based solid state quantum computation. Although the electrostatic confinement of single electrons in BLG quantum dot (QD) devices has been demonstrated, and their single particle spectrum has been studied in detail [1], their relaxation dynamics remain so far mostly unexplored [2]. Here, we report on measurements of the spin relaxation times (T1) of single-electron spin states in a BLG QD. Using pulsed gate spectroscopy, we extract T1 times exceeding 0.2ms at out-of-plane magnetic fields below 2T. The measured values for T1 show a strong dependence on the spin splitting and increase by about two orders of magnitude when decreasing the magnetic field from 2-3T, suggesting that T1 could be significantly larger at low magnetic fields [3].

[1] A. Kurzmann et al., Phys. Rev. Lett. 123, 026803 (2019).
[2] L. Banszerus et al., Phys. Rev. B 103, L081404 (2021).
[3] L. Banszerus et al., arXiv 2110.13051 (2021).

QI 1.3 Mon 10:15 H8

Microwave spectroscopy of rare earth spin ensembles at zero magnetic field — •Ana Strinic[1,2], Kirill G. Fedorov[1,2], Rudolf Gross[1,2,3], and Nadezhda Kukharchyk[1,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [2]Physik-Department, Technische Universität München, Garching, Germany — [3]Munich Center for Quantum Science and Technologies, Munich, Germany

Operating at microwave frequencies and in the absence of external magnetic fields, superconducting circuits show exceptional potential for the development of quantum processors. Realizing a quantum memory, which operates in the microwave regime and in the vicinity of zero magnetic field, would allow for a direct interface to such quantum processors. In this regard, rare earth doped crystals are highly attractive, as they exhibit long optical and spin coherence times and possess transitions in the microwave frequency range [1,2]. In order to identify transitions, which form a suitable quantum memory scheme, we have performed microwave spectroscopy on a ^{167}Er:^{7}LiYF$_4$ crystal in a magnetically shielded environment. The experimental findings of the spectroscopy study are then compared to simulations of the spin Hamiltonian. [1] N. Kukharchyk et al. New J. Phys. **20**, 023044 (2018) [2] J.V. Rakonjac et al. Phys. Rev. B **101**, 184430 (2020)

QI 1.4 Mon 10:30 H8

Nuclear Spin Quantum Memory in Silicon Carbide — •Benedikt Tissot[1], Michael Trupke[2,3], Philipp Koller[2], Thomas Astner[2], and Guido Burkard[1] — [1]Department of Physics, University of Konstanz, D-78457 Konstanz, Germany — [2]Faculty of Physics, University of Vienna, Boltzmanngasse 5, 1090 Vienna, Austria — [3]Institute for Quantum Optics and Quantum Information (IQOQI) Vienna, Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria

Transition metal (TM) defects in silicon carbide (SiC) are a promising platform for applications in quantum technology. Some TM defects, e.g. vanadium, emit in one of the telecom bands, but the large ground state hyperfine manifold poses a problem for applications which require pure quantum states. We develop a driven, dissipative protocol to polarize the nuclear spin, based on a rigorous theoretical model of the defect. We further show that nuclear-spin polarization enables the use of well-known methods for initialization and long-time coherent storage of quantum states. The proposed nuclear-spin preparation protocol thus marks the first step towards an all-optically controlled integrated platform for quantum technology with TM defects in SiC.

QI 1.5 Mon 10:45 H8

Cavity-mediated quantum gates between driven remote spin qubits — •Florian Kayatz, Jonas Mielke, and Guido Burkard — University of Konstanz, Konstanz D-78457, Germany

The implementation of two-qubit gates between distant qubits is of fundamental importance for quantum computing architectures involving many qubits. Considering cold ions confined in a linear trap, the Cirac-Zoller gate (CZ-gate) [1,2] constitutes such a two-qubit gate by exploiting the coupling of the ions through the collective quantized ion motion.

Here, we theoretically demonstrate a CZ-like gate between two spin qubits realized in gate defined semiconductor double quantum dots. In the envisioned system both spin qubits are coupled to a microwave resonator mode that has a similar function as the collective ion motion in the original CZ-gate. Recently, strong spin-photon coupling has been demonstrated [3] and, thus, allows for coherent population exchange between the spin qubit and the resonator mode. Thereby, two of the three main steps in the CZ-gate protocol can be realized. We describe in detail how the remaining step that requires the generation of a phase depending on the state of the second qubit and the resonator photon number can be implemented by driving the second DQD-system.

[1] Cirac, J. I. and Zoller, P., PRL **74**, 4091 (1995)
[2] Schmidt-Kaler et al., Nature **422**, 408-411 (2003)
[3] Mi et al., Nature **555**, 7698 (2018)

15 min. break

QI 1.6 Mon 11:15 H8

Coherence improvements at a higher-order sweet spot in double quantum dots — •Morten I. K. Munk[1,2], Martin Leijnse[1], and Peter Samuelsson[2] — [1]NanoLund and Division of Solid State Physics, Lund University, Lund, Sweden — [2]NanoLund and Division of Mathematical Physics, Lund University, Lund, Sweden

One of the main limiting factors for designing a useful qubit is its dephasing time. In order to improve this, qubits are often operated at optimal points, or so-called "sweet spots", but in recent years, several systems have been proposed which can be tuned to higher-order sweet spots. These qubits often fail in practice, due for example to coupling to leakage states or a lack of protection against other relevant noise sources. In this work we propose a straightforward way of achieving a third-order sweet spot in a double quantum dot with two electrons in the singlet sector. This experimentally feasible qubit has the combined advantages of being operated at strong tunneling strengths, where leakage states are well separated from the qubit states, as well as being possible to construct in a way in which there are no relevant unprotected noise channels. We investigate the decoherence rate due to pure dephasing for a broad range of system parameters and for different noise spectral densities. It is found, in general, that higher-order sweet spots allow for substantially increased dephasing times, suggesting a guiding principle in optimizing the coherence properties of charge qubits in double quantum dots and related systems.

QI 1.7 Mon 11:30 H8

Quantum-optical Characterization of Single-photon Sources based on Chlorine-doped ZnSe/ZnMgSe Nanopillars — •Christine Falter, Yurii Kutovyi, Nils von den Driesch, Thorsten Brazda, Detlev Grützmacher, and Alexander Pawlis — Peter Grünberg Institute PGI-9, Forschungszentrum Jülich GmbH

The realization of optical quantum computers and secure quantum communication networks requires the development of efficient and scalable sources of single, indistinguishable photons that can be integrated onto photonic chips. Here we report on a novel type of single-photon source (SPS) device based on individual Cl donors in ZnSe/ZnMgSe quantum well nanopillars. On top of each nanopillar a solid immersion lens is fabricated, employing the photoresist previously used to define the nanopillars. For optimized conditions the external quantum efficiency is increased by up to one order of magnitude. Excitation-power-dependent photoluminescence measurements confirm that the emission stems from a true two-level system and the single photon purity of the source is verified by measuring the second order correlation function. Finally, we investigate the grade of sequential indistinguishability of subsequent single-photons from our devices by Hong-Ou-Mandel type experiments. This work paves the way for efficient generation of polarization entanglement between two sufficiently indistinguishable photons. Consequently, future applications of these SPSs are envisioned in all-optical based quantum cryptography or to interconnect distant nodes in quantum networks.

QI 1.8 Mon 11:45 H8

A Reversible Classical Half-Adder Implemented with Trapped Ion Qubits — •Patrick Huber[1], Sagar Pratapsi[2,3], Patrick Barthel[1], Sougato Bose[4,5], Yasser Omar[2,3,6], and Christof Wunderlich[1] — [1]Department of Physics, School of Science and Technology, University of Siegen, 57068 Siegen, Germany — [2]Physics of Information and Quantum Technologies Group, Instituto de Telecomunicações, Portugal — [3]Instituto Superior Técnico, U. Lisbon, Portugal — [4]Department of Physics and Astronomy, University College London, London WC1E 6BT, UK — [5]Department of Electronic & Electrical Engineering, University College London, WC1E 7JE London, UK — [6]Portuguese Quantum Institute, Portugal

We experimentally realise a Toffoli gate and a Half-Adder circuit suitable for classical computation, using qubits encoded into trapped $^{171}Yb^+$ ions. The microwave-controlled qubits are coupled by an all-to-all $\sigma_z\sigma_z$ interaction. A comprehensive analysis is given of the energy required to operate the gates, both from first principles and by experimental measurements. This allows for identifying decisive improvements that could lead to energetically efficient classical computation. Our analysis indicates that a novel planar ion trap-setup will already be 10^5 times more efficient.

QI 1.9 Mon 12:00 H8

Improving quantum state detection with adaptive sequential observations — Shawn Geller[1,2], Daniel Cole[1], Scott Glancy[1,2], and •Emanuel Knill[1,2] — [1]National Institute of Standards and Technology, Boulder, CO, USA — [2]University of Colorado at Boulder, Boulder, CO USA

For many quantum systems intended for information processing, one detects the logical state of a qubit by integrating a continuously observed quantity over time. For example, ion and atom qubits are typically measured by driving a cycling transition and counting the number of photons observed from the resulting fluorescence. Instead of recording only the total observed count in a fixed time interval, one can observe the photon arrival times and get a state detection advantage by using the temporal structure in a model such as a Hidden Markov Model. We study what further advantage may be achieved by applying pulses to adaptively transform the state during the observation. We give a three-state example where adaptively chosen transformations yield a clear advantage, and we compare performances on an ion example, where we see improvements in some regimes.

QI 1.10 Mon 12:15 H8

Quantum Information Transfer in a Chain of Trapped Ions — •Theeraphot Sriarunothai, Patrick Barthel, Patrick Huber, Gouri S. Giri, and Christof Wunderlich — Department of Physics, School of Science and Technology, University of Siegen, 57068 Siegen, Germany

We explore a quantum teleportation scheme with four trapped $^{171}Yb^+$ ions in a non-segmented linear Paul trap, each radiofrequency-controlled ion representing one qubit. The $\sigma_z\sigma_z$ interaction between qubits is mediated by Magnetic Gradient Induced Coupling (MAGIC) [1]. The 4×4 interaction matrix of the qubit-system is measured and, taking advantage of all-to-all connectivity, is used to create Bell states between pairs of nearest neighbours and second-nearest neighbours, respectively. Furthermore, it is demonstrated how, while creating an entangled pair, another qubit serves as a decoupled quantum memory. This memory qubit is protected from decoherence with the same dynamical decoupling sequence as the one applied to perform the Bell-state operations. We developed and implemented a blueprint to demonstrate quantum state transfer using a quantum teleportation scheme. First experimental results on teleportation indicate the transfer of a superposition state from one end to another end of a quantum register. The method and techniques developed here can be applied to a larger system, for example, a full quantum byte or across quantum registers.

[1] Ch. Piltz et al., Science Advances **2**, e1600093 (2016).

QI 1.11 Mon 12:30 H8

Dressed $^{171}Yb^+$ Hyperfine Qubits in a Multi-layer Planar Ion Trap — •Elham Esteki[1], Bogdan Okhrimenko[1], Friederike Giebel[2,3,4], Eike Iseke[2,3,4], Konstantin Thronberens[3,4], Nila Krishnakumar[2,4], Jacob Stupp[2,3], Amado Bautista Salvador[2,3,4], Christian Ospelkaus[2,3,4], Ivan Boldin[1], and Christof Wunderlich[1] — [1]Dept. Physik, Nat.-Techn. Fak., Universität Siegen, 57068 Siegen — [2]Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [3]Laboratory for Nano - and Quantum Engineering, Schneiderberg 39, 30167 Hannover — [4]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig

Dressed qubit states – the eigenstates of the Hamiltonian of a qubit subject to a near-resonant driving field – can be used to store and process quantum information instead of bare state qubits. We present a microfabricated ion trap chip, designed for the realization of quantum information processing based on radiofrequency-dressed qubits using hyperfine states of $^{171}Yb^+$ ions [1]. The ion trap chip consists of multiple layers [2], one of which includes an integrated microwave resonator. It creates a gradient of the microwave magnetic field amplitude which is needed for the realization of qubit addressing and qubit-qubit coupling. We experimentally characterize this novel ion trap chip and demonstrate preparation and detection of RF-dressed qubits, as well as single-qubit- and two-qubit operations.

[1] S. Wölk, Ch. Wunderlich, New J.Phys. **19**, 083021 (2017).
[2] A. Bautista-Salvador et al., New J. Phys. **21**, 043011 (2019).