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 Γ 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 (Λ) 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 Λ 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 μeV. 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.