Tuesday Contributed Sessions (TUE)

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Overview of Sessions

(Lecture halls ZHG001, ZHG002, ZHG003, ZHG004, ZHG006, ZHG007, ZHG008, ZHG009, ZHG101, ZHG103, ZHG104, and ZHG105)

Sessions

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TUE 3.1–3.7	Tue	14:15–16:00	ZHG003	**Quantum Field Theory**
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TUE 6.1–6.7	Tue	14:15–16:00	ZHG007	**Quantum Computing and Communication: Contributed Session I (Algorithms & Theory)**
TUE 7.1–7.6	Tue	14:15–15:45	ZHG008	**Entanglement and Complexity: Contributed Session to Symposium I**
TUE 8.1–8.7	Tue	14:15–16:00	ZHG009	**Correlated Quantum Matter: Contributed Session to Symposium I**
TUE 9.1–9.8	Tue	14:15–16:15	ZHG101	**Quantum Physics in Strong Fields: Contributed Session to Symposium**
TUE 10.1–10.8	Tue	14:15–16:15	ZHG103	**Foundational / Mathematical Aspects – Rigorous Results**
TUE 11.1–11.8	Tue	14:15–16:15	ZHG104	**Quantum Optics and Quantum Computation**
TUE 12.1–12.7	Tue	14:15–16:00	ZHG105	**Quantum Sensing and Decoherence: Contributed Session to Symposium III**

TUE 1: QIP Implementations: Photons III

Time: Tuesday 14:15–16:00 Location: ZHG001

TUE 1.1 Tue 14:15 ZHG001

Bose-Einstein Condensation of Photons in Lattice Potentials — •Andreas Redmann, Christian Kurtscheid, Niels Wolf, Frank Vewinger, Julian Schmitt, and Martin Weitz — Institut für Angewandte Physik, Universität Bonn, Germany

Thermalization of radiation by contact to matter is a well-known concept, but the application of thermodynamic methods to complex quantum states of light remains a challenge. Using a controlled mirror surface delamination technique to imprint micro-wells in different lattice geometries [1,2], we study thermalization of light in a dye-filled microcavity at room temperature in variable trapping potentials.

In recent work, we have demonstrated Bose-Einstein condensation of photons in a four-site quantum ring [3]. We observe macroscopic accumulation of photons in the ground state with no phase winding above a critical photon number. In other work, we have thermalised photons in a double well system, realizing the textbook-character problem of N bosons populating a two-state system.

[1] C. Kurtscheid et al., Science 366, 894-897 (2019)
[2] C. Kurtscheid et al., EPL 130, 54001 (2020)
[3] A. Redmann et al., Phys. Rev. Lett. 133, 093602 (2024)

TUE 1.2 Tue 14:30 ZHG001

Hollow-core light cages: Towards scalable multiplexed quantum memories — •Esteban Gómez-López[1], Dominik Ritter[1], Jisoo Kim[2], Harald Kübler[3], Markus A. Schmidt[2,4], and Oliver Benson[1] — [1]Humboldt-Universität zu Berlin, Berlin, Germany — [2]Leibniz Institute of Photonic Technology, Jena, Germany — [3]Universität Stuttgart, Stuttgart, Germany — [4]Otto Schott Institute of Material Research, Jena, Germany

Quantum memories play a fundamental role in synchronizing quantum network nodes. Using electromagnetically induced transparency (EIT) in hot atomic vapors provides easy-to-handle systems capable of storing light for up to seconds [1]. Employing a novel photonic structure -a nanoprinted hollow-core light cage (LC)- can enhance the effects of EIT when interfaced with Cs vapor, offering the advantage of faster atomic diffusion inside the core compared to other hollow-core structures [2]. In this work, we show the storage of faint coherent light pulses in the atomic medium confined within the core of the LC for hundreds of nanoseconds. The intrinsic efficiency of the memory was optimized by performing a parameter scan on the signal bandwidth and control power driving the memory [3]. This paves the way towards an on-chip integrated module for quantum memories and as a platform for coherent interaction of light and warm atomic vapors. [1] Katz, O. and Firstenberg, O., Nat. Commun. 9, 2074 (2018). [2] Davidson-Marquis, F., et al., Light. Sci. Appl. 10, 114 (2021). [3] Gómez-López, E., et al., Preprint: arXiv:2503.22423 (2025).

TUE 1.3 Tue 14:45 ZHG001

Storage of single photons from a semiconductor quantum dot in a room-temperature atomic vapor memory with on-demand retrieval — •Benjamin Maass[1,2], Avijit Barua[2], Norman Vincenz Ewald[1], Elizabeth Jane Robertson[1], Kartik Gaur[2], Suk In Park[3], Sven Rodt[2], Jin-Dong Song[3], Stephan Reitzenstein[2], and Janik Wolters[1,2,4] — [1]Institute of Space Research, German Aerospace Center (DLR), Germany — [2]Institutes of Physics, Technische Universität Berlin, Germany — [3]Korean Institute of Technology, Seoul, Republic of Korea — [4]Einstein Center Digital Future (ECDF), Berlin, Germany

On-demand storage and retrieval of single photons in coherent light-matter interfaces is a key requirement for distributing quantum information. Here, we demonstrate storage of single photons from a semiconductor quantum dot device in a room-temperature atomic vapor memory and their on-demand retrieval [1]. A deterministically fabricated InGaAs quantum dot light source emits single photons at the cesium D1 transition wavelength (895 nm) with a linewidth of 5.1(7) GHz which are subsequently stored in a low-noise ladder-type cesium vapor memory. We show control over the interaction between the single photons and the atomic vapor, allowing for variable retrieval times of up to 19.8(3) ns and a maximum internal efficiency of $\eta_{\mathrm{int}} = 0.6(1)\%$. This QD-memory interface provides an unprecedented level of control over the temporal mode of the single-photon emitter and represents a step towards heterogeneous platforms for quantum network nodes.

[1] B.Maaß et al. arXiv:2501.15663 (2025)

TUE 1.4 Tue 15:00 ZHG001

Stark Effect Limitations in Optical Addressing of Phosphorus Donors in Si-28 — •Nico Eggeling[1], Jens Hübner[1], Michael Oestreich[1], and N.V. Abrosimov[2] — [1]Leibniz Universität Hannover, Germany — [2]IKZ Berlin, Germany

Phosphorus donors in isotopically pure Si-28 serve as powerful qubits in electrical measurements. Combining these donors with optical methods seems highly promising[1]. However, surprisingly, spectral hole-burning experiments have not yet achieved Fourier-limited line shapes, a crucial requirement for efficient optical addressing[2]. For the first time on Si-28, we employ time-resolved spectral hole-burning spectroscopy to demonstrate that the primary cause is a random quadratic Stark-Effect, rooted in the formation of ionized donor-acceptor pairs. Monte Carlo simulations validate that the unavoidable acceptor background doping in silicon is responsible for this limitation and open a method to suppress the influence of these acceptors efficiently. This approach not only improves the optical performance of phosphorus-doped Si-28 but also paves the way for the further advancement of solid-state qubits.

[1] Sauter et al., Phys. Rev. Lett. **126**, 137402 (2021)
[2] Yang et al., Appl. Phys. Lett. **95**, 122113 (2009)

TUE 1.5 Tue 15:15 ZHG001

Experimental quantum metrology for fast-varying systems — •Lukas Rückle[1,2] and Stefanie Barz[1,2] — [1]Institute for Functional Matter and Quantum Technologies, University of Stuttgart, 70569 Stuttgart, Germany — [2]Center for Integrated Quantum Science and Technology (IQST), Universitity of Stuttgart, 70569 Stuttgart, Germany

The use of quantum states for metrology tasks has been proven to surpass classical limits on the precision of estimating parameters. Recently, the framework of probably approximate correct (PAC) metrology has been introduced. It not only enables the estimation of a parameter in an arbitrarily big parameter space without prior knowledge, but also gives bounds for few- and single-shot metrology settings. It thus bridges the rather theoretical case of performing infinitely many measurements and practical metrology tasks.

Here, we present experimental results in a photonic metrology setting. We show how to use different states and measurements and how for each case to optimize the prediction strategy of the parameter that shall be estimated. Our work shows how to implement the given new framework of PAC metrology and thus helps improving the precision of applications that only allow for a few measurements, e.g. when measuring fast varying systems.

TUE 1.6 Tue 15:30 ZHG001

Hetero-integration of diamond nanostructures on AlGaN-based photonic circuits — •Domenica Romina Bermeo Alvaro[1,2], Sinan Gündogdu[1,2], Lea M. Rektorschek[2], Pascal Frehle[2], Marco E. Stucki[1,2], Maarten H. van der Hoeven[2], Julian M. Bopp[2,1], Tim Kolbe[2], Sylvia Hagedorn[2], Markus Weyers[2], Tommaso Pregnolato[1,2], and Tim Schröder[2,1] — [1]Ferdinand-Braun-Institut (FBH), Gustav-Kirchhoff-Str. 4, 12489 Berlin, Germany — [2]Department of Physics, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany

Spin-photon interfaces are crucial for the development of large quantum networks. A highly efficient spin-photon interface can be achieved when diamond color centers are embedded in photonic crystal cavities, which enhance the light-matter interaction and boost the emission rate of photons generated by the coherent zero-phonon-line transition. While the diamond substrate allows for the nanofabrication of such devices, achieving a monolithic platform that will take advantage of those photonic crystal cavities on a large scale remains a challenge. To overcome these limitations, we propose the hetero-integration of diamond nanostructures into AlGaN-based photonic circuits. By embedding diamond nanostructures within AlGaN-based circuits, we aim to create highly efficient, scalable spin-photon interfaces. Our approach involves the design, fabrication and characterization of a low-loss coupling section between diamond and AlGaN waveguides. Finally, we show the first integration on an AlGaN-based photonic circuit of a Sawfish cavity, our newly proposed photonic crystal cavity.

TUE 1.7 Tue 15:45 ZHG001

Experimental Quantum Strong Coin Flipping using a Deterministic Single-Photon Source — •Koray Kaymazlar[1], Daniel Vajner[1], Fenja Drauschke[2], Lucas Rickert[1], Martin von Helversen[1], Shulun Li[3], Zhichuan Niu[3], Anna Pappa[2], and Tobias Heindel[1] — [1]Institute of Physics and Astronomy, Technische Univeristät Berlin, Germany — [2]Electrical Engineering and Computer Science Department, Technische Univeristät Berlin, Germany — [3]Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

Strong coin flipping (SCF) is a fundamental cryptographic protocol allowing two distrustful parties to agree on randomly generated bit. In this work, we report the first implementation of a quantum strong coin flipping protocol that yields a quantum advantage compared to both its classical counterpart and an implementation using weak coherent pulses [1]. The quantum advantage is enabled by employing a state-of-the-art deterministic single-photon source based on a quantum dot embedded in a high-Purcell microcavity. Using a fiber-based electro-optic modulator (EOM) we realize fast dynamic, random polarization-state encoding at 80 MHz clock-rate. Our QSCF implementation enables a coin flipping rate of 1.5 kHz and an average quantum bit error ratio (QBER) below 3%, sufficient to realize a quantum advantage.

[1] D. A. Vajner, K. Kaymazlar, F. Drauschke, L. Rickert, M. von Helversen, H. Liu, S. Li, H. Ni, Z. Niu, A. Pappa, T. Heindel, Single-Photon Advantage in Quantum Cryptography Beyond QKD, arXiv:2412.14993 (2024)

TUE 2: Quantum Networks: Technologies

Time: Tuesday 14:15–16:15 Location: ZHG002

TUE 2.1 Tue 14:15 ZHG002

Quantum Dots for Quantum Networks — •Klaus D. Jöns — PhoQS Institute, CeOPP, and Department of Physics, Paderborn University

Germany has started more than a decade ago to invest in a platform-agnostic approach to quantum repeaters, funding multiple technological pathways, including semiconductor-based quantum dots as one of the brightest quantum light sources. I will highlight some of the remarkable achievements based on quantum dots and discuss the feasibility of on-demand generation of entangled photon pairs for quantum repeaters architectures that integrate external quantum memories. I will critically discuss bottlenecks and challenges to deploy quantum dots and put our results in a broader perspective.

TUE 2.2 Tue 14:30 ZHG002

Development of Site-Controlled Quantum Dot Arrays for Multicore-Fiber-Coupled Quantum-Communication Source Modules — •Martin Podhorský[1], Maximilian Klonz[1], Lux Böhmer[1], Sebastian Kulig[1], Phillip Manley[2], Martin Hammerschmidt[2], Stefan Link[3], Gunnar Böttger[3], Henning Schröder[3], Nikolay Ledentsov[4], Vitaly Shchukin[4], Sven Rodt[1], and Stephan Reizenstein[1] — [1]Institut für Physik und Astronomie, Technische Universität Berlin, Hardenbergstraße 36, D-10623 Berlin, Germany — [2]JCMwave GmbH, Bolivarallee 22, 14050 Berlin, Germany — [3]Fraunhofer IZM, G.-Meyer-Allee 25, 13355 Berlin, Germany — [4]VI Systems GmbH, Hardenbergstr. 7, 10623 Berlin, Germany

Fiber-based optical quantum communication is emerging as a robust alternative for traditional secure data transfer. We propose a monolithic device in which classical and quantum communication channels can be realised simultaneously using semiconductor quantum dots embedded in resonant cavities. We report on growth of positioned InGaAs quantum dots via the buried stressor method, achieving high precision, uniformity and reproducibility of the quantum dot placement. A detailed statistical analysis shows controlled quantum dot density variation and positioning accuracy. Furthermore, we present a micro-manufactured glass holder design for a passive multicore-fiber-coupling process, enabling scalable, efficient, and practical utilisation in quantum communication networks.

TUE 2.3 Tue 14:45 ZHG002

Building Blocks for Hybrid Quantum Repeaters — •Marlon Schäfer, Tobias Bauer, Pascal Baumgart, Max Bergerhoff, Christian Haen, Dennis Herrmann, David Lindler, Jonas Meiers, Robert Morsch, Jürgen Eschner, and Christoph Becher — Universität des Saarlandes, Fachrichtung Physik, Campus E2 6, 66123 Saarbrücken

Large-scale quantum networks require the development of quantum repeaters capable of high-fidelity entanglement distribution over long distances. We report progress toward heterogeneous quantum repeater nodes that integrate solid-state and atomic platforms. Specifically, tin-vacancy (SnV) centers in diamond and trapped calcium ions ($^{40}Ca^{+}$) are employed as quantum memories, with quantum frequency conversion bridging their respective emission to the low-loss telecom band. We demonstrate frequency conversion of indistinguishable photons from SnV centers and $^{40}Ca^{+}$ ions, and present results on quantum interference between photons emitted by these systems. To evaluate performance under realistic conditions, we operate a 14 km-long urban fiber testbed with a stable frequency reference frame distributed over the fiber link. These results represent critical steps toward scalable, hybrid quantum repeater architectures.

TUE 2.4 Tue 15:00 ZHG002

Automated Large-Scale Characterization of Solid-State Color Centers for Quantum Communication — •Julian M. Bopp[1,2], Maarten H. van der Hoeven[1], Marco E. Stucki[1,2], Tommaso Pregnolato[1,2], and Tim Schröder[1,2] — [1]Department of Physics, Humboldt-Universität zu Berlin, 12489 Berlin, Germany — [2]Ferdinand-Braun-Institut (FBH), 12489 Berlin, Germany

Extending quantum networks toward a global quantum internet requires the serial-production of standardized building blocks, including highly efficient spin-photon interfaces. Due to variations in the local environment of optically active solid-state spin qubits, like diamond color centers, their quality differs spatially across sample substrates. Consequently, all spin qubits have to be characterized thoroughly before incorporating them into quantum network building blocks. However, characterization experiments are time-consuming since they regularly involve addressing qubits manually with a confocal microscope.

Paving the way toward the deterministic fabrication of quantum network building blocks on the wafer scale, we present the fully automated large-scale characterization of such solid-state qubits employing a combined widefield and confocal microscope. Moreover, we employ means of artificial intelligence to classify hundreds of acquired spectra and second-order correlation functions. Our approach enables the automated selection of qubits that are best suitable for quantum networking and the statistical investigation of sample treatment effects on the qubits [1].

[1] E. Corte et al., Adv. Photonics Res. 3, 2100148 (2021)

TUE 2.5 Tue 15:15 ZHG002

Quantum networking with microfabricated atomic vapor cells — •Roberto Mottola, Gianni Buser, Suyash Gaikwad, and Philipp Treutlein — Universität Basel, Basel, Schweiz

Quantum memories for photons are building blocks of quantum networks. Memories implemented in hot alkali vapor are attractive as they operate due to their technological simplicity and have been proven to perform well in a multitude of figures of merit [1]. In [2] we report on an elementary, hybrid network interconnect. We combine a low-noise quantum memory implemented in hot Rb vapor based on electromagnetically induced transparency with a tailored downconversion source. By spin polarizing the atomic ensemble and exploiting polarization selection rules we were able to significantly reduce the noise of the memory. This allowed us to observe for the first time a non-classical $g^{(2)}_{ret}$ for photons stored and retrieved in a broadband, ground-state alkali vapor quantum memory - yielding a measured $g^{(2)}_{ret} = 0.177(23)$ well below the classical limit of 1. Realistic visions of large-scale networks require a scalable and mass-producible platform. In this respect, microfabricated vapor cells are very promising. MEMS fabrication techniques have already been successfully used to miniaturize atomic quantum sensors, as atomic clocks, magnetometers, and gyroscopes. We report on the first implementation of an alkali vapor memory in microfabricated Rb cells compatible with wafer-scale mass production [3] - a crucial step towards scalability. [1] C. Simon et al., *Eur. Phys. J. D* **58**, 1–22 (2010). [2] G. Buser et al., *PRX Quantum* **3**, 020349 (2022). [3] R. Mottola et al., *Phys. Rev. Lett.* **131**, 260801 (2023).

TUE 2.6 Tue 15:30 ZHG002

Evaluating Cavity-enhanced Telecom-wavelength Quantum Dot Single-photon Sources for Quantum Cryptography — •Robert Behrends[1], Koray Kaymazlar[1], Mareike Lach[1], Martin v. Helversen[1], Pratim Saha[1], Daniel Vajner[1], Jochen Knaupp[2], Yorick Reum[2], Tobias Huber-Loyola[2], Sven Höfling[2], Andreas Pfenning[2], and Tobias Heindel[1] — [1]Institute of Physics and Astronomy, Technische Univeristät Berlin, 10623 Berlin, Germany — [2]Technische Physik, Physikalisches Institut and Würzburg-Dresden Cluster of Excellence ct.qmat, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany

Great advances are made in the fabrication of telecom-wavelength quantum light sources based on semiconductor quantum dots (QDs)[1]. Yet, further progress is needed towards practical applications. Here, we evaluate QD-based single-photon sources for applications in quantum cryptography in the telecom C-band. Exploiting cavity-enhanced devices with embedded InAs/InAlGaAs QDs, we achieve emitter lifetimes of 500 ps and g(2)(0)=0.044 under pulsed quasi-resonant excitation. Employed in a quantum cryptography testbed, we investigate dynamic polarization-state encoding using a customized fiber-coupled electro-optic modulator in single-pass configuration, which is controlled by an arbitrary waveform generator. The random preparation of four polarization states with low loss and low quantum bit error ratio thereby is crucial for applications in quantum key distribution and beyond[2].

[1] Holewa et al., Nanophotonics, 10.1515/nanoph-2024-0747 (2025)
[2] Vajner et al., arXiv:2412.14993 (2024)

TUE 2.7 Tue 15:45 ZHG002

Integrated quantum network nodes — •Jonas C. J. Zatsch[1,2], Tim Engling[1,2], Jeldrik Huster[1,2], Louis L. Hohmann[1,2], Shreya Kumar[1,2], and Stefanie Barz[1,2] — [1]Institute for Functional Matter and Quantum Technologies, University of Stuttgart, 70569 Stuttgart, Germany — [2]Center for Integrated Quantum Science and Technology (IQST)

Quantum networks require both local quantum information processing and the transmission of quantum information across the network. Integrated photonic circuits are promising candidates for quantum nodes, as they offer a compact footprint and scalability, while optical fibres allow for low-loss transmission between such nodes. A key challenge is the transfer of quantum states generated or manipulated on-chip to the network; and vice versa. Here, we present a silicon-on-insulator integrated photonic circuit capable of high-fidelity preparation of two-qubit states, which can be transferred to optical networks. In turn, quantum states sent over an optical network can be analysed using the same chip. We demonstrate its functionality by preparing different two-qubit states on-chip and transferring them to fibres. Additionally, we show its reverse operation by using the chip as a two-qubit quantum state tomography unit for an off-chip prepared state. This bidirectional operation makes our chip a versatile platform for the implementation of quantum networked protocols.

TUE 2.8 Tue 16:00 ZHG002

Synchronization of remote Time Taggers for quantum communication applications — •Mickey Martini, Edoardo Mornacchi, Timon Eichhorn, Jan Bruin, and Mirco Kolarczik — Swabian Instruments GmbH, Stuttgart, Germany

Synchronous detection of photon events at large distances is a key enabler for quantum communication. While local Time Taggers reach a timing resolution below 2 ps, synchronization of Time Taggers on the scale of kilometers at a comparable resolution level is a challenge. The precise correlation between photon streams and characterization of single events within the stream allows for advanced filtering mechanisms that can target for suppression of background noise as well as for recognition of attacks on the communication channel. The impact of these approaches depends strongly on the effective timing resolution of the synchronized time-tagging system.

In this presentation, we give an overview of software components that contribute to a flexible and easy-to-use synchronization solution. As a first level of synchronization, we demonstrate the use of commercially available White Rabbit (WR) technology for clock distribution. WR promises sub-nanosecond accuracy (clock offsets) at picosecond precision (clock stabilization). We demonstrate that the additional jitter of such a system is below 4 ps. To handle the data from remote sites, we present a merging solution based on standard network protocols. Finally, we provide insights into the development of a second synchronization layer that aligns the photon streams.

TUE 3: Quantum Field Theory

Time: Tuesday 14:15–16:00 Location: ZHG003

TUE 3.1 Tue 14:15 ZHG003

Photonic simulation of quantum field dynamics — •Mauro D'Achille[1], Martin Gärttner[1], and Tobias Haas[2] — [1]Friedrich-Schiller-Universität Jena — [2]Universität Ulm

Photonic multimode systems are an emerging quantum simulation platform ideally suited for emulating non-equilibrium problems in quantum field theory.

I will present a new decomposition for the time evolution generated by a large class of field-theoretic quadratic Hamiltonians in terms of optical elements. The peculiarity of this decomposition consists in the way the time parameter is taken into account. Indeed, for such a class, it is always possible to decouple the time evolution in time-dependent phase shifters by means of a proper time-independent symplectic transformation composed by squeezers and beam splitters.

I will conclude with physically relevant examples and applications aimed to analyze and simulate how the entanglement entropy associated to local and non-local theories spreads over time.

TUE 3.2 Tue 14:30 ZHG003

Topologically Charged Vortices at Superconductor/Quantum Hall Interfaces — •Enderalp Yakaboylu and Thomas L Schmidt — Department of Physics and Materials Science, University of Luxembourg, L-1511 Luxembourg

We explore interface states between two paradigmatic mesoscopic many-body quantum phases: a type-II s-wave superconductor (SC) and a Chern insulator in the $\nu = 1$ quantum Hall (QH) regime. We show that effective interactions at the SC/QH boundary give rise to two emergent Abelian Higgs fields, representing paired electrons localized at the interface. These fields couple through a Chern-Simons term originating from the QH sector, which induces a topological mass for photons and imparts a fractional topological charge to the interface vortices. These findings, particularly the emergence of vortices carrying fractional charge, corresponding to Abelian anyons, bridge topological condensed matter physics and quantum information science, suggesting a new platform for engineering anyonic excitations and advancing toward fault-tolerant topological quantum computation.

TUE 3.3 Tue 14:45 ZHG003

Quark confinement due to unified magnetic monopoles and vortices reduced from symmetric instantons with holography — •Kei-Ichi Kondo — Chiba University, Chiba 263-8522, Japan

We present a new rigorous scheme for understanding quark confinement based on the non-perturbative vacuum disordered by some topological defects. We start from the 4-dim. Euclidean Yang-Mills theory and require the conformal equivalence between the 4-dim.Euclidean space and the possible curved spacetimes with some compact dimensions. This requirement forces us to restrict the gauge configurations of 4-dim.Yang-Mills instantons to those with some space symmetries (called symmetric instantons) which are identified with magnetic monopoles and vortices living in the lower-dimensional curved spacetime with non-zero curvature through the dimensional reduction. The new scheme gives the direct built-in equivalence between (3-dim.hyperbolic) magnetic monopoles (of Atiyah type) and (2-dim.hyperbolic) vortices (of Witten-Manton type), which have been assumed without any rigorous proof to be the dominant contributors to quark confinement. This unified treatment of two topological defects is shown to give the semi-classical picture for quark confinement in the sense of Wilson. At the same time, this scheme caused by the dimensional reduction give a holographic description of magnetic monopole dominance on AdS3 in the rigorous way without any further assumptions. Moreover, the asymptotic freedom is also shown to be derived by performing the pertutbative deformation on the vacuum with these topological defects. [Paper in preparation to be submitted to ArXiv]

TUE 3.4 Tue 15:00 ZHG003

Spinorial Superspaces and Supersymmetric Yang-Mills Theories — •Johannes Moerland — University of Göttingen

In physics literature about supersymmetry, many authors refer to "super Minkowski spaces". These spaces are extensions of ordinary Minkowski spaces by spinorial directions. More abstractly, super Minkowski spaces are affine supermanifolds (i.e., locally ringed spaces with a $\mathbb{Z}_2$-graded algebra of functions) with distinguished spin structures.

In this talk, we formalise these spin structures, allowing us to generalise the setup to curved supermanifolds. Apart from the possibility of formulating field theories on topologically non-trivial superspaces, our approach bears two advantages: Firstly, the language of graded geometry allows for a global and inherently coordinate-free formulation of field theories on the superspace. Secondly, the approach to superspaces via graded geometry endows many algebraic manipulations with a concise geometric meaning. For example, the Dirac γ matrices can be identified with the torsion of the superspace along the spinorial directions.

After exploring the geometric properties of spinorial superspaces, we apply the rather general theory to $\mathcal{N} = 1$ super Yang-Mills theories on curved superspaces of space-time dimensions 3 and 4 and show that the effective theory on an embedded ordinary space-time manifold, obtained by integrating over the spinorial directions, reproduces a coupled system of Yang-Mills and twisted Dirac Lagrangians.

TUE 3.5 Tue 15:15 ZHG003

A short review of the worldline approach to strong-field QED — •Christian Schubert — Facultad de Ciencias Físico-Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Avenida Francisco J. Mújica, 58060 Morelia, Michoacán, Mexico

The worldline formalism offers an alternative to the standard Feynman diagram approach in QED that has been found particularly efficient for processes in external field, primarily because it avoids the segmenting of fermion lines or loops into individual propagators. Here I will give a short summary of the method and its present range of applications, with examples ranging from Schwinger pair creation in various types of electric fields to photon-graviton conversion in a magnetic field.

TUE 3.6 Tue 15:30 ZHG003

Measurement of the Casimir force during free fall — •Sascha Kulas — International University of Applied Sciences (IU), Hannover, Germany

The Casimir force still has a lot of unknown aspects. Here this force is measured in a tuning fork experiment during free fall and compared with a measurement on ground. It seems like the Casimir force is strongly suppressed during fall. This is a hint that the Casimir force does not have its origin in the Van der Waals force, which would not change in reduced gravity. Independent drop tower experiments have to validate these results. Further conclusions concerning gravity and Dark Energy are raised by establishing a first phenomenological approach based on the measurement results and Verlindes entropic gravity. The main conclusion is that Dark Energy is coupled to baryonic matter.

TUE 3.7 Tue 15:45 ZHG003

Forward Physics at the LHC — •Rainer Schicker — Phys. Institute, Heidelberg University

Quantum-Chromodynamics (QCD) was formulated 50 years ago as a gauge theory for describing the interaction between quarks and gluons. The underlying SU(3) symmetry of the color degree of freedom leads to self-couplings of gluons, which results in two very intriguing features of QCD, confinement and asymptotic freedom. A perturbative treatment of QCD processes is only possible for large momentum transfers Q^2. The nonperturbative sector of QCD still carries many mysteries which are very poorly understood, or not at all. Many of these enigmas reveal their nature in soft interactions which are experimentally accessible in forward and very forward measurements at the LHC.

I will outline how future forward measurements at the LHC could contribute to shed light on the many unsolved mysteries of nonperturbative QCD.

TUE 4: Education and Outreach

Time: Tuesday 14:15–16:00 Location: ZHG004

TUE 4.1 Tue 14:15 ZHG004

Shaping Quantum Education: National Networks, European Programs, and the CFQT — •Franziska Greinert and Rainer Müller — Technische Universität Braunschweig, Institut für Fachdidaktik der Naturwissenschaften

As quantum technologies approach industrial application, education systems face increasing pressure to respond to emerging skill demands. This talk outlines current initiatives – from a German educator network to European programs – aimed at building quantum competences across sectors. A central focus lies on the European Competence Framework for Quantum Technologies (CFQT), developed through iterative research and stakeholder engagement. The CFQT provides a structured model for mapping and comparing competences, supporting curriculum planning and workforce development. The talk introduces the CFQT with selected use cases, highlighting its role in aligning education with evolving quantum workforce needs.

TUE 4.2 Tue 14:30 ZHG004

Heisenberg's Philosophy of Quantum Mechanics: A Road to Pragmatic Positivism — •Kanan Purkayastha — The Philosophical Society, Oxford, United Kingdom

One of the key figures in the development of quantum mechanics was Werner Heisenberg (1901-1976). Heisenberg developed both the first quantum mechanical mathematical framework, matrix mechanics. He also outlined the philosophical basis underpinning it, named thereafter the *uncertainty principle.*

On the other hand, a central contribution to the understanding of science in general and physics in particular, is the naturalistic analysis of the subject by philosopher Willard Van Orman Quine (1908-2000). This is evident in Quine*s works on the nature of language. Within Heisenberg*s writings there is a substantial attention directed to analysing nature of language, and especially its relation to epistemic questions within science.

This paper argues that in spite of Heisenberg being a physicist working in an area of quantum mechanics and Quine being an analytic philosopher concerned with the broader questions of epistemology both of them are led to strikingly similar conclusions about the nature of reality. Also, the abstract account of how science progresses that Quine provides matches closely with the Heisenberg's philosophical ideas of how science in general and physics in particular makes crucial advances. The paper concludes that both Heisenberg and Quine opt for a pragmatic positivism rather than logical positivism.

TUE 4.3 Tue 14:45 ZHG004

Quantencomputer in der Oberstufe: Unterrichtsmaterial für MINT-Fächer und für einen Projektkurs im Abitur — •Jörg Gutschank[1,3] und Jörg Thorwart[2,4] — [1]Leibniz Gymnasium, Dortmund, Germany — [2]Albert-Einstein-Gymnasium, Ulm, Germany — [3]Science on Stage Germany, Berlin, Germany — [4]European School Brussels II, Belgium

Quantencomputer sind mehr als ein technologischer Trend - sie eröffnen neue Perspektiven für die physikalische, mathematische und informatische Bildung. Im Rahmen einer internationalen Zusammenarbeit von Lehrkräften aus Physik, Mathematik und Informatik wurde unter der Koordination von *Science on Stage* Unterrichtsmaterial entwickelt, das Lehrkräfte einsetzen können, um Schüler:innen der Sekundarstufe II einen praxisnahen Zugang zum Quantencomputing zu ermöglichen.

Das Projekt befindet sich aktuell in der Abschlussphase; die Materialien werden in Kürze online verfügbar sein unter: https://www.science-on-stage.eu/quantumcomputing

Die Materialien wurden von Lehrkräften für Lehrkräfte entwickelt und bieten vielfältige Zugänge - von Schülerexperimenten und Online-Animationen bis zu Programmieraufgaben und eigenständigen Arbeitsformen. Sie eignen sich für einzelne MINT-Fächer und projektorientierte Abiturkurse.

Im Vortrag werden das interdisziplinäre Material und Umsetzungsbeispiele aus den MINT-Fächern vorgestellt. Ziel ist es, das Potenzial für fächerverbindenden Unterricht zum Quantencomputing aufzuzeigen.

TUE 4.4 Tue 15:00 ZHG004

Mehr als Chemie: Die Kontakte von Carl Auer von Welsbach zu Niels Bohr & Co — •Gerd Löffler — Carl Auer von Welsbach Museum, Althofen, Österreich

Carl Auer von Welsbach ermöglichte durch seine hochreinen chemischen Präparate fundamentale experimentelle Bestätigungen in der frühen Quantenphysik. Niels Bohr hatte auf Basis seines Atommodells vorausgesagt, dass Lutetium das letzte Element der Lanthanoidreihe sei und diamagnetische Eigenschaften aufweise. Der experimentelle Nachweis dieser Vorhersagen gelang erst durch Welsbachs exzellente Lutetiumpräparate, die Stefan Meyer in Wien erfolgreich einsetzte. Die hohe chemische Reinheit war entscheidend für die Reproduzierbarkeit der magnetischen Messungen. Aufbauend auf diesen experimentellen Grundlagen entwickelte Friedrich Hund 1925 sein quantenmechanisches Modell der Elektronenkonfiguration, das als *Hundsche Regel* bekannt wurde. Diese Modellbildung stand in enger Übereinstimmung mit den empirischen Ergebnissen aus Wien. Darüber hinaus bestimmte Auer von Welsbach die Atomgewichte von Ytterbium und Lutetium mit außergewöhnlicher Genauigkeit – ein beachtlicher Erfolg angesichts der damaligen analytischen Möglichkeiten. Seine Arbeiten bilden eine zentrale Schnittstelle zwischen präparativer Chemie und theoretischer Quantenphysik und trugen wesentlich zum Verständnis der magnetischen Eigenschaften seltener Erden bei.

Weitere Informationen finden Sie auf der Webseite des Museums https://www.auer-von-welsbach-museum.at/de/unser-museum/vortraege-veroeffentlichungen

TUE 4.5 Tue 15:15 ZHG004

Modular Setup for Coherent Control Experiments on NV Centers in Diamond — •David Ahlmer[1], Dennis Stiegekötter[1], Jonas Homrighausen[2], Marina Peters[2,3], Markus Gregor[2], and Peter Glösekötter[1] — [1]Department of Electrical Engineering and Computer Science, FH Münster, 48565 Steinfurt, Germany — [2]Department of Engineering Physics, FH Münster, 48565 Steinfurt, Germany — [3]Experimentalphysik, Universität des Saarlandes, 66123 Saarbrücken, Germany

Hands-on access to quantum state control experiments is often limited by cost and complexity. Initially kits allowing for experiments with NV centers have been presented. [1,2] We introduce a modular, 3D printable teaching platform that performs key experiments on colour centres in bulk diamond within a modular setup for educational purposes. The complete hardware costs about €500 split among electronics, cabling and optical components, making the system affordable for schools and undergraduate laboratories. The platform supports experiments to investigate optically detected magnetic resonance (ODMR), coherent Rabi oscillations, longitudinal relaxation (T1) and spin-echo coherence (T2) measurements on nitrogen-vacancy (NV) centres. Pulse sequences are generated by a microcontroller with a timing resolution of 53 ns [3]. By tuning the microwave drive power, the $\pi/2$-pulse duration can be set to integer multiples of this step size, enabling robust coherent spin control. [1] Stegemann, J. et al. Eur. J. Phys.44, 35402 (2023). [2] Haverkamp, N. et al. EPJ Quantum Technol. 12, 27 (2025). [3] Stiegekötter, D. et al. Sensors. 24, 3138 (2024).

TUE 4.6 Tue 15:30 ZHG004

Interaktive Spiele zur Vermittlung der Quantenmechanik in der Grund- und Sekundarbildung: Eine forschungsbasierte Entwicklung mit Scratch, Python, CSS und JavaScript — •João Marcos Brandet, Gabriel da Silva Cardoso, Fabrício Lorenzo Monfernatti Ramos und Vinicius Sanches da Luz — SEED, Londrina, Brazil

Diese Forschung präsentiert die Entwicklung und Validierung interaktiver Lernspiele zur Einführung der Quantenmechanik auf verschiedenen Ebenen der Grund- und Sekundarbildung. Die Spiele wurden kollaborativ von Lehrkräften und Schülern mithilfe von visueller Blockprogrammierung (Scratch) sowie textbasierten Programmiersprachen (Python, CSS und JavaScript) entwickelt. Ziel ist es, komplexe Konzepte der Quantenphysik durch spielerische und partizipative Methoden verständlich zu machen. Der Entwicklungsprozess basiert auf konstruktivistischen und konstruktionistischen Ansätzen und folgt den Prinzipien des Game-Based Learning sowie der Maker-Pädagogik. Die Validierung erfolgte durch Expertenanalysen, Usability-Tests und Pilotanwendungen in realen Unterrichtsszenarien. Erste Ergebnisse zeigen, dass die Spiele sowohl die Motivation als auch das konzeptuelle Verständnis der Schülerinnen und Schüler signifikant fördern. Dieses Projekt stellt einen innovativen Beitrag zur naturwissenschaftlichen Bildung dar und zeigt Wege auf, wie abstrakte Inhalte durch digitale Werkzeuge und kreative Lernumgebungen zugänglich gemacht werden können.

TUE 4.7 Tue 15:45 ZHG004

Über die Quantenkompetenz hinaus: Zukunft der Bildung in einer vernetzten Welt — •Zrinka Stimac — Leibniz-Institut für Bildungsmedien, Freisestr. 1, 38118 Braunschweig

Mit diesem Vortrag stelle ich das interdisziplinäre Projekt "Neue Menschenbilder, neues Denken? Quantentechnologie als Herausforderung der Bildung" vor und frage, ob quantenphilosophische Perspektiven die Zukunft der Bildung mitgestalten können. Im deutschen Kontext und aus geistes- und sozialwissenschaftlicher Perspektive analysiert das Projekt, wie Bildungssysteme auf die wachsende Präsenz von Quantentechnologien reagieren - insbesondere im Hinblick auf analoge und digitale Bildungsmedien sowie die Bedürfnisse der Bildungsakteure. Die Studie geht über die Vermittlung von Quantenkompetenz hinaus und untersucht, ob Konzepte wie Indeterminiertheit, Verschränkung und Relationalität neue Impulse für das fächerübergreifende Lernen geben können. Theoretisch stützt sie sich auf Arbeiten von Karen Barad, Ernst Cassirer, Matthias Jung und Lev Wygotsky. Statt einen konkreten pädagogischen Wandel zu fordern, eröffnet die Präsentation einen Raum für Reflexion: Könnten die konzeptuellen Rahmen der Quantentheorie dazu beitragen, Lehren, Lernen und Welterschließung anders zu denken? Anknüpfend an UNESCOs Vision von Wissenskonvergenz und zukünftigen Kompetenzen wird gefragt, was es bedeutet, Bildungskonzepte für eine vernetzte, nichtlineare und komplexe Zukunft zu gestalten.

TUE 5: QIP Certification and Benchmarking

Time: Tuesday 14:15–16:00 Location: ZHG006

TUE 5.1 Tue 14:15 ZHG006

Photonic Fidelity Witnesses — •Riko Schadow[1], Naomi Spier[2], Stefan N van den Hoven[2], Malaquias C Anguita[2], Redlef B G Braamhaar[2], Sara Marzban[2], Jens Eisert[1], Jelmer J Renema[2], and Nathan Walk[1] — [1]Freie Universität Berlin — [2]University of Twente

Certification and benchmarking represent a key challenge across all platforms for quantum information science and technology. A fundamental task in this regard is the verifiable creation of a particular quantum state. This can be accomplished via a fidelity witness - an empirical procedure that verifies with high probability that the experimentally prepared state has at least a certain fidelity with a desired target state. A promising avenue for experiments and applications is photonics, specifically the manipulation of photon number states through linear optics, which can directly demonstrate a quantum computational advantage via BosonSampling and, combined with adaptivity, universal, fault-tolerant quantum computation. Here, we design several sample-complexity efficient fidelity witnesses tailored to photonic systems and implement them on multi-photon entangled states generated by spontaneous parametric down-conversion sources injected into an integrated waveguide chip. We compare the witnesses in terms of required assumptions, closeness to the true fidelity and overall experimental effort. Using the best witnesses we certify sufficiently fidelities with highly entangled target states to verify the generated entanglement structure. We expect these tools to have further applications for quantum communication, computation and metrology.

TUE 5.2 Tue 14:30 ZHG006

Characterizing multimode linear optical devices via Scattershot Boson Sampling — •Cheeranjiv Pandey[1], Robert Schade[2], Jan-Lucas Eickmann[1], Jonas Lammers[1], Florian Lütkewitte[1], Fabian Schlue[1], Kai Hong Luo[1], Simone Atzeni[1], Mikhail Roiz[1], Christian Plessl[2], Benjamin Brecht[1], Michael Stefszky[1], and Christine Silberhorn[1] — [1]Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS) Warburger Str. 100, 33098, Paderborn, Germany — [2]Paderborn Center for Parallel Computing, Paderborn University, Warburger Str. 100, 33098 Paderborn, Germany

Photonics has recently emerged as a promising platform for implementing various quantum computational and communication schemes. At the heart of many such schemes lie multimode linear optical devices, composed of integrated arrays of beam splitters and phase shifters. Previous work has demonstrated that any arbitrary unitary matrix can be decomposed into an array of these components. Consequently, these devices can implement any unitary transformation between their input and output channels by precisely controlling the beam splitter transmissivities and phase shifter values. However, real devices often deviate from their ideal behavior due to fabrication imperfections and thermal cross-talk, making accurate device characterization essential. We showcase our ongoing research focused on developing characterization techniques that will allow us to reconstruct the unitary matrix implemented by such devices using data obtained from Scattershot Boson Sampling (SBS) experiments.

TUE 5.3 Tue 14:45 ZHG006

Probing Continuous Variable Quantum Interference with Photon Counting — •Fabian Schlue[1], Patrick Folge[1], Takefumi Nomura[2], Philip Held[1], Federico Pegoraro[1], Michael Stefszky[1], Benjamin Brecht[1], Stephen M. Barnett[3], and Christine Silberhorn[1] — [1]Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Paderborn University, Paderborn, Germany — [2]Department of Applied Physics, School of Engineering, The University of Tokyo, Tokyo, Japan — [3]School of Physics and Astronomy, University of Glasgow, Glasgow G4 8QQ, UK

The interference of squeezed quantum states on a balanced beam splitter is the most fundamental element in hybdrid photonic quantum computing circuits such as Gaussian boson sampling, where photon counting is deployed at the output of the circuit.

We demonstrate the generation of two independent single-mode squeezed states from the interference of two modes of a two-mode squeezed state from a dispersion-engineered parametric down-conversion source on a balanced beam splitter. We measure the joint photon-number statistics by using photon-number resolved coincidence detection. If the two modes are indistinguishable, the photon statistics become decorrelated, which we prove with different statistical measures. On the other hand, partial distinguishability gives rise to a richer structure that cannot be explained in a standard single-mode picture anymore.

Our investigations shed important insight into the inner workings of hybrid quantum photonic networks with many photons.

TUE 5.4 Tue 15:00 ZHG006

Benchmarking of Large Photonic Systems — •Jan-Lucas Eickmann[1], Jonas Lammers[1], Mikhail Roiz[1], Kai-Hong Luo[1], Simone Atzeni[1], Florian Lütkewitte[1], Fabian Schlue[1], Cheeranjiv Pandey[1], Timon Schapeler[2], Benjamin Brecht[1], Tim J. Bartley[2], Michael Stefszky[1], and Christine Silberhorn[1] — [1]Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Paderborn University, Warburger Str. 100, Paderborn 33098, Germany — [2]Department of Physics & Institute for Photonic Quantum Systems (PhoQS), Paderborn University, Warburger Str. 100, Paderborn 33098, Germany

Photonics is a promising platform for noisy intermediate-scale quantum technologies due to its scalability and room-temperature operation. Taking advantage of deterministic squeezed state generation in parametric down-conversion, Gaussian boson sampling (GBS) has been proven to be a scalable approach towards photonic quantum simulation. The scheme consists of many single-mode squeezed states that are sent into an interferometer, before measuring the photon-number outputs. However, many factors impact the performance, like photon loss, interference quality, and spectral single-modeness of the quantum light source, requiring detailed system characterization. We present methods to characterize large photonic quantum systems, focusing on benchmarking quantum state generation and interference as well as estimating total system efficiency. We apply these methods to characterize the Paderborn Quantum Sampler (PaQS), a 12-mode Gaussian boson sampling device that incorporates many integrated components.

TUE 5.5 Tue 15:15 ZHG006

Certifying Quantum Gates via dimensional advantage — •Anna Schroeder[1,2], Jan Nöller[1], Nikolai Miklin[3], Lucas B. Vieira[1], and Mariami Gachechiladze[1] — [1]Department of Computer Science, Technical University of Darmstadt, Darmstadt, Germany — [2]Merck KGaA, Darmstadt, Germany — [3]Institute for Quantum-Inspired and Quantum Optimization, Hamburg University of Technology, Germany

Certifying individual quantum devices efficiently and with minimal assumptions remains a significant challenge. Traditional device-independent approaches often rely on space-like separation or computational hardness assumptions, which are both difficult to realize in practice. Recently, a robust certification framework,*Quantum System Quizzing (QSQ),*has been introduced under the sole assumption of bounded dimension. This protocol uniquely identifies the underlying quantum model for a universal gate set.*Leveraging concepts from automata theory, we explore the dimension gap between classical and quantum models in deterministic protocols and characterize the classical simulation cost of the observed deterministic*responses. We identify a family of certification schemes that exhibit increasing quantum advantage and analyze their robustness in the presence of noise on quantum hardware.*Our approach shifts the focus from spatial correlations to deterministic tests in temporal scenarios, which are more amenable to implementation on NISQ devices, paving the way for reliable and resource-efficient quantum certification protocols.

TUE 5.6 Tue 15:30 ZHG006

SPAM-free sound certification of quantum gates via quantum system quizzing — •Nikolai Miklin[1], Jan Nöller[2], Martin Kliesch[1], and Mariami Gachechiladze[2] — [1]Hamburg University of Technology — [2]Technical University of Darmstadt

The rapid advancement of quantum hardware necessitates the development of reliable methods to certify its correct functioning. However, existing certification tests often fall short: they either rely on flawless state preparation and measurement, or fail to provide soundness guarantees, meaning that they do not ensure the correct implementation of the target operation by a quantum device. We introduce an approach, which we call quantum system quizzing, for certification of quantum gates in a practical server-user scenario, where a classical user tests the results of exact quantum computations performed by a quantum server. Importantly, this approach is free from state preparation and measurement (SPAM) errors. For a wide range of relevant gates, including a gate set universal for quantum computation, we demonstrate that our approach offers soundness guarantees based solely on the dimension assumption. Additionally, for a highly-relevant single-qubit phase gate - which corresponds experimentally to a pi/2-pulse - we prove that the method's sample complexity scales inverse-linearly relative to the average gate infidelity. By combining the SPAM-error-free and sound notion of certification with practical applicability, our approach paves the way for promising research into efficient and reliable certification methods for quantum computation.

TUE 5.7 Tue 15:45 ZHG006

A digital twin of atomic ensemble quantum memories — •Elizabeth Robertson[1], Benjamin Maass[1], Konrad Tschernig[1], and Janik Wolters[1,2,3,4] — [1]Institute of Space Research, German Aerospace Center, Berlin, Germany — [2]nstitutes of Physics, Technische Universität Berlin, Berlin, Germany — [3]Einstein Center Digital Future (ECDF) Berlin, Germany — [4]AQLS UG Haftungsbeschränkt, Germany

Performance estimation of experimentally demonstrated quantum memories is key for their deployment in quantum communication and quantum computing networks [1]. While existing platforms like Qiskit and Strawberry Fields enable quantum simulations, they do not natively account for the lossy and noisy nature of physical devices. We present a practical framework for modeling ensemble-based atomic quantum memories using the quantum channel formalism. By representing several state-of-the-art experimental memories with Kraus operators, we highlight key performance metrics of each of the memories and enable direct comparison between them. We further demonstrate the utility of this approach by simulating a memory-assisted quantum token protocol for authentication, for different experimentally demonstrated memories [2]. [1] Gündoğan, M. et al. Proposal for space-borne quantum memories for global quantum networking. npj Quantum Inf 7, 128 (2021) [2] Manuscript in preparation.

TUE 6: Quantum Computing and Communication: Contributed Session I (Algorithms & Theory)

Time: Tuesday 14:15–16:00 Location: ZHG007

TUE 6.1 Tue 14:15 ZHG007

Measurement-driven quantum advantages in shallow circuits — •Chenfeng Cao[1] and Jens Eisert[1,2] — [1]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — [2]Helmholtz-Zentrum Berlin für Materialien und Energie, 14109 Berlin, Germany

Quantum advantage schemes probe the boundary between classically simulatable quantum systems and those that computationally go beyond this realm. Here, we introduce a constant-depth measurement-driven approach for efficiently sampling from a broad class of dense instantaneous quantum polynomial-time circuits and associated Hamiltonian phase states, previously requiring polynomial-depth unitary circuits. Leveraging measurement-adaptive fan-out staircases, our "dynamical circuits" circumvent light-cone constraints, enabling global entanglement with flexible auxiliary qubit usage on bounded-degree lattices. Generated Hamiltonian phase states exhibit statistical metrics indistinguishable from those of fully random architectures. Additionally, we demonstrate measurement-driven globally entangled feature maps capable of distinguishing phases of an extended SSH model from random eigenstates using a quantum reservoir-computing benchmark. Technologically, our results harness the power of mid-circuit measurements for realizing quantum advantages on hardware with a favorable topology. Conceptually, we highlight their power in achieving rigorous computational speedups.

TUE 6.2 Tue 14:30 ZHG007

A quantum protocol for applying arbitrary phase transformations — Siavash Davani[1,2] and •Falk Eilenberger[3,1,2] — [1]Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University Jena, 07745 Jena, Germany — [2]Max Planck School of Photonics, 07745 Jena, Germany — [3]Fraunhofer-Institute for Applied Optics and Precision Engineering, 07745 Jena, Germany

The standard approach to developing algorithms for quantum computers involves constructing a sequence of unitary gates to manipulate a quantum register. We show an alternative approach that directly uses quantum information stored in memory as instructions and performs a transformation on a register based on the state of the instruction state. This enables programming quantum computers by encoding different instructions as quantum information in the memory. The approach unifies the role of memory in quantum computers as containing both data and software similar to the von Neumann architecture in classical computers. Using this technique, we introduce a protocol capable of arbitrary phase transformations on wavefunctions, allowing for the simulation of large classes of Hamiltonians on quantum computers. The protocol functions by temporarily entangling the instruction and data registers, and it consumes the instruction state during the process.

TUE 6.3 Tue 14:45 ZHG007

Quantum Approximate Optimization via Weak Measurements — •Tobias Stollenwerk[1] and Stuart Hadfield[2] — [1]Forschungszentrum Jülich — [2]NASA Quantum Artificial Intelligence Laboratory

Algorithms based on non-unitary evolution have attracted much interest for ground state preparation on quantum computers. One recently proposed method makes use of ancilla qubits and controlled unitary operators to implement weak measurements related to imaginary-time evolution. In this work we specialize and extend this approach to the setting of combinatorial optimization. We first generalize the algorithm from exact to approximate optimization. We then show how to modify the paradigm to the setting of constrained optimization for a number of important classes of hard problem constraints. For this we adapt the algorithm to penalty-based approaches and elucidate the resource overhead. As an alternative approach we show how one may design and employ operators that preserve the subspace of feasible problem solutions in order to to avoid the overhead of penalty terms. In particular, we show that mixing operators from the quantum alternating operator ansatz may be directly imported, both for the necessary eigenstate scrambling operator and for initial state preparation, and discuss quantum resource tradeoffs. Finally, we consider the effects of hardware noise and propose further algorithmic variants towards ameliorating its effects.

TUE 6.4 Tue 15:00 ZHG007

State Specific Measurement Protocols for the Variational Quantum Eigensolver — •Davide Bincoletto — University of Augsburg, Augsburg, Germany

A central roadblock in the realization of variational quantum eigensolvers on quantum hardware is the high overhead associated with measurement repetitions, which hampers the computation of complex problems, such as the simulation of mid- and large-sized molecules. In this work, we propose a novel measurement protocol which relies on computing an approximation of the Hamiltonian expectation value. The method involves measuring cheap grouped operators directly and estimating the residual elements through iterative measurements of new grouped operators in different bases, with the process being truncated at a certain stage. The measured elements comprehend the operators defined by the Hard-Core Bosonic approximation, which encode electron-pair annihilation and creation operators. These can be easily decomposed into three self-commuting groups which can be measured simultaneously. Applied to molecular systems, the method achieves a reduction of 30% to 80% in the number of measurement and gates depth in the measuring circuits compared to state-of-the-art methods. This provides a scalable and cheap measurement protocol, advancing the application of variational approaches for simulating physical systems.

TUE 6.5 Tue 15:15 ZHG007

A complexity theory for non-local quantum computation — •Simon Höfer[1], Andreas Bluhm[1], Alex May[2,3], Mikka Stasiuk[2], Philip Verduyn Lunel[4], and Henry Yuen[5] — [1]Univ. Grenoble Alpes, CNRS, Grenoble INP, LIG — [2]Perimeter Institute for Theoretical Physics — [3]Institute for Quantum Computing, Waterloo, Ontario — [4]Sorbonne Université, Paris — [5]Columbia University

Non-local quantum computation (NLQC) replaces a local interaction between two systems with a single round of communication and shared entanglement.

Despite many partial results, it is known that a characterization of entanglement cost in at least certain NLQC tasks would imply significant breakthroughs in complexity theory, so we take an indirect approach to understanding resource requirements in NLQC, by studying the relative hardness of different NLQC tasks by identifying resource efficient reductions between them.

Most significantly, we prove that f-measure and f-route, the two best studied NLQC tasks, are in fact equivalent under reductions, with only constant overhead in the entanglement cost, regardless of the function f.

This result simplifies many existing proofs in the literature and extends several new properties to f-measure, such as sub-exponential upper bounds on entanglement cost.

Beyond this, we study a number of other examples of NLQC tasks and their relationships.

TUE 6.6 Tue 15:30 ZHG007

Application of quantum computing in Life Sciences - a Case Study — •Klaus Mayer, Artemiy Burov, Clément Javerzac-Galy, and Oliver Mülken — School of Life Sciences, FHNW Fachhochschule Nordwestschweiz, Hofackerstr. 30, 4132 Muttenz, Switzerland

We study the practical application of currently available intermediate-scale Quantum Computers in the Life Sciences context [1]. Among the various conceivable applications where quantum utility or even advantage may be achieved, Hamiltonian simulation is among the most relevant.

As a concrete example, we explore the applicability of modern quantum computing algorithms (such as Qubitization and Quantum Signal Processing) to the simulation of nuclear magnetic resonance (NMR) spectra, which are highly relevant, for instance, in the field of protein characterization for drug discovery or in the material sciences. To this end, a Heisenberg Hamiltonian for liquid-state NMR is mapped to a higher-dimensional unitary which can be implemented in a Quantum Computer. We investigate resource scaling of the implementation and compare our results to product formula implementations [2].

[1] K. Mayer, A. Burov, C. Javerzac-Galy, O. Mülken (2025), *to be submitted*
[2] A. Burov, O. Nagl, C. Javerzac-Galy (2024), *arXiv:2404.17548*

TUE 6.7 Tue 15:45 ZHG007

Beyond Classical Approximation Guarantees in the NISQ Era
— •Chinonso Onah[1,2] and Kristel Michielsen[2,3] — [1]Volkswagen Group, Germany — [2]Department of Physics, RWTH Aachen, Germany — [3]Forschungszentrum Jülich, Germany

We present the first constant-low-depth, ancilla-free constrained QAOA variant that (1) provably concentrates inverse-polynomial probability on the target bit-strings, (2) exponentially outperforms generic QAOA at any depth by massively boosting the probability of legal solutions, (3) amplifies any generic QAOA parameter set by a super-exponential factor, and (4) serves as the quantum core of an Exact Hybrid Quantum*Classical solver that is a fully-polynomial randomized approximation scheme whose success probability*and additive-gap performance under Hungarian repair*cannot be matched by any polynomial-time classical sampler unless NP is contained in BPP. On the QOPTLib TSP benchmark (all instances up to one hundred qubits that fit on today*s superconducting hardware), our solver recovers or improves upon every previously published tour*achieving up to a 12.3 percent shorter route on the hardest instance. This dramatic gain on the most challenging benchmarks underlines the practical promise of our approach on near-term devices.

TUE 7: Entanglement and Complexity: Contributed Session to Symposium I

Time: Tuesday 14:15–15:45 Location: ZHG008

TUE 7.1 Tue 14:15 ZHG008

Experimental Demonstration of Electron-Photon Entanglement
— •Sergei Bogdanov[1,2], Alexander Preimesberger[1,2], Isobel C. Bicket[1,2], Phila Rembold[1], and Philipp Haslinger[1,2] — [1]Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Vienna, Austria — [2]University Service Centre for Transmission Electron Microscopy (USTEM), TU Wien, Vienna, Austria

Quantum entanglement, a fundamental resource for quantum technologies, describes correlations between particles that cannot be explained by classical physics. While transmission electron microscopes (TEMs) are well-established tools with exceptional spatial resolution, their potential for exploring quantum correlations remains largely underexplored. In this study, we demonstrate entanglement between electrons and photons generated via cathodoluminescence inside a TEM. To produce correlated electron-photon pairs we use a TEM working at 200 keV to illuminate a 50 nm silicon membrane. Inelastic scattering of electrons may lead to the emission of cathodoluminescent coherent photons. Due to energy and momentum conservation, transmitted electrons and emitted photons are correlated in position and momentum. A custom-made parabolic mirror directs the photons out of the TEM to an optical detection system. To perform coincidence measurements, an absorptive grating mask is used as the object for ghost image formation. We reconstruct near- and far-field "ghost" images of the periodic masks and show a violation of the classical uncertainty bound. Hence, we demonstrate position-momentum entanglement of electron-photon pairs, bridging quantum optics and electron microscopy.

TUE 7.2 Tue 14:30 ZHG008

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

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

TUE 7.3 Tue 14:45 ZHG008

Why Quantum Mechanics needs 'Hidden' Variables
— •Wolfgang Paul — Martin-Luther-Universität Halle-Wittenberg, Institut für Physik, 06099 Halle

One early culmination point of the discussion on whether the Hilbert space description of quantum mechanics can be considered complete or not are the famous breakfast and dinner conversations between Bohr and Einstein during the 5th Solvay Conference 1927. While Einstein thought that it should be augmented by ontological objects (hidden variables) Bohr insisted that this can not be done.

Bohr was well aware that he declared the death of a good part at the heart of physics as it had been established for the preceding 300 years: his position denied quantum physics the ability to model the measurement process and reduced it to the accounting of measurement results.

Based on Nelson's stochastic mechanics approach [1], one can formulate a model of particles with spin as possessing position and orientation degrees of freedom and describe the measurement process in the Stern Gerlach experiment as well as the Einstein-Podolski-Rosen-Bohm thought experiment [2]. The outcome statistics agree with the Hilbert space quantum mechanical predictions, even reproducing the violation of Bell's inequalities, but in addition the complete measurement process can be followed in a time-resolved manner, so there is no measurement problem any more.

[1] E. Nelson, Phys. Rev. **150**, 1079 (1966)
[2] M. Beyer, W. Paul, Found. Phys. **54**, 20 (2024)

TUE 7.4 Tue 15:00 ZHG008

The dynamic meaning of the Lorentz transforms of mass and time
— •Grit Kalies[1] and Duong D. Do[2] — [1]HTW University of Applied Sciences, Dresden, Germany — [2]The University of Queensland, Brisbane, Australia

We describe acceleration as a complex process in which a particle or body changes several of its properties, not just its momentum. Consequently, during acceleration, several forms of energy of an object change, not just its motion energy, which means that its so-called rest energy becomes Lorentz-variant. This insight is made possible by representing particles as physical waves and by applying thermodynamic principles to individual quantum objects, whose property changes are described by several simultaneously occurring forms of quantum work. The results form the basis for the emerging field of quantum-process thermodynamics.

TUE 7.5 Tue 15:15 ZHG008

Role of Nonstabilizerness in Quantum Optimization
— •Chiara Capecci[1,2], Gopal Chandra Santra[1,2], Alberto Bottarelli[1,2], Emanuele Tirrito[3], and Philipp Hauke[1,2] — [1]Pitaevskii BEC Center, CNR-INO and Department of Physics, University of Trento, Via Sommarive 14, I-38123 Trento, Italy — [2]INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Via Sommarive 14, I-38123 Trento, Italy — [3]The Abdus Salam International Centre for Theoretical Physics (ICTP), Strada Costiera 11, 34151 Trieste, Italy

Quantum optimization is a promising method for tackling complicated classical problems using quantum devices. However, the extent to which these algorithms exploit genuine quantum resources and the role of these resources remain open questions. We investigate the resource requirements of the Quantum Approximate Optimization Algorithm (QAOA) using nonstabilizerness measurements. We demonstrate that nonstabilizerness increases with circuit depth, reaches a maximum, then decreases approaching the solution state — creating a barrier that limits algorithm's capability for shallow circuits. We find that curves for different depths collapse under simple rescaling and uncover a relationship between final nonstabilizerness and success probability. A similar barrier is found in quantum annealing. These results clarify how quantum resources influence quantum optimization.

TUE 7.6 Tue 15:30 ZHG008

Rethinking Quantization: Toward a Local, Realistic Interpretation — •Falk Rühl — D52159 Roetgen, Auf der Alm 14

More than a century after the birth of quantum theory, its formalism has matured, but its interpretation remains entangled with the early 20th-century notion of 'early quantization'. In this conventional view, central to the Copenhagen interpretation, proposed by A. Einstein and N. Bohr, quanta are treated as discrete property carrying objects, generated at sources and transmitted without loss to distant targets.

In this talk, I will present an alternative framework: 'late quantization'. Here, quantum phenomena arise not from the emission, transfer, and absorption of discrete quanta, but from the interaction of radiation from all possible sources, with continuously evolving states of the targets themselves. This shift allows for a local and realistic interpretation of quantum processes, dispensing with the need for non-locality, wave-function collapse, or quantum jumps.

A key feature of this approach is that efficient detection of sources only occurs, when the source radiation drives closed cycles in the target's state space. This makes only a small subset of the continuously evolving 'beable' states of sources 'observable' states.

This new interpretation not only provides conceptual clarity but also eliminates longstanding quantum puzzles within a fully local and deterministic framework.

TUE 8: Correlated Quantum Matter: Contributed Session to Symposium I

Time: Tuesday 14:15–16:00 Location: ZHG009

TUE 8.1 Tue 14:15 ZHG009

Optical signatures of dynamical excitonic condensates — •Alexander Osterkorn[1], Yuta Murakami[2], Tatsuya Kaneko[3], Zhiyuan Sun[4], Andrew J. Millis[5,6], and Denis Golež[1,7] — [1]Jožef Stefan Institute, Ljubljana, Slovenia — [2]RIKEN, Wako, Japan — [3]Osaka University, Toyonaka, Japan — [4]Tsinghua University, Beijing, P.R. China — [5]Columbia University, New York, USA — [6]Flatiron Institute, New York, USA — [7]University of Ljubljana, Ljubljana, Slovenia

Excitons, or bound electron-hole pairs, can condense into an excitonic insulator state, similarly to Cooper pairs in superconductors. A nonequilibrium carrier concentration, such as the one transiently induced by photo-doping or sustained by a tuneable bias voltage in bilayers, can create a dynamical excitonic insulator state. However, proving phase coherence in such setups remains challenging. We examine the condensate phase behavior theoretically and show that optical spectroscopy can distinguish between phase-trapped and phase-delocalized dynamical regimes. In the weak-bias regime, trapped phase dynamics result in an in-gap absorption peak nearly independent of bias voltage, while at higher biases its frequency increases approximately linearly. In the large bias regime, the response current grows strongly under the application of a weak electric probe leading to negative weight in the optical response, which we analyze relative to predictions from a minimal model for the phase. This work opens new avenues for experimentally probing coherence in excitonic condensates and the detection of their dynamical regimes. Preprint: arXiv:2410.22116

TUE 8.2 Tue 14:30 ZHG009

Dissipative loading of ultracold atom tweezer arrays — •Lara Giebeler[1], Alexander Schnell[1], Monika Aidelsburger[2,3,4], and André Eckardt[1] — [1]Institute for Physics and Astronomy, Technical University Berlin — [2]Munich Center for Quantum Science and Technology — [3]Max-Planck-Institut für Quantenoptik — [4]Fakultät für Physik, LMU Munich

Using ultracold atoms in quantum computing and simulation often requires arbitrary single-atom control, typically achieved with optical tweezer arrays. However, defect-free loading of large-scale arrays remains challenging due to the slow speed of adiabatic preparation methods.

To overcome these limitations, in this work we introduce a dissipative scheme for loading fermionic atoms into tweezers, mediated by lasercoupled interactions with a fermionic bath. In particular, we explore the trade-off between loading time and efficiency depending on the system bath coupling and the impact of reservoir size and temperature.

TUE 8.3 Tue 14:45 ZHG009

A general scheme for detecting phases of lattice-confined ultracold atomic clouds — •Niklas Euler[1,2], Christof Weitenberg[3], and Martin Gärttner[1] — [1]Institut für Festkörpertheorie und Optik, FSU Jena, Jena — [2]Physikalisches Institut, Universität Heidelberg, Heidelberg — [3]Fakultät Physik, TU Dortmund, Dortmund

Over the past decade, quantum-gas microscopes have become an invaluable tool for cold-atom experiments, delivering unprecedented single-site resolution. The now available high-precision density measurements have been used successfully to probe strongly correlated quantum matter, perform quantum simulation tasks, or investigate out-of-equilibrium dynamics, among other applications. However, reconstructing phase distributions of ultracold atomic clouds from matter-wave images has remained challenging, especially for large phase fluctuations. Here, we propose a new measurement scheme that reliably reconstructs initial-state phases and density fluctuations from a single matter-wave inference image in an efficient manner. Our method works by decomposing the initial state into individual spatially localized modes and evolving them independently, which is well justified in the regime of weak nonlinear interactions. Furthermore, by comparing the reconstructed image with measurement data, the plausibility of the resulting distributions can easily be verified. Finally, we show first numerical results, demonstrating that our method is robust under typical experimental conditions.

TUE 8.4 Tue 15:00 ZHG009

Modelling of collisional spin entanglement beyond the Born-Markov approximation — •Robert Weiss[1], Scott Parkins[2,3], Mikkel F. Andersen[3,4], and Sandro Wimberger[5,6] — [1]Institut für theoretische Physik, Universität Heidelberg — [2]Department of Physics, University of Auckland — [3]Dodd-Walls Centre for Photonic and Quantum Technologies — [4]Department of Physics, University of Otago — [5]Department of Mathematical, Physical and Computer Sciences, Parma University — [6]INFN, Sezione Milano-Bicocca, Parma group

It was shown experimentally that colliding cold atoms produce entanglement between their spin states [1]. A thorough theoretical foundation and prediction was restricted in modelling the internal and external atomic degrees of freedom due to computational constraints. We demonstrate why established analytical techniques restricting to the spins only and relying on the Born-Markov approximation fail to reproduce the experimental results. The Markov approximation is not applicable because the correlations in the motional degree of freedom do not decay on a short enough time scale. The Born approximation is questionable as the interatomic interaction is too strong. Numerical models are presented which capture the observed dynamics well including non-Markovian effects and the relative motion.

[1] P. Sompet et. al., Nat. Comm. **10**, 1889 (2019)

TUE 8.5 Tue 15:15 ZHG009

Universal theory for heavy impurities in ultracold Fermi gases — •Eugen Dizer, Xin Chen, Emilio Ramos Rodriguez, and Richard Schmidt — Institut für Theoretische Physik, Universität Heidelberg, D-69120 Heidelberg, Germany

Single impurities immersed in a degenerate Fermi gas exhibit fascinating many-body phenomena, such as the polaron-to-molecule transition and Anderson's orthogonality catastrophe (OC). It is known that mobile impurities of finite mass can be described as quasiparticles, so called Fermi polarons. In contrast, Anderson showed in 1967 that the ground state of a static, infinitely heavy impurity in a Fermi sea is orthogonal to the ground state of the system without impurity - a hallmark of the OC and a fundamentally non-perturbative effect. As a result, conventional variational approaches or path integral methods fail to capture this phenomenon accurately. Despite decades of research, a unified approach connecting the quasiparticle description of Fermi polarons with Anderson's OC has remained elusive. In this work, we present a theoretical framework for arbitrary-mass impurities in a Fermi sea that incorporates Anderson's OC, the polaron-to-molecule transition and the quasiparticle picture. Our theory provides new insights into the nature of impurity physics and many-body correlations, describing how quasiparticle behavior and the polaron-to-molecule transition emerge from the OC.

TUE 8.6 Tue 15:30 ZHG009

Quantum phases of bosonic mixture with dipolar interaction — •Rukmani Bai and Luis Santos — Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstrasse 2, D-30167 Hannover, Germany

Ultracold dipoles in optical lattices, characterized by strong inter-site interactions, open new possibilities for ground-state phases as well as an intriguing dynamics. Recent experiments on dipolar mixtures of magnetic lanthanide atoms are especially interesting, not only due to the dipolar interaction, but also because these atoms are particularly suitable for realizing component-dependent lattices. Using a combination of DMRG and cluster Gutzwiller methods, we study the ground-state physics that may result when the two components experience mutually intertwined optical lattices, which resemble interacting bilayer geometries.

TUE 8.7 Tue 15:45 ZHG009

Static impurity in a mesoscopic system of SU(N) fermionic matter-waves — •Juan Polo[1], Wayne Chetcuti[1], Andreas Osterloh[1], Anna Minguzzi[3], and Luigi Amico[1,2] — [1]Quantum Research Center, Technology Innovation Institute, Abu Dhabi 9639, UAE — [2]Dipartimento di Fisica e Astronomia Ettore Majorana University of Catania, Via S. Sofia 64, 95123 Catania, Italy — [3]Université Grenoble Alpes, CNRS, LPMMC, 38000 Grenoble, France

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

TUE 9: Quantum Physics in Strong Fields: Contributed Session to Symposium

Time: Tuesday 14:15–16:15 Location: ZHG101

TUE 9.1 Tue 14:15 ZHG101

LUXE: a high-precision experiment to study non-perturbative QED in electron-laser and photon-laser collisions — •Tom Blackburn — Department of Physics, University of Gothenburg, 41296 Gothenburg, Sweden

The Laser Und XFEL Experiment (LUXE), in planning at DESY Hamburg, is intended to study quantum electrodynamics (QED) in strong electromagnetic fields, and in particular the transition from perturbative to non-perturbative. In the non-perturbative regime, electron-positron pairs tunnel out of the vacuum in a manner akin to the Schwinger process. The experiment will make precision measurements of the photon and positron rates in collisions between a high-intensity laser pulse and the 16.5 GeV electron beam of the European XFEL, or the high-energy secondary photons it produces. This talk will provide an overview and update on the work of the LUXE collaboration, as the experiment moves towards implementation.

TUE 9.2 Tue 14:30 ZHG101

The Quantum Superluminality of Tunnel-ionization — •Ossama Kullie[1] and Igor Ivanov[2] — [1]Department of Mathematics and Natural Sciences. University of Kassel, 34132 Kassel, Germany. — [2]Department of Fundamental and Theoretical Physics, Australian National University, Australia

Tunneling is one of the most interesting phenomena in quantum physics. In our tunnel-ionization model [1, 2, 3], we have shown that the time-delay of the adiabatic and nonadiabatic tunnel-ionization determines the barrier time-delay in a good agreement with the attoclock measurement and that it corresponds to the dwell time and the interaction time. In the present work, we show that the barrier time-delay for H-like atoms with a large nuclear charge can be superluminal (quantum superluminality), which can be experimentally validated using the attoclock scheme. Furthermore, we accompany our model with the numerical integration of time-dependent Schödinger equation (NTTDSE), where we expect good agreement with our model as in earlier work [2]. We investigate the quantum superluminality for the different experimental calibrations (adiabatic and nonadiabatic tunnel-ionization) of the attoclock [4] and discuss its interpretation. [1] O. Kullie, J. Phyis. Commun. 9, 015003, (2025). [2] O. Kullie and I. Ivanov, Annals of Physics 464, 169648 (2024). [3] O. Kullie, Annals of Physics 389, 333 (2018). [4] O. Kullie and I. A. Ivanov, Quantum superluminality of Tunnel-Ionization. In preparation.

TUE 9.3 Tue 14:45 ZHG101

Theoretical strong-field quantum physics in Dresden: An Overview — •Christian Kohlfürst — Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany

We provide an overview of the research area of strong-field quantum electrodynamics, focusing particularly on the topics covered by the Strong-Field research group within the Institute of Theoretical Physics at the Helmholtz-Zentrum Dresden Rossendorf. Special emphasis is placed on non-equilibrium quantum dynamics and the scattering of light by light.

TUE 9.4 Tue 15:00 ZHG101

Femtosecond and attosecond correlations in multi-electron pulses — •Rudolf Haindl[1,2], Valerio Di Giulio[1,2], Armin Feist[1,2], and Claus Ropers[1,2] — [1]Max Planck Institute for Multidisciplinary Sciences, Göttingen, Germany — [2]4th Physical Institute, University of Göttingen, Göttingen, Germany

Correlations between electrons are at the core of numerous phenomena in atomic, molecular, and solid-state physics. In femtosecond electron emission from nanoscale field emitters, Coulomb interactions result in structured few-electron states with strong correlations in energy [1,2], transverse momentum [2], and time[3].

In this contribution [4], we combine femtosecond-gated, event-based detection with inelastic electron-light scattering to directly map the photoelectron phase-space distribution of two-electron states. Our experiments demonstrate a bimodal structure in longitudinal phase space, with distinct contributions from interparticle interaction and dispersion. Moreover, we theoretically reveal that global phase modulation coherently shapes the few-electron phase-space distribution to exhibit attosecond temporal correlations. This controlled phasing of few-electron states leads to a multi-electron quantum walk and can be harnessed to produce tailored excitations and super-radiance via two-electron energy post-selection.

[1] R. Haindl et al., *Nat. Phys.* **19**, 1410-1417 (2023).
[2] S. Meier et al., *Nat. Phys.* **19**, 1402-1409 (2023).
[3] J. Kuttruff et al., *Sci. Adv.* **10**, eadl6543 (2024).
[4] R. Haindl et al., *arXiv*, arXiv:2412.11929 (2024).

TUE 9.5 Tue 15:15 ZHG101

Quantum simulation of strong field phenomena and curved spaces in deformed optical lattices — •Nikodem Szpak — Faculty of Physics, University of Duisburg-Essen

Low energy excitations in specially designed optical lattice systems can behave like relativistic particles. Inhomogeneous perturbations of these lattices can give rise to effective coupling to artificial electromagnetic fields and curvature. We give a review of interesting strong field phenomena, like spontaneous pair creation or graviational lensing, still not accessible in direct experiments, which can be simulated with cold atoms in finite size optical lattices.

TUE 9.6 Tue 15:30 ZHG101

Scattering matrix approach to dynamical Sauter-Schwinger process: vortex- vs. spiral structures — •Mateusz Majczak, Katarzyna Krajewska, Jerzy Kamiński, and Adam Bechler — Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

The dynamical Sauter-Schwinger mechanism of electron-positron (e^-e^+) pair creation by electric field pulses is considered using the S-matrix approach and reduction formulas. They lead to the development of framework that treats the external electric field to all orders and is based on the solutions of the Dirac equation with the so-called Feynman- or anti-Feynman boundary conditions. The asymptotic properties of those solutions are linked to the electron and positron spin(helicity)-resolved probability amplitudes. Most importantly, the corresponding spin- or helicity-resolved distributions, when summed over spin or helicity configurations, reproduce the momentum distributions of created particles calculated with other methods that are typically used in this context, such as the DHW function approach. In contrast to those approaches, however, the S-matrix method provides the information about the phase of the probability amplitude of e^-e^+ pair creation. Therefore, it allows one to study the vortex- and spiral structures in momentum distributions of produced particles. As it follows from our numerical studies, a momentum spiral is created as a result of the vortex-antivortex annihilation. Moreover, as we show, in order to observe such annihilation one has to drive the pair creation with electric field pulses of the time reversal symmetry.

TUE 9.7 Tue 15:45 ZHG101

Vortex Structures and Spin Effects in Dynamical Schwinger Process — •Wojciech Smialek[1], Mateusz Majczak[1], Adam Bechler[1], Jerzy Kamiński[1], Carsten Müller[2], and Katarzyna Krajewska[1] — [1]Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Poland — [2]Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, Germany

The dynamical Schwinger effect offers a unique opportunity to probe the nonperturbative regime of QFT under controlled conditions. While the spectra and yields of particles created in this process have been studied in great detail, the currently dominant tools for nonperturbative analysis of this process within QED do not allow for a full examination of the spin properties of the created pairs.

In order to study the angular momentum effects in the dynamical Schwinger process, we present a novel S-matrix-based formalism that grants access to the full information about the state of the created pairs through spin-resolved probability amplitudes. This formalism has been adapted to Dirac and Klein-Gordon fields to provide further insight into spin effects.

Our numerical analysis reveals the occurrence of vortical phase singularities in the complex probability amplitude of spinor and scalar pairs when the QED vacuum is exposed to a circularly polarized electric field. The occurrence of phase vortices is linked to a nonvanishing orbital angular momentum carried by the particles, and as we show, the structure of vortices for fermionic and bosonic pairs complies with the principle of angular momentum conservation.

TUE 9.8 Tue 16:00 ZHG101

Photon-graviton conversion in a magnetic field — •Naser Ahmadiniaz — Helmholtz Zentrum Dresden Rossendorf, Dresden, Germany

In this talk, I will first give a brief overview of the worldline formalism, a first-quantized approach to quantum field theory that streamlines the computation of scattering amplitudes in gauge theory and gravity. This method is particularly well suited to incorporating background fields non-perturbatively and reveals the underlying geometric structure of amplitudes. The main focus will be on photon–graviton conversion in an external magnetic field. While this process is typically studied at tree level, one-loop corrections due to scalar and spinor fields have also been computed. Unlike the tree-level result, the one-loop amplitude exhibits a dependence on the photon polarization, leading to vacuum dichroism. I will present a worldline-based derivation of this one-loop effect and show how the formalism naturally captures the emergence of dichroism. Furthermore, I will discuss the role of a previously neglected tadpole contribution. Although such diagrams often vanish in conventional treatments, we find that in this context the tadpole gives a finite contribution to the amplitude that must be included to obtain a complete result.

TUE 10: Foundational / Mathematical Aspects – Rigorous Results

Time: Tuesday 14:15–16:15 Location: ZHG103

TUE 10.1 Tue 14:15 ZHG103

Classicality enforced by consistent value assignments — •Giuseppe Antonio Nisticò — University of Calabria, Rende, Italy

The problem of the "emergence of classicality", in rough synthesis, consists in explaining why "macroscopic" systems behave obeying classical laws rather than quantum laws. The present work pursues an approach to this problem alternative to the typical approaches in the literature. The basic step is to identify the deepest origin of non-classicality in the empirically ascertained impossibility of a simultaneous value assignment to all quantum observables. Specific macrosopicity conditions are introduced, which characterize the physical system as rigid homogeneous body. These conditions enforce the possibility of extending the value assignment provided by actually performed measurements to both the position and the velocity of the center of mass of the body, without loosing empirical and quantum theoretical consistency. This made possible by the use of the quantum concept of "evaluation" developed in [Int.J.Theor.Phys., 55 1798 (2016)]. Under regularity conditions for the interaction, it is proved that a center of mass trajectory can be consistently assigned by quantum theory, which satisfies the classical laws of motion.

TUE 10.2 Tue 14:30 ZHG103

In a closed universe, orbital angular momentum has non-integer values — •Daniel Burgarth[1] and Paolo Facchi[2] — [1]Friedrich Alexander University — [2]Bari University

We show that the spectrum of orbital angular momentum in quantum mechanics is the union of two parts when the underlying space has periodic boundaries. While the first part corresponds to the usual textbook integer quantized values, the second is a continuous band arising from the edge of space with respect to the center of rotation. The spectrum thus contains not only half-integer values (often thought impossible for orbital angular momentum), but even irrational ones. This effect is independent of the size of space. We argue that such spectral components would be invisible in the laboratory but might nonetheless have observable consequences on the cosmic scale.

TUE 10.3 Tue 14:45 ZHG103

Proof of the ionization conjecture for Engel-Dreizler atoms — •Heinz Siedentop — Mathematisches Institut, Ludwig-Maximilians-Universität München, Theresienstr. 39, 80333 München

We show that the number of electrons that an atom described by the relativistic density functional introduced by Engel and Dreizler is bounded uniformly in Z. The presentation is based on joined work with Rafael Benguria, Santiago, Chile.

TUE 10.4 Tue 15:00 ZHG103

Robust quantification of spectral transitions in perturbed quantum systems — Zsolt Szabó[1,2], Stefan Gehr[3], Paolo Facchi[4,5], Kazuya Yuasa[6], Daniel Burgarth[3], and •Davide Lonigro[3] — [1]School of Mathematical and Physical Sciences, Mac-

quarie University, NSW 2109, Australia — [2]ARC Centre of Excellence for Engineered Quantum Systems, Macquarie University, NSW 2109, Australia — [3]Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstraße 7, 91058 Erlangen, Germany — [4]Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy — [5]INFN, Sezione di Bari, I-70126 Bari, Italy — [6]Department of Physics, Waseda University, Tokyo 169-8555, Japan

A quantum system subject to an external perturbation can experience leakage between uncoupled regions of its energy spectrum separated by a gap. To quantify this phenomenon, we present two complementary results. First, we establish time-independent bounds on the distances between the true dynamics and the dynamics generated by block-diagonal effective evolutions constructed via the Schrieffer-Wolff and Bloch methods. Second, we prove that, under the right conditions, this leakage remains small eternally. That is, we derive a time-independent bound on the leakage itself, expressed in terms of the spectral gap of the unperturbed Hamiltonian and the norm of the perturbation, ensuring its validity for arbitrarily large times. Our approach only requires the existence of a finite spectral gap, thus accommodating continuous and unbounded spectra.

Based on arXiv:2505.19904.

TUE 10.5 Tue 15:15 ZHG103

Lie symmetries and ghost-free representations of the Pais-Uhlenbeck model — •Alexander Felski — Max Planck Institute for the Science of Light, Erlangen, Germany

Ghost-ridden quantum systems manifest in various forms. Typically, this means that parts of their spectra are not bounded from below or that they contain non-normalisable states, leading to a violation of unitarity. We investigate the Pais-Uhlenbeck model, a prominently ghost-ridden system and paradigmatic example of a higher time-derivative theory, by identifying the Lie symmetries of its associated fourth-order dynamical equation. Exploiting these symmetries in conjunction with the model's Bi-Hamiltonian structure, we construct distinct Poisson bracket formulations that preserve the system's dynamics. This allows us to recast the Pais-Uhlenbeck model in a positive definite manner, offering a solution to the long-standing problem of ghost instabilities. Furthermore, we systematically explore a family of transformations that reduce the Pais-Uhlenbeck model to equivalent first-order, higher-dimensional systems. Our approach yields a unified framework for interpreting and stabilizing higher time-derivative dynamics through a symmetry analysis.

TUE 10.6 Tue 15:30 ZHG103

Macroscopic Hall-Current Response in Infinite-Volume Systems — •Marius Wesle[1], Giovanna Marcelli[2], Tadahiro Miyao[3], Domenico Monaco[4], and Stefan Teufel[1] — [1]Universität Tübingen, Germany — [2]Università di Roma Tre, Italy — [3]Hokkaido University, Japan — [4]Sapienza Università di Roma, Italy

Given a 2-dimensional system of interacting fermions, the Hall-conductivity is defined as the linear response coefficient that is associated to the current induced in one direction when applying a homogeneous electric field in the perpendicular direction.

In this talk I will explain how in infinitely-extended periodic systems of interacting lattice fermions with a spectral gap, one can rigorously realise the linear response definition of the Hall-conductivity described above. By using the NEASS (Non-Equilibrium Almost-Stationary State) approach to linear response theory we can rigorously control the induced Hall-current, despite the fact that even a very small homogeneous electric field closes the spectral gap. Our proof recovers a many-body version of the double-commutator formula for the Hall-conductivity and shows, that the current response is purely linear with no polynomial corrections. It also allows for a simple argument that shows that the Hall-conductivity is constant within topological phases. This talk is based on arXiv:2411.06967.

TUE 10.7 Tue 15:45 ZHG103

Particle propagation bounds for bosonic lattice systems with long range interactions — •Carla Rubiliani[1], Marius Lemm[1], and Jingxuan Zhang[2] — [1]University of Tübingen, Germany — [2]Tsinghua University, China

We study the quantum time evolution of a system of bosons on a lattice generated by a long-range Hamiltonian with power-law decaying terms. We establish the first thermodynamically stable particle propagation bound in this setting, thus showing the finiteness of the speed of boson transport across the lattice. The main novelty in our proof is a multi-scale adaptation of the adiabatic space-time localisation observable method, which allows removing the dependence of the error term from far-away particles. Following this strategy, we were also able to control higher moments of the number operator. This opens the door to proving the first thermodynamically stable Lieb-Robinson bounds for bosonic systems with long-range hopping. This talk is based on arxiv:2310.14896

TUE 10.8 Tue 16:00 ZHG103

Quantum Incompatibility in Parallel *vs* Antiparallel Spins — Ram K Patra[1], •Kunika Agarwal[1], Biswajit Paul[2], Snehasish R Chowdhury[1], Sahil G Naik[1], and Manik Banik[1] — [1]Department of Physics of Complex Systems, S. N. Bose National Center for Basic Sciences, Block JD, Sector III, Salt Lake, Kolkata 700106, India — [2]Department of Mathematics, Balagarh Bijoy Krishna Mahavidyalaya, Balagarh, Hooghly-712501, West Bengal, India

We investigate the joint measurability of incompatible quantum observables on ensembles of parallel and antiparallel spin pairs. In parallel configuration, two systems are identically prepared, whereas in antiparallel configuration each system is paired with its spin-flipped counterpart. We demonstrate that the antiparallel configuration enables exact simultaneous prediction of three mutually orthogonal spin components*an advantage unattainable in the parallel case. As we show, this enhanced measurement compatibility in antiparallel configuration is better explained within the framework of generalized probabilistic theories, which allow a broader class of composite structures while preserving quantum descriptions at the subsystem level. Furthermore, this approach extends the study of measurement incompatibility to more general configurations beyond just the parallel and antiparallel cases, providing deeper insights into the boundary between physical and unphysical quantum state evolutions. To this end, we discuss how the enhanced measurement compatibility in antiparallel configuration can be observed on a finite ensemble of qubit states, paving the way for an experimental demonstration of this advantage.

TUE 11: Quantum Optics and Quantum Computation

Time: Tuesday 14:15–16:15 Location: ZHG104

TUE 11.1 Tue 14:15 ZHG104

Collective photon emission of correlated atoms in free space — •Joachim von Zanthier[1], Stefan Richter[1], Sebastian Wolf[2], and Ferdinand Schmidt-Kaler[2] — [1]Universität Erlangen-Nürnberg, 91058 Erlangen — [2]Universität Mainz, 55128 Mainz

Superradiance is one of the enigmatic problems in quantum optics since Dicke introduced the concept of coherent spontaneous emission by an ensemble of identical atoms in highly entangled Dicke states [1]. While single excited Dicke states have been investigated, the production of Dicke states with higher number of excitations remains a challenge. We generate these states via successive measurement of photons at particular positions in the far field starting from the fully excited system [2]. In this case, the collective system cascades down the ladder of symmetric Dicke states each time a photon is recorded. We apply this scheme to demonstrate directional super- and subradiance with two trapped Ca+ ions [3]. The arrangement for preparing the Dicke states and subsequently recording directional super- and subradiance corresponds to a generalized HBT setup. This shows that the two fundamental phenomena of quantum optics, Dicke superradiance and HBT interference, are two sides of the same coin. We also outline how to map the symmetric Dicke states onto the long-lived ground state Zeemann-levels of the Ca+ ions [4].

[1] R. H. Dicke, Phys. Rev. 93, 99 (1954).
[2] S. Oppel et al., PRL 113, 263606 (2014).
[3] S. Richter et al., PRR 5, 013163 (2023).
[4] M. Verde et al., ArXiv 2404.12513.

TUE 11.2 Tue 14:30 ZHG104

Training non-linear optical neural networks with Scat-

tering Backpropagation — •Nicola Dal Cin[1,2], Florian Marquardt[1,2], and Clara Wanjura[1] — [1]Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany — [2]Department of Physics, University of Erlangen-Nuremberg, 91058 Erlangen, Germany

As deep learning applications continue to deploy increasingly large artificial neural networks, the associated high energy demands are creating a need for alternative neuromorphic approaches. Optics and photonics are particularly compelling as they offer high speeds and energy efficiency. Neuromorphic systems based on non-linear optics promise high expressivity with a minimal number of parameters. However, so far, there is no efficient and generic physics-based training method with gradients for non-linear optical systems with dissipation. In this work, we present "Scattering Backpropagation", the first efficient physics-inspired method for experimentally measuring approximated gradients for nonlinear optical neural networks. Remarkably, our approach does not require a mathematical model of the physical nonlinearity, and only involves two measurements of the system to compute all gradient approximations. In addition, the estimation precision depends on the deviation from reciprocity. We successfully apply our method to well-known benchmarks such as XOR and MNIST. Our method is widely applicable to existing state-of-the-art, scalable platforms, such as optics, microwave, and also extends to other physical platforms such as electrical circuits.

TUE 11.3 Tue 14:45 ZHG104

Hybrid Qubit Encoding: Splitting Fock Space into Fermionic and Bosonic Subspaces

— •Francisco Javier del Arco Santos — Institute for Computer Science, University of Augsburg, Augsburg, Germany

The main issue of computational chemistry is solving the Schrodinger Equation. In consequence, many methods have been developed in order to approximate the ground and first excited molecular states. It has already been predicted that the application of quantum computers would be useful for this research area. However, nowadays quantum computers still being reduced in number of qubits (order of a few hundred) and with relatively high noise. Efficient encoding of electronic operators into qubits is essential for quantum chemistry simulations. Most of the methods treat Fermionic degrees of freedom and qubits one a one-to-one fashion, handling their interactions. Alternatively, pairs of electrons can be represented as quasi-particles and encoded into qubits, significantly simplifying calculations. This work presents a Hybrid Encoding that allows splitting the Fock space into Fermionic and Bosonic subspaces. By leveraging the strengths of both approaches, we provide a flexible framework for optimizing quantum simulations based on molecular characteristics and hardware constraints. Afterwards, it has been applied in order to simulate molecular systems, which would be prohibitive without this hybrid schema.

TUE 11.4 Tue 15:00 ZHG104

Thermodynamics of the micromaser

— •Anja Seegebrecht and Tanja Schilling — University of Freiburg, Freiburg, Germany

The micromaser is a very simple model to study light-matter interactions and a prototypical example in quantum optics. It can also be used in various ways to discuss quantum thermodynamics. The interaction of thermal atoms with the cavity can be interpreted as a the action of a heat bath since field ends up in a Gibbs state. But the relaxation towards steady state can be non-monotonic. This is a peculiar feature for a thermalization process. Additionally we observe that heating and cooling happen at different rates. The trapping state feature can be used to construct a quantum battery model. With coherent atoms actually useful work (ergotropy) can be stored in the cavity by preparing a pure state. We explore the charging power, extraction protocols and stability of this setup.

TUE 11.5 Tue 15:15 ZHG104

Measuring nuclear resonant phase shifts with a nanoscale double-slit experiment

— •Leon Merten Lohse[1,3], Ralf Röhlsberger[4,5,6,3], and Tim Salditt[2] — [1]Universität Hamburg — [2]Georg-August-Universität Göttingen — [3]Deutsches Elektronen-Synchrotron DESY, Hamburg — [4]Friedrich-Schiller-Universität Jena — [5]Helmholtz-Institut Jena — [6]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt

An electromagnetic wave scattering with atoms experiences a phase shift that encodes information about the atoms' quantum states and photon-matter interaction. While interferometers are readily available in the optical regime, measuring phase shifts in the x-ray regime is notoriously challenging, especially at the nanometer scale. To that end, we have devised and implemented a double-waveguide interferometer on the nanometer scale, reminiscent of Thomas Young's celebrated experiment from 1801. The interferometer has enabled us to measure the phase shift that an ultrathin layer of ^{57}Fe Mössbauer nuclei coherently imprints onto x-ray photons propagating through a single-mode x-ray waveguide. Using the extracted phase shift, we were able to accurately quantify the coupling strength between photons and nuclei. Based on this, one can envision to actively control the phase in x-ray nanophotonic devices.

TUE 11.6 Tue 15:30 ZHG104

Observation of Shapiro steps in an ultracold atomic Josephson junction

— •Erik Bernhart[1], Marvin Röhrle[1], Florian Binoth[1], Vijay Pal Singh[2], Ludwig Mathey[3], Luigi Amico[2,4], and Herwig Ott[1] — [1]Department of Physics and Research Center OPTIMAS, RPTU Kaiserslautern-Landau, Germany — [2]Quantum Research Centre, Technology Innovation Institute, Abu Dhabi, UAE — [3]Zentrum für Optische Quantentechnologien and Institut für Quantenphysik, Universität Hamburg — [4]INFN-Sezione di Catania, Via S. Sofia 64, 95127 Catania, Italy

An ultracold atomic Josephson junction is an elementary example of quantum transport and offers a unique platform for quantum simulation of superconducting circuits. The related Josephson effect, where a dissipation-less supercurrent through a tunneling barrier is caused by a phase difference, is well known in superconductors. Is such a junction externally driven, the current-voltage characteristic displays discrete steps, named Shapiro steps, the basis of today's voltage standard. We report on the experimental observation of Shapiro steps in a driven Josephson junction in a gas of ultracold atoms. We demonstrate the universal features of the steps, most noticeable the quantization of the step height. Our experiment provides insights in the microscopic dissipative dynamics, where we observe that the dynamics are caused by phonon emission and collective excitations. The experimental results are underpinned by extensive numerical simulations. Our work expands the understanding of the microscopic dynamics of Shapiro steps and it transfers the voltage standard to ultracold quantum gases.

TUE 11.7 Tue 15:45 ZHG104

Shaping Slow Electron Beam with Plasmonic Near-field

— •Fatemeh Chahshouri[1] and Nahid Talebi[1,2] — [1]Institute of Experimental and Applied Physics, Kiel University, 24098 Kiel, Germany — [2]Kiel, Nano, Surface, and Interface Science KiNSIS, Kiel University, 24098 Kiel, Germany

Recent progress in laser-induced near-field electron-photon interactions has opened new possibilities for quantum-coherent manipulation of free-electron wavepackets. In this work, we investigate how polarization, phase control, and field symmetry control inelastic and elastic interactions between slow electrons and plasmonic near-fields near gold nanorods beyond the nonrecoil approximation. First, we explore how the direction of the linear laser pulse controls energy transfer and transverse recoil of the electron beam. Extending this approach, we employ a sequential phase-locked interaction scheme and show that the initial optical phase and the phase offset between localized dipolar zones influence both amplitude and phase modulation of the electron wavepacket. Finally, we study electron shaping under the influence of a rotating plasmonic field, considering plasmonic rotors generated by two orthogonally polarized laser pulses with a controlled phase delay and circularly polarized light with defined handedness. We demonstrate angular momentum transfer and directional dependence of the electron modulation on the handedness of the plasmonic field in both real and reciprocal space. These results highlight the versatility of tailored near-fields for shaping free-electron beams and offer new tools for ultrafast interferometry and quantum-coherent electron microscopy.

TUE 11.8 Tue 16:00 ZHG104

Probing MHz Charge Dynamics in Diamond Using a Tin-Vacancy Color Center

— Charlotta Gurr[1], •Cem Güney Torun[1], Gregor Pieplow[1], and Tim Schröder[1,2] — [1]Humboldt-Universität zu Berlin, Germany — [2]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, Berlin, Germany

Color centers in diamond are affected by electric noise originating from the diamond host material itself [1]. This noise arises from free charge carriers being intermittently trapped and released by defects (charge traps) in the diamond lattice, generating a fluctuating electric field that shifts the energy levels of the color centers. As a result, the opti-

cal transitions become unstable, posing challenges for applications that rely on consistent sources of indistinguishable photons. Despite their significance, the characteristics of these charge traps remain poorly understood. In this work, we present a method to probe the dynamics of individual charge processes in diamond with MHz temporal resolution, utilizing a tin-vacancy color center. Our measurements reveal that charge capture and release rates vary across two orders of magnitude, from Hz to kHz, suggesting the presence of two distinct mechanisms governing these processes. Additionally, we observe that illumination with 520 nm light more strongly affects the charge release rates than higher-energy 445 nm light. These results provide new insights into the nature of charge traps in diamond and the underlying dynamics of single-charge trapping and release.

[1] Pieplow, Torun et al., *Quantum Electrometer for Time-resolved Material Science at the Atomic Lattice Scale*, arXiv:2401.14290, 2024

TUE 12: Quantum Sensing and Decoherence: Contributed Session to Symposium III

Time: Tuesday 14:15–16:00 Location: ZHG105

TUE 12.1 Tue 14:15 ZHG105

Inelastic electron-light interaction probed by holographic scanning transmission electron microscopy — •Nora Bach[1,2], Tim Dauwe[1,2], Murat Sivis[1,2], and Claus Ropers[1,2] — [1]Max Planck Institute for Multidisciplinary Sciences, Göttingen, Germany — [2]4th Physical Institute, University of Göttingen, Germany

In an ultrafast transmission electron microscope (UTEM), inelastic scattering between free electrons and optical near fields allows for coherent manipulations of the electron quantum state [1]. Recently, different techniques have been developed to reveal the near-field phase imprinted onto the electron wave function, but offer only limited variability in tailoring the electron-light interactions and require a highly coherent electron source [2,3]. In this contribution, we introduce scanning transmission electron microscopy with spatially separated coherent electron probes [4] for the full imaging of complex optical near fields at relaxed coherence requirements. In the far field, these electron probes interfere to form a hologram from which we reconstruct phase shifts induced both by elastic scattering processes and by stimulated inelastic interactions. By superimposing multiple parallel interactions, our approach can be extended to tailoring of the electron spectral distribution beyond what is achievable with a single interaction.

[1] Feist et al., Nature 521, (2015)
[2] Gaida et al., Nature Communications 14, (2023)
[3] Gaida et al., Nature Photonics 18 (2024)
[4] Fehmi et al., Journal of Physics D: Applied Physics 51 (2018)

TUE 12.2 Tue 14:30 ZHG105

A nonlinear extension of crystallography - X-ray-optical wavemixing on valence charges — •Dietrich Krebs — Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

As we celebrate 100 years of Quantum Physics, the field of x-ray crystallography simultaneously approaches its 111th anniversary. Both fields are closely intertwined - with innumerable advances in solid-state and quantum physics being propelled by crystallography's outstanding ability to determine the structure of matter microscopically. Yet, crystallography itself never quite progressed into the quantum realm. Instead, it largely remains a method rooted in concepts of classical waves and (spherical) charge densities.

In this talk, we outline how ideas from nonlinear optics and the use of modern x-ray free-electron lasers (XFEL) help to extend crystallography to the next order, namely nonlinear crystallography. Basing this extension on x-ray-optical wavemixing, it offers atomic-scale resolution - similar to regular x-ray crystallography - combined with the spectroscopic sensitivity of optical techniques. We present our results from a recent XFEL-experiment, which demonstrate the feasibility of nonlinear crystallography on laser-excited diamond. In particular, we showcase the 3D-reconstruction of the newly accessible valence-response function, which agrees well with our theoretical predictions from nonrelativistic Quantum Electrodynamics.

TUE 12.3 Tue 14:45 ZHG105

Measurement of electron wave phase shifts with Angstrom spatial resolution to analyse electric double layers — Jonas Lindner[1], Ulrich Ross[1,2], Tobias Meyer[1], Sung Sakong[3], Axel Gross[3], Michael Seibt[2], and •Christian Jooss[1] — [1]Institute of Materials Physics, University of Goettingen, Germany. — [2]4th Institute of Physics, Solids and Nanostructures, University of Goettingen, Germany — [3]Institute of Theoretical Chemistry, University Ulm, Germany

Using phase shifting off-axis holography in a transmission electron microscope (TEM), phase shift measurements of electron waves with 1 Angstrom spatial resolution and $2\pi/452$ phase sensitivity was achieved. The detection of phase shifts is then applied to the measurement of atomic scale electric potentials of electric double layers at electrode water interfaces. The effect of inelastic scattering due to gas ambient on electron coherence is studied. The achieved progress in spatial resolution and phase detection allows us to observe ordered water layers at the dynamic state of a platinum (111) surface as well as water reorganization under applied electric potentials. The obtained projected electric potential of water dipole layers is quantitatively compared to ab-initio molecular dynamics simulations. The experimental results reveal an extended ordered water region. The bias-dependent reorientation of molecular dipole network gives new insights into the atomic scale electric field at Helmholtz layers and its impact on proton-coupled electron transfer at interfaces. Finally, we discuss general conclusions on quantum coherence of scattered matter waves.

TUE 12.4 Tue 15:00 ZHG105

Quantum Sensing with a Strongly Driven Spin — •Dhruv Deshmukh and Joachim Ankerhold — Institute for complex quantum systems, Ulm University, Germany

Quantum systems, when exposed to suitably-tuned strong time-periodic fields, may exhibit subharmonic dynamics, the most prominent case being that of period doubling. In this presentation, we introduce conditions required for period k-tupling dynamics to manifest in the simplest paradigmatic quantum system, namely, a single driven two-level system [1]. Experimental observations, with a driven NV centre, verifying period doubling and higher multiplicities up to period quintupling are showcased [2]. Building upon these results, we show how the period k-tupling dynamics can be used for quantum metrology with a few specific examples. First, we explain how the period doubling dynamics of a driven NV centre depends upon its temperature based zero-field splitting, making it a promising tool for thermometry. Next, we also show how the special case of period-1 dynamical freezing may be used for vector magnetometry due to its direction dependent sensitivity on magnetic field [1]. We also briefly discuss the possibilities of detecting neighbouring nuclear spins through their effect on the driven NV centre dynamics.

Research Articles (to be published soon): [1] Period k-tupling in Driven Two-Level Systems (Dhruv Deshmukh and Joachim Ankerhold) [2] Observation of period doubling and higher multiplicity in a driven single-spin system (Dhruv Deshmukh, Raúl B. González, Roberto Sailer, Ressa S. Said, Fedor Jelezko and Joachim Ankerhold)

TUE 12.5 Tue 15:15 ZHG105

Sensing Spins on Surfaces and Following them into Chemical Bonds with Scanning Probe Microscopy — •Dmitriy Borodin — IBS Center for Quantum Nanoscience, Seoul, South Korea

Spins on surfaces have been recently proposed as a promising qubit platform and also for atomic-scale quantum sensing. Control and readout are enabled by single atom electron spin resonance via scanning tunneling microscopes (ESR-STM).

In this work we show that quantum sensing can be enabled by following the electron spin resonance of a single molecule bound to the tip of a scanning probe microscope. We demonstrate that weak electrostatic and magnetic fields of single atomic objects can be quantified with sub-angstrom spatial resolution. The atomic-scale quantum sensor if universally applicable to conductive surfaces.

The spin lifetimes and phase coherence times (T1 and T2) of atomic spins on surfaces were so far limited by electron scattering with the metal - a limitation of STM based spin detection. Therefore, we have implemented sensing of single atom spins using the magnetic exchange force (MxF) between a magnetic tip and an ad-atom on the surface.

Surprisingly, studying the spin-spin interaction we observe pattern that reflect the formation of a chemical bond between the surface bound atom and the magnetic atom at the tip.

TUE 12.6 Tue 15:30 ZHG105

Exploring Coherent Manipulation of Spin Systems via the Near-Field of a Modulated Electron Beam — •Thomas Spielauer[1], Matthias Kolb[1], Thomas Weigner[1], Johann Toyfl[1], Giovanni Boero[2], Dennis Rätzel[3], and Philipp Haslinger[1] — [1]VCQ, Technische Universität Wien, Atominstitut, Stadionallee 2, 1020 Vienna, Austria — [2]EPFL, BM 3110 Station 17, CH-1015 Lausanne, Switzerland — [3]ZARM, Universität Bremen, Am Fallturm 2, 28359 Bremen

Electron spin resonance (ESR) is a versatile analytical technique with broad applications in medicine, biology, and material science. While conventional ESR methods rely on magnetic field gradients or sophisticated resonator designs to provide spatial resolution, we explore an alternative approach utilizing the non-radiative near field of a modulated electron beam, implemented within a modified scanning electron microscope.

Our custom-built in-situ ESR platform allows us to investigate the interaction between the modulated electron beam and solid-state spin systems. Using a benchmark sample (Koelsch radical, α,γ-bisdiphenylene-β-phenylallyl) and a conventional ESR detection scheme, we observe signatures compatible with spin interactions driven by the collective non-radiative near field of the beam.

These findings establish a pathway toward coherent spin manipulation using a modulated, free-space electron beam, potentially enabling nanoscale spatial resolution for coherent quantum system control.

TUE 12.7 Tue 15:45 ZHG105

Direct imaging of magnetotransport at graphene-metal interfaces with a single-spin quantum sensor — •Chaoxin Ding, Marius Palm, Kevin Kohli, and Christian Degen — ETH Zurich, Zurich, Switzerland

Magnetotransport underlines many important phenomena in condensed matter physics, such as the Hall effect and magnetoresistance (MR) effect, and forms the basis for applications in magnetic memories and spintronic devices. Thus far, most magnetotransport studies have been based on bulk resistance measurements, without direct access to the nanoscale spatial transport pattern. Here, we discuss nanoscale quantum imaging of magnetotransport in a monolayer graphene with an embedded metal disc using a scanning nitrogen-vacancy magnetometer. By visualizing the current flow under an out-of-plane magnetic field around 0.5 T, we directly observe Lorentz-force-induced current deflection at the graphene-to-metal interface. As the carrier density in graphene increases, the current flowing through the graphene sheet is enhanced. In addition, we observe that the MR is more prominent in the ambipolar regime compared to the electron- or hole- doped regimes, which can be attributed to the intrinsic MR effect. Finally, we show that spatial current imaging uncovers non-uniform contact resistances along the circular graphene-metal interfaces, which cannot be easily identified by optical, electrical or topographic characterization.