Q 56: Quantum Optics and Control I

Time: Thursday 14:30–16:30 Location: P 3

Invited Talk Q 56.1 Thu 14:30 P 3

Quantum logic control of transition metal and molecular ions — Till Rehmert[1,2], Maximilian J. Zawierucha[1,2], Kai Dietze[1,2], Piet O. Schmidt[1,2], Sergey G. Porsev[3], Dmytro Filin[3], Charles Cheung[3], Marianna S Safronova[3], and •Fabian Wolf[1] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [3]Department of Physics and Astronomy, University of Delaware, Delaware 19716, USA

Extending quantum control to increasingly complex systems, such as molecular ions, is essential for advancing quantum technologies and probing fundamental physics.

Quantum logic spectroscopy offers a promising route to controlling molecular ions: a well-controlled atomic ion is co-trapped with a molecular ion and enables manipulation and readout of its quantum state via shared motional modes. As we move toward quantum logic spectroscopy of single molecular MgH^+ ions, we are also exploring the applicability of these techniques to other species. Recently, we demonstrated quantum logic control of a single titanium ion, showing that these methods extend to previously inaccessible atomic systems.

By expanding quantum control to new classes of ions, our work enables new opportunities in precision spectroscopy, quantum technology, and fundamental physics.

Q 56.2 Thu 15:00 P 3

Multi-Path and Multi-Particle Tests of Complex versus Hyper-Complex Quantum Theory — Ece Ipek Saruhan, Joachim von Zanthier, and •Marc-Oliver Pleinert — Quantum Optics and Quantum Information Group, Friedrich-Alexander Universität Erlangen-Nürnberg, Staudtstr. 1, 91058 Erlangen, Germany

The axioms of quantum mechanics provide limited information regarding the structure of the Hilbert space, such as the underlying number system. The latter is generally regarded as complex, but generalizations of complex numbers, so-called hyper-complex numbers, cannot be ruled out in theory. Therefore, specialized experiments to test for hyper-complex quantum mechanics are needed. To date, experimental tests are limited to single-particle interference exploiting a closed phase relation in a three-path interferometer called the Peres test. The latter distinguishes complex quantum mechanics from quaternionic quantum mechanics. Here, we propose a general matrix formalism putting the Peres test on a solid mathematical ground. On this basis, we introduce multi-path and multi-particle interference tests, which provide a direct probe for any dimension of the number system of quantum mechanics.

[Phys. Rev. Lett. 134, 060201 (2025)]

Q 56.3 Thu 15:15 P 3

Towards generalized pump beam engineering for maximal entanglement in Laguerre-Gaussian modes — •Richard Bernecker[1,2], Baghdasar Baghdasaryan[3], and Stephan Fritzsche[1,2] — [1]Institute for Theoretical Physics, Friedrich Schiller University Jena, Fröbelstieg 1, 07743 Jena, Germany — [2]Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany — [3]Institute of Applied Physics, Friedrich Schiller University Jena, Albert-Einstein-Str. 6, 07745 Jena, Germany

The spatial entanglement of photons in Laguerre-Gaussian (LG) modes has proven to be a powerful resource for high-dimensional quantum information processing. LG modes are indexed by a radial number p and an azimuthal number ℓ, the latter being associated with orbital angular momentum (OAM). While most studies over the past decades have focused on the OAM, recent advances now enable full-mode characterization, including the radial index p. However, no general strategy exists to generate specific high-dimensional target states in the full LG basis.

In this contribution, we present a generalized approach to spatial pump-beam engineering that enables the generation of maximally entangled states (MESs) from spontaneous parametric down-conversion. MESs constitute the high-dimensional analogue of Bell states and form ideal resources for quantum information tasks. We show that a tailored superposition of LG pump modes, combined with an optimized choice of the detection subspace, allows for the controlled engineering of MESs across both radial and azimuthal mode indices.

Q 56.4 Thu 15:30 P 3

Observation of entanglement between free electrons and photons — •Jan-Wilke Henke[1,2], Hao Jeng[1,2], Murat Sivis[1,2], and Claus Ropers[1,2] — [1]Max Planck Institute for Multidisciplinary Sciences, Göttingen, Germany — [2]University of Göttingen, 4th Physical Institute, Göttingen, Germany

Entanglement is central to most emerging quantum technologies from quantum computation to quantum sensing. Generating entangled quantum states is thus highly relevant for future applications, and has been achieved in various combinations of quantum systems. Here, we demonstrate the quantum entanglement between free electrons and photons [1]. In a quantum eraser-type scheme [2], we use a coherently split electron beam to generate photons of distinct polarisation at a specifically designed nanostructure placed in a transmission electron microscope. Performing electron-photon coincidence measurements in different bases, we reconstruct the joint electron-photon state and show that it violates the Peres-Horodecki entanglement criterion by more than 7 standard deviations. Laying the basis for quantum-enhanced sensing in the electron microscope, the proof of electron-photon entanglement represents a cornerstone of free electron quantum optics. [1] J.-W. Henke et al., arXiv:2504.13047 (2025); [2] J.-W. Henke, H. Jeng & C. Ropers, Phys. Rev. A 111, 012610 (2025)

Q 56.5 Thu 15:45 P 3

Single- and many-body interference in a generalized Mach-Zehnder interferometer — •Farouk Albalacy, Gabriel Dufour, and Andreas Buchleitner — Physikalisches Institut & EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg

We study the interplay of single- and many-body interference effects by injecting one quantum object per port in a generalized Mach-Zehnder interferometer with three ports. Single-body interference is controlled by the phase shifts between the paths of the interferometer. The effect of bosonic many-body interference is singled out by tuning the individual constituents' mutual distinguishabilities through their internal states. We analyze the output counting statistics for three partially distinguishable bosons, as a function of their internal states and of the interferometer phases.

Q 56.6 Thu 16:00 P 3

Entanglement shortcuts in the geometry of micromaser state preparation — •Matthias Bundy[1], Christoph Dittel[1,2], and Andreas Buchleitner[1,2] — [1]Physikalisches Institut, Albert-Ludwigs-Universität, Hermann-Herder-Straße 3, 79104 Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, 79104 Freiburg, Germany

Any desired state of a single, quantized cavity mode can be prepared by sequentially interacting with a string of two-level atoms. However, the fidelity of the preparation process much depends on the desired target state, the number of atoms, and the degree of their mutual entanglement. Here we investigate the state preparation process from a geometric perspective, by establishing an appropriate metric for the length of state preparation trajectories. We quantify how the entanglement of the atomic string shortens the path from the cavity mode's initial to target state, and discuss how these trajectories differ for classical and non-classical target states.

Q 56.7 Thu 16:15 P 3

Phase-sensitivity enhancement in Mach-Zehnder interferometer via local Gaussian operations — Taj Kumar, Krishna Mohan Mishra, Aviral Kumar Pandey, Vikas Kumar Prajapati, and •Devendra Kumar Mishra — Department of Physics, Institute of Science, Banaras Hindu University, Varanasi-221005, Uttar Pradesh, India

We investigate the role of local Gaussian operations, specifically local displacement operation (LDO) and local squeezing operation (LSO), in enhancing the phase sensitivity of the Mach-Zehnder interferometer (MZI). We considered two scenarios: when these operations are applied in a single arm only and when they are applied in both arms of the MZI. Using coherent and squeezed vacuum states as inputs and homodyne detection, we analyze the phase sensitivity and the quantum

Cramér-Rao bound (QCRB) under both ideal and lossy conditions. Our study reveals that both single- and dual-arm LDO schemes offer equivalent improvements in phase sensitivity. However, the single-arm LSO scheme offers improved phase sensitivity that is superior to its dual-arm counterpart as well. In short, the single-arm configuration is found to be more resource-efficient, providing improved phase sensitivity and enhanced robustness against photon losses. These results emphasize the advantages of the Gaussian operations, such as LDO and LSO, as an experimentally feasible approach with a low implementation cost for achieving enhanced phase sensitivity and robustness against photon losses.