Q 50: Matter Wave Interferometry and Metrology II

Time: Thursday 11:00–13:00 Location: P 11

Q 50.1 Thu 11:00 P 11

Quantum Metrology of Spin Sensing with Free Space Electrons — Santiago Beltran Romero[1], •Michael Gaida[2], Philipp Haslinger[1], Dennis Rätzel[1], and Stefan Nimmrichter[3] — [1]Atominstitut, Technische Universität Wien, Stadionallee 2, 1020 Vienna, Austria — [2]Institute for Complex Quantum Systems and Center for Integrated Quantum Science and Technology, Ulm University, Albert-Einstein-Allee 11, 89069 Ulm, Germany — [3]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, 57068 Siegen, Germany

Advances in transmission electron microscopy (TEM) are bringing single-spin-sensitive spin-resonance spectroscopy within reach. We analyze the quantum precision limits for sensing magnetic moments with free-electron probes using a scattering model of an electron wavepacket interacting with a localized spin. We study two tasks: estimating the magnitude of a magnetic moment and detecting the presence of a spin. For estimation, we compare the classical Fisher information for typical measurements with the quantum limit and find that standard TEM imaging can saturate this bound when probe backaction is negligible. When backaction is significant, measuring the electron's orbital angular momentum can offer higher sensitivity. Our results establish the quantum limits of spin sensing in TEM and guide the design of experiments targeting individual electron spins or nanoscale nuclear-spin ensembles.

Q 50.2 Thu 11:15 P 11

Optimal Ramsey protocols employing QND-squeezed states — •Maja Scharnagl[1] and Klemens Hammerer[1,2] — [1]Institute for theoretical physics, Leibniz Universität Hannover, Germany — [2]Institute for theoretical physics, Universität Innsbruck, Austria

We investigate quantum non-demolition (QND) measurements and their application in Ramsey protocols. In doing so, we optimize the axes of signal imprint and measurement and perform clock simulations for comparing the optimized protocols to QND-protocols with feedback, aligning the squeezed state with the equator of the Bloch sphere. We include individual and collective dephasing in our description and minimize the analytically calculated Allan deviation of these protocols over the QND-squeezing-strength.

Q 50.3 Thu 11:30 P 11

An industrial single-ion optical frequency standard with a systematic uncertainty below 2×10^{-17} — Axel Friedenauer[1], •Pierre Thoumany[1], Christoph Tresp[1], Daniel Heinrich[1], Saaswath Jeyalathaa Karthikeyan[2], Burghardt Lipphardt[2], Nils Huntemann[2], Stephan Ritter[1], and Jürgen Stuhler[1] — [1]TOPTICA Photonics SE, Gräfelfing, Germany — [2]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Rapid advances in research on optical frequency standards (OFS) have enabled ultra-precise instruments and plans for a redefinition of the second. While most of the current OFS are highly specialized laboratory systems, development of commercially available optical clocks that are robust and transportable with high uptime and high performance is crucial for applications such as timing, geodesy and navigation. Building on the expertise obtained within the funded research project *opticlock*, we present here a commercial OFS prototype, TOPTICLOCK, based on the $^2S_{1/2}(F=0) \rightarrow {}^2D_{3/2}(F=2)$ electric quadrupole transition (E2) at 435.5 nm of a single $^{171}\mathrm{Yb}^+$ ion and contained in two 19" racks. The OFS has been transported to the German metrology institute PTB in June 2025 for a full metrological evaluation within the EU project Qu-Test. In comparison with the more stable optical frequency standard PTB-Yb1E3, using a difference frequency comb (TOPTICA DFC) a frequency instability of $5 \times 10^{-15}/\sqrt{\tau}$ with a total systematic uncertainty below 2×10^{-17} of the OFS was demonstrated. Even for averaging times beyond 10^5 s, the system shows white frequency noise behavior.

Q 50.4 Thu 11:45 P 11

Anomalous tilts and shifts of diffraction orders in Bragg beam-splitters — •Adam Abdalla, Abhay Mishra, Oleksandr Marchukov, and Reinhold Walser — TU Darmstadt, Institute of Applied Physics, Darmstadt, Germany

Interferometric measurements can be used for quantum metrology and inertial sensing or fundamental physics in space [1]. Atomic beam-splitters are integral devices for in three-dimensional matter-wave interferometers. In typical interferometric experiments with Bose-Einstein condensates, one has a superposition of several wavelets (diffraction orders) that extend in the longitudinal x-direction over many optical wavelength λ_L and are much smaller than the Gaussian laser waist $w_0 \gg \sigma_{y,z}$ in the transversal direction [2].

In this contribution, we analyze the Bragg beam splitting of a decentered BEC in real three-dimensional Gaussian laser beams. We find that a Bragg pulse leads to a spatial displacement (shift) of the diffraction wave packets as well as a correction (tilt) to the Bragg momentum $2k_L$ [3]. This is analogous to the Goos-Hänchen effect in optics [4]. The results are supported by (3+1)D simulations of the Gross-Pitaevskii equation. This results will be relevant for any matter-wave interferometers experiments, for example the QUANTUS Collaboration (DLR, grant number 50WM2450E).

[1] D. Becker, et al., Nature **562**, 391 (2018)
[2] A. Neumann, et al., Phys. Rev. A **103**, 043306 (2021)
[3] A. D. Ludlow, Yun Je, et al., Rev. Mod. Phys. **87**, 637 (2015)
[4] F. Goos and H. Hänchen, Annalen der Physik **436**, 333 (1947)

Q 50.5 Thu 12:00 P 11

Unified Theory of Large Momentum Transfer in Optical Lattices — •Patrik Mönkeberg[1], Ashkan Alibabaei[2], Naceur Gaaloul[2], and Klemens Hammerer[1,3,4] — [1]Institute for Theoretical Physics, Leibniz University of Hannover, Germany — [2]Institute of Quantum Optics, Leibniz University of Hannover, Germany — [3]Institute for Theoretical Physics, University of Innsbruck, Austria — [4]Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck, Austria

Large-momentum-transfer techniques are essential tools to enhance the sensitivity of atom interferometers. So far, elastic scattering processes like Bloch oscillations and sequential Bragg diffractions have proven to be effective means of implementing large momentum transfer. To fully exploit the potential of these methods, an accurate theoretical description is crucial. In this work, we utilize a Floquet-theoretical approach to describe both Bloch oscillations and sequential Bragg diffractions as two special cases of a more general framework. We compare different regimes by analyzing losses and phases and offer criteria to reach the fundamental efficiency and accuracy limits. We verify the accuracy of our model through comparisons with exact numerical solutions of the Schrödinger equation and current state-of-the-art experiments [Rodzinka et al., Nat Commun 15, 10281 (2024)].

Q 50.6 Thu 12:15 P 11

Composite light-pulse atom interferometry with Bragg and Raman double diffraction — •Simon Kanthak[1], Ekim T. Hanimeli[2], Matthias Gersemann[3], Mikhail Cheredinov[3], Markus Krutzik[1], Sven Herrmann[2], Sven Abend[3], Ernst M. Rasel[3], and the QUANTUS team[1,2,3,4] — [1]Institut für Physik, HU Berlin — [2]ZARM, Universität Bremen — [3]Institut für Quantenoptik, LU Hannover — [4]Technische Universität Darmstadt

Double diffraction in light-pulse atom interferometry gives rise to symmetric interferometer geometries via oppositely directed momentum transfers. This technique intrinsically doubles the phase sensitivity of the interferometer and suppresses systematic uncertainties, however suffers from spurious atoms in parasitic interferometer paths. While double-diffraction schemes have been implemented using either Bragg or Raman transitions, one has to decide between an enhanced noise-suppression and the straight-forward application of blow-away pulses depending on the absence or presence of internal state changes.

This talk presents a composite light-pulse approach, which relies on a sequence of Bragg and Raman pulses rather than individual ones to exploit manipulations of both the internal and external degrees of atoms. Specifically, we demonstrate the application of Raman state-flips in double Bragg interferometry to recover the interferometric contrast alongside a reduction of the intrinsic phase noise.

The project is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) under grant number DLR 50 WM 2450B.

Q 50.7 Thu 12:30 P 11

Operation of a ring-laser-gyroscope using beam ellipticity — •Marlon Demmerle, Thomas Gereons, Jannik Zenner, and Simon Stellmer — Universität Bonn, Germany

This work introduces a ring-laser-gyroscope exploiting the Sagnac effect to achieve precise rotation sensing, focusing on long-term frequency stability. It uses an ellipticity based locking scheme that leverages higher-order spatial modes without relying on conventional modulation techniques and is directly applicable to all non-linear resonator geometries. By analyzing subtle, mode-dependent changes in the beam shape, the setup attains robust cavity locking while effectively suppressing technical noise. This enables a compact, low-complexity platform for precision rotation measurements and advanced optical metrology.

Q 50.8 Thu 12:45 P 11

Quantum state-selective matter wave diffraction of cold molecules — •Shilpa Yadav, Sejun An, Kilian Hügel, JuHyeon Lee, Gerard Meijer, and Sandra Eibenberger-Arias — Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, 14195 Berlin, Germany.

We propose a novel scheme to spatially separate quantum states of molecules in the gas-phase. In our experiment, we will demonstrate quantum state-selective matter-wave diffraction at an optical grating. In combination with enantiomer-specific quantum state control [1, 2], this will even allow for the spatial separation of chiral molecules in the gas-phase. In my presentation, I will give details on the underlying motivation and physical principles [3,4], as well as information on the current status of the experiment.

1. S. Eibenberger, J. Doyle, and D. Patterson: Enantiomer-Specific State Transfer of Chiral Molecules. Physical Review Letters118, 123002 (2017)
2. J. H. Lee, E. Abdiha, B. G. Sartakov, G. Meijer, and S. Eibenberger-Arias: Near-complete chiral selection in rotational quantum states. Nature Communications 15, 7441 (2024)
3. A. D. Cronin, J. Schmiedmayer, and D. E. Pritchard: Optics and interferometry with atoms and molecules. Reviews of Modern Physics 81, 1051-1129 (2009)
4. K. Hornberger, S. Gerlich, P. Haslinger, S. Nimmrichter, and M. Arndt. Colloquium: Quantum interference of clusters and molecules. Reviews of modern Physics 84, 157-173 (2012)