Q 22: Precision Measurements and Metrology I (joint session Q/A)

Time: Tuesday 16:30–18:30 Location: P

Q 22.1 Tue 16:30 P

Towards dual species interferometry in space: MAIUS-B laser system — •Pawel Arciszewski[1], Klaus Döringshoff[1], Achim Peters[1], and The MAIUS Team[1,2,3,4,5] — [1]Institut für Physik, Humboldt-Universität zu Berlin — [2]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, Berlin — [3]ZARM, Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation, Bremen — [4]Institut für Physik, JGU Mainz — [5]IQO, Leibniz Universität Hannover

The first production of a space-borne BEC carried out during the MAIUS-1 sounding rocket mission in January 2017 paved the way for more advanced experiments with an ultra-cold matter in space. The goal of upcoming MAIUS-2 and MAIUS-3 missions is to perform dual-species interferometry onboard a sounding rocket to investigate the weak equivalence principle.

To make that possible a new laser system was developed. The designed equipment can provide the light needed for simultaneous laser cooling of rubidium and potassium and further stages used in atom interferometry experiments. Moreover, the system has to be robust and reliable to meet the demands of a sounding rocket mission.

We report on the current status of the system, its assembly process, and used technologies as well, as tests carried out to assure the equipment can face the present needs of the mission.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50WP1432.

Q 22.2 Tue 16:30 P

Third-order atomic Raman diffraction in microgravity — •Sabrina Hartmann[1], Jens Jenewein[1], Sven Abend[4], Albert Roura[2], and Enno Giese[1,3,4] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ$^{\mathrm{ST}}$), Universität Ulm — [2]Institut für Quantentechnologien, DLR — [3]Institut Angewandte Physik, TU Darmstadt — [4]Institut für Quantenoptik, Leibniz Universität Hannover

Large-momentum-transfer (LMT) applications such as sequential pulses, higher-order Bragg diffraction and Bloch oscillations are essential tools to increase the enclosed area of an atom interferometer and thus, its sensitivity. However up to now only sequential pulses have routinely been employed with Raman diffraction.

We show theoretically [1] that double Raman diffraction [2,3] enables third order diffraction. We compare the process to a sequence of first-order pulses with the same total momentum transfer and demonstrate that third-order diffraction gives higher diffraction efficiencies for ultracold atoms. Hence, it is a competitive tool for atom interferometry with BECs in microgravity which increases the momentum transfer by a factor of six. Moreover, it allows us to reduce the complexity of the experimental setup and the total duration of the diffraction process.

The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry of Economics and Energy (BMWi) under grant number 50WM1956 (QUANTUS V).

[1] *PRA* **102**, 063326 (2020). [3] *PRL* **103**, 080405 (2009).
[2] *PRA* **101**, 053610 (2020).

Q 22.3 Tue 16:30 P

Towards high-precision Bragg atom interferometry using rubidium Bose-Einstein condensates — •Dorothee Tell[1], Christian Meiners[1], Henning Albers[1], Ann Sabu[1,2], Klaus H. Zipfel[1], Ernst M. Rasel[1], and Dennis Schlippert[1] — [1]Leibniz Universität Hannover, Institut für Quantenoptik, Deutschland — [2]Cochin University of Science and Technology (CUSAT), Kerala, India

The Very Long Baseline Atom Interferometry (VLBAI) facility at the university of Hannover aims for high precision measurements of inertial quantities. Goals span from contributions to absolute geodesy as well as fundamental physics at the interface between quantum mechanics and general relativity. The VLBAI facility makes use of a freely falling ensemble of ultracold atoms as a probe for inertial forces, interrogating the atoms in an interferometer scheme using near-resonant light pulses.

Here we present details of the fast, all-optical preparation of rubidium Bose-Einstein condensates in time-averaged dynamic optical dipole traps. We will show first proof-of-principle Bragg beam splitting and interferometry in a reduced baseline of up to 30 cm. Prospects and challenges of extending the free fall distance to more than 10 m in the frame of the VLBAI facility will be discussed.

We acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Project-ID 434617780 - SFB 1464 as well as CRC 1227 (DQ-mat), project B07. The VLBAI facility is a major research equipment funded by the DFG.

Q 22.4 Tue 16:30 P

Second-quantized effective models for Raman diffraction with center-of-mass motion — •Nikolija Momčilović[1], Alexander Friedrich[1], and Wolfgang P. Schleich[1,2] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ$^{\mathrm{ST}}$), Universität Ulm — [2]Institut für Quantentechnologien, Deutsches Zentrum für Luft- und Raumfahrt

Two-photon Raman transitions are commonly used to facilitate $\pi/2$- and π-pulses in atom interferometry, and are the analogue of beam splitters and mirrors in optical interferometers. In practice, these transitions are driven by laser light which can be described semi-classically as quasi-coherent states. Thus quantization effects are averaged out due to the broad photon distribution in typical beams. However, technological progress moves towards the use of optical cavities due to their superior optical properties. Theoretical modeling of such configurations demands a second-quantized description of the light fields which we pursue based on the light-matter interaction of two second-quantized single-mode light fields and an effective two-level atom. In our contribution we derive and investigate a two-photon Rabi model with center-of-mass motion including intensity-dependent operator-valued couplings between the light field and the center-of-mass motion. We show, that under certain approximations we obtain an effective Jaynes-Cummings model with a center-of-mass dependent detuning.

The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50WM1956.

Q 22.5 Tue 16:30 P

Light-pulse atom interferometry with quantized light fields — •Tobias Assmann[1], Fabio Di Pumpo[1], Katharina Soukup[1], Enno Giese[2], and Wolfgang P. Schleich[1,3] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ$^{\mathrm{ST}}$), Universität Ulm — [2]Institut für Angewandte Physik, Technische Universität Darmstadt — [3]Institute of Quantum Technologies, German Aerospace Center (DLR)

The analogues of optical elements in light-pulse atom interferometers are generated from the interaction of matter waves with light, where the latter is usually treated as a classical field. Nonetheless, light fields are inherently quantum, which has fundamental implications for atom interferometry.

In particular, *quantized* light fields lead to a reduced visibility in the observed interference [J. Chem. Phys. **154**, 164310 (2021)]. This loss is a consequence of the encoded which-way information about the atom's path. However, the quantum nature of the atom-optical elements also offers possibilities to mitigate such effects: We demonstrate that involving superpositions in every light field yields an improved visibility, and an infinitely-strong coherent state recovers full visibility. Moreover, entanglement between all light fields can erase information about the atom's path and by that partially recovers the visibility.
The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) due to an enactment of the German Bundestag under grant DLR 50WM1956 (QUANTUS V).

Q 22.6 Tue 16:30 P

Hybridized atom interferometer with an opto-mechanical resonator — •Ashwin Rajagopalan[1], Lee Kumanchik[2,3], Claus Braxmaier[2,3], Felipe Guzmán[4], Ernst M. Rasel[1], Sven Abend[1], and Dennis Schlippert[1] — [1]Leibniz Universität Hannover, Institut für Quantenoptik, Hannover — [2]DLR - Institute of Space Systems, Bremen — [3]University of Bremen - Center of Applied Space Technology and Microgravity (ZARM),Bremen — [4]Department of Aerospace Engineering & Physics, Texas A&M University, College Station, TX 77843, USA

Vibrational noise coupling through the inertial reference mirror hinders the atom interferometer (AI) performance, so we use a novel opto-mechanical resonator (OMR) in order to suppress it. We have utilized the OMR signal to resolve a T = 10 ms AI fringe, which would have otherwise been obscured by an average ambient vibrational noise of 3.2 mm/s^2 in our laboratory. By incorporating the OMR in our AI we could demonstrate operation in a noisy environment without the use of bulky vibration isolation equipment, therefore paving a way for miniaturization of the AI sensor head. We show our sensor fusion concept and discuss prospects for tailored setups by design and implementation of customized OMRs.

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC-2123 QuantumFrontiers - 390837967. This work is supported by the DLR with funds provided by the BMWi under grant no. DLR 50RK1957 (QGyro) and DLR 50NA2106 (QGyro+).

Q 22.7 Tue 16:30 P

Multi-axis quantum gyroscope with multi loop atomic Sagnac interferometry — •Yueyang Zou[1], Mouine Abidi[1], Philipp Barbey[1], Ashwin Rajagopalan[1], Christian Schubert[1,2], Matthias Gersemann[1], Dennis Schlippert[1], Sven Abend[1], and Ernst M. Rasel[1] — [1]Institut für Quantenoptik - Leibniz Universität, Welfgarten 1, 30167 Hannover — [2]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Satellitengeodäsie und Inertialsensorik, Germany

The interferometric Sagnac phase shift can be used for rotation detection in inertial navigation. We are designing a transportable demonstrator aiming at a multi-axis inertial sensor, not only for the precise measurement of rotations but also for accelerations. This poster will give an overview of the multi-loop atomic Sagnac interferometry theory, and present a preliminary system design for the demonstrator with Bose-Einstein condensates (BECs) of 87Rb atoms.

We acknowledge financial support from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC-2123 QuantumFrontiers - 390837967 and through the CRC 1227 (DQ-mat), as well as support from DLR with funds provided by the BMWi under grant no. DLR 50RK1957 (QGyro) and DLR 50NA2106 (QGyro+).

Q 22.8 Tue 16:30 P

Single-photon transitions in atom interferometry — •Alexander Bott[1], Fabio Di Pumpo[1], Enno Giese[2], and Wolfgang P. Schleich[1,3] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany — [2]Institut für Angewandte Physik, Technische Universität Darmstadt, Schlossgartenstr. 7, Darmstadt D-64289, Germany — [3]Institut für Quantentechnologien, Deutsches Zentrum für Luft- und Raumfahrt, Söflinger Str. 100, D-89077 Ulm, Germany

Differential measurements with atom interferometers have been employed for the measurement of gravity gradients and are promising for the detection of gravitational waves. By using only a single laser to create atom interferometers in a differential setup, phase noise from secondary laser beams cannot influence the measurement. However, with a single laser two-photon transitions are no longer possible. Instead, single-photon transitions have to be employed to create the interferometers. In our contribution we perform a detailed discussion of possible types of single-photon transitions and investigate their advantages and draw-backs for atom interferometers. Specifically, we focus on the effects of the coupling induced by the dispersion relation of the laser driving the single-photon transitions in earth-bound experiments.

The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50WM1956 (QUANTUS V).

Q 22.9 Tue 16:30 P

Absolute light-shift compensated laser system for a twin-lattice atom interferometry — •Mikhail Cheredinov[1], Matthias Gersemann[1], Martina Gebbe[2], Ekim T. Hanimeli[2], Simon Kanthak[3], Sven Abend[1], Ernst M. Rasel[1], and the QUANTUS team[1,2,3,4,5,6] — [1]Institut für Quantenoptik, LU Hannover — [2]ZARM, Uni Bremen — [3]Institut für Physik, HU zu Berlin — [4]Institut für Quantenphysik, Uni Ulm — [5]Institut für Angewandte Physik, TU Darmstadt — [6]Institut für Physik, JGU Mainz

Twin-lattice interferometry is a method to form symmetric interferometers featuring matter waves with large relative momentum by employing two counterpropagating optical lattices. A limiting factor here is loss of contrast, linked to the AC-Stark effect from far detuned light. This contribution presents the realisation of an absolute light-shift compensation and its potential to increase the interferometric contrast. The optical setup utilizes two independent frequency doubling stages. Key features are beam overlap on an interference filter with low power loss and coupling of high optical power in a photonic crystal fiber, opening up possibilities for new records in momentum transfer.

This work is supported by the DLR with funds provided by the BMWi under grant no. DLR 50WM1952-1957 (Q-V-Ft), DLR 50RK1957 (QGyro) and DLR 50NA2106 (QGyro+), the VDI with funds provided by the BMBF under grant no. VDI 13N14838 (TAIOL) and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy EXC-2123 QuantumFrontiers 390837967.

Q 22.10 Tue 16:30 P

An ytterbium setup for gravity measurements at VLBAI — •Ali Lezeik[1], Abhishek Purohit[1], Klaus Zipfel[1], Christian Schubert[1,2], Ernst M. Rasel[1], and Dennis Schlippert[1] — [1]Leibniz Universität Hannover - Institut für Quantenoptik — [2]Institute for Satellite Geodesy and Inertial Sensing - German Aerospace Center (DLR)

Atoms such as strontium (Sr) and ytterbium (Yb) have no magnetic moments in their spin-singlet ground state making them nearly insensitive to external magnetic fields and hence appealing for precision measurements through atomic interferometry. Furthermore, Yb's high mass and hence low expansion rate in addition to its narrow clock transition in the optical frequency range creates an ideal candidate for gravity measurements tests.

We present the Yb-174 setup for producing a robust, high-flux source of laser-cooled ytterbium atoms for the Very Large Baseline Atomic Interferometry (VLBAI) facility [1,2]. We present the laser system, the cooling sequence, the transfer cavity for frequency stabilization of the cooling beams, and a clock cavity for the 1156nm clock transition beam. We outline possible implementations of this system for atom-interferometric tests of the universality of gravitational redshift [3].

[1] É. Wodey et al., J. Phys. B: At. Mol. Opt. Phys. 54 035301 (2021)

[2] D. Schlippert et al., arXiv:1909.08524 (2019)

[3] C. Ufrecht, ..., C. Schubert, D. Schlippert, E. M. Rasel, E. Giese, arxiv:2001.09754 (2020)

Q 22.11 Tue 16:30 P

An overview of Very Long Baseline Atom Interferometry facility — •Abhishek Purohit[1], Klaus H. Zipfel[1], Ali Lezeik[1], Dorothee Tell[1], Christian Meiners[1], Christian Schubert[1,2], Ernst M. Rasel[1], and Dennis Schlippert[1] — [1]Leibniz Universität Hannover, Institut für Quantenoptik, Germany — [2]German Aerospace Center (DLR), Institute for Satellite Geodesy and Inertial Sensing, Hannover, Germany

Our Very Long Baseline Atom Interferometry (VLBAI) facility aims for a complementary method to the state-of-the-art gradiometers and gravimeters when operated with a single atomic species, and for quantum tests of the universality of free fall at levels comparable to the best classical tests and beyond in a mode with two atomic species.

We discuss the main components of the Hannover VLBAI facility: the sources for ultra-cold atom samples, a magnetically shielded interferometry zone, state-of-the-art vibration isolation and gravity gradient mapping and modeling with an uncertainty below the 10 nm/s^2 level. We also show the design and target performance for applications in geodesy and tests of fundamental physics.

The VLBAI facility is a major research equipment funded by the DFG. We acknowledge support from the CRCs 1128 *geo-Q* and 1227 *DQ-mat*

Q 22.12 Tue 16:30 P

Testing trapped atom interferometry with time-averaged optical potentials — •Knut Stolzenberg, Sebastian Bode, Alexander Herbst, Henning Albers, and Dennis Schlippert — Institute of Quantum Optics, Leibniz University Hannover, Welfengarten 1, 30167 Hannover, Germany

Time-averaged optical potentials can be used to realise flexible quantum sensors, for example by exploiting the tunnel effect for beam split-

ters and recombiners.
We use an acousto-optical deflector (AOD) to diffract the laserlight of a 55 W MOPA with a wavelength of 1064 nm to create dynamic time-averaged traps such as harmonic and double well potentials.
We demonstrate creation of a ^{87}Rb BEC in a crossed optical dipole trap and our first results on coherent beam splitting by momentum driven tunneling, showing stable interference patterns 37 ms after the BEC is split at a potential barrier.

Q 22.13 Tue 16:30 P

Analytic Theory for Diffraction Phases in Bragg Interferometry — •Jan-Niclas Siemss[1,2], Florian Fitzek[1,2], Ernst M. Rasel[2], Naceur Gaaloul[2], and Klemens Hammerer[1] — [1]Institut für Theoretische Physik, Leibniz Universität Hannover, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Germany

High-fidelity Bragg pulses operate in the quasi-Bragg regime. While such pulses enable an efficient population transfer essential for state-of-the-art atom interferometers, the diffraction phase and its dependence on the pulse parameters are currently not well characterized despite playing a key role in the systematics of these interferometers. We demonstrate that the diffraction phase when measuring relative atom numbers originates from the fact that quasi-Bragg beam splitters and mirrors are fundamentally multi-port operations governed by Landau-Zener physics (Siemß et al., Phys. Rev. A 102, 033709).

We develop a multi-port scattering matrix representation of the popular Mach-Zehnder atom interferometer and discuss the connection between its phase estimation properties and the parameters of the Bragg pulses. Furthermore, our model includes the effects of linear Doppler shifts applicable to narrow atomic velocity distributions on the scale of the photon recoil of the optical lattice.

This work is supported through the Deutsche Forschungsgemeinschaft (DFG) under EXC 2123 QuantumFrontiers, Project-ID 390837967 and under the CRC1227 within Project No. A05 as well as by the VDI with funds provided by the BMBF under Grant No. VDI 13N14838 (TAIOL).

Q 22.14 Tue 16:30 P

Systematic Approach To Phaseshifts of Matter Wave Interferometers in Weekly Curved Spacetimes — •Michael Werner and Klemens Hammerer — Institut für theoretische Physik, Leibniz Universität Hannover, Germany

We present a systematic approach to calculate all relativistic phase-shift effects in matter wave interferometer (MWI) experiments up to (and including) order c^{-2}, placed in a weak gravitational field. The whole analysis is derived from first principles and even admits test of General Relativity (GR) apart from the usual Einstein Equivalence Principle (EEP) tests, consisting of universality of free fall (UFF) and local position invariance (LPI) deviations, by using the more general 'parametrized post-Newtonian' (PPN) formalism. We collect general phase-shift formulas for a variety of well-known MWI schemes and calculate how modern experimental setups could measure PPN induced deviations from GR without the use of macroscopic test masses. This procedure should be seen as a way to easily calculate certain phase contributions, without having to redo all relativistic calculations in new MWI setups.

Q 22.15 Tue 16:30 P

Universal atom interferometer simulator — •Gabriel Müller, Christian Struckmann, Stefan Seckmeyer, Florian Fitzek, and Naceur Gaaloul — Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover

The simulation of matter-wave light-pulse interaction is crucial for designing and understanding atom interferometry (AI) experiments. However, the usual approach of solving the associated system of ordinary differential equations is limited by a quadratic scaling with the number of coupling states. Here, the universal atom interferometer simulator (UATIS) [1] overcomes this limitation with log-linear scaling while solving the problem of atom-light diffraction in the elastic case for all regimes. By interpreting a light-pulse beam as an external potential, UATIS achieves high numerical accuracy while maintaining great flexibility. We propose intuitive methods for assembling various atom-light interactions into AI sequences. We expect UATIS to lead to a straightforward modelling of experiments and to be promoted to a widely used tool.
[1] Fitzek et al. Universal atom interferometer simulation of elastic scattering processes. Sci Rep 10, 22120 (2020).