Q 36: Matter Wave Interferometry and Metrology I

Time: Wednesday 14:30–16:30 Location: P 11

Q 36.1 Wed 14:30 P 11

Optimal Squeezing in Lossy Bragg Interferometers — •Julian Günther[1,2], Rui Li[2], Jan-Niclas Kirsten-Siemss[2], Naceur Gaaloul[2], and Klemens Hammerer[3] — [1]Institut für Theoretische Physik, Leibniz Universität Hannover, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Germany — [3]Institute for Theoretical Physics, University of Innsbruck, Austria

Using entanglement for N-particle states in matter wave interferometers allows one to outperform the standard quantum limit of $\frac{1}{\sqrt{N}}$ for the uncertainty in the phase measurement. We consider the use of one-axis twisted, spin squeezed atomic states in light-pulse Bragg interferometers. We evaluate the interferometric phase uncertainty taking into account the fundamental multi-port and multi-path nature of higher-order Bragg processes, and determine optimally squeezed states for a given geometry and pulse shapes. For Gaussian temporal pulses we demonstrate the necessary tradeoff between the squeezing strength and momentum distribution of the incoming atomic state to benefit from the entanglement.
This project was funded within the QuantERA II Programme that has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 101017733 with funding organisation DFG (project number 499225223).

Q 36.2 Wed 14:45 P 11

Differential phase estimation and bias correction techniques in cold atom interferometer experiments — •David B. Reinhardt and Matthias Meister — German Aerospace Center (DLR e.V.), Institute of Quantum Technologies, Ulm, Germany

Ellipses are omnipresent in mathematics, computer vision and science. For instance, when analyzing differential interferometric data or performing clock comparisons one often needs to fit an ellipse to a given noisy data set. There are mainly two different approaches to achieve this, the algebraic and the geometric method. However, all fitting methods regardless of the approach typically have different accuracy (bias) vs. precision(variance) trade-offs, and therefore can produce quite different outcomes. In this talk, we present new insights regarding the origin of bias in the differential phase estimation. Further, we show how this knowledge can be used to correct bias in cold atom interferometry experiments and also provide rigorous bounds for the achievable estimation precision. The new findings and methods presented in this talk thus have significant consequences for the understanding and handling of measurement errors of quantum sensors based on differential interferometers.

Q 36.3 Wed 15:00 P 11

Frequency shifts of a transportable Al^+ quantum logic optical clock — •Joost Hinrichs[1,2], Constantin Nauk[1,2], Gayatri Sasidharan[1,2], M. Mazin Amir[1,2], Alexander Bernet[1,2], Pascal Engelhardt[1,2], Sofia Herbers[1], and Piet O. Schmidt[1,2] — [1]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — [2]Leibniz University Hannover, 30167 Hannover, Germany

Optical atomic clocks are the most precise measurement tools, achieving fractional frequency uncertainties below 10^{-18}. Transportable systems can exploit this accuracy in a broader range of applications. High-precision frequency ratio measurements on-site at various metrology institutes contribute to fulfill the requirements towards a redefinition of the SI second. Furthermore, transportable optical clocks can be used for relativistic geodesy as they allow height measurements on the cm level over large distances.
Our fully rack-integrated clock setup is based on the $^1S_0 \rightarrow ^3P_0$ transition in $^{27}Al^+$. A co-trapped $^{40}Ca^+$ ion allows for sympathetic cooling and state detection through quantum logic spectroscopy. We present the results of our investigation of various frequency shifts in our optical clock, with a focus on effects related to the linear segmented multilayer Paul trap, like micromotion, heating rates, and ac magnetic fields. Furthermore, we present ground state cooling of an Al^+/Ca^+ two-ion crystal.

Q 36.4 Wed 15:15 P 11

Ultra-low phase noise from X- to the THz-band enabled by Difference Frequency Comb. — •Sebastian Müller, Mikhail Volkov, and Thomas Puppe — Lochhamer Schlag 19, 82166 Graefelfing, Germany

Frequency-comb-based generation of RF and THz signals with record-low phase noise becomes an enabling technology for a variety of appliciations from spectroscopy to communication. Here, using an offset-free difference frequency comb, we report ultra-low noise 9.6 GHz microwaves reaching -165 dBc/Hz using optical frequency division (OFD). We also show tunable sub-THz frequency synthesis (0.1-0.5 THz) for characterization of RF components.

Q 36.5 Wed 15:30 P 11

Theoretical optimization of BEC sources for Atom Interferometry — •Claudia Puertas González[1,2], Timothé Estrampes[1,2], Naceur Gaaloul[1], Dana-Codruta Marinica[2], and Eric Charron[2] — [1]Institute of Quantum Optics, Leibniz University Hannover, Welfengarten 1, 30167, Hannover, Germany — [2]Intitute of Molecular Science of Orsay, University Paris-Saclay, 598 Rue André Rivière, 91400, Orsay, France

Bose Einstein condensates (BECs) serve as excellent sources for atom interferometry due to their intrinsic coherence, which can be exploited to test the Universality of Free Fall. The key observable in such experiments is the phase difference between the interferometer arms, that depends on the interrogation time T. The Very Long Baseline Atom Interferometry (VLBAI) experiment, a 10-m high atomic fountain in Hannover, enables interrogation times of several seconds in both single- and dual-species configurations.

Reaching such long T requires a drastic reduction of the BECs expansion, as its natural expansion velocity is too large for precision measurements. In-Trap Lensing (ITL) and Delta-Kick Collimation (DKC) therefore play a crucial role in collimating the condensate prior to interferometry. I present here a theoretical framework for optimizing VLBAI source preparation and illustrate, using numerical simulations, how ITL and DKC enhance collimation and improve overall source quality. Efficient transport from the source to the launch position is equally essential and can be realized through shortcuts to adiabaticity (STA), which suppress excitations and help preserve coherence.

Q 36.6 Wed 15:45 P 11

Vortex N00N states in ring lattices — •Lars Arne Schäfer[1] and Reinhold Walser[2] — [1]Institut für Angewandte Physik, TU Darmstadt — [2]Institut für Angewandte Physik, TU Darmstadt

We study a gas of few bosons in a ring trap that can be superimposed with a light-induced azimuthal lattice potential. Light sculpting permits almost arbitrary control of the potential [1]. We describe a technique that uses time-dependent variations of the lattice to create matter-wave vortex N00N states, where N particles are in an all-or-nothing superposition of two counter-rotating states. To do that, we load the gas adiabatically into the lattice, perform resonant state transfer by Bragg scattering between the interacting many-body eigenstates and release them adiabatically into the free ring. In a Sagnac interferometer, the resulting state can improve measurement precision beyond the standard quantum limit $\Delta\theta_{\mathrm{SQL}}$ to the Heisenberg limit $\Delta\theta_{\mathrm{HL}} = 1/N$.

[1] G. Gauthier, I. Lenton, N. McKay Parry, M. Baker, M. J. Davis, H. Rubinsztein-Dunlop, and T. W. Neely, Direct imaging of a digital-micromirror device for configurable microscopic optical potentials, Optica 3, 1136 (2016).

[2] L. Pezzè, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, Quantum metrology with nonclassical states of atomic ensembles, Rev. Mod. Phys. 90, 035005 (2018).

Q 36.7 Wed 16:00 P 11

Diffraction-phase-free Bragg atom interferometry — •Victor Jose Martinez Lahuerta[1], Jan-Niclas Kirsten-Siemss[1], Klemens Hammerer[2,3,4], and Naceur Gaaloul[1] — [1]Leibniz University Hannover, Institut of Quantum Optics, Welfengarten 1, 30167 Hannover, Germany — [2]Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria — [3]Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, 6020 Innsbruck, Austria — [4]Institute for Theoretical Physics, Leibniz University Hannover, Appelstrasse 2, 30167 Hannover, Germany

Bragg Diffraction of matter waves is an established technique used in

the most accurate quantum sensors. It is also the method of choice to operate large-momentum-transfer, high-sensitivity atom interferometers. It suffers, however, from an intrinsic multi-path character. Optimal control theory has recently led to an improved robustness of atom interferometers to a range of challenging environmental effects such as vibrations or platform accelerations. In this theoretical work, we apply OCT protocols to control the Bragg diffraction phase shifts thereby enhancing the metrological accuracy of the interferometer. We show a minimization of the diffraction phase for realistic conditions of finite temperature of the incoming wavepacket in a multi-path, high-order Bragg interferometer in a Mach-Zehnder configuration. We study input states with different momentum widths and find that our approach mitigates diffraction phases below the microradian level in the case of 1% of the photon recoil, thereby eliminating one of the leading systematic effects in atom interferometry.

Q 36.8 Wed 16:15 P 11

'Goos-Hänchen' shifts and tilts in Bragg-Beam splitters with Bose-Einstein condensate — •Abhay Mishra, Adam Abdalla, Oleksandr V. Marchukov, and Reinhold Walser — Institute of Applied Physics, Technical University Darmstadt, Hochschulstr 4a, D-64289, Darmstadt, Germany

The wave optical phenomena of shifts and tilts of finite sized beam interacting with an interface was experimentally proven by F. Goos and H. Hänchen, now collectively known as Goos-Hänchen (GH) effect [1]. This lateral shift of beam was also observed before by Newton [2].

Our work here shows GH shifts in position and momenta of reflected Bose-Einstein condensate (BEC) wavelets emerging from Bragg-beam splitter.These effects become particularly important for precision measurements in long-time atom interferometry, where it can accumulate and result in loss of coherence. Using an analytical picture of superimposing Gaussian wavelets ansatz, we have quantified GH shifts of wavepackets from the expected classical trajectory. It matches with our numerical results of (3+1)D Gross-Pitaeviskii simulations and, significant for QUANTUS collaboration (DLR, grant number 50WM2450E) and broader matter-wave community.

[1] F. Goos and H. Hänchen, Ann. Phys. (Leipzig) 436, 333 (1947).
[2] I. Newton, Opticks, or, A Treatise of the Reflections, Refractions, Inflections and Colours of Light (Prometheus Books, New York, 2003), 4th ed.
[3] McKay, Samuel, et al. Physical Review Letters 134(9),093803 (2025).