Q 2: Matter Wave Optics

Time: Monday 11:00–13:00 Location: E001

Invited Talk Q 2.1 Mon 11:00 E001

Interferometry with Bose-Einstein Condensates for inertial sensing — •Sven Abend[1], Christian Schubert[2], Matthias Gersemann[1], Ernst M. Rasel[1], and QUANTUS-QGYRO Teams[1] — [1]Institut für Quantenoptik, LU Hannover — [2]DLR-SI, Hannover

Matter-wave interferometers show great a potential for improving inertial sensing. The absence of drifts recommends them for a variety of applications in geodesy, navigation, or fundamental physics. Bose-Einstein condensates (BECs) provide the means to achieve the lowest expansion energies of few picokelvin.

Such ensembles, bring in reach extremely accurate gravimeters, accelerometers and gyroscopes. An atom interferometer with scalable area may be formed in a twin lattice combined with a relaunch mechanism to obtain multi loops as well. Due to this scalability, it offers the perspective of reaching unprecedented sensitivities for rotations in comparably compact sensor head setups.

Moreover, atom-chip technologies offer the possibility to generate a BEC, paving the way for field-deployable miniaturized atomic devices. The extremely low expansion energies of BECs open up to extend the time atoms spend in the interferometer to tens of seconds. This brings in reach unprecedented sensitivities in space-borne applications.

Q 2.2 Mon 11:30 E001

Wave-packet evolution during laser pulses driving an atomic clock transition — •Nadja Augst and Albert Roura — Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm

Single-photon optical transitions enable novel applications of atom interferometry to dark-matter and gravitational-wave detection [1–3]. This work investigates the wave-packet evolution for an atom's center of mass during a laser pulse driving such a transition. Particular attention is paid to the effects of finite pulse duration on the central trajectory of the atomic wave packets and the phase that they acquire in the diffraction process. While the resulting deviations of the central trajectories are typically quite small, they can have a significant impact on the interferometric phase shift in high-precision measurements and a detailed analysis is therefore important. Our approach relies on a description of the matter-wave propagation in terms of central trajectories and centered wave packets [4].

[1] Y. A. El-Neaj et al., *EPJ Quantum Technol.* **7**, 6 (2020).
[2] M. Abe et al., *Quantum Sci. Technol.* **6**, 044003 (2021).
[3] L. Badurina et al., *J. Cosmol. Astropart. Phys.* **05** (2020) 011.
[4] A. Roura, *Phys. Rev. X* **10**, 021014 (2020).

Q 2.3 Mon 11:45 E001

Transverse motion of diffraction wavelets in a matter-wave beam-splitter — •Oleksandr Marchukov and Reinhold Walser — Institut für Angewandte Physik, Technische Universität Darmstadt, Hochschulstr. 4a, D-64289, Darmstadt, Germany

Matter-wave interferometry with Bose-Einstein condensates (BECs) is a rapidly developing tool for precision measurements [1]. A crucial element of matter-wave interferometers is a beam-splitter that employs the interaction of atoms with laser beams and creates superposition of macroscopically occupied momentum states.

We consider the Bragg beam-splitting of an off-axis BEC with three-dimensional Gaussian laser beams [2]. The transverse position offset leads to the inseparability of the longitudinal and transverse motion during the pulse. Experimentally, this manifests as transverse momentum kicks. In order to describe both the Bragg oscillations between the momenta components and the motion of the BEC, we model the wavefunction of the condensate via a superposition of squeezed coherent states, initially separated by even multiples of laser photon momentum. We construct a Lagrangian field theory using the variational ansatz [3] that leads to a system of coupled Bragg-Schrödinger equations and Newtonian equations for the Bragg fragments. We compare our results with the (3+1)D numerical simulations, using realistic experimental parameters, and find a good agreement.

[1] D. Becker, et al., Nature 562, 3910395 (2018)
[2] A. Neumann, et al., Phys. Rev. A 103, 043306 (2021)
[3] R. Walser, et al. New J. Phys., 10(4), 045020 (2008)

Q 2.4 Mon 12:00 E001

Four-Wave Mixing Neurons — •Kai Niklas Hansmann and Reinhold Walser — Institut für Angewandte Physik, Technische Universität Darmstadt, Hochschulstraße 4a, D-64289 Darmstadt, Germany

Artificial neural networks, and especially deep learning, are a rapidly increasing field and have found numerous applications in research and industry over recent years [1]. We propose to implement such a network in a physical system, utilizing the non-linearity of interacting ultracold quantum gases.

For this, we study the four-wave mixing process in bosonic matter waves [2, 3]. Given a superposition of three waves, the four-wave mixing process generates a fourth signal wave. We identify the three initial waves as input and the signal wave as output of an artificial neuron. We show, that the constructed system fulfills all requirements for neuron activity and responds to the input in a non-linear fashion. We perform benchmark calculations to determine the performance of the neuron.

Considering a homogeneous Bose-Einstein condensate in three dimensions with present plane matter waves, we find Josephson-like oscillations beyond the undepleted pump approximation. These can be expressed analytically and agree with numerical Gross-Pitaevskii simulations.

[1] O. Abiodun et al., *Heliyon* **4**, e00938 (2018).
[2] L. Deng et al., *Nature* **398**, 218-220 (1999).
[3] J.M. Vogels et al., *Phys. Rev. Lett.* **89**, 020401 (2002).

Q 2.5 Mon 12:15 E001

Multipole analysis for matter-wave optics — •Jan Teske and Reinhold Walser — Institut für Angewandte Physik, Technische Universität Darmstadt, Hochschulstraße 4A, Darmstadt, D-64289, Germany

In 1934 Frits Zernike introduced his orthogonal "Kreisflächenpolynome" to describe wavefront aberrations in optics. Nowadays, technical matter-wave optics requires [1] high precision modeling as interferometry with Bose-Einstein condensates [2] is paving the way to a new era of quantum technologies.

In this contribution, we present a (3+1)D multipole expansion adapting Zernike's for a consistent and efficient description for matter-wave optics with BECs. For this purpose, we are characterizing external potentials obtained by magnetic chip traps and Laguerre-Gaussian beams used for trapping, guiding and delta-kick collimation. Afterwards, we demonstrate an efficient approximation scheme for different density distributions. Further, we discuss density and phase perturbations that we analyze in terms of our partial wave expansion. Finally, we discuss phase aberrations caused during delta-kick collimation and the resulting density distortions after long expansion times.

[1] C. Deppner et al., PRL 127 (2021)
[2] M. Lachmann et al., Nature Communications 12, 1317 (2021)

Q 2.6 Mon 12:30 E001

A reflective atom interferometer — •Johannes Fiedler and Bodil Holst — University of Bergen, Bergen, Norway

The field of atom interferometry has expanded enormously over the last few decades. Atom interferometers are used in various applications, from measuring fundamental physics constants to atomic clocks. Detailed planning is ongoing for using atom interferometers as dark matter and gravitational wave detectors. Most applications use cold atoms or BEC and split the wave function via laser pulses. Transmission interferometer with thermal atoms uses dielectric objects [1] or a standing laser field [2] to split the beam. Via these techniques, the matter wave can only be separated over a few mrad [3]. A reflected atom interferometer can dramatically enhance the beam splitting to a rad. In this talk, we will present a scheme for a reflective atom interferometer using the surface diffraction of two parallel plates to achieve the large-angle separation of the wave function [4]. We will show a realisable interferometer setup and demonstrate the expected interference patterns.

[1] N. Gack et al. Phys. Rev. Lett. 125, 050401 (2020). [2] S. Eibenberger et al. Phys. Rev. Lett. 112, 250402 (2014). [3] C. Brand et al. Nature Nanotechnology 10, 845 (2015). [4] J. Fiedler et al. in preparation.

Q 2.7 Mon 12:45 E001

QUANTUS-2: Double Bragg atom interferometry in microgravity on long time scales — •Laura Pätzold[1], Merle Cornelius[1], Dorthe Leopoldt[2], Julia Pahl[3], Anurag Bhadane[4], Waldemar Herr[2,5], Patrick Windpassinger[4], Christian Schubert[5], Markus Krutzik[3,6], Sven Herrmann[1], Ernst M. Rasel[2], and The QUANTUS Team[1,2,3,4,7,8] — [1]U Bremen — [2]LU Hannover — [3]HU Berlin — [4]JGU Mainz — [5]DLR SI — [6]FBH Berlin — [7]U Ulm — [8]TU Darmstadt

Matter wave interferometry allows for quantum sensors with a wide range of applications, e.g. in geodesy or tests of fundamental physics. As a pathfinder for future space missions, QUANTUS-2 is a high-flux Rb-87 Bose-Einstein condensate (BEC) experiment operating in microgravity at the ZARM drop tower in Bremen. By applying a magnetic lens, we are able to reduce the total internal kinetic energy of the BEC to $\frac{3}{2}k_\mathrm{B}\cdot 38\,\mathrm{pK}$ in three dimensions [1]. This is required to enhance the atomic signal for interferometry on time scales in the order of seconds as envisioned for future space based precision experiments. Via a retro-reflex interferometry setup, QUANTUS-2 is performing atom interferometry based on double Bragg diffraction in free fall. In this talk, we present our latest results on the performance of open Mach-Zehnder type interferometers on extended time scales.

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[1] C. Deppner et al., Phys. Rev. Lett. **127**, 100401 (2021)