Q 82: Matter Wave Interferometry, Metrology, and Fundamental Physics IV

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

Q 82.1 Fri 14:30 P 11

Extracting signal from noisy very-long baseline atom interferometers — •Michael Werner and Naceur Gaaloul — Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

Light pulse atom interferometers (AIFs) are exquisite highly quan- tum sensors for inertial forces. State-of-the-art AIFs are used to mea- sure the fine-structure constant, or analyze the gravitational field and its spatial and temporal variations to high accuracy. Distinguish- ing between actual signals and noise is a critical challenge, especially when aiming to detect gravitational waves or dark matter in the mid- frequency range. Understanding each noise source in the interfero- metric process is essential for the success of future initiatives. In our study, we examine how various prominent noise sources impact one- dimensional AIFs of different configurations and identify the most sta- ble setups for the example of the VLBAI facility in Hannover

Q 82.2 Fri 14:45 P 11

Simulation Framework for Space-borne Quantum Sensors — •Gina Kleinsteinberg[1], Christian Struckmann[1], Christian Schubert[2], and Naceur Gaaloul[1] — [1]Institute of Quantum Optics, Leibniz University Hannover, Welfengarten 1, 30167 Hannover, Germany — [2]German Aerospace Center (DLR), Institute for Satellite Geodesy and Inertial Sensing, Callinstr. 30b, 30167 Hannover, Germany

Space-borne cold atom interferometers are promising sensors to probe accelerations and rotations at unprecedented levels of sensitivity. To advance the necessary technology readiness level and mature the space-deployment for future missions, technological demonstrators are needed. Among them are embarked testbeds, such as the *BECCAL* project which is planned to be deployed onboard the ISS and the *CARIOQA* mission, a future pathfinder for quantum accelerometry for Earth observation. To derive the experimental requirements and sensor performances, dedicated simulations are needed.

We present a *Python* based simulation framework that generates realistic phase signals for space-borne atom interferometers. This includes simulations of the atom interferometer itself as well as detailed analyses of systematic effects arising from environmental influences. To define the best operational mode of the experimental setup, multi-objective optimisation is used to explore options for balancing the multitude of mission parameters, while simultaneously optimising the sensor performance. We demonstrate the framework's capabilities through applications to the *CARIOQA* and the *BECCAL* project.

Q 82.3 Fri 15:00 P 11

Constraining the Casimir-Polder force via the scanning angle method — •Matthieu Bruneau[1,2], Gabin Routier[1], Etienne De Girolamo[1], Nathalie Fabre[1], Eric Charron[3], Thorsten Emig[4], Gabriel Dutier[1], Quentin Bouton[1], and Naceur Gaaloul[2] — [1]LPL, Université Sorbonne Paris Nord, Vil- letaneuse, France — [2]IQO, Leibniz Universität Hannover, Germany — [3]ISMO, CNRS, Université Paris-Saclay, Orsay, France — [4]LPTMS, CNRS, Université Paris-Saclay, Orsay, France

The Casimir-Polder (C-P) force is a universal atom-surface interaction arising from quantum fluctuations. Dominant at nanometric distances, it is closely linked to possible non-Newtonian gravitational effects. In this work, we model an experiment in which cold atoms are diffracted by a nanostructure, with C-P interactions encoded in the resulting diffraction pattern.

Current experimental sensitivity is limited mainly by the geometry of available nanogratings. To improve precision, we introduce a scanning-angle detection method and examine the influence of several C-P models, from simple van der Waals summations to full QED calculations based on multiple-scattering expansions. This approach enhances sensitivity, paving the way to more accurate characterization of atom-surface interactions and providing tighter constraints on hypothetical deviations from Newtonian gravity.

This work is supported by BMWK DLR funds (50WM2450A QUANTUS-VI).

Q 82.4 Fri 15:15 P 11

Advances in matter-wave interference of metal nanoparticles — •Richard Ferstl[1], Sebastian Pedalino[1], Bruno E. Ramírez-Galindo[1], Klaus Hornberger[2], Stefan Gerlich[1], and Markus Arndt[1] — [1]Faculty of Physics, University of Vienna, Vienna, Austria — [2]Faculty of Physics, University of Duisburg-Essen, Duisburg, Germany

Metal nanoparticles are a promising platform for universal near-field matter-wave interference experiments with scalable masses. Such experiments require innovative methods for beam formation, coherent beam splitters and efficient detectors. Here we present the state of the art in quantum interference experiments based on photodepletion beam splitters using 266 nm deep ultraviolet light gratings. Our experiment confirms the quantum wave nature of massive sodium nanoparticles, establishing the highest macroscopicity in a quantum experiment to date. The observed phase stability and high sensitivity to external forces opens our experimental platform to precision sensing applications, both in the regime of quantum wave and classical ray optics.

Q 82.5 Fri 15:30 P 11

Relativistic effects and their test in atom interferometry — •Christian Niehof, Daniel Derr, and Enno Giese — Technische Universität Darmstadt, Fachbereich Physik, Institut für Angewandte Physik, Schlossgartenstr. 7, D-64289 Darmstadt, Germany

Light-pulse atom interferometry with ultracold atoms enables high-precision experiments with applications ranging from inertial sensing to fundamental physics. Some gravitational-wave and dark-matter detectors are already proposed based on these techniques. However, achieving the required sensitivities demands large spacetime-area interferometers with substantial arm separations. This makes finite light propagation times and related relativistic effects non-negligible [1]. Thus, a consistent phase description must include state-dependent atomic Compton frequencies resulting from internal-state mass defects and gravitational influences on light and atoms. Additionally, resonant operation in accelerating frames requires laser-frequency chirps.

We present a unified framework that incorporates these effects for arbitrary interferometer geometries and diffraction mechanisms. When applied to Mach-Zehnder gravimeters that use either single-photon, Bragg, Raman, or recoilless E1-M1 transitions, our framework yields exact phase expressions under resonant chirping. These expressions show strong suppression of finite-speed-of-light terms and offer a method to remove residual velocity dependence. We also propose an experimentally feasible test of these predictions.

[1] J. Liu et al., Quantum Frontiers **3**, 2 (2024)

Q 82.6 Fri 15:45 P 11

Towards measuring the gravitational influence of a test mass using the Very Long Baseline Atom Interferometry facility. — •Guillermo A. Perez Lobato, Vishu Gupta, Kai C. Grensemann, Klaus H. Zipfel, Ernst M. Rasel, and Dennis Schlippert — Leibniz Universität Hannover, Institut für Quantenoptik

One of the scientific objectives of the Very Long Baseline Atom Interferometry (VLBAI) facility in Hannover is to investigate how gravity affects quantum objects such as macroscopically delocallized atomic wave functions. Using the 10 m baseline we plan to position additional test masses at 15 cm from the atoms. Including and removing the additional test mass will allow us to perform a differential measurement in order to determine the gravitational influence of the test mass on the atomic wave function. For this measurement to be possible, a series of technical requirements have to be met. For example: launching an ultracold sample of atoms with sub-nanokelvin effective energies, and giving the atoms a differential momentum sufficient to macroscopically delocallize the wave function. This contribution focuses on the progress in the facility during the past year, including the prototype system for positioning the masses with mm accuracy, demonstrating atom interferometry, and the plans to achieve the full potential of the facility. These include the progress towards achieving highly delocallized matter waves by the manipulation of rubidium atoms utilizing purely optical potentials for matter wave lensing, and control of the kinematics of the atoms for manipulation with Bragg beam splitting processes and Bloch oscillations for launch.

Q 82.7 Fri 16:00 P 11

Towards matter-wave interferometry of proteins — •Olga

Rybakova[1], Josef Reisinger[1], Amal S. Kumar[2], Valentin Köhler[2], Marcel Mayor[2], Stefan Gerlich[1], Philipp Geyer[1], and Markus Arndt[1] — [1]University of Vienna, Faculty of Physics & Vienna Doctoral School of Physics Boltzmangasse 5, 1090 Wien, Austria — [2]University of Basel, Department of Chemistry St. Johanns-Ring 19, 4056 Basel, Switzerland

In recent years, our team has provided experimental evidence for the wave nature of tailored organic molecules with masses up to 25 kDa, as well as for that of vitamins and antibiotic polypeptides. We now aim to step our studies up to a significantly higher level of molecular complexity by enabling matter-wave interference with genuine proteins.

Achieving this goal requires coordinated advances on several technological fronts, including generation of stable, slow, and cold molecular beams, coherent manipulation of complex particles, and, potentially, their detection in a neutral state. In this contribution, we outline our approach toward enabling protein interferometry and present recent progress on implementing a molecular beam splitting mechanism based on specially designed photocleavable tags.

Q 82.8 Fri 16:15 P 11

In-trap Collimation for BEC Interferometry in Space — •Gabriel Müller[1], Timothé Estrampes[1,2], Eric Charron[2], Wolfgang P. Schleich[3], Nicholas P. Bigelow[4], Naceur Gaaloul[1], and the CUAS consortium[4] — [1]Institute of Quantum Optics, Leibniz University Hannover, Germany — [2]Institut des Sciences Moléculaires d'Orsay, Université Paris-Saclay, CNRS, France — [3]Institute of Quantum Optics and Center for Integrated Quantum Science and Technology (IQST), Ulm University, Germany — [4]Department of Physics and Astronomy, University of Rochester, USA

Performing dual-species atom interferometry in space allows for precise tests of Einstein's Equivalence Principle, enhanced in sensitivity by extended interrogation times in weightlessness. The accuracy of such experiments is limited by the expansion energies of the dual-species mixtures as well as their differential CoM control. For the simultaneous preparation of condensed mixtures, we propose an in-trap collimation technique featuring in-situ excitations of collective modes compatible with state-of-the-art atom-chip setups. Employing this technique, we demonstrate the 2D collimation of condensed ^{87}Rb atoms in the Cold Atom Laboratory aboard the International Space Station. By careful characterization of the atom dynamics induced by time-dependent magnetic fields, we reduce the expansion energies and control the CoM release dynamics, enabling the observation of a freely expanding BEC up to 700 ms.