Q 45: Quantum Metrology for Fundamental Physics

Time: Thursday 11:00–13:00 Location: HS 1221

Invited Talk Q 45.1 Thu 11:00 HS 1221

Quantum Sensing in Space for Fundamental Physics and Applications — •Naceur Gaaloul — Leibniz University of Hanover, Institute of Quantum Optics, Hanover, Germany

Space-borne quantum technologies, particularly those based on atom interferometry, are heralding a new era of strategic and robust space exploration. The unique conditions of space, characterized by low-noise and low-gravity environments, open up diverse possibilities for applications ranging from precise time and frequency transfer to Earth Observation and the search of new Physics.

This contribution focuses on recent mission concepts utilizing quantum-gas sensors. The first mission, Space-Time Explorer and Quantum Equivalence Principle Space Test (STE-QUEST), introduces a dual-species atom interferometer operating over extended durations. This mission aims to tackle fundamental questions in Physics, such as testing the universality of free fall with unprecedented accuracy (better than one part in 10^{-17}), exploring various forms of Ultra-Light Dark Matter, and scrutinizing the foundations of Quantum Mechanics.

The second satellite mission is the CARIOQA pathfinder, recently endorsed by the European Commission. It is set to lay the groundwork for a space Geodesy mission, utilizing atom accelerometers to map temporal variations in Earth's gravity field.

To conclude, this presentation offers an overview of recent experimental results from orbital quantum laboratories, highlighting the cutting-edge advancements in the field of space-based quantum technologies.

Q 45.2 Thu 11:30 HS 1221

Polarization dynamics in a self-compensated comagnetometer for dark matter searches — •Daniel Gavilan-Martin[1,2], Mikhail Padniuk[3], Emmanuel Klinger[1,2,4], Grzegorz Lukasiewicz[3], Szymon Pustelny[3], Derek Jackson Kimball[5], Dmitry Budker[1,2,6], and Arne Wickenbrock[1,2] — [1]Helmholtz-Institut Mainz — [2]Johannes Gutenberg-Universität Mainz — [3]Marian Smoluchowski Institute of Physics, Jagiellonian University in Krakow — [4]Université de Franche-Comté — [5]Department of Physics, California State University East Bay, Hayward — [6]Department of Physics, University of California, Berkeley

Self-compensated comagnetometers, employing overlapping samples of spin-polarized alkali and noble gases (for example K-3He) are promising sensors for exotic beyond-the-standard-model fields and high-precision metrology such as rotation sensing. We propose and demonstrate a general method to calibrate the response of an atomic comagnetometer, to any possible perturbation of the atomic spins. The method uses a convenient, easy-to-implement protocol that is experimentally verified by successfully using it to predict the comagnetometer response to rotations. Furthermore, I will discuss the prospects of a search for gradient coupled axion-like dark matter conducted with such machine.

Q 45.3 Thu 11:45 HS 1221

Parity violation in atomic ytterbium: a progress report — •Stefanos Nanos, Iraklis Papigkiotis, Timoleon Avgeris, and Dionysios Antypas — Department of Physics, University of Crete, GR-70013 Heraklion, Greece

Small-scale tabletop experiments are emerging as a complement to their large-scale high-energy-physics counterparts conducted in large facilities, for studies on fundamental physics. Specifically, atomic parity violation (APV) serves as a gateway to understanding the effects of weak interaction in atoms. Recent observations on how the APV effect varies among a chain of ytterbium (Yb) isotopes motivate the implementation of this method as a versatile probe of nuclear and particle physics.

In this spirit, our team has initiated construction of an atomic beam apparatus, focusing on detecting isotopic variation of APV in Yb. The new setup is currently under development at the Physics Department of the University of Crete in Greece, with the purpose of measuring the Yb $6s^2\ {}^1S_0 \rightarrow 5d6s\ {}^3D_1$ optical transition at 408 nm. The project aims to significantly expand existing approaches, through high-precision APV measurements, with a focus on probing the neutron distributions in the Yb nuclei. These investigations seek to address questions related to the size of neutron-rich nuclei and neutron stars. Moreover, the method will serve as a probe of physics beyond the Standard Model, involving studies of electron-nucleon interactions which would be mediated by additional Z bosons.

Q 45.4 Thu 12:00 HS 1221

Dark Energy Detection at the Einstein-Elevator — •Charles Garcion[1], Magdalena Misslisch[1], Sukhjovan Gill[1], Ioannis Papadakis[2], Sheng-wey Chiow[3], Nan Yu[3], and Ernst Rasel[1] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Germany — [2]Ferdinand Braun Institut, Humboldt Universität Berlin, Germany — [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, United States of America

Investigating dark energy, which constitutes 70% of the universe's energy and drives its accelerated expansion, remains a fundamental challenge. Scalar fields with screening mechanisms such as chameleon, symmetron and galileon have been proposed as potential explanations for dark energy. Cold atom experiments, particularly in chameleon and symmetron parameter constraints, have been valuable but face limitations due to the uncertainties on the gravity interactions between test masses and atoms.

This presentation discusses the collaborative D3E3/DESIRE project between JPL and Leibniz University Hannover. Utilizing atom interferometers in the microgravity environment of the Einstein-Elevator, the project aims to modify the scientific payload from the MAIUS-1 sounding rocket mission. This modification involves implementing a periodic test masse and multi-loop atom interferometers to enhance dark energy model constraints.

The DESIRE project is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics Affairs and Climate Action (BMWK) under grant number 50WM2155

Q 45.5 Thu 12:15 HS 1221

Reflective atom interferometer and its applications — •Johannes Fiedler and Bodil Holst — Department of Physics and Technology, University of Bergen, Norway

The field of atom interferometry has experienced significant growth in recent decades, finding applications in diverse areas, from measuring fundamental physics constants to precision atomic clocks. Many applications involve the use of cold atoms or Bose-Einstein condensates, employing laser pulses to split the atomic wave function. In contrast, transmission interferometers with thermal atoms utilize dielectric objects [1] or a standing laser field [2] for beam splitting, limiting the separation to a few milliradians [3]. This presentation introduces a reflective atom interferometer scheme, leveraging surface diffraction between two parallel plates to achieve a large-angle separation of the wave function [4]. The talk covers a feasible interferometer setup, showcases expected interference patterns, and outlines optimal designs for applications in acceleration measurements and velocity selection.

[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. Phys. Rev. A 108, 023306 (2023).

Q 45.6 Thu 12:30 HS 1221

Theory of multi-axis atom interferometric sensing for inertial navigation — •Christian Struckmann, Knut Stolzenberg, Dennis Schlippert, and Naceur Gaaloul — Leibniz University Hannover, Institute of Quantum Optics, Welfengarten 1, 30167 Hannover, Germany

Quantum sensors based on the interference of matter waves provide an exceptional measurement tool for inertial forces, and are considered next generation accelerometers for applications in geodesy, navigation, or fundamental physics due to the absence of drifts. However, conventional atom interferometers are only able to measure inertial forces along one single axis, resulting in one acceleration and one rotation component. To determine the motion of a moving body, an inertial measurement unit needs to measure the acceleration and rotation of the body along three perpendicular directions. Extending this atom interferometeric measurement scheme to multiple components would normally require the subsequent measurement along a differently oriented axis.

In this contribution, we present our theory and simulation efforts based on experimental schemes enabling three dimensional sensing using simultaneously operated single-axis atom interferometers. We detail the sensitivity and dimensionality scaling of the measurement as well as its potential and improvement avenues.

This work is supported by DLR funds from the BMWi (50WM2263A-CARIOQA-GE and 50WM2253A-(AI)ˆ2).

Q 45.7 Thu 12:45 HS 1221

Scenario building for Earth Observation Space Missions Featuring Quantum Sensors — •Gina Kleinsteinberg, Christian Struckmann, Naceur Gaaloul, and for the CARIOQA Consortium — Institute of Quantum Optics, Leibniz University Hanover, Welfengarten 1, 30167 Hanover, Germany

Being extremely sensitive to accelerations and rotations with high stability at low frequencies, atom interferometer configurations offer a versatile approach not only for Fundamental Physics research but also for Earth Observation. The latter is currently gaining more and more significance, as consequences of climate change, e.g. sea level rise and changes in water mass distributions are directly reflected in Earth's gravity field. In order to increase the maturity of quantum sensors in space, the European Commission envisages a quantum pathfinder mission, CARIOQA-PMP (Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry - Pathfinder Mission Preparation), to be launched by the end of this decade. In this contribution, we present a simulation tool capable to analyse the mission scenarios for the quantum pathfinder as well as for the follow-on full-fledge quantum gravimetry mission. The mission scenario is developed in close cooperation with the geodesy community within the CARIOQA-PMP project from the classical satellite simulations, the quantum measurement and finally the recovery of the gravity field from the interferometer signal. This work is supported by DLR funds from the BMWi (50WM2263A-CARIOQA-GE and 50WM2253A-(AI)ˆ2).