Q 53: Matter Wave Interferometry II

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

Q 53.1 Thu 11:00 HS I

Bayesian optimization for state engineering of quantum gases — •Gabriel Müller, Victor Jose Martinez-Lahuerta, and Naceur Gaaloul — Leibniz University Hannover, Institute for Quantum Optics, Hannover, Germany

State engineering of quantum objects is a central requirement for precision sensing. When the quantum dynamics can be described by analytical solutions or simple approximation models, optimal state preparation protocols have been theoretically proposed and experimentally realized. For more complex systems such as interacting quantum gases, simplifying assumptions do not apply anymore and the optimization techniques become computationally impractical. Here [1], we propose Bayesian optimization based on multi-output Gaussian processes to learn the physical properties of a Bose Einstein condensate within few simulations only. We evaluate its performance on an optimization study case of diabatically transporting the quantum gas while keeping it in its ground state. Within a few hundred executions, we reach a competitive performance to other protocols. This paves the way for efficient state engineering of complex quantum systems including mixtures of interacting gases or cold molecules.

[1] Gabriel Müller *et al* 2025 *Quantum Sci. Technol.* **10** 015033

Q 53.2 Thu 11:15 HS I

Robust Double Bragg Diffraction via Detuning Control — •Rui Li[1,2], Victor Martinez-Lahuerta[1], Stefan Seckmeyer[1], Naceur Gaaloul[1], Klemens Hammerer[2], and QUANTUS-1 Team[1,3,4] — [1]Leibniz University Hanover, Institute of Quantum Optics, Hannover, Germany — [2]Leibniz University Hanover, Institute of Theoretical Physics, Hannover, Germany — [3]Humboldt-Universität zu Berlin, Institut für Physik, Berlin, Germany — [4]University Bremen, Center of Applied Space Technology and Microgravity, Bremen, Germany

We present a new theoretical model and numerical optimization of double Bragg diffraction (DBD), a widely used technique in atom interferometry. Using the effective Hamiltonians derived in our theoretical model, we investigate the impacts of AC-Stark shift and polarization errors on the double Bragg beam-splitter efficiency, along with their mitigations through detuning control. Notably, we design a linear detuning sweep that demonstrates robust DBD efficiency exceeding 99.5% against polarization errors up to 8.5%. Moreover, we develop an artificial intelligence-aided optimal detuning control protocol, showcasing enhanced robustness against both polarization errors and Doppler effects. Recently, we have experimentally achieved the proposed detuning-sweep DBDs in the QUANTUS-1 BEC Laboratory situated in Bremen and have observed their enhanced efficiency and robustness compared to the traditional DBDs. Finally, we propose a construction of a full Mach-Zehnder type gravimeter using detuning-sweep DBD pulses for enhanced contrast.

Q 53.3 Thu 11:30 HS I

Squeezing Enhancement in Atom Interferometers Based on Bragg Diffraction — •Julian Günther[1,2], Jan-Niclas Kirsten-Siemss[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

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 a Bragg Mach-Zehnder interferometer. We evaluate the phase uncertainty in the phase measurement taking into account the fundamental multi-port and multi-path nature of the Bragg processes, and determine optimally squeezed states for a given geometry. We show, that Gaussian pulses need to be chosen carefully with respect to the squeezing strength and momentum distribution of the incoming particles 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 53.4 Thu 11:45 HS I

Simulation of atomic diffraction through a nanograting — •Matthieu Bruneau[1,2], Julien Lecoffre[1], Ayoub Hadi[1], Charles Garcion[1,2], Nathalie Fabre[1], Eric Charron[3], Gabriel Dutier[1], Quentin Bouton[1], and Naceur Gaaloul[2] — [1]Laboratoire de physique des lasers, Université Sorbonne Paris Nord, Villetaneuse, France — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Germany — [3]Université Paris-Saclay, CNRS, Institut des Sciences Moléculaires d'Orsay, France

Tremendous advancements in cold atom physics have transformed atomic interferometry into a powerful tool for precision measurements.

This work models an experiment involving the diffraction of cold argon atoms through a transmission nanograting, where the observed pattern is intrinsically related to short-range Casimir-Polder (C-P) forces. Accurate modeling of these forces is critical for exploring non-Newtonian gravitational effects and advancing nanotechnology.

Using a quantum numerical model combined with QED calculations, we validate experimental data and achieve a state-of-the-art determination of the atom-surface potential strength parameter, $C_3 = 6.87 \pm 1.18$ meV·nm^3. Sensitivity is constrained primarily by nanograting geometry. To enhance precision, we are implementing a scanning angle method and extending our 1D model to a 2D framework with new QED calculations to fully characterize the 2D C-P potential.

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

Q 53.5 Thu 12:00 HS I

Robust Bragg diffraction for atom interferometers using optimal control theory — •Victor Jose Martinez Lahuerta[1], Jan-Niclas Kirsten-Siemss[1], Klemens Hammerer[2], and Naceur Gaaloul[1] — [1]Leibniz University Hannover, Institut of Quantum Optics, Welfengarten 1, 30167 Hannover, Germany — [2]Leibniz University Hannover, Institute for Theoretical physics, Hannover, Germany

Algorithms from the field of artificial intelligence (AI) and machine learning have been used in recent years to efficiently solve multidimensional problems. In physics, these algorithms are applied with increasing success, e.g., to solve the Schrödinger equation for many-body problems, or used experimentally to generate ultracold atoms and control lasers. Here we report on our results obtained optimizing Bragg diffraction with optimal control theory. Great progress has been achieved recently in sensitivity and robustness under certain vibrations, accelerations, and experimental problems. Nevertheless, we focus on the accuracy of the interferometer by minimizing the diffraction phase in a close-to-ideal scenario accounting for a finite temperature of the BEC and the multi-path nature of high-order Bragg diffraction.

Q 53.6 Thu 12:15 HS I

Local Measurement Scheme of Gravitational Curvature using Atom Interferometers — •Michael Werner[1,2], Ali Lezeik[2], Dennis Schlippert[2], Ernst Rasel[2], Naceur Gaaloul[2], and Klemens Hammerer[1] — [1]Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

Light pulse atom interferometers (AIFs) are exquisite quantum probes of spatial inhomogeneity and gravitational curvature. Moreover, detailed measurement and calibration are necessary prerequisites for very-long-baseline atom interferometry (VLBAI). Here we present a method in which the differential signal of two co-located interferometers singles out a phase shift proportional to the curvature of the gravitational potential. The scale factor depends only on well controlled quantities, namely the photon wave number, the interferometer time and the atomic recoil, which allows the curvature to be accurately inferred from a measured phase. As a case study, we numerically simulate such a co-located gradiometric interferometer in the context of the Hannover VLBAI facility and prove the robustness of the phase shift in gravitational fields with complex spatial dependence. We define an estimator of the gravitational curvature for non-trivial gravitational fields and calculate the trade-off between signal strength and estimation accuracy with regard to spatial resolution. As a perspective, we discuss the case of a time-dependent gravitational field and corresponding measurement strategies.

Q 53.7 Thu 12:30 HS I

All-optical squeezed BEC generation for microgravity operation — •Jan Simon Haase[1] and The INTENTAS Team[1,2,3,4,5,6,7] — [1]Institut für Quantenoptik, Leibniz Universität Hannover — [2]Institut für Transport- und Automatisierungstechnik, Leibniz Universität Hannover — [3]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology Ulm — [4]Ferdinand-Braun-Institut Berlin — [5]Institut für Angewandte Physik,Technische Universität Darmstadt — [6]Deutsches Zentrum für Luft- und Raumfahrt e.V., Institut für Satellitengeodäsie und Inertialsensorik, Hannover — [7]Humboldt Universität zu Berlin

Atom interferometers serve as high-precision sensors for quantities like acceleration, rotation, or magnetic fields. The sensitivity of atom interferometers is greatly enhanced by long interrogation times, as they are available in spaceborne applications. Second-long interrogation times favor the employment of atomic Bose-Einstein condensates (BECs) with their well-controlled spatial mode and their slow expansion rates. The sensitivity can be increased even further by employing squeezed atomic ensembles that enable measurements beyond the standards quantum limit. The INTENTAS project develops a source of entangled atoms that can be tested under microgravity conditions. Microgravity is provided by Hannover's Einstein Elevator, which offers up to 4s of free fall. A key feature is the fast all-optical BEC generation which is performed in a crossed-beam optical dipole trap. In this talk, the status of the project will be presented which includes fast BEC generation on ground and first results from microgravity tests.

Q 53.8 Thu 12:45 HS I

Theory of multi-axis atom interferometric sensing for inertial navigation — •Christian Struckmann, Knut Stolzenberg, Ernst M. Rasel, 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 a highly sensitive and stable measurement tool for inertial forces with applications in geodesy, navigation, or fundamental physics. Conventional atom interferometers, however, can only measure inertial forces along a single axis, yielding information about one acceleration and one rotation component. To fully characterize the motion of a moving body, an inertial measurement unit must capture the acceleration and rotation along three perpendicular directions. Extending this atom interferometric measurement scheme to multiple components would normally require subsequent measurements along various spatial directions.

In this contribution, we present the theory behind PIXL (Parallelized Interferometers for XLerometry), a novel method to operate a quantum sensor based on a 2D array of Bose-Einstein Condensates enabling multi-axis sensing through simultaneously operated single-axis atom interferometers [K. Stolzenberg et al., arXiv:2403.08762 (2024)]. We detail the multi-dimensional scaling of the inertial phases as well as the capabilities of such a multi-axis measurement unit.