The Abdus Salam International Centre for Theoretical Physics

## Frontiers of Matter Wave Optics School and Conference | (SMR 3735)

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P01

# Magnetic Shielding for Long Baseline Atom Interferometry

**Mahiro Abe** [1], **Yijun Jiang** [2], **Sam Carman** [1], **Benjamin Garber** [1], **Megan Nantel** [2], **Jan Rudolph** [1], **Hunter Swan** [1], **Thomas Wilkason** [1], **and Jason Hogan** [1]

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Since the sensitivity of an atom interferometer scales proportionally with its baseline length, larger-scale interferometers are now actively being discussed as an exciting new research area for probing fundamental physics. One of the challenges in scaling up these precision devices is shielding from background magnetic fields, which can imprint unwanted phase shifts on the atom wavepackets. We present recent progress in the magnetic shield design for a 10m strontium gradiometer tower being built at Stanford, and the 100m MAGIS Collaboration experiment to be installed at Fermilab. [1]

The shield design consists of four layers of mumetal sheets pressed against each other to form an octagonal-cross-section tube. We have obtained preliminary magnetometry data for this design with the 10m tower. By minimizing layer-to-layer gaps and performing multiple steps of degaussing, we achieve field homogeneity to order 1mG inside the tower, sufficient for gradiometers operating with strontium. The presence of the shield also enhances the performance of an internal bias field necessary during interferometry, thus further reducing magnetic field systematic errors.

For MAGIS, the 100m baseline will be constructed by lowering 17 identical segments with the aforementioned octagonal shield, that will be lowered down into a vertical shaft. The installation constraints of this structure result in inter-segment shield gaps that are not covered by the mumetal shield. For these regions, we have designed shield couplers and compensation coils as alternative methods of background field suppression. Ultimately, the MAGIS magnetic shielding system accounting for shield gaps and shield edges aims to suppress magnetic field effects on the atom interferometer to below the quantum noise limit, while being compatible with the mechanical and electronic constraints of a large-scale experiment.

[1] M. Abe, P. Adamson, *et al*, Quantum Sci. Technol. **6**, 044003 (2021).

P02

# Rotation Sensing Using Point Source Atom Interferometry

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In Point Source Atom Interferometry (PSI) [1] , a sequence of Raman laser pulses interact with an expanding ball of cold atoms, to split, redirect and recombine the matter-wave. It exploits the correlation between the position and velocity of the atoms to produce a spatially imprinted interference pattern across the atomic cloud. Since the phase of atoms contains information about inertial effects on the system, the interferometer can be used to detect angular rates. Therefore, PSI can be used as a sensor that can take measurements for inertial navigation applications. We plan to develop such a rotation sensor and test out optimal control pulses [2] to improve the performance of the interferometer, tackling issues involving scale factor instability and low contrast. As a preliminary step, we characterised the response of the $I\&Q$ modulator needed to control the phase of the optimised pulses, thus reducing the errors caused by potential non-linearities.

[1] S. Dickerson et al., PRL **111**, 083001 (2013).
[2] J. Saywell et al., Phys. Rev. A . **98**, 023625 (2018).

P03

# Talbot-enhanced, maximum-visibility imaging of BEC interference

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In a double-slit geometry we use magnetic levitation to obtain clear spatial interference between two BECs that are initially axially separated. Fringes with periods of up to 85um are observed using non-tomographic resonant absorption imaging, utilising the magnifying effect of a weak axial inverted parabolic potential [1]. Through independent control of the detuning of the light for absorption imaging and of the imaging plane of our optical system we harness the Talbot effect to yield enhanced single-shot interference visibility of >135%, compared to the ideal visibility for resonant light [2].

[1] M. E. Zawadzki et al., "Spatial interference from well-separated split condensates," Phys. Rev. A 81, 043608 (2010).
[2] Y. Zhai et al., "Talbot-enhanced, maximum-visibility imaging of condensate interference," Optica 5, 80 (2018).

P04

# Effective field theory for matter waves of cobosons derived from elementary particles

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Matter-wave interferometers, such as atomic clocks and atom interferometers, use the coupling of internal and center-of-mass degrees of freedom of a bound system, such as an atom, to electromagnetic fields. These atoms are usually treated in a first quantized framework, assuming the atom to behave as a fundamental particle, which raises the question of a fundamental derivation from elementary-particle physics. Moreover, existing field theories for atoms, like BEC field theory, rely on bosonic field operators available on the atomic level rather than on the constituent level and do not address the derivation from elementary particles.

In this work, we choose a second-quantized approach from quantum field theory to describe atoms as composite particles formed by two elementary fermions. Our derivation starts from potential nonrelativistic quantum electrodynamics [1] giving rise to bound-state charged particles with cobosonic character [2] rather than elementary bosons. We derive this effective theory with a projection formalism that allows the projection of the fundamental-particle Hamiltonian to the bound-state level of atoms, i.e. it contains only cobosonic field operators that create or destroy simultaneously a nucleus and its corresponding bound-state electron.

Furthermore, we introduce a second-quantized version of the PZW transformation [3] which brings the Hamiltonian into the more familiar form where the internal degrees of freedom of the atom couple to the electric and magnetic field rather than the vector potential. Thus, the resulting Hamiltonian of the effective theory describes an interacting coboson field which can directly be used for calculations regarding matter-wave and quantum-clock interferometry.

**Acknowledgement –** The projects "Building composite particles from quantum field theory on dilaton gravity" (BOnD) and "Metrology with interfering Unruh-DeWitt detectors" (MIUnD) are funded by the Carl Zeiss Foundation (Carl-Zeiss-Stiftung). The QUANTUS and INTENTAS projects are supported by the German Space Agency at the German Aerospace Center (Deutsche Raumfahrtagentur im Deutschen Zentrum für Luft- und Raumfahrt, DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (Bundesministerium für Wirtschaft und Klimaschutz, BMWK) due to an enactment of the German Bundestag under Grant Nos. 50WM1956 (QUANTUS V), 50WM2250D-2250E (QUANTUS+), as well as 50WM2177-2178 (INTENTAS). E.G. thanks the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) for a Mercator Fellowship within CRC 1227 (DQ-mat).

[1] A. Pineda and J. Soto, Phys. Rev. D **59**, 016005 (1998).
[2] M. Combescot et al., Phys. Rep. **463**, 215 (2008).
[3] R. Lopp and E. Martín-Martínez, Phys. Rev. A **103**, 013703 (2021)

P05

# Towards Neutral Atom Sagnac Interferometry with RF-Dressed State-Dependent Potentials

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At University of Nottingham Cold Atoms group we are working on atomic chip traps for Sagnac interferometry. We employ RF-dressed potentials in order to achieve state-dependent transport around the ring-shaped trap [1, 2]. The scheme relies on Rb-87 atoms having Lande g-factor of almost equal magnitude and opposite sign for its two hyperfine ground states. By using multiple phase-locked RF sources with different polarisation we modify a quadrupole potential through precise phase control of each RF channel. Such traps can then be used to realise a guided Sagnac interferometer with atoms confined in all 3 spatial dimensions [3, 4]. We experimentally demonstrate the feasibility of such transport scheme by driving several thousands of Rb-87 atoms in F=1 and F=2 ground states in counter-propagating directions.

[1] T. Fernholz, R. Gerritsma, P. Krüger, and R. J. C. Spreeuw Phys. Rev. A **75**, 063406 (2007).
[2] F. Gentile, J. Johnson, K. Poulios, T. Fernholz, arXiv:1909.01186 (2019).
[3] R. Stevenson, M. R. Hush, T. Bishop, I. Lesanovsky, T. Fernholz, Phys. Rev. Lett. **115**, 163001 (2015).
[4] J. Johnson, B. Foxon, V. Atkocius, F. Gentile, S. Jammi, K. Poulios, T. Fernholz, Proceedings of SPIE, 11296 (2020).

P06

# Wave-packet evolution during laser pulses driving an atomic clock transition

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Single-photon optical transitions enable novel applications of atom interferometry to dark-matter and gravitational-wave detection [1, 2, 3, 4]. 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 [5].

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[2] Y. Abou El-Neaj, et al., EPJ Quantum Technology **7**, 1-27 (2020).
[3] M. Abe, et al., Quantum Science and Technology **6**, 044003 (2021).
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[5] A. Roura, Phys. Rev. X **10**, 021014 (2020).

P07

# Atom interferometry based on narrow-linewidth transitions in cadmium and strontium

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Atom interferometers with their extremely high sensitivity to inertial forces are an excellent method for investigating and understanding gravity and its gradients. One emerging and novel class of atom interferometer is based upon narrow linewidth inter-combination transitions, allowing for new schemes such as single-photon interferometers to be performed. Work done towards the realization of such novel interferometers based on cadmium and strontium atoms, which allow access to narrow linewidth transitions in the UV and optical regimes respectively, is presented [1]. While Sr is well established in terms of laser technology and also as an interferometry choice, Cd is less explored, so particular attention is paid to the generation of the necessary atom samples and techniques for matter-wave manipulation. The experiment requires a new generation of UV laser systems, characterized by high-power and low-noise performances which are not commercially available and have been built and tested [2,3,4]. State-of-art cooling techniques for the generation of ultra-cold cadmium samples have been numerically simulated and presented here. The prospects of an optical dipole trap of cadmium atoms and the launch of the atoms is likewise also discussed.

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[3] S. Manzoor, J. N. Tinsley, S. Bandarupally, M. Chiarotti, N. Poli, Opt. Lett. 47, 2582 (2022).
[4] Mauro Chiarotti, Jonathan N. Tinsley, Satvika Bandarupally, Shamaila Manzoor, Michele Sacco, Leonardo Salvi, and Nicola Poli, arXiv:2206.05145v1 [physics.atom-ph] 10 Jun 2022.

P08

# Large momentum transfer atom interferometer with an ultra-cold atom source

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Over the last years, cold-atom inertial sensors based on atom interferometry have reached sensitivity and accuracy levels competing with inertial sensors based on different technologies. Light pulse atom interferometers are implemented for precision measurements in various areas such as gravito-inertial measurements, fundamental physics tests or measuring fundamental constants [1]. The sensitivity of such apparatus increases with the momentum separation between the two arms of the interferometer. Bragg diffraction is a corner stone for new schemes of Large Momentum Transfer (LMT) beam splitters since it allows multiphoton transitions coupling momentum states into the same internal state. However, its multiport nature, in the quasi-Bragg regime [2], can lead to spurious diffraction phases and parasitic interferometer paths that distort the interferences fringes [3,4].

In this poster session, I will present an experimental setup producing an all-optical Bose-Einstein condensate diffracted in the quasi-Bragg regime. We perform a 104 $\hbar k$ LMT-interferometer based on sequential Bragg pulses showing a fringe visibility of around 20%. I will also present an experimental study of the phase response function of our interferometer and comment the inherent multi-state nature of quasi-Bragg interferometers that limits the phase estimation.
Finally, I will present our method to prepare the atomic source in the sub-nanoKelvin range velocity dispersion leading to a better control of the systematic effects linked to Bragg diffraction.

[1] Tino et al., Atom interferometry : proceedings of the International School of Physics "Enrico Fermi", course 188 (2014).
[2] Siemß et al., Analytic theory for Bragg atom interferometry based on the adiabatic theorem, Phys. Rev. A, **102**, 033709 (2020).
[3] Béguin et al., Characterization of an atom interferometer in the quasi-Bragg regime, Phys. Rev. A, **105**, 033302 (2022).
[4] Parker et al., Controlling the multiport nature of Bragg diffraction in atom interferometry , Phys. Rev. A, **94**, 053618 (2016).

P09

# Precision measurement of the fine structure constant as a test of the Standard Model

Precision measurement of the fine structure constant α provides a powerful opportunity to test the Standard Model of particle physics. We are conducting such a measurement via the recoil frequency of cesium atoms in a matter-wave interferometer. We constructed a 5-m tall atomic fountain, which uses Bragg diffraction and Bloch oscillations to impart a large momentum splitting in cesium-133 atoms. During free fall, each atom accrues phase proportional to the recoil frequency, from which the fine structure constant is determined. Comparing recoil-based α measurements against measurements deduced from the g-2 electron anomaly (Hanneke et al 2008) allows tests of Standard Model calculations. Previous atom-interferometric measurements of α have reached accuracies of 200 parts per trillion (ppt) (Parker et al 2018) and 80 ppt (Morel et al 2020). Our current measurement seeks a sensitivity of 20 ppt. To reach this sensitivity, we plan to reduce key systematic effects related to the interferometry beam quality. Our new vacuum chamber is 50cm wide and can accommodate beam waists up to 5 cm, ten times the beam waist used in our group's previous measurement (Parker et al 2018). Additionally, we're improving beam characterization methods to better investigate systematics from Gouy phase and wavefront inhomogeneities. And to study errors introduced by the thermal motion of atoms, we've upgraded our detection system to include spatial resolution of the atomic cloud.

P10

# Sagnac atom interferometer gyroscope with large enclosed area and multiple orbits

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Sagnac atom interferometers are a promising technique for high-performance rotation sensing, with potential applications for inertial navigation. The use of trapped atoms for the interferometer avoids the need for long free-fall distances that would be incompatible with a navigation apparatus. We have previously demonstrated a dual Sagnac interferometer using Bose-condensed atoms in a time-orbiting potential trap. We report here on improvements to this approach, including a 3-fold increase in the orbit radius and the use of multiple orbits. These improvements lead to an enclosed area of 8.2 $mm^2$, which corresponds to a rotation sensitivity of $6\times10{-}7$ rad/s at shot-noise-limited detection. While shot-noise-limited performance has not yet be achieved, the interferometer operation is sufficiently stable to permit useful averaging times longer than $10^4$ s. We also discuss a new, more compact, version of the apparatus that is based on an atom chip and which will be suitable for environmental testing.

P11

# Beam Splitters and Mirrors with Aberrations in Matter-Wave Interferometry

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Light-pulse atom interferometers have matured into capable sensors for small inertial and electromagnetic forces and are employed to test the foundations of physics. Today, most cold-atom based matter-wave interferometers use either single-photon [1] or two-photon transitions [2, 3] in combination with large-momentum-transfer techniques. These schemes are susceptible to imperfections in the optical beams which may arise, e.g., from mirror vibrations, imperfectly aligned optics, polarization mixing in optical fibers or the strain pattern in the windows of the experimental chamber. In order to fully capture and determine the influence of typical experimental conditions, a fully 3D and often costly numerical modeling is necessary [5].

In our contribution, aberrations are assumed to be locally small perturbations of a classical electromagnetic field which facilitates an analytical treatment, to circumvent long computation times of numerical simulations. We introduce an effective analytical model for diffraction including parasitic spatio-temporal effects during a light-pulse. Such models can be derived from a general perturbative approach for two-level quantum systems with non-commutative elements in the quasi-resonant regime. In this case we show, how to reconstruct an approximate analytic solution by exploiting the oscillatory properties of the unperturbed solution. After comparison of this solution with the ideal case we are able to identify the effect of perturbative optical potentials with a modified local momentum transfer [4] as well as time- and space-dependent detunings and transition frequencies [6]. Based on such a model effective beam splitters and mirrors are derived.

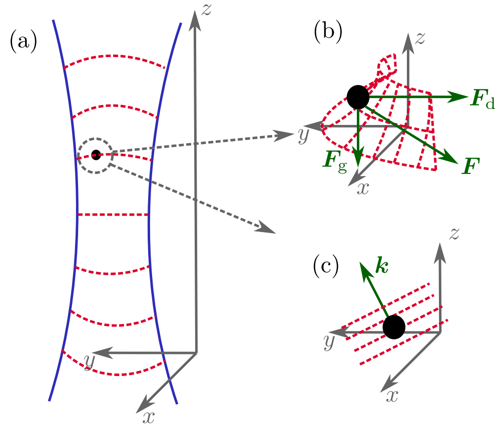


**Fig. 1:** During the a pulse the atoms are (a) locally sensitive to the wave-front curvature of the laser beam. Local dipole forces induce a dressing of the motion (b) and modified momentum transfer (c).

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P12

# Towards probing the hydrogen - graphene interaction by diffraction

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Irradiating graphene with a beam of fast atoms is a common approach to augment its properties by introducing foreign atoms and defects into the lattice [1]. The interaction process between the atoms and graphene is however only partly understood. To resolve this issue, we plan to diffract atomic hydrogen with a velocity of up to 120 000 m/s through the 246 pm lattice of graphene [2]. Thereby, we aim to directly probe the atom-graphene interaction during transmission in a non-destructive way, using the diffraction pattern as the read out. Various parameters, such as the fraction of transmitted particles and coherence will be evaluated as a factor of beam energy, irradiation time and sample temperature. Furthermore, we plan to investigate charge transfer between a beam of protons and graphene.

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[2] Brand et al. New J. Phys. **21**, 033004 (2019).

P13

# Ultra-cold atomic source on chip for on-board applications


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The use of cold atom quantum sensors is of particular interest for various space missions such as space geodesy, equivalence principle test, gravitational wave observation or fundamental physics experiments. The space environment imposes constraints of compactness, robustness and limited power consumption. The objective of this work is to develop a new type of ultra-cold atom source, compatible with on-board applications. The source represented in *Figure 1* integrates on a chip the magnetic trapping with microscopic wires as well as a diffraction grating that generates the beam configuration for Magneto-Optical Trapping (MOT). With such a source, we will combine the advantages of robustness of the grating MOT and the low energy consumption as well as the high atomic flux of a magnetic chip[1].

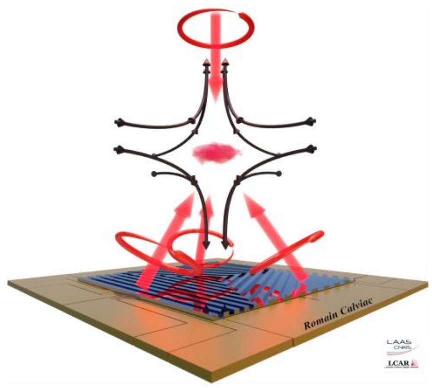


*Figure 1 View of the new ultra cold atom source combining a grating MOT and a magnetic chip.*

The different diffracted orders of the grating must meet specific constraints of intensity, polarization and direction for an efficient cooling [2, 3, 4]. The target geometrical parameters for the clean room fabrication of the gratings are predicted with a numerical simulations based on the Fourier modal method. After an experimental characterisation, we have chosen a grating based on Al/Si stack with a diffraction angle of 40°.

The magnetic chip placed under the grating consists on Z-shaped copper wires deposited on an AlN substrate. Size calculations have shown that we can achieve trapping frequencies of the order of 500Hz at 500µm from the surface with a current around 8A.

To be able to bring the magnetically trapped atoms as close as possible to the wires, thus ensuring a fast and efficient evaporative cooling, the diffraction grating has to be thinned and bonded to the magnetic chip with an ultra-high vacuum compatible epoxy glue. The magnetic chip is then In-brazed to a bulk copper holder with a macroscopic Z-wire.

In this poster, I will present a full design to achieve the new ultra-cold atom source. I will explain the grating and magnetic chip sizing, realization and there hybridization.


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P14

# MAGIS-100 Ultracold Atom Source and Laser System Design

**Sam Carman[1], Mahiro Abe[1], Benjamin Garber[1], Yijun Jiang[2], Megan Nantel[2], Jan Rudolph[1], Hunter Swan[1], Thomas Wilkason[1], and Jason Hogan[1]**

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MAGIS-100 is a 100-meter baseline atom interferometer under construction at Fermilab that aims to explore fundamental physics by combining state-of-the-art techniques in long-baseline atom interferometry and technological advances in atomic clocks. This novel detector will search for ultralight dark matter and new fundamental interactions, test quantum mechanics in new regimes, and serve as a technology pathfinder for future km-scale atom-based gravitational wave detectors. At the core of the instrument are three atom sources placed along the baseline that are used to prepare, launch, and image clouds of ultracold Sr atoms. Since they will be installed underground in the MINOS access shaft, these atom sources will be protected by custom temperature-controlled enclosures, and will feature all of the vacuum, electronics, and optics hardware required to prepare multiple isotopes of strontium. I will present the progress on the design and assembly of the atom source hardware as well as the associated optical frequency comb-stabilized laser system.

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P15

# Practical Limits on Large-Momentum-Transfer Clock Atom Interferometers

**Mauro Chiarotti**[1], **Jonathan N. Tinsley**[1], **Satvika Bandarupally**[1], **Shamaila Manzoor**[1], **Michele Sacco**[1], **Leonardo Salvi**[1,2] **and Nicola Poli**[1,2,3]

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Atom interferometry utilising single-photon optical transitions represents an emerging technology with the ability to probe physics in a variety of previously untested regimes [1,2]. Multiple experiments based upon the clock transition of Sr at 698 nm have been proposed to search for a wide set of fundamental physics goals, such as gravitational wave detection [3]. Crucial to meeting these experiments' required sensitivities is the implementation of large momentum transfer (LMT), with very large enhancements of $10^3$-$10^4$ ħk ultimately proposed for terrestrial experiments currently in the development stage [4]. In practice, this typically means increasing the momentum separation between the two paths of the wavepacket by applying a series of π pulses. Such a manipulation of the atom samples is highly susceptible to the noise performance of the interferometry laser: within the quantum community-framework of the operational fidelity [5], we have been simulating the effect of the intensity and frequency noise on a single atom at rest interacting with resonant light [6]. Our results, considering a typical square pulse sequence [3], show the challenging nature of the proposed experiments, suggesting that the limiting role played by the laser frequency spectrum must be accounted for when studying the practical feasibility of a gravimeter sequence. Particularly, the equivalent laser linewidth is required be considerably lower than has previously been suggested. Within this framework, we further present and analyse two high-power, frequency-stabilised laser sources designed to perform interferometry on the 1S0 - 3P0 clock transitions of cadmium and strontium, respectively operating at 332 nm and 698 nm [6].

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P16

# Probing the quantum Fisher information of passive states

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The quantum Fisher information (QFI) is a measure of the metrological enhancement obtained from quantum correlations. As such, it provides a bridge between quantum metrology and the study of entanglement. Recent works have leveraged this connection to use the QFI as a scalable tool for certifying the presence of multipartite entanglement in quantum many-body systems. However, in general, it remains a challenge to calculate and measure the QFI for both theory and experiment and this limits its usage for entanglement detection. In this talk, we discuss a protocol for extracting the QFI of thermal states and how it can be extended to a much broader class of equilibrium states. More specifically, we study so-called passive states and how virtual temperatures can be used to obtain the QFI with the help of linear response theory. Numerical results showcase our generalized protocol for a specific model. Our work broadens the scope of applicability of the QFI and opens interesting questions regarding possible extensions to different entanglement measures.

P17

# Triply State Entangled Quantum Cheshire Cat Observed in Neutron Interferometry

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The phenomenon of the Quantum Cheshire Cat [1] is a paradoxical effect in which different properties of a particle seem to be spatially separated. To observe the effect, weak measurements [2] are applied in between pre and postselection in an interferometer setup. One may use weak values to quantify the perceived path occupations of the properties. While the effect's first demonstration was in neutron interferometry where particle and spin properties were split [3], in the presented experiment the energy degree of freedom is additionally separated into a third partial neutron beam [4]. Some light is shed on the first order behaviour of weak values and the Cheshire Cat behaviour is compared to a complementarity relation.

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P18

# Strapdown multi-axis quantum inertial sensor

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Inertial navigation systems integrate the rotation rates and accelerations from triads of accelerometers and gyroscopes to compute their trajectory in time and determine their position. They are typically limited by bias drifts of their inertial sensors. Our team aims to create mobile bias-free quantum inertial sensors that will, in the future, revolutionize commercial inertial guidance systems by enabling accurate long-term navigation without feedback from satellite-based GPS.

The exploitation of quantum physics allowed the development of matter waves interferometers. Like classical optics, the idea is to split and recombine coherently these wave packets thanks to light pulses, to create multiple interfering paths. The phase of the fringes is sensitive to inertial effects due to the mass of the atoms. These quantum sensors have excellent measurement noise and long-term stability which make them candidates for a technological breakthrough in the field of inertial navigation.

After a theoretical study to define the architecture of the multi-axis atom interferometer, the experimental application of these new concepts has led to the apparatus developed in iXAtom laboratory [1]. The multi-axis atom interferometer has then been hybridized with a triad of classical accelerometers, allowing to avoid dead times and increase the dynamic range of the quantum sensor to be compliant with inertial navigation. With our current setup and a static sensor head at a given tilt angle, we have reached a short-term accuracy of 7.7 µg on the acceleration vector norm, and a long-term stability of 60 ng. Moreover, unlike in the laboratory, residual acceleration and rotations of the vehicle can cause strong losses of contrast of the atom interferometer. Concerning the vibrations, a hybridization technique between classical accelerometers and atomic interferometers patented by the iXAtom team was implemented and led to the performances mentioned above [2]. For the rotations, they represent the next major issue to tackle for strapdown applications, and an ongoing work consists in rotating dynamically the reference mirror during the interferometry sequence while adding rotation-induced phase terms compensation (Coriolis acceleration notably). This study also includes data processing between the gyroscopes and the hybrid 3D accelerometer. As for now, fringes contrast can be retrieved for rotation rates below 300 mrad/s and interrogation times up to 15 ms (for the laser close to the vertical). Furthermore, a first order phase correction led to fringes reconstruction with a contrast around 35% and a SNR around 6, for T = 10 ms and rotations rates up to 150 mrad/s.

Once this study completed, the full hybrid quantum IMU will be tested on a measurement campaign which should pave the way for future applications such as navigation and onboard gravimetry.

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P19

# AN ATOM INTERFEROMETER DRIVEN BY A PICOSECOND FREQUENCY COMB

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Light-pulse atom interferometry where lasers are used to coherently split and recombine atom wave packet has led to extremely sensitive sensor. For instance, it allows fundamental tests such has measuring fundamental constants [1] or testing Einstein equivalence principle [2]. We demonstrate such an interferometer using a picosecond frequency comb. More specially, we perform stimulated Raman transition on free falling $^{87}$Rb between the $|5s^2S_{1/2}, F = 1\rangle$ and $|5s^2S_{1/2}, F = 2\rangle$ and reach a relative incertitude of $\sim 10^{-5}$ on Earth gravitational acceleration .

Using a mode-locked laser makes conversion in non linear crystal more efficient. Allowing to extend interferometry in the deep-UV, and for instance on anti-hydrogen, opening the door for a very stringent test of the interaction of antimatter with gravity.

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P20

# A geometric approach to optimal control design of Raman beam-splitter pulses

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Light-pulse atom interferometry exploits coherent control of matter waves by means of laser fields to detect inertial quantities such as angular rates and accelerations [1]. The disruptive potential of this technology could enable free-inertial navigation without the aid of Global Navigation Satellite Systems [2]. However, interferometer performance in real-world applications is severely affected by non-optimal laser-atom interaction, e.g. owing to variations in laser intensity and atomic velocity. [3].
Optimal control offers a solution by allowing the design of laser pulses whose effects are robust to pulse-length and off-resonance errors, thus enabling good performance in harsh dynamic environments [4]. Within this framework we propose a method to design optimized Raman beam-splitter pulses that exhibit a minimal phase dispersion over a range of different detunings and Rabi frequencies. This ensures that a) the residual sensitivity to steady detuning due to Mach-Zehnder pulse sequence asymmetry is reduced; b) the scale factor stability due to inter-pulse Rabi frequency variations is enhanced. The proposed design method provides a link between optimal control and sensitivity function formalism. Moreover, the optimization problem can be easily understood geometrically in terms of trajectories on the Bloch sphere.

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P21

# Abstract template for Frontiers of Matter Wave Optics School and Conference (12 Sep 2022 – 23 Sep 2022)


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We explored the stability of persistent flows of a 6Li molecular BEC confined in a ring trap. When such a superfluid is confined in a multi-connected geometry, the irrotational nature of its velocity field implies quantized circulation. The presence of an obstacle within the torus trap causes the system to have a critical value of this circulation, i.e. a critical current, above which a phase slip occurs, manifested by the formation of a vortex thus decreasing the current [1]. We found that by increasing the number of these obstacles within the torus trap, this critical current increases, thus creating a more stable system. We observed this effect both experimentally and with numerical simulations performed with both a three and two-dimensional GPE, finding good agreement between all of them. Since external influences also affect the quantum phase, this system can be a useful test bed for creating a rotational superfluid sensor in the future, finding various applications in fields such as geodesy, seismology, inertial navigation and gravity research.



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P22

# Optimised Mobile Atom Interferometry

**R.H. Eagle**[1,2]**, R. Thomas**[1]**, S. Legge**[1]**, S.A Haine**[1]**, and J. Close**[1]

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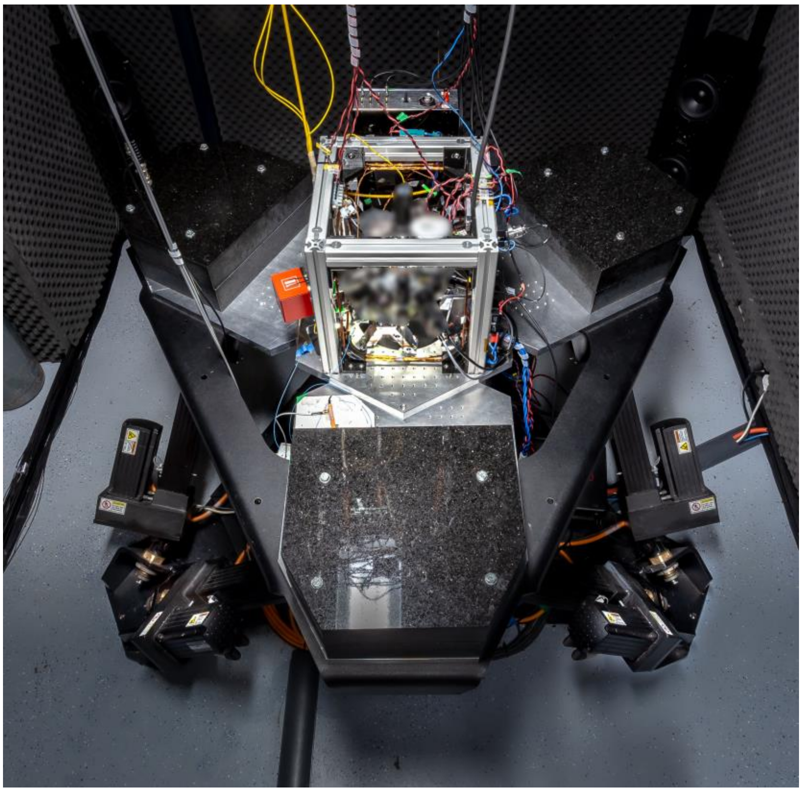
In the 30 years since its inception, lab-based atom interferometers have provided some of the most accurate measurements of gravity, gravity gradients, and acceleration with prospects to advance, mineral exploration, groundwater management, inertial navigation on earth, and in space, and subsurface planetary exploration among other applications. **Why then have we not seen atom interferometers used in these applications?** The major issue is the detrimental effect of platform motion: the rolling of a ship, the turbulence of a plane, the vibrations of a truck or lunar rover. Initial steps to solving this problem are the topic of this work.

I present a simulation of a mobile Raman atom interferometer subject to translational vehicle motion. We investigate how design choices such as maximum laser power, beam width, and cloud temperature along with noise mitigation techniques such as the use of composite pulses, vibration isolation systems, and hybrid classical-quantum accelerometers improve an atom interferometer's short-term sensitivity, systematic errors, and drift. These results provide the scoping and design requirements for field deployable sensors that we will build and test on our flight simulator.



*A portable atom interferometer attached to our flight simulator platform*

P23

# A Phase Shear Detection System for the MAGIS-100 and AION Experiments

Gedminas Elertas, on behalf of the MAGIS and AION collaborations,

University of Liverpool, UK.

MAGIS-100 is a next-generation quantum sensor under construction at Fermilab that aims to explore fundamental physics with atom interferometry over a 100-meter baseline. AION is a UK initiative to further develop the technology towards AION-100 and establish a prototype tower at the University of Oxford. MAGIS & AION will search for the ultralight dark matter fields with the ultimate goal of developing the technology for a future kilometre-scale detector and satellite-based experiments that would be sufficiently sensitive to detect gravitational waves from known sources [1-3].

Several technological challenges must be overcome to reach the sensitivity required to probe the ultralight dark matter range from $10^{-22}$ eV – $10^{-3}$ eV [1,4]. To achieve this, MAGIS-100 and AION will have to demonstrate the shot-noise limited detection, ability to launch atoms for tens of meters, maintaining the record-breaking spatial separation of the wave packets, and account for multiple systematic uncertainties.

As part of UK input to MAGIS-100 and a future AION experiment, the University of Liverpool is contributing to the development of a phase-shear detection platform. The phase-shear detection method is a novel technique which imprints the interference fringes across the atom cloud allowing single-shot measurements of the phase and contrast, increasing the repetition rate of the experiment and better control of the systematics [5]. The ability to angle the interferometry beam is also achieved through this method, which is essential in countering the unwanted Coriolis force contribution. The phase-shear platform and its integration into the detection system for the experiment will be presented.

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P24

# Spectroscopy of a thermal beam for laser frequency stabilisation

**D. Evans**[1]

On behalf of the Imperial College London AION Group

[1] *Imperial College London*

The Atom Interferometer Observation and Network (AION) project is a collaboration that aims to build a detector to be sensitive to Dark Matter candidates in the ultralight regime of parameter space. This next-generation detector should also have the capability to detect mid-frequency gravitational waves which would contribute to the field of multi-messenger astronomy[1]. My contributions to the project have been towards achieving atom spectroscopy as part of the construction of an apparatus capable of cooling $Sr^{87}$ to microkelvin temperatures.

A blue, 461-nm laser will be directed into the chamber where the atoms will be loaded. The laser targets a broad transition in $Sr^{87}$ atoms, namely the $5s^2\ ^1S_0 \rightarrow 5s5p\ ^1P_1$ transition[2]. The cooling process will use Magneto-Optic Trapping, which will require the 461-nm laser to have a frequency stability of $\Delta\nu$ ¡¡ $\Gamma$ = 32 MHz[3]. By measuring the absorption of 461-nm light by the thermal beam of Sr atoms, we are able to characterise both the flow of atoms into the chamber and resolve a spectroscopic feature that can be utilised for frequency feedback.

This process involves integrating various physical components with the control systems of the experiment. The photodetector will be placed just before the atom chamber and will be used to collect data on the laser. The input beam to the photodetector has passed through the atoms twice, having been retro-reflected on the other side of the chamber. The data will feed back to a central processor and used to calculate laser stability. The atoms will scatter a different proportion of the input light depending on the frequency of light entering the chamber. The absorption spectroscopy data forms the basis of the stabilisation of this laser. It reaches a minimum voltage response at the resonant frequency when the atoms scatter the greatest number of photons, so we can perform a sweep in frequency to identify the minimum response from the photodetector. The minimum will correspond to the resonant frequency of the transition. As the laser drifts, we can modulate the frequency to restore the laser to resonance. We can adjust the laser frequency by feeding back to the piezo of the laser, which controls the resonant frequency of the cavity. The cooling sequence of $Sr^{87}$ involves a 2D and 3D blue MOT to cool the atom to microkelvin temperatures, so ensuring the stability of both via this control loop is vital.

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P25

# Diffracting Molecular Matter-Waves at a Standing Wave Light Grating in the Deep UV

Other members of the group working on same topic & poster, discussed with Markus Arndt.

P26

# Topological Van Hove singularities at phase transitions in Weyl metals

In 3D topological metals a subset of the Van Hove singularities of the density of states sits exactly at the transitions between topological and trivial gapless phases. By analysing two minimal models, we show that they originate from saddle points located between Weyl points with opposite chiralities, and portrait their topological nature through their magnetotransport properties. Finally, we exemplify the relation between Van Hove singularities and topological phase transitions in Weyl systems by presenting our results about the 3D Hofstadter model, which offers a simple and interesting playground to consider different kinds of Weyl metals and understand the features of their density of states.

P27

# The frustration of bein odd

We consider the effects of so-called Frustrated Boundary Conditions (FBC) on quantum spin chains, namely periodic BC with an odd number of sites. First, we show that, in absence of external fields, FBC allow for the direct determination of correlation functions that signal a spontaneous symmetry breaking, such as the spontaneous magnetization. When paired with anti-ferromagnetic interactions, FBC introduce geometrical frustration into the system and the ground state develops properties which differ from those present with other boundary conditions, thus brining striking, yet puzzling, evidence that certain boundary conditions can affect the bulk properties of a 1D system. Finally, we argue that FBC introduce long-range order in the system, similar to that enjoyed by SPT phases. Our results prove that even the weakest form of geometrical frustration can deeply affect a system's properties and pave a way for a bottom-up approach to better understand the effects of frustration and their exploitations also for technological purposes.

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# Adiabatic Perturbation Theory for Large-Momentum-Transfer Atom Optics

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In recent years atom interferometers have become increasingly popular as high-precision sensors with various applications such as gravimeters, rotation sensors, general inertial sensing tasks [1], and quantum clock interferometry [6]. Starting out as extremly precise sensors to test the foundations of relativity and quantum mechanics they have slowly matured into practical instruments. For future commercial applications, more compact and miniaturized setups are necessary and already in development. In all these cases, both high precision and large sensitivity are essential. One technique to increase the sensitivity is to use Large-Momentum-Transfer (LMT) methods such as double Bragg diffraction, sequential pulses or Bloch oscillations in different types of interferometers [1, 2, 3]. In our contribution we propose a semi-analytical approach based on the adiabatic perturbation theory (APT) [4, 5] to the description of light-pulse beam splitters and mirrors. This approach allows us to treat Bragg diffraction and Bloch oscillations in a unified framework. Specifically, we can use the APT to model the effects of imprinted phases (e.g. non-adiabatic effects) during Bragg and LMT-pulses. Compared with previous results using a simpler form of APT [5] or simple rotating-wave arguments [2] we obtain additional corrections for the adiabatic approximation leading to small, but first-order corrections to the phase. Furthermore, we verify our model by full numerical simulations and characterize limitations of APT.

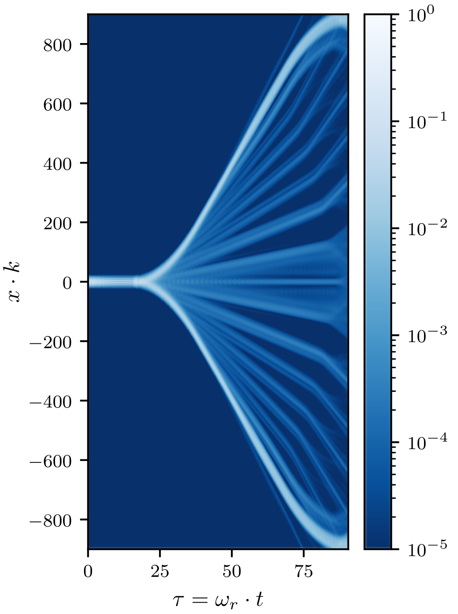


**Fig. 1:** Simulated spatial probability density $\rho_\psi(x,t) = |\psi(x,t)|^2$ in a symmetric lattice based LMT beam splitter.

**Acknowledgement –** The QUANTUS and INTENTAS projects are supported by the German Space Agency at the German Aerospace Center (Deutsche Raumfahrtagentur im Deutschen Zentrum für Luft- und Raumfahrt, DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (Bundesministerium für Wirtschaft und Klimaschutz, BMWK) due to an enactment of the German Bundestag under Grant Nos. 50WM2250D-2250E (QUANTUS+) and 50WM2177-2178 (INTENTAS). E.G. thanks the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) for a Mercator Fellowship within CRC 1227 (DQ-mat).

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P29

# Single-shot measurements from a contrast interferometer

Bose-Einstein condensates offer many advantages as the evolving medium for atom interferometry. With extremely narrow velocity distributions they overcome issues that affect cold-atom-based devices that arise due to the finite temperature and size of these sources. Here we report on recent developments in BEC atom-interferometry experiments for precision measurements at Strathclyde. We discuss an atom interferometer that is inherently insensitive to the phase noise of the readout system. We will describe new features developed in our Bose-Einstein condensate system, including tuneable, high-fidelity, symmetric atomic-beamsplitters through a multi-pulse, Kapitza-Dirac scheme. This system is used to measure ambient magnetic field gradients at the level of 1e-4 T/m. Additionally, we investigate contrast interferometry, an atomic homodyne detection method that transfers the atomic phase into a temporal atomic beatnote, and show how the entire interferometric signal can be readout in a single shot.

P30

# Towards Matter-Wave Interference with Optically Levitated Nanospheres (Poster and Talk)

**A. Grinin** [1] , **William Eom** [1] , **and A. A. Geraci** [2]

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In our efforts to demonstrate particle-wave duality through the realization of a double-slit-like experiment for optically levitated nanospheres, we have developed a cryogenic, XHV chamber suitable for optical levitation and laser-cooling of dielectric nanoobjects. Several experimental challenges like motional ground state cooling [1], pressures below $1 \cdot 10^{-15}$mbar, internal temperatures below 100K and relative position stability of only few tens of nanometres must be overcome in order to preserve a coherence time of approx. 200 milliseconds. I will present our current system, ideas and calculations on how to achieve these goals.

A demonstration of matter-wave interference with such large objects would extend the current matter-wave interference limit [2] by three to four orders of magnitude, and test possible wave function collapse models as well as push toward experiments with gravity-induced entanglement [3]. Such an exceptionally calm environment also facilitates short-range force measurements to test Newtonian gravity, matter neutrality and other fundamental forces [4].

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P31

# Dark State Dependent Sub-Wavelength Width Optical Lattice


**Edvinas Gvozdiovas, Povilas Račkauskas, and Gediminas Juzeliūnas**

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Optical lattices are typically created by interfering two or more light beams, so that atoms are trapped at minima or maxima of the emerging interference pattern depending on the sign of the atomic polarizability [1]. They are highly tunable and play an essential role in manipulation of ultracold atoms [2, 3]. Yet the spatial resolution of optical lattices is restricted by the diffraction limit. However, this limit does not necessarily apply to optical lattices relying on coherent coupling between atomic internal states. It was recently demonstrated in theoretical and experimental publications that a periodic array of sub-wavelength barriers can be formed for atoms populating a long-lived dark state of the Λ-type atom-light coupling [4, 5]. The Λ scheme has a single dark state, so no spin (or quasi-spin) degree of freedom is involved for the atomic motion in the dark state manifold.

In this work we demonstrate that a Tripod atom light coupling scheme shown in Fig. 1 can be used to create a lattice with spin-dependent sub-wavelength barriers [6,7]. The tripod scheme is characterized by two dark states playing the role of quasi-spin states. Introducing this spinor degree of freedom provides new possibilities for controlling the spectral and kinetic properties of atoms in the lattice. The tripod lattice can be realized using current experimental techniques.

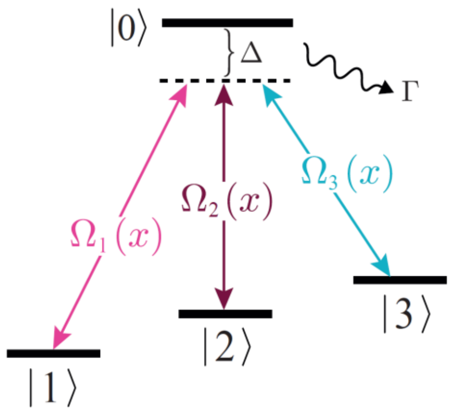


Figure 1. Tripod atom-light coupling scheme.


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P32

# Upgrades to the University of Liverpool Atom Interferometer

**Leonie Hawkins** [1], **on behalf of the Liverpool atom interferometry group.**

[1] *University of Liverpool, UK.*

An atom interferometer employing Rubidium-85 atoms has been constructed at the University of Liverpool. The device is a prototype detector to test for concepts of fundamental physics beyond the standard model, and can act as a test stand for quantum technology and inertial sensing applications [1]. The current set-up employs an atomic drop configuration after loading ~$10^8$ atoms and cooling them down to 10 μK. Atom interferometry has been demonstrated via Ramsey fringes, with coherent control of states being achieved via Rabi oscillations [2].

A significant upgrade to this atom interferometer is underway, involving the construction of a new vacuum chamber and atom source, the set up of new atom-optics, an active vibration control system and a new detection system. The new interferometer will be in a fountain configuration, allowing for extended interrogation times therefore increasing the sensitivity of the device, and will also incorporate an initial cold source of atoms to the MOT to increase the repeititon rate of the experiement. Progress on the upgrade will be reported.

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P33

# The Design of the BECCAL Laser System and its Capabilities

**Victoria A. Henderson[1,2*], Tim Kroh[1,2], Marc Kitzmann[1], Jakob Pohl[1,2], Matthias Schoch[1], Christoph Weise[1], Hrudya Thaivalappil Sunilkumar[1], Bastian Leykauf[1], Evgeny Kovalchuck[1], Achim Peters[1,2], and the BECCAL Collaboration[1-10]**

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BECCAL (Bose-Einstein Condensate and Cold Atom Laboratory) [1] is a cold atom experiment designed for operation on the ISS. It is a DLR and NASA collaboration, built on a heritage of sounding rocket and drop tower experiments, and NASA's CAL [2]. This multi-user facility enables the exploration of fundamental physics with Rb and K BECs and ultra-cold atoms in microgravity, facilitating prolonged timescales and ultra-low energy scales. The scientific envelope targets atom interferometry, atom optics, scalar and spinor BECs, quantum gas mixtures, strongly interacting gases and molecules, and quantum information.

We will present an overview of the current design and capabilities of the BECCAL laser system, focusing on the unique challenges faced when designing for such ambitious functionality. To meet stringent size, weight and power limitations, we combine micro-integrated diode lasers [3], and Zerodur boards of miniaturized free-space optics [4], connected via fibre optics. The flexibility of the resulting system allows for a wide variety of architectures making the laser system design particularly crucial for potential experiments. We will additionally suggest how the laser system can be utilised to enable possible experiments such as a quantum memory [5].

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economic Affairs and Climate Action (BMWK) under grant numbers DLR 50WP1702, and 50WP2102.

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P34

# Towards a large-scale Atomic Interferometer Observatory and Network (AION) using ultracold strontium atoms

Chung Chuan Hsu [1] , Brian Bostwick[1] , Zachary Eyler[1] , Xintong Su[1] , Kimberly Tkalčec[1] , Tiffany Harte[1] , and Ulrich Schneider[1]

[1]*University of Cambridge*

Dark matter and gravitational waves hold the key to unlocking many intricacies of the universe. However, detection sensitivities remain limited. Atom interferometers were thus proposed as a means to complement and expand the detection ranges of current devices. An example is the Atom Interferometry Observatory and Network (AION) [1], a planned series of atom interferometers in a vertical shaft where differential measurements will be performed using single-photon transitions of strontium. Currently, we are building a small-scale technology demonstrator. Constructions will then scale up to increasing heights from 10m to 1km for enhanced sensitivities.

These large-scale detectors will require significant improvements both in temperature and atom number. At the University of Cambridge, we are working towards the preparation of suitable clouds of ultracold spin-polarized fermionic strontium and to optically transport them into the main interferometer shaft. I will present the current status of our work.

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P35

# Finite Pulse-Time Effects in Quantum-Clock Interferometry


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Quantum-clock interferometry [1, 2] has been suggested as a quantum probe to test the universality of free fall (UFF) and the universality of gravitational redshift (UGR) in Refs. [4, 5]. Both interferometer schemes are sensitive to violations of UGR while the second is also sensitive to UFF violations. In each case the UGR sensitivity arises from the internal transitions during the interferometer. In case of the scheme in Ref. [4] a quantum-clock is initialized within the interferometer sequence with Doppler-free E1-M1 transitions. Similarly, the sequence of Ref. [5] relies either on technically challenging (optical) Raman transitions or a more simple combination of Bragg diffraction and E1-M1 transitions. However, the recoil-less two-photon transitions necessary for these setups have been investigated [3] mostly in quantum systems at rest. Therefore, the interplay between the quantized center-of-mass (COM) motion and the clock transitions are not yet known. In our contribution we derive a model including this internal-external coupling as well as position-dependent laser intensities. Furthermore, we investigate the effects of the COM motion during quantum-clock pulses in a Gaussian laser beam and show that additional interferometer branches arise for finite-duration clock initialization pulses (see also Fig. 1). Finally, we determine the effects of these additional branches on the signal of UGR and UFF tests with the two interferometer schemes presented in Refs. [4, 5, 6].

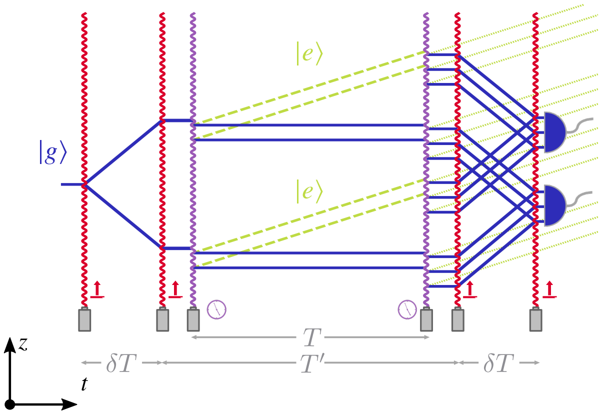


**Fig. 1:** Interferometer scheme from Ref. [5] including additional branches due to the COM-motion during the clock pulses.


**Acknowledgement –** The QUANTUS and INTENTAS projects are supported by the German Space Agency at the German Aerospace Center (Deutsche Raumfahrtagentur im Deutschen Zentrum für Luft- und Raumfahrt, DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (Bundesministerium für Wirtschaft und Klimaschutz, BMWK) due to an enactment of the German Bundestag under Grant Nos. 50WM1956 (QUANTUS V), 50WM2250D-2250E (QUANTUS+), as well as 50WM2177-2178 (INTENTAS).



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P36

# An experimental setup for diffracting atoms through graphene

**C. Kanitz [1], J. Bühler [1], and C. Brand [1]**

[1] *German Aerospace Center (DLR), Institute of Quantum Technologies, Wilhelm-Runge-Strasse 10, 89081 Ulm, Germany*

Diffraction at nanomechanical transmission gratings is independent of the matter wave's internal structure, and in this sense universal. To reach large diffraction angles, small grating periods are required, which are bounded by the precision of the fabrication process and the mechanical stability of the resulting structure. To overcome these limitations, we aim to directly use the natural structure of graphene as transmission grating for atomic matter waves [1]. Its period of 246 pm is more than 400 times smaller than that of state-of-the-art nanomachined gratings [2], leading to diffraction angles in the mrad-regime. Here, we present the experimental setup for this endeavour alongside the commissioning progress. Besides the experimental setup itself, we will discuss the experimental control system and the preparation of the graphene gratings.

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# Preparation for the Integration of the BECCAL Laser System

**Marc Kitzmann[1], Victoria A. Henderson[1,2*], Tim Kroh[1,2], Jakob Pohl[1,2], Matthias Schoch[1], Christoph Weise[1], Hrudya Thaivalappil Sunilkumar[1], Bastian Leykauf [1], Evgeny Kovalchuck[1], Achim Peters[1,2], and the BECCAL Collaboration[1-10]**

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[2]*Ferdinand-Braun-Institut, Leibniz Institut für Höchstfrequenztechnik, Berlin, Germany*
[3]*Johannes Gutenberg-Universität, Mainz, Germany*
[4]*Leibniz Universität Hannover, Hannover, Germany*
[5]*DLR Institut für Satellitengeodäsie und Inertialsensorik, Hannover, Germany*
[6]*DLR Institut für Quantentechnologien, Ulm, Germany*
[7]*Universität Ulm, Ulm, Germany*
[8]*ZARM, Universität Bremen, Bremen, Germany*
[9]*DLR Institute for Space Systems, Bremen, Germany*
[10]*DLR Simulations-und Softwaretechnik, Braunschweig, Germany*

BECCAL (Bose-Einstein Condensate and Cold Atom Laboratory) [1] is a cold atom experiment designed for operation on the ISS. It is a DLR and NASA collaboration, built on a heritage of sounding rocket and drop tower experiments, and NASA's CAL [2]. This multi-user facility enables the exploration of fundamental physics with Rb and K BECs and ultra-cold atoms in microgravity, facilitating prolonged timescales and ultra-low energy scales. The scientific envelope targets atom interferometry, atom optics, scalar and spinor BECs, quantum gas mixtures, strongly interacting gases and molecules, and quantum information.

The BECCAL laser system faces unique challenges in design for its ambitious functionality and in planning the integration for such a complex space based system. To meet stringent size, weight and power limitations, we combine micro-integrated diode lasers [3], and Zerodur boards of miniaturized free-space optics [4], connected via fibre optics. In contrast to lab based cold atom experiments, BECCAL must be operable without interference for three years on the ISS. To reach that goal, we have to fulfil stringent product assurance requirements for the laser system including higher cleanliness facilities and ESD protection. In this context, the planning and implementation of the specific lab setup and the first essential integration tests will be presented with the help of mock-ups.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economic Affairs and Climate Action (BMWK) under grant numbers DLR 50WP1702, and 50WP2102.

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P38

# $T^4$-Atom Interferometer Sensitive to Angular Acceleration

**Bernd Konrad**[1] **and Maxim A. Efremov**[1,2]

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Atom interferometers have become a core setup for the measurement of acceleration, constant rotation, and gravity gradient with enormous precision.
Inspired by the recent progress in matter-wave interferometry, we proposed a novel scheme for a closed light-pulse atom interferometer with the phase linearly proportional to the small angular acceleration and scaling with $T^4$, where $T$ is the total interferometer time. In addition, we have shown that in the next order with respect to the small initial angular velocity $\Omega_0$, the contrast does not change, whereas the interferometer phase has a correction term scaling with $\Omega_0^3$. These results allow us to derive conditions under which one can use the proposed scheme as a promising tool to measure angular accelerations precisely.

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# Searching for chameleon fields using atom interferometry

**B V Lanigan[1], G Peng [1], A Kausik[1], J P Cotter[1], B E Sauer[1] and E A Hinds[1]**

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There are a number of models that aim to reconcile the observed accelerating expansion of the universe with our current understanding of general relativity [1]. One interesting model proposes the existence of a scalar field that is screened in regions of high matter density and can therefore go unnoticed in experiments performed on Earth – colloquially referred to as the ‘chameleon field’ [2-4].

In 2015 Burrage et al showed that atoms inside a vacuum chamber are too small to screen the chameleon field and could therefore be used as a probe to measure it [5]. Since then a number of experimental searches have been undertaken using cold atoms, but have so far failed to observe its existence [6-8].

Here, we describe a number of upgrades to our experiment at Imperial College that improve our precision and reduce systematic sources of errors. We are now planning a series of experiments that will probe the remaining region in parameter space where a signature of the elusive chameleon field may exist.

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P40

# Fiber-based Atom Interferometric Sensors

**Yu Wang [1], Zilong Chen [1], Mingjie Xin [1], Wui Seng Leong [1], and Shau-Yu Lan [1]**

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Atom interferometric sensors commonly use optical pulses along atoms' trajectories to split, deflect and recombine two interferometer arms under quantum superposition. While large-scale free space interferometers have shown unprecedented sensitivity in inertial sensing and test of fundamental physics, the apparatus that is used to house atoms typically has a cross-section of tens of centimeters, set by the large laser beam sizes that are used to interact with atoms. Shrinking the apparatus size could lead to a compact device and allow the atoms to gain proximity to a source field of interest to enhance the signal, relaxing the stringent requirements in developing a portable sensor under dynamic environments.

In free space, reducing the laser beam waist comes at the cost of shortening the distance that atoms can effectively interact with the interferometer beams, thus decreasing the interferometer's sensitivity. Alternatively, hollow-core fibers offer a sub-millimeter enclosure that can guide the interferometer beams over diffraction-free and configurable paths. However, most free space high sensitivity interferometers require the preparation of ultra-cold atoms at a sub-μK temperature in a low noise environment, and strategies to create such conditions for fiber atom interferometers remain to be developed.

In this presentation, I will discuss our development of fiber-based atom interferometers [1-3]. This includes the building blocks of loading, cooling, and guiding atoms inside fibers. In particular, I will show the use of Λ-enhanced gray molasses and delta-kick cooling to cool atoms inside a 22-cm-long negative curvature hollow-core photonic crystal fiber from 32 μK to sub-μK in 4 ms [3]. The in-fiber cooling overcomes the inevitable heating during the atom loading process and allows a shallow guiding optical potential to minimize decoherence. We employ these cold atoms in an inertia-sensitive atom interferometer optically guided inside a hollow-core photonic crystal fiber with an interferometer time of 20 ms, limited by the vibration of the interferometer beams. Our results could permit bringing atoms close to source fields for sensing and lead to compact inertial quantum sensors with a sub-millimeter resolution.

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# P41

The Casimir-Polder (CP) force is an atom-surface interaction that originates from the quantum vacuum fluctuations. This force can be described as the interaction between the fluctuating dipole of the atom with its own reflection into a surface and becomes predominant at short distances, typically below the micrometer.

Accurate knowledge and control of this interaction is essential for the development of nano-technology, exploration of potential new physics such as short gravity forces (5th force). However, due to technical constraints, accurate measurement of the CP interaction have never been done.

In the Laboratory of Laser Physics in Paris, we developed an experiment to measure with high accuracy this interaction: argon atoms are diffracted trough a self-made nano-grating with 100 nm slits width. Passing trough the slits of the nanograting, the atoms come close to the surface of the grating (below 50 nm) and are strongly subjected to the CP interaction. The diffraction pattern measured is therefore deeply impacted by this interaction.

Our goal is to study this atomic interference pattern (our observable) to extract information related to the CP forces.
The main difficulty is in the number of parameters that affect our observable and therefore all CP measurements. A knowledge of geometry of the nanograting at the order of the nanometer is needed, since the measurement of the CP interaction is strongly dependent on this geometry.

To overcome this limitation, we are using a tomographic effect never studied to this day.
This method could allow a measurement of CP at an unprecedented level and could open a way to the exploration of new mechanisms to control CP or the search of the 5th force.

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# Hollow core photonic crystal fibers as sources for levitated nanoparticles in future quantum experiments

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Levitated nanoparticles have been established as a promising platform for testing quantum physics on a macroscopic scale [1, 2, 3], but as of today environmental decoherence [4] still poses a substantial roadblock hindering the access to extended quantum experiments with these objects. Especially the coherence destroying interaction with background gas molecules has to be overcome by reducing the pressure these experiments are conducted in. The attainable pressures for most levitation experiments are directly related to the type of particle loading scheme in place. Here we present a novel method for loading nanoparticles via hollow core photonic crystal fibers [5], that will allow direct loading of these nanoparticles into pressures in the ultra high vacuum regime.

In this method two counter-propagating laser beams of equal wavelength are guided through the hollow core fiber to create an optical standing wave. This fiber connects the main vacuum chamber to a secondary "loading" vacuum chamber. Particles are dispersed in the loading chamber and by detuning one of the two lasers with respect to the other, these particles can be transported through the fiber. Once the fiber is aligned with respect to the target trap, the particles can be directly deposited into it. This handover of particles has been demonstrated down to pressures of $10^{-2}$ mbar and is currently extended to enable direct loading into ultra high vacuum environments.

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P43

# Investigation of Josephson vortices in coaxial ring-shaped Bose-Einstein condensates

TECHNISCHE UNIVERSITÄT DARMSTADT

**30. Juni 2022**

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## Abstract

Josephson vortices (JV) attract considerable interest due to their perspectives for application in ultra-sensitive rotation sensors and quantum information processing systems. Remarkably, Josephson vortices, being extensively investigated for decades, have not yet been demonstrated experimentally in atomic BECs. The first direct observation of rotational JVs in bosonic junctions now appears as a realistic goal. We investigate the generation of JVs between two coaxial toroidal BECs coupled in a coplanar and in a vertically stacked system. In both systems we generate counter-rotating flows and demonstrate the formation of the JVs. Our results open up a way to the first direct experimental observation of rotational JVs in atomic BECs. We present experimental schemes for the creation of two coupled coaxial rings in a coplanar system based on optical dipole potentials and ultra cold-atoms. Utilizing a digital micromirror device, arbitrary topological charges can be accessed and imprinted onto the coaxial rings. We investigate the feasibility of these techniques to create the desired states, atom distributions, and dynamic behavior.

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# Abstract template for Frontiers of Matter Wave Optics School and Conference (start_date: 12 Sep 2022 – end_date: 23 Sep 2022)


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Thanks to common-mode noise rejection, differential configurations are crucial for realistic applications of phase and frequency estimation with atom interferometers [1, 3]. Differential interferometry can be understood as a distributed multiparameter estimation problem and can benefit from both mode and particle entanglement [4]. Currently, differential protocols with uncorrelated particles and mode-separable settings reach a sensitivity bounded by the standard quantum limit (SQL) [5, 6].
Here, we propose to overcome the SQL by exploiting spin-squeezing in an atomic quantum network. A single spin-squeezed state is mode-swapped among common interferometric modes. The mode swapping is optimized to estimate the differential phase shift with sub-SQL sensitivity. Numerical calculations are supported by analytical approximations that guide the optimization of the protocol. The scheme is also tested with simulation of noise in atomic clocks and interferometers.



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# Quantum droplets in quasi-1D bose gas with non-local interactions

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The dilute ultracold quantum gases interacting by non-local forces have been a subject of great interest recently. Under certain conditions, the interplay between the short-range repulsion and long-range attraction leads to the formation of self-bound structures such as quantum droplets. Although these objects were originally observed for atoms trapped in a harmonic potential, they may also be found in quasi-one-dimensional optical lattices [1]. The discretization of the model allows us to use numerical many-body methods to study them, in contrast to mean-field approaches. In this project, we have identified a regime where self-bound structures can be observed. We have also investigated the droplet behavior after a sudden quench from a regime of strongly repulsive contact interaction to the attractive one. This analysis is an extension of the widely studied phenomenon known as super-Tonks-Girardeau gas [2].

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P46

# A hybrid cold atom accelerometer for space geodesy missions

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Space gravimetry missions such as GRACE or GOCE determine the distribution of masses on Earth with great accuracy [1]. This knowledge is very useful for the sciences of climatology, hydrology or geophysics and to understand global change [2]. These missions board state-of-the-art space electrostatic accelerometers displaying very good performances. Nevertheless, they could be improved by taking advantage of the high stability of cold atoms accelerometers. The hybridisation of the two instruments allows the correction of the drift and the scale factor of the electrostatic accelerometer. To this day, no acceleration measurements with a cold atom accelerometer has been performed in space, mostly because of the harmful effect of the satellite's rotation on the interferometer output [3].

In this paper, we present our ongoing experimental work concerning the development of a hybridised electrostatic/atomic accelerometer. This prototype aims to assess the potential of this configuration for future space missions. In particular, we addressed the problematic of satellite rotation and its detrimental effect on the cold atom interferometer contrast.

The hybrid lab prototype is made of an electrostatic accelerometer and a cold atom interferometer. The test mass of the electrostatic accelerometer, very well controlled in angle and position, is employed as the retro-reflection mirror of the interferometer. By spinning the test mass, we studied the impact of angular velocity and angular acceleration on the atomic interferometer. Through this method, we can characterise the position and velocity distributions of the atomic cloud. Moreover, we are working on the rotation compensation technique: the test mass is rotated in order to limit the impact of the whole instrument's rotation. This technique provides up to 80% contrast recovery under rotation [4]. The next step is to understand the limits of this technique and its impact on the acceleration measurement.

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# ‘Squash Locking’ for stabilization of Laser Injection Locking

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Laser frequency stabilization is an integral part of precision measurement experiments. Our group recently developed a novel technique for laser frequency locking to a reference cavity using beam ellipticity as an error signal [1] – termed “squash locking”. Here, we extend the scope of this technique to the stabilization of injection locking of a 780 nm distributed feedback (DFB) laser. The error signal here allows stabilizing the driving current of the seeded laser at the ideal injection locking point. The error signal in this setup originates from the interference of the fundamental mode from the seeded laser and the reflected second order mode on injection from the seeding laser beam. This provides a passive technique for injection locking stabilization, and would help in increasing the laser frequency tuning range while injection locked.

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P48

# Second-Quantized Effective Models for Atomic Diffraction with Center-of-Mass Dynamics


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Atomic diffraction in the form of two-photon Raman transitions is commonly used to facilitate $\pi/2$- and $\pi$-pulses in atom interferometry which constitute the analogue of beam splitters and mirrors in optical interferometers. In practice these transitions are driven by laser light which can be approximated semi-classically as quasi-coherent states. Consequently quantization effects are averaged out due to the broad photon distribution in typical beams. However, technological progress moves towards the use of optical cavities due to their superior optical properties. Thus in specific configurations quantization effects of the light field can become relevant or even dominant [1, 2] and will make a second-quantized description necessary. In our contribution [3] we pursue this task based on the light-matter interaction of two second-quantized single-mode light fields coupled to first quantized few-level atom. Subsequently, we show (a) how a two-photon Rabi model including center-of-mass dynamics can be derived via generalized adiabatic elimination [5, 4] (b) these models intrinsically posses operator-valued couplings between the light field and the center-of-mass motion. From this result we determine an approximate center-of-mass and intensity dependent Jaynes-Cummings model and obtain its generalized beam-splitter operator. Lastly, we discuss the quantum and semi-classical limit of our model and provide an outlook at similar models including fully second-quantized matter degrees of freedom.

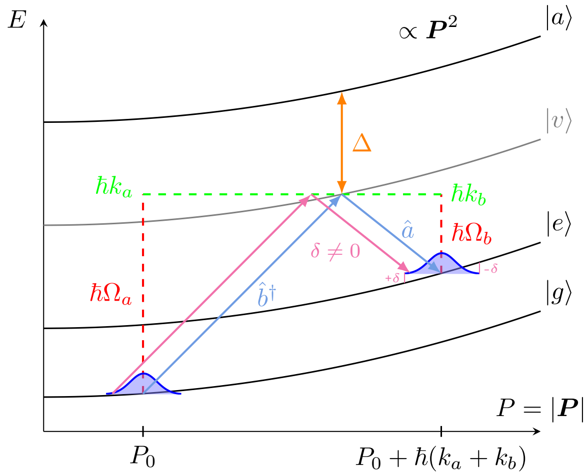


**Fig. 1:** Energy-momentum diagram of a resonant two-photon Raman process $|g\rangle \longrightarrow |e\rangle$ between ground and excited state.


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# Dynamic Coherence Control of RF-Dressed Potentials Using Microwave Dressing Fields

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We investigate the strength and linewidth of a transition between two RF-Dressed ground states for Rubidium-87 in a non-uniform magnetic field. The linewidth of the selected transition is broadened due to a mismatch of trapping potentials. This arises from a difference in Landé g-factor magnitude between the two hyperfine ground states. A scheme is presented wherein the magnetic field dependence of the transition frequency between two RF-dressed Rubidium-87 states is reduced by the introduction of a microwave dressing field, increasing coherence times and reducing transition linewidth [1]. Preliminary measurements are presented with the outlook of incorporating this method into the operation of a chip-based atom interferometer [2].

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# CMOS Fabricated Atom Chips for Integration of Electronics and Sensors.

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Cold atom systems have shown great promise as a basis for stable clocks, precise sensors for acceleration and a tool for fundamental physics. With applications ranging from gravimetry and magnetometry based navigation [1, 2], highly accurate intertial sensors [3], measurements of fundamental constants [4] and clocks for stable frequency sources and measurements of relativity [5]. Whilst current sensors do not reach the full potential of cold atom technologies through Heisenberg limit interferometry, they can serve to complement classical systems through long term stability, and the development of atomic clocks is shown to be fairly mature through the availability of commercial clocks [6].

One of the primary hurdles in applying these schemes are the size, weight and power (SWaP) requirements of the current state of the art, with even the smallest systems being around a meter tall [7]. Consequently, we hope to use semiconductor fabrication techniques to greatly reduce the SWaP requirements of cold atom devices through integrated electronics, sensors and photonics. Complementary-metal-oxide-semiconductor (CMOS) technology is a fabrication technique used to produce IC chips such as op-amps, processors and camera sensors, which comes with high quality tools for the design and simulation of chips, and allows us to include digital/analogue electronics and semiconductor based sensors such as Hall-probes and photodiodes onto the chip. The poster will discuss our progress in producing and testing these CMOS based atom chips.

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# Shortcuts to adiabaticity in Feedback-driven quantum engines

In this study we will present a prototype of quantum engine based on Markovian feedback control. We consider a system of Bosonic particles in a double quantum well that can be described via the Bose-Hubbard model. The quantum well can be manipulated and it can expand and contract by means of external work. We then introduce a Markovian feedback control that can be used to produce a thermal bath as it has been shown that the control parameter can be mapped to the temperature of the system. We are then in the position to control both the size of the system and its temperature and we then want to use the Shortcuts to Adiabaticity to optimize the efficiency of this quantum engine.

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# An Injected Laser System for Cooling and Squeezing Strontium-87 in AION

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The Atom Interferometer and Observatory Network (AION) [1] project aims to develop and operate a next-generation differential atom interferometer to detect gravitational waves and search for dark matter. The role of my team at Imperial College London is to perform squeezing on the atoms to improve the sensitivity of the detector. In this work I present, the 689 nm laser system which will be used to target the $^1S_0$-$^3P_1$ transition of $Sr^{87}$ for laser cooling [2] of the atoms (in a 3D Magneto-Optical Trap) down to micro-Kelvin temperatures in preparation for spin-state squeezing and subsequent atom interferometry. Spin squeezing [3] involves the entanglement of many atoms to reduce the spin measurement noise (which obeys the Heisenberg's uncertainty principle) in a particular direction (i.e., Jy) while increasing the noise in the other direction i.e. Jz. This in turn increases the resolution of the interferometer by reducing the noise in the differential phase measurements.

A 689 nm laser beam is passed from a <10 Hz frequency stabilised master laser and through an optical system which includes an Acousto-Optical Modulator (AOM), used to control the optical frequency and the intensity of the output beam. A laser diode is included in the set-up which is injected [4] by the master laser for light amplification. An injection lock ensures the preservation of the stability of the master laser. The frequency of the 689 nm light can be modulated by an EOM, and the frequency sidebands are applied to address the F= 9/2 → 9/2 transition, resulting in "stirring" of the red MOT, a method used to redistribute the population in the $m_F$ sublevels and increase the efficiency of trapping [5]. This injected laser system will also ensure the intensity stabilisation of the output beams and perform frequency sweeps to allow for the selection of the detuning of the MOT and pump.

The 689 nm laser system responsible for the cooling of atoms and squeezing is under development. Once completed, it will be integrated into the 3D MOT to cool the Sr atoms down to micro-Kelvin temperatures and entangle the atoms to allow measurements below the standard quantum limit. Applications of squeezing beyond AION include atomic clocks, inertial sensors, and other fundamental physics experiments e.g., searches for electron electric dipole moment [3].

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Poster abstract submission for Frontiers of Matter Wave Optics 2022

# QUANTUS-2: Towards dual species atom interferometry in microgravity

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Matter wave interferometry allows for precise quantum sensors, which can be applied for geodesy or for tests of fundamental physics. As a pathfinder for future space missions, the QUANTUS-2 experiment enables rapid BEC production of Rb-87 with over $10^5$ atoms and performs atom interferometry under extended free fall at the ZARM drop tower in Bremen (falling distance: $110\,\mathrm{m}$, μg-time: $4.72\,\mathrm{s}$ in drop mode). By applying a magnetic lens, we are able to collimate the matter wave and reduce the total internal kinetic energy of the BEC to $\frac{3}{2}k_{\mathrm{B}} \cdot 38\,\mathrm{pK}$ in three dimensions [1]. Such collimation is a necessary prerequisite to extend interferometry times in microgravity and thus to obtain largely increased scale factors. Here, we present the latest results on single species interferometry experiments in QUANTUS-2. In an upcoming upgrade of the experiment, K-41 will be implemented as a second atomic species, which requires the integration of a second laser system. This next step will enable us to study and manipulate quantum gas mixtures, as well as to perform dual species atom interferometry in microgravity.

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# Pushing the mass limits of matter-wave interferometry using metal nanoparticles

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Matter-wave interferometry with massive objects is a paradigmatic example of quantum physics at the interface to classical phenomena. Using the Long-Baseline Universal Matter-wave Interferometer (LUMI) we successfully demonstrated interference of massive molecules consisting of up to 2000 atoms and with masses up to 28.000 amu [1]. One also can use the high sensitivity of the interference fringes to probe molecules and atoms with regard to their magnetic, electric or optical properties. With LUMI we have for example measured the polarizability of fullerenes with improve accuracy [2], the diamagnetic susceptibility of barium and strontium atoms [3] and other fundamental magnetic phenomena in atoms and molecules [4].

Pushing the limits towards higher masses requires advances interferometer schemes but also suitable molecular sources and efficient detection mechanisms. We here present a material class that fulfills all requirements for future matter-wave experiments.

The results of this study show that the metal cluster source together with the improved detection scheme will allow realizing a next generation Talbot-Lau interferometer with three 266 nm depleting lasers as beam splitters [5]. We believe that these metal nanoparticles will help us to push the mass limit for matter-wave towards $10^6$ amu in the near-future.

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# Atom interferometry with ultra-cold atoms onboard a Zero G plane for space applications

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Quantum sensors based on cold-atom interferometry offer promising results for inertial measurement and fundamental physics tests such as the Universality of Free Fall (UFF). On Earth, the accuracy of such experiment is limited by the free-fall time of the atoms in the vacuum chamber. Microgravity environments enable to study atoms with longer interrogation time thus reaching higher sensitivity.

The ICE project (Interférométrie à source Cohérente pour l'Espace) aims to be a proof of concept for a space mission using quantum particles, i.e., atomic clouds of potassium and rubidium in a matter-wave interferometer to test the Weak Equivalence Principle (WEP) in microgravity. The development of a portable experiment adapted to the Zero G plane led to the world's first demonstration of the use of atomic inertial sensors for such a test in microgravity [1]. In parallel, a microgravity simulator installed in the laboratory allows to put the science chamber (200 kg) in weightlessness during 500 ms, with a good reproducibility and a high duty cycle (~13 s). Additionally, ultra-cold atom sources are required to increase the interrogation time and the sensitivity of the measurement. That's why we settled an all-optical method to produce Bose-Einstein Condensates (BEC) [2], combining of grey molasses cooling, light-shift engineering and optical trapping in a painted potential. Moreover, we showed our method is compliant with microgravity and forced evaporative cooling results in 4 × 104 condensed atoms every 13.5 s on the simulator, with a temperature as low as 35 nK. More recently we demonstrated the same all optical method is transposable onboard the aircraft, showing the high robustness of our method and the possibility to achieve evaporative cooling in microgravity in a dipole trap despite the absence of the sag. We also show that this method can be applied to Potassium atoms, paving the way to a WEP test using two species Rubidium-Potassium ultra-cold atom gases. Finally, using ultra-cold sources in microgravity leads to a particular regime of atomic interferometry called double diffraction, which we study theoretically and experimentally on the simulator.  We will present our first results of interferometry in this double diffraction regime in the horizontal configuration, and we anticipate the equivalent experiment in microgravity in a near future.

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# Design and Construction of the first Portable Quantum Gravimeter in Mexico

**Hellmunt Peña Vega[1], Cristian J López-Monjaraz[1], Diego Alegria Meza[3], Josue G Carmona Moreno[2], Neil V Corzo[1], Eduardo De Carlos Lopez[5], Jesus Flores Mijangos[1], John A Franco[2] , Eduardo Gomez[2], Karina Jimenez-Garcia[1], Jose Jimenez-Mier[3], José L López-González[2], Dai López Jacinto3, J. Mauricio López Romero[1], Alejandra López Vazquez[2], Ricardo Mendes-Fragoso[3],Georgina Olivares Rentería[2],Carlos A Ortiz Cardona[5], Joaquín G Raboño Borbolla[1], Fernando Ramirez Martinez[3] and Victor M Valenzuela Jimenez[4].**

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At present, the world is undergoing an important technological revolution where new devices, including sensors based on quantum systems, with unprecedented degree of sensitivity are being developed. Scientists are working toward practical and portable implementations on new generation quantum sensors, and with the present project Mexico joins this important international effort through the "Grávico" collaboration.

Grávico is a multi-institutional collaboration that gathers some of the main research groups on the manipulation of quantum systems in México. Its main goal is to design and build a portable Quantum Gravimeter. Its design will allow to realize absolute gravity measurements based on atom interferometry of free-falling cold atoms.

Our portable Quantum Gravimeter is composed of three main modules: a stabilized narrow-linewidth laser source, a modulation system for the generation of multiple laser beams, and a UHV system stabilized with respect to mechanical vibration. Here we present progress toward the construction of the first Quantum Gravimeter in Mexico. The development of this Quantum Technology may lead to improved prediction models for the location of aquifers, hydrocarbon exploration, minerals, tectonic fault monitoring, as well as for the development of new sensors and navigation systems.

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# Bose-Einstein Condensates in quasi-periodic lattices: bosonic Josephson junction and multi-mode dynamics

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Collective dynamics of two interacting spatially localized Bose-Einstein condensates (BECs) is one of the basic problems in the physics of condensed bosonic atoms. BECs confined in a double-well trap is a typical example, where one can find such fundamental phenomena, as coherent oscillations, spontaneous symmetry breaking, non-linear selftrapping, coupled solitons, etc. We show that an alternative, and in several aspects even more general, setting allowing the physical realisation of the mentioned phenomena is a BEC loaded in one-dimensional bichromatic optical lattices with constituent sublattices having incommensurate periods.

Using the rational approximations for the incommensurate periods, we show that below the mobility edge the localised states are distributed nearly homogeneously in the space. We obtain an alternative realisation of the bosonic Josephson junction, whose coherent oscillations display beatings or switching in the weakly nonlinear regime, as well as self-trapping. These phenomena can be observed for different pairs of modes, which are localised due to interference rather than due to the walls of the confining trap, providing a more general implementation of this junction. Furthermore, by considering several modes coupled by the nonlinearity, we investigate the four-mode dynamics, mimicking coherent oscillations and self-trapping in four-well potentials. The results obtained using few-mode approximations are compared with the direct numerical simulations of the one-dimensional Gross-Pitaevskii equation.

P58

# Matter-wave lenses

**Vishnupriya Puthiya Veettil [1,2] , Giannis Drougakis [1] , Apostolos Brimis[1,3] , Dimitris Papazoglou [1,2] Konstantinos Makris [1,3] and Wolf von Klitzing [1]**

*[1]Institute of Electronic Structure and Laser, Foundation of Research and Technology, Hellas, Heraklion 70013, Greece*
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*[3]Department of Physics, University of Crete, Heraklion 70013, Greece*

At ultra-cold temperatures, bosons occupy a single state forming a BEC. The first experimental realisation of matter wave guiding of 87Rb BEC over large distances, preserving the internal coherence, was demonstrated at Cretan matter waves group using a Time Averaged Adiabatic Potential (TAAP) trap [1]. Using a harmonic magnetic potential we can manipulate the matter waves and can focus in 3D [2].

We aim at realising atom-optical elements that are analogous to conventional optical devices such as lenses, mirrors etc using magnetic potential for matter wave imaging. These real- time matter wave lenses has far reaching applications in interferometry [3], lithography and detection of small condensate fractions[4].Matter wave lensing can improve the sensitivity of interferometric measurements and it could in principle result in patterns in nanometric scale. The scope of this work is to investigate the limiting factors of the imaging such as aberrations caused by the anharmonicities in trapping potentials, three body recombination and shape oscillations.

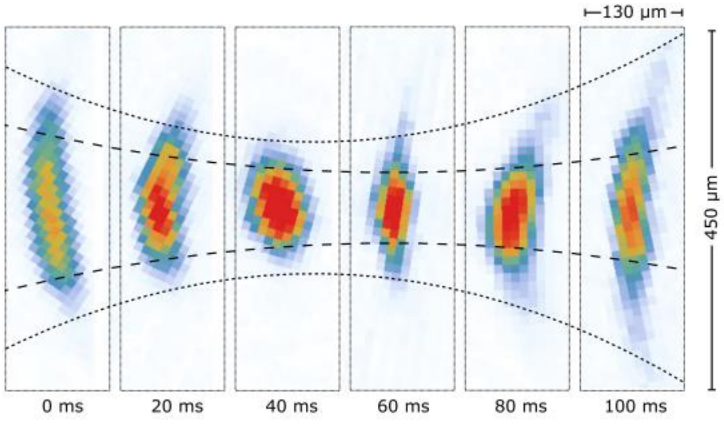


Figure 1: Focusing of BECs and ultracold thermal clouds in a ring-shaped matter-wave guide [3].

[1] S. Pandey et al., Nature 570, 205 (2019)
[2] Cornell E A, Monroe C and Wieman C E, Phys. Rev. Lett. 67, 2439 (1991)
[3] S. Pandey et al., Phys. Rev. Lett. 126, 170402 (2021)
[4] I. Shvarchuck et al., Phys. Rev. Lett. 89, 270404 (2002)

P59

# Generation of Nanpparticle in vacuum for loading optical cavity

Will be submitted later upon acceptance at the conference. This has been discussed with Prof Markus Arndt.

P60

# An algebraic geometric study of the solution space of the 1D Gross-Pitaevskii equation

**David Reinhardt**[1], **Matthias Meister**[1], **Dean Lee**[2] **and Wolfgang P. Schleich**[3]

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[3] Ulm University, Institute of Quantum Physics, Germany

The stationary solutions of the Schrödinger equation considering box or periodic boundaries show a clear correspondence to solutions found for the non-linear Gross-Pitaevskii equation commonly used to model Bose-Einstein condensates. However, in the non-linear case there exists an additional class of solutions for periodic boundaries first identified by L.D. Carr et al. [1], [2]. These nodeless complex symmetry breaking solutions have no counterpart in the linear case. To examine how these solutions behave in the limit of vanishing non-linearity we consider an algebraic geometric picture. Therefore, we treat both equations in the hydrodynamic frame, resulting in a first order differential for the density determined by a quadratic polynomial in the linear case and by a cubic polynomial in the non-linear case, respectively. Our approach allows for a clear geometric interpretation of the solution space in terms of the nature and location of the roots of these polynomials. Going one step further and including three body interactions in the meanfield regime we are faced with a quartic polynomial in the density. Interestingly, the solutions of the cubic and quartic system can be linked by means of a conformal duality. This new approach allows to establish correspondence between these two systems.

[1] Lincoln D. Carr et al. , Phys. Rev. A **62**, 063610 (2000).
[2] Lincoln D. Carr et al. , Phys. Rev. A **62**, 063611 (2000).

# Building a Strontium Atom Interferometer

**P.Robert**[1] , **C.-H. Feng**[1] , **M. Prevedelli**[1-2] , **B. Canuel**[1] , **A. Bertoldi**[1]

[1]*LP2N, Laboratoire Photonique, Numérique et Nanosciences, Université Bordeaux-IOGS-CNRS:UMR 5298 F-33400 Talence*
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Atom inteferometers promise to expand the gravitational waves detection sensitivity bu using ballistic cold atoms in free fall.
We are building a prototype using strontium atoms coherently probed on the clock transition at 698 nm.
The choice of this atom allows to address atomic interferences using only one transition and thus avoid using Raman transitions where the two laser's noises are not in common mode.
Strontium atoms can be trapped in a Magneto-Optical Trap via a red transition at 689 nm below the microK level but it need to be precooled down before via a blue transition at 461 nm to the mK level.
This blue transition requires a non negligible amount of power and a paper has been published by our group [1] about a Watt-level continuous and single frequency blue laser at 461 nm for this purpose .

[1] C-H Feng, P.Robert, Opt. Expr. **29**, 27760 (2021).

P62

# Bose-Einstein Condensate and quasi-Bragg diffraction for large separation atom interferometers.

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[1]*Laboratoire Collisions Agrégats Réactivité, Université Paul Sabatier, 118 route de Narbonne, 31062 Toulouse Cedex 4, France*

Atom interferometers are used for inertial sensors, geophysics, fundamental constant measurements or fundamental physics tests [1]. To improve the sensitivity of this effects, large momentum interferometers are developed using high order diffraction processes or Large Momentum Transfer methods such as sequential Bragg pulses.

Our interferometer uses the quasi-Bragg diffraction of a Bose-Einstein Condensate. I will present our work on the characterization of an atom Mach-Zehnder interferometer based on quasi-Bragg diffraction up to fifth diffraction order [2]. The discussion is about two sub-regimes, (short and long interaction time) limited by "non-adiabatic losses" or strong velocity selection. That non-adiabatic losses impact diffraction phase shifts and create parasitic interferometer paths which can bias the phase estimation [3].

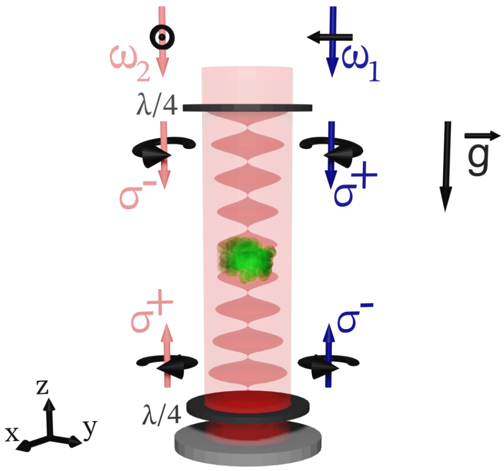



FIG. 1: Ultracold-atoms in a vertical optical lattice, in a retro-reflected configuration, created by two laser beams at frequencies $\omega_1$ and $\omega_2$ with orthogonal polarizations.

[1] G. M. Tino, M. A. Kasevich, Atom Interferometry: Proceedings of the International School of Physics "Enrico Fermi", Course 188, Varenna on Lake Como, Villa Monastero, 15-20 July 2013 (2014).

[2] A. Béguin, T. Rodzinka, J. Vigué, B. Allard, A. Gauguet, Characterization of an atom interferometer in the quasi-Bragg regime, Phys. Rev. A **105**, 033302 (2022).

[3] J-N. Siemß, F. Fitzek, S. Abend, E. M. Rasel, N. Gaaloul, K. Hammerer, Analytic theory for Bragg atom interferometry based on the adiabatic theorem, Phys. Rev. A, **102**, 033709 (2020).

# Development of an onboard cold atom inertial measurement unit

**<u>C. Salducci</u> [1], Y. Bidel [1], M. Cadoret[1, 2], J. Bernard[1,2], A. Bonnin[1], N. Zahzam[1], S. Schwarz[1], C. Blanchard[1], A. Bresson[1]**

*[1]DPHY, ONERA – The French Aerospace Lab – Palaiseau - France*
*[2]LNE-CNAM – Trappes - France*

Since 1990s, a new generation of inertial sensor based on matter-wave interferometry has appeared: accelerometers [1], gradiometers [2] and gyroscope [3] have been developed and shown high sensitivity and accuracy. Major applications for atom interferometers are today geophysics, inertial navigation and fundamental physics.

However, for measurements in a dynamic environment, people use for now classical (non quantum) sensors which require calibration and a correction to their inherent drift. Most of the atom interferometry-based sensors are laboratories experiments and cannot perform onboard measurements, except for some notable exceptions such as ONERA's marine and airborne gravimeter [4].

In this paper, we present our ongoing work about the development of a cold atom inertial measurement unit (IMU). Instead of having six independent sensors, we aim to build a single atomic sensor that measures sequentially each inertial component.

The atomic sensor is in fact hybridized with classical accelerometers and gyroscopes which provide continuous measurement. Thus, an hybridized cold atom IMU affords continuous measurements provided by the classical sensors whose biases are tracked and removed by the atom interferometers.

Until now, a vertical accelerometer [5] and horizontal accelerometer [6,7] have been studied. The next step of the project will be first to develop of a cold atom gyroscope. As compactness is crucial for onboard applications, we will be limited by the short interrogation time of the atoms in the vacuum cell. We will then aim to use large momentum transfer to increase the scale factor of the gyroscope. The second step will be to increase the dynamic range as, for now, the contrast of the interference fringes decreases drastically when the system rotates. Finally, each atom sensor will be hybridized with its classical counterpart in order to build a full IMU affording bias free absolute continuous inertial measurements.

[1] V. Menoret, P. Vermeulen, N. Le Moigne, S. Bonvalot, P. Bouyer, A. Landragin & B. Desruelle, **Gravity measurement below $10^{-9}$ g with a transportable absolute quantum gravimeter**, Sci. Report, (2018)
[2] J.M. McGuirk G.T. Foster, J.B. Fixler, M.J. Snadden, and M.A. Kasevich., **Sensitive absolute-gravity gradiometry using atom interferometry,** Phys. Rev. A, (2002)
[3] T.L. Gustavon P. Bouyer, and M.A. Kasevich. **Precision rotation measurements with an atom interferometer gyroscope,** Phys. Rev. Lett. (1997)
[4] Y. Bidel, N. Zahzam, C. Blanchard, A. Bonnin, M. Cadoret, A. Bresson, D. Rouxel and M. F. Lequentrec-Lalancette. **Absolute marine gravimetry with matter-wave interferometry**. *Nat. Commun.* (2018).
[5] F. Theron **Dévoloppement d'un gradio-gravimètre à atomes froids et d'un système laser télécom doublé pour application embarquées**, PhD Thesis (2015)
[6] I. Perrin, J. Bernard, Y. Bidel, A. Bonnin, N. Zahzam, C. Blanchard, A. Bresson, and M. Cadoret. **Zero-velocity atom interferometry using a retroreflected frequency-chirped laser.** *Phys. Rev. A* (2019).
[7] J. Bernard, Y. Bidel, M. Cadoret, C. Salducci, A. Bonnin, N. Zahzam, S. Schwarz C. Blanchard, A. Bresson, **Atom interferometry using $\sigma^+ - \sigma^-$ Raman transitions between $|F = 1, m_F = \mp 1 >$ and $|F =, m_F = \pm 1 >$**, *Phys. Rev. A* (2021).

P64

# Precision measurement of the fine structure constant by atom interferometry

**Yair Segev [1], Zachary Pagel[1], Madeline Bernstein[1], Jack Roth[1], Andrew Neely [1], and Holger Müller [1]**

[1]*Department of Physics, University of California, Berkeley*

The fine structure constant, α, quantifies the strength of the electromagnetic interaction. The value of α, approximately 1/137, can be extracted from various experiments, such as measurements of the electron's magnetic moment and the recoil of an atom absorbing a photon, and the consistency of α serves as a test of the Standard Model. I will present the next-generation experiment under construction at Berkeley, which aims to improve on the precision of previous atom recoil measurements of α. Our apparatus is an atom interferometer which uses Bragg diffraction and Bloch oscillations to coherently impart hundreds of recoils to cesium atoms in free-fall. A simultaneous, conjugate interferometer geometry leads to cancelation of many common-mode errors and uncertainties. We plan to suppress the dominant remaining systematic errors, due to thermal motion of atoms and interferometry pulse imperfections, by using large diameter laser beams. The new setup will allow hundreds of milliseconds of phase evolution, as well as an investigation of spatial deviations of the phase in the atom cloud. The combined improvements should enable a precision surpassing previous records of 200 ppt with Cs [1] and 80 ppt with Rb [2]. Combining our data with an upcoming measurement of the electron's gyromagnetic anomaly by the Gabrielse group will constitute one of the most stringent tests of the Standard Model to date.

[1] R. Parker et al., Science **360**, 6385 (2018).
[2] L. Morel et al., Nature **588**, 7836 (2020).

P65

# Optical zerodur bench system for the BECCAL ISS quantum gas experiment

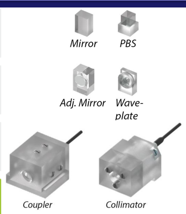

Faruk Alexander Sellami[1], Jean Pierre Marburger[1], Esther del Pino Rosendo[1], André Wenzlawski[1], Ortwin Hellmig[2], Klaus Sengstock[2], Patrick Windpassinger[1], and the MAIUS and BECCAL team[1,2,3,4,5,6,7]

[1]Institut für Physik, JGU, Mainz — [2]ILP, UHH, Hamburg — [3]Institut für Physik, HU Berlin, Berlin — [4]FBH, Berlin — [5]IQ & IMS, LUH, Hannover — [6]ZARM, Bremen — [7]Institut für Quantenphysik, Universität Ulm, Ulm


## Introduction

### Motivation

- Numerous quantum optics experiments benefit from µg
- Microgravity environments often imply rocket launches
- Harsh physical conditions aboard rocket
- Zerodur



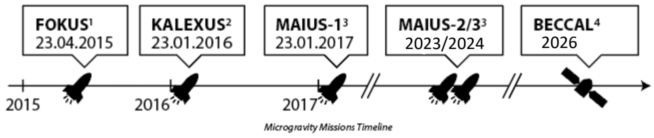

- Negligible thermal expansion: CTE of 0 ± 7 · $10^{-9}$ (0°C to 50°C)
- Zerodur optical components glued onto Zerodur benches[1]

**Combination with COTS components:**

- Switching by AOM and shutter
- Highly efficient fiber fiber coupling (e.g. Maius 1 > 90%)
- Density (2.53 g/cm³) comparable with aluminium

[1] H.Duncker et al. Applied Optics 53(20):4468, jul 2014

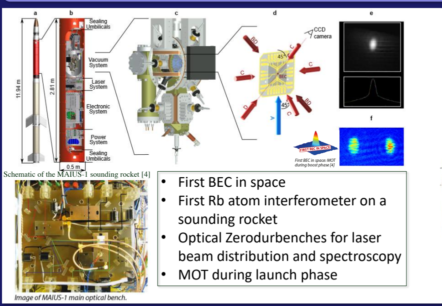
### Mission Heritage




[1]Faserbasierter Optischer Kammergenerator unter Schwerelosigkeit [2]Kalium Laserexperimente unter Schwerelosigkeit [3]Materiewellen-Interferometrie unter Schwerelosigkeit [4]Bose-Einstein Condensate and Cold Atom Laboratory

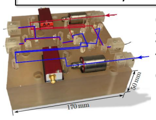
## The Missions

### Maius 1, 2 & 3




- Dual species Rb/K atom interferometer aboard sounding rocket
- Test of weak equivalence principle
- MAIUS II-III: Simultaneous interferometry of Rb and K

- First BEC in space
- First Rb atom interferometer on a sounding rocket
- Optical Zerodurbenches for laser beam distribution and spectroscopy
- MOT during launch phase



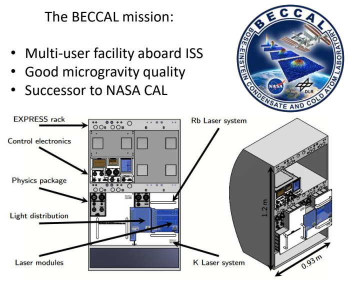

**Opt. Zerodurbench for laser beam distribution**

[2] V.Schkolnik et al. Applied Physics B, 122(8), jul 2016
[3] D.Becker et al. Nature, 562(7227):391-395, oct 2018

### Scientific goals of BECCAL

The BECCAL mission:

- Multi-user facility aboard ISS
- Good microgravity quality
- Successor to NASA CAL



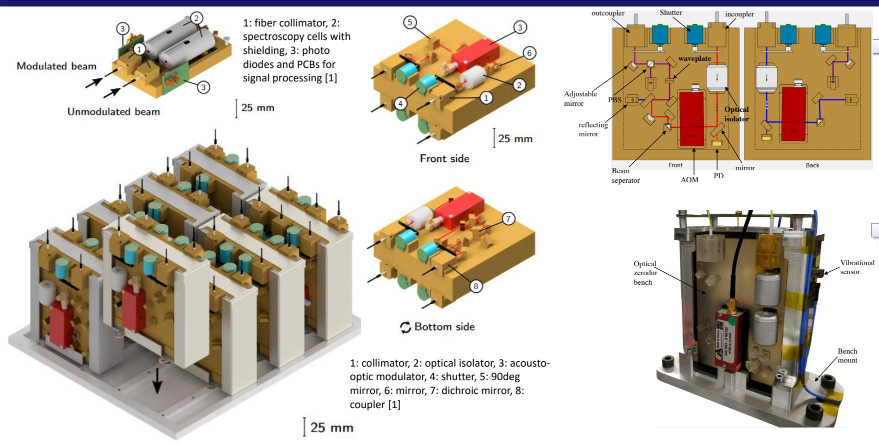

**Broad spectrum of experiments is anticipated with use of a stable generated BEC in the ISS:**

- Atom Interferometry (e.g. dual-species Rb/K atom interferometry for test of WEP)
- Coherent atom optics
- Scalar Bose-Einstein condensates
- Spinor Bose-Einstein condensates and quantum gas mixtures
- trongly interacting gases and molecules
- Quantum information

- Project requires significant enhancements to the technology
- ISS requires long run times and safety of the experiment

## The Toolkit

### Highly stable optical benches for BECCAL




a) Schematic of the bench layout for the 1064 nm demonstrator bench. The optical beam path is shown in red.

b) Image of bench demonstrator (front side) as used in the shaker-test, including mounting structure. Vibrational sensors were attached to the bench to record the frequency response during the test. A PCB on top of the assembly is used to distribute electronic signals.

**Features and advantages**

- 2 spectroscopy benches for frequenzy stabilisation FMS & MTS of Rb and K atoms
- 8 optical benches for laser light distribution and switching
- Optical benches are equipped on both sides
- Core feature is the ability to generate ultracold or condensed ensembles of rubidium, potassium and mixtures of both
- Mounting structure safely locks the optical benches into place without applying any localized force that can lead to stress or deformation

[4] "The Bose-Einstein Condensate and Cold Atom Laboratory", K. Frye et al, submitted to journal (2020)
[5] "A highly stable optical bench system for the NASA-DLR BECCAL mission", J.P. Marburger et al.E-mail: jemarbur@uni-mainz.de, Telephone: +49 6131 39 27650, P.W.: E-mail: windpass@uni-mainz.de, Telephone: +49 6131 39 20202, Website: qoqi.physik.uni-mainz.de

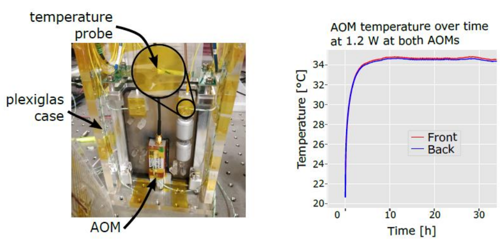
## BECCAL

### Testing of a Zerodur bench prototype

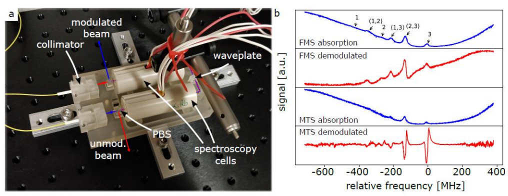
- **Shaker test for optical bench along three axes was performed (random vibrations at an exaggerated qualification level of more than 11 gRMS and a half-sine shock for each axis)**
- **BECCAL payload imposes new challenges on thermal management. As Zerodur is a poor thermal conductor, we try to carefully limit the amount of heat generated by elements mounted on the optical benches.**
- **BECCAL needs precise and flexible frequency control of the scientific light fields, as well as a stable frequency reference → enable the stabilization of one master laser each for rubidium and potassium to relevant transitions.**

Experimental setup:

- To evaluate how temperature influence of the AOMs affects the optical benches, thermal tests on the demonstrator have been performed in a plexi-glas (to limit convection)
- AOMs were then switched on and the temperature monitored. The setup is shown at upper photo at the right (front plexiglas wall removed for better visibility)
- Spectroscopy demonstrator: 1064 nm cw laser, collimator, fiber optic EOM, 2 spectroscopy cells with the relevant atoms, PBS, WP → setup enables a stable lock to multiple transitions for each atom




Photograph of demonstrator as used in thermal tests[2]




Photograph of the sepctroscopy demonstrator. The modulated and unmodulated light beams are illustarted as blue and red lines, respectively. The photodiodes used to record the signals are off-image. (b) FMS and MTS signals recorded for Rb.[5]

**Results of the test**

- Shaker test: Bench and mounting structure performed well, without variations of power before and after the test of more than **10%**.
- AOM Temp. test: At a power of 1.2 W, which corresponds to the optimum operating power for AOMs at 780nm and ambient temperature of 21 °C, both AOMs heated up by roughly 14 K. Further thermal tests at different operation parameters are running

**Conclusion**

- The Zerodur-based optical bench system is ideally suited for environments where high mechanical and thermal stability, as well as a high level of miniturization are required.
- Toolkit has been succesfully adapted to the requirements of the BECCAL ISS mission
- A total of ten compact and robust optical benches will be part of the BECCAL scientificc payload. Technical demonstrators were constructed to test and verify the proper function of the enhancements.
- The goal is to start the assembly of the zerodur benches for BECCAL at the beginning of 2023

[5] "A highly stable optical bench system for the NASA-DLR BECCAL mission", J.P. Marburger et al.E-mail: jemarbur@uni-mainz.de, Telephone: +49 6131 39 27650, P.W.: E-mail: windpass@uni-mainz.de, Telephone: +49 6131 39 20202, Website: qoqi.physik.uni-mainz.de

Project Partners

The following companies and faculties are involved in the BECCAL project: OHB SE; Deutsches Zentrum für Luft und Raumfahrt e.V. (DLR); DPG-SC; DPG-SI; DPG-QT Simmulations und Softwaretechnik; Institut für Physik, Johannes Gutenberg-Universität Mainz; Institut für Laserphysik, Universität Hamburg; Institut für Physik, Humboldt-Universität zu Berlin; Institut für Quantenoptik, Leibniz Universität Hannover; Ferdinand Braun Institut Berlin; Leibniz-Institut für Höchstfrequenztechnik; Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation (ZARM); Universität Bremen; Universität Ulm, Institut für Quantenphysik


Funding

BECCAL is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economic Affairs and Energy Climate Action under grant number WP 1703 and WP 2103, respectively

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# Developing a transportable accelerometer and gyroscope based on atom interferometry

**S. Shi [1], H. G. Sewell [1], K. He [1], T. Krastev [1], A. Kaushik [1], E. A. Hinds [1], J. P. Cotter [1]**

[1] *Centre of Cold Mater, Physics Department, Imperial College London, UK*

In situations where Global Navigation Satellite Systems (GNSS) cannot be relied upon, Inertial Navigation Systems (INS) provide an attractive alternative. These devices measure the acceleration and rotation rate of the platform being navigated and infer its displacement with respect to a known starting point through frame transformations and double integration. Current classical INS typically suffer from drifts in the underpinning accelerometers and gyroscopes that prevent accurate position determination after a few minutes.

At Imperial we are developing quantum-enhanced inertial sensors for long-range navigation using atom interferometry. Here, we describe our recent work to develop a transportable quantum-enhanced inertial sensor that can cope with the harsh environments experienced outside of the laboratory. We are now pushing this technology towards practical applications with field trials on land and at sea.

Laboratoire Kastler Brossel
Physique quantique et applications

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# **Title** : Advanced modeling for ultimate performances of atomic interferometers

R. SI-AHMED[1], S. Guellati-Khelifa[1,2], P. Cladé[1]

*1 Laboratoire Kastler Brossel, Sorbonne Universite´, CNRS, ENS-PSL University, Colle`ge de France, 4 place Jussieu, 75005 Paris*
*2 Conservatoire National des Arts et Me´tiers, 292 rue Saint Martin, 75003 Paris, France*

**Abstract** : We will present the implement modeling tools and numerical simulations to evaluate the systematic effects that limit the accuracy of atom interferometers. In particular, we work in tandem with experiments to reduce the dominant systematic effects such as the effect of phase and intensity inhomogeneity of the laser's beams used to manipulate the atomic wave-packets.

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# Diffracting molecular matter-waves at a standing wave light grating in the deep UV

(discussed w/ Markus Arndt)

P69

**Generation and detection of mass-selected neutral molecular beams**

MARCEL STRAUSS[1], MARTIN MAUSER[1], ARMIN SHAYEGHI[1], PHILIPP GEYER[1], YONG HUA[2], VALENTIN KÖHLER[2], MARCEL MAYOR[2,3,] , STEVEN DALY[6], JAN COMMANDEUR[6], MARIO CASTANEDA[4], ANDREAS FOGNINI[4], AND MARKUS ARNDT[1]

[1]Faculty of Physics, University of Vienna — [2]Department of Chemistry, University of Basel — [3]Institute of Nanotechnology, Karlsruhe Institute of Technology — [4]Single Quantum, Delft (SQ) — [6]MSVISION, Almere

Gas phase studies of biomolecules have attracted increasing interest because they enable measurements of molecular properties of isolated peptides and proteins depending on their charge, temperature and micro-environment. Slow and neutral proteins will be essential for new applications in biomolecular deflectometry and spectroscopy as well as studies in quantum optics. Here we report on recent experiments on the optical charge-control and neutralization of polypeptide beams. Peptides and proteins labeled with photocleavable subunits allow us to control the molecular charge state in high vacuum when using intense laser light. Based on successful experiments with deep-UV [1] we here discuss new experiments in a color range beyond the absorption band of typical proteins, avoiding competition of absorption with natural chromophores. While neutral biomolecules may be detected by a second photocleavage stage for post-ionization, we discuss new realizations of superconducting nanowire devices (SNWD) as detectors for slow molecular ions and even neutral particles.

[1] Schätti et al., Chem. Commun. 55, 12507(2019)

# Dimensional reduction in cavity QED and the light-matter interaction

**Jannik Ströhle** [1] **and Richard Lopp** [1]

*(Presenting author underlined)*
[1]*Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ$^{ST}$), Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany*

Performing experiments with atoms in cavity QED setups has advantages for a multitude of reasons when comparing to free-space settings; for instance power enhancement, more precise spatial filtering and more accurate beam profiles. From the theoretical side, a number of quantum optical approximations can also be applied to simplify the computations. One of those approximation is the dimensional reduction, i.e. treating a three-dimensional cavity as a one-dimensional problem. This is usually justified by having one length of the cavity much larger than the remaining ones, and is usually done in an *ad hoc* fashion without a derivation from first principles.

Starting from the Helmholtz equation, we show how to rigorously obtain a lower-dimensional model from 3D cavity QED for general cavity geometries that are separable in its longitudinal and transverse degrees of freedom. This is an extension to [1] where this problem has been studied with a scalar version of the atom-light interaction. Here, however, we actively account for the vector nature of electromagnetism. In the process, the electric and magnetic fields decompose into an infinite collection of vector-valued *subfields* which live on the remaining single dimension but encode geometrical information of the cavity in the other two spatial dimensions. This procedure naturally extends to any light-matter interaction terms included in the theory, such as due to laser beams. A dimensional reduction approximation can then be obtained via a single-mode or few-mode approximation on those subfields. Due to corrections that arise from the higher-dimensional theory, it is generally not equivalent to the usual way of prescribing this approximation *ad hoc*. This is in particular true in the common regime of having a very long but narrow cavity. Finally, we show when this modified dimensional reduction is valid, i.e. in which regimes a single or a few subfields are sufficient to reconstruct the full 3D dynamics.

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# Using the Gravimetric Atom Interferometer GAIN as a Testbed for Elements of BECCAL Laser System

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BECCAL (Bose-Einstein Condensate and Cold Atom Laboratory) [1] is a cold atom experiment designed for operation on the ISS. It is a DLR and NASA collaboration, built on the heritage of sounding rocket and drop tower experiments, and NASA's CAL [2]. This multi-user facility will enable the exploration of fundamental physics with Rb and K BECs and ultra-cold atoms in microgravity, facilitating prolonged timescales and ultra-low energy scales. The scientific envelope targets atom interferometry, atom optics, scalar and spinor BECs, quantum gas mixtures, strongly interacting gases and molecules, and quantum information.

The Gravimetric Atom Interferometer GAIN, is based on interfering ensembles of laser cooled $^{87}$Rb atoms in a fountain setup using stimulated Raman transitions. The rugged transportable design of the instrument enables precise and accurate on-site gravity measurements. Its performance has been compared to other state-of-the-art gravimeters in the past measurement campaigns at Wettzell, Germany and Onsala, Sweden with an accuracy on the $10^{-9}$ level in $g$ and a long-term stability of 0.5 nm $s^{-2}$ [3].

Various features of the BECCAL laser system equipment need to be tested before it is integrated to such a complex space-based experiment. We will present the aspects of using GAIN as a testbed for the interferometric measurements of the BECCAL laser system.

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# A single beam airborne cesium gravity gradiometer

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We previously reported a compact cold Cesium gravimeter, MiniG, that achieved a sensitivity of 37 $\mu$Gal/$\sqrt{\text{Hz}}$ and a long term stability of 2 $\mu$Gal [1, 2]. Now we describe recent progress in the construction of FlyG, our drone-based atomic gravity gradiometer for airborne gravity surveys. Our device will measure the vertical gravity gradient with a target sensitivity of 10 Eotvos/$\sqrt{\text{Hz}}$ while mounted on an unmanned quad-rotor aircraft capable of 30 minute to 1 hour flight times. The total mass of the aircraft and sensor payload will be 100-150 Kg. The gradient is measured by differencing two vertically displaced, simultaneous Mach-Zehnder interferometers probed with the same lasers. This differencing scheme cancels the dominant contribution of vertical vibration noise that is unavoidable in-flight.

Major upgrades since our previous gravimeter include using a split pyramid reflector for generating the cooling and trapping laser beams, and using a state-of-the-art flat-top beam shaper for interferometry pulses, simplifying the optics module, and flight-hardening our electronic control and power systems.

Our vacuum chamber has two split-pyramid reflectors which redirect our single laser beam to form the upper and lower magneto optical traps.

The optics module achieves atom cooling/trapping, interferometry, and imaging using a single laser diode, no external cavity, and no optical amplifiers. This simple design is a guiding philosophy for our project, and enforces a strict laser-power budget. Compared to our previous design, we have replaced one acousto-optic modulator (AOM) with fiber-coupled electro-optic modulator, which offers much larger tuning bandwidth. This design increases our flexibility in atom-optics and will allow us to attempt to achieve larger momentum transfer. Furthermore, we have consolidated the function of two AOMs into a single AOM. This reduces the number of discrete optical components and alignment degrees of freedom. Our interferometry beams use a refractive flat-top beam shaper. This ensures uniform pulse strength across the cross-section of our beam without sacrificing laser power as an apodizing filter would. This helps minimize our sensitivity to transverse vibrations.

Our electronic control system is based on the embedded microcontroller package developed for our ground-based gravimeter, MiniG [3]. MiniG had several commercial electronics modules which require AC power, which was provided by our onboard battery and inverter. To meet the flight-constrained weight budget, we cut out the inverter by replacing these modules with our own electronics designs that natively run on DC power. We will be open-sourcing all of our electronic schematics and printed circuit board designs under the GPL3 license when they are sufficiently developed and tested.

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# BECCAL

The Bose Einstein Condensate and Cold Atom Laboratory, BECCAL, is a facility to investigate cold and condensed atoms on board the international space station. In my talk I present the current status of the payload and the applications of the relevant technology in ground and space based environments. The talk will represent the work of the BECCAL consortium including national and international partners. It is financed through a collaboration by NASA and DLR funding different research institutions in the process.

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# Towards the development of an optical lattice clock using bosonic isotopes of mercury

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Time references are based on atomic frequencies generated by atomic clocks since 1967 and they are key resources for science and for society. Atomic clocks can also be based on optical transitions and they have reached better accuracies than the historical microwave clocks, close now to 1 x $10^{-18}$. Thanks to their extremely low uncertainties, they are used as tools for various applications, such as chronometric geodesy, tests of General Relativity, search for physics beyond the Standard Model or redefinition of the SI second [1].

Compared to some other atoms, mercury and its various stable isotopes has not been much investigated in cold atoms or quantum gas experiments, thus many of their properties are still to be explored. Nevertheless, optical lattice clocks based on mercury are studied because of certain advantages over other neutral atoms. In particular, the mercury clock transition$^1S_0$ - $^3P_0$ has a low sensitivity to black-body radiation (BBR), that is to say the energy level shift due to the thermal radiation of an environment at a non zero temperature. Its sensitivity to BBR is 16 times lower than ytterbium and 30 times lower than strontium, two of the most successful clock species. It also has a high saturation vapor pressure favorable to implement a 2D magneto-optical trap as an efficient source of pre-cooled atoms. The mercury clock transition has a relatively high sensitivity to a putative variation of the fine structure constant, and hence allows to constrain theories aiming to unify gravity with other interactions and to search for dark matter. Working with mercury implies using UV-transitions which is one of the main experimental challenges with the on-going technologies. Developments of optical lattice clocks using mercury have been focusing so far on the $^{199}$Hg fermionic isotope [2].

The clock transition$^1S_0$ - $^3P_0$ of $^{199}$Hg is naturally allowed thanks to the hyperfine mixing due to the 1/2 nuclear spin of $^{199}$Hg. But the lifetime of the state $^3P_0$ is becoming smaller than the longer probing time allowed by the new generation of ultrastable lasers, so it is a limiting factor to fully exploit the potential of these novel technology lasers. Instead in bosonic isotopes with a zero nuclear spin, the $^3P_0$ state has hypothetically an unlimited lifetime. The $^1S_0$ - $^3P_0$ transition can be induced with an external magnetic field by a quenching scheme, and thereby giving the possibility to adapt the strength of this coupling to the probe laser characteristics [3]. $^{174}$Yb was studied with this method. $^{88}$Sr clocks also based on this approach were also studied and have shown promising accuracy [4].

In this poster, we will describe the laser cooling methods used, which open the way to study collisional properties. We will describe the optical lattice clock at SYRTE and we will report the achievement made so far on the $^{199}$Hg isotope (stability, accuracy budget, comparisons). We will mention limitations of our current setup and explain the scheme, the expectations and the future steps for making a clock using bosonic isotopes of mercury.

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