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Frontiers of Matter Wave Optics Conference | (SMR 3769)

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P01

Multi-axis and high precision rotation sensing with Bose-Einstein condensates

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Inertial sensors based on matter-wave interference show great potential for navigation, geodesy, or fundamental physics. The principle drift-free nature of such sensors represents an interesting property for autonomous navigation. In this context, we demonstrate a compact geometry of differential atomic interferometers for acceleration and rotation rate discrimination and present a concept for a compact six-axis sensor. Similar to the Sagnac effect, their sensitivity to rotations increases with the space-time area enclosed by the interferometer. In the case of light interferometers, the latter can be enlarged by forming multiple fibre loops. However, the equivalent for matter-wave interferometers remains an experimental challenge. We presented a concept for an atom interferometer with a scalable area formed by multiple light pulses in a twin lattice. It exploits ultra-cold atomic ensembles combined with symmetric beam splitting and a relaunch mechanism. Due to its scalability it offers the perspective of reaching unprecedented sensitivities for rotations in compact sensor head setups.
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[2] Tennstedt, B., Weddig, N. & Schön, S. Improved Inertial Navigation With Cold Atom Interferometry. Gyroscopy Navig. 12, 294–307 (2021). https://doi.org/10.1134/S207510872104009X
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P02

Quantum Hybridized accelerometer for Inertial Navigation

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Today, precise inertial navigation and positioning systems are the basis for controlling vehicles such as aircraft, ships, or satellites. However classical inertial sensors suffer from device-dependent drifts and re-quire GNSS corrections that themselves rely on the availability of the signal broadcasted by the satellites. This leads to the non-usability of classical sensors in some environments like in-between buildings, underground, or space.

Hybrid quantum navigation, based on the combination of classical Inertial Measurement Units with quantum sensors based on atom interferometry [1], is a serious candidate for a new technology that meets the demand of our time requirements for inertial navigation.

Atom interferometers have proven to measure drift-free at very high sensitivities. The main challenge is to transfer a complex laboratory-based device to a robust and compact measurement unit that can be used regardless of its small bandwidth and dynamic range to subtract the drifts of the classical devices [2]. This is done by our partner ife with testing new algorithms for the conception of the quantum sensor and specification of dynamics and noise processes from sensors and trajectories [3].

We present the current status of our teststand for a quantum accelerometer based on an atom interferometer in a Mach-Zehnder geometry using a compact and robust laser system made from off-the-shelf fiber-based components along with a commercial vacuum system from ColdQuanta and new optics geometry that enhance the quantum sensor sensitivity while the final device is employed on a gyro-stabilized platform designed and made from our partner iMAR.

[1] Richardson, L.L., Rajagopalan, A., Albers, H. et al. Optomechanical resonator enhanced atom interferometry. Commun Phys 3, 208 (2020).

[2] Gersemann, M., Gebbe, Abend, S., Schubert, C., and Rasel, E.M. (2020). Differential interferometry using a Bose-Einstein condensate. Eur. Phys. J. D, 74 10203.

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P03

Quantum Soliton Transport in Superconducting Circuits

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Superconducting junctions constitute a promising platform for future implementation of quantum processors. Arrays of Transmon qubits naturally implement the Bose-Hubbard model, with negative (attractive) on-site interaction[1]. Source-to-drain transport has recently been experimentally characterised in an array of Transmon qubits[2]. In this work[3], we present several protocols to both prepare a quantum soliton in a lattice and realise coherent evolution of bosonic excitations through a circuit of superconducting transmon qubits. Implications for the actual experimental realisations are discussed, with a focus on experimental feasibility.

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[2] G. P. Fedorov, S. V. Remizov, D. S. Shapiro, W. V. Pogosov, E. Egorova, I. Tsitsilin, M. Andronik, A.A. Dobronosova, I. A. Rodionov, O. V. Astafiev, and A. V. Ustinov Phys. Rev. Lett. 126, 180503 (2021).

[3] Ben Blain, Giampiero Marchegiani, and Luigi Amico (In preparation)

P04

Interference dynamics of matter-waves of SU(N) fermions

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We consider an atomtronic circuit comprised of strongly interacting SU(N) fermions, pierced by an effective magnetic flux. Inspired by the experimental know-how in the field, we perform an in-depth analysis of the matter-wave interference patterns of SU(N) fermions as a function of the operating conditions of the synthetic gauge field, particle numbers and in the interaction regimes ranging from attractive to repulsive. Through the so-called homodyne and self-heterodyne protocols, which are two protocols that are widely employed in the current experimental setups for interfering ultracold matter-waves, we highlight the different physics exhibited by the repulsive and attractive regimes. Furthermore, we show how the number of particles as well as the number of components of SU(N) fermions, two quantities that are notoriously hard to extract experimentally, can be detected through our analysis.

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P05

Towards interferometry with novel geometries

Advances in matter-wave interferometry have the potential to enable a variety of applications, from fundamental physics to inertial sensing. In the QUANTUS-1 experiment we investigate interferometry with a Bose-Einstein condensates released from a magnetic chip trap. Previously, we have demonstrated an interferometer with a large Sagnac area in a baseline of only 2.43 mm, employing symmetric momentum splitting of more than 400 photon recoils.[1] Here, we present an overview of the techniques we are exploring in order to achieve novel interferometer topologies, and to improve on our previous results. We work on using combinations of Raman and Bragg pulses, which allows the generation of clock states, or the use of blow-away pulses to selectively eliminate unwanted momentum states. Moreover, we study more compact interferometers in guided geometries. Lastly, we aim to overcome the limitations set by the beam-profile on large momentum transfer interferometry by implementing AC Stark shift compensation. [1] Gebbe, M., Siemß, JN., Gersemann, M. et al. Twin-lattice atom interferometry. Nat Commun 12, 2544 (2021). https://doi.org/10.1038/s41467-021-22823-8

P06

The Design of the BECCAL Laser System and its Capabilities

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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].

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P07

Neutron diffraction in the multi-wave regime: experimental observation of the Pendellösung effect under low-coherence conditions

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We report on experimental observation of the Pendellösung interference effect for first and second order diffraction, using a low-coherence beam of slow neutrons (wavelength around 3.5 nm) and optically thin diffraction gratings (holographic nanoparticle-polymer composite gratings [1]) with 500 nm period.

We demonstrate the dependence of the effect on the grating thickness and confirm its wavelength-dependence qualitatively. In contrast to typical single-crystal diffraction experiments, multiple diffraction orders are observed for a given angle of incidence, so that a rigorous coupled-wave theory [2] is employed for the analysis. The latter theory allows access to the full information (amplitudes and phases) of the Fourier components of the grating profile as a by-product [3]. We give a short overview of potential applications in neutron interferometry and imaging.

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P08

Fiber-based Atom Interferometric Sensors

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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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P09

Towards an experimental realization of an atom interferometer for a Bell inequality test

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The "Quantum Atom Optics" team from Laboratoire Charles Fabry is specialized in the realization of Bose-Einstein condensates (BEC) of metastable helium, used as reservoirs of coherent atoms.

From a BEC our team is able to emit pairs of atoms whose momenta are strongly correlated by a process called four-wave mixing which consists in using an optical lattice.[1] The pairs of atoms are used as the input of an interferometer, which relies on Bragg diffraction to transfer momentum to the atoms and therefore coupling the momentum modes. The detector used in the experiment, a Microchannel Plate (MCP) makes it possible to detect a single atom and gives access to its momentum in each direction. With this setup, we performed a Hong-Ou-Mandel experiment[2], thus proving the entanglement of the input state.

The goal of the team now consists in testing a violation of Bell inequality with these momentum entangled atoms. To do so, inspired by the interferometer described by Rarity and Tapster[3] (which exhibited a violation of Bell inequality with momentum entangled photons), we need to realize a two-particle four-mode interferometer[4] for which the phase difference between the two sub-interferometers A and B is well controlled (Fig. 1).

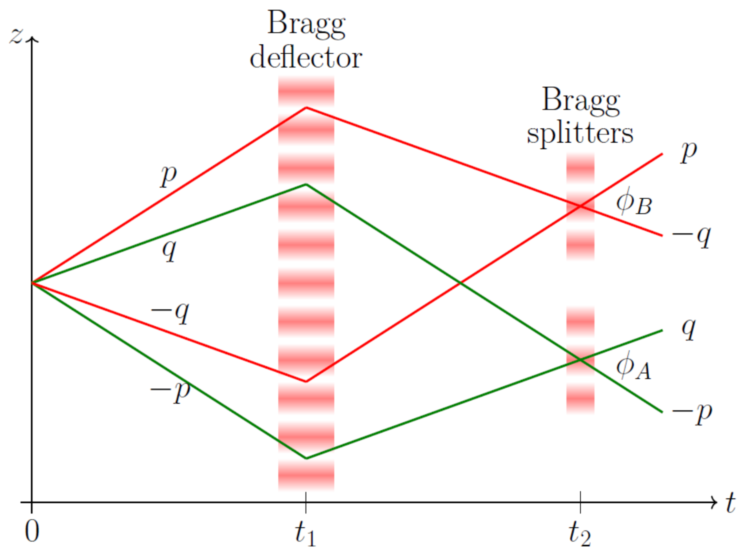

Figure 1: Scheme of the interferometer

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P10

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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We propose an estimation scheme based on the distribution of a single squeezed state among d interferometers to achieve highly sensitive estimation of multiple parameters. The scheme admits different implementations ranging from optical to atom interferometry. The fundamental component of our scheme is the "quantum circuit" (QC), a linear network that optimally distributes the squeezing generated at one of its inputs among d simple (Mach-Zehnder or Ramsey) interferometers, where d unknown parameters are then imprinted and the number of particles at the outputs finally measured. For any given linear combination of the parameters, we identify the optimal configuration of the QC that allows its estimation with maximal, sub-shot-noise sensitivity. Our "entangled" strategy, based on the mode-entanglement created by the QC, outperforms the rival and more common "separable" strategy, in which the same unknown parameters are estimated independently: the sensitivity gain being a factor d, at most. We show that these results are robust against the noise which may arise in the sensor network. Our new scheme paves the ways to a variety of applications in distributed quantum sensing [1-6].

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P11

Efficient atomic lensing of quantum gas mixtures

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Mixtures of ultracold quantum gases are at the heart of currently planned high-precision quantum tests of the weak equivalence principle, where dual-species Bose-Einstein condensates are probed with atom interferometry techniques. An important challenge for such experiments is to reach very low expansion velocities by means of time-dependent potentials acting as matter-wave lenses while ensuring the co-location of the two atomic species and matching their expansion rates during the whole free evolution. To achieve the required control, one lensing pulse is needed for each independent spatial direction and atomic species, which makes a full 3D implementation rather impractical.

Here we propose to overcome these challenges by taking advantage of special magic wavelengths for optical dipole traps where the ratio of the optical potentials is given by the ratio of the masses of the different species. In this case the center-of-mass dynamics is identical for all species, resulting in a perfect co-location of the mixture even in an Earth-based laboratory. Most importantly, optical dipole traps with such a magic laser wavelength give rise to a common expansion dynamics for both species and therefore guarantee that the relative shape of the mixture is conserved during the entire evolution, including when the lensing potentials are applied. Hence, our approach enables an efficient collimation of mixtures of ultracold atoms in order to reach the very low expansion rates that are necessary for high-precision measurements while cutting in half the number of required lensing pulses compared to standard approaches.

P12

Momentum entanglement for atom interferometry

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Compared to light interferometers, the flux in cold-atom interferometers is low and the associated shot noise large. Sensitivities beyond this limitation require the preparation of entangled atoms in different momentum modes.
Such an entangled source, compatible with present-day light-pulse atom interferometers, is presented here. Utilizing a quasi-adiabatic ramp through a quantum phase transition, highly-entangled twin-Fock states are deterministically created in the internal spin-degree of freedom of a Bose-Einstein condensate. Hereupon, the entanglement is transferred to distinct momentum-modes by a stimulated Raman coupling and verified by the direct measurement of an entanglement criterion.
The observed mode quality and the residual expansion demonstrate that this entangled source is well-suited to the successive application in light-pulse atom interferometers and opens up a path towards gravimetry beyond the standard quantum limit. In the long run, similar entangled sources could specifically enhance the performance of gravity gradiometers and atomic gravitational wave detectors.

P13

Solitons and phonons in a dipolar Tonks-Girardeau droplets

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In the recent paper [1] we have predicted that the 1D dipolar gas transforms into droplets, even in the strongly interacting regime. We use in our research an unusual extension of the Gross-Pitaevskii equation, which we called LL-GPE, and then studied in [2], known under many names in the literature [3]. The *ab initio* calculation with the DMRG method supports parts of our results. After discussing the crucial findings of papers [1, 2], I would like to show new results: the existence of phonons and solitary waves inside a dipolar droplet. We derive analytical formulas for the solitary waves in extreme regimes. The solutions turned out to be peculiar – their width can be extremely wide and therefore possibly easy to detect, whereas the density of the motionless wave does not touch zero. Consequently, in certain regimes, only grey solitons can exist inside a droplet.

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P14

An atom interferometer to searching for chameleon fields

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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 in high 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 [6,7,8].

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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P15

Mach-Zehnder interferometry with atomic BECs trapped in beat-note superlattices

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We are working on an array of trapped atom double well interferometers using BECs of ^{39}K. Having more than one correlated interferometers operating simultaneously allows to cancel the common noise affecting the sensors via differential analysis, thus improving the sensitivity. In particular, in our setup we can load the atomic sample in three independent double well potentials.

We realize such trapping potential with a novel technique we call beat-note superlattice [1], which exploits the superposition of three commensurate standard optical lattices on the same mirror. This scheme lets us control atoms over large distances without renouncing to the stability of ordinary lattices, and the use of atoms with tunable interaction allows us to get a first realization of in-trap full Mach-Zender interferometer, which is now under study. We are also investigating the possibility of producing number squeezed states introducing repulsive interaction in our system.

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P16

Performance enhancement of an atom interferometer with an optomechanical resonator

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Atom interferometers possess the potential to serve as long term stable and highly sensitive measuring instruments of inertial effects for various field applications. But currently they are mostly operated in controlled laboratory environments owing to their operational sensitivity to environmental effects. There is a growing interest in the field of quantum technologies on various domains including quantum sensing, due to specific advantages over its classical counterparts by exploiting the principles of quantum mechanics. Therefore, the atom interferometer should be compact, robust and portable for implementation in real field applications such as gravimetry or inertial navigation.

Ambient vibrational noise and the cyclic measurement nature of atom interferometers are the main limiting factors for application in high noise field applications. We have used a novel Optomechanical resonator (OMR) in order to suppress the effects of vibrational noise coupling in our atom interferometer. By means of hybridizing the atom interferometer with the OMR, we enhance the sensitivity and the dynamic range of our atom interferometer therefore making it robust and suitable for field applications. We have demonstrated ambient vibrational noise post-correction on a T = 10 ms atom interferometer without any vibration isolation, which can be found in reference [1]. The primary advantages of the OMR over classical accelerometers amongst others are, compact dimensions, vacuum compatibility and the possibility to have it tailored for any atom interferometer to maximize performance. The compact dimensions of the OMR enable the possibility for direct integration onto the retro-reflection mirror, therefore paving a way for miniaturization of the atom interferometer sensor head.

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P17

Efficient atomic lensing of quantum gas mixtures

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Mixtures of ultracold quantum gases are at the heart of currently planned high-precision quantum tests of the weak equivalence principle, where dual-species Bose-Einstein condensates are probed with atom interferometry techniques. An important challenge for such experiments is to reach very low expansion velocities by means of time-dependent potentials acting as matter-wave lenses while ensuring the co-location of the two atomic species and matching their expansion rates during the whole free evolution. To achieve the required control, one lensing pulse is needed for each independent spatial direction and atomic species, which makes a full 3D implementation rather impractical.

Here we propose to overcome these challenges by taking advantage of special magic wavelengths for optical dipole traps where the ratio of the optical potentials is given by the ratio of the masses of the different species. In this case the center-of-mass dynamics is identical for all species, resulting in a perfect co-location of the mixture even in an Earth-based laboratory. Most importantly, optical dipole traps with such a magic laser wavelength give rise to a common expansion dynamics for both species and therefore guarantee that the relative shape of the mixture is conserved during the entire evolution, including when the lensing potentials are applied. Hence, our approach enables an efficient collimation of mixtures of ultracold atoms in order to reach the very low expansion rates that are necessary for high-precision measurements while cutting in half the number of required lensing pulses compared to standard approaches.

P18

Multi-loop atomic Sagnac interferometry

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Analogous to the Sagnac effect in light interferometers, the phase shift due to rotations in atom interferometers scales linearly with the enclosed area. We propose a geometry with atoms in free fall utilising symmetric beam splitters and relaunches to enable multiple round trips of the atoms. Consequently, our approach exploits the linear scaling of the phase shift without increasing the size of the sensor head. Based on our estimated parameters, we anticipate a sensitivity of 20 prad/s at 1 s [1].

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P19

Conformer selection and enantiomer superpositions from matter-wave interference

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Molecular matter-wave interferometry enables novel strategies for manipulating the mechanical motion of complex molecules [1]. In this presentation, I will argue how chiral molecules can be prepared in a quantum superposition of two enantiomers by far-field matter-wave diffraction and how the resulting tunnelling dynamics can be observed [2]. I will discuss the impact of ro-vibrational phase averaging and propose a setup for sensing enantiomer-dependent forces and environment-induced superselection of handedness.

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P20

An Alternative Hybridisation Scheme for Atom Interferometers used in Navigation

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Atom interferometers (AI) based on cold atoms and Bose-Einstein condensates are a promising option for future navigation systems due to their superior long-term stability and sensitivity. While applications for the measurement of gravity are already commercially available, the way to a fully functional quantum inertial navigation system able to measure accelerations and rotation rates on three spatial axes comes with different challenges that need to be faced.

The disadvantage of atom interferometry is the comparably small data rate and the disability to resolve large changes of inertial accelerations during the measurement cycle, leading to a limited dynamic range. Thus, hybridisation with accelerations measured by conventional sensors are currently the state of the art in order to use AI as inertial sensor for navigation purposes. A common method is the convolution of acceleration signals with the interferometer response function, in order to resolve the ambiguity of the AI and reconstruct the fringe pattern [1-2].

Here we present an alternative hybridisation scheme based on the prediction of the position of the atom wave packet in the coordinate system spanned by the Raman laser field with conventional inertial measurement units [3]. This allows to resolve the fringe ambiguity and also to account for rotations of the frame during the AI measurement cycle.

Based on experimental AI measurements with an optomechanical resonator as well as a proprietary accelerometer, we will show that the new method and the existing convolution method lead to comparable results. Furthermore, this new method can be included as a prediction step in an extended Kalman filter framework in order to estimate the bias of the conventional sensor, as will be demonstrated for both conventional sensors in the experiment.

Furthermore, an outlook for the inclusion of multi-axis AI sensors [4] will be given.

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P21

The MAGIS and AION experiments for fundamental physics

The Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100) [1] is a 100 m vertical baseline detector under construction at Fermilab. It works closely with the Atom Interferometry Observatory Network (AION) [2], a UK based program also investigating the construction of a long baseline atom interferometer. Forming a LIGO/VIRGO style collaboration. Both programs will use the latest in atomic interferometry to search for dark matter, test quantum mechanics, and investigate the feasibility for constructing future kilometre baseline detectors. Atom interferometers have a sensitivity to a broad range of low-mass dark matter candidates (10-22 - 10-15 eV), probing this region will place greater restraints on parameter space. At a kilometre scale, atom interferometers are sensitive to the mid-band region of gravitational waves (30 mHz - 10 Hz), between the aLIGO and LISA experiments. This is an unexplored frequency range which has the promise for new discoveries in both fundamental science and astrophysics. [1] M. Abe, et al. Matter-Wave Atomic Gradiometer Interferometric Sensor (MAGIS-100) arXiv:2104.02835 (2021), Quantum Sci. Technol. 6 044003 [2] L. Badurina, et al. An Atom Interferometer Observatory Network arXiv:1911.11755, JCAP05(2020)011

P22

Levitated Atom Interferometry with T^2 Scaling

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Levitated atom interferometry, in which atoms are suspended against gravity rather than freely falling, has exciting prospects for fundamental research, e.g. for local force sensing, as well as practical applications, e.g. for achieving long interrogation times in a compact apparatus. Most levitations schemes to date prohibit relative motion between interferometer arms [1-4], which limits acceleration sensitivity to scale linearly with T. In this contribution we propose a levitation method compatible with a nonzero velocity between the interferometer arms, as in the Mach-Zehnder (MZ) scheme, which can achieve much better sensitivity owing to its T^2 scaling. The levitation relies on repeated Raman-based momentum kicks applied in a ~800 Hz repetition rate to counteract free fall.

The interferometer sequence, shown in Fig. 1 is a modified MZ scheme, comprised of beamsplitter, mirror and recombiner pulses. During the time between the beamsplitter and the recombiner, Raman "levitation" pulses are repeatedly applied. To achieve levitation (rather than LMT), both arms should occupy the same internal state. As the total number of the levitation pulses is 10s-100s, they must have a >99% fidelity (per-pulse). To this end, Adiabatic Rapid Passage (ARP) pulses will be employed. To keep the direction of the impulses upwards, the direction of **k** should be reversed between every 2 levitation pulses. The resulting interferometer is expected to be localized, limited only by thermal and recoil motion (≤ few cm), and extremely sensitive, thanks to the combination of large T and favorable scaling. We will present the detailed design of the above scheme, discuss the main challenges – such as dynamic phase arising from the ARP, and present the work done towards realizing a levitated interferometer.

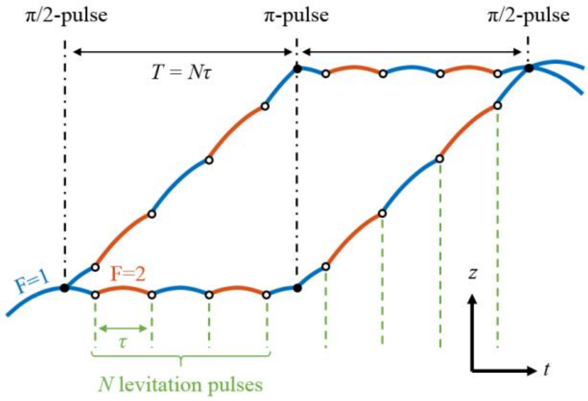

Figure 1. Proposed scheme for a levitated MZ interferometer. Both arms of the interferometer occupy the same internal state at all times. High-fidelity levitation pulses are used to impart two photon momenta in the same direction to both arms of the interferometer, effectively suspending it against gravity.

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P23

Systematic description of matter wave interferometers using elastic scattering in weakly curved space-times

We present a systematic approach to calculate all relativistic phase-shift effects in light-pulse matter wave interferometer (MWI) experiments using elastic scattering processes like Bragg and Bloch transitions up to (and including) order c^{-2}, placed in a weak gravitational field. The whole analysis is derived from first principles and even admits test of General Relativity (GR) apart from the usual Einstein Equivalence Principle (EEP) tests, consisting of universality of free fall (UFF) and local position invariance (LPI) deviations, by using the more general 'parameterized post-Newtonian' (PPN) formalism. We collect general phase-shift formulas for a variety of well-known MWI schemes and present how modern experimental setups could measure PPN induced deviations from GR without the use of macroscopic test masses. This procedure should be seen as a way to easily calculate certain phase contributions, without having to redo all relativistic calculations in new MWI setups and come up with possibly new measurement strategies. Our description bases on a series expansion in 1/c and small dimensionless parameters like \hbar \kappa/mc, gT/c, v_0/c and \Gamma T^2, where \Gamma is the gravity gradient. Using this we are able to systematically calculate the phase shift to an arbitrary order. Furthermore we make our Python code open source, such that everyone can reproduce our results.