Topical: Quantum tests of gravity with entangled atom interferometry

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INTRODUCTION

The cornerstones of modern quantum science – coherence, correlations and entanglement – can provide unique probes into the nature of gravity. Continuing developments in the control of quantum systems have already enabled ultra-precise measurements of gravitational forces and even more exotic phenomena, such as gravitational waves. While the quantum phenomenon of entanglement is widely appreciated as a resource for improving the precision of such measurements, it can also provide a probe of gravity in fundamentally new ways. For example, quantum mechanical formulations of gravity could have crucial implications for the creation and behavior of entanglement in quantum matter, while entangled quantum states enable us to construct truly quantum tests of classical concepts such as the equivalence principle.

Ultra-cold atoms are an exceptional experimental platform for probing these fundamental aspects of gravity in the context of entanglement. These systems are demonstrated to measure gravity with unprecedented precision and accuracy [1–4]. Furthermore, highly entangled quantum states can be manufactured in these systems with entangling interactions [5–10]. And recent work actively targets [6, 11–13], and even demonstrates [14], atom interferometer experiments with entangled states. Blending gravimetry with entangled states in this fashion using either quantum information science protocols or spin squeezing opens new possibilities for constraining gravitational theories with matter wave interference.

QUANTUM MECHANICAL TESTS OF GRAVITY

A broad range of proposals exists for testing gravity with cold atom interferometers [2]. These include searches for modifications to the inverse square law at short distances, violations of the Einstein Equivalence Principle, signatures of dark matter and dark energy, and gravitational wave detection. All of these research thrusts require not only advancing the metrological performance of current state-of-the-art atom interferometers to unprecedented levels, but also developing their capability as a modular tool in complex experiments. A well-known opportunity for improving the precision of these measurements is leveraging signal enhancement beyond the standard quantum limit using entangled states [11, 14, 15]. Figure 1 shows a conceptual implementation of multiple entangled atom interferometers. Though initial demonstrations are very promising [14], significant research opportunity remains. Ground based investigations of entanglement in matter wave interference experiments are thus crucial to better understand and mollify the associated challenges and discover its full potential [11, 15].

Going beyond the paradigm of quantum-enhanced precision, entangled quantum systems can provide new paths for the characterization of gravity in fundamentally new ways. In particular, entangled states have long been acknowledged as uniquely suitable probes for investigating the interplay between quantum theory and gravity via, e.g., the decoherence of quantum systems due to coupling to gravitational fields [16–18]. A recent perspective on the long-standing problem of quantum gravity has been to identify no-go theorems on the potential classical/quantum nature of gravity that do not require identifying specific models and provide an operational path forward for near-term experiments. Crucially, it has been argued [19, 20] that only if a quantized description of gravity exists, i.e., in terms of quantum gravitons that mediate the gravitational force between massive systems, can gravitational interactions induce entanglement. In this form, tests for quantum gravity can be reduced to metrology problems where the task at hand is to sensitively

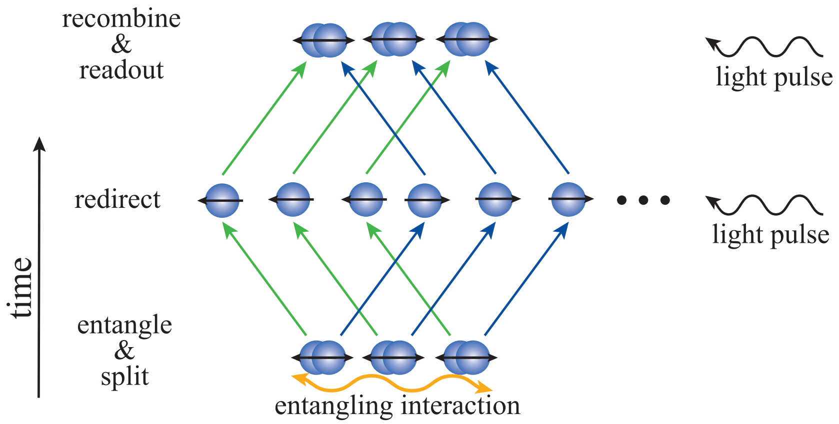

FIG. 1. Gravity test with entangled atom interferometers. Entangled momentum states are created via entangling interactions. Resonant light pulses are used to impart momentum transfer and setup multiple adjacent atom interferometers entangled with one another. For a GHZ-type implementation, the interferometers are in a superposition of all atoms either going left (green) or right (blue).

characterize the weak generation of entanglement between a probe and a proof mass [19–21]. This immediately prompts important theoretical questions regarding the identification of optimal (and experimentally reasonable) protocols and probe states to discern entanglement [22]. Moreover, simple descriptions of the gravitational interaction between quantum systems using a quantized model of gravity [19, 21] have clear connections to Hamiltonians and machinery routinely applied in quantum optics and atomic physics experiments [23]. Beyond the near-term, where these connections might be used to adapt established metrological protocols harnessing entanglement, it also motivates long-term questions regarding whether quantum features of gravity such as projection noise might become accessible by coupling to judiciously designed entangled probes or amplifying its role using tools such as squeezing [24].

Complementary to this, quantum states featuring coherence and entanglement provide new ways to probe the Weak Equivalence Principle (WEP) [25, 26]. While recent studies have leveraged the exquisite control of quantum systems at the single-particle level to introduce mass-energy equivalence into WEP tests by comparing the free fall of atoms prepared in distinct internal energy states, a new frontier are truly quantum tests of WEP that study the free fall of a *superposition* of internal energy states [27] or an entangled pair of different isotopes [26]. Looking forward, and motivated by the lack of concrete theoretical predictions for WEP violations in quantum systems, it will be illuminating to develop experiments capable of extending these tests to entangled quantum states of matter, or even the creation of bespoke entangled states of multiple particles and superpositions of many-body energy eigenstates.

EXPERIMENTAL APPROACH FOR INTERFEROMETRY WITH ENTANGLED ATOMS

Prospective platforms and experimental capabilities: Experimental quantum control of atomic systems offers outstanding new capabilities for quantum mechanical tests of gravity. Spectacular demonstrations in this field point to imminent realizations of matter wave interference experiments using entangled states for gravity measurements. The predominant approaches for generating metrologically useful entanglement in these systems are spin-squeezing [6, 7] and quantum information processing (QIP) techniques for the creation of GHZ or Schrödinger-cat states [11, 28]. Both approaches in principle facilitate quantum-enhanced precision beyond the standard quantum limit (SQL) [29], and there have been recent ground-breaking experimental demonstrations in the context of squeezed states for optical atomic clocks [30] and matter-wave interferometry [14].

In terms of generating maximally entangled atomic spin states such as GHZ states, a fruitful approach employs QIP techniques with entangling quantum gates. In neutral atom systems suitable for measuring gravity, the most promising method for generating high-fidelity GHZ states of atomic spins is by using Rydberg-mediated interactions in arrays of ultracold, optically trapped neutral atoms [31]. Owing to the inherent ability of this approach for single- and many-atom control and detection, a QIP-like probe with arbitrary entangled quantum states can be envisioned. Interesting possibilities include quantum sensing near a phase transition [32] or optimal quantum states for metrology [22]. Recent demonstrations in QIP platforms include gates with fidelities as high as 97% [33, 34], Bell-state preparation fidelity of $> 99.1\%$ [35] and controlled-Z gates within arrays of 121 sites [36]. GHZ states of 20 atomic spins have been generated in these systems [8] with still larger systems demonstrating quantum complex many-body simulations with up to 256 qubits [37]. Proposed advances such as the use of rapid adiabatic Rydberg dressing [38] and continued technical improvements are likely to further increase the number of entangled atoms and enhance fidelity in these systems. The unique and exciting potential of this platform for testing quantum gravity is largely unexplored. Experimental blending and tailoring of the QIP approach with the superb gravitational sensing demonstrations of atom interferometers is a vital research thrust in order to enable new measurements and capabilities for the next decade.

At larger scales, light pulse atom interferometry using spin-squeezed ensembles presents an interesting new frontier for tests of gravity. Effective techniques include, but are not limited to, entangled spinor Bose-Einstein condensates (BEC) [6, 12] and cold atoms squeezed via interaction with optical cavity photons [7, 14, 15]. Here, we focus on the unique opportunities presented by an entangled spinor BEC. In these systems, spin-changing contact interactions directly generate entanglement between atoms in different hyperfine states [39] with possibilities to create fascinating quantum entangled states such as: spin-nematic squeezed states [40], coherent spin-squeezed states [41], twin-entangled matter-waves [42], and even more exotic non-Gaussian states [43] and massively entangled states [44]. This generation of entanglement can be readily controlled via a range of experimental knobs, including: microwave dressing, choice of quench time, and initial state preparation [12, 45, 46]. From a technical standpoint, entangled spinor BEC light pulse interferometers also present new opportunities based on the choice of atomic species. For example, a sodium spinor BEC features a relatively small atomic mass, which can enable a comparatively large velocity change per absorbed photon (relative to other candidates such as Rb or Cs) when applying Raman or Bragg light-pulses to impart photon-recoil momentum in the interferometer. This leads to a rapid and large splitting of the ultracold clouds within less than a ms, faster than the timescale for collisional spin evolution, which is typically on the order of tens of ms. Control over the coupling between spin and spatial degrees of freedom could therefore be maintained during the interferometer sequence. Continued investment in the development of spin-squeezing techniques for gravitational measurements will be crucial for advancing technical capability and fundamental knowledge.

Quantum tests of the weak equivalence principle: As outlined above, the diversity and versatility of entangling interactions available in atomic systems, combined with their comparative isolation and control, position them favourably as core components in ambitious tests of gravity. A concrete example is for fundamentally new tests of the WEP with intrinsically quantum systems,

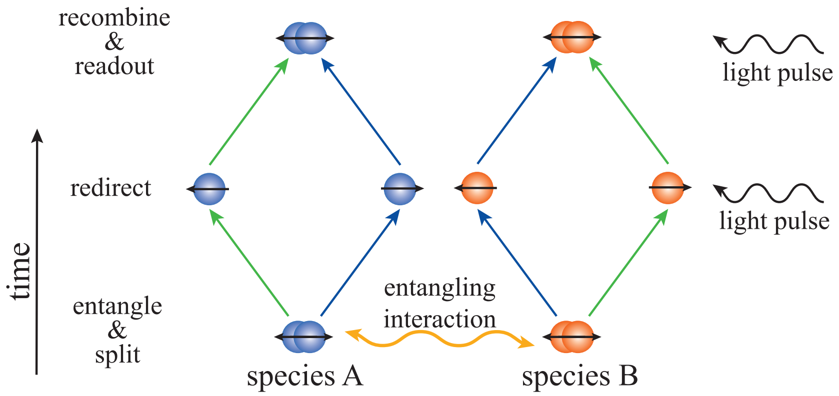

FIG. 2. WEP test with dual-species entangled atom interferometers. Entanglement between two atomic species is created via Rydberg interactions. Resonant light pulses create simultaneous interferometers with the two species using photon recoils. The paths of the two atom interferometers are correlated according to color coding.

such as those based on entangled superpositions of atoms with different masses [26] or internal configurations [27]. In the case of the former, a key ingredient has been demonstrated with QIP techniques using Rydberg interactions to entangle different isotopes of rubidium [47]. Expanding this idea further, QIP-based entanglement of pairs or ensembles of atoms of distinct species, as opposed to different isotopes, using Rydberg state interactions [48] can enable experiments with significantly enhanced mass differences as illustrated in Figure 2. Complementary to this, contact or spin-dependent collisions in degenerate Bose gases (discussed above) provide an attractive opportunity to concurrently generate [49] or transform [6] entanglement between both internal (e.g., hyperfine) and external (momentum) degrees of freedom. Such dynamics can be used fruitfully to test the WEP with large entangled ensembles of cold atoms using atom interferometers [26].

Entanglement mediated by quantum gravity: In the longer term, there are prospects to explore atom interferometry techniques for novel probes of the quantum nature of gravity [19, 21]. Figure 3 illustrates an example adapted from Ref. [19], which originally envisioned a pair of Stern-Gerlach interferometers using nanocrystals with embedded spins. When the gravitational interaction of the massive objects passing through each interferometer is described by a quantum field h_{00} then, combined with the spatial superposition of each possible path, it is predicted to lead to entanglement that can be certified by measurements at the output ports of the interferometer [19, 20].

An example experiment would entail a pair of spinor BEC light pulse interferometers that are operated simultaneously and within close proximity, by splitting a single initial atomic cloud into two identical and coherent ensembles (by, e.g., an additional light pulse) that are then fed into the input of the respective interferometers. While the use of ultracold atomic ensembles comes with comparative disadvantages, such as a relatively low total mass and thus gravitational interaction, they provide unique advantages in terms of isolation and control. Moreover, by pushing the technical frontiers, adjusting the role of entanglement [21], or using a hybrid scheme with spinor BEC and a mechanical oscillator [21], it might be feasible to overcome this challenge. Atomic entanglement could be introduced in a number of ways, including by using spin-changing collisions to entangle the input of each interferometer independently (after the initial splitting) or together (by introducing collisions before splitting the original common atomic ensemble).

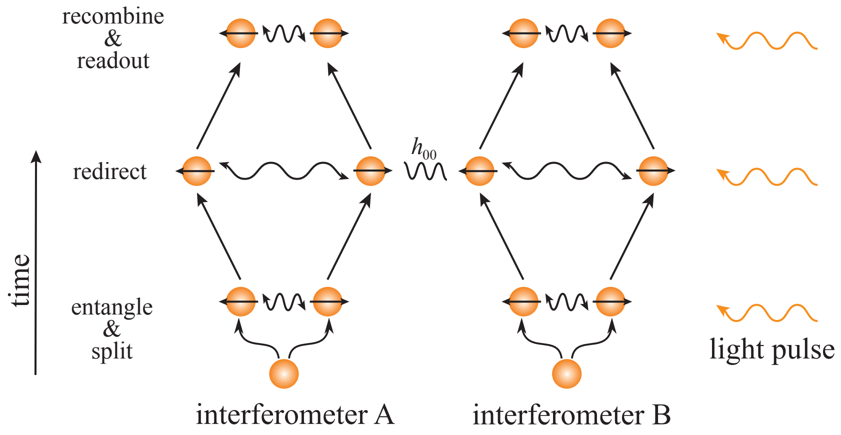

FIG. 3. Quantum gravity test with spinor BECs. Resonant light pulses are used to impart momentum transfer and setup two adjacent atom interferometers. Entanglement between the interferometers is generated by a quantum gravity field h_{00} [19]. Entanglement can also be introduced via spin-exchange collisions, denoted by black wavy lines, to enhance the experimental response.

Considerations for space-based experiments: Space-based experiments are the ultimately desirable platform for performing all of the tests described in this whitepaper. Operating in isolated microgravity environments can lead to a range of technical benefits that, combined with the fundamentally unique paradigm provided by entangled atomic systems, will be necessary to achieve the exquisite precision required for tests of ultra-weak gravitational effects. Most obviously, space-based experiments can enable long free fall/interrogation times for matter-wave interferometry experiments, which provides an enormous benefit as the sensitivity of such interferometers generally scales with the square of the drop time. Simultaneously, the exquisite purity and ultra-long duration of free fall available in space is likely to be far more optimal than a trapped approach for the preservation of fragile entangled states. The absence of strong gravity also leads to substantial benefits in the trapping and confinement of cold atoms. As weaker traps can be used, one can achieve colder temperatures, reduce systematic biases and suppress spurious sources of decoherence. Furthermore, microgravity presents new advantages for overcoming the technical challenges of position control and low atom loss sequences which are unique to working with entangled systems [11, 14, 15]. Finally, technical noise from ambient fields, vibration and gravitational clutter are substantially diminished. To achieve these advantages, the inherent experimental challenges associated with producing and controlling entangled states will require extensive terrestrial investigations to ensure maturation of experimental techniques and technological capabilities before a mission research campaign can be deployed.

SUMMARY

The precision requirements for fundamental tests of gravity and its relation to quantum mechanics will require breakthrough developments in our technical capability to generate and control entangled quantum systems. Ultra-cold atoms provide an exceptional opportunity in this direction, with the prospect of uniting established precision measurement techniques with insight from modern quantum information science to open new possibilities for constraining and elucidating gravitational theories.

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