Quantum metrology and sensing with an atomic spatial superposition state coherent for one minute

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Exceptional levels of quantum control and coherence are necessary for performing quantum metrology and sensing with the utmost precision. Atom interferometers are powerful physical experiments that probe fundamental physics and perform everyday sensing, with results that range from the measurement of fundamental constants and tests of general relativity to the quantum sensing of gravity and inertial effects in the field for geophysical, defense and industrial applications. However, the use of atoms in free fall has so far limited their measurement times to a few seconds.

Here, we realize interferometers with atoms suspended in an optical lattice for an unprecedented 70 seconds. These atom optical methods are particularly well suited for probing localized potentials. I will show how, for the first time, we (1) optimize the gravitational sensitivity of the lattice interferometer and (2) use a system of signal inversions and switches to suppress and quantify systematic effects. This enables us to measure the attraction of a miniature source mass with record accuracy of 6.2 nm/s^2, less than a billionth of Earth's gravity and four times as good as the best similar measurements with freely falling atoms. This performance demonstrates the advantages of lattice interferometry in fundamental physics measurements.

In addition, optical lattice atom interferometers have intrinsic advantages that can overcome the limits of current atomic gravimeters for applications in the field: long measurement times in compact systems, insensitivity to vibrations and magnetic fields and in principle, ability to operate in an arbitrary orientation. Finally, I will discuss current progress towards next-generation lattice atom interferometers and their applications in searching for new physics and quantum inertial sensing in the real world.

Research Background. The strength of gravity, captured by Newton's gravitational constant "big G", and the inverse-square law scaling with distance are some of the earliest physical principles to be established through measurement, more than two hundred years ago. They are still primarily tested using classical sensors today. However, recent advances in quantum science have enabled control of atomic states at the single quantum level with high precision, achieving competitive precision and state-of-the-art accuracy with relatively few atoms. Applying these techniques to the study of fundamental inertial physics and gravity will transform our knowledge of nature and reshape technology and society by enabling quantum sensing of gravitational and motional signals in the real world.

Today, searches for new physics increasingly rely on a new wave of ultra-accurate quantum devices, many performed in table-top experimental setups in university research labs. Atom interferometers perform inertial measurements with record precision: they accurately quantify fundamental constants, search for deviations from Newtonian gravity due to dark matter and dark energy, test general relativity and search for effects of gravitational interactions in quantum systems. Advancing our understanding of these topics requires significant gains in precision, which is limited in typical atomic fountain interferometer experiments by the available interrogation time to a few seconds.

In contrast, the experiments proposed here suspend atoms in an optical lattice, a standing wave of light (OLAI), which produces atom interferometric coherence lasting for up to one-minute [1]. Furthermore, interferometer sensitivity (which scales with interferometer space-time area) can be increased by holding the atoms longer without requiring larger experimental volumes. Therefore, OLAI can be implemented in "small-scale" experimental setups and is particularly suitable for measuring inertial interactions with localized potentials, such as those due to cm or mm-sized objects [2]. This recent measurement (Figure 1) of gravitational attraction of a tungsten source mass inside a vacuum system achieved sensitivity that was

5 times better than any previous atom interferometric measurement and rejected systematic effects through differential measurement.

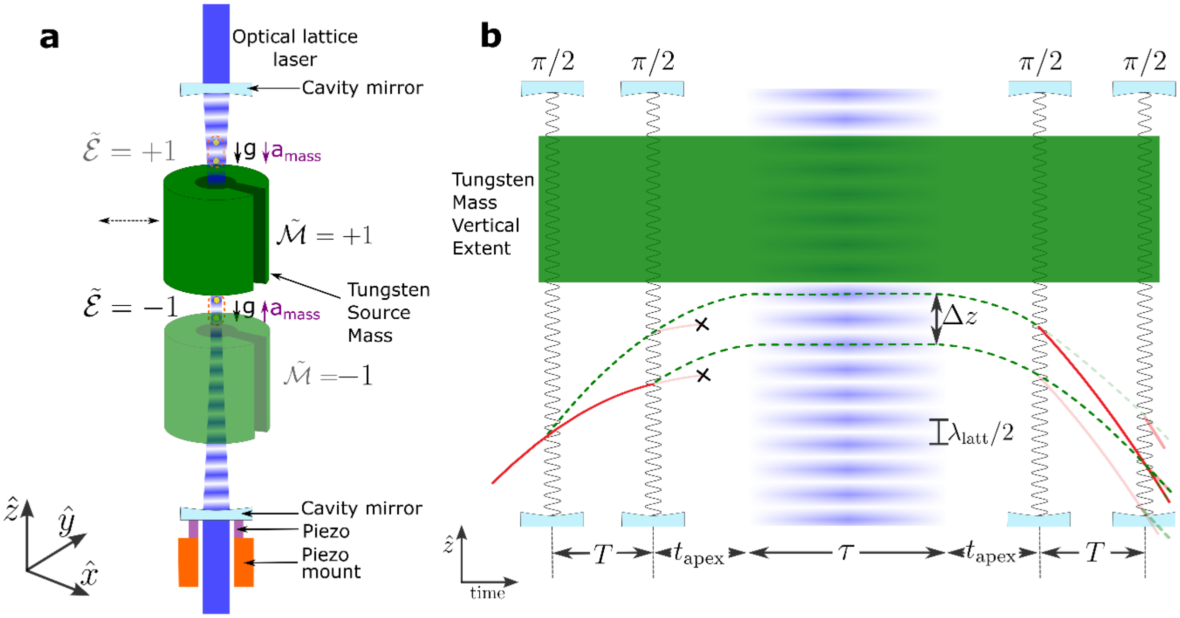

Figure 1. Apparatus used to measure localized gravitational potentials. a. A far-detuned, vertical optical lattice (dark blue, wavelength $\lambda_{latt} = 1064$ nm) is formed by the mode of an optical cavity established by two mirrors (light blue), which is length-stabilized by a ring-piezo (purple). Atoms in a spatial superposition state (yellow circles surrounded by a dashed orange contour) are held in the high-intensity regions of the lattice. They measure the acceleration either above or below the source mass (green), $\tilde{\mathcal{E}} = \pm 1$. In addition, the source mass can be moved above or below the atoms, $\widetilde{\mathcal{M}} = \pm 1$. A differential measurement between these configurations yields a_{mass}. **b. Trajectories of the atoms near the source mass.** The cavity mode passes through the center of the tungsten source mass (green). Pairs of π/2 pulses (wavy vertical lines) separated by time T split, redirect, and interfere the atomic wavepackets. At their apex, the wavepackets are loaded into the optical lattice where they remain for time τ. The internal atomic state is one of the $F = 3$ (red, solid lines) or $F = 4$ (green, dashed lines) hyperfine levels.

However, a quantum spatial superposition state confined in an optical lattice is a rich physical system with complex dynamics. For example, the optical lattice required to balance Earth's gravity is formed by Gaussian laser beams, which have significant non-harmonic trapping potential components. This causes complex quantum dynamics of the trapped atoms, which can combine with experimental imperfections to limit coherence and sensitivity and may generate systematic effects. Improving experimental sensitivity and increasing quantum coherence requires new characterization of these effects.

Research Goals. We are developing quantum control technology for next-generation OLAI to study the limiting influences on the coherence of atomic spatial superpositions in optical lattices (Figure 2). We will address the limitations of existing experiments (residual atom motion and tilt vibrations) [1] in a new experiment that includes two major technical advances: (1) a rigid Zerodur optical resonator to inertially stabilize the atom interferometer axis and (2) an upgraded atom source to produce nanokelvin atom samples. These will enable coherence at the few-minute scale (currently 70 s) and spatial separations between the atomic wavepackets beyond 100 µm (currently a few microns), creating quantum spatial superposition states with coherence at the human scale. These advances will enable more than three orders of magnitude improved precision.

This experimental sensitivity will unlock a new lab-based platform for testing gravity by measuring G and searching for deviations from the expected Newtonian gravity of well-characterized source masses.

Previous atom interferometric G measurements were limited by systematics arising from (1) the challenge of characterizing large source masses weighing ~500 kg and (2) the limited precision in controlling the position of the atoms with respect to the gravitational source mass.

Our experiment addresses both limitations by measuring gravity using stationary atoms, with precisely known positions. In addition, this means that reducing the source mass size has a much smaller effect on interferometer statistical sensitivity. We will measure the gravitational attraction of ~10 kg-scale mass (rather than ~500 kg), whose bulk and surface properties can be carefully characterized. Since the optical lattice potential localizes the atoms, positioning of the atoms with respect to the source mass can be controlled and measured using spatial triangulation imaging methods to better than 10 μm, sufficient to reduce systematics related to atom positioning with respect to the source mass to the part-per-million level.

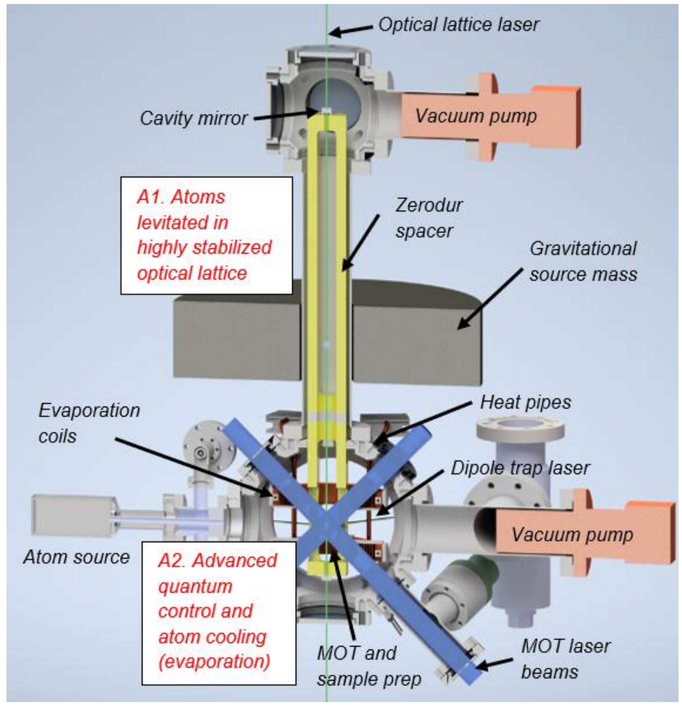

Figure 2. Experimental Design. Primary advances include a highly stabilized optical lattice to levitate the atoms **(A1)** and evaporative atom cooling to reduce the temperature of the Cs atoms to a few nanoKelvin **(A2)**. The pictured source mass is illustrative only; the system is compatible with multiple source mass configurations.

The optical lattice must hold the atoms against Earth's gravity, which is 9-10 orders of magnitude larger than the measurement sensitivity. While the optical lattice potential is mostly common mode between the interferometer arms, a systematic effect due to the optical lattice gradient remains. We suppress this in our experiments by using a relatively large optical lattice mode (830 microns) and by holding the atoms to within 100 microns of the waist. Using these parameters, we estimate that systematic contributions from the lattice gradient can be constrained below the 5 ppm level. We will further suppress these effects with differential measurement methods that move the source mass and atom relative positions.

Quantum technology advances. We have developed several novel technologies in our lab that optimize experiment design and performance. One of the major technical advances necessary to implement the research plans described here is an electromagnet that can operate inside our ultra-high-vacuum chamber while maintaining pressures below 10^{-10} torr (see Figure 2 and [3]). Thermal management of the heat dissipated by the electromagnet in done using a novel configuration of heatpipes, which are copper tubes filled with fluid that use convection to transfer heat. Their thermal transfer efficiency can surpass similarly sized conduction-based heat transfer methods by up to three orders of magnitude. We adapted this technology to in-vacuum use by developing technical methods to braze the heatpipes inside conflat flanges and finding ways to connect them to the electromagnet wire windings that are fully ultra-high vacuum compatible.

This cooling method can continuously dissipate up to 150 Watts of heat with no increase in vacuum pressure below the 10^{-10} torr level. This power level is sufficient to create magnetic field gradients of up to 100 G/cm. In comparison to coils that are placed outside of the vacuum system, the in-vacuum coils are compact and have reduced weight and low power use. In addition, traditional out-of-vacuum coils are often limited by the induced Eddy currents in the vacuum chamber walls. In contrast, the in-vacuum coils enable quick changes in the magnetic field configuration (switching time ~100 us). We will use this design for multiple quantum control stages, e.g, to generate the magnetic field used for evaporative cooling or during atom lensing operations.

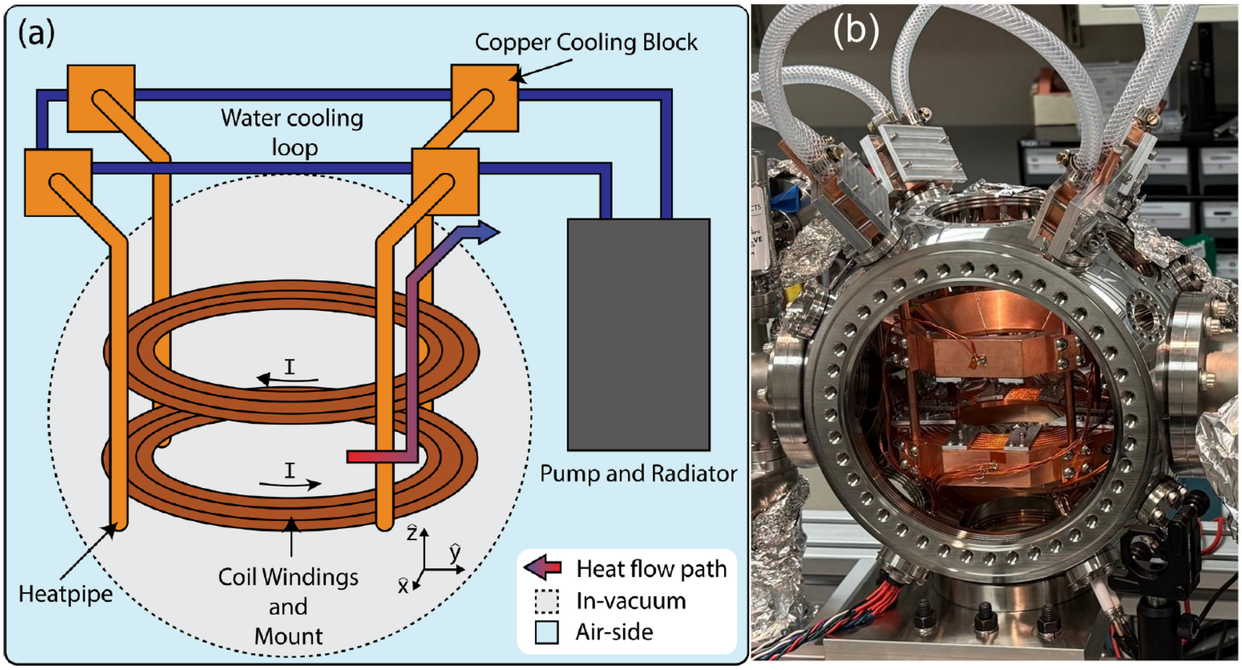

Figure 3. Heatpipe-cooled in-vacuum electromagnet used for quantum control of ultracold atoms, (a) schematic and (b) image in our laboratory [3].

The exploration of the **physics of atomic spatial superpositions held by optical lattices against gravity** will lead to the development of new **quantum control techniques.** These will be applicable to a variety of experiments, including quantum sensors based on optical lattice atomic clocks, quantum simulators of solid-state systems, and quantum information with neutral atoms in optical lattices. Using cavity coupling to generate quantum entanglement within the atomic sample (1) could enable quantum-enhanced sensitivity to new physics and (2) will reveal leading influences and increase robustness of the atomic quantum superposition state to imperfections.

Performing the first precise measurements of G in an OLAI experiment may enable the testing of elusive properties of gravity and new physics such as modified gravity in a completely new experimental system. Utilizing the advantages of high-sensitivity experiments with few atoms in precisely known quantum states that can be precisely positioned with respect to source masses will enable gains in accuracy that push quantum tests of gravitational physics into a new regime.

References

[1] C. D. Panda, M. Tao, J. Egelhoff, M. Ceja, V. Xu, and H. Müller, Coherence limits in lattice atom interferometry at the one-minute scale, Nat. Phys. **20**, 1234 (2024).

[2] C. D. Panda, M. J. Tao, M. Ceja, J. Khoury, G. M. Tino, and H. Müller, Measuring gravitational attraction with a lattice atom interferometer, Nature **631**, 515 (2024).

[3] K. (中曽根ケネス) Nakasone, P. Luna, A. Zhukov, M. Tao, G. Louie, and C. D. Panda, Heatpipe-cooled in-vacuum electromagnet for quantum science experiments, Rev. Sci. Instrum. **96**, 083201 (2025).