Large momentum transfer optics: A means to probe the interplay between gravity and quantum mechanics

Shraddha Agrawal

Department of Physics,
University of Illinois at Urbana-Champaign
Urbana, IL 61801, USA
sa30@illinois.edu

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Abstract

A consistent description of gravity in quantum mechanics and general relativity is becoming increasingly accessible to table-top experiments. In this essay, I introduce the experimental technique of large momentum transfer optics as a means to probe gravity at microscopic scales. I argue, with the help of recent experimental observations, that large momentum transfer optics is the *best* experimental technique to do so. I conclude with possible future directions using large momentum transfer optics.

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Need for low energy experiments to probe quantum gravity

General relativity and quantum mechanics are the pillars of theoretical physics. Both theories have been extensively tested experimentally in different regimes. However, a consistent framework unifying general relativity and quantum mechanics is still elusive. The relevant scale for probing gravitational interactions is set by the Planck mass, M_{pl}, which is of order 10^{15} TeV. Currently, the large hadron collider has the capability to probe the electroweak scale, M_{EW}, which is of order 10 TeV [1]. This 15 orders of magnitude energy disparity is a bottleneck for physicists to experimentally explore quantum gravity.

However, there are low energy, table-top experiments that can test general relativity in both classical and quantum systems. One such class of experiments is atom interferometry, where it has recently become a powerful tool for precision measurements. For example, atom-based interferometry has been used to test the weak equivalence principle, investigate gravity at microscopic levels, and measure space-time curvature [2] [3].

Atom interferometry is conceptually similar to optical interferometry. In both cases, the initial wave is split into two paths using a beam splitter. The two partial waves propagate, until their propagation dynamics are reversed with the help of mirrors. The partial waves accrue a path-dependent phase, which can be measured after the partial waves overlap on a final beam splitter to produce an interference pattern.

In the atomic case, therefore, atoms are natural sensors sensitive to any potentials and forces which might change the interference pattern. The sensitivity of this atom interferometer is set by the atomic de Broglie wavelength which is inversely proportional to the momentum imparted to the atoms by the beam splitter in the interferometer.

The next subsection describes the need for optics that impart large momentum transfer to atoms in detail.

Why large Momentum transfer optics?

Consider the atom-interferometer described above, also called a Mach-Zender interferometer. The normalized atomic populations P_1 and P_2 measured in the two output ports of an atom interferometer depend on the interferometer phase shift $\Delta\phi$ according to [4]-

$$P_1 = \frac{1}{2} + \frac{1}{2}\cos\Delta\phi \tag{1}$$

and

$$P_2 = \frac{1}{2} - \frac{1}{2}\cos\Delta\phi \tag{2}$$

The resulting phase shift of an atom interferometer for a spatially and temporally constant gravitational acceleration g is [5] -

$$\Delta\phi = \frac{mg\Delta z_{max}T}{\hbar} \tag{3}$$

where Δz_{max} is the maximum path separation reached in the interferometer, T, is the pulse spacing, and $\Delta z_{max} T$ is the enclosed space-time area. *The sensitivity of atom interferometers scales as the enclosed space-time area.*

To increase an atom-interferometer's sensitivity, the enclosed space-time must be increased. T can be increased by increasing the pulse spacing [1]. Additionally, by implementing beam splitters that impart more momentum to the atoms, Δz_{max} can be increased.

In the next section, I briefly describe sequential Bragg large momentum transfer optics (SB-LMT), a technique with which a momentum of $102\hbar k$ can be transferred to the atoms.

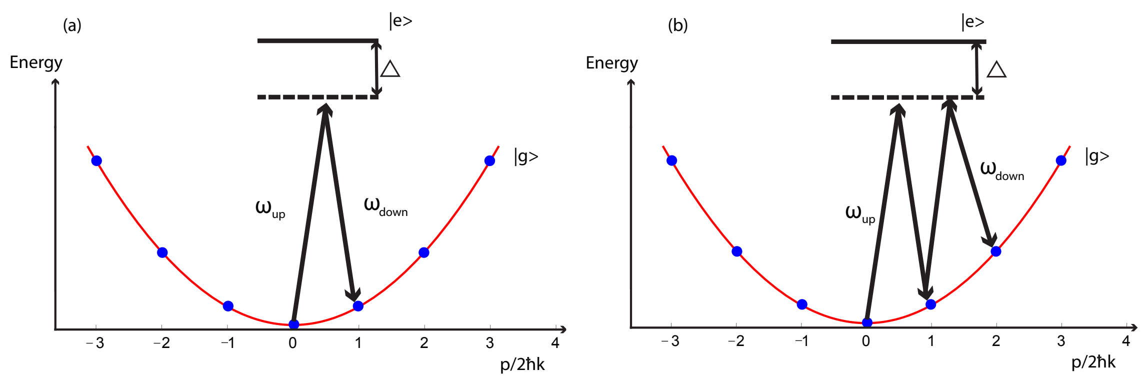

Figure 1: A schematic of Bragg transitions. (a) Atoms undergo a transition via the stimulated exchange of photons between the fields denoted by ω_{up} and ω_{down}. This process leads to a momentum change of $2\hbar k$. (b) Multiphoton Bragg transition that transfers of $4\hbar k$ of momentum. The transition arises from stimulated absorption of two photons from ω_{up} and stimulated emission of two photons into ω_{down}. Image adapted from [5]

SB-LMT optics

Consider a two level system- an atom of mass M with ground state $|g\rangle$ and excited state $|e\rangle$. In the absence of a trap and atomic interactions, $|g\rangle$, exhibits a quadratic dispersion relation (see Figure 1). Now consider a two photon process, in which this two level system is exposed to two counter-propagating beams, denoted by ω_{up} and ω_{down}. The light-matter interaction will change the atomic momenta by $\pm 2\hbar k$, characterized by virtual photon absorption from one field and stimulated emission into another.

Let us say that the atoms in $|g\rangle$ have momentum p_0. We denote the state by $|p_0\rangle$. Upon sequential Bragg transitions, the state changes from $|p_0\rangle \rightarrow |p_0 + 2\hbar k\rangle \rightarrow |p_0 + 4\hbar k\rangle$ and so on.

It is also possible to drive the transition $|p_0\rangle \rightarrow |p_0 + 2n\hbar k\rangle$ via higher order multiphoton Bragg transitions.

[1] The pulse spacing is limited by the time it takes for the atoms to hit the ground. Mark Kasevich's group at Stanford has constructed a 10 m atomic fountain to maximixe T [6]

Currently, largest space-time area atom interferometer has been realized by Mark Kasevich's group at Stanford, where they have used sequential multiphoton Bragg optics to demonstrate an atom interferometer with momentum splittings up to $102\hbar k$ [7]. With SB-LMT optics, $\Delta z_{max} = n(\hbar k/m)T$, where k is the laser wavenumber, n is the number of photon recoils ($\hbar k$) transferred to the atoms by the beam splitter, and T is the interrogation time. For a total momentum transfer of $90\hbar k$, on a timescale of $T = 1s$, a quantum superposition state over 54 cm can be realized [8]!

Experimental set-ups involving SB-LMT optics has been instrumental in several experiments that probe gravity in quantum mechanical systems [9] [10][11].

Examples of experiments on gravity in quantum mechanical systems

The gravitational Aharanov-Bohm phase

It has been shown that a time-dependent gravitational potential can induce a non-zero phase shift between the two arms of an interferometer, even in the absence of any forces along the atomic trajectories [4]. This phase is reminiscent of an Aharonov-Bohm phase, the phase accrued by charged particles in the presence of electromagnetic potential even when the electric field vanishes.

This phase shift, ϕ_{AB}, is given by the action difference ΔS between the two arms [11]-

$$\phi_{AB} = \frac{\Delta S}{\hbar} = \frac{m}{\hbar}\int [V(x_1,t) - V(x_2,t)]dt \tag{4}$$

Chris Overstreet et al reported the measurement of a gravitational Aharonov-Bohm phase [11]. A key element in the success of this experiment is creating large atomic superpositions coupled with long time atom interferometry. Prior experiments were not sensitive to measure ϕ_{AB} because $\Delta S \approx 0$ for small wavepacket separations in interferometers.

Qualitatively, since gravity is a non-local force, non-local tests must be performed to observe gravitational effects. In the experiment performed by Overstreet et al, the relevant length scales are the wave packet separation and the length scale of the gravitational potential. Therefore, in order for the experiment to be non-local, the wave packet separation has to be larger than the distance between the source mass and the interferometer arms.

In their experiment, Overstreet et al employ a wave packet separation of 25 cm with the help of SB-LMT optics, while the distance of closest approach between the source mass and an interferometer arm is 7.5 cm.

Test of the weak equivalence principle

All quantum mechanical systems are associated with an energy uncertainty $\Delta E \Delta t \sim \hbar$. Therefore, there is a strong reason to believe that the weak equivalence principle is violated in quantum mechanics, as the gravitational and inertial masses may fluctuate as well.

Violation of the weak equivalence principle (WEP) is quantified by the Eötvös parameter-

$$\eta_{A-B} = 2\frac{|a_A - a_B|}{|a_A + a_B|} \tag{5}$$

where a_A and a_B are the free fall accelerations of two test bodies A and B, respectively.

The WEP has been tested in microscopic objects with remarkable accuracy [12][13][14]. However, there is no inherent "quantumness" in some of the the experiments mentioned above. For example, the WEP violation tests conducted using different atomic species or different isotopes, are not qualitatively different from the WEP violation tests conducted with classical macroscopic objects such as torsion balances.

In the quantum mechanical picture, the mass-energy operators can be written as [9] -

$$\hat{M}_k = m_k \hat{I} + \frac{\hat{H}_k}{c^2} \tag{6}$$

where k=R,I,G refers to the rest, inertial and gravitational masses, respectively, m_k is the mass of the system when the internal energy is in its lowest energy eigenstate, H_k is the internal energy operator for k=R,I,G.

In this picture, the WEP requires $\hat{M}_I = \hat{M}_G$. The operator $\hat{M}_I \hat{M}_G^{-1}$, can be represented to the lowest order in $1/c^2$ by a Hermitian operator. In the subspace spanned by the $|1\rangle$ and $|2\rangle$, the eigenstates of the internal energy operator $\hat{H}_I$, $\hat{M}_I \hat{M}_G^{-1}$ is a 2×2 matrix. For the WEP, the diagonal elements must be equal while the off-diagonal elements must vanish. This idea differentiates between the gravitational motion of different internal energy states and their *superpositions*.

To the address the WEP in the regime of quantum mechanics, Rosi *et al.* [9] measure the Eötvös parameter of free falling ^{87}Rb atoms prepared in a *coherent superposition* of the internal states $|1\rangle = |F=1, m_F=0\rangle$ and $|2\rangle = |F=2, m_F=0\rangle$.

This experiment was implemented using multiphoton Bragg transitions. The measured Eötvös parameter for states $|1\rangle$ and $|2\rangle$ was reported to be $(1.0 \pm 1.4) \times 10^{-9}$ while the off diagonal element of $\hat{M}_I \hat{M}_G^{-1}$ was reported to have an upper bound of 5×10^{-8}.

A comparison of atom interferometry with other experiments

Violations of the equivalence principle (EP) are low energy predictions of various quantum gravity models [19]. To compare the usefulness of different techniques in atom interferometry for probing gravity in quantum mechanics, I choose the Eötvös parameter. The Eötvös parameter is a good quantitative parameter because it indicates the sensitivity of different experiments, and is reported by most state-of-the-art interferometry experiments to constrain EP violations. It also quantifies the WEP.

Figure 2 shows a comparison of measurements of the Eötvös parameter in different atom interferometry experiments. While the highest sensitivities achieved in torsion experiments [20] and MICROSCOPE [21] are about 10^{-13} and 10^{-14} respectively, in atom interferometry experiments, SB-LMT optics based interferometry is particularly useful for exploring gravity in quantum mechanics.

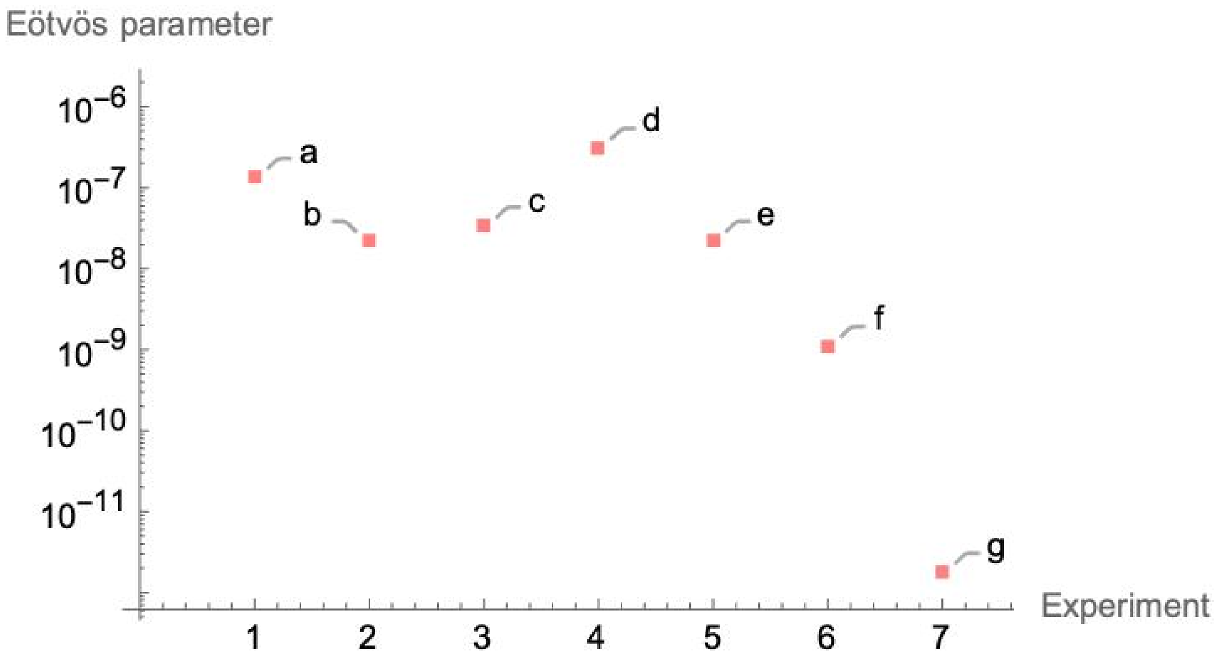

Figure 2: Figure 2 plots the measured **Eötvös parameter** of different experiments labelled (a) through (g). (a) Atom-interferometer experiment based on effective absorption gratings of light (2004) [15]. (b) Differential measurement of the Bloch frequency for two isotopes of Strontium atoms (2014) [16]. (c) Raman-type interferometer measurement for ^{87}Rb and ^{39}K (2014) [12]. (d) Four-wave double-diffraction Raman transition scheme for two isotopes of Rubidium (2015) [17]. (e) Gravity comparision between two m_F levels of ^{8}7Rb using a Mach-Zender atom interferometer (2016) [18]. (f) **Bragg pulse interferometer**, implementing a multi-photon higher order Bragg transition corresponding to a momentum splitting of $6\hbar k$ (2017) [9]. (g) describes an **SB-LMT beam-splitter** measurement with momentum splittings of $102\hbar k$(2011) [7]

In atom interferometry experiments, the best sensitivity to the Eötvös parameter is obtained using SB-LMT optics.

What's next?

Among all the matter wave interference experiments, SB-LMT optics has achieved the highest sensitivity to the WEP violation.

The sensitivity can be enhanced in microgravity environments, because vibrations and non-gravitational effects can be reduced to very low levels. Moreover, longer interrogation times, T, can be achieved when both atoms and the platform are in free fall. The sensitivity of the atom-based interferometers scales as T^2, and the longer interrogation times, along with low noise levels, show promise for WEP tests at the 10^{-15} level [2].

Another quantum mechanical advantage is entanglement. Entangled atoms in matter-wave interferometry experiments using SB-LMT optics serve two purposes. The phase difference accrued between different arms of an interferometer encodes the physical quantity (e.g. acceleration, time) associated with the measurement. For uncorrelated ensembles, the uncertainty in this phase measurement scales as $\Delta\phi = 1/\sqrt{N}$, where N is the particle number. However, for entangled particles, the uncertainty in the phase measurement scales as $1/N$. Since the phases associated with gravitational acceleration depend on the gravitational constant G, using entangled atoms can enable more precise measurements of G.

In addition to more sensitive phase measurements, using entangled particles pushes these atom interferometry experiments into a truly quantum mechanical regime, since entanglement has no classical explanation or analogue. For example, large momentum transfer machinery with entangled atoms can be used to test the WEP. Another interesting case to pursue might be the measurement of gravitational force between entangled particles using SB-LMT optics.

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References

[1] B. A. Dobrescu. “LHC probes of the 10 TeV scale”. In: *arXiv preprint arXiv:1912.13155* (2019).

[2] G. Tino et al. “Precision gravity tests and the Einstein equivalence principle”. In: *Progress in Particle and Nuclear Physics* 112 (2020), p. 103772.

[3] M. Jaffe and H. Müller. “Measuring the Tidal Force on a Particle’s Matter Wave”. In: *Physics* 10 (2017), p. 47.

[4] C. Overstreet. *Atom-Interferometric Test of the Equivalence Principle and Observation of a Quantum System in Curved Spacetime*. Stanford University, 2020.

[5] T. Kovachy. *New techniques for precision atom interferometry and applications to fundamental tests of gravity and of quantum mechanics*. Stanford University, 2016.

[6] A. Sugarbaker. *Atom interferometry in a 10 m fountain*. Stanford University, 2014.

[7] S.-w. Chiow et al. “102 $\hbar$ k large area atom interferometers”. In: *Physical review letters* 107.13 (2011), p. 130403.

[8] T. Kovachy et al. “Quantum superposition at the half-metre scale”. In: *Nature* 528.7583 (2015), pp. 530–533.

[9] G. Rosi et al. “Quantum test of the equivalence principle for atoms in coherent superposition of internal energy states”. In: *Nature communications* 8.1 (2017), pp. 1–6.

[10] P. Asenbaum et al. “Phase shift in an atom interferometer due to spacetime curvature across its wave function”. In: *Physical review letters* 118.18 (2017), p. 183602.

[11] C. Overstreet et al. “Observation of a gravitational Aharonov-Bohm effect”. In: *Science* 375.6577 (2022), pp. 226–229.

[12] D. Schlippert et al. “Quantum test of the universality of free fall”. In: *Physical Review Letters* 112.20 (2014), p. 203002.

[13] F. Witteborn and W. Fairbank. “Experimental comparison of the gravitational force on freely falling electrons and metallic electrons”. In: *Physical Review Letters* 19.18 (1967), p. 1049.

[14] U. Bonse and T. Wroblewski. “Measurement of neutron quantum interference in noninertial frames”. In: *Physical Review Letters* 51.16 (1983), p. 1401.

[15] S. Fray et al. “Atomic interferometer with amplitude gratings of light and its applications to atom based tests of the equivalence principle”. In: *Physical Review Letters* 93.24 (2004), p. 240404.

[16] M. G. Tarallo et al. “Test of Einstein equivalence principle for 0-spin and half-integer-spin atoms: search for spin-gravity coupling effects”. In: *Physical review letters* 113.2 (2014), p. 023005.

[17] L. Zhou et al. “Test of equivalence principle at 1 0- 8 level by a dual-species double-diffraction Raman atom interferometer”. In: *Physical review letters* 115.1 (2015), p. 013004.

[18] X.-C. Duan et al. “Test of the universality of free fall with atoms in different spin orientations”. In: *Physical Review Letters* 117.2 (2016), p. 023001.

[19] V. A. Kosteleckỳ. “Gravity, Lorentz violation, and the standard model”. In: *Physical Review D* 69.10 (2004), p. 105009.

[20] T. A. Wagner et al. “Torsion-balance tests of the weak equivalence principle”. In: *Classical and Quantum Gravity* 29.18 (2012), p. 184002.

[21] P. Touboul et al. “MICROSCOPE mission: first results of a space test of the equivalence principle”. In: *Physical review letters* 119.23 (2017), p. 231101.