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Testing the Quantum Coherent Behaviour of Gravity

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Although quantum gravity is a highly pursued research topic, the more basic question of whether gravity is quantum has not yet been answered. Here we present a table-top experiment, feasible with forseeable advances in technology, which can demonstrate that the Newtonian field from an object is a bonafide quantum entity. This is demonstrated through the development of a verifiable entanglement between two matter wave interferometers with mesoscopic objects as entanglement between systems which are not directly interacting, can only be mediated by a quantum system.

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1. Introduction

In this contribution, we are going to discuss our recent proposal for testing the quantum nature of gravity in a table-top experiment [1]. While the quantization of gravity is intensively pursued, and an unambiguous methodology to quantize gravity exists in the low energy limit, the lack of empirical evidence has lead to the question of whether gravity is a quantum entity. For example, it is well established that the Newtonian field, with its characteristic $\sim \frac{1}{r}$ dependence can be produced through the exchange of virtual (offshell) gravitons [2] between two objects. However, from existing experiments, such as the Newtonian force between two objects, it is not possible to establish whether the field is quantum or classical. Indeed even the necessity of quantum gravity can be questioned as a purely classical gravitational field, with action modified, can alleviate many of the oft-cited necessities for quantum gravity [3]. There are also hitherto untested mechanisms to make quantum matter consistent with classical gravity [4, 5, 6, 7, 8, 9], making it imperative to ask whether gravity is quantum.

Here we show that we can exploit a principle from quantum information theory, namely that entanglement cannot be created by local operations and classical communications (LOCC) [10] to show that gravity is indeed is a quantum entity. We essentially propose a feasible way of creating quantum entanglement between two masses through their gravitational interaction. Witnessing such gravitationally mediated entanglement tests the quantum nature of gravity *only* if we make two *crucial* (but perfectly consistent with our current understanding of the world) assumptions: (a) the gravitational interaction between two masses is "mediated" by a field (in other words, it is *not* a direct interaction-at-a-distance), (b) the validity of a central principle of quantum information theory: entanglement between two systems *cannot* be created by Local Operatons and Classical Communication (LOCC) [10]. That a classical entity going between two quantum objects cannot entangle them has also been shown in Refs.[11, 12]. Under this principle, since gravity conveys entanglement between separated masses, it serves as a quantum communication channel, and any quantum communication channel must involve quantum entities travelling between parties (in this case the parties are the masses and the agent going between them is gravity).

We first consider a schematic version that clarifies how the states of two neutral test masses m_1 and m_2, each held in a superposition of two spatially separated states $|L\rangle$ and $|R\rangle$ as shown in Fig.1(a) for a time τ, get entangled. Imagine the centres of $|L\rangle$ and $|R\rangle$ to be separated by a distance Δx, while each of the states $|L\rangle$ and $|R\rangle$ are localized wavepackets so that we can assume $\langle L|R\rangle = 0$. There is a separation d between the centres of the superpositions as shown in Fig.1(a) so that even for the closest approach of the masses $(d-\Delta x)$, the short-range Casimir-Polder force is negligible (This means that the allowed distance of closest approach is $d-\Delta x \approx 200\mu$m, which is the distance at which the Casimir-Polder interaction ~ 0.1 of the gravitational potential, where, to take an explicit material, we have assumed $R \sim 1\mu$m radius diamond microspheres with dielectric constant $\varepsilon \sim 5.7$ [1]). Under these circumstances, the time evolution of the joint state of the two masses is purely due to their mutual gravitational interaction, and given by

$$|\Psi(t=0)\rangle_{12} = \frac{1}{\sqrt{2}}(|L\rangle_1 + |R\rangle_1)\frac{1}{\sqrt{2}}(|L\rangle_2 + |R\rangle_2) \tag{1.1}$$

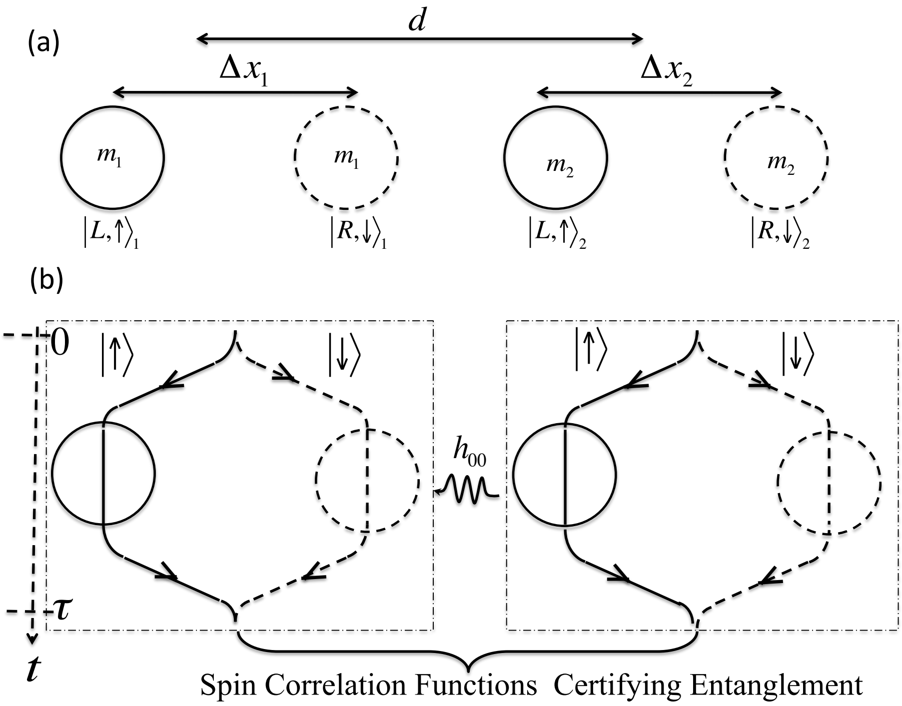

Figure 1: (a) Two test masses held adjacently in superposition of spatially localized states $|L\rangle$ and $|R\rangle$. (b) Adjacent Stern-Gerlach interferometers are prepared in states $|L,\uparrow\rangle_j + |R,\downarrow\rangle_j$ $(j = 1,2)$. Evolution under mutual gravitational interaction for a time τ entangles the test masses by imparting appropriate phases to the components of the superposition. This entanglement can only result from the exchange of quantum entities – if all interactions aside gravity are absent, then this must be the gravitational field (labelled h_{00} where $h_{\mu\nu}$ are weak perturbations on the flat space-time metric $\eta_{\mu\nu}$). This entanglement between test masses evidencing quantized gravity can be verified by completing each interferometer and measuring spin correlations.

$$\rightarrow |\Psi(t=\tau)\rangle_{12} = \frac{e^{i\phi}}{\sqrt{2}}\{|L\rangle_1 \frac{1}{\sqrt{2}}(|L\rangle_2 + e^{i\Delta\phi_{LR}}|R\rangle_2) + |R\rangle_1 \frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|L\rangle_2 + |R\rangle_2)\} \tag{1.2}$$

where $\Delta\phi_{RL} = \phi_{RL} - \phi, \Delta\phi_{LR} = \phi_{LR} - \phi$, and

$$\phi_{RL} \sim \frac{Gm_1 m_2 \tau}{\hbar(d-\Delta x)},\ \phi_{LR} \sim \frac{Gm_1 m_2 \tau}{\hbar(d+\Delta x)},\ \phi \sim \frac{Gm_1 m_2 \tau}{\hbar d}.$$

One can now think of each mass as an effective “orbital qubit" with spatial states $|L\rangle$ and $|R\rangle$, which we can call orbital states. As long as $\frac{1}{\sqrt{2}}(|L\rangle_2 + e^{i\Delta\phi_{LR}}|R\rangle_2)$ and $\frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|L\rangle_2 + |R\rangle_2)$ are not the *same* state (which is very generic, happens for any $\Delta\phi_{LR} + \Delta\phi_{RL} \neq 2n\pi$, with integral n), it is clear that the state $|\Psi(t=\tau)\rangle_{12}$ cannot be factorized and is thereby an entangled state of the two orbital qubits. Note that we can get

$$\phi_{RL} \sim \frac{Gm_1 m_2 \tau}{\hbar(d-\Delta x)} \sim O(1) \tag{1.3}$$

if the duration for which we can hold the superposition without decoherence is $\tau \sim 2$s. Such a significant phase accumulation leads to a significant entanglement between the masses as the entanglement increases monotonically over $\Delta\phi_{LR} + \Delta\phi_{RL}$ evolving from 0 to π and reaches maxiaml value for π. In practice, it is very difficult to witness directly the entanglement between the dichotomized spatial orbital degrees of freedom as generated above as, for that, one will need to measure the spatial degrees of freedom in more than one spatial bases (which involves constructing ideal two port beam-splitters for massive objects). We next show how we naturally solve this problem by resorting to a modified version of the Stern-Gerlach (SG) interferometry which has recently been achieved with neutral atoms [13], and proposed for freely propagating nano-crystals with embedded spins [14].

The SG interferometry [cf. Fig. 1(b)] includes the following three steps on a neutral mass with an embedded electronic spin, a very low internal crystal temperature (77 K) – to prevent Black-body photons from decohering the superposition, and falling in a vacuum under very low ambient pressure (10^{-15}Pa) to prevent atomic collisions from decohering the superposition:

Step 1: A spin dependent spatial splitting of the centre of mass (COM) state of a test mass m_j in an inhomogeneous magnetic field depicted by the evolution:

$$|C\rangle_j \frac{1}{\sqrt{2}}(|\uparrow\rangle_j + |\downarrow\rangle_j) \rightarrow \frac{1}{\sqrt{2}}(|L,\uparrow\rangle_j + |R,\downarrow\rangle_j), \tag{1.4}$$

where $|C\rangle$ is the initial localized state of m_j at the centre of the axis of the SG apparatus and $|L\rangle$ and $|R\rangle$ are separated states localized on its opposite sides along the axis (these are qualitatively the same ones as shown in Fig.1). For a micro-object of mass $m_j \sim 10^{-14}$ kg, freely falling in an uniform magnetic field gradient in the horizontal direction of $\sim 10^6$ T m^{-1} [14] for a time $\tau_{acc} \sim 500$ ms (with a suitable spin flip at half the time, so that the mass comes to a stop at time τ_{acc}), the separation $\Delta x \sim 250\mu$m between states $|L,\uparrow\rangle_j$ and $|R,\downarrow\rangle_j$ can be achieved.

Step 2: "Holding" the coherent superposition created above (Eq.(1.4) for a time τ (Consider the magnetic field of the SG effectively switched off for a duration τ). This is accomplished by swapping the spin state from electronic spins to nuclear spins so that effectively the magnetic field is not seen any more by the spin and it stops accelerating/deccelerating and falls freely.

Step 3: The third and final step brings back the superposition through the unitary transformations

$$|L,\uparrow\rangle_j \rightarrow |C,\uparrow\rangle_j,\ |R,\downarrow\rangle_j \rightarrow |C,\downarrow\rangle_j, \tag{1.5}$$

which is, essentially, a backwards running of step 1).

For our scheme, two such SG interferometers with neutral test masses m_1 and m_2 operate in parallel while being separated by about $d \sim 450$ μm so as not to have a significant Casimir-Polder interaction. Moreover, for simplicity, we assume temporarily consider the accumulation of a non-gravitational phase solely during the step 2 of the SG interferometry (by this way we are only underestimating the phase that results in entanglement, not overestimating it). Due to the Newtonian interaction of the masses, the joint state of the two test masses evolves exactly as in Eq.(1.1)-Eq.(1.2) with the orbital qubit states $|L\rangle_j$ and $|R\rangle_j$ replaced by “spin-orbital" qubit states $|L,\uparrow\rangle_j$ and $|R,\downarrow\rangle_j$. When we follow-up the evolution of Eq.(1.2) of spin-orbital qubits with the step 3 of Eq.(1.5), then we obtain the state at the end of the SG interferometry to be

$$\begin{aligned}|\Psi(t=t_{End})\rangle_{12} = & \frac{1}{\sqrt{2}}\{|\uparrow\rangle_1 \frac{1}{\sqrt{2}}(|\uparrow\rangle_2 + e^{i\Delta\phi_{LR}}|\downarrow\rangle_2) \\ & + |\downarrow\rangle_1 \frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|\uparrow\rangle_2 + |\downarrow\rangle_2)\}|C\rangle_1|C\rangle_2,\end{aligned}$$

where the unimportant overall phase factor outside the state has been omitted. The above is manifestly an entangled state of the spins of the two test masses. It can be verified by measuring the spin correlations in two complementary bases in order to estimate as entanglement witness such as $\mathscr{W} = |\langle\sigma_x^{(1)} \otimes \sigma_z^{(2)}\rangle + \langle\sigma_y^{(1)} \otimes \sigma_y^{(2)}\rangle|$. If $\mathscr{W}$ is found to exceed unity then the state is proven to be entangled, and, thereby, the mediator, the gravitational field, a quantum entity.

While gravity is one of the fundamental forces, its weakness has made it difficult to test theories on its nature. In particular it is important to answer the question, "is gravity a quantum entity?" Here, based on the principle that classical mediators *cannot* entangle [10], we have discussed an idea to solve this problem: to observe the entanglement of two test masses to ascertain whether the gravitational field is a quantum entity. Moreover, the prominence of our effect stems from a very simple fact: a Planck's constant in the denominator fighting with the Gravitational constant in the numerator of a relevant phase factor. The prescriptions we have provided for overcoming the challenges (more details in the supplementary materials of Ref.[1]) will set out a roadmap towards quantum gravity experiments and could have other beneficial spin-offs on the way, such as the measurement of the Newtonian potential for microspheres [15] or compact meter-scale detectors for low frequency gravitational waves [16].

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