Nano-particle Matter-Wave Interferometry for Ultra-Sensitive Rotation Sensing and Test of Quantum Gravity

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In this presentation, we will describe a technique for realizing a matter-wave Mach-Zehnder Interferometer (MZI) for a diamond nano-particle containing a single NV color center, using the Stern-Gerlach process, for ultra-sensitive rotation sensing, and test of quantum gravity. Briefly, the process works as follows. The nano-particle is first placed in an optical dipole force trap, and cooled down to the ground state of its center of mass motion. An optical push beam is used to launch the particle upward. The NV color center is initially prepared in the spin-up state. A $\pi/2$ pulse is applied to rotate the NV center to an equal super-position of the spin-up and spin-down states. A magnetic field with a big gradient is turned on, pushing the spin-up and the spin-down state to opposite directions horizontally. A π pulse is applied to flip the spin. After the spin is flipped, the two states of the particle begin to decelerate horizontally. When the velocities of the two states decrease to zero horizontally, the magnetic field is turned off. After some propagation time, another magnetic field with a matching gradient is turned on, pushing the two states towards each other. A pi pulse is applied to flip the spin. After the spin is flipped, the two states begin to decelerate horizontally. When the velocities of the two states decrease to zero horizontally, they also overlap. A $\pi/2$ pulse is applied to induce interference. At the end of the process, a probe beam is applied to detect the state of the NV center. A typical set of parameters for the process are as follows. The mass of the particle is 10 pico-gram, the gradient of the magnetic field is a Tesla per micron, the total evolution time is 3.5 s, and the separation between the two arms is 0.25 mm.

Such an MZI can serve two purposes. First, it can be used to realize a gyroscope that is far more sensitive than the best atom interferometric gyroscope, as well as the best of any type of gyroscope demonstrated to date. This is because the sensitivity of a matter wave gyroscope is proportional to the Compton frequency of the particle, given by its relativistic rest energy divided by the Planck's constant. For a single ^{87}Rb atom, this frequency is $\sim 2 \times 10^{25}$ Hz. For a particle with a weight of 10 pico-gram, the Compton frequency is higher by a factor of $\sim 7 \times 10^{10}$. Of course, the sensitivity of an (unsqueezed) atom interferometric MZI scales with root-N, where N is the number of particles. In a typical MZI employing ^{87}Rb atoms, the value of N is $\sim 10^6$, while it is unity for a nano-particle based MZI. When this factor is taken into account, the nano-particle MZI would still be more sensitive by a factor of $\sim 7 \times 10^7$, if the areas enclosed are the same.

Second, it can be used to test whether gravity behaves classically or quantum mechanically. If gravity behaves classically, it leads to a modification of the Schroedinger Equation (SE) by adding the gravitational attraction between spatially separated parts of the wavefunction. This is known as the Schroedinger Newton Equation (SNE), originally suggested by Roger Penrose. The free-space evolution of the wave-packet for any particle is modified due to the self-gravitating effect, when compared to the prediction of the conventional SE. For example, consider the case of a Gaussian wave-packet for an electron. SE predicts that it will spread out, due to the fact that free-space is dispersive for matter-wave. However, the self-gravitation effect predicts a force that counters this spread. As such, it is possible to find conditions under which the wave-packet reaches a steady-state size, corresponding to a soliton. However, for a particle such as an electron or an atom, the experimental conditions necessary for testing this effect are experimentally unfeasible currently. On the other hand, the matter-wave MZI with the parameters identified above can produce signals that can be used to discern between the prediction of the SE and the SNE. If the prediction of SNE is found to be correct, it would prove that gravity behaves classically; if not, it would prove that gravity behaves quantum mechanically.

One of the potential concerns about the SNE is that the gravitational interaction between different parts of the wave-function is taken to be instantaneous, which follows from the Newtonian laws of gravity. This leads to thought experiments using entangled states of particles that predict superluminal signaling. We have developed an augmented version of the SNE that eliminates this concern. In this model, the gravitational attraction is modeled using the linear (weak-field) limit of General Relativity (GR). In this limit, the equations of GR become formally identical to those of electro-magnetism. As such, the gravitational potential contains the retardation effect, so that the gravitational force is not felt instantaneously. We have coined the term ”Linearized GR Augmented SE (LIGRASE)” to describe this version of the modified SE. For the matter-wave MZI, the prediction of the LIGRASE is very close to that of the SNE, since the distance scale is very small.

Acknowledgements: This work has been supported in equal parts by the DOD Center of Excellence in Advanced Quantum Sensing under ARO Grant W911NF202076, and the W.M. Keck Foundation Grant AWD00002837.