Neutrons and Gravity

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Neutrons not only fall classically in the gravitational field of the Earth as potatoes and other normal objects do; at certain conditions, they reveal quantum behavior, or even form well-defined gravitational quantum states. Due to the relative simplicity of quantum mechanical rules for solving this problem, we could predict analytically the motion of a neutron in a gravitational field in the vicinity of a reflecting surface. Such a bouncing neutron can have only certain, discrete values of energy. These extremely small energy values turn out to be very sensitive probes to the presence of even tiny extra interactions, in particular those between the neutron and the mirror. Moreover, several emerging fields of research profit from experience and knowledge gained in the recent experimental observation of gravitational quantum states of ultracold neutrons, and extend the developed methods to atoms and anti-atoms, to whispering-gallery effect and other domains, thus providing more and more application for the method. Quantum bouncing particles could play their role in quantum tests of the equivalence principle, in explorations of gravitational properties of antimatter, in searching for new fundamental short-range and other interactions beyond the Standard Model of particle physics, in surface and thin-layer physics, in chemistry, and so on. In this short note we mention results of a few previous years and project nearest developments..

1 Introduction

Results presented in this talk have been published in detailed publications, and related references are given below. More information could also be found in reviews [1,2], (and in references therein), in particular in proceedings of GRANIT workshops [4,5], which take place every fourth "Olympic" year and cover the topics, which are very close to the subject of this short note. Luckily, precisely during the days of the "Rencontres de Moriond 50" conference, our textbook [5] was published, which analyses all relevant topics; therefore we only list the main results briefly, and refer the reader to original publications.

2 Quantum bouncing

A particular feature of a falling quantum particle is that its "fall" depends on its mass. In order words, in contradiction to a naively interpreted classical equivalence principle, the probability

to observe a quantum particle as a function of time and height does depend on the value of the particle mass. This conclusion follows from the fact that the neutron mass(es) cannot be reduced from the corresponding Schrdinger equation $(-\frac{\hbar^2}{2m}\frac{d^2}{dz^2} + Mgz)\varphi(z) = E\varphi(z)$, where $\hbar$ is the reduced Planck constant, m is the inertial mass of the particle, M is the gravitational mass of the particle, g is the gravitational acceleration, $\varphi(z)$ is the wave function, and E is the energy of the particle. In order to estimate the importance of quantum effects, it is useful to introduce two scales: the spatial scale $l_o = \sqrt[3]{\frac{\hbar^2}{2mMg}}$ and the energy scale $\varepsilon - 0 = \sqrt[3]{\frac{\hbar^2 M^2 g^2}{2m}}$.

For a particle with the mass equal to that of neutron, hydrogen or anti-hydrogen atom, these values are equal to 6μ and $0.6peV$ respectively. As far the raising height of such a particle in the gravitational field above a mirror is approaching 6μ, or as far as the energy of such a particle is approaching $0.6peV$, quantum effects could not be ignored. In the limit of minimum raising heights (energies) the particle is found in pure gravitational quantum states. An evident equation $t_0 = \frac{\hbar}{\varepsilon_0} = \sqrt[3]{\frac{2m\hbar}{M^2g^2}}$ relates the energy scale to the time scale; it is the time interval needed to form a low quantum state. Another relation $T_0 = \frac{2}{3k}\varepsilon 0$, where k is the Boltzmann constant, allows us to estimate that the effective temperature T_0 of such a particle is equal $4.6nK$, much lower than the temperature of a macroscopic experimental setup you could achieve!

3 Observations

Gravitational quantum states of neutrons [6,7,8] were observed experimentally [9,10,11,12] at ILL; analogous states of anti-hydrogen atoms [13,14,15] are going to be observed by GBAR collaboration in CERN [16,17,18]. For a much lighter particle, say positronium, the length scale will be much larger and the energy scale will be much smaller [19]; in contrast, for heavier particles, like heavier atoms or nanoparticles, energies are larger and distances are smaller [20]. We consider theoretically a variety of such options, and concluded that corresponding experiments are not completely unrealistic. Although a gravitational field provides an extraordinary stable wall for the potential well, which forms quantum states [21], it is not automatically the case for the opposite wall of the quantum well that corresponds to the bottom mirror. In order to make an experiment realistic, the bottom mirror should represent a uniform potential barrier with no internal structure, and the particles should reflect elastically from the mirror. We selected ultracold neutrons (UCNs) [22,23,24] for first experiments, because the mentioned conditions are met for UCNs with good accuracy. This is so essentially due to the fact the UCN wavelengths are much larger than interatomic distances, and thus UCNs interact coherently with many atoms (nuclei) simultaneously, like with a uniform mean repulsive potential wall [25]. However, UCNs seem not to be the only object for observing gravitational quantum states, because many particles with sufficiently large wavelength would reflect elastically from the surface due to so-called quantum reflection [26,27,28,29]; in fact, counterintuitively, an attractive van der Waals/Casimir-Polder potential repulses an atom because its range is shorter than the atom wavelength – just as it is the case in a simple quantum-mechanical problem of the reflection of a slow particle from a deep and sharp negative potential step. In accordance to the equivalence principle, motion of a mirror with the acceleration g (in the absence of the gravitational field) is equivalent to its rest in the presence of the gravitational field; both these situations are also equivalent to the whispering-gallery motion of a particle along a concave cylindrical mirror. Such whispering-gallery quantum states were observed with neutrons [30,31,32], and could be also observed with antiatoms [33,34] and atoms in the future.

4 Applications

Soon after the first experimental observation of gravitational quantum states of neutrons, we analyzed some applications and developments in the field, and proposed experimental methods

for their realization [35]. Presently these studies are carried out by several independent research groups, with the aim of application of these phenomena for various problems in fundamental and applied physics. Thus new results on gravitational quantum states of UCNs are available from qBounce [36,37,38] and Tokyo [39,40]collaborations. A dedicated facility GRANIT [41,42] for precision experiments with gravitational quantum states of neutrons and related topics is under commissioning at ILL. Applications of gravitational and whispering-gallery quantum states of neutrons, atoms and antiatoms include constraints for fundamental short-range forces of different nature, exploration of physics beyond the Standard Model, non-commutative quantum mechanics, studies of nature of gravity, precision surface-physics methods, studies of quantum phenomena [43–56], (to give a non-exhaustive list of examples). The absolute precision of measurements is a common key parameter in most cases; an optimum sensitivity to a certain range of characteristic distances is another key parameter in many studies. The application of methods of gravitational and whispering-gallery quantum spectroscopy and interferometry provides in some cases crucial advantages. To give some examples: 1) precision interference methods, long observation time and optimized sensitivity as a function of interaction range provide the best constraints for fundamental short-range forces in the range of ten(s) nanometers [31,50]; 2) precision spectroscopic methods, long observation times localization of antiatoms in space and energy provide smaller systematic effects and lower costs for direct measurements of gravitational fall of antimatter, thus the most precise method under discussion for direct measurements of gravitational fall of antimatter [14,15].

5 Prospects

The method of gravitational quantum states is rapidly gaining attention and support of broad scientific community that is a good sign, which means that the method is powerful and"eas" for implementation. Neutron, and neutron-related, constraints for fundamental short-range forces are steadily improving due to the efforts of different groups using different methods. All these activities are efficient in terms of the ratio results/resources. There are no reasons to doubt that these tendencies will continue for the observable future.

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As real authors of this note are all people participating in the original works overviewed above, and also as they could not be co-authors of this short note, we give full references to their work to underline their names.

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