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Experiments with gravitationally-bound ultracold neutrons at the European Spallation Source ESS

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Abstract

Experiments with gravitationally-bound ultracold neutrons have made substantial progress in the last decade. They have been contributing to answer scientific questions ranging from gravity tests at micron distances, the direct search for dark matter particles as axions, and dark energy realizations. Comparing the present accuracy of around 10^{-14} eV - achieved with a gravity resonance spectroscopy technique - with the by many orders of magnitude expected smaller size of inevitable systematic errors, one may conclude that the present experiments are heavily restricted by the limited strength of today's ultracold neutron (UCN) sources.
We propose to build a dedicated UCN source at the European Spallation Source in order to perform experiments with gravitationally-bound UCN.

Keywords: European Spallation source; ESS; ultracold neutron; gravitationally bound UCN; qBounce; GRANIT.

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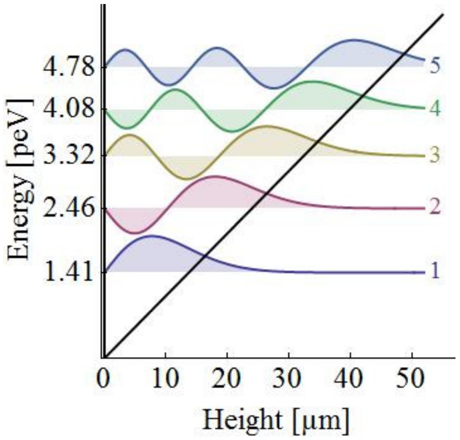

Fig. 1. Quantum States of UCN in the earth's gravity field.

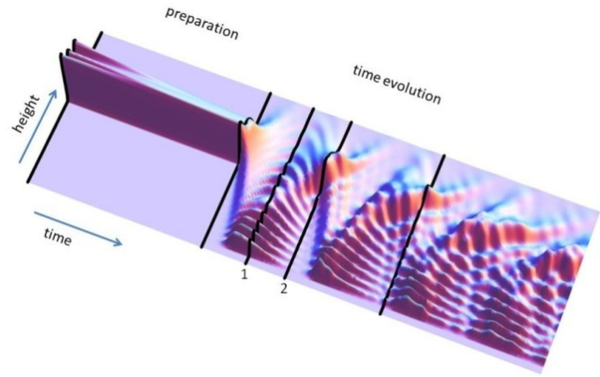

Fig. 2. Time evolution of the Quantum Bouncing Ball. Neutrons are prepared in a wavepacket consisting of the lower states. Dropping this wavepacket leads to a characteristic interference pattern with collapses (1) and revivals (2) of the wavefunction.

1. Introduction

When neutrons become so slow that their corresponding de Broglie-wavelength is many orders of magnitude larger than typical interatomic distances of matter, they totally reflect from surfaces under any angle of incidence. Such ultracold neutrons (UCN) are provided at neutron research facilities all over the world. The instrument PF2 at the Institute Laue-Langevin operates the only source for ultracold neutrons at a continuous high-flux research reactor [1]. Here, three individual experiments may be operated simultaneously by sharing one UCN beam. An additional beam line exists for test experiments. Currently, at many neutron research facilities, superthermal UCN sources are planned, constructed or tested [2-6], most of them for dedicated next generation UCN experiments.

The reason for this high interest in powerful UCN sources is the fact that several UCN experiments contribute or are expected to contribute to answer fundamental questions of physics [7,8]. For example, the most precise measurements of the neutron's lifetime are done in UCN storage experiments [9]. These experiments are complementary to standard in-beam methods. Another UCN experiment, one of the most precise ones in the world, is the search for a non-vanishing electric dipole moment of the free neutron [10] by an application of Ramsey's method of separated oscillating fields.

A relatively new field of interest emerged with the observation of quantum-mechanical bound states of ultracold neutrons in the Earth's gravitational field [11-13]. With their tiny non-equidistant eigenenergies in the pico-eV range and characteristic size of a few tens of microns, these states offer the fascinating possibility to combine tests of Newton's gravity law at short distances with the high precision resonance spectroscopy methods of quantum mechanics.

In the frame of this article, we will argue that a powerful UCN source at the European Spallation Source (ESS) is needed in order to perform experiments using gravitationally bound UCN.

2. Experiments with gravitationally bound UCN

Above a horizontal mirror, UCN form bound states in the linear gravity potential of the earth. The solutions of the corresponding Schrödinger equation are superpositions of Airy functions. The first five eigenfunctions are shown in Fig.1. Their eigenenergies are given only by the reduced Planck's constant $\hbar$, the neutron's mass m, the earth's acceleration g, and the n-th zero ξ_n of the Airy function:

$$E_n = \xi_n \sqrt[3]{\frac{\hbar^2 m g^2}{2}} \tag{1}$$

Because the eigenenergies are non-equidistant, any two eigenstates may be treated as two-level-system. This offers the possibility to apply all measuring techniques of resonance spectroscopy.

2.1. Scientific Impact

Ultracold neutrons build the bridge between gravity experiments and quantum mechanics. This is interesting for various reasons:

Experiments with gravitationally bound UCN might be used to perform weak equivalence principle tests conceptually different from classical tests [14], because the ratio of inertial mass m_i and gravitational mass m_gr does not enter the Schrödinger equation in a trivial, linear way:

$$\left(-\frac{\hbar^2}{2m_\mathrm{i}}\frac{\partial^2}{\partial z^2} + m_\mathrm{gr} g\, z\right)\varphi_n = E_n \varphi_n \tag{2}$$

The time evolution of gravitationally bound quantum states, the Quantum Bouncer [15,16], shows interesting properties, for example collapses and revivals of the wavefunction and probability minima constant in time and space, forming the so-called quantum carpet. A calculation of the time evolution of a quantum bouncing ball with UCN is shown in Fig. 2.

Gravitationally bound UCN might also be used to test Newton's Inverse Square Law of gravity at short distances from 0.1-100 µm. This is done by comparing the measured eigenenergies with their theoretically expected values. High-precision tests make use of resonance spectroscopy techniques such as Rabi's or Ramsey's method. These methods relate energy measurements to determinations of oscillation frequencies, which can be done with unprecedented precision. The measurements can be used to substantiate or exclude any hypothetical gravity-like interaction with an interaction range in the micron-regime. Prominent examples are the search for large extra dimensions [17], supersymmetric large extradimensions [18], and models of quintessence such as chameleon fields [19,20].

Another active field is the search for hypothetical spin-mass couplings mediated for example by axions. Here, experiments using neutrons aim to close the gap in the axion parameter space, the so-called axion window, which is not accessible by other experiments. Experimental limits from measurements using gravitationally bound UCN are published in [21,22].

Another proposal addresses the test of neutron's neutrality [23]. If the neutron would carry a small, but non-zero electric charge, transition frequencies would change in dependence on the direction of an electric field parallel or anti-parallel to gravity.

2.2. State of the Art

In the last decade, gravity experiments with ultracold neutrons have made progress. In 2002, the first observation of such bound states succeeded [11]. In the original work, Nesvizhevsky et. al. measured the transmission of UCNs through an adjustable slit between two neutron mirrors. In this slit, the neutrons form bound states in the gravity potential. The upper mirror was equipped with a rough surface and an absorbing layer leading to a loss mechanism for higher states. The observed transmission showed a sharp decrease below slit widths of approx. 15 µm, which corresponds to the scale of the ground state and cannot be explained classically. This pioneering experiment has triggered a whole bunch of activities: Several groups studied the influence of rough boundary conditions on gravitationally bound quantum states [24-26]. Shortly after the first experiment, detector developments started to measure directly the probability densities of these states using track detectors with an excellent spatial resolution. In first experiments, the incoherent sum of states was measured with a spatial resolution of a few microns [12,13].

In the following, new research groups investigated different scientific directions: The GRANIT collaboration started to build a dedicated spectrometer to study transitions between gravitationally bound quantum states of UCN induced by magnetic gradient fields [26,27]. Recently, they connected the newly-built instrument with their own, dedicated super-thermal UCN source [3]. A collaboration from Japan recently measured ultracold neutrons in the gravitational potential of the earth using a different detector concept of a pixel-detector in combination with a perfect cylinder [28]. The collaboration reports a detector sensitivity of sub-micron resolution. Following the original work published in [11-13], in 2007, the *q*BOUNCE collaboration started to realize a so-called quantum bouncing ball, which is a coherent superposition of gravitationally bound states. For this purpose, track detectors with ^{10}B converter were developed as well as automated read-out procedures [29]. First results are published in [30,31]. Since 2009, resonant transitions between different quantum states can be driven [32,33]. Here, the transitions are induced using mechanical oscillations of the neutron mirrors imposing the boundary conditions.

3. Present limitations, long-term goals and perspectives

Presently, experiments with gravitationally bound UCN are severely restricted by statistics. Typical detector count rates for present GRS experiments at the UCN source PF2 are in the range of 1 count per minute. This is mainly due to the extremely small phase space covered by the experiment. The most precise experiment up to now achieved an energy sensitivity of 10^{-14} eV [33,22] which corresponds to a precision in the percent-range. In comparison, systematic influences independent of the experimental set-up are far below this energy level, see Table 1. Additional, systematic effects due to the quality of the neutron mirrors, the long-term stability of the set-up, the stability of the UCN source, the magnetic-field background, and so forth, are small as well. Presently, in the most precise experiment [22], they are controlled on the 10^{-15} eV-level.

Table 1. Systematic Influences.

Effect	Energy Scale [eV]	$\Delta g/g$
Polarizability Effects (Casimir/Van der Waals-forces)	1×10^{-28}	3×10^{-16}
Tidal Effects	2×10^{-19}	4×10^{-7}
Moon rotation	3×10^{-18}	7×10^{-6}
Coriolis force	$< 4\times10^{-17}$	$< 1\times10^{-4}$

There are several proposals for future experiments with gravitationally bound UCN:
The GRANIT collaboration [26,27] aims at increasing the observation time of neutron quantum states by building a material trap. As compared to a flow through setup where neutrons are passing for about 50 ms, one could get a gain in observation time by several orders of magnitude [26].

The qBounce collaboration is planning to build a Ramsey-type spectrometer [34] to measure transitions of gravitationally bound UCN with a precision of up to 10^{-21} eV. There, the transitions will be driven by mechanical oscillations of the boundary condition. In a first realization, the spectrometer will operate in in-flight mode. The long-term goal is to trap gravitationally bound UCN in order to increase the observation time significantly. This setup can also be used to test for neutron's neutrality [23].

4. Conclusion: Requirements for ESS

In conclusion, experiments with gravitationally-bound UCN have made substantial progress in the last decade. Such experiments may contribute to answer a long list of scientific questions ranging from gravity tests at micron distances, the direct search for dark matter particles or dark energy realizations, weak equivalence principle tests in the quantum regime, and so forth. Comparing the present systematic and statistical accuracy of about 10^{-14} eV (achieved with a gravity resonance spectroscopy technique) with the size of unavoidable systematic effects (see Table 1), we conclude that the present experiments are heavily restricted by the strength of today's UCN sources.

Therefore, we propose to build a dedicated UCN source at the European Spallation Source in order to perform experiments with gravitationally-bound UCN. For in-flight experiments, this source should have the option to be operated continuously. As the neutron velocity enters the resonance width of induced transitions reciprocally, slower UCN are preferred. For storing experiments, a high UCN density is needed at a reasonable rate.

Moreover, precision experiments with gravitationally bound UCN are subject to certain requirements: First, the experimental area should have a length (in-beam direction) of more than 5m and a width of more than 3m. Second, as these experiments are very sensitive to vibrations, a separation of the experimental area from the experiment control area, a stable floor and mechanical decoupling from other experimental zones, are strongly desirable. As for most precision experiments in UCN physics, cleanroom and greyroom conditions in some parts of the experimental area are necessary.

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