Gravity Resonance Spectroscopy and Einstein-Cartan Gravity

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The qBounce experiment offers a new way of looking at gravitation based on quantum interference. An ultracold neutron is reflected in well-defined quantum states in the gravity potential of the Earth by a mirror, which allows to apply the concept of gravity resonance spectroscopy (GRS). This experiment with neutrons gives access to all gravity parameters as the dependences on distance, mass, curvature, energy-momentum as well as on torsion. Here, we concentrate on torsion.

1 Introduction

In the past few years, the qBounce collaboration has developed a new quantum-technique based on ultra-cold neutrons. Due to their quantum nature, neutrons can be manipulated in novel ways for gravity research. For that purpose a gravitational resonance spectroscopy (GRS) technique has been implemented to measure the discrete energy eigenstates of ultra-cold neutrons in the gravity potential of the Earth, see Fig. 1. The energy levels are probed, using neutrons bouncing off a horizontal mirror with increasing accuracy. In 2011 [1], we demonstrated that such a resonance spectroscopy can be realized by a coupling to an external resonator, i.e., a vibrating mirror. In 2014, the first precision measurements of gravitational quantum states with this method were presented. The energy differences between eigenstates shown in Fig. 1 are probed with an energy resolution of 10^{-14} eV. At this level of precision, we are able to provide constraints on any possible gravity-like interaction. Then, we determined experimental limits, first, for a prominent quintessence theory (chameleon fields) and, second, for axions at short distances [2]. Detailed information on an experimental realization of the quantum bouncing ball by measuring the neutron density distribution given by the wave function can be found in [3, 4]. The demonstration of the neutron's quantum states in the gravity potential of the Earth has been published in [5, 6].

It is planned to extend the sensitivity of this method to an energy resolution of 10^{-17}eV, and in the long run to 10^{-21}eV. The resonance spectroscopy method will therefore be extended to a Ramsey-like spectroscopy technique [7].

At this level of sensitivity, the experiment addresses some important problems of particle, nuclear and astrophysics: Three of the most important current theoretical and experimental problems of cosmology and particle physics are i) the current phase (late–time) acceleration of the expansion of the Universe [8, 9, 10], ii) the nature of dark energy, which accounts for about 69 % of the density in the Universe, i.e. $\Omega_\Lambda \approx 0.69$ [11, 12], and iii) the possible existence

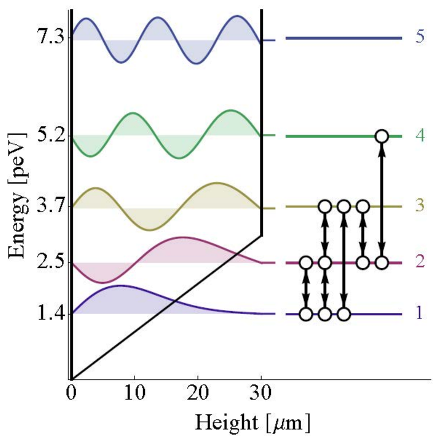

Figure 1: Pico-eV energy eigenstates E_1 to E_5 and Airy-function solutions of the Schrödinger equation for bound ultra-cold neutrons in the linear gravity potential of the Earth. The energy eigenstates are used for gravity resonance spectroscopy and the observed transitions between energy eigenstates are indicated by black arrows.

and nature of torsion, providing a basis for e.g. Einstein–Cartan gravity [13, 14, 15, 16, 17]. One of the simplest explanations for the acceleration of the expansion of the Universe and dark energy is the introduction of the cosmological constant [12], which was introduced for the first time in 1917 by Einstein in his paper "*Cosmological Considerations in the General Theory of Relativity*" [18]. Einstein's original motivation, outdated by Hubble's discovery of the expansion of the Universe soon afterwards, was to obtain a static solution for the Universe. However, modern quantum field theories naturally connect the cosmological constant with the vacuum–energy of quantum fields. To account for the experimentally observed expansion of the Universe consistent with theories of the history of the Universe, the so-called chameleon scalar fields have been introduced. To avoid any conflict with observations at terrestrial and solar system scales, the properties of these new chameleon fields have to depend on the environmental density. Especially, the effective mass of the chameleon field, and therefore the effective range of its interactions, depend on the density of the environment [19, 20]. The chameleon field is a specific realization of *quintessence* [21]. The chameleon field as a source of dark energy has been discussed in [22].

2 Einstein–Cartan Gravity

In 1922 - 1925 Cartan proposed a theory [13, 14], which is an important generalization of Einstein's general theory of relativity [15]. In contrast to general relativity, Einstein–Cartan theory allows space–time to have torsion in addition to curvature, which may in principle couple to a particle spin. For a long time Einstein–Cartan theory was unfamiliar to physicists and did not attract any attention. In the beginning of the '60s of the last century the theory of gravitation with torsion and spin was rediscovered by Kibble [16] and Sciama [17]. From the 1970s on, Einstein–Cartan theory has been intensively investigated [23, 28]. Recently, it has been shown [29] that in the non–relativistic approximation of the Dirac equation in the effective gravitational potential of the Earth, a torsion–matter interaction naturally appears after taking into account also chameleon fields. Such a result demonstrates that chameleon fields can also serve as an origin of space–time torsion. Gravity with torsion, caused by a scalar field, was discussed in detail by Hammond in the review paper [25].

In Einstein–Cartan gravity torsion appears as the antisymmetric part of the affine connection [23]. Thus, torsion is an additional natural geometrical quantity characterizing space–time geometry through spin–matter interactions [23]–[28]. It allows to probe the rotational degrees of freedom of space–time in terrestrial laboratories. Torsion may be described by a third rank tensor $\mathcal{T}_{\alpha\mu\nu}$, which is antisymmetric with respect to last two indices $\mathcal{T}_{\alpha\mu\nu} = -\mathcal{T}_{\alpha\nu\mu}$. It can be represented in the following general form [26]: $\mathcal{T}_{\alpha\mu\nu} = \frac{1}{2}(g_{\alpha\mu}\mathcal{T}_\nu - g_{\alpha\nu}\mathcal{T}_\mu) - \frac{1}{6}\,\varepsilon_{\alpha\mu\nu\beta}\mathcal{A}^\beta + \mathcal{M}_{\alpha\mu\nu}$, where $g_{\alpha\sigma}$ and $\varepsilon_{\alpha\mu\nu\beta}$ are the metric and the Levi–Civita tensor, respectively. It possesses 24 independent degrees of freedom, which are related to a 4–vector $\mathcal{T}_\mu$, a 4–axial–vector $\mathcal{A}_\mu$ and a 16–tensor $\mathcal{M}_{\alpha\mu\nu}$. The tensor degrees of freedom $\mathcal{M}_{\alpha\mu\nu}$ obey the constraints $g^{\alpha\mu}\mathcal{M}_{\alpha\mu\nu} = \varepsilon^{\sigma\alpha\mu\nu}\mathcal{M}_{\alpha\mu\nu} = 0$. A minimal inclusion of torsion in terms of the affine connection leads to torsion–matter interactions, caused by the 4–axial degrees of freedom only. As it has been shown in [24, 26, 27] the effects of the torsion axial–vector degrees of freedom are extremely small. An upper bound of $(10^{-22} - 10^{-18})\,\mathrm{eV}$ has been obtained from the null results on measurements of Lorentz invariance violation. Recent measurements of neutron spin rotation in liquid ^{4}He, carried out by Lehnert *et al.* [30], have lead to the upper bound $|\zeta| < 5.4\times10^{-5}\,\mathrm{eV}$ on a parity violating linear combination of the time–components of the vector $\mathcal{T}_\mu$ and the axial–vector $\mathcal{A}_\mu$. Since the order of the time–component of the torsion axial–vector is about $10^{-18}\,\mathrm{eV}$ [26], an enhancement of the torsion–spin–neutron parity violating interaction can be attributed to a contribution of the time–component of the torsion vector $\mathcal{T}_\mu$. Unfortunately, interactions of both the torsion vector $\mathcal{T}_\mu$ and the torsion tensor $\mathcal{M}_{\alpha\mu\nu}$ degrees of freedom can be introduced only phenomenologically in a non–minimal way [26]. This diminishes a little bit the predicting power of the experimental data [30], since the experimental quantity ζ depends on some set of phenomenological parameters multiplied by the time–components of the torsion vector $\mathcal{T}_0$, and axial–vector, $\mathcal{A}_0$. Nevertheless, the experimental upper bound by Lehnert *et al.* [30] can be accepted as a hint on a possible dominance of the torsion vector degrees of freedom $\mathcal{T}_\mu$ over the torsion axial–vector ones $\mathcal{A}_\mu$.

3 The *q*Bounce Experiment

Concerning chameleon fields, the corresponding solutions of the non-linear equations of motion confined between two mirrors have been obtained in [31] and used in [2] in the extraction of the contribution to the transition frequencies of quantum gravitational states of ultra-cold neutrons (UCNs).

Furthermore, the development of a version of Einstein–Cartan gravity with the torsion vector $\mathcal{T}_\mu$ degrees of freedom introduced in a minimal way becomes meaningful and challenging. Clearly, such an extension of general relativity must not contradict well–known data on the late–time acceleration of the expansion of the Universe and dark energy dynamics. A possible route is using our results [29] and taking the torsion vector components $\mathcal{T}_\mu$ as the gradient of the chameleon field. Such a version of a torsion gravity theory allows to retain all properties of the chameleon field, which are necessary for the explanation of the late–time acceleration of the Universe expansion, dark energy dynamics and the equivalence principle [32] (see also [19, 20]) and to extend them by chameleon–photon and chameleon–electroweak boson interactions, introduced in a minimal way.

For the experimental analysis of these chameleon induced torsion - matter interactions very sensitive experiments are needed, which need to overcome the barrier of extremely small magnitudes of the torsion degrees of freedom. As has been pointed out in [35, 31] and proved

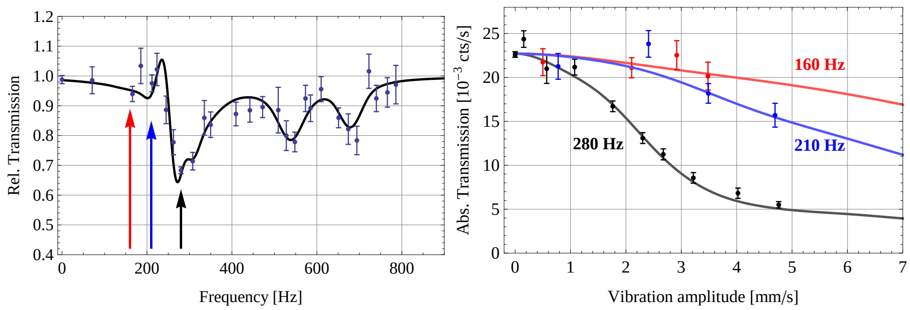

Figure 2: Results for the employed GRS. Left: The transmission curve determined from the neutron count rate behind the mirrors as a function of oscillation frequency showing dips corresponding to the transitions shown in Fig 1. Right: Upon resonance at 280 Hz, the transmission decreases with the oscillation amplitude in contrast to the detuned 160 Hz. Because of the damping, no revival occurs. A detailed description of the experiment can be found in [2].

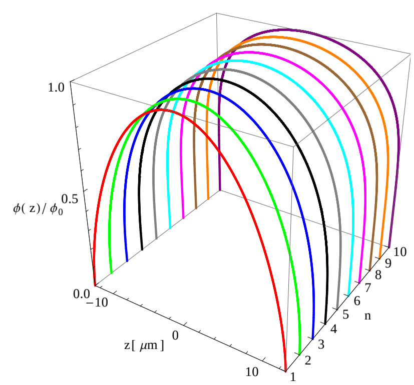

Figure 3: The profiles of the chameleon field, calculated in the strong coupling limit $\beta > 10^5$ in the spatial region $z^2 \leq d^2/4$ for $d = 30.1\,\mu$m and $n \in [1, 10]$ in [31] and used for the extraction of the upper bound of the coupling constant β, i.e. $\beta < 5.8 \times 10^8$ [2].

experimentally in [2], UCNs, bouncing in the gravitational field of the Earth above a mirror and between two mirrors can be a good laboratory for testing chameleon–matter field interactions. The quantum energy scale of UCNs is $\varepsilon = mg\ell_0 = 0.602\,$peV, where m, g and ℓ_0 are the neutron mass, the Newtonian gravitational acceleration [11] and the quantum spatial scale of UCNs such as $\ell_0 = (2mg^2)^{-1/3} = 5.87\,\mu\mathrm{m} = 29.75\,\mathrm{eV}^{-1}$ [2, 7]. In Fig. 2 we plot the transmission curves of the transitions between the quantum states shown in Fig. 1. The extraction of the upper bound of β, i.e. $\beta < 5.8 \times 10^8$, has been performed within chameleon field theory using the Ratra–Peebles potential for the chameleon self–interaction [19, 20, 35, 31]. The profiles of the chameleon field, confined between two mirrors and separated by a distance $d = 30.1\,\mu$m have been calculated in [31] and are shown in Fig. 3.

A precision analysis of the chameleon–matter coupling constant β can be performed by neutron interferometry as proposed by Brax *et al.* [36, 37] and has been realized by Lemmel *et al.* [33]. Best limits on β have been achieved by atom interferometry in [34]

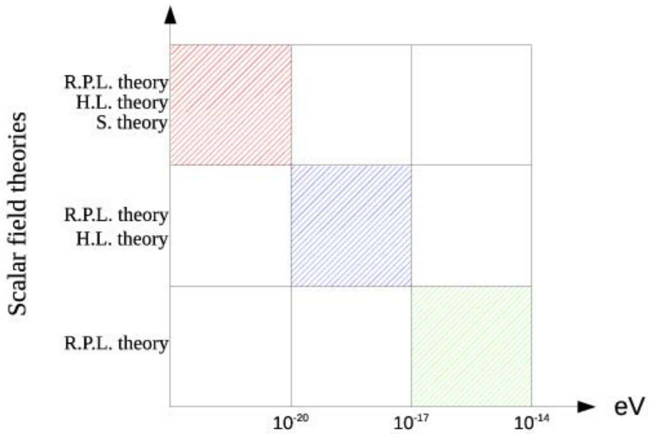

Figure 4: The dependence of the observation of the potential of the self–interaction of scalar (chameleon) field theory on the sensitivity of the experimental data on the transition frequencies of quantum gravitational states of UCNs, measured in qBounce experiments.

As it is well known, the Ratra–Peebles potential is just one possible potential for the self–interaction of scalar fields ϕ. The potential can also be taken in the Higgs–like form [38] (see also [39]) and in the symmetric form [40, 41], respectively. The scalar field with a self–interaction potential, which is symmetric with respect to a transformation $\phi \to -\phi$, is called *symmetron*. As it has been shown in [31], the qBounce experiments with UCNs are able to distinguish the shape of the self–interaction potential of the scalar field. In Fig. 3 we show the dependence of the shape of the self–interaction potential of the scalar field on the sensitivity of the experimental data of the qBounce experiments. One may see that the region of accuracies $\Delta E = (10^{-17} - 10^{-14})\,\mathrm{eV}$ is sensitive to the Ratra–Peebles potential only. In turn, the regions of accuracies $\Delta E = (10^{-20} - 10^{-17})\,\mathrm{eV}$ and $\Delta E < 10^{-20}\,\mathrm{eV}$ are sensitive to the scalar field theories with the Higgs–like potential and the symmetron, respectively. The sensitivity of about $\Delta E \sim 10^{-21}\,\mathrm{eV}$ is feasible in the qBounce experiments [7]. Hence, qBounce experiments can be a good tool for measurements of the effective low–energy torsion–spin–matter (neutron) interactions, which can be derived from those obtained in [28]. The use of the qBounce experiments for measurements of torsion–spin–matter (neutron) interactions should be helpful to overcome the barrier of extremely small magnitudes of torsion.

The new method profits from small systematic effects in such systems, mainly due to the fact that in contrast to atoms, the electric polarisability of the neutron is extremely low. Neutrons are also not disturbed by short range electric forces such as van der Waals or Coulomb forces and other polarisability effects such as the Casimir–Polder interaction of UCNs with reflecting mirrors. Together with the neutron neutrality, this provides the key to a sensitivity of several orders of magnitude below the strength of electromagnetism. A search for a non-vanishing charge of the neutron is also possible.

Hence, experimental measurements of the transition frequencies of quantum gravitational states of UCNs in the qBounce experiments [1, 2, 7] and the quantum free fall of UCNs together with the experimental investigations of the phase shifts of the wave functions of slow neutrons in neutron interferometry [33] are very important tools for probing dark energy and theories of torsion gravity [28, 29].

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