Searches for Exotic Short-range Gravity and Weakly Coupled Spin-Dependent Interactions using Slow Neutrons

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The special properties of slow neutrons enable unique types of measurements sensitivite to a variety of exotic weakly-coupled interactions from BSM physics. We describe recent work and future opportunities. This work relies on continued access to neutron sources and instrumentation.

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The special properties of slow neutrons enable unique types of precision measurement. The electrical neutrality of the neutron coupled with its small magnetic moment and very small electric polarizability make it insensitive to many of the electromagnetic backgrounds which can plague experiments that employ test masses made of atoms. The ability of slow neutrons to penetrate macroscopic amounts of matter and to interact in the medium with negligible decoherence allows the quantum amplitudes governing their motion to accumulate large phase shifts which can be sensed with interferometric measurements [1–3]. These features of slow neutron interactions have been exploited in several searches for possible new weakly coupled interactions of various types, including chameleon dark energy fields, light Z' bosons, in-matter gravitational torsion and nonmetricity of spacetime, axion-like particles, and exotic parity-odd interactions [4–17]. This strategy can succeed despite the uncertainties in our knowledge of the neutron-nucleus strong interaction. In the slow neutron regime with $kR \ll 1$ where k is the neutron wave vector and R is the range of the neutron-nucleus strong interaction, neutron-nucleus scattering amplitudes are dominated by s-wave scattering lengths which are accurately measured experimentally. This makes coherent neutron interactions with matter sufficiently insensitive to the complicated details of the strong nucleon-nucleus interaction that one can cleanly interpret and analyze searches for small, exotic effects.

In this brief note we preset neutron searches for exotic gravity as an example. Many theories beyond the Standard Model postulate short-range modifications to gravity which produce deviations of Newton's gravitational potential from a strict $1/r$ dependence. Example speculations include the idea of compact extra dimensions of spacetime accessible only to the gravitational field [18–20] and the idea that gravity might be modified on the length scale of 100 microns corresponding to the scale set by the dark energy density [21]. Many extensions to the Standard Model of particle physics produce weakly coupled, long-range interactions [22, 23]. Certain candidates for dark matter in the sub-GeV mass range can induce Casimir-Polder-type interactions between nucleons [24, 25] with ranges from nuclear to atomic scales.

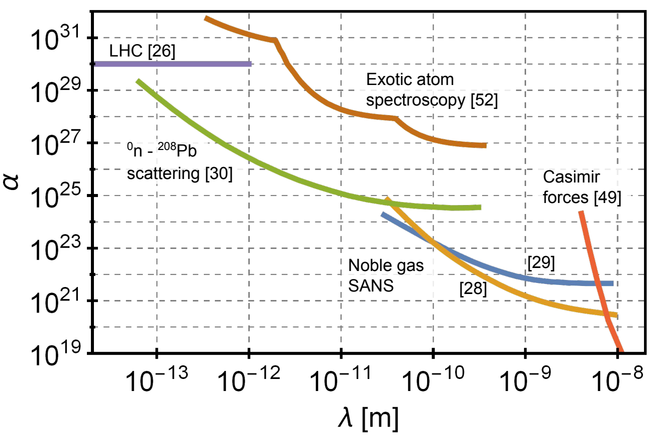

FIG. 1: Limits on the strength and range of short-range gravitational interactions of matter using neutrons and other probes in the $10^{-8} - 10^{-13}$ meter range.

It is common to analyze experiments searching for these modifications [26] using a potential of the form $V'(r) = -\frac{GMm}{r}[1 + \alpha \exp\{(-r/\lambda)\}]$. The best present constraints on α for λ between 10^{-8} and 10^{-13} m come from neutron scattering. Some constraints come from analysis of the neutron energy and A dependence of neutron-nucleus scattering lengths [47] measured to better than 0.1% accuracy for several nuclei. Other experiments have measured the angular distribution of neutrons scattered from noble gases to search for a deviation from that expected in this theoretically calculable system [28, 29]. At shorter distances the best limits come from the measured energy dependence of neutron-nucleus cross sections in lead [4, 30] and from very high-energy forward cross-section measurements at accelerator facilities [31].

The prospects for continued experimental progress are excellent. Ultracold neutrons are employed in gravity

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*Electronic address: `wsnow@indiana.edu` resonance spectroscopy [35, 36], which creates coherent superpositions of bound states of neutrons formed in a potential from the Earth's gravity and a flat mirror. One can drive and resolve resonance transitions using acoustic transducers in a vibrational version of Ramsey spectroscopy. qBOUNCE has successfully conducted proof of principle measurements demonstrating vibrational Rabi spectroscopy [37], and has sought several different types of exotic interactions [12, 17, 38–40] through the influence of interactions sourced by the mirror material on the neutrons [41]. A new qBOUNCE apparatus which implements vibrational Ramsey spectroscopy has seen its first signal [42]. The GRANIT UCN spectrometer [32] at the ILL/Grenoble can conduct precision measurements on UCN gravitational bound states [33] with higher statistics when it is fed by a superfluid-helium-based UCN source [34]. With a bright very-cold neutron (VCN) source one could employ a Lloyd's mirror interferometer [43–45] to look for exotic interaction phase shifts from the mirror surface. Dynamical diffraction in perfect crystals can measure neutron scattering amplitudes at values of q of about an inverse Angstrom and is sensitive to several types of exotic interactions [50, 51]. The angular distribution of neutron scattering from noble gas atoms is sensitive to exotic Yukawa interactions through the q dependence of the scattering form factor and measurements in progress at JPARC promise to better constrain exotic Yukawa interactions with ranges near the Angstrom scale.

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