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Search for spin-dependent macroscopic short-range interactions using neutron spin precession close to a mirror

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ABSTRACT

Free neutrons can be employed as a sensitive probe to search for spin-dependent macroscopic short-range interactions induced by axion-like particles. In this Letter it is proposed to use pseudomagnetic precession of ultracold neutrons propagating close to a massive mirror of a trap. The method should be several orders of magnitude more sensitive than other methods proposed so far.

Spin-dependent short-range interactions may be induced by light, pseudoscalar bosons such as the axion which was proposed to explain why parity (P) and time reversal (T) violating couplings are so small in QCD [1,2]. Axions and axion-like particles [3] would mediate a P- and T-violating interaction between a fermion and the spin of another fermion. The corresponding interaction between a neutron with mass m_n and spin $\frac{1}{2}\hbar\boldsymbol{\sigma}$, and a nucleon at distance $\mathbf{r}$ would be of a "monopole–dipole" type with range λ [4]

$$V(\mathbf{r}) = \frac{\hbar^2 g_S g_P}{8\pi m_n} \mathbf{n}\cdot\boldsymbol{\sigma}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}, \qquad (1)$$

with unitless scalar and pseudoscalar coupling constants g_S and g_P between the fermions and the exchanged boson. $\mathbf{n} = \mathbf{r}/r$ is a unit distance vector from the neutron to the nucleon. Astrophysical and cosmological arguments, based on the observed neutrino signal from the supernova SN1987 and the possible role of axions as dark matter component, suggest that [3], if axions exist, they should have masses within an "axion window" $10\ \mu\text{eV} \lesssim m_A \lesssim 10\ \text{meV}$, corresponding to a range $2\ \text{cm} \gtrsim \lambda \gtrsim 20\ \mu\text{m}$. It is therefore of high current interest to search for axion-like particles in laboratory experiments.

A first limit within the axion window was recently established using gravitationally bound quantum states of the free neutron in a Stern–Gerlach-type experiment [5]. The authors analysed neutron transmission through a slit between an absorber and a horizontal mirror, which probes the shape of the spatial neutron wave function. Spin-dependent short-range forces as in Eq. (1) due to mirror and absorber would modify the transmission as a function of absorber height. In a planned upgrade of the experiment, then involving polarised neutrons, the authors expect a significant improvement of sensitivity [5]. Here a spin precession experiment is proposed that should be several further orders of magnitude more sensitive.

The potential between a free neutron and a plane plate with thickness d and nucleon number density N is obtained by integration of Eq. (1) over the volume of the plate. Denoting by z the coordinate normal to the plate with a neutron reflective surface at $z = 0$, it is given by[1]

$$V(z) = V(0)\left(e^{-|z|/\lambda} - e^{-|z+d|/\lambda}\right)\sigma_z, \quad V(0) = \frac{\hbar^2 N}{4m_n} g_S g_P \lambda. \qquad (2)$$

Since $V(z)$ has the same analytic form as the interaction of the neutron magnetic moment with a magnetic field pointing in z direction, it can be probed by searching for a pseudomagnetic precession of neutrons polarised parallel to the surface of the plate.

A large precession angle may be accumulated for ultracold neutrons (UCN) trapped between two parallel, reflective plates with distance D (also called "mirrors", although specular reflections are

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[1] Eq. (2) holds also inside the mirror. The potential is sizeable only for $|z| \lesssim \lambda$, in contrast to spin-independent short-range interactions, for which the potential attains its maximum value inside the mirror [6].

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not necessary for the arguments given here). Neutrons bouncing forth and back between $z = 0$ and $z = D$ sense the spatial average $\bar{V}$ of the spin-dependent potential $V(z)$. Due to the operator $\mathbf{n} \cdot \boldsymbol{\sigma}$ in Eq. (1) the two plates induce precessions in opposite directions. The net precession angle is therefore proportional to the difference $N_{\text{heavy}} - N_{\text{light}}$ of the mass densities of the plates (for equal plate thicknesses or if for both plates $d \gg \lambda$). $\bar{V}$ is maximized by choosing $N_{\text{heavy}} - N_{\text{light}}$ as large as possible and $d \gg \lambda$, while the negative effect of the light plate can be further reduced if we choose $d_{\text{light}} < \lambda$. Neglecting the influence of the quantum-mechanical boundary conditions on the neutron probability density close to the mirrors, and the contribution due to the light one, we have

$$\bar{V} = \pm \frac{1}{D} \int_0^D V(z)\,\mathrm{d}z = \pm V(0)\frac{\lambda}{D}\left(1 - \mathrm{e}^{-D/\lambda}\right)\left(1 - \mathrm{e}^{-d/\lambda}\right). \tag{3}$$

The signs apply for spin parallel and anti-parallel to the z direction. The corresponding angular frequency of neutron precession is given by $\omega = 2|\bar{V}|/\hbar$. The signs get inverted under inversion of the trap orientation with respect to z, leading to precession in opposite sense. We may thus determine $\bar{V}$ from the difference

$$\omega_{\uparrow} - \omega_{\downarrow} = 4|\bar{V}|/\hbar \tag{4}$$

of angular neutron precession frequencies for the two trap orientations.

To search for such a precession, Ramsey's resonance method applied to trapped ultracold neutrons (UCN) seems particularly well suited. A homogeneous magnetic field **B** applied in z direction induces Larmor precession, to which adds the pseudomagnetic precession with frequency $\omega_{\uparrow}$ or $\omega_{\downarrow}$, depending on the trap orientation with respect to the magnetic field. Ramsey's method is employed in ongoing searches for the electric dipole moment (EDM) of the neutron which have matured to sensitivity beyond 10^{-21} eV for the corresponding spin-dependent potential. In the proposed experiment an EDM Ramsey chamber basically has to be replaced by a mass-asymmetric trap, e.g. a cylindrical trap with a heavy and a light lid.

The counting statistical uncertainty of the determination of $\bar{V}$ from the frequency difference in Eq. (4) is given by (see, e.g. Ref. [7] for the analog EDM search)

$$\sigma(\bar{V}) = \frac{\hbar}{2\alpha T\sqrt{N_{\text{n}}}}, \tag{5}$$

where N_{n} is the total number of UCNs counted in a series of measurement cycles, T is the time of UCN storage per cycle, and α denotes the visibility of the Ramsey fringes. The new interaction will thus be detectable if

$$g_{\text{S}}g_{\text{P}} \geqslant \frac{2m_{\text{n}}}{\alpha T N\hbar\sqrt{N_{\text{n}}}}\frac{D}{\lambda^2}\left(1 - \mathrm{e}^{-D/\lambda}\right)^{-1}\left(1 - \mathrm{e}^{-d/\lambda}\right)^{-1}. \tag{6}$$

For a conservative estimate of the statistical sensitivity we consider employing a trap within an existing EDM apparatus, with parameters $D = 0.1$ m, $T = 100$ s, $\alpha = 0.5$, $N_{\text{n}} = 10^8$ (attainable during one reactor cycle at the present UCN source at the ILL), and one plate of the trap made from a dense material such as lead[2] ($N = 6.86 \times 10^{30}\ \text{m}^{-3}$). We thus might detect a signal if

$$g_{\text{S}}g_{\text{P}} \geqslant \frac{10^{-30}}{\lambda^2[\text{m}]}\left(1 - \mathrm{e}^{-0.1/\lambda[\text{m}]}\right)^{-1}\left(1 - \mathrm{e}^{-d/\lambda}\right)^{-1}. \tag{7}$$

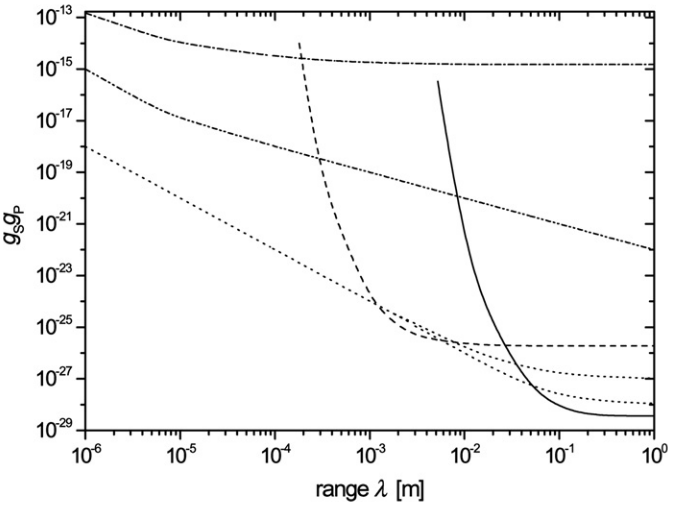

Fig. 1. Constraints and sensitivity limits to the coupling constant product $g_{\text{S}}g_{\text{P}}$ as a function of the range λ of the macroscopic force. Limits due to measurements are shown as: dash-dotted – gravitational levels [5], solid – ^{199}Hg/Cs precession frequency comparison [8], dashed – superconducting torsion balance [9]. Proposed sensitivity limits: dotted – neutron spin precession (Eq. (7) with $d = 0.01$ m (upper line), and $d = 0.1$ m (lower)), dash–dot-dotted – upgraded gravitational level experiment [5].

Fig. 1 shows this sensitivity limit, together with limits established from three experimental results and the proposed limit of an upgraded gravitational level experiment. In the experiments [8,9] a macroscopic minimum distance l between spins and masses truncated the range of best sensitivity to values $\lambda \gtrsim l$. In the neutron experiments this is avoided, since neutrons are reflected directly from the test mass of the mirror (otherwise an additional factor $\exp(-l/\lambda)$ would appear in Eq. (3)).

In order to establish via pseudomagnetic precession a new limit or even find a signal due to a non-vanishing $g_{\text{S}}g_{\text{P}}$, a careful consideration of possible systematic effects is required. In particular magnetic influences can easily mimic the sought effect. An analysis of systematic effects is not in the scope of this Letter but only some general ideas shall be presented here. Many of the systematic effects which have to be dealt with in the neutron EDM search are relevant here as well. Obviously absent is the problem of geometric phases due to neutron motion in magnetic field gradients in presence of an applied electric field [10].

In all present neutron EDM setups, the Ramsey cells are protected from external magnetic influences by several layers of magnetic screen, wherein a weak magnetic field (usually 1–2 μT) produces neutron precession for application of the magnetic resonance technique. In the neutron EDM search one looks for a tiny change of neutron precession frequency under reversal of an electric field with respect to the magnetic field. The search for CP-violation induced by the coupling $g_{\text{S}}g_{\text{P}}$ can be done similarly, using instead a reversal of the orientation of a mass-asymmetric trap. Crucial in both cases is to monitor the magnetic field during free neutron precession. Ratios $\tilde{\omega}_{\uparrow\downarrow} = \omega_{\uparrow\downarrow}/\omega_{\text{mag}\uparrow\downarrow}$, of the two frequencies $\omega_{\uparrow\downarrow}$ in Eq. (4) with simultaneously determined frequencies $\omega_{\text{mag}\uparrow\downarrow}$ of additional magnetometers, are insensitive to common magnetic field drifts in a well-designed setup.

Current methods of magnetometry in EDM setups involve Cs cells in proximity to neutron Ramsey chambers [11], or a cohabiting ^{199}Hg magnetometer [12]. Both techniques might be employed in the search for $g_{\text{S}}g_{\text{P}}$. Cs-magnetometers surrounding a neutron Ramsey chamber should be placed out of reach of the sought spin-dependent force. The ^{199}Hg co-magnetometer might be more appropriate in presence of sizeable magnetic field gradients. Note that, despite neutrons and ^{199}Hg both probe the spin-

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[2] Although lead is not too bad for neutron storage, a thin coating of a material with large Fermi potential and low UCN loss per wall collision will improve T and N_{n}. A lower mass density of the coating reduces sensitivity only for λ smaller than the layer thickness, for which a few tenths of a μm are sufficient.

dependent force fields close to the trap walls, an effect would persist in the relative precession frequency of both species, due to the opposite signs of the magnetic g-factors of neutron and ^{199}Hg [13]. As another advantage of a co-magnetometer both species would probe the local fields of eventual magnetic impurities on the surface of the container walls. With one or another variant of magnetometers in place there are still several possibilities to measure an effect due to $g_S g_P$.

First, one has the choice either to invert the magnetic field or the trap orientation to determine the two relative precession frequencies $\tilde{\omega}_{\uparrow\downarrow}$. Under field reversal, remanence of the magnetic screen around the Ramsey cell may cause large changes of field gradients difficult to correct for if spatial averaging of neutrons and magnetometers is not perfect [14]. Therefore, inversion of the trap orientation within a constant magnetic field seems the better option. In Ref. [8] it was proposed to swap baths of mercury as variable test masses. If one wants to envisage such a scheme for the present study, a UCN trap should be made of mechanically supported UCN-reflecting foils to allow for close contact of UCN and mercury, in order to avoid loss of sensitivity for small λ.

Second, one may employ simultaneously two stacked, adjacent chambers possessing opposite mass asymmetry with respect to the magnetic field and measure corresponding frequencies $\omega_{\uparrow 1}$ and $\omega_{\downarrow 2}$. The effect due to $g_S g_P$ would show up in $\Delta\omega = \omega_{\uparrow 1} - \omega_{\downarrow 2}$ but could as such not yet be distinguished from an effect due to different mean magnetic fields in the chambers. The experiment therefore has to be repeated with the two chambers arranged with opposite mass asymmetry with respect to the magnetic field in order to measure $\Delta\omega' = \omega_{\downarrow 1} - \omega_{\uparrow 2}$, while keeping magnetic field gradients constant during both measurements. With $\Delta\omega - \Delta\omega' = 8|\bar{V}|/\hbar$ one thus obtains doubled sensitivity compared to Eq. (4) for a single trap. Clearly, additional (co-)magnetometry should be used, and interchange of the position of the two geometrically identical chambers might help to test for some systematic effect due to different magnetic contamination of the trap walls. For the neutron EDM search the concept of a double-chamber setup was developed and successfully employed by the Gatchina group [11]. Good control over field gradients might be achieved with the neutron chambers sandwiched between two large-area magnetometers (or magnetometer arrays) [15]. A method to correct for higher order magnetic field gradients was proposed for the neutron EDM search by Serebrov [16]. Translated to the search of spin-dependent CP-violating short-range forces it would correspond to a stack of mass-asymmetric pairs of Ramsey chambers supplemented by mass-symmetric chambers for magnetometry.

In closing I note that pseudomagnetic spin precession as discussed before may also induce depolarisation of trapped neutrons which for a cylindrical trap oriented along the magnetic field would occur at the cylindrical wall [17]. This provides an alternative access to $g_S g_P$ in a simple UCN storage experiment, although, as pointed out in [17], with less sensitivity than the search for a shift in magnetic resonance described here. In an independent development, coherent neutron spin precession has recently been employed by Pignol and co-workers for a very sensitive test of Lorentz invariance [18]. A proposal building on a preprint of this publication [19] to extend the application of neutron spin precession to shorter ranges λ in perfect-crystal diffraction can be found in Ref. [20].

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