Constraining spin-dependent short range interactions using neutron spin precession close to a mirror

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Abstract
Spin-dependent short range interactions of free neutrons with matter may be searched for in various ways. This short note discusses pseudomagnetic precession of trapped ultracold neutrons in vicinity to bulk matter, which should be several orders of magnitude more sensitive than any other method proposed so far.

Keywords: ultra-cold neutrons, UCN, pseudomagnetic precession

Spin-dependent short-range interactions may be induced by light, pseudoscalar bosons such as the axion invented to solve the strong CP problem \[1\]. These hypothetic particles are proposed to mediate a parity and time reversal violating interaction between a fermion and the spin of another fermion, which is parameterised by a Yukawa-type potential with range \(\lambda\) and with a monopole-dipole coupling. Considering a neutron with mass \(m_n\) and spin \(\frac{1}{2} \hbar \sigma\) interacting with another nucleon at distance \(r\) it may be written as

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

with unitless scalar and pseudo-scalar coupling constants \(g_S\) and \(g_P\) between the neutron and the exchanged boson. \(\mathbf{n} = r/r\) is a unit distance vector from the neutron to the nucleon. Prior experiments and astronomical observations suggest that, if the axion exists, its mass should lie within the “axion window” \(1 \mu\text{eV} \lesssim m_A \lesssim 1\) meV, corresponding to a range \(0.2 \text{ mm} \lesssim \lambda \lesssim 20\) mm.

A first limit on such an interaction was provided in \[2\] along with a proposal for further improvement using gravitationally bound quantum states of the free neutron. The suggested Stern-Gerlach type experiment employs neutron transmission through a slit between an absorber and a horizontal mirror, which is sensitive to the shape of the spatial neutron wave function. The hypothetic short-range forces of mirror and absorber would induce a spin dependence. In this short note a spin precession experiment is proposed that should be more sensitive by several orders of magnitude.

Consider a neutron close to the surface of a massive plane mirror with thickness \(d\). Let \(z\) denote the coordinate normal to the mirror with \(z = 0\) at the surface. The effective potential of the mirror with nucleon number density \(N\) is obtained by integration of eq. (1) over the mirror volume and is given by\[3\]

\[V(z) = V(0) \left( e^{-|z|/\lambda} - e^{-|z+d|/\lambda} \right) \sigma_z, \quad V(0) = 2\pi N \kappa \lambda. \quad (2)\]

\[1\]Equation (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 \[3\].
With respect to spin dependence it has the same analytic form as the interaction of the neutron magnetic moment with a magnetic field pointing in \(z\) direction. \(V(\zeta)\) can therefore be probed by searching for a pseudomagnetic precession of neutrons polarised parallel to the surface of the mirror. For this investigation Ramsey’s resonance method applied to ultracold neutrons (UCN) is particularly well suited. The proposed experiment requires only slight modification of devices employed in ongoing searches for the electric dipole moment (EDM) of the neutron which have matured to sensitivity beyond \(10^{-21}\) eV.

Here we consider spin precession of UCN stored in a trap made of two plane mirrors with distance \(D\) and with a large difference in mass density. Let the mirror surfaces be located at \(z = 0\) and \(z = D\), and a homogeneous magnetic field \(\mathbf{B}\) be applied in \(z\) direction. For maximum strength of the potential \(V(z)\) the thickness of the mirror with high mass density is to be chosen \(d \gg \lambda\). The trapped neutrons sense the spatially averaged spin-dependent potential, which, neglecting the influence of the quantum-mechanical boundary conditions on the probability density close to the mirror, and also a small contribution due to the light mirror, is given by:

\[
\nabla = \pm \frac{1}{D} \int_0^D V(z) \, dz = \pm V(0) \frac{\lambda}{D} \left(1 - e^{-D/\lambda}\right) \left(1 - e^{-d/\lambda}\right),
\]

(3)

with the signs for spin parallel and anti-parallel to \(\mathbf{B}\). Due to the operator \(\mathbf{n} \cdot \mathbf{\sigma}\) in eq. (1) the signs get inverted under inversion of the trap orientation relative to \(\mathbf{B}\). Hence, neglecting for the moment the issue of magnetic field instability, we may determine \(V\) from the difference

\[
\omega_+ - \omega_- = 2 |\nabla| / \hbar
\]

(4)

of neutron precession frequencies for the two trap orientations with respect to the magnetic field.

The counting statistical uncertainty of this basic measuring procedure is given by (see, e.g. ref. [4] for the analogue EDM search)

\[
\sigma(V) = \frac{\hbar}{2\alpha T \sqrt{N_n}},
\]

(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 \(\alpha\) denotes the visibility of the Ramsey fringes. The new interaction will thus be detectable if

\[
g_{SgP} \geq \frac{2 m_n}{\alpha T N_h \sqrt{N_n}} \frac{D}{\lambda^2} \left(1 - e^{-D/\lambda}\right)^{-1} \left(1 - e^{-d/\lambda}\right)^{-1}.
\]

(6)

For a conservative estimate of the statistical sensitivity we consider employing one of the existing devices to search for the neutron EDM, equipped with a mirror made from lead\(^2\) \((N = 6.86 \times 10^{30} \text{ m}^{-3})\), and taking \(T = 100\) s, and \(N_n = 10^8\) (attainable during one reactor cycle at the present UCN source at the ILL). To allow for imperfect polarisation efficiency we set \(\alpha = 0.5\). With \(D = 0.1\) m we thus might detect a signal if

\[
g_{SgP} \geq \frac{10^{-30}}{\lambda^2 \text{[m]}} \left(1 - e^{-0.1/\lambda[m]}\right)^{-1} \left(1 - e^{-d/\lambda}\right)^{-1}.
\]

(7)

Figure 1 shows this sensitivity limit on \(g_{SgP}\), together with limits provided by two other measurements and the proposed limit of an upgraded gravitational level experiment. In order to

\footnote{Although lead is not too bad for neutron storage, a thin coating with a material with large Fermi potential and low UCN loss per wall collision will improve \(T\) and \(N_n\). Its lower mass density reduces sensitivity only for small \(\lambda\) in the \(\mu\) m range out of the axion window.}
establish such a limit or even find a signal, a careful consideration of possible systematics is required. Here only some general ideas are presented.

It is well known that instability and inhomogeneity of the magnetic field may provide generous sources of systematic effects in neutron EDM searches which partly are also relevant here. Past experiments have converged to the strategy to let trapped neutrons precess in a $\mu$T field of a solenoid, protected from external influences by several layers of magnetic screen. Field monitoring has been performed with magnetometers using Cs in proximity to the neutron Ramsey chamber [6], or using $^{199}$Hg as a co-magnetometer [7]. For the search of a spin-dependent short-range force a neutron Ramsey chamber has to be surrounded by magnetometers out of reach of the force, and $\omega_\pm$ in eq. (4) be measured as relative precession frequencies. Control of global field drifts on a level required for a sensitivity on $g_{SGP}$ as given in eq. (7) is met by state-of-the-art magnetometry in EDM experiments, in particular using a double Ramsey chamber setup mentioned further below. Note also that the problem of geometric phases due to neutron motion in an applied electric field in conjunction with magnetic field gradients [8] is absent.

In order to cover the axion window and probe forces even down to the $\mu$m range the test mass should be in close contact with the precessing fermions. The experiment [9] obtained an excellent limit on $g_{SGP}$ for $\lambda \gtrsim$ a few cm. It was obtained by comparing relative precession frequencies of Hg and Cs magnetometers as a function of the position of two 475 kg lead masses with respect to an applied magnetic field. A minimum distance $l$ between the test mass and the magnetometer cells gives rise to an additional factor $\exp(-l/\lambda)$ in eq. (3), which truncates the

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A first experiment using the old apparatus of the Rutherford/Sussex/ILL neutron EDM collaboration [7] is under way [5].
range of best sensitivity to values \( \lambda \gtrsim l \). For a gas of ultracold neutrons close contact with the test mass can easily be established by replacing one of the electrodes of an EDM chamber by a heavy mirror.

Using the combination of a single neutron Ramsey chamber with atomic magnetometers one may either invert the magnetic field or the trap orientation to determine two relative neutron precession frequencies \( \omega_{\pm} \). Due to the presence of remanent magnetic materials for shielding external fields, a field reversal may change field gradients which in turn may affect the relative precession frequencies due to inappropriate spatial averaging \([10]\). Therefore it seems to be a better option to keep the field constant and rotate the trap inside the magnetic shield. As an alternative one may swap baths of mercury as variable test masses as proposed in \([9]\). In this variant the UCN trap should be made of mechanically supported UCN-reflecting foils to allow for close contact of UCN and mercury to avoid loss of sensitivity for small \( \lambda \).

Best results might be obtained using a double-chamber with opposite mass polarity with respect to the magnetic field. It offers a large degree of intrinsic cancellation of magnetic field drifts. For the neutron EDM search the concept of a double-chamber setup was developed and successfully employed by the Gatchina group \([6]\). To get good control over field gradients, the neutron chambers should be sandwiched between two large area magnetometers (or magnetometer arrays) \([11]\). Higher order magnetic field gradients may be corrected for using a stack of mass-polar pairs of Ramsey chambers which could be supplemented by mass-symmetric neutron chambers for magnetometry. A corresponding scheme was proposed for the neutron EDM search by A. Serebrov (for latest update see \([12]\)).

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