A New Constraint for the Coupling of Axion-like particles to Matter via an Ultra-Cold Neutron Gravitational Experiments

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We present a new constraint for the axion monopole-dipole coupling in the range of 1 µm – a few mm, previously unavailable for experimental study. The constraint was obtained using our recent results on the observation of neutron quantum states in the Earth’s gravitational field. We exploit the ultimate sensitivity of ultra-cold neutrons (UCN) in the lowest gravitational states above a material surface to any additional interaction between the UCN and the matter, if the characteristic interaction range is within the mentioned domain. In particular, we find that the upper limit for the axion monopole-dipole coupling constant is $g_p g_s / (\hbar c) < 2 \times 10^{-15}$ for the axion mass in the “promising” axion mass region $M_A \sim 1$ meV.

A vanishing value for the neutron electric dipole moment motivated the introduction of hypothetical light (pseudo) scalar bosons (commonly called axions), as an extension of the Standard Model [1, 2, 3, 4]. According to the suggested theories the axion mass could be in the range of $10^{-6} < M_A < 10^{-1}$ eV, while its coupling to photons, leptons and nucleons is not fixed by the existing models (though it is extremely weak). Following the theoretical predictions mentioned intensive searches for axions have been performed over recent decades. These studies include testing the astrophysical consequences of the axion theories, QED effects (axion-two photon coupling) and macroscopic forces (spin-matter coupling). They put severe constraints on axion-matter coupling in different axion mass ranges. A detailed review of axion studies can be found in [5, 6].

The recently reported positive results of the PVLAS experiment on light polarization rotation in a vacuum in the presence of a transverse magnetic field [7] may be seen as evidence of the long sought axion [8]. According to [7], the mass of neutral boson possibly responsible for the observed signal is $1 < M_A < 1.5$ meV.

The value of the axion-photon coupling strength obtained from the PVLAS experiment is in contradiction with recent CAST observations [9]. Several ideas have been discussed recently, in [10, 11], capable of explaining this discrepancy.

This intriguing result makes it particularly important to carry out independent testing on the axion-matter coupling in the corresponding distance range of $130 < \lambda < 200 \mu m$.

In the present Letter we report on constraints for axion monopole-dipole coupling. Such coupling results in a spin-matter CP violating Yukawa-type interaction potential [12]

$$V(\vec{r}) = \hbar g_p g_s \frac{\vec{\sigma} \cdot \vec{n}}{8 \pi m c \lambda} \left( \frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-r/\lambda}$$

(1)

between spin and matter, where $g_p g_s$ is the product of couplings at the scalar and polarized vertices and $\lambda$ is the force range. Here $r$ is the distance between a neutron and a nucleus, $\vec{n} = \vec{r}/r$ is a unitary vector, and $m$ is the nucleon mass.

Only a few experiments for distances below 100 mm have placed upper limits on the product coupling in a system of magnetized media and test masses [6]. One experiment [13] had peak sensitivity at $\sim 100$ mm and two other ones [14, 15] had peak sensitivity at $\sim 10$ mm.

The constraint for the $g_p g_s$ presented in this article is competitive in the distance range of $1 < \lambda < 10^3 \mu m$.

In the experimental method used [16, 17, 18, 19] UCN move above a nearly perfect horizontal mirror in the presence of the Earth’s gravitational field. A combination of a mirror and the gravitational potential binds neutrons close to the mirror surface in the so-called gravitational states. The characteristic scale of this problem is $l_0 = \sqrt{\hbar^2 / (2m^2 g)} = 5.87$ µm, while the characteristic size of the lowest gravitational neutron state (a quasi classical turning point height) is $\sim 2.4l_0 = 13.7$ µm. The neutron spatial distribution, directly measured in our experiment, turns out to be very...
FIG. 1: The general experimental scheme. From the left to right: vertical solid lines indicate two plates of the entrance collimator (1); solid arrows show classical neutron trajectories (2) between the collimators and the entrance to the slit between a mirror (3, grey rectangle on bottom) and a scatterer (4, black rectangle on top); Dashed horizontal lines show quantum motion of neutrons above the mirror (5); black box indicates a neutron detector (6). The size of the slit between the mirror and the scatterer can be finely tuned and measured.

FIG. 2: A dependence of the neutron flux through a slit between the mirror and the scatterer versus the slit size. The circles show the data points, the curve is the theoretical description within the quasi classical approach. The horizontal lines indicate the detector background and its uncertainty.

sensitive to any additional potential, with a characteristic range from fractions to tens of $l_0$. This property of the neutron states enables us to establish a new limit on $g_s g_p$. In the following we will describe the experimental setup and the estimation of the axion-mediated interaction intensity constraint.

The experiment [17, 18, 19] involved the measurement of the neutron flux through the horizontal gap (slit) between a horizontal mirror (below) and a scatterer (above), as a function of the slit size $\Delta h$ (see figure 1).

The aim of the experiment was to demonstrate, for the first time, the existence of the quantum states of matter in a gravitational field. An example of the dependence of the neutron flux on the slit size $\Delta h$ is presented in figure 2 [18].

This dependence is sensitive to the presence of quantum states of neutrons in the potential well formed by the Earths gravitational field and the mirror. In particular, the neutron flux was found to be equal to zero within the experimental accuracy if the slit size $\Delta h$ is smaller than the characteristic spatial size (a quasi classical turning point height) of the lowest quantum state of $\sim 15 \mu$m in this potential well.
This flux was fitted by a quasi classical function \[18\] and the results for the two lowest quantum states

\[ z_{1\text{exp}}^{\text{exp}} = 12.2 \pm 0.7 \mu\text{m}, \]
\[ z_{2\text{exp}}^{\text{exp}} = 21.6 \pm 0.7 \mu\text{m}, \]

are in agreement (25%) with the expected values

\[ z_{1\text{qc}} = 13.7 \mu\text{m}, \]
\[ z_{2\text{qc}} = 24.0 \mu\text{m}. \] (3)

It should also be mentioned that the method used in this experiment (based on position sensitive detectors) to visualize the wave functions of the low lying states \[18, 20\] also revealed no deviation from expected theoretical behavior.

An additional interaction \[1\] between a neutron and a mirror’s nuclei produces an additional neutron-mirror interaction potential.

If the mirrors density is constant and equal to \( \rho_m \), an additional potential of the interaction between neutrons situated at height \( z \) above the mirror surface and the bulk of the mirror is given by

\[ V_a(z) = \int_{\text{mirror}} V(x', y', z + z') d^3r'. \] (4)

The volume integral is calculated over the mirror bulk: \(-\infty < x', y' < \infty, z' < 0\) (in fact, over the neutrons vicinity with the size of the order of a few \( \lambda \) due to the exponential convergence of these integrals). This integral can be calculated explicitly. Thus a neutron with a given spin projection to the vertical axis (orthogonal to the mirror surface) will be affected by an additional exponential potential:

\[ V_a(z) = g_p g_s \frac{\pi \hbar \rho_m \lambda}{2m^2 c} e^{-z/\lambda}. \] (5)

Let us constrain the intensity of the axion-mediated interaction \( V_a \) from the experimental data. We will consider the potential mentioned to be much weaker than the gravitational potential and will therefore apply the perturbation theory. As previously mentioned, the quantity extracted from the experimental data is a classical turning point height \( z_n \) for the neutron state \( n \) in the gravitational plus axion-mediated potential. In the absence of any additional interaction a turning point \( z_n \) is related to an energy of the “pure gravitational” state \( E_n \), as:

\[ m g z_n = E_n. \] (6)

In the presence of axion-mediated interaction neutrons are affected both by interaction with mirror (below) and with scatterer (above). The height of the scatterer \( \Delta h \) at which the transmission through the slit starts for the \( n \)-th quantum state is called \( H_n \). Here, the resulting potential has the form:

\[ W_a(z) = V_a(z) - V_a(H_n - z). \] (7)

In the presence of \( W_a(z) \) the shift of a turning point height is given by

\[ m g (z_n + \Delta z_n) + W_a(z_n + \Delta z_n) = E_n + \Delta E_n. \] (8)

In the first order of the perturbation theory expansion we get:

\[ \Delta z_n \approx \langle \psi_n | W_a | \psi_n \rangle - W_a(z_n) \]
\[ m g + dW_a/dz(z_n). \] (9)

Here \( \psi_n \) is a normalized wave-function of a neutron gravitational state \( n \). The analytical expressions for a gravitational state wave-functions \( \psi_n \) and gravitational eigen-energies are well-known (see \[23\] and references therein):

\[ \psi_n(z) = \frac{\text{Ai}'((z - z_n)/l_0)}{|\text{Ai}'(-z_n/l_0)|}, \]
\[ \text{Ai}(-z_n/l_0) = 0. \] (10) (11)

Here \( \text{Ai}(z) \) is the Airy function \[22\].

Expression \[9\] allows the axion-mediated interaction intensity to be constrained using the neutron flux measurement, passed between the mirror and the scatterer in the presence of the Earth’s gravitational field \[18\]. The experimental
values of $z_n$ were established within 25\% accuracy for the first two states; this can be considered as the upper limit for $\Delta z_n$. The constraints for $g_s g_p/(\hbar c)$, obtained with the above-mentioned data, are shown in Figure 3. In the same plot we show the existing experimental constraints from refs. [13, 14, 15]. Note that in these experiments the polarized particles were electrons whereas in our experiments the polarized particle is neutron.

The signal reported by the PVLAS collaboration corresponds to the axion mass $1 < M_A < 1.5$ meV ($130 < \lambda < 200 \mu m$). In this domain $\lambda/l_0 \sim 30 \gg 1$, so the expression (9) can be written as:

$$\Delta z_n \approx \frac{g_p g_s}{3\pi m g} \frac{\hbar \rho_m z_n}{2m^2c}$$  \hspace{1cm} (12)

It follows from our results that $g_s g_p/(\hbar c) < 2 \cdot 10^{-15}$ in this range of axion masses.

We should mention that a further increase in sensitivity could be achieved, either by increasing the statistics, by using highly excited quantum states, or by using the more intense UCN sources now being developed, or by increasing observation time $T$ (for experiments with specular traps without scatterer during storage of the UCN) [21, 24]. In the future experiment we plan to use polarized neutrons and we expect to improve the relative accuracy of the energy measurements for the quantum states by, at least, two orders of magnitudes (dash-dotted line in figure 3). In this case possible false effects caused by small magnetic impurities in surface have to be carefully investigated.

We have thus established a constraint for the axion monopole-dipole spin-matter coupling $g_s g_p/(\hbar c)$ in the axion mass range of $0.1 < M_A < 200$ meV from the measurement of the spatial distribution of UCN, passing along a horizontal mirror in the presence of the Earth’s gravitational field. In the axion mass domain of $1 < M_A < 1.5$ meV, where the positive signal of the PVLAS experiment was reported, we found that $g_s g_p/(\hbar c) < 2 \cdot 10^{-15}$. The range of the axion masses studied was previously out of reach of experimental study in the domain of spin-matter coupling.

This limit can be improved by a few orders of magnitude in future experiments with polarized UCN trapped inside the gravitational states.

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