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Constraint on the coupling of axionlike particles to matter via an ultracold neutron gravitational experiment

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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 ultracold 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.

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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 [1–4]. 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 Polarizzazione del Vuoto con LASer (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 axion [8]. According to [7], the mass of the 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 [10–12], capable of explaining this discrepancy. This result makes it important to carry out independent testing on the axion-matter coupling in the corresponding distance range of $130 < \lambda < 200$ μm.

In the present paper we report on constraints for axion monopole-dipole coupling. Such coupling results in a spin-matter *CP* violating Yukawa-type interaction potential [13]

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

between spin and matter, where $g_p g_s$ is the product of couplings at the scalar and polarized vertices and λ is the force range. Here r is the distance between a neutron and a nucleus, $\vec{n} = \vec{r}/r$ is a unity 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 [14] had peak sensitivity at ~100 mm and two other ones [15,16] had peak sensitivity at ~10 mm.

In the experimental method used [17–20], ultracold neutrons (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 $l_0 = \sqrt[3]{\hbar^2/(2m^2 g)} = 5.87$ μm, while the characteristic size of the lowest gravitational neutron state (a quasiclassical turning point height) is $\sim 2.4 l_0 = 13.7$ μm. The neutron spatial distribution, directly measured in our experiment, turns out to be very 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 distance range of $1 < \lambda < 10^3$ μm. In a major part of this range of λ, the ratio $l_0/\lambda \ll 1$.

The experiment [18–20] 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 Δh (see Fig. 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 Δh is presented in Fig. 2 [19].

This dependence is sensitive to the presence of quantum states of neutrons in the potential well formed by the Earth's 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 Δh is smaller than the characteristic spatial size (a quasiclassical turning point height) of the lowest quantum state of ~ 15 μm in this potential well.

This flux was fitted by a quasiclassical function [19]. For a given state n with a turning point position z_n, the neutron flux $F(\Delta h)$ as a function of the slit size Δh has the form

$$F(\Delta h; z_n) = N_n \exp(-\alpha \chi(\Delta h, z_n)). \tag{2}$$

N_n is population of the nth level, α is a constant independent on the state number n; and

$$\chi(\Delta h; z_n) = \begin{cases} \exp\left(-\frac{4}{3}\left(\frac{\Delta h - z_n}{l_0}\right)^{3/2}\right), & \Delta h > z_n, \\ 1 & \Delta h < z_n. \end{cases} \tag{3}$$

The results of the fit (solid line in Fig. 2) for the two lowest quantum states,

$$\begin{aligned} z_1^{\text{exp}} &= 12,2 \pm 0,7_{\text{stat}} \pm 1,8_{\text{sys}} \ \mu\text{m}, \\ z_2^{\text{exp}} &= 21,6 \pm 0,7_{\text{stat}} \pm 2,2_{\text{sys}} \ \mu\text{m}, \end{aligned} \tag{4}$$

are in agreement (25%) with the expected values

$$\begin{aligned} z_1^{\text{qc}} &= 2.34 \sqrt[3]{\frac{\hbar^2}{2m^2 g}} = 13,7 \ \mu\text{m}, \\ z_2^{\text{qc}} &= 4.09 \sqrt[3]{\frac{\hbar^2}{2m^2 g}} = 24,0 \ \mu\text{m}. \end{aligned} \tag{5}$$

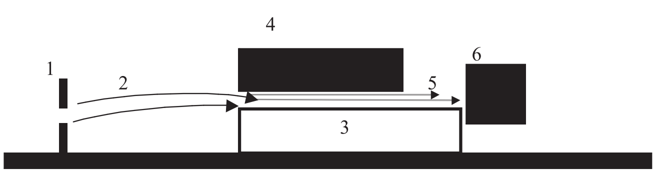

FIG. 1. The general experimental scheme. From left to right: vertical solid lines indicate two plates of the entrance collimator (1); solid arrows show classical neutron trajectories (2) between the collimators and the entrance to the slit between a mirror (3, gray rectangle on bottom) and a scatterer (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.

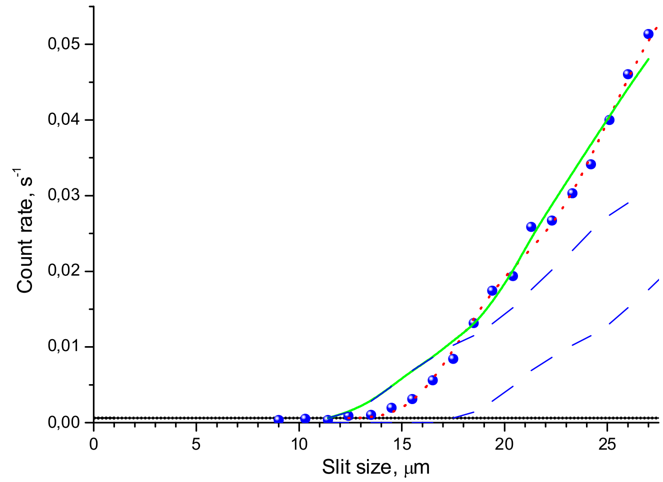

FIG. 2 (color online). A dependence of the neutron flux through a slit between the mirror and the scatterer versus the slit size. The circles show the data points, the dotted curve is the theoretical description within the quasiclassical approach. The horizontal lines indicate the detector background and its uncertainty. The solid line corresponds to the neutron flux modified by the spin-dependent axionlike interaction (the two dashed lines correspond to the two contributions of opposite neutron polarizations).

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 [19,21] 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 and could be observed experimentally even with an unpolarized neutron beam. In order to illustrate this, it is useful to refer to an analogy with the Stern-Gerlach experiment, in which spin-dependent interaction separates an initially unpolarized neutron beam in two spatially different components. In our case, a spin-dependent interaction (different for two spin polarization components) will modify the spatial wave functions of neutrons (as in the Stern-Gerlach experiment). The method to detect neutrons in the flow-through mode is sensitive to the spatial size of the neutron wave function. Roughly speaking, as long as the slit size is smaller than the size of the neutron wave function, the neutron flux through the slit equals zero. Any additional interaction which modifies the neutron wave function (increase or decrease its characteristic size) would change the value of the slit size, at which the neutron flux becomes different from zero.

If the density of the mirror is constant and equal to ρ_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

$$V_a(z) = \int_{\text{mirror}} V(x', y', z + z') d^3 r'. \tag{6}$$

The volume integral is calculated over the mirror bulk: $-\infty < x', y' < \infty$, $z' < 0$ (in fact, over the neutron's vicinity with the size of the order of a few λ 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:

$$V_a(z) = \frac{g_p g_s}{4\pi} \frac{\pi\hbar\rho_m\lambda}{2m^2c} e^{-z/\lambda}. \tag{7}$$

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

$$W_a(z) = V_a(z) - V_a(H_n - z). \tag{8}$$

For instance, in the major part of the range of λ, the ratio $l_0/\lambda \ll 1$, the interaction (7) and (8) leads to a renormalization of the gravitational acceleration g:

$$g_{\pm}^{\text{eff}} \approx g \mp 2\frac{g_p g_s}{4\pi} \frac{\pi\hbar\rho_m}{2m^2c}. \tag{9}$$

Here g_-^{eff} and g_+^{eff} are values of the renormalized gravitational acceleration g for neutrons with opposite vertical spin projections. The rapid change (steplike behavior) of the transmitted flux for the component with g_-^{eff} would occur at smaller values of the slit size than that for the component with g_+^{eff}. Thus, the value of a turning point z_n for a given quantum state would be split into a $\{z_n^-; z_n^+\}$ pair. The resulting transmission curve $F_a(\Delta h)$ would be equal to

$$F_a(\Delta h) = \frac{F(\Delta h; z_n^-) + F(\Delta h; z_n^+)}{2}. \tag{10}$$

To evaluate an upper limit on a level splitting, we performed a fit of the experimental data with an additional (with respect to that from Ref. [19]) free parameter corresponding to this splitting. All characteristics of the levels coincide with that obtained previously in Ref. [19]. The maximum splitting for the ground state was obtained to be equal to ± 2.8 μm on the 95% confidence level. As an illustration, for the case of $|z_1^{\pm} - z_1| = 2.8$ μm, the resulting flux is shown in Fig. 2 with the dotted line. The discrepancy between this curve and the experimental data is clearly evident at the values of the slit size $\Delta h \approx 15$ μm (two dashed lines correspond to two contributions of opposite neutron polarizations).

Note that the installation was shielded against external magnetic fields and an adequate choice of the mirror material allowed to avoid its residual magnetization. An absence of significant residual magnetic fields was controlled experimentally [19]. Thus the quantization axis for the spin states would be defined by the axionlike interaction (if it exists).

This allows the axion-mediated interaction intensity to be constrained using the neutron flux measurement. The constraints for $g_s g_p/(\hbar c)$, corresponding to the experimental uncertainty for the turning point value equal to 3 μm, are shown in Fig. 3 with a solid line. In the range of small λ, where the formula (9) is no more valid, an exact numerical solution was used. In the same plot we show the existing experimental constraints from Refs. [14–16]. Note that in some of these experiments the polarized particles were electrons (Ref. [14] has similar constraints for polarized electrons and polarized neutrons).

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) [22,23]. 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, 2 orders of magnitudes (dash-dotted line in Fig. 3). In this case, possible false effects caused by small magnetic impurities in the 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 gravita-

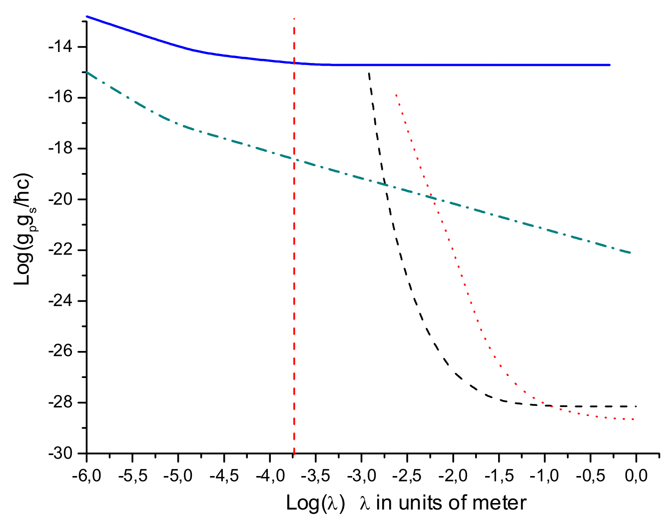

FIG. 3 (color online). Constraints for the axion coupling. The solid line indicates the present result, the dotted line corresponds to the result of [14], the dashed line shows the results of [15,16] (approximately the same within graphical accuracy), and the dash-dotted line illustrates the sensitivity estimation for a future UCN experiment. The vertical dashed line shows the characteristic range λ, for which a PVLAS signal has been claimed.

tional 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 $g_s g_p/(\hbar c) < 2 \times 10^{-15}$. 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 in the gravitational quantum states.

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