Physics Letters B 745 (2015) 58–63

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Constraining interactions mediated by axion-like particles with ultracold neutrons

S. Afach [a,b,c], G. Ban [d], G. Bison [b], K. Bodek [e], M. Burghoff [f], M. Daum [b], M. Fertl [a,b,1], B. Franke [a,b,*,2], Z.D. Grujić [g], V. Hélaine [b,d], M. Kasprzak [g], Y. Kermaïdic [h], K. Kirch [a,b], P. Knowles [g,3], H.-C. Koch [g,i], S. Komposch [a,b], A. Kozela [j], J. Krempel [a], B. Lauss [b,*], T. Lefort [d], Y. Lemière [d], A. Mtchedlishvili [b], O. Naviliat-Cuncic [d,4], F.M. Piegsa [a], G. Pignol [h], P.N. Prashanth [k], G. Quéméner [d], D. Rebreyend [h], D. Ries [a,b], S. Roccia [l,*], P. Schmidt-Wellenburg [b], A. Schnabel [f], N. Severijns [k], J. Voigt [f], A. Weis [g], G. Wyszynski [a,e], J. Zejma [e], J. Zenner [a], G. Zsigmond [b]

[a] *ETH Zürich, Institute for Particle Physics, CH-8093 Zürich, Switzerland*
[b] *Paul Scherrer Institute (PSI), CH-5232 Villigen-PSI, Switzerland*
[c] *Hans Berger Department of Neurology, Jena University Hospital, D-07747 Jena, Germany*
[d] *LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, Caen, France*
[e] *Marian Smoluchowski Institute of Physics, Jagiellonian University, 30-059 Cracow, Poland*
[f] *Physikalisch Technische Bundesanstalt, D-10587 Berlin, Germany*
[g] *Physics Department, University of Fribourg, CH-1700 Fribourg, Switzerland*
[h] *LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble, France*
[i] *Institut für Physik, Johannes–Gutenberg–Universität, D-55128 Mainz, Germany*
[j] *Henryk Niedwodniczański Institute for Nuclear Physics, 31-342 Cracow, Poland*
[k] *Instituut voor Kern–en Stralingsfysica, University of Leuven, B-3001 Leuven, Belgium*
[l] *CSNSM, Université Paris Sud, CNRS/IN2P3, Orsay Campus, France*

ARTICLE INFO

Article history:
Received 9 December 2014
Received in revised form 30 March 2015
Accepted 14 April 2015
Available online 20 April 2015
Editor: M. Doser

Keywords:
CP violation
Short range spin-dependent interaction
Axion
Axion-like particle
Ultracold neutrons
Neutron electric dipole moment

ABSTRACT

We report a new limit on a possible short range spin-dependent interaction from the precise measurement of the ratio of Larmor precession frequencies of stored ultracold neutrons and ^{199}Hg atoms confined in the same volume. The measurement was performed in a $\sim 1\,\mu$T vertical magnetic holding field with the apparatus searching for a permanent electric dipole moment of the neutron at the Paul Scherrer Institute. A possible coupling between freely precessing polarized neutron spins and unpolarized nucleons of the wall material can be investigated by searching for a tiny change of the precession frequencies of neutron and mercury spins. Such a frequency change can be interpreted as a consequence of a short range spin-dependent interaction that could possibly be mediated by axions or axion-like particles. The interaction strength is proportional to the CP violating product of scalar and pseudoscalar coupling constants $g_S g_P$. Our result confirms limits from complementary experiments with spin-polarized nuclei in a model-independent way. Limits from other neutron experiments are improved by up to two orders of magnitude in the interaction range of $10^{-6} < \lambda < 10^{-4}$ m.

1. Introduction

We present an interpretation of our recent measurement of the ratio γ_n/γ_{Hg} of the neutron and ^{199}Hg magnetic moments [1] in terms of the strength of a possible short range spin-dependent neutron–nucleon interaction. This ratio was inferred from a comparison of the simultaneously recorded Larmor precession frequencies of the two species contained in the same storage volume. The

* Corresponding author.
E-mail addresses: beatrice.franke@mpq.mpg.de (B. Franke), bernhard.lauss@psi.ch (B. Lauss), stephanie.roccia@csnsm.in2p3.fr (S. Roccia).
[1] Now at University of Washington, Seattle WA, USA.
[2] Now at Max-Planck-Institute of Quantum Optics, Garching, Germany.
[3] Now at LogrusData, Vienna, Austria.
[4] Now at Michigan State University, East-Lansing, USA.

http://dx.doi.org/10.1016/j.physletb.2015.04.024

measurement was performed using the apparatus dedicated to the search for the neutron electric dipole moment (nEDM) [2] by the nEDM Collaboration at the source for ultracold neutrons [3] of the Paul Scherrer Institute, Switzerland.

In the central storage vessel of the apparatus, the spins of the neutrons and mercury atoms are made to precess simultaneously in the same volume. The ratio

$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} \quad (1)$$

constitutes a sensitive tool for the control of systematic effects during the measurement of the nEDM. By correcting R properly for known differences of the Larmor precession of the two species neutrons and ^{199}Hg, respectively, the ratio of magnetic moments $\gamma_{\mathrm{n}}/\gamma_{\mathrm{Hg}}$ can be extracted. A data set of R taken in 2012 was independently analysed in [1] and in [4], where we additionally examined its sensitivity to hypothetical short range spin-dependent interactions. Possible force mediators are axions, or axion-like particles and the interaction strength is proportional to the product of scalar and pseudoscalar coupling constants $g_S g_P$. It has been proposed in [5,6] to use an nEDM apparatus for the investigation of such a force.

A motivation to search for an interaction involving $g_S g_P$ is given in Section 2. The influence of a short range spin-dependent interaction on the observable R is explained and derived in Section 3, where additionally some related details about the experiment are shown. Our result is compared to other current limits on the product $g_S g_P$ in Section 4.

2. Motivation

The investigation of CP violating processes is a major line of research in particle physics. In contrast to the weak interaction, there is so far no evidence that the strong interaction violates CP symmetry. The non-observation of an nEDM at current sensitivity levels constrains the CP violating term (θ-*term*) in the Lagrangian of the strong interaction to be nine orders of magnitude smaller than naturally expected [7]. This fact is known as *the strong CP problem* and a solution to it was proposed in [8], where the spontaneously broken Peccei–Quinn symmetry was introduced.

A new pseudoscalar boson emerges from this symmetry, the axion [9,10]. An intrinsic feature of the Peccei–Quinn model is a fixed relation between mass and interaction strength of the axion. The originally assumed symmetry breaking scale (corresponding to the electroweak scale) was ruled out, leaving only higher energy scales possible. For the axion one thus expects a small mass and a feeble interaction with other particles. The possible mass of the axion is constrained by cosmology and astro-particle physics measurements to the so-called *axion window* [11].

A short range spin-dependent interaction which could be mediated by an axion was proposed in [12]. There, three classes of interactions were presented, involving either g_S^2-, $g_S g_P$-, or g_P^2-couplings, whereas $g_S g_P$-couplings are considered of particular interest, since they violate CP symmetry. A $g_S g_P$-coupling diagram is shown in Fig. 1(a) and takes place between an unpolarized particle Ψ (where *unpolarized* means randomly polarized with respect to any quantization axis) and a polarized particle $\Phi^\diamond$. The symbol $^\diamond$ is used to denote properties of the particle interacting at the pseudoscalar vertex with a strength proportional to the coupling constant $g_P^\diamond$ of the particle $\Phi^\diamond$. The potential caused by such a $g_S g_P^\diamond$-coupling between an unpolarized particle and a polarized particle with mass $m^\diamond$ and spin $\boldsymbol{\sigma}^\diamond$ is derived as [12]:

$$V(\boldsymbol{r}) = g_S g_P^\diamond \frac{(\hbar c)^2}{8\pi m^\diamond c^2} (\hat{\boldsymbol{\sigma}}^\diamond \cdot \hat{\boldsymbol{r}}) \left(\frac{1}{r\lambda} + \frac{1}{r^2} \right) e^{-r/\lambda}, \quad (2)$$

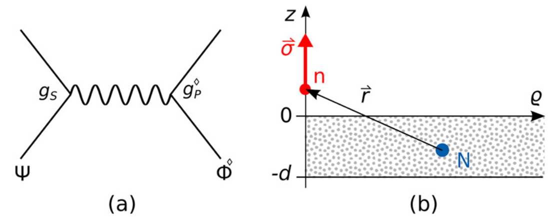

Fig. 1. (a) Interaction diagram of a scalar-pseudoscalar coupling between particles Ψ and $\Phi^\diamond$. Ψ is unpolarized and interacts at the scalar vertex with the coupling constant g_S, whereas $\Phi^\diamond$ is polarized and interacts at the pseudoscalar vertex with the coupling constant $g_P^\diamond$. The total interaction strength is proportional to the product $g_S g_P^\diamond$. (b) A polarized neutron n with spin $\boldsymbol{\sigma}$ interacts with an unpolarized nucleon N at distance $\boldsymbol{r}$ within bulk matter shaped as a plate of thickness d. A view of the ϱ–z plane in a cylindrical coordinate system (ϱ, ϕ, z) is shown.

where $\hat{\boldsymbol{\sigma}}^\diamond$ is the unit vector of the spin, $\hat{\boldsymbol{r}}$ is the unit vector along the distance $\boldsymbol{r}$ between the particles, and λ the interaction range. The product $(\hat{\boldsymbol{\sigma}}^\diamond \cdot \hat{\boldsymbol{r}})$ also violates parity P and time reversal symmetry T.

$g_S g_P$-couplings can also be mediated by other hypothetical spin-zero particles which are generic to the axion and usually referred to as axion-like particles. However, for these generic bosons no relation between mass and interaction strength is given, as compared to the genuine axion. The origin of such particles can be symmetries other than Peccei–Quinn symmetry, which are broken at very high energies and often postulated in theories beyond the Standard Model of particle physics, such as e.g. String Theory. Thus, both axions and axion-like particles, are intriguing dark matter candidates and beyond Standard Model physics probes [13–15].

However, due to the non-observation of the nEDM a short range spin-dependent interaction mediated by an axion is constrained to $g_S g_P < 10^{-40} \ldots 10^{-34}$ [16]. On the other hand, if the force is mediated by an axion-like particle, g_S and g_P are not related to a specific symmetry breaking scale. Thus, no significant constraint (i.e. comparable to experimental sensitivity ranges) on $g_S g_P$ can be deduced from current EDM limits [16] for the case of a generic boson being the interaction mediator.

Our measurement with ultracold neutrons is particularly sensitive to axion-like particles with a mass in the range of roughly 10 meV to 100 meV coupling to fermions. It also matches the mass range targeted by helioscopes such as CAST [17] which would be sensitive to axion-like particles coupling to photons.

3. The measurement with the nEDM apparatus

The experiment is performed by confining ultracold neutrons (UCN) of energies below 160 neV [18,19] in a cylindrical storage chamber with vertical axis at the center of the nEDM apparatus. The dimensions of the storage chamber and some specific features are shown in Fig. 2. A homogeneous vertical magnetic holding field of $\sim$1 µT is applied with a $\cos\theta$-coil wound around the horizontally cylindrical vacuum tank. This vacuum tank is enclosed by a four-layer magnetic shielding [20] and an active magnetic field stabilisation system for the external magnetic field [21].

Spin-polarized UCN are filled into the storage chamber approximately every 340 s where they precess freely for 180 s during the described measurements. The precession frequency is inferred using Ramsey's method [2]. The spins of polarized ^{199}Hg atoms precess simultaneously in the same volume allowing to correct the Larmor precession frequency of the neutrons for potential, small magnetic field fluctuations which can occur inside the four-layer magnetic shielding made of µ-metal.

We search for a signature of a spin-dependent interaction between polarized particles inside the storage chamber and the unpolarized wall of this chamber. This interaction can be described