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Published in:
Physics Letters B

DOI:
10.1016/j.physletb.2012.04.069

Publication date:
2012

Document Version
Peer reviewed version

Link to publication

Citation for pulished version (HARVARD):
Sarrazin, M, Pignol, G, Petit, F & Nesvizhevsky, VV 2012, 'Experimental limits on neutron disappearance into another braneworld', *Physics Letters B*, vol. 712, no. 3, pp. 213-218. https://doi.org/10.1016/j.physletb.2012.04.069

Experimental limits on neutron disappearance into another braneworld

Michaël Sarrazin[a,*], Guillaume Pignol[b], Fabrice Petit[c], Valery V. Nesvizhevsky[d]

[a]*Department of Physics, University of Namur (FUNDP), 61 rue de Bruxelles, B-5000 Namur, Belgium*
[b]*LPSC, Université Joseph Fourier, CNRS/IN2P3 - INPG, 53 rue des Martyrs, F-38026 Grenoble, France*
[c]*BCRC (Member of EMRA), 4 avenue du gouverneur Cornez, B-7000 Mons, Belgium*
[d]*Institut Laue-Langevin, 6 rue Jules Horowitz, F-38042 Grenoble, France*

Abstract

Recent theoretical works have shown that matter swapping between two parallel braneworlds could occur under the influence of magnetic vector potentials. In our visible world, galactic magnetism possibly produces a huge magnetic potential. As a consequence, this paper discusses the possibility to observe neutron disappearance into another braneworld in certain circumstances. The setup under consideration involves stored ultracold neutrons − in a vessel − which should exhibit a non-zero probability p to disappear into an invisible brane at each wall collision. An upper limit of p is assessed based on available experimental results. This value is then used to constrain the parameters of the theoretical model. Possible improvements of the experiments are discussed, including enhanced stimulated swapping by artificial means.

Keywords: Brane phenomenology, Braneworlds, Matter disappearance, Ultracold neutrons

1. Introduction

According to the braneworld hypothesis, our observable Universe can be considered as a three-dimensional space sheet (a 3-brane) embedded in a larger spacetime with $N > 4$ dimensions (the bulk) [1]. Brane is a concept inherited from high energy physics and unification models. Testing the existence of branes or extra dimensions is therefore becoming a fundamental challenge. Such evidences are expected to be obtained through high energy collisions [2–4], but it has been also demonstrated that some detectable effects could also be observed at low energy [2, 3, 5–20] . This is the topic of the present paper.

Some authors have early underlined or suggested that the particles of the standard model could be able to escape out of our visible world [2, 3, 6]. Many effects can be considered and have been explored until now along this line of thought. For instance, in some approaches, particles are expected to leak into the bulk through a tunnel effect [7]. Other works also considered that fluctuations of our home-brane could yield small bubbles branes, which carry chargeless matter particles (such as neutrons for instance) into the bulk [3]. In another context, other approaches consider some coupling between certain particles of the standard model and some hidden or dark sectors [6, 8–14]. It is sometimes suspected that such hidden sectors could live in other branes. It is the case with the photon-hidden photon kinetic mixing [8–10]. A $U(1)$ field on a hidden brane can be coupled to the $U(1)$ photon field of our brane through a one-loop process in a stringy context [9, 10]. In the mirror world approaches, the matter-mirror matter mixing is also considered (with neutron and mirror neutron [11] for instance) though, in the best of our knowledge, a full derivation through a brane formalism is still lacking. Actually, ultracold neutron (UCN) experiments related to the neutron disappearance are then fundamental since they could allow to quantify or to distinguish among the different predicted phenomenologies [21, 22].

In previous works [15–19], two of the present authors (Sarrazin and Petit) have shown that for a bulk containing at least two parallel 3-branes hidden to each other, matter swapping between these two worlds should occur. The particle must be massive, can be electrically charged[1] or not, but must be endowed with a magnetic moment. This swapping effect between two neighboring 3-branes is triggered by using suitable magnetic vector potentials. More important, this new effect − different from those previously described in literature − could be detected and controlled with present day technology which opens the door to a possible experimental confirmation of the braneworld hypothesis. For charged particles, the swapping is possible though a few more difficult to achieve [17]. As a consequence, for a sake of simplicity and in order to be able to distinguish the swapping effect with other kind of predicted phenomena, we suggested the use of neutron for a prospective experiment.

In the present work we discuss the possibility that an astrophysical magnetic vector potential could lead to such a matter

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*Corresponding author

Email addresses: `michael.sarrazin@fundp.ac.be` (Michaël Sarrazin), `guillaume.pignol@lpsc.in2p3.fr` (Guillaume Pignol), `f.petit@bcrc.be` (Fabrice Petit), `nesvizhevsky@ill.eu` (Valery V. Nesvizhevsky)

[1] The model used in the present work can be proved and derived [15] from a domain wall approach in which the Dvali-Gabadadze-Shifman mechanism [23] is responsible for the gauge field localization on the brane. This mechanism allows electric charge leaks [23] contrary to other models, such as the bubble brane approach [3] for instance.

Preprint submitted to Physics Letters B *May 16, 2012*

swapping. The basic argument is that the astrophysical vector potentials are considerably larger than any other counterpart generated in a laboratory. A possible consequence for free neutrons would be then high frequency and small amplitude oscillations of the matter swapping probability between the two branes. Ultracold neutrons stored in a vessel would therefore have a non-zero probability p to escape from our brane toward the hidden brane at each wall collision. Such a process would be perceived as a neutron disappearance from the point of view of an observer located in our brane. The purpose of this paper is to assess an upper limit on p based on already published data in literature. This upper limit is then used to constrain the parameters of the model. On the basis of this assessment, more sensitive experiments are suggested and described.

In section 2, the model describing the low-energy dynamics of a neutron in a two-brane Universe is recalled. The conditions leading to matter swapping between branes are given. We discuss the origin − and the magnitude − of the ambient magnetic vector potential, which is required to observe matter exchange between branes. The gravitational environment that can impede the swapping to occur, is also discussed. In section 3, available data from literature are analyzed and used to constrain the parameters of the two-brane Universe model. Finally, in section 4 improvements of the experimental setup are suggested. A variable-collision-rate experiment is proposed. A long timescale experiment as well as a laser-induced matter swapping experiment are also discussed.

2. Matter swapping between two braneworlds

In previous works [15, 16], it was shown that in a Universe containing two parallel braneworlds invisible to each other, the quantum dynamics of a spin−1/2 fermion can be described by a two-brane Pauli equation at low energies. For a neutron outside a nucleus, in electromagnetic and gravitational fields, the relevant equations can be written as [15]:

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\psi_+\\ \psi_-\end{pmatrix}=\{\mathbf{H}_0+\mathbf{H}_{cm}\}\begin{pmatrix}\psi_+\\ \psi_-\end{pmatrix} \tag{1}$$

where the indices ± are purely conventional and simply allow to discriminate the two branes. ψ_+ and ψ_- are usual Pauli spinors corresponding to the wave functions in the (+) and (−) branes respectively, and where

$$\mathbf{H}_0=\begin{pmatrix}\mu\sigma\cdot\mathbf{B}_++V_+ & 0\\ 0 & \mu\sigma\cdot\mathbf{B}_-+V_-\end{pmatrix} \tag{2}$$

and

$$\mathbf{H}_{cm}=-ig\mu\begin{pmatrix}0 & \sigma\cdot\{\mathbf{A}_+-\mathbf{A}_-\}\\ -\sigma\cdot\{\mathbf{A}_+-\mathbf{A}_-\} & 0\end{pmatrix} \tag{3}$$

such that $\mathbf{A}_+$ and $\mathbf{A}_-$ correspond to the magnetic vector potentials in the branes (+) and (−) respectively. The same convention is applied to the magnetic fields $\mathbf{B}_\pm$ and to the gravitational potentials $V_\pm$. μ is the magnetic moment of the particle. Each diagonal term of $\mathbf{H}_0$ is simply the usual Pauli Hamiltonian for each brane. In addition to these usual terms, the two-brane Hamiltonian comprises also a new term $\mathbf{H}_{cm}$ fully specific of a Universe with two branes [15]. $\mathbf{H}_{cm}$ implies that matter exchange between branes depends on the magnetic moment and on the difference between the local (i.e. on a brane) values of the magnetic vector potentials. $\mathbf{H}_{cm}$ leads to a phenomenology which shares some similarities with the mirror matter paradigm [6, 11–13] or other approaches involving some hidden or dark matter sectors [14]. Nevertheless the present approach differs in several ways:

- In the mirror (or hidden) matter formalism, it is often considered by implication that only one four-dimensional manifold exists and that particles split into two families: the standard and the mirror sectors. By contrast, in the present model, particles are restricted to those of the standard model but they have access to two distinct 3-branes (i.e. two distinct four-dimensional manifolds). As a consequence, in the mirror matter approach, matter and mirror matter particles undergo the same gravitational fields (i.e. $V_+ = V_-$) [2] whereas in the present braneworld approach, matter is subjected to the gravitational fields of each brane (i.e. $V_+ \neq V_-$) that possess their own gravitational sources.
- The coupling between the particles of each brane occurs in a specific way without recourse of the coupling considered in the mirror matter concept. The coupling term $\mathbf{H}_{cm}$ is specific to the braneworld approach [15]. Since its value can be changed by modifying the local value of the magnetic vector potential, it can be consequently controlled by artificial means. The effects related to $\mathbf{H}_{cm}$ [18, 19] can be then distinguished from those related to coupling from other models [11, 12].

However, instead of considering artificial (i.e. generated in a laboratory) vector potentials we are now focusing on the case of an ambient magnetic potential with an astrophysical origin (section 2.1). Let $\mathbf{A}_{amb} = \mathbf{A}_{amb,+} - \mathbf{A}_{amb,-}$ be the difference of ambient magnetic potentials of each brane[3]. Assuming that $\mu B_\pm \ll V_\pm$, i.e. one can neglect the magnetic fields in the branes (especially one assumes that $\nabla\times\mathbf{A}_{amb} = \mathbf{0}$), then by solving the Pauli equation, it can be shown that the probability for a neutron initially localized in our brane to be found in the other brane is:

$$P=\frac{4\Omega^2}{\eta^2+4\Omega^2}\sin^2\left((1/2)\sqrt{\eta^2+4\Omega^2}t\right) \tag{4}$$

where $\eta = |V_+ - V_-|/\hbar$ and $\Omega = g\mu A_{amb}/\hbar$. Eq. (4) shows that the neutron in the potential A_{amb} undergoes Rabi-like oscillations between the branes. Note that the probability does

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[2] Note that, in a recent paper [24] and in a different context related to the dark matter gravity, Berezhiani *et al* suggested that matter and mirror matter could not necessarily feel exactly the same gravitational interaction in the context of a bigravity approach.

[3] Usually, assessment of the value and direction of this cosmological magnetic potential field is ambiguous because it has no physical meaning in non-exotic gauge invariant physics. But in the present context the difference of the field between both branes would become physical.

not depend on the neutron spin state by contrast with the magnetic vector potential direction in space. As detailed in previous papers [17, 18], the environmental interactions (related to $V_\pm$) are usually strong enough to almost suppress these oscillations. This can be verified by considering Eq. (4) showing that P decreases as η increases relatively to Ω. Since no such oscillations have been observed so far, we can assume that the ratio Ω/η is usually very small. As a consequence, the oscillations present a weak amplitude and a high angular frequency of the order $\eta/2$. Let us now consider a neutron gas in a vessel. In the general case, it is in a superposition of two states: neutron in our brane vs. neutron in the other brane. A collision between the neutron and a wall of the vessel acts therefore as a measurement and the neutron collapses either in our brane with a probability $1-p$ or in the other invisible brane with a probability p. It is therefore natural to consider that the neutron swapping rate Γ into the other brane is related to the collision rate γ between the neutron and the vessel walls, i.e.

$$\Gamma = \gamma p \tag{5}$$

with $\gamma = 1/\left\langle t_f \right\rangle$ where $\left\langle t_f \right\rangle$ is the average flight time of neutrons between two collisions on vessel walls. The probability p is the average of P according to the statistical distribution of the free flight times, i.e.

$$p = \langle P \rangle \sim \frac{2\Omega^2}{\eta^2} \tag{6}$$

Equations (5) and (6) are valid provided a large number of oscillations occur during a given time interval. This must be verified for $\left\langle t_f \right\rangle$ (i.e. $\eta \gg \gamma$) but also during the duration δt of a neutron collision on a wall (i.e. $\eta \gg 1/\delta t$) [4]. As shown hereafter, the lowest considered energies $\eta\hbar$ are about 10^{-2} eV, i.e. $\eta \approx 2 \times 10^{13}$ Hz, while $1/\delta t \approx 2 \times 10^{8}$ Hz and the greatest values of γ are about 20 Hz. As a consequence, the Eqs. (5) and (6) are legitimate in the present context.

2.1. Ambient magnetic vector potential

Let us now consider that a natural astrophysical magnetic vector potential $\mathbf{A}_{amb}$ may have on the neutron dynamics in the vessel. The magnitude of such a potential was recently discussed in literature since it allows to constrain the photon mass [26, 27]. Of course, in the present work, we are not concerned by such exotic property of photon, which is assumed to be massless. $\mathbf{A}_{amb}$ corresponds typically to a sum of individual contributions coming from astrophysical objects (star, planet, galaxy,...) that surround us. Indeed, each astrophysical object endowed with a magnetic moment $\mathbf{m}$ induces a magnetic potential:

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi}\frac{\mathbf{m}\times\mathbf{r}}{r^3} \tag{7}$$

from which the magnetic field $\mathbf{B}(\mathbf{r}) = \nabla\times\mathbf{A}(\mathbf{r})$ produced by the object can be deduced. We get $A \sim RB$ where R is the typical distance from the astrophysical source. In the vicinity of Earth for instance, and at large distances from sources, we note that $\mathbf{A}$ is then almost constant (i.e. $\nabla\times\mathbf{A}_{amb} \approx \mathbf{0}$) and cannot be canceled with magnetic shields [26]. The magnitude of the main expected contributions to $\mathbf{A}_{amb}$ can be easily deduced. For instance, the Earth contribution to A_{amb} is about 200 T·m while it is only 10 T·m for the Sun [26]. Now, if we consider the galactic magnetic field **(**about 1 μG [28]**)** relatively to the Milky Way core **(**at about 1.9×10^{19} m**)** one gets $A \approx 2\times10^{9}$ T·m [26, 27]. Note that in Refs. [26] a value of $A \approx 10^{12}$ T·m was derived for the Coma galactic cluster. Unfortunately, other authors (see Goldhaber and Nieto in Ref. [27] for instance), underlined that substantial inhomogeneities can exist in the field distributions such that A_{amb} may strongly vary in different regions. As a consequence, there is a lack of knowledge concerning the magnitude of contributions from extragalactic scales [27, 29]. Therefore the value given in [26] cannot be presently considered as reliable enough to be used here. In addition, Eq. (3) shows that it is the difference $\mathbf{A}_{amb} = \mathbf{A}_{amb,+} - \mathbf{A}_{amb,-}$ between the vector potentials of the two braneworlds that is relevant. Since $\mathbf{A}_{amb,-}$ depends on unknown sources in the other brane, we cannot assess its value. For all these reasons, we should consider $\mathbf{A}_{amb}$ as an unknown parameter of the model. Nevertheless, we will admit that a value of $A_{amb} \approx 2\times10^{9}$ T·m is probably of the right order of magnitude [26, 27].

2.2. Gravitational potential η

In the present context, $\eta = |V_+ - V_-|/\hbar$ and only gravitational interactions are relevant. It is difficult to specify the value of $\eta\hbar$. Indeed, since the gravitational contribution of the hidden world (V_-) is unknown, η must be therefore an unknown parameter of the model. However, according to the estimations given in previous works [17], V_+ could be of the order of 500 eV due to the Milky Way core gravitational potential acting on neutron. By contrast, the Sun, the Earth and the Moon contribute for about 9 eV, 0.65 eV and 0.1 meV. As a consequence, one can fairly suppose that the value of η is included in a range from few meV up to few keV.

At last, one notes that η must be also time-dependent. Let us consider the significant motion of Earth around the Sun. Owing to the Sun gravitational potential only, the energy of a neutron varies from 9.12 eV to 9.43 eV between the aphelion and the perihelion. This corresponds to an absolute shift of η of about 1.7 meV per day. Of course, the full time-dependence of η could also have other origins. For instance, the relative neutron motion with respect to the unknown matter distribution in the hidden brane. Nevertheless, it seems unlikely that our own solar system is "close" enough to a similar mass distribution (in the other brane) to induce a time-dependence on a timescale of the order of one day or one year. In this context, the most likely time-dependence will be induced by the Earth motion around the Sun, such that $\Delta\eta \approx 0.31$ eV on one year. From Eq. (6), one can then expect a relative variation of the measured probability p about $\Delta p/p \sim 2\Delta\eta/\eta$. If the neutron oscillation between branes is detected and presents an annual dependence through Δp, since we can estimate $\Delta\eta$ we can therefore expect specifying the value of η.

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[4] δt can be estimated as the time needed for a neutron to make a round trip along the penetration depth d of the wall (typically $d \approx 10$ nm [25]). With $\delta t \sim 2d/v$ (where v is the UCN velocity, here $v \approx 4$ m·s^{-1}), one gets $\delta t \approx 5$ ns.

Experiment	τ_{st}[s]	γ[Hz]	$p_{\max} \times 10^6$
Mampe *et al* [33]	713	17	16 ± 2
Nesvizhevsky *et al* [34]	875	4	5 ± 1
Arzumanov *et al* [35]	780	9	17 ± 4
Serebrov *et al* [36]	873	2.6	6 ± 1
Pichlmaier *et al* [37]	771	13	13 ± 1

Table 1: Summary of UCN storage experiments, with measured UCN storage time and wall collision rate taken from the original literature. The maximum loss probability at wall collision is derived for each experiment.

3. Measurements and analysis

3.1. Limit of the swapping probability

In a typical experiment, ultracold neutrons are stored in a bottle, with a mean wall collision rate γ which is typically in the range from 1 Hz to 100 Hz. The number of stored neutrons decays by following a nearly exponential law with a decay time τ_{st}. This storage time τ_{st} is measured by counting the remaining neutrons after a storage period of variable duration. The inverse of the storage time is the sum of the neutron beta decay rate and the loss rate due to wall collisions:

$$\frac{1}{\tau_{\text{st}}} = \Gamma_\beta + \Gamma_{\text{loss}} + \gamma p \tag{8}$$

Here we have separated the contribution from the normal loss rate Γ_{loss} (due to inelastic scattering of neutrons at the surface for example) and that corresponding to a disappearance in the other brane γp.

The purpose of trap experiments is to measure the beta decay lifetime of the neutron $\tau_n = 1/\Gamma_\beta$, by extrapolating the storage time to the ideal case where there is no extra losses. The extrapolation procedure is far from trivial and, as stated in the Particle Data Group compilation [30], the different experimental results are contradictory. Here we reinterpret some of the performed experiments to provide an upper limit on the exotic disappearance probability p.

Since the extrapolation procedure is in question, we will not try to account for the normal losses. Instead we shall attribute all the losses to the exotic phenomenon, and treat the obtained value for the loss as an upper limit on p: $\Gamma_{\text{loss}} + \gamma p < \gamma p_{\text{lim}}$. This way the presented analysis is not concerned by the present dispute about the neutron decay lifetime (the normal losses certainly satisfy $\Gamma_{\text{loss}} > 0$!).

The idea of the analysis is to compare the neutron decay rate measured in the absence of brane swapping and the storage time of stored ultracold neutrons where swapping occur at a rate γp. When measuring τ_n with the beam method, one really measures the beta decay channel: one measures the absolute proton activity of a cold neutron beamline. Byrne *et al* [31] measured the rate of proton production of a well-defined section of a cold neutron beam at the ILL and have reported a neutron lifetime of $\tau_n = 889.2 \pm 4.8\,\text{s}$. Using the same improved technique, Nico *et al* [32] measured $\tau_n = 886.3 \pm 3.4\,\text{s}$. The two independent results can be combined:

$$\tau_n = 887.3 \pm 2.8\,\text{s} \tag{9}$$

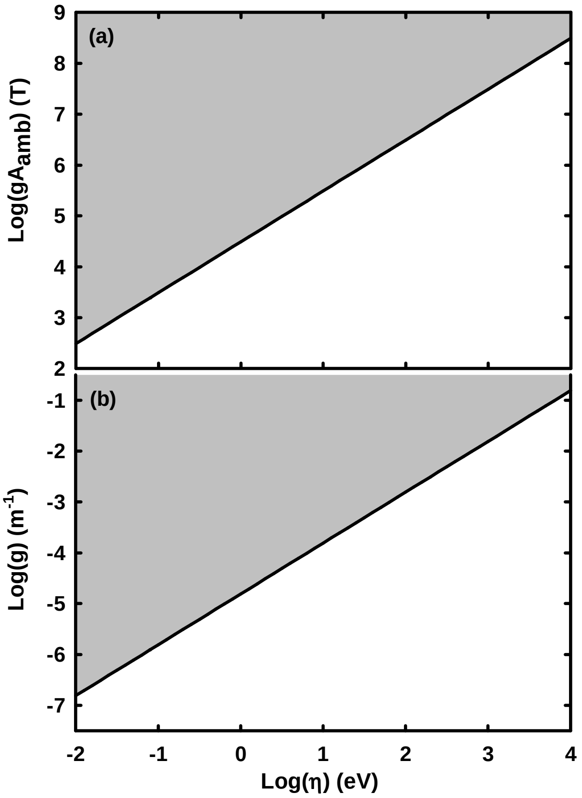

Figure 1: Experimental limits against the confinement energy $\eta\hbar$ of gA_{amb} (a) and g (b) for $A_{amb} = 2 \times 10^9$ T·m. Grey domains are excluded.

Next we consider the UCN trap experiments [33, 35–37] performed at the ultracold neutron beamline PF2 at the Institut Laue Langevin, using UCN traps coated with fluorinated polyether oil (Fomblin). We also consider the experiment [34] performed at the Saint Petersburg Institute of Nuclear Physics using a trap coated with solid Oxygen. In these experiments, the geometry of the UCN trap could be changed (thus changing γ) and several measurements of τ_{st} are done corresponding to different γ values. Table 1 shows the results extracted from the publications using only the data with the best storage time. In the last column, the maximal allowed probability for a neutron to escape in the other brane p_{lim} is extracted for each storage experiment using (8) and the pure beta decay lifetime value (9).

This analysis allows us finally to conclude

$$p < 7 \times 10^{-6} \qquad \text{(at 95\% C.L.)} \tag{10}$$

This conservative bound could be made even more robust by considering also τ_n value extracted from magnetic trapping of UCNs when available. Indeed, when neutrons are magnetically trapped they cannot swap to the other brane, thus the lifetime value measured with magnetic traps could eventually be combined with the beam average (9).

3.2. Constraints on g and η

As a consequence of Eqs. (6) and (10), it becomes possible to constrain the values of the coupling constant g between the two braneworlds, and also the environmental potential η. Fig.

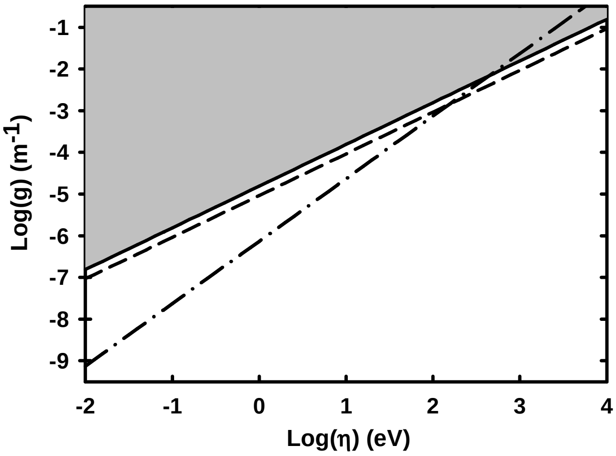

Figure 2: Solid line: Experimental limits for the coupling constant g against the confinement energy $\eta\hbar$. Dashed-doted line: expected limits for a yearly experiment. Dashed line: expected limits for a resonant experiment (laser-induced). Grey domain is excluded.

1a shows gA_{amb} limits as a function of the confining energy η. Similarly, Fig. 1b shows the limit for g and varying η (assuming $A_{amb} = 2 \times 10^9$ T·m). The resulting constraint is much better than our previous assessment in earlier works where the upper limit of g was obtained from considerations about millicharged particles [16]. In this case, it was shown that the upper constraint on millicharge $q = \pm\varepsilon e$ is given by $\varepsilon = (g/2m_e)^2$ (e is the absolute value of the electron charge and m_e the electron mass). From Ref. [16], we get $g < 3 \times 10^{10}$ m^{-1} from the millicharge constraint $\varepsilon < 4.1 \times 10^{-5}$ [38]. Even with more recent and stringent constraints [13, 39], we get $g < 9 \times 10^7$ m^{-1} from $\varepsilon < 3 \times 10^{-10}$ (see Berezhiani and Lepidi in Ref. [39]). As a result, ultracold neutron experiments appear as a relevant approach to constrain g (Some other possibilities are not considered for obvious reasons[5] [40, 41]).

4. Further experiments

4.1. Variable-collision-rate experiment

The most simple further experiment relies on a device with variable geometry, such that the ratio *volume/surface* of the vessel can be controlled. The collision rate γ then varies as the geometrical ratio. Obviously, the broader the sampling of γ is, the more accurate the knowledge of p. Moreover, for a given collision rate, the statistical sensitivity on the loss probability is

$$\Delta p = \frac{1}{\gamma}\frac{\Delta\tau}{\tau_n^2} \tag{11}$$

It is then relevant to increase the value of γ to decrease Δp. For instance, the statistical sensitivity of present UCN storage experiments is about $\Delta\tau \approx 1$ s when measuring the neutron lifetime $\tau_n \approx 900$ s. With a current wall collision rate of $\gamma = 10$ Hz, this translates into $\Delta p \approx 10^{-7}$. By contrast, with $\gamma = 100$ Hz, $\Delta p \approx 10^{-8}$ is a fair reachable sensitivity. Such an experimental approach can be accepted with confidence. Indeed, the lowest considered frequencies of the swapping probability are about 10^{13} Hz in relation to η (see section 2). This is far to the highest expected collision rates, and then Eqs. (5) and (6) are still valid.

4.2. Yearly experiment

As suggested in section 2.2, it would be highly beneficial to perform the experiment on a long timescale (typically one year) to take into account the motion of Earth around the Sun and the related time-dependence of η. Such a motion should lead to a time-modulation of the swapping probability p. If one can detect such a modulation it would be a strong indication that matter swapping really occurs. Indeed, with such an experiment it could be possible to discriminate the exotic losses due to matter swapping from normal losses, which are not time-dependent, in the neutron trap. In addition, if the neutron swapping between braneworlds is detected and presents an annual dependence through Δp, since one can estimate $\Delta\eta$ one could then assess the value of η.

Moreover, a clear benefit of any long time experiment would be to constrain the unknown value of Δp against time. This allows to improve the constraints on gA_{amb} (or g) against η by contrast with experiments related to the upper limit of p only. In the present paper, in order to underline the relevance of the yearly experiment, we can just suggest a test value for the limit of Δp. As shown from (11), $\Delta p \approx 10^{-7}$ when $\gamma = 10$ Hz. Since the uncertainty varies as $1/\sqrt{N}$, $\Delta p \approx 10^{-8}$ is a fair reachable upper experimental limit[6] for a one year experiment.

If we assume that $\Delta\eta \approx 0.31$ eV on one year (see section 2.2) from the above values and since $\Delta p/p \sim 2\Delta\eta/\eta$, we can then further improve the constraint on gA_{amb} (or g) against η. Fig. 2 shows the expected limits for the coupling constant g against η for a yearly experiment (dashed-doted line). The result is compared with that found previously in section 3.1. It becomes obvious that a yearly experiment allows getting a much better assessment of g when $\eta \leq 2(p/\Delta p)\Delta\eta$. The rule is clearly that the weaker the relative uncertainty of p is, the better the constraint is. From the above benchmark values, one deduces that the yearly experiment could offer a better estimation when $\eta \leq 434$ eV by contrast with the present experimental constraints (solid line). For the lower values of η considered here, the gain could reach two orders of magnitude.

4.3. Laser-induced matter swapping

In previous works [17, 18], it has been suggested that a rotative magnetic vector potential could be considered instead of

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[5] Other ways could be expected to constrain g but are not relevant for now. Constraint from the primordial nucleosynthesis [40] cannot be obtained since the value of a primordial cosmological magnetic vector potential cannot be assessed at present. In addition, constraint from disappearance of bound neutrons in nuclei [41] would need for a rigorous expression of the swapping probability in this case. There is no simple relation between the disappearance probabilities of free neutron and neutron in nuclei and this complex topic is far beyond the scope of the present paper [42].

[6] At present, values about 50 neutrons per cm^3 are reachable. 500 neutrons per cm^3 are expected soon. In addition, a one year experiment would allow to obtain at least ten times more of measurements. As a consequence, the number of events N would be hundred times greater than now.

a static one. In that case a resonant swapping occurs with Rabi oscillations given by:

$$P = \frac{4\Omega^2}{(\eta-\omega)^2+4\Omega^2}\sin^2\left((1/2)\sqrt{(\eta-\omega)^2+4\Omega^2}t\right) \qquad (12)$$

where ω is the angular frequency of the magnetic potential. Equation (12) shows that a resonant matter exchange between branes occurs whenever the magnetic vector potential rotates with an angular frequency $\omega = \eta$. Of course, in this case, we do not consider an astrophysical field, and the rotative magnetic potential is supplied by an electromagnetic wave.

In a recent paper [18], it has been suggested that a set of coherent electromagnetic pulses (a frequency comb) could artificially induce the swapping of a neutron into a hidden braneworld. The neutron swapping rate Γ is then given by [18]:

$$\Gamma = K\frac{f_r\tau^2NI}{\eta^2}g^2 \qquad (13)$$

where f_r is the frequency of repetition of the pulses, τ is the pulse duration, N is the number of pulses felt by neutrons, I is the intensity of the pulse. In the above expression, η is given in eV, f_r in GHz, I in PW·cm^{-2}, τ in fs, and $K = \mu^2/(50c\varepsilon_0e^2) \approx 2.74\times10^{-14}$ (in the relevant units).

From the uncertainty on (9), a relevant criterion to confirm the reality of this effect is to achieve $\Gamma \geq \Delta\tau_n/\tau_n^2 = 3\times10^{-3}\cdot\Gamma_\beta$. In Fig. 2, one shows the expected limits for such a resonant experiment assuming that the laser frequency can be continuously tuned (dashed line). This figure was derived assuming the following values for the frequency comb source: $\tau = 1$ ps, $f_r = 100$ GHz, $N = 150$, $I = 10^8$ PW·cm^{-2}. These values are quite usual for some frequency comb sources (see references in [18]). Though the intensity is more specific to certain pulsed sources (see discussions in Refs. [43]), such a value could be achieved for a frequency comb as well. It is striking that the theoretical limit (dashed line) is very close to the present experimental limit (solid line). Due to the regular improvement of laser sources, we expect that such a resonant experiment will become relevant in the next decades by contrast to passive experiments to explore the space of parameters (η, g).

5. Conclusion

Using results from performed experiments, we have assessed an upper limit on the probability for a stored ultracold neutron to disappear into another braneworld. This limit has been used to constrain the parameters of the brane model introduced in recent theoretical works [15–17], which had shown the possibility of matter exchange between two braneworlds invisible to each other. We have discussed the sensibility of further experiments to probe the existence of a neighboring brane through an annual study. It is also suggested that a laser-induced matter swapping towards a hidden braneworld could be tested in the next decades.

Note added in proof

During the process of publication of this paper, we learned about the work of Berezhiani and Nesti [44] whose results could be reminiscent of ours. Nevertheless, the results of Ref. [44] are independent of ours. Indeed, our present work rests on a different physical approach, which is fully specific to the braneworld concept [15]. In addition, our present model allows for enhanced induced matter exchange between parallel braneworlds by artificial means [17, 18]. In this case, the efficiency of the matter swapping rate is not limited and is proportional to the intensity of the available laser sources (see Eq. (13)) [18].

Acknowledgement

The authors are grateful to Gia Dvali and Vladimir Tretyak for their useful advices and comments.

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