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Search for passing-through-walls neutrons constrains hidden braneworlds

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ABSTRACT

In many theoretical frameworks our visible world is a 3-brane, embedded in a multidimensional bulk, possibly coexisting with hidden braneworlds. Some works have also shown that matter swapping between braneworlds can occur. Here we report the results of an experiment – at the Institut Laue-Langevin (Grenoble, France) – designed to detect thermal neutron swapping to and from another braneworld, thus constraining the probability p^2 of such an event. The limit, $p < 4.6 \times 10^{-10}$ at 95% C.L., is 4 orders of magnitude better than the previous bound based on the disappearance of stored ultracold neutrons. In the simplest braneworld scenario, for two parallel Planck-scale branes separated by a distance d, we conclude that $d > 87$ in Planck length units.

Our observable Universe could be a braneworld: a four-dimensional surface embedded in a higher dimensional spacetime (the bulk) [1–7]. This idea is frequently considered in connection with the deepest questions of fundamental physics. In particular, quantum theories of gravity foresee the existence of extra dimensions to describe the spacetime at the Planck scale. Hidden braneworlds are also invoked to solve the hierarchy problem [8–10] or to elucidate the nature of dark matter and dark energy [11–16]. However, empirical evidence supporting braneworlds is currently lacking. In this paper, we report the results of a neutron-passing-through-walls experiment designed specifically to detect neutron swapping to and from another braneworld [17]. Indeed, as detailed hereafter, the theory allows for particles swapping between two adjacent branes in the bulk [17–19]. We used the nuclear reactor of the Institut Laue-Langevin (Grenoble, France): a very bright source of neutrons which possibly also emits neutrons copiously into a hidden braneworld. To detect neutrons swapping back from the hidden world, we used a helium-3 counter shielded against the neutron background of the reactor hall with a rejection factor of about a million. Even without significant excess of events in the detector, we can set a limit on the neutron – hidden neutron swapping probability. Our experiment constitutes a unique experimental window to braneworlds and to Planck scale physics. Beyond braneworlds, our improved bound is relevant for other new-physics scenarios predicting oscillations of the neutron into a sterile particle [20–24]: quite a common concept.

Let us first assume that our 3D world consists in fact of a braneworld – a ξ-thick domain wall – in a higher dimensional bulk [1,6,7] (see Fig. 1a). Standard-Model particles are trapped along this wall which is realized in the bulk as a scalar-field soliton [1], as suggested by the effective field theories relating to the low-energy limit of string theory [6]. Although many braneworlds could coexist within the bulk [5,11–13,15,17–19], in the following we consider a two-brane Universe consisting of two copies of the Standard Model, localized in two adjacent 3D branes (see Fig. 1a). While – for processes below the brane energy scale $\hbar c/\xi$ – these two sectors are mutually invisible to each other at the zeroth-order approximation, matter fields in separate branes mix at the first-order approximation through $\mathcal{L}_c = ig\overline{\psi}_+\gamma^5\psi_- + ig\overline{\psi}_-\gamma^5\psi_+$,

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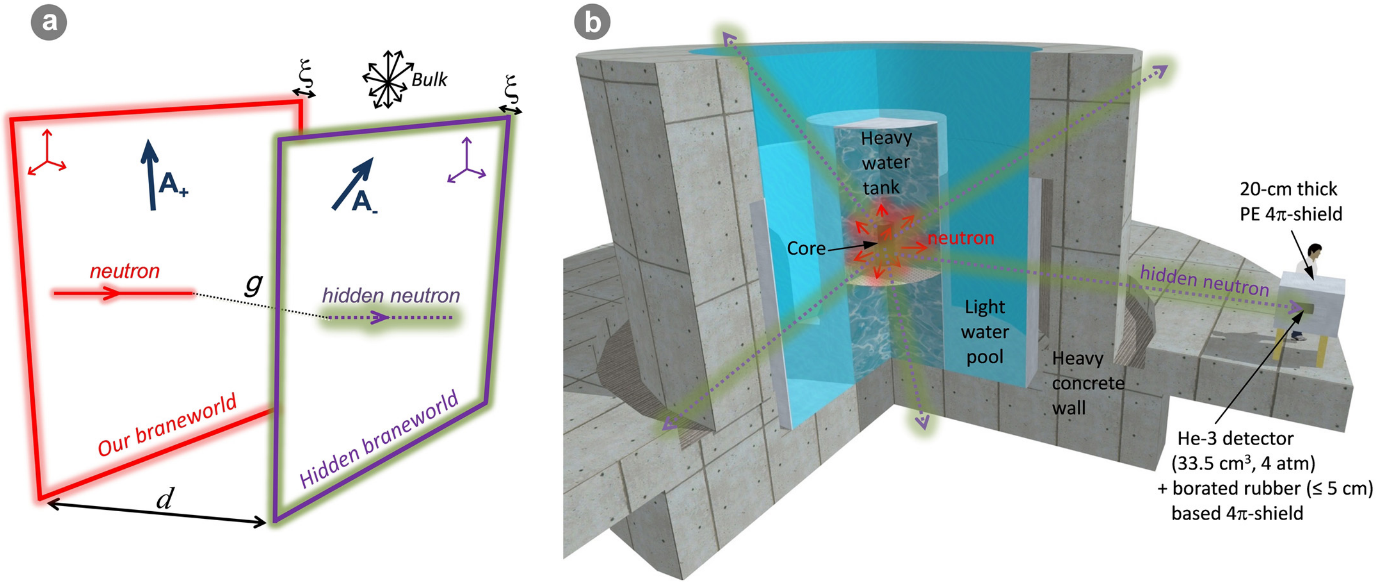

Fig. 1. Scheme of the measurement. (a) Neutron swapping from our braneworld to a hidden one situated at a distance d in the bulk. (b) Simplified scale diagram of the experiment at the Institute Laue-Langevin. The nuclear reactor (thermal power 58 MW) produces a neutron flux of about 1.5×10^{15} neutrons/s/cm^2. A compact fuel element sits in the centre of a 2.5 m diameter tank containing the heavy water moderator. Details such as inserts for neutron beam lines are not shown. The heavy water tank serves as a source of hidden neutrons generated by the ($n + D_2O \to$ hidden $n + D_2O$) scattering processes [17]. The detector is situated behind the biological shielding (1.5 m thick light water and 1.7 m thick dense concrete) at 7.35 m ± 0.15 m from the centre of the reactor and at 30 cm below the median plane. We used a cylindrical helium-3 (+5% of CO_2) counter with a volume of 33.5 cm^3 and a gas pressure of 4 atm at 20 °C. The detector was surrounded by a dedicated multilayer neutron shield. The innermost layer is a cylindrical box made of borated rubber (40% boron content, thickness from 2 cm to 5 cm). The outermost layer is a 20-cm-thick polyethylene box.

where $\psi_\pm$ are the Dirac fermionic fields in each braneworld – denoted $(+)$ and $(-)$ [18]. The interbrane coupling g intrinsically depends on the distance d between branes and on their thicknesses ξ as $g \sim (1/\xi)\exp(-d/\xi)$ [18]. The brane energy scale could be as high as the Planck scale $m_{\mathrm{Pl}} \approx 10^{19}$ GeV: well beyond the reach of direct searches at high energy particle colliders. Still, it is possible to explore the braneworld through matter swapping induced by the coupling g at low energy. Indeed, precision experiments, in particular with neutrons, can be designed to monitor matter disappearance or disappearance–reappearance processes [17,19].

Within the nonrelativistic limit, one can show that a neutron could oscillate between two states, one localized in our brane, the other localized in the hidden world. In fact, the oscillation would be driven by the effective magnetic field $\mathbf{B}_\perp = g(\mathbf{A}_+ - \mathbf{A}_-)$ transverse to the branes, where $\mathbf{A}_\pm$ are the magnetic vector potentials in each brane (see Fig. 1a). Specifically, the interaction Hamiltonian $\mathbf{H}_c$ between the Pauli spinors of the visible and hidden worlds is given by [15,17–19]:

$$\mathbf{H}_c = \hbar\Omega \begin{pmatrix} 0 & \varepsilon \\ \varepsilon^\dagger & 0 \end{pmatrix}, \tag{1}$$

where $\varepsilon = -i\sigma \cdot \mathbf{B}_\perp / B_\perp$ is a unitary matrix acting on the spin, and $\hbar\Omega = \mu_n B_\perp$, μ_n is the magnetic moment of the neutron. Here vector potentials $\mathbf{A}_\pm$ are dominated by the huge ($\sim 10^9$ T m to 10^{12} T m) overall astrophysical magnetic vector potential, related to the magnetic fields of all the astrophysical objects (planets, stars, galaxies, etc.) [25,26]. Since the magnitude of $|\mathbf{A}_+ - \mathbf{A}_-|$ is fundamentally unknown [15,19], the relevant parameter quantifying the coupling between the braneworlds is $B_\perp = g\,|\mathbf{A}_+ - \mathbf{A}_-|$ rather than just g.

Due to the coupling (1) the neutron's wavefunction oscillates between the visible and the hidden states, at an angular frequency η given by the energy difference between both sectors: $\eta\hbar = V_{grav,+} - V_{grav,-}$, where $V_{grav,\pm}$ are the gravitational potential energies felt by the neutron in each brane. It is likely that the energy difference is big ($\eta \gg \Omega$), resulting in very high frequency and low amplitude oscillations. In this case, the mean swapping probability p between the visible and hidden sectors [15,17–19] is given by: $p = 2\Omega^2/\eta^2$.

Here, we present a neutron-passing-through-walls experiment [17] (see Fig. 1b), from which we set an upper limit on the probability p for a neutron to convert into a hidden state. We will then interpret the result in terms of braneworld physics.

A neutron n could transform into a hidden neutron n' when colliding with a nucleus. This process is quantified by the microscopic cross section $\sigma(n + \text{nucleus} \to n' + \text{nucleus}) = (p/2)\sigma_s$ where σ_s is the normal elastic scattering cross section. From a practical point of view, each collision at a nucleus acts as a quantum measurement and the neutron is reduced either in our, visible, world or in the other, invisible, braneworld (to become a hidden neutron) with a probability $p/2$ [17]. Hidden neutrons could, therefore, be generated in the moderator medium of a nuclear reactor, where a high flux of neutrons undergoes many elastic collisions. Being located in another braneworld, these hidden neutrons would interact very weakly with matter and freely escape the reactor. However, the reverse swapping process would permit us to detect them – with an efficiency also proportional to p – using a usual neutron detector located close to the reactor. The disappearance and reappearance of neutrons due to the swapping between braneworlds would lead to the possibility of neutrons passing through a wall.

More precisely, if we know the map of the neutron flux $\Phi_+(\mathbf{r})$ inside the moderator of a nuclear core we can calculate the source term $S_-(\mathbf{r})$; it corresponds to the number of hidden neutrons generated per unit volume and unit time [17]:

$$S_-(\mathbf{r}) = \frac{1}{2}\, p\, \Sigma_s\, \Phi_+(\mathbf{r}), \tag{2}$$

where Σ_s is the macroscopic cross section for elastic scattering. The latter is obtained by multiplying the microscopic cross section σ_s by the number density of nuclei in the moderator. Then, the hidden neutron flux Φ_- at the position $\mathbf{r_d}$ of a detector outside the reactor is given by the standard expression for an extended