Searching hidden neutrons with a reactor neutrino experiment: new constraint from the STEREO experiment

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Different extensions of the Standard Model of particle physics, such as braneworld or mirror matter models, predict the existence of a neutron sterile state, possibly as a Dark Matter candidate. This letter reports a new experimental constraint on the probability \( p \) for neutron conversion into a hidden neutron, set by the STEREO experiment at the high flux reactor of the Institut Laue-Langevin. The limit is \( p < 3.1 \times 10^{-11} \) at 95% C.L. improving the previous limit by a factor 13. This result demonstrates that short-baseline neutrino experiments can be used as competitive passing-through-walls-neutron experiments to search for hidden neutrons.

Since many decades, the existence of sterile or hidden particles interacting only gravitationally or very weakly with the known particles of the Standard Model is considered through many theoretical works \([1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16]\). They could result in dark matter candidates \([1,3,7,13]\) or could shed light on primordial cosmology \([1,5,7,10,12]\). Some of them can be sterile copies of particles of the Standard Model (SM) in our usual spacetime \([1,14]\), allowing for instance for mirror neutrons. Others can be SM particles hidden in a brane lurking in the neighborhood of our visible world in a higher-dimensional bulk \([8,18]\), in particular neutrons \([13,16]\). In the following, hidden neutron will be used as a generic term.

Visible neutrons \( n \) can convert into hidden neutrons \( n' \) and several experiments search for neutron disappearance \([13,14]\). Hidden neutrons can also convert into visible neutrons. As a result, \( n \rightarrow n' \rightarrow n \) processes allow for neutron disappearance-reappearance experiments. In the last five years, dedicated passing-through-walls-neutron experiments \([27,28]\) have been developed in the vicinity of nuclear research reactors in order to test those scenarios. In this Letter, we use the STEREO experiment \([30]\) installed near the nuclear reactor of the Institut Laue-Langevin (ILL) in Grenoble (France) to derive a new constraint on the neutron/hidden neutron swapping probability, demonstrating that short-baseline neutrino experiments \([31,34]\) are opportunistic but competitive passing-through-walls-neutron experiments, thanks to their ability to detect neutrons. New upper bounds on the coupling parameters between the hidden state and visible state are also inferred.

The two-level Hamiltonian \( \mathbf{H} \) describing the present problem can be written as \([11,28]\):

\[
\mathbf{H} = \begin{pmatrix}
E_v & \varepsilon \kappa \\
\varepsilon \kappa^* & E_h
\end{pmatrix},
\]

where \( E_v \) and \( E_h \) are the energies in vacuum of the visible and hidden states, respectively, \( \varepsilon \) is the coupling parameter between the visible and hidden states, and \( \kappa \) is a unitary matrix whose exact expression depends on the physics behind but does not change the phenomenology \([11,12]\).

When neutrons travel through a medium, the production rate of hidden neutrons is governed by both the Hamiltonian \( \mathbf{H} \) and the neutron-nuclei collision rate \( \Gamma \) which writes \( \Gamma = v \Sigma_S \) with \( v \), the neutron velocity and \( \Sigma_S \) the macroscopic cross section for neutron scattering in the medium. The collisions act as quantum projection in visible and hidden states but the rate of quantum projection is \( \Gamma/2 \). The factor 1/2 comes from the fact that collisions project only the visible state. This picture is supported by the full treatment of the density matrix evolution with a Lindblad equation \([3,27]\). The neutron/hidden neutron swapping probability \( p \) at each projection can be obtained by solving Lindblad equations or by following the quantum projection approach:

\[
p = \frac{2\varepsilon^2}{(\Delta E + V_F)^2 + 4\varepsilon^2 + \hbar^2 \Gamma^2 / 4},
\]

provided that \( p \ll 1 \) \([27]\), and where \( \Delta E = E_v - E_h \) is the degeneracy-lifting energy difference between visible and hidden states. The Fermi potential \( V_F \) of the visible neutron in the medium is added to describe the neutron-medium interaction \([35]\).
For a free neutron, Eq. 2 matches with the related time-averaged Rabi probability usually measured in earlier experiments [26].

At a macroscopic scale, the hidden neutron source term (number of hidden neutrons produced per unit volume and per unit time) is obtained by multiplying the swapping probability \( p \) by the volumic rate of projections in the source:

\[
S_h(r) = p \frac{\sum S}{2} \Phi_v(r),
\]

(3)

where \( \Phi_v(r) \) is the visible neutron flux. Thus, a huge number of coherent neutron-nuclei scatterings allows to enhance the probability to get the neutron into a hidden state in contrast to a free motion in vacuum. Then, neutrons from the reactor core could disappear and freely escape the reactor. At a position \( r_d \), the hidden neutron flux can be written [27]:

\[
\Phi_h(r_d) = \frac{1}{4\pi} \int_{\text{Reactor}} \frac{S_h(r)}{|r - r_d|^2} d^3r.
\]

(4)

Similarly, the reverse effect allows neutron reappearance in a detector located close to the reactor. By measuring the neutron flux inside a detection volume shielded from ambient neutrons [27], it is possible to infer the swapping probability, or to set an upper limit, provided the knowledge of the neutron flux \( \Phi_v \) in the reactor. The sensitivity of this kind of experiments mainly relies on the volume of material enhancing the conversion of hidden neutrons, on the neutron detection efficiency and particularly on the ability to avoid as much as possible any background sources. Considering reactor antineutrino experiments, neutrino detection is based on the Inverse Beta Decay (IBD) reaction, \( \bar{\nu} + p \rightarrow n + e^+ \), where a delayed-coincidence approach is used with positron detection followed by the detection of the signal from the neutron capture in Gd or Li loaded scintillator [30–34]. Since these experiments are designed to maximize the neutron detection efficiency and usually use large-volume detectors to increase neutrino detection rate, it is then natural to explore the use of short baseline neutrino experiments as passing-through-walls neutron experiments.

The Stereo experiment (see Fig. 1) was located at about 10 m from the center of the High Flux Reactor of the ILL operated with a 93% \(^{235}\text{U}\) enriched fuel and heavy water as moderator. The reactor core consists of a single compact fuel element (80 cm high, 40 cm diameter) at the center of a heavy-water tank (1.8 m high, 2.5 m diameter). The neutron flux map within the reactor \( \Phi_v(r) \) has been evaluated for [28], using convenient numerical computations with Monte Carlo N-Particle transport code (MCNP). At nominal power (58.3 MWth), the neutron flux inside the moderator is comprised between about \( 10^{14} \) and \( 1.5 \times 10^{15} \) neutrons per cm\(^2\) per second, which is one of the highest continuous fluxes worldwide. It is largely dominated by thermal neutrons, except in the vicinity of the fuel cylinder, and decreases very fast outside the heavy water tank. Given these results, we can consider the elastic scattering of thermal neutrons in
heavy water, for which the macroscopic cross section is \( \Sigma_{Gd}^{Sc} = 0.49 \text{ cm}^{-1} \) [39], as the dominating hidden neutron conversion mechanism. Neglecting higher energy neutrons and neutron scattering in the light water tank are conservative assumptions.

Since a simplified geometry was implemented in our simulation, we consider a systematic uncertainty of 20%, corresponding to the maximum observed discrepancy when comparing with the neutron flux from a full geometry simulation, available only in the median plane [28]. This systematic uncertainty on the neutron flux could be improved by running a precise simulation but would not change our final result which is limited by other uncertainties as shown below. All other systematic uncertainties related to the hidden neutron source, e.g. the time variations due to the fuel evolution, are negligible, at the percent level or below [30].

The STEREO detector [30] is made of different volumes. The innermost part, the target, is a \( 2 \text{ m}^3 \) acrylic aquarium divided in 6 identical cells and filled with liquid scintillator doped with gadolinium (Gd) to detect the thermal neutrons via the radiative capture which emits a gamma cascade with a total energy of about 8 MeV. The target is surrounded by an outer crown of 37 cm thickness, namely the gamma-catcher, divided in four cells and filled with liquid scintillator without Gd. It ensures a better detection efficiency of the gammas from positron annihilation and neutron capture which can escape the target. For both volumes, the scintillation light is read out from top with a total of 48 photomultipliers. The gamma-catcher vessel is positioned inside a shielding made of borated polyethylene, lead and boron-loaded rubber (B4C) to mitigate gamma and neutron backgrounds. On the top of the shielding, a water Cerenkov detector is installed as muon veto.

In the standard neutrino selection [37], neutron capture events are tagged requiring a reconstructed energy in the whole detector between 4.5 and 10 MeV. The lower bound was chosen to accept also neutrons whose part of gammas escape the detector or depose their energy in non-scintillating components. The request of a time correlation between the prompt and delayed events of IBD candidates rejects most of the gamma background, important at these energies. In the case of the hidden neutrons converting into visible thermal neutrons, we expect only single events. We optimize the signal to background ratio by using a 7 to 10 MeV energy window.

STEREO was installed at the surface level and, even if it profits from 15 m.w.e. overburden from the building and a water transfer channel of the reactor, cosmic induced events constitute a significant part of the neutron background. To reject them, we require no other event in the detector nor in the muon veto in a time window \( \pm 400 \mu \text{s} \) around the neutron events. The time window size has been defined by optimizing the signal to background ratio. This anti-coincidence selection generates a dead-time of about 50% during ON periods. The precision of the dead time correction is at the percent level.

To be detected, the hidden neutrons have first to be converted into visible neutrons. The conversion can happen either via an elastic scattering in the materials of the detector, namely the liquid scintillator, or directly via a capture on gadolinium. The former process is more probable, \( \Sigma_{Gd}^{Calc} = 1.90 \text{ cm}^{-1} \) [41] compared to \( \Sigma_{C}^{Calc} = 0.33 \text{ cm}^{-1} \) [42], whereas the latter has a slightly larger detection efficiency since regenerated thermal neutrons can escape the target volume or be captured on hydrogen.

We denote \( \epsilon_i \) (\( r_d \)), the detection efficiency of a thermal neutron, regenerated at the position \( r_d \), to be detected in the target cell \( i \) and \( \epsilon_i (r_d) \), the detection efficiency of a neutron swapped back directly through a capture on gadolinium at the position \( r_d \) whose vertex is reconstructed in the cell \( i \).

Therefore, the detection rate in the target cell \( i \) can be written as an integral over the detector:

\[
\Gamma_i = \int_{Det} \left( \frac{\Sigma_{Sc}^{Calc}}{2} \epsilon_i (r_d) + \frac{\Sigma_{Gd}^{Calc}}{2} \epsilon_i (r_d) \right) \Phi_h (r_d) d^3 r_d
\]

To simplify the computation, the integral can be replaced by a Riemann sum on the target and gamma-catcher cells. The cell thickness, 37 cm, is small enough, compared to the distance to the core, to assume that the hidden neutron flux is constant within each cell.

Detection efficiencies have been computed using the STEREO GEANT4 simulation code which has been extensively tested using gamma and neutron calibrations and validated at the percent level [37]. Particularly, the use of the FIFRELIN code improved significantly the Gd gamma cascade simulation [38]. For \( \epsilon_i (r_d) \), thermal neutrons have been generated in the whole detector, including the shielding. Indeed, as shown in [29], the shielding materials, and particularly the lead, can enhance the hidden neutron sensitivity. In our case, it appears that the lead is too far from the target, all regenerated neutrons are captured in the boron-loaded polyethylene. The neutron detection efficiency of a given cell is constant only when the neutron is regenerated in this cell (between 29.9% and 33.4% depending on the cell) or in the adjacent cells (between 1.6% and 4.4%). To compute \( \epsilon_i (r_d) \), we select from the same simulation the Gd captures. As expected, the values are slightly higher (between 32.1% and 35.8% for the vertex cell, between 3.6% and 4.5% for the adjacent cells). The relative uncertainties on the efficiencies are comprised between 1% and 3%.

The STEREO experiment has been taking data for 387 days of reactor ON between 2017 and 2020, distributed in three phases [39]. However, the whole period is not suited for the hidden neutron search. During phase-I, detector defects (repaired for the next phases) prevented an accurate simulation of the absolute efficiency of all cells.

This systematic uncertainty on the neutron flux could be estimated using the FIFRELIN code improved significantly the Gd gamma cascade simulation [38]. For \( \epsilon_i (r_d) \), thermal neutrons have been generated in the whole detector, including the shielding. Indeed, as shown in [29], the shielding materials, and particularly the lead, can enhance the hidden neutron sensitivity. In our case, it appears that the lead is too far from the target, all regenerated neutrons are captured in the boron-loaded polyethylene. The neutron detection efficiency of a given cell is constant only when the neutron is regenerated in this cell (between 29.9% and 33.4% depending on the cell) or in the adjacent cells (between 1.6% and 4.4%). To compute \( \epsilon_i (r_d) \), we select from the same simulation the Gd captures. As expected, the values are slightly higher (between 32.1% and 35.8% for the vertex cell, between 3.6% and 4.5% for the adjacent cells). The relative uncertainties on the efficiencies are comprised between 1% and 3%.
The computed detection efficiencies hold only for phase-II and phase-III. Moreover, the neutron background at the STEREO location varies a lot, by more than two orders of magnitude, depending on the running conditions of the neighboring experiments. A BF$_3$ counter located on top of the muon veto monitored the neutron rate outside the shielding. During ON periods, the measured rates range between a few neutrons per second to a few hundreds neutrons per second and are strongly correlated with the neutron rates in the target cells. Thus, we only consider periods where the BF$_3$ counting rate is below 5 neutrons per second, averaged per 1 h slot. For these periods, Fig. 2 shows the evolution of neutron rates for each cell.

The seven ON periods are clearly visible with higher and fluctuating rates while the rates are almost constant during OFF periods in-between. Cells 1 and 6 present higher rates because they are less shielded than the center cells. Two main conclusions can be drawn from this figure. Firstly, the fluctuations during ON periods show that the rates cannot correspond to hidden neutrons because their rate depends only on the reactor power which is almost constant during operation. Secondly, we can take advantage of OFF periods to measure the reactor-operation-independent background and subtract it from ON rates. To that end, we use a linear interpolation between periods of 3 days before and after each ON cycle. In addition to the statistical uncertainties of the OFF rates, we have to consider a systematic uncertainty to cover a variation of the background during the ON period. This uncertainty can be estimated by testing the subtraction procedure over the whole OFF dataset. The standard deviation of the residuals after subtraction, which includes both statistical and systematic uncertainties, is 2% of the OFF rates.

After the OFF subtraction, the lowest measured rates are in beginning of September 2020 when we could benefit from several days with the neighboring experiments not running. For cell 1, which is the most sensitive cell for hidden neutrons as the closest cell to the reactor and the most shielded against cosmic rays, the lowest measured rate is $\Gamma_{\text{OFF}} = (5.3 \pm 2.1) \times 10^{-3}$ neutrons per second. The uncertainty of about 40% comes from both the ON statistical uncertainty and the OFF subtraction (statistical and systematic uncertainties). Others cells present similar or higher counting rates. Thus, they are less sensitive and we will ignore them in the following.

Considering that the measured rate $\Gamma_1$ could still be dominated by background events, we derive an upper limit on the swapping probability $p$ between hidden and visible states. From Eqs. 3, 4 and 5 and taking into account the reactor power in the relevant period, we obtain:

$$p < 3.1 \times 10^{-11} \quad \text{(at 95% C.L.)}$$

a constraint 13 times better than the previous one obtained from a dedicated experiment, MURMUR, with a $^3$He counter [29]. The main reason for this improvement is a factor hundred lower counting rate per volume unit thanks to a better shielding against fast neutrons and cosmic events.

The exclusion contour in the $(\varepsilon, E)$ parameter space, obtained from Eqs. 2 and 3 is shown on Fig. 3 and compared to the previous contour of the MURMUR experiment [29]. While $\Delta E$ should be zero or close to zero in the context of the original mirror matter approaches [11], it could reach larger values in some scenarios with bimeetric gravity [2, 3]. For comparison, bounds obtained from Ultra Cold Neutrons (UCN) experiments [20, 24] are also given.
In braneworld approaches, $\Delta E$ naturally merges with the difference of gravitational potential energies – felt by the neutron in each brane [13] – and due to some cosmological and astrophysical origins detailed elsewhere [13,17]. Using recent data [40], the expected value is around $\Delta E = 2$ keV. Concerning the coupling parameter, it can be shown that the maximum expected value is $\varepsilon = 2.9$ meV if the brane energy scale equals the Planck energy [10,18]. With a new experimental upper limit $\varepsilon(\Delta E = 2$ keV) = 7.9 meV, the STEREO experiment gets closer to the expected values, see Fig. 3.

The present work justifies the interest and the relevance for short-baseline neutrino experiments to test neutron physics beyond the Standard Model in the quest for hidden sectors. This approach is very competitive compared to dedicated experiments [29] in braneworld phenomenology or to other kinds of experiments related to mirror matter [19,23]. For a short-baseline neutrino experiment, the three parameters to be optimized are: the hidden neutron flux (i.e. the neutron flux within the reactor but also its extension and material content since the key parameter is the total number of neutron scatterings per second), the distance between the core and the detector and, last but not least, the level of background. For the first two, the ILL site turns out to be quite optimal. The large ratio of scattering to absorption cross sections in heavy water significantly increases the mean number of collisions per neutron before its capture (two orders of magnitude difference between pure heavy water and water). Therefore, this result is limited by neutron background from neighbouring experiments and, in spite of the 15 m.w.e. overburden at the STEREO site, from cosmic rays.

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![FIG. 3. Exclusion contours from STEREO (blue) and MURMUR (green) experiments compared to the exclusion contours obtained with Ultra Cold Neutrons (magenta). The dark (light) green and blue contours correspond to the $\Delta E > 0$ ($\Delta E < 0$) case. The two most sensitive points $\Delta E = 11$ neV and 167 neV - result from the Fermi potentials of the scintillator and D$_2$O, respectively. The ratio $2(\varepsilon/\Delta E)^2$ has been chosen as y-axis to allow a better comparison between experiments and because it corresponds to the swapping probability for high values of $\Delta E$. The expected region corresponding to the two-brane Universe model is also plotted (red).}](image-url)
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