A possible shortcut for neutron–antineutron oscillation

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Existing limits on the neutron-antineutron mass mixing imply a strict upper limit on $n - \bar{n}$ transition probability after a flight time $t$, $P_{n\bar{n}}(t) < (t/0.1 s)^2 \times 10^{-18}$. In this letter we propose a new mechanism of $n - \bar{n}$ transition mediated via the neutron mixings with the hypothetical states of mirror neutron $n'$ and antineutron $\bar{n}'$. The existing limits allow $n - n'$ and $n - \bar{n}'$ mixings to be rather large, remarkably without any contradiction with the nuclear stability bounds. This opens up a possibility of $n - \bar{n}$ transition with the probability as large as $P_{n\bar{n}}(t) = P_{nn'}(t)P_{n\bar{n}'}(t) \sim (t/0.1 s)^2 \times 10^{-8}$. For achieving so effective conversion of the neutron into the antineutron in real experiments the magnetic field should be properly tuned with the precision of 1 mG or so.

1. Discovery of neutron–antineutron oscillation \cite{1} would be a clear evidence of the baryon number violation shedding a light on the origin of the matter–antimatter asymmetry in the Universe \cite{2}. Nowadays this phenomenon is actively discussed (see \cite{3} for a review) and new projects for its experimental search are under consideration \cite{4, 5}.

In the Standard Model (SM) frame the neutron has only the Dirac mass term $m \bar{n}n$ conserving baryon number $B$. However, the effective six-fermion operators \( \frac{1}{m}(udd)^2 \) involving $u$ and $d$ quarks, $M$ being a large cutoff scale originated from new physics, can induce a small Majorana mass term violating $B$ by two units:

\[
\frac{\delta}{2} \left( n^T C n + \bar{n} C \bar{n} T \right) = \frac{\delta}{2} \left( \bar{n} C n + n C \bar{n} \right),
\]

where $C$ is the charge conjugation matrix and $n_c = C n_T$. (Generically, these operators induce four bilinear terms \( \bar{n} n_c, n \bar{n}_c, \bar{n} \bar{n}_c, n \bar{n}_c \), with complex constants. However, by a proper redefinition of the fields, these terms can be reduced to just one combination \( \delta ) \) with a real $\delta$ which is explicitly invariant under $C$ transformation (\(6\).)

This mixing of the neutron $n$ and antineutron $\bar{n}$ fields induces $n-\bar{n}$ oscillation, $\bar{n}$ denoting the antineutron state.

In perfect conditions, $n - \bar{n}$ transition probability after a flight time $t$ would be $P_{n\bar{n}}(t) = \sin^2 \left( t/\tau_{n\bar{n}} \right)$ where $\tau_{n\bar{n}} = \frac{1}{\delta}$ is the characteristic oscillation time. (In present experiments the free flight times are rather small, $t \sim 0.1 s$ or so, and the neutron decay can be neglected.) However, $n - \bar{n}$ oscillation is hampered by the medium effects. In particular, in the presence of magnetic field $B$ the oscillation probability reads \(3\):

\[
P_{n\bar{n}}(t) = \frac{\delta^2 \sin^2 \left( \frac{\sqrt{\Omega^2} + \delta^2}{\Omega^2} t \right)}{\Omega^2 + \delta^2} < \frac{\delta^2}{\Omega^2} \tag{2}
\]

where $\Omega = |\mu B| = (B/1 \text{ mG}) \times 9 \text{ s}^{-1}$, $\mu = 6 \times 10^{-12} \text{ eV/G}$ being the neutron magnetic moment. The same formula with $\Omega \rightarrow |U_n - U_{\bar{n}}|/2$ applies in the presence of matter, with $U_n$ and $U_{\bar{n}}$ being the matter induced potentials respectively for $n$ and $\bar{n}$. If $\Omega t \gg 1$, the time dependent factor can be averaged and the mean oscillation probability is small, $P_{n\bar{n}} = \frac{\delta}{2}(\delta/\Omega)^2$. Therefore, the medium effects should be properly suppressed for achieving a quasi-free regime $\Omega t \ll 1$ in which case one obtains $P_{n\bar{n}}(t) = (\delta t)^2 = (t/\tau_{n\bar{n}})^2$.

Experiment on direct search for $n - \bar{n}$ oscillations was performed in Institut Laue-Langevin (ILL) using the cold neutron beam (with intensity $10^{11} \text{ n/s}$ propagating in a long vessel (80 m) before reaching the antineutron detector, with a mean flight time $t \sim 0.1 \text{ s}$). The quasi-free condition was fulfilled by suppressing the residual gas pressure (< $2 \times 10^{-4} \text{ Pa}$) and the magnetic field (< 0.1 mG) in the drift vessel. No antineutron was detected in a running time of $2.4 \times 10^5$ s, and the lower limit on $n - \bar{n}$ oscillation time $\tau_{n\bar{n}} > 0.86 \times 10^8$ s (90 % C.L.) was reported \(4\) which in turn translates into an upper limit on $n - \bar{n}$ mass mixing $\delta < 7.7 \times 10^{-24} \text{ eV}$.

Somewhat stronger but indirect bounds can be obtained from the nuclear stability. Namely, experimental limits on decays of iron and oxygen imply respectively $\delta < 1.3 \times 10^{-24} \text{ eV}$ \(5\) and $\delta < 2.5 \times 10^{-24} \text{ eV}$ \(6\).

In view of these bounds, the maximal conversion probability due to direct $n - \bar{n}$ mixing \(1\) which can be reached for realistic flight times in quasi-free regime is limited as

\[
P_{n\bar{n}}(t) = \frac{t^2}{\tau_{n\bar{n}}} < \left( \frac{t}{0.1 \text{ s}} \right)^2 \times 10^{-18}. \tag{3}
\]

In this letter we show that effective channel for $n - \bar{n}$ conversion can emerge by the mixings of $n$ and $\bar{n}$ with the hypothetical $n'$ and $\bar{n}'$ states from the parallel mirror world. As it was shown in Refs. \(10, 11\), $n - n'$ oscillation can be much faster then the neutron decay. This possibility, which can have intriguing implications for extreme energy cosmic rays \(12\) and may also help to resolve the neutron lifetime puzzle \(13\), is not excluded neither by nuclear stability bounds \(10\) nor by dedicated experiments \(14, 18\). Moreover, some of these experiments show significant deviations from null-hypothesis which can be explained via $n - n'$ oscillations with characteristic time of few seconds \(19\). Provided that also $n - \bar{n}'$ oscillation is fast enough, $n - \bar{n}$ conversion can be effectively induced with the probability $P_{n\bar{n}}(t) = P_{nn'}(t)P_{n\bar{n}'}(t)$ which, in properly settled experimental conditions, can exceed the benchmark \(3\) by many orders of magnitude.
2. There may exist a shadow sector of particles which mirrors the observable particle sector, so that all known particles: electron $e$, proton $p$, neutron $n$, neutrinos $\nu$ etc. have invisible twins: $e'$, $p'$, $n'$, $\nu'$ etc. which do not have our $SU(3) \times SU(2) \times U(1)$ interactions but their own $SU(3)' \times SU(2)' \times U(1)'$ interactions. Namely, one can consider a theory based on the product $G \times G'$ of two identical gauge factors (SM or some its extension), ordinary (O) particles belonging to $G$ and mirror (M) particles to $G'$. Both sectors can have identical Lagrangians owing to a discrete $\mathbb{Z}_2$ symmetry $G \leftrightarrow G'$ when all our particles (fermions, Higgses and gauge fields) exchange places with their shadow twins (’primed’ fermions, Higgses and gauge fields). Such an exchange can be imposed without or with the chirality change between the O and M fermion states. The latter case can be interpreted as a generalization of parity: for our particles being left-handed (LH) in weak interactions, mirror particles must be right-handed (RH) in their weak interactions (for review, see [20]).

A direct way to establish existence of mirror matter is the experimental search for oscillation phenomena between O and M particles. In fact, any neutral particle, elementary (as e.g. neutrinos) or composite (as the neutron) can have a mixing with its mass degenerate mirror twin. In particular, the active-sterile mixing between O and M neutrons can construct $\ell$ to a discrete twin. In particular, the active-sterile mixing between $O(RH)$ in their weak interactions (for review, see [20]).

Concerning the O and M neutrons $n$ and $n'$, for their Dirac mass terms $m \bar{m}_n$ and $m' \bar{m}'_n$ mirror parity implies $m = m'$. If some new physics induces the neutron Majorana mass $\nu_R$ violating B by two units, then by mirror parity also M neutron should have the analogous mass term $\frac{\alpha}{2}(\bar{n}'_L n' + n'_L \bar{n})$ violating $B'$ by two units. But in the following we assume that the direct mixing between $n$ and $n_c$ is negligibly small and set $\delta = 0$, concentrating instead on their mixings with the mirror neutron $n'$ and antineutron $n'_c$ fields.

In ordinary sector $SU(3) \times SU(2) \times U(1)$ the LH quarks $q_L = (u_L, d_L)$ transform as electroweak doublets and the RH ones $u_R, d_R$ are singlets ($B = 1/3$), whereas the antiquarks: $q'_R = (u'_R, d'_R)$ and $u'_L, d'_L$ ($B = -1/3$), have the opposite chiralities and gauge charges. Then M sector $SU(3)' \times SU(2)' \times U(1)'$ must have exactly the same field content, modulo the fermion chiralities. The M quarks are $q'_R = (u'_R, d'_R)$, $u'_L, d'_L$ ($B = 1/3$) and antiquarks are $q''_L = (u''_L, d''_L)$ and $u''_R, d''_R$ ($B = -1/3$). Therefore, one can construct $D = 9$ operators conserving $B + B'$:

$$\frac{1}{M^5}(u'd'd')_L + h.c.,$$

where the parentheses contain the gauge invariant spin $1/2$ chiral combinations of three O or M quarks which can be composed as $(u''_R L C d''_R)_L$ and $(u''_R L C d''_L)_L$. These operators can be obtained e.g. via a seesaw like mechanism discussed in Refs. [10, 23], with the cutoff scale $M$ depending on the masses of intermediate particles, and they induce $n - n'$ mass mixing terms:

$$\frac{\epsilon}{2}(\bar{n}'n' + \bar{n}n'_c + \bar{n}'_c n'_e)$$

with $\epsilon \sim N_{QCD}/M^5 \approx (10 \text{ TeV}/M)^5 \times 10^{-15} \text{ eV}$, or

$$\tau_{nn'} = \epsilon^{-1} \sim \left(\frac{M}{10 \text{ TeV}}\right)^5 \times 1 \text{ s}.$$  

On the other hand, operators conserving $B - B'$ cannot be induced without breaking of electroweak symmetries since $d_L \subset q_L$ and $d'_R \subset q'_R$ states are parts of weak doublets. Thus, these operators require the insertion of VEVs $\langle \phi \rangle = \langle \phi' \rangle = \nu$ of Higgs doublets $\phi$ and $\phi'$ and so their minimal dimension is $D = 10$:

$$\frac{\kappa}{M^6}\left[(u'd'd')_L L + (u'd'd')_R (u'd'd')_R\right] + h.c.$$  

These operators induce $n - n'_c$ mixing terms

$$\frac{\kappa}{2}(\bar{n}'_c n' + \bar{n}_c n'_c) + \frac{\kappa^*}{2}(\bar{n}_c n' + \bar{n}'_c n)$$

with $\kappa/\epsilon = kv/M$. Hence $\tau_{nn'} = \kappa^{-1}$ is parametrically larger than $\tau_{nn'}$ [3], modulo a numerical factor $\kappa$. For simplicity, we take $\kappa$ real, discussing the CP violating effects in the neutron oscillations elsewhere.

In the following we assume that direct mixing between $n$ and $n_c$ is negligibly small and set $\delta = 0$, concentrating fully on the oscillation phenomena induced by the mass mixing terms [3] and [5] between ordinary and mirror states.

4. In this case, the time evolution of the wavefunction $\Psi = (\psi_n, \psi_{n'}', \psi_{n''})^T$ in medium is described by the Schrödinger equation $i \partial_t \Psi = H \Psi$, with the Hamiltonian

$$H = \begin{pmatrix} U_n + \Omega \sigma & 0 & \epsilon & \kappa \\ 0 & U_{n'} - \Omega \sigma & \kappa & \epsilon \\ \epsilon & \kappa & U_{n''} + \Omega' \sigma & 0 \\ \kappa & \epsilon & 0 & U_{n'''} - \Omega' \sigma \end{pmatrix}$$

where each component is in itself a 2 × 2 matrix acting on two spin states [3]. Here $U_n, U_{n'}$ etc. are the matter induced potentials for respective states, $\sigma = (\sigma_x, \sigma_y, \sigma_z)$ are the Pauli matrices, and $\Omega = \mu B$ and $\Omega' = \mu B'$ describe the energy splittings induced by magnetic fields $B$ and $B'$.

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1 These operators induce also the mixing terms involving $\gamma^5$ which can be eliminated by proper redefinition of the fields, as in [3].

2 These oscillations could occur also via the neutron transitional magnetic moments into $n'$ and $n''$ states [23], not discussed here.

3 Wavefunctions $\psi_n, \psi_{n'}$ etc. are in fact two component spinors.
The Hamiltonian eigenstates $n_{1,2,3,4}$ are superpositions

\[
\begin{pmatrix}
n_1 \\
n_2 \\
n_3 \\
n_4
\end{pmatrix} = \begin{pmatrix}
S_{1n} & S_{1\bar{n}} & S_{1n'} & S_{1\bar{n}'} \\
S_{2n} & S_{2\bar{n}} & S_{2n'} & S_{2\bar{n}'} \\
S_{3n} & S_{3\bar{n}} & S_{3n'} & S_{3\bar{n}'} \\
S_{4n} & S_{4\bar{n}} & S_{4n'} & S_{4\bar{n}'}
\end{pmatrix} \begin{pmatrix}
n \\
\bar{n} \\
n' \\
\bar{n}'
\end{pmatrix}
\tag{10}
\]

of the ‘flavor’ states. This mixing matrix determines the probability $P_{n\bar{n}}(t) = |\langle \psi_{n}(t)|^{2}$ to detect antineutron after time $t$ if the initial state at $t = 0$ is $\Psi(0) = n = (1,0,0,0)^{T}$, as well as probabilities $P_{nn'}(t)$ and $P_{\bar{n}\bar{n}'}(t)$.

If the oscillation periods are shorter than the flight time, the time dependent factors can be averaged. The mean oscillation probabilities can be readily deduced, considering that creation of the state $n$ means to create the eigenstates $n_i$ with the respective probabilities $|S_{in}|^2$. The eigenstates do not oscillate between each other but just propagate, and any eigenstate $n_i$ is detectable as $\bar{n}$ with the probability $|S_{in}|^2$. Thus we get $P_{\bar{n}\bar{n}} = \sum |S_{in}|^2|S_{in}|^2$, and similarly for $P_{nn'}$ and $P_{\bar{n}\bar{n}'}$. Let us consider first the simplest hypothesis adopted in Ref. [14] that there is no mirror matter in the Earth (i.e. $U_{nn'},U_{\bar{n}\bar{n}'} = 0$) and mirror magnetic field is vanishingly small ($\Omega' = |\mu B'| \ll t^{-1}$). Then in large ordinary magnetic field, $\Omega \gg 1$, all oscillations can be averaged and one would have $P_{nn'} = 2\cos^2|\Omega'/2$, $P_{\bar{n}\bar{n}'} = 2\sin^2|\Omega'/2$ and $P_{n\bar{n}} = P_{nn'}P_{\bar{n}\bar{n}'} = 4\cos^2|\Omega'/2$. But by suppressing the magnetic field one can fulfill the quasi-free condition $\Omega t \ll 1$, as in experiment [7], in which case the oscillation probabilities after time $t$ read

\[
P_{nn'}(t) = (\epsilon t)^2, \quad P_{\bar{n}\bar{n}'}(t) = (\epsilon t)^2, \quad P_{nn}(t) = (\epsilon t^2)^2.
\tag{11}
\]

This can be easily derived by integrating the Schrödinger equation, $\Psi(t) = e^{-iHt}\Psi(0) \approx (1 - iHt - \frac{1}{2}H^2t^2)\Psi(0)$. Then the experimental limit on $n - \bar{n}$ transition $P_{n\bar{n}}(t) < 10^{-18}$ merely implies $\tau_{nn'}\tau_{\bar{n}\bar{n}'} > 10^{17}$ s² or so.

Under this minimalistic hypothesis, experiments searching for $n - \bar{n}'$ oscillation by comparing the ultra-cold neutron (UCN) losses in the conditions of small ($\Omega t \ll 1$) and large ($\Omega t \gg 1$) magnetic fields [13-18] set strict bounds on $n - n'$ oscillation time, with the strongest limit $\tau_{nn'} > 10^4$ s reported in Ref. [13]. However, these limits become invalid if mirror magnetic field at the Earth is non-negligible, $\Omega t > 1$ [11]. Then, assuming no tuning and taking $|\Omega - \Omega'|t \gg 1$, the mean probabilities can be calculated following the techniques of Ref. [11]:

\[
P_{nn'} = \frac{2\epsilon^2 \cos^2(\beta/2)}{(\Omega - \Omega')^2} + \frac{2\epsilon^2 \sin^2(\beta/2)}{(\Omega + \Omega')^2},
\]

\[
P_{\bar{n}\bar{n}'} = \frac{2\epsilon^2 \sin^2(\beta/2)}{(\Omega - \Omega')^2} + \frac{2\epsilon^2 \cos^2(\beta/2)}{(\Omega + \Omega')^2}
\tag{12}
\]

and $P_{n\bar{n}} = P_{nn'}P_{\bar{n}\bar{n}'}$, where $\beta$ is the (unknown) angle between the vectors $B$ and $B'$. Therefore, the null result of ILL experiment [7] performed with screened magnetic field, $B \approx 0$, yields $P_{n\bar{n}} = 4\epsilon^2(\Omega'^2/\Omega^2) < 10^{-18}$ which in turn translates into rather flexible bound

\[
\tau_{nn'}\tau_{\bar{n}\bar{n}'} > \left(\frac{0.5 \text{ G}}{B'}\right)^2 \times 10^{8}\text{ s}^2.
\tag{13}
\]

Mirror magnetic field cannot be controlled in the experiments. However, the ordinary one can be varied and when $\Omega$ gets closer to $\Omega'$, the oscillation probabilities resonantly increase and can reach the values

\[
P_{nn'}(t) = \left(\frac{t}{\tau_{nn'}}\right)^2 \sin^2 \frac{\beta}{2}, \quad P_{\bar{n}\bar{n}'}(t) = \left(\frac{t}{\tau_{\bar{n}\bar{n}'}}\right)^2 \sin^2 \frac{\beta}{4}
\tag{14}
\]

in quasi-free regime $|\Omega - \Omega'|t < 1$ (i.e. $|B - B'| < 10^{-3}$ G for $t = 0.1$ s). Thus, we have numerically

\[
P_{n\bar{n}}(t) = \frac{\sin^2 \beta}{4} \left(\frac{t}{0.1 \text{ s}}\right)^4 \left(\frac{0.1 \text{ G}}{\text{B'}}\right)^2 \times 10^{-8}
\]

\[
< \frac{\sin^2 \beta}{4} \left(\frac{t}{0.1 \text{ s}}\right)^4 \left(\frac{B'}{0.5 \text{ G}}\right)^4 \times 10^{-8}.
\tag{15}
\]

Note that this bound following from the is billion times weaker than bound [13] related to direct $n - \bar{n}$ mixing [11].

Another question is how fast can $n - n'$ and $n - \bar{n}'$ oscillations be themselves. The results of the neutron disappearance experiments [14-18] are summarized in Ref. [18] where the respective limits on $\tau_{nn'}$ are given as the function the inferred value of mirror magnetic field $B'$. In particular, for $B' < 0.25$ G one has $\tau_{nn'} > 17$ s while for $B' > 0.5$ G $\tau_{nn'}$ smaller than 1 second are allowed. Moreover, some of these experiments show significant deviations from null hypothesis. Namely, detailed analysis of the experimental results of Ref. [16] shows 5.2σ anomaly [19] which can be interpreted as a signal of $n - n'$ oscillation in the presence of mirror magnetic field $B' = 0.15 \pm 0.35$ G provided that $\tau_{nn'} = \sqrt{\cos \beta(5/\sqrt{2})}$ s. Intriguing enough, also the results of experiment [16] show 2.2σ deviation compatible with the above parameter range.

If $n - \bar{n}$ mixing is also present, then the neutron disappearance probability is $P_{nn'} + P_{\bar{n}\bar{n}'}$, so that the above limits apply to the combination $\tau_{\text{eff}} = 1/\sqrt{[\epsilon^2 + \epsilon^2]}$ which is essentially $\tau_{nn'}$ if, by the reasons discussed in previous section, $\epsilon < \epsilon$. In any case, the disappearance experiments [14-18] cannot exclude $\tau_{nn'}\tau_{\bar{n}\bar{n}'} \sim 10^{2\pm 3}$ s² provided that $B' > 50$ mG or so, see Fig. 7 in Ref. [18].

5. The neutron, via $n - \bar{n}$ mixing, can annihilate with other nucleons into pions with total energy roughly equal to two nucleon masses, transforming initial nucleus with atomic number $A$ into a nucleus with $A - 2$ [20]. In fact, $^{16}$O stability bound on $n - \bar{n}$ mass mixing [11], $5^{-1} = \tau_{nn'} > 2.7 \times 10^{8}$ s [9], is about 3 times stronger than the direct experimental limit $\tau_{\text{n}} > 0.86 \times 10^{8}$ s [7].

In its own, $n - n'$ mixing cannot destroy the nuclei, simply by kinematical reasons (energy conservation) [10]. But in combination with $n - \bar{n}'$ mixing it can: $n - \bar{n}$ mixing emerges at second order from $n - n'$ and $n - \bar{n}'$ mixings.

The neutron oscillations in nuclear medium is described again by Hamiltonian [9] with $U_{n} = -V_{n}$ where $V_{n}$ is nucleon binding energy typically of few MeV. The
antineutron potential \( U_n = -V_n - iW_n \) has both real and imaginary (effective) parts, both being of the order of 100 MeV \[27\]. Mirror states have vanishing potentials, \( U_{\nu}, U_{\bar{\nu}} = 0 \), and the magnetic contributions are negligible. Then mixing matrix \[10\] can be directly computed: \( S_{1\nu'} = \epsilon/V_n, S_{1\bar{\nu}'} = \kappa/V_n, |S_{1\nu}| = 2\epsilon\kappa/|V_n(V_n - iW_n)| \).

The neutron stationary state in nuclei can be viewed as the eigenstate \( n_1 = S_{1\nu}n + S_{1\bar{\nu}}\bar{n} + S_{1\bar{\nu}'}\bar{n}' \). It contains antineutron state \( \bar{n} \) with the weight \( S_{1\nu} \), and can annihilate with other nucleons \( (N = p, n) \) producing pions with the rate \( \Gamma_{nN} = |S_{1\nu'}S_{1\bar{\nu}'}|^2\Gamma_{\bar{n}} \), where \( \Gamma_{\bar{n}} = 2W_{\bar{n}} \) is the antineutron annihilation width at nuclear densities.

In addition, as far as \( n_1 \) contains \( n' \) and \( \bar{n}' \) states respectively with the weights \( S_{1\nu'} \) and \( S_{1\bar{\nu}'} \), two neutrons in the nucleus can annihilate as \( n'n' \rightarrow \bar{n}\bar{n}' \) (invisible) mirror pions, with the rate \( \Gamma_{n'n'} = |S_{1\nu'}S_{1\bar{\nu}}|^2\Gamma_{\bar{n}} \times (1 - Z/A) \), where \( 1 - Z/A \approx 0.5 \) is the neutron fraction in nucleus.

Taking our benchmark value \( \tau_{nn}/\tau_{n\bar{n}} \sim 100 \) s we get

\[
\Gamma_{nN} = \frac{4\epsilon^2\kappa^2\Gamma_{\bar{n}}}{V_n^2W_{\bar{n}} + W_n^2} \sim \left( \frac{100 s^2}{\tau_{nn}/\tau_{n\bar{n}}} \right)^2 \times 10^{-62} \text{yr}^{-1},
\]

\[
\Gamma_{n'n'} = \frac{\epsilon^2\kappa^2\Gamma_{\bar{n}}}{2V_n^4} \sim \left( \frac{100 s^2}{\tau_{nn}/\tau_{n\bar{n}}} \right)^2 \times 10^{-60} \text{yr}^{-1}.
\]

Thus, our mechanism is perfectly safe. For comparison, the Super-Kamiokande limit on \( ^{16}\text{O} \) decays yields \( \Gamma_{nN} < (1.9 \times 10^{32}) \text{ yr}^{-1} \) while the KamLAND limit on the pionless \( ^{12}\text{C} \) decays is \( \Gamma_{n'n'} < (1.4 \times 10^{30}) \text{ yr}^{-1} \) \[28\].

6. Concluding, we have discussed a fascinating possibility that the neutron could travel to parallel mirror world and return to our world as the antineutron with rather large probabilities. The reason why this effect cannot be seen immediately in the experiments can be related to the environmental factors, as the existence of the mirror magnetic fields at the Earth. This hypothesis may sound not so weird considering that there can exist dynamical interactions between ordinary and mirror particles mediated by the photon–mirror photon kinetic mixing \[29\] or by some common gauge bosons \[30\]. Namely, the mirror magnetic field comparable to Earth magnetic field \( B \sim 0.5 \text{ G} \) can be induced the mechanism of the mirror electron drag by the Earth rotation \[31\] provided that the Earth is capable to capture some rather tiny amount of mirror matter via these interactions.

There may exist other environmental factors as e.g. hypothetical long range fifth forces induced e.g. via very light \( B - L \) photons. In this case the Earth and sun could effective induce the potentials \( U_n = -U_{\bar{n}} \sim 10^{-11} \text{ eV} \) \[32\] in \( \bar{n} \). Alternatively, ordinary and mirror neutrons can have some mass splitting, due to spontaneous breaking of \( M \) parity which induces a difference between the Higgs VEVs \( \langle \phi \rangle \) and \( \langle \phi' \rangle \) \[33\] which can be rather tiny \[34\].

For testing this possibility, the experiments on \( n - \bar{n} \) search should be performed by scanning different values of magnetic field instead of suppressing it as in \[7\]. In particular, this can be done in the project for searching \( n \rightarrow n' \rightarrow \bar{n} \) regeneration at the ORNL \[36\] by modifying it for searching \( n \rightarrow n' \rightarrow \bar{n} \), just substituting the neutron detector by the antineutron one.

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