On the experimental search for neutron→mirror neutron oscillations

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Abstract

Fast neutron→mirror neutron (n → n’) oscillations were proposed recently as the explanation of the GZK puzzle. We discuss possible laboratory experiments to search for such oscillations and to improve the present very weak constraints on the value of the n → n’ oscillation probability.

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1 Introduction.

Mirror asymmetry [1] of our world is a well established fact. The idea that the Nature, if not P-symmetric, is CP-symmetric [2] has not been supported by experiment. But in the seminal paper [1], where the parity non-conservation hypothesis was first proposed, the existence was suggested of new particles with the reversed asymmetry: ”If such asymmetry is indeed found, the question still could be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will be over-all right-left symmetry”. According to [1] the transformation in the particle space responsible for the space inversion is not a simple reflection $P : \vec{r} \rightarrow -\vec{r}$, but a more complicated $PR$ transformation, where $R$ is the transition of the particle into the reflected state in the mirror particle space. From this point of view the Nature is PR-symmetric, the equivalence between left and right is restored.

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This idea has been revived [3] after the observation of CP-violation. In this paper it was shown that mirror particles, if they exist, can not interact with usual particles through strong or electromagnetic interaction, but only through some weak and predominantly through gravitational interactions. They proposed also that mirror particles and massive objects can be present in our Universe.

Many new ideas appeared during the last forty years on this subject. There were found strong arguments that the dark matter in the Universe may be the mirror matter. Serious implications of the experimental search for the dark matter were discussed recently. For example the results of DAMA [4] and CRESST [5] experiments were interpreted [6] as the evidence of scattering of mirror particles in the detectors. Mirror matter concept has found also development from superstring theories. The recent reviews of the state of art of theoretical and experimental investigations in the field of mirror particles may be found in [6, 7].

The idea was put forward recently [8] (see also [9]) that fast $n \rightarrow n'$ oscillations could provide a very effective mechanism for transport of ultra high energy cosmic protons, with the energy exceeding the Greisen-Zatsepin-Kuzmin cutoff $5 \times 10^{19}eV$, over very large cosmological distances.

Irrespective of this particular mechanism it turned out that existing experimental constraints on $n \rightarrow n'$ oscillations are very weak. The experimental limit on the neutron→antineutron oscillation time is strong enough [10] due to the high energy release of the antineutron annihilation $\sim 2$ GeV. There is no such signal in the case of $n \rightarrow n'$ transition. Real constraints on the characteristic time of this process are much smaller than the neutron lifetime [8]. Indeed, the only signal for $n \rightarrow n'$ transformation is the disappearance of neutrons from the beam. No special experiment with the aim to search for such a disappearance has been performed before. Very rough estimate of the loss of the neutron beam from the experimental search for the $n \rightarrow \tilde{n}$ - oscillations [10, 8] gives a constraint for the time of $n \rightarrow n'$ oscillation at the level of 1 s. The neutron balance in reactors gives not better precision. Since there is no firm predictions for the probability of the $n \rightarrow n'$ oscillations, an experimental search for this transition has to be performed with the highest possible precision.

The present limit on the oscillation time of the $\sigma$–positronium to the mirror $\sigma$–positronium is $\approx 1$ ms (see experiment [11] with reinterpretation in [12]). There are plans to improve this limit on one-two orders of magnitude [12].
The phenomenology of the neutron→mirror neutron oscillations is similar to that of neutral kaon, muon→antimuon and \( n \rightarrow \bar{n} \) oscillation. Starting from \( n - n' \) mass matrix

\[
L = \bar{\psi} M \psi, \tag{1}
\]

where spinor

\[
\psi = \begin{pmatrix} n \\ n' \end{pmatrix}, \tag{2}
\]

and

\[
M = \begin{pmatrix} M & \delta m \\ \delta m & M' \end{pmatrix}, \tag{3}
\]

we have standard solution for evolution of the mirror neutron component with the initial number of ordinary neutrons \( n_0 \):

\[
n'(t) = n(0) \frac{\delta m^2}{\delta m^2 + \Delta E^2} \sin^2(\sqrt{\Delta E^2 + \delta m^2} \cdot t). \tag{4}
\]

Here \( \delta m \) is the transition mass and \( 2\Delta E = M - M' \) is the mass difference of the neutron and mirror neutron states. When oscillations take place in free space the only contribution to \( \Delta E \) comes from the neutron interaction with external magnetic field \( B \): \( 2\Delta E = \mu B \), where \( \mu = 6 \cdot 10^{-12} \text{ eV/G} \) is the neutron magnetic moment. Introducing \( \tau_{osc} = \hbar/\delta m \) and \( \omega = \Delta E/\hbar \) we obtain

\[
n'(t) = \frac{n(0)}{1 + (\omega \tau_{osc})^2} \sin^2(\sqrt{1 + (\omega \tau_{osc})^2} \cdot t/\tau_{osc}), \tag{5}
\]

\( \omega \approx 4.8 \times 10^3 \text{ s}^{-1} \) in the field \( B = 1 \text{ G} \).

Since experimentally we have always \( \omega \tau_{osc} \gg 1 \), two limiting cases are possible: \( \omega t \gg 1 \) and \( \omega t \ll 1 \). In the first case the average of oscillating term is equal to \( 1/2 \), and

\[
n'(t) = \frac{1}{2(\omega \tau_{osc})^2}. \tag{6}
\]

The second case gives

\[
n'(t) = (t/\tau_{osc})^2. \tag{7}
\]

The second, more experimentally sensitive situation, is realized when coherent evolution of the wave function \( \psi \) takes place in the well magnetically shielded conditions (from external and the Earth magnetic fields).
Now let us consider possible experimental approaches to the search of $n \rightarrow n'$ oscillations. There are two such approaches: the neutron beam experiments and the storage of ultracold neutrons [14].

Two kinds of the beam experiments are possible: the first one – based on the measurement of disappearance of neutrons from the beam due to $n \rightarrow n'$ transformation and the second one, when after such hypothetical transformation the incident neutron beam is stopped by the neutron absorber, and the mirror component then again can be re-transformed to the ordinary neutron component according to Eq. (6). Let us estimate possible sensitivity.

### 2 Disappearance of the neutrons from the beam.

Let the neutron beam with the flux $\phi_0$ and the average velocity $v$ enters the magnetically shielded neutron flight path of the length $L$. The flux of mirror neutrons at the end of the flight path is $\phi_n(t) = \phi_0(L/v\tau_{osc})^2$. It is just the number of neutrons disappeared from the beam. To forbid the $n \rightarrow n'$ transformation the magnetic field $B$ such that $\omega_B t \gg 1$ should be switched on along the flight path. Since the change in counts due to $n \rightarrow n'$ transformation is expected to be small, in the limit of one standard error during the time $T_{exp}$ for each of the measurements – with permitting and forbidding of oscillations, we get

$$\phi_0\left(\frac{L}{v\tau_{osc}}\right)^2T_{exp} < (2\phi_0T_{exp})^{1/2},$$  \hspace{1cm} (8)

and

$$\tau_{osc} > \frac{L}{v}(\phi_0T_{exp}/2)^{1/4}.$$  \hspace{1cm} (9)

With $\phi_0 \approx 3 \times 10^7$ s$^{-1}$[13], $v \approx 100$ m/s, $L = 5$ m, and the experimental time $T_{exp} = 1$ month $\approx 2.5 \cdot 10^6$ s, we get $\tau_{osc} > 125$ s.

### 3 Process $n \rightarrow n' \rightarrow n$.

In this approach the flight path consists of two magnetically shielded sections with the length of $L/2$ each, with the perfect absorber of neutrons in the middle. In the first section the neutrons transform to the mirror state with the probability $w = (L/2v\tau_{osc})^2$, then the incident neutrons are absorbed,
and, in the second section the transformation $n' \rightarrow n$ should take place with the same probability. The neutron intensity at the end of the flight path is

$$\phi_{n'}(t) = \phi_0\left(\frac{L}{2uv\tau_{osc}}\right)^4,$$

(10)

The magnetic field in any of the sections will forbid the oscillations. If the neutron detector count rate with stopped beam is $\phi_{bgr}$ the same considerations give:

$$\phi_0\left(\frac{L}{2uv\tau_{osc}}\right)^4T_{exp} < (2\phi_{bgr}T_{exp})^{1/2},$$

(11)

with the result

$$\tau_{osc} > \frac{L}{2v}\left(\phi_0\right)^{1/4}\left(\frac{T_{exp}}{2\phi_{bgr}}\right)^{1/8}.$$  

(12)

With the same parameters of the experiment and assuming $\phi_{bgr} = 0.01 \text{ s}^{-1}$, we get $\tau_{osc} > 20 \text{ s}$.

4 The storage of ultracold neutrons.

The above calculation is not applicable to the ultracold (UCN) storage experiments [14], where the neutrons are confined in the closed chambers. In this case the neutron-wall collisions at the rate $f \approx <v>/ <d>$, where $v$ is the neutron velocity and $d$ is the distance between collisions, cause decoherence, disrupting the oscillation, the mirror component being lost, penetrating into the wall with the rate $\lambda \approx 1/f\tau_{osc}^2$ in the case of degaussed storage chamber, and with the rate $\lambda \approx f/2(\omega_B\tau)^2$ in the magnetic field $B$, ($\omega_B = \omega \cdot B(G)$), when the transition to the mirror state is suppressed. If the neutron lifetime storage measurements are performed in degaussed and non-degaussed conditions with the precision 1 s, what corresponds to the uncertainty of $\alpha \sim 10^{-6} \text{ s}^{-1}$ in the decay constant, we get the precision for the oscillation time $\tau_{osc} > 1/(f\alpha)^{1/2}$. At the typical $f \sim (5 - 10)$ we get $\tau_{osc} > 300 - 500 \text{ s}$.

No previous neutron lifetime measurements in UCN storage mode were performed in degaussed conditions. The interesting observation exists, however, that the measurements of the neutron lifetime by two different methods: the first one – the measurement of the neutron density in the decay volume and counting the $\beta$-decay products (electrons or protons), and the second one – the storage of ultracold neutrons, give slightly different results. The table contains the results of all the measurements, which display the errors
not exceeding 10 s. The first method is insensitive to any invisible decay or disappearance of neutrons from the decay volume, the second method, to the contrary, is sensitive. The difference in the results of these methods, if correct, gives a hint at some invisible channel of disappearance of neutrons from storage chambers. Without the result [27] the difference in decay constants is \((5.47 \pm 2.85) \cdot 10^{-6} \text{s}^{-1}\), with taking into account [27] this difference is \((9.7 \pm 2.8) \cdot 10^{-6} \text{s}^{-1}\). The predicted neutron decay constant into a hydrogen atom: \(n \rightarrow H + \bar{\nu}_e\) [28] is as low as \(\sim 4 \cdot 10^{-9} \text{s}^{-1}\), (branching ratio \(\sim 3.8 \cdot 10^{-6}\)) and can not explain the observed difference (see also [29] where the estimate of the neutron decay constant to the atomic mode has been performed, based on the earlier neutron lifetime measurements).

The UCN storage measurements were performed in the Earth magnetic field \(\sim 0.5 \text{ G}\), and using the above expression for the rate of the neutron loss from the chamber with the neutron-wall collision frequency \(f\), \(\lambda = f/2(\omega_B \tau_{osc})^2\), we get the oscillation time \(\tau_{osc} = (f/2\lambda)^{1/2}/\omega_B\). With \(f \approx (5 - 10) \text{s}^{-1}\), \(\omega_B \sim 2.4 \cdot 10^3 \text{s}^{-1}\), and \(\lambda = 5 \cdot 10^{-6} \text{s}^{-1}\), we get \(\tau_{osc} = 0.3 - 0.4 \text{s}\) - the figure close to the necessary one for the mechanism [8]! It is difficult to say at this moment how seriously this should be taken. But it is clear that high precision neutron lifetime experiments of both classes are important. On the other hand, we should not ignore the obvious trend of beam experiment lifetime data to the lesser values, in the direction of better agreement with the neutron storage results.

5 UCN flow experiment.

This approach seems somewhat simpler than the precise UCN storage measurements. Consider UCN constant flow through the storage chamber with entrance and exit windows (it is assumed isotropic angular distribution). The neutron balance equation has the view:

\[
\frac{dN}{dt} = \phi_0 s_{in} - \rho \frac{S v}{4} \mu - \rho \frac{(s_{in} + s_{out})v}{4} - \frac{N}{\tau_n} = 0. \tag{13}
\]

Here \(N\) is the equilibrium number of neutrons in the chamber, \(\phi_0\) is the neutron flux density at the entrance to the chamber, \(s_{in}\) and \(s_{out}\) are the areas of entrance and exit windows, \(\rho\) is the neutron density in the chamber, \(v\) is the mean neutron velocity, \(V\) and \(S\) are the volume and the area of the internal surface of the chamber, \(\mu\) is the neutron loss probability per
bounce, \( \tau_n \) is the neutron \( \beta \)-decay lifetime. The first term at the right side is the neutron influx to the chamber, the second one is the neutron loss due to collisions with the internal surface, the third one is the neutron efflux to both holes, and the last one is the neutron \( \beta \)-decay.

If \( \phi_0 = \text{const} \), the equilibrium neutron density

\[
\rho = \frac{4 \phi_0 s_{in}}{v(S\mu + s_{in} + s_{out} + \delta)},
\]

where \( \delta = 4V/v\tau_n \).

We can estimate the sensitivity of equilibrium neutron density to the change of neutron loss coefficient

\[
\frac{d\rho}{d\mu} = -\frac{4 \phi_0 Ss_{in}}{v(S\mu + s_{in} + s_{out} + \delta)^2}.
\]

The detector count rate is

\[
I_{det} = \rho s_{out} v/4 = \frac{\phi_0 s_{in}s_{out} v}{S\mu + s_{in} + s_{out} + \delta}.
\]

Its variations because of variation \( \Delta \mu \) of the neutron loss probability is

\[
\Delta I = -\frac{\phi_0 Ss_{in}s_{out} \Delta \mu}{(S\mu + s_{in} + s_{out} + \delta)^2}.
\]

At the effect of oscillations in the limit of one error during the measurement times \( T_{exp} \) with and without the magnetic field we have:

\[
\frac{1}{(f\tau_{osc})^2} \frac{\phi_0 Ss_{in}s_{out} T_{exp}}{(S\mu + s_{in} + s_{out} + \delta)^2} < \left( \frac{2 \phi_0 Ss_{in}s_{out} T_{exp}}{(S\mu + s_{in} + s_{out} + \delta)} \right)^{1/2}.
\]

Finally, we have

\[
\tau_{osc} > \frac{1}{2^{1/4} f} \frac{(T_{exp} \phi_0 s_{in}s_{out})^{1/4} S^{1/2}}{(S\mu + s_{in} + s_{out} + \delta)^{3/4}}.
\]

At \( \mu \sim 10^{-5} \) achieved with the Fomblin oil or grease cover of the wall surface (see Fig. 1 in the recent review [15]), reasonably \( S\mu \ll s_{in}, s_{out} \). With the \( f \approx < v > / < d >, < d > \sim 4V/S \), taking \( s_{in} = s_{out} = s \), demanding that the neutron decay does not decrease essentially the neutron density in the chamber: \( s \gg 4V/(\tau_n v) \), and assuming that the storage chamber is a cylinder with the diameter and the height \( l \) we get:

\[
\tau_{osc} \approx 0.13 \left( \frac{T_{exp} \phi_0}{s} \right)^{1/4} \frac{l^2}{v}.
\]
During one month measurements with and without the magnetic field \( T_{\text{exp}} \approx 2.5 \cdot 10^6 \text{ s} \), with \( \phi_0 = 10^3 \text{ cm}^{-2} \text{ s}^{-1} \), \( l = 100 \text{ cm} \), \( s = 10 \text{ cm}^2 \), and \( v = 400 \text{ cm/s} \), we get \( \tau_{\text{osc}} \approx 420 \text{ s} \).

We neglected the gravity in this estimate. More detailed optimization of the experiment in respect to all parameters taking into account the effect of gravity may increase the sensitivity considerably.

In all described types of experiments the switching on weak magnetic field to forbid \( n \rightarrow n' \) oscillations, and increasing the detector’s count rate, can, in principle, produce the opposite effect due to neutron reflection from small magnetic potential \( U = \mu B \). For the smooth potential this effect is exponentially small – the reflection coefficient for the neutrons with the energy \( E \) incident at the potential of the height \( U_0 \ll E \), which is changing continuously over the region \( x_0 \), is proportional to \( \sim \exp(-4\pi k x_0) \), where \( k \) is the neutron wave vector. In the worst case \( x_0 \sim 10 \text{ cm} \), \( k \sim 10^6 \text{ cm}^{-1} \).

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The results of the neutron lifetime measurements in the beam experiments and in the UCN storage experiments. Only the results with uncertainties not exceeding 10 s were taken into consideration.

| Beam experiments | Storage experiments |
|------------------|---------------------|
| 891±9 (1988)\[16\] | 877±10 (1989)\[17\] |
| 893.6±3.8±3.7 (1990)\[20\] | 870±8 (1989)\[18\] |
| 889.2±3.0±3.8 (1996)\[23\] | 887.6±3.0 (1989)\[19\] |
| 886.8±1.2±3.2 (2003)\[26\] | 888.4±3.3 (1992)\[21\] |
|                     | 882.6±2.7 (1993)\[22\]| |
|                     | 885.4±0.9±0.4 (2000)\[24\]| |
|                     | 881.±3.0 (2000)\[25\]| |
|                     | 878.5±0.7±0.3 (2004)\[27\]| |
| **Averaged value** | **Average value without**\[27\]| |
| 889.2±2.4          | 884.9±0.8          |
|                   | **Average value including**\[27\]| |
|                   | 881.6±0.6          |