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On the experimental search for neutron → mirror neutron oscillations

Yu.N. Pokotilovski *

Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia

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Abstract

Fast neutron → mirror neutron ($n \to n'$) 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 $n \to n'$ oscillation probability.

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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 $P : \vec{r} \to -\vec{r}$, 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.

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 ordinary strong or electromagnetic interaction, but only through some new weak and predominantly through gravitational interactions. In the mirror world exist mirror photons, mirror gluons, mirror intermediate bosons, which form mirror elementary particles, atoms, molecules etc. 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 some 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 $n \to n'$ oscillations could provide a very effective mechanism for transport of ultra high energy cosmic protons, with the energy exceeding the Greisen–Zatsepin–Kuzmin cutoff 5×10^{19} eV [10], over very large cosmological distances.

Irrespective of this particular mechanism it turned out that existing experimental constraints on $n \to n'$ oscillations are very weak. The experimental limit on the neutron → antineutron oscillation time is strong enough [11] due to the high energy release of the antineutron annihilation ~ 2 GeV. There is no such signal in the case of $n \to n'$ transition. Real constraints

* Tel.: +7 49621 62790; fax: +7 49621 65429.
E-mail address: pokot@nf.jinr.ru (Yu.N. Pokotilovski).

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on the characteristic time of this process are much smaller than the neutron lifetime [8]. Indeed, the only signal for $n \to n'$ 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 $n \to \bar{n}$ oscillations [8,11] gives a constraint for the time of $n \to n'$ 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 $n \to n'$ 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 o-positronium to the mirror o-positronium is ~ 3 ms (see experiment [12] with reinterpretation in [13]). Fast annihilation of o-positronium presents serious impediment to significant increasing this level. Nevertheless there are plans to improve this limit on one-two orders of magnitude [13]. It seems that the search for the direct transition to the mirror state of any charged particles or neutral atoms is much less sensitive, and the neutron is the most appropriate object for that.

The phenomenology of the neutron $\to$ mirror neutron oscillations is similar to that of neutral kaon, muon $\to$ antimuon and $n \to \bar{n}$ oscillation [14]. The standard solution for evolution of the mirror neutron component with the initial number of ordinary neutrons n_0 is:

$$n'(t) = \frac{n_0}{1 + (\omega\tau_{osc})^2} \sin^2\left(\sqrt{1 + (\omega\tau_{osc})^2} \times t/\tau_{osc}\right), \quad (1)$$

where $\omega = \Delta E/\hbar$, $2\Delta E$ is the energy difference of the neutron and mirror neutron states, τ_{osc} is the oscillation time. When oscillations take place in free space the only contribution to ΔE comes from the neutron interaction with external magnetic field B: $2\Delta E = \mu B$, where $\mu = 6 \times 10^{-12}$ eV/G is the neutron magnetic moment, $\omega \approx 4.8 \times 10^3\ \mathrm{s}^{-1}$ in the field $B = 1$ G.

Since in the experimental search for longest τ_{osc} we have $\omega\tau_{osc} \gg 1$, 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

$$n'(t) = \frac{n_0}{2(\omega\tau_{osc})^2}. \quad (2)$$

The second case gives

$$n'(t) = n_0(t/\tau_{osc})^2. \quad (3)$$

The second, more experimentally sensitive situation, is realized when coherent evolution of the wave function ψ takes place in the well magnetically shielded conditions (from external and the Earth magnetic fields).

It is assumed in what follows that at the experiment's site there is no significant concentration of the mirror matter and currents which can produce splitting of the neutron and mirror neutron states through the interaction of the mirror magnetic field with magnetic moment of the mirror neutron.

Now let us consider possible experimental approaches to the search of $n \to n'$ oscillations. There are two such approaches: the neutron beam experiments and the storage of ultracold neutrons [15].

Two kinds of the beam experiments are possible: the first one—based on the measurement of disappearance of neutrons from the beam due to $n \to n'$ 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 the Eq. (3).

Disappearance of the neutrons from the beam. Let the neutron beam with the flux ϕ_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 $n \to n'$ 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 $n \to n'$ transformation is expected to be small, in the condition for non-observation of $n \to n'$ oscillations in the limit of one standard error during the time T_{exp} for each of the measurements—with permitting and forbidding the oscillations, we get:

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

and

$$\tau_{osc} > \frac{L}{v}(\phi_0 T_{exp}/2)^{1/4}. \quad (5)$$

With $\phi_0 \approx 3 \times 10^7\ \mathrm{s}^{-1}$,[1] $v \approx 100$ m/s, $L = 5$ m, and the experimental time $T_{exp} = 1$ month $\approx 2.5 \times 10^6$ s, we get $\tau_{osc} > 125$ s. Generally in the Maxwellian neutron spectrum $\phi_0 \sim v^4$, and we do not see any gain from using more energetic neutron flux. But higher energy spectrum permits much longer neutron flight base. For example if to use the existing (ILL) 70 m—long magnetically shielded beam used previously in the $n \to \bar{n}$ search [11], with its flight-time $L/v \approx 0.07$ s and possible neutron flux up to $5 \times 10^{11}\ \mathrm{s}^{-1}$, we can obtain the sensitivity $\tau_{osc} > 2000$ s.

Process $n \to n' \to n$. 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 $n' \to n$ should take place with the same probability. The neutron intensity at the end of the flight path is

$$\phi_n(t) = \phi_0 \left(\frac{L}{2v\tau_{osc}}\right)^4. \quad (6)$$

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

$$\phi_0 \left(\frac{L}{2v\tau_{osc}}\right)^4 T_{exp} < (2\phi_{bgr} T_{exp})^{1/2}, \quad (7)$$

[1] The very cold neutron flux through the area $\sim 25\ \mathrm{cm}^2$ at the VCN channel of the Institute Laue-Langevin, Grenoble, France. The author is grateful to Dr. P. Geltenbort for this information.