On neutron-antineutron oscillation processes in solar cosmic-rays and the possibility of their observation

L. S. Molchatsky *†

Abstract

The experimental observation of neutron - antineutron oscillations is one of the oldest problems of elementary-particle physics. However, the search for these processes in the laboratories on the Earth have thus far yielded no results. In this paper, we consider the possibility of finding $n - \bar{n}$ oscillations in the solar cosmic rays at flare increases. There are two arguments in favour of such an approach to this problem: a long distance for a neutron run and a weak magnetic field in the solar cosmic-ray environment. Therefore, the presence of antinucleons in solar cosmic rays may be a evidence of the existence of $n - \bar{n}$ oscillations. The intensities expected of the $\bar{n}$ and $\bar{p}$ fluxes near the Earth are found.

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1. Introduction

The notion of baryon number (or baryon charge) was introduced by Stueckelberg in 1938 to explain the stability of atoms. However, numerous experiments give evidence to the fact that a baryon field is absent. In view of the contemporary physical theories, based on symmetry principles, it means that baryon charge does not make dynamical sense and, consequently, it is not related to any gauge symmetry. In turn, it means that baryon number can not be strictly reserved.

There are only two kinds of possible experiments aimed on the observation of the processes with the non-conservation of baryon number: attempts to reveal proton decays and neutron-antineutron oscillations.

Experiments on proton decays determined the lower limit for mean lifetime of this particle: $\tau_p > 10^{33}$ years [1]. The possibilities of these experiments fall off. The experiments, aimed at finding $n - \bar{n}$ oscillations, are carried out in Grenoble. In these experiments, neutrons travel from the reactor to the target in which antineutrons should be annihilated. The lower limit for the oscillation period is $T_0 > 0.86 \times 10^8$ s [1]. At present, the main question discussed is the experiments with ultra-cold neutrons confined in a trap [2, 3].

*Department of Theoretical Physics, PGSGA, M. Gor’ky Street 65/67, 443099 Samara, Russian Federation
†e-mail: levmol@yandex.ru
We consider here the possibility for finding the $n - \bar{n}$ oscillations in the solar cosmic-ray at flare increases. According to the astrophysical data [4 - 6], powerful neutron fluxes arise at solar flare increases. These fluxes were detected by many neutron monitors around the world. This fact is very attractive taking into account that the suppression of the $n - \bar{n}$ oscillations in cosmic-rays should be weaker than that on the Earth.

2. The $n - \bar{n}$ mixing. Oscillations

At a non-conservation of baryon number, the states $\left| n > \right|$ and $\left| \bar{n} > \right|$ are not stationary. In this case the $\left| n > \right|$ and $\left| \bar{n} > \right|$ states are related with stationary ones of $\left| 1 > \right|$ and $\left| 2 > \right|$ by the orthogonal transformations

$$\left| 1 > \right| = \cos \theta \left| n > \right| + \sin \theta \left| \bar{n} > \right|,$$

$$\left| 2 > \right| = -\sin \theta \left| n > \right| + \cos \theta \left| \bar{n} > \right|,$$

(1)

where $\theta$ is the mixing angle which defines the power of breakdown of a charge conservation law.

Let an initial state of the neutron-antineutron system at $t' = 0$ be neutron, i.e. $\psi(0) = \left| n > \right|$. If the transformation (1) takes place, then, as a result of quantum mechanical evolution, at $t' = t > 0$ the system should be in the state

$$\psi(t) = \cos \theta e^{-iE'_1 t}\left| 1 > \right| - \sin \theta e^{-iE'_2 t}\left| 2 > \right| = \cos \theta e^{-iE'_1 t}(\cos \theta \left| n > \right| + \sin \theta \left| \bar{n} > \right|)$$

$$- \sin \theta e^{-iE'_2 t}(-\sin \theta \left| n > \right| + \cos \theta \left| \bar{n} > \right|) = (\cos^2 \theta e^{-iE'_1 t} + \sin^2 \theta e^{-iE'_2 t})\left| n > \right|$$

$$+ (1/2)\sin 2\theta (e^{-iE'_1 t} - e^{-iE'_2 t})\left| \bar{n} > \right|. $$

From this equation we find that the amplitude for transition $n \rightarrow \bar{n}$ is

$$A(n \rightarrow \bar{n}) = \frac{1}{2}\sin 2\theta (e^{-iE'_1 t} - e^{-iE'_2 t}).$$

(2)

Here and further we suppose $\hbar = 1$.

At conservation of baryon number, the energetic levels of a free system are generated, i.e. $E'_1 = E'_2$. In other cases, the stationary state levels are splitting, i.e. $\Delta E' = E'_1 - E'_2 \neq 0$. For those cases, we write the energetic levels in the form

$$E'_1 = E' + \frac{\Delta E'}{2}; \quad E'_2 = E' - \frac{\Delta E'}{2}.$$

Besides, it is necessary to take into consideration the fact that free neutrons and antineutrons are the $\beta$-decay particles and therefore energetic levels of the system have the width $\Gamma = 1/\tau_n$, where $\tau_n$ is mean lifetime for neutron. To take into account neutron instability we assume $E' = E - i\Gamma/2$. As consequence of these additions, formula (2) acquires the form

$$A(n \rightarrow \bar{n}) = -i e^{-iE't} e^{-\Gamma t/2} \sin 2\theta \sin(\Delta E'/2) t. $$

Thus, the probability for the conversion $n \rightarrow \bar{n}$ is defined by

$$P(n \rightarrow \bar{n}) = e^{-\Gamma t} \sin^2 2\theta \sin^2(\Delta E'/2) t.$$
3. Influence of external field upon $n - \tilde{n}$ oscillations

At baryon charge non-conservation, the off-diagonal matrix element $\delta$ of the Hamilton operator in the charge representation is not equal to zero, i.e.

$$\delta = <\tilde{n}|\hat{H}|n> = <n|\hat{H}|\tilde{n> \neq 0.}

The parameter $\delta$, as well as the angle $\theta$, point to degree of the baryon charge non-conservation. Their relation is given by

$$\sin 2\theta = \frac{2\delta}{E_1 - E_2},$$

where

$$\Delta E = E_1 - E_2 = \sqrt{(E_n - E_{\tilde{n}})^2 + 4\delta^2}.$$  \(\text{(5)}\)

Here $E_n = <n|\hat{H}|n>$, $E_{\tilde{n}} = <\tilde{n}|\hat{H}|\tilde{n>}$ are the diagonal matrix elements of the Hamilton operator. In deducing formulae (4) and (5) transformation (1) has been used in inverse form.

So from formulae (3), (4), and (5) we extract the following conclusion. Free oscillation is described by

$$P_{\text{free}}(n \rightarrow \tilde{n}) = e^{-\Gamma t} \sin^2 \delta t,$$  \(\text{(6)}\)

because in this case $E_n = E_{\tilde{n}}$.

Difference between $E_n$ and $E_{\tilde{n}}$ due to magnetic field is $|E_n - E_{\tilde{n}}| = 2|\mu|B$, consequently,

$$P_{\text{field}}(n \rightarrow \tilde{n}) = \frac{\delta^2}{(\mu B)^2 + \delta^2} e^{-\Gamma t} \sin^2 \sqrt{(\mu B)^2 + \delta^2} t.$$  \(\text{(7)}\)

4. Antineutrons and antiprotons in vicinity of the Earth as a consequence of $n - \tilde{n}$ oscillations

If the oscillation exists, then the transitions

$$n \rightarrow \tilde{n} \rightarrow \bar{p} + e^+ + \nu_e$$  \(\text{(8)}\)

must occur in solar neutron fluxes. Therefore, the observation of the $\tilde{n}$ and $\bar{p}$ particles in solar cosmic-ray might give evidence to the existence of these processes.

We can now proceed to the estimate of count rate of the $\tilde{n}$ and $\bar{p}$ fluxes near the Earth with respect to the $n$ flux at the Sun.

Proceeding from the experiment data [1], period free oscillation is assumed to be $T_0 \approx 0.86 \times 10^8$ s. By using this we find corresponding value for the mixing parameter:

$$\delta \approx 1 \times 10^{-23} \text{eV}.$$  

It is deduced from (6).

As to magnitude $\mu B$, its estimate gives $\mu B \approx 3 \times 10^{-16} \text{eV}$ because $B \approx 5 \times 10^{-5} \text{G}$ in the solar cosmic-rays. So we establish that $(\mu B)^2 \gg \delta^2$.

In addition to this, we have $T \ll t$, where $T$ is the oscillation period in interplanetary space and $t$ is run time for particles. This relation takes place because
according to (7) the oscillation period in magnetic field is $T = \pi / (\mu B) \approx 7$ s, whereas the run time for the neutron with $E = 100 \ MeV$ is $t = 1 \times 10^3$ s.

For these conditions, formula (7) takes the form

$$P(n - \tilde{n}) = \frac{\delta^2}{2(\mu B)^2} e^{-\Gamma t}.$$  \hspace{1cm} (9)

This formula defines the $n - \tilde{n}$ transition probability at a neutron run from the Sun to the Earth.

As a consequence of this, the probability of the $\bar{p}$ production by means of transitions (8) is

$$P(n \rightarrow \tilde{n} \rightarrow \bar{p}e^+\nu_e) = \int_0^t P_{n-\tilde{n}}(t')\Gamma dt' = \frac{\delta^2}{2(\mu B)^2} (1 - e^{-\Gamma t}).$$  \hspace{1cm} (10)

Formulae (9) and (10) show that a magnetic field leads to a strong suppression of the $n - \tilde{n}$ oscillations. Intensities of these processes on the Earth surface and in the environment of the solar cosmic-rays are related by

$$I_E/I_{c-r} = (B_{c-r}/B_E)^2 \propto 10^{-8}.$$  

This result is the main evidence in favour of the experiments with solar cosmic-ray.

The results of calculations for the $\tilde{n}$ and $\bar{p}$ fluxes expected at the Earth is summarized in Table 1.

| $E$, MeV | $I(\tilde{n})/I(n)$ | $I(\bar{p})/I(n)$ | $I(\tilde{n})+I(\bar{p})/I(n)$ |
|----------|---------------------|-------------------|-----------------------------|
| 10       | $0.1 \times 10^{-16}$ | $6.0 \times 10^{-16}$ | $6.1 \times 10^{-16}$ |
| 100      | $1.6 \times 10^{-16}$ | $3.5 \times 10^{-16}$ | $5.1 \times 10^{-16}$ |
| 1000     | $2.2 \times 10^{-16}$ | $0.9 \times 10^{-16}$ | $3.1 \times 10^{-16}$ |

Here $I(\tilde{n})/I(n)$ and $I(\bar{p})/I(n)$ are expected ratios of the $\tilde{n}$ and $\bar{p}$ fluxes at the Earth to initial neutron flux from the Sun. The calculations are carried out by means of formulae (9) and (10).

The results obtained show that the $\bar{p}$ flux should be dominating in the antinucleon flux at low-energies (about 10 MeV). However, the $\tilde{n}$ rate increases as the energy increases. At the energies about 100 MeV the fluxes of $\tilde{n}$ and $\bar{p}$ should be approximately equal. Nevertheless, the total antinucleon flux decreases with increasing energy.

As to the neutron flux emanated from the Sun, it falls as $I \propto E^{-5.5}$ [4].

Thus, the existence of antinucleons in the solar cosmic-rays near the Earth should be dominating at low-energies.

5. Concluding remark

It should be noted that neutrino oscillations have been found just in the neutrino fluxes traveling from the Sun to the Earth. It is possible that the search for neutron-antineutron oscillations in solar neutron fluxes may also be effective.

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