On neutron-antineutron oscillations

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An experiment on the search for direct neutron-antineutron transitions in a vacuum with a violation of the baryon number, which can be more sensitive than experiments in search of proton instability, is proposed.

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The proton instability, which has been predicted in a number of unified models of strong, weak, and electromagnetic interactions, has recently been vigorously discussed. Generally, some models, in addition to proton decay, also predict the existence of weak, neutron-antineutron oscillations ($n \leftrightarrow \bar{n}$ transition), which are of interest in themselves.

We propose an experiment on the search for direct $n \leftrightarrow \bar{n}$ transitions in which the conservation law for baryon number is violated.[1)]

In 1970, one of the authors (V.K.), because of the need to explain the baryon asymmetry of the universe, pointed out the importance of experimental search for any processes in which the baryon number is not conserved, and in particular, the $n \leftrightarrow \bar{n}$ oscillation processes in a vacuum.[2] This process was examined phenomenologically and its possible oscillation rate was estimated.

In an idealized approach, the experiment could be set up in the following way. A stream of thermal neutrons from an atomic reactor, after traveling a certain distance R in a vacuum, strikes a target. The antineutrons can be detected from the annihilation reaction produced by them in the target.

We shall estimate the sensitivity of the proposed experiment. The effective interaction, which describes the $n \leftrightarrow \bar{n}$ transition in a vacuum, has the form

$$H_1 = \epsilon\, \bar{\psi}_{\bar{n}} \psi_n + \text{Hermitian conjugate}, \qquad (1)$$

where ϵ is a certain small energy parameter which determines the strength of the interaction with $\Delta B = 2$ (B is the baryon number) and ψ_n and $\psi_{\bar{n}}$ are the fields corresponding to the neutron and antineutron, respectively. The earth's magnetic field B replaces the effective Hamiltonian (1) by

$$H_B = H_1 + \mu B\, (\bar{\psi}_n \psi_n - \bar{\psi}_{\bar{n}} \psi_{\bar{n}}), \qquad (2)$$

where μ is the magnetic moment of a neutron, $\mu = 6.02 \times 10^{-18}$ MeV/G. We assume that the nucleon spin is parallel to the earth's magnetic field $\mathbf{B}$; allowance for nonpolarization of the original neutron does not change the final results of the analysis.

The probability, corresponding to the interaction (2), of finding an anti-neutron $\bar{n}$ at the time t if at $t = 0$ we have a neutron n is

$$P(t) = \frac{\epsilon^2}{\epsilon^2 + (\mu B)^2} \sin^2\left(\frac{[(\mu B)^2 + \epsilon^2]^{1/2}}{\hbar} t\right). \tag{3}$$

The corrections in Eq. (3) due to the neutron instability are of the order of t/τ, where $\tau \sim 10^3$ sec is the neutron lifetime; these corrections are small for $t \ll \tau$. From Eq. (3) the period of the $\bar{n} \leftrightarrow n$ oscillations for $B = 0$ is $T = 2\pi\hbar/\epsilon$.

The constraint on the parameter ϵ can be determined on the basis of experiments on nucleon instability. The presence of $n \leftrightarrow \bar{n}$ oscillations leads to the replacement of a neutron in the nucleus by an antineutron, followed by its annihilation with the release of $\sim$2-GeV energy. In second-order perturbation theory with allowance for damping of the intermediate state (or for unitarity), we can show that the width Γ of the nuclear decay as a result of $n \leftrightarrow \bar{n}$ transition is

$$\Gamma = \frac{\epsilon^2 \Gamma_{ann}}{(\Delta M)^2 + \left(\frac{\Gamma_{ann}}{2}\right)^2} (A - Z), \tag{4}$$

where Γ_{ann} is the width of "quasinuclear" decay, in which one neutron is replaced by an antineutron, $(A - Z)$ is the number of neutrons in the nucleus, and ΔM is the difference in the neutron and antineutron energies in the nucleus.

Since it is known from experiments on the search for proton instability that[3]

$$\frac{\hbar}{\Gamma} \gtrsim \frac{\hbar}{A\Gamma_o} = \frac{10^{30}}{A} \text{ year},$$

we have for $\Gamma_{ann} \gg \Delta M \sim 10$ MeV

$$\epsilon \lesssim \frac{1}{2} \left[\frac{A}{A - Z} \Gamma_o \Gamma_{ann}\right]^{1/2}. \tag{5}$$

If $A = 2Z$ and $\Gamma_{ann} \sim 100$ MeV are used for the estimate,[4] then it follows from the nuclear stability that $\epsilon \lesssim 10^{-29}$ MeV or $T \gtrsim 4 \times 10^8$ sec. It is difficult to identify the effect which can change these estimates by more than an order of magnitude.

A similar estimate was obtained in Ref. 2.

Let us determine whether the limitation on the strength of the interaction with $\Delta B = 2$ can be improved in direct experiments on the search for the $n \leftrightarrow \bar{n}$ transition. Since almost always $\mu B \gg \epsilon$, it follows from Eq. (3) that the maximum number of antineutrons strike the target when

$$\frac{\mu B R}{v\hbar} \lesssim 1, \tag{6}$$

where v is the average neutron velocity, i.e., for thermal neutrons when $BR \lesssim 0.25$ G·m

We can see from Eq. (6) that to optimize the experiment we can set $B \sim 0.025$ G for a neutron path length of ~ 10 m, which corresponds to only a factor of 20 reduction of the earth's magnetic field.

For a tube length of ~ 10 m the probability for conversion of a neutron into an antineutron at $\epsilon = 10^{-29}$ MeV is

$$P = \frac{\bar{n}}{n} = \left(\frac{\epsilon R}{v\hbar}\right)^2 \approx 10^{-20}.$$

Thus, to increase the constraint on the strength of the interaction with $\Delta B = 2$ beyond the present limit of the experiments on the search for nucleon instability,[3] we must achieve a sensitivity better than 10^{-20} in the proposed experiment.

The proposed experiment is an important, independent approach in the search for interactions that do not conserve the baryon number, and it is possible that this experiment will have a higher sensitivity that that on the search for nucleon instability.

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After this paper was completed, we became aware of the paper[5] in which similar discussion appeared but somewhat different estimates were obtained. We thank R. E. Marshak and R. N. Mohapatra for pointing out this paper to us.

[1)]The baryon oscillation process was apparently mentioned for the first time by Gell-Mann and Pais.[1]

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