$N\bar{N}$ oscillations: the possibility of observing them using ultracold neutrons

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(Submitted 1 June 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **34**, No. 1, 49–53 (5 July 1981)

The process of neutron-antineutron oscillations in different media and systems is analyzed. The conditions under which an experiment on the search for the direct $N\bar{N}$ transitions in an ultracold neutron beam may prove to be promising are determined.

PACS numbers: 14.20.Cq

The effects produced due to nonconservation of the baryon number, in particular, the $N\bar{N}$ oscillations, have lately attracted considerable interest.[1,2] An experiment on $N \rightarrow \bar{N}$ transition in a cold-neutron flux from a nuclear reactor,[3] which was initially proposed in Refs. 1 and 2, has been performed. The feasibility of setting up such experiments with thermal[1,2] and ultracold neutrons[4] has been widely discussed.

A small fraction of ultracold neutrons (UCN) in the total thermal neutron flux from a reactor ($\sim 10^{-10} - 10^{-11}$) and a noticeable antineutron absorption after each reflection from the trap wall[2] decrease substantially the intensity of the recorded events of $N \rightarrow \bar{N}$ transitions in experiments with ultracold neutrons (UCN) compared to those with thermal neutrons. It should not be ruled out, however, that the low

 0021-3640/81/10048-04$00.60

velocity of the UCN, the possibility of their long-term storage in traps, markedly improved background and many other advantages of using UCN can compensate for these shortcomings. Accordingly, Yoshiki[4] obtained some estimates of the predicted $N \to \bar{N}$ intensity in an experiment with UCN by making simple assumptions about the interaction with the trap wall and about the superposition of neutron and antineutron states. Considering the importance of this problem, we have thoroughly investigated the behavior of this superposition and determined the conditions under which the experiment with UCN may prove to be promising.

The behavior of a two-component superposition

$$\Psi = \alpha |n> + \beta |\bar{n}> \qquad (1)$$

of neutron and antineutron states in a medium can be conveniently described phenomenologically by using the Schrödinger equation

$$E\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = -\frac{\hbar^2}{2m}\Delta\begin{pmatrix} \alpha \\ \beta \end{pmatrix} + \hat{U}\begin{pmatrix} \alpha \\ \beta \end{pmatrix}, \quad \hat{U} = \begin{pmatrix} U_n & \epsilon \\ \epsilon & U_{\bar{n}} \end{pmatrix}, \qquad (2)$$

where U_n and $U_{\bar{n}}$ are the effective optical potentials for N and $\bar{N}$ and ϵ is the parameter which characterizes the mixing of the $|n\rangle$ and $|\bar{n}\rangle$ states and which is related to the $N\bar{N}$-oscillation period T_0 in a vacuum by the relation $\epsilon = 2\pi\hbar/T_0$. The real parts of the U_n and $U_{\bar{n}}$ potentials represent the average energy of interaction of N and $\bar{N}$, respectively, with the atoms of the medium and with the magnetic field, and the imaginary parts take into account all the processes which knock out N and $\bar{N}$ from the initial, coherent state (1). In our case these processes are the effective absorption (which unifies all the possible nuclear reactions) and heating due to scattering by gas molecules in a trap or due to heat absorption as a result of collisions with the wall, as well as due to the decay. Consequently, we have

$$U_{n,\bar{n}} = \frac{2\pi\hbar^2}{m}\left(1 + \frac{1}{A}\right) N(a_{n,\bar{n}} - i\Delta a_{n,\bar{n}}) \pm \mu B - \frac{i\Gamma}{2}. \qquad (3)$$

Here N is the number of nuclei in the medium per unit volume, A is their mass number, a_n and $a_{\bar{n}}$ are the lengths of N and $\bar{N}$ scattering[1)] by these nuclei in the c.m. frame, Δa_n and $\Delta a_{\bar{n}}$ are the effective corrections to a_n and $a_{\bar{n}}$, which must be included in order to take into account the contribution of the coherent state (1) to the imaginary part of the potentials due to heating of N and $\bar{N}$, Γ is the neutron width relative to the β decay, μ is its magnetic moment, and B is the magnetic induction; the $\pm$ signs in front of μB depend on the spin orientation of the superposition (1), but are always opposite for N and $\bar{N}$.

To estimate the scattering length $a_{\bar{n}}$, we must take into account its coupling with the Ψ function of the $\bar{N}$ + nucleus system within the limit of the zero-point energy of relative motion

$$\Psi_{\bar{n}} = \text{const}\,(1 - a_{\bar{n}}/r),$$

where r is the distance between the antineutron and the center of the nucleus. Because of strong antineutron absorption in nuclear matter, $\Psi_{\bar{n}}$ must decrease rapidly as the antineutron penetrates deeper into the nucleus. Since $|\Psi_{\bar{n}}|^2$ is small inside the nucleus, the real absorption of $\bar{N}$ is weak as a result of collision with the nucleus: The interaction of $\bar{N}$ with the nucleus occurs in such a way that would suggest its "ejection" from the nucleus.[2] Consequently, the real part of $a_{\bar{n}}$ must be close to the nuclear radius and the imaginary part must be relatively small. The calculations within the framework of different models confirm this picture. The variations of the distribution of nuclear density and of the potential within reasonable limits give a spread,

$$\left(1 + \frac{1}{A}\right)\mathrm{Re}\, a_{\bar{n}} = 4{,}2 \div 6{,}0\ \mathrm{F}; \qquad -\left(1 + \frac{1}{A}\right)\mathrm{Im}\, a_{\bar{n}} = 0{,}2 \div 1{,}8\ \mathrm{F}. \tag{4}$$

Note that the cross section for absorption of thermal $\bar{N}$ by nuclei nonetheless turns out to be very large,

$$\sigma = -4\pi\left[\frac{1}{k}\,\mathrm{Im}\, a_{\bar{n}} + |a_{\bar{n}}|^2\right] \approx 10^3 \div 10^4\,\mathrm{bH} \tag{5}$$

(k is the wave number) and it is three orders of magnitude larger for ultracold $\bar{N}$. Because of this, the $\Delta a_{\bar{n}}$ term, which is attributable to the heating of $\bar{N}$ (and which, just as for neutrons, is characterized by cross sections that are two to three orders of magnitude smaller), can be ignored.

In a homogeneous medium, at $|U| \gg \epsilon$ $(U = U_n - U_{\bar{n}})$, the eigenfunctions of Eq. (2) are the combinations

$$|1> = \left(|n> + \frac{\epsilon}{U}|\bar{n}>\right)e^{ik_1 r}, \qquad |2> = \left(|n> - \frac{\epsilon}{U}|n>\right)e^{ik_2 r},$$

$$k_{1,2} = \left[\frac{2m}{\hbar^2}(E - U_{n,\bar{n}})\right]^{1/2} + 0(\epsilon^2). \tag{6}$$

The superposition (1) (with $\alpha = 1, \beta = 0$ for $Z = 0$) oscillates along the trajectory (along the Z axis)

$$\Psi = e^{ik_1 Z}\left\{|n> + \frac{\epsilon}{U}\left[1 - \exp\left(i\frac{U}{2k_1}Z\right)\right]|\bar{n}>\right\} \tag{7}$$

(it is assumed that $|k_1 - k_2| \ll k_1$). The amplitude and length of these oscillations are inversely proportional to $|U|$, since a "dephasing"[3] due to the difference between the refractive indices of the neutron and antineutron waves (i.e., k_1 and k_2) occurs between the $|n\rangle$ and $|\bar{n}\rangle$ states.

Let us now examine the behavior of the ultracold superposition (1) in the trap provided[4] that $E < \min\,[\mathrm{Re}\, U_n, \mathrm{Re}\, U_{\bar{n}}]$. The solution of Eq. (2) gives the following correlation between the $\alpha_{\mathrm{in}}, \beta_{\mathrm{in}}$ and $\alpha_{\mathrm{out}}, \beta_{\mathrm{out}}$ coefficients (before and after the collision with the trap wall, respectively):

$$\alpha_{out} = \exp(i\phi_n - \delta_n)\, \alpha_{in}, \qquad \beta_{out} = \exp(i\phi_{\bar n} - \delta_{\bar n})\, \beta_{in}, \tag{8}$$

$$\exp(i\phi_{n,\bar n} - \delta_{n,\bar n}) = \frac{1 - i\kappa_{n,\bar n}}{1 + i\kappa_{n,\bar n}}, \qquad \kappa_{n,\bar n} = (U_{n,\bar n}/E\cos\theta - 1)^{1/2} \tag{9}$$

(θ is the angle of incidence). Thus an additional dephasing of the $|n\rangle$ and $|\bar n\rangle$ states due to the difference between the real parts of U_n and $U_{\bar n}$ occurs after each collision and the amplitudes decrease at $|n\rangle$ and $|\bar n\rangle$ due to absorption and heating of the wall. The experiment with UCN is therefore most effective when Re U_n differs little from Re $U_{\bar n}$ and when Im U_n and Im $U_{\bar n}$ are small. It can easily be shown in this case that the probability of recording[5] an antineutron per neutron in the trap is

$$P = 2R\epsilon^2 \int_0^{\text{cutoff}} \frac{F(v)}{v}\, dv\, \bar\delta_{\bar n}(\bar\delta_{\bar n}^2 + \Delta\bar\phi^2)^{-1}(\Gamma + 2v/R\bar\delta_n)^{-1}, \tag{10}$$

where R is the average size of the trap, $\Phi(\nu) = 4\nu^3/\nu_{\text{cutoff}}^4$ is the spectrum (with respect to the velocities ν) of the UCN source [ν_{cutoff} is the maximum velocity of the superposition (1) in the trap], and $\delta_{n,\bar n}$ and $\phi_n - \phi_{\bar n}$, which are averaged over the angles, are

$$\bar\delta_{n,\bar n} = \frac{\text{Im}\, U_{n,\bar n}}{\text{Re}\, U_{n,\bar n}}\, \chi\left(\frac{v}{v_{\text{cutoff}}}\right), \qquad \Delta\bar\phi = \chi\left(\frac{v}{v_{\text{cutoff}}}\right)\frac{2\text{Re}(U_n - U_{\bar n})}{\text{Re}(U_n + U_{\bar n})},$$

$$\chi(u) = \frac{1}{u^2}\arcsin u - \left(\frac{1}{u^2} - 1\right)^{1/2}. \tag{11}$$

For a total UCN flux of the order of 10^5 sec^{-1}, $R = 1.5$ m, average lifetime of UCN in the trap ~500 sec, $\nu_{\text{cutoff}} = 5$ m/sec, and $|\phi_n - \phi_{\bar n}| < 0.02$, we have obtained ~1 count per week, a value that is currently well within experimental observation.

We must emphasize that Re $a_{\bar n}$ must be known to within an accuracy better than 5% in order to perform such an experiment and evaluate its data.

In conclusion, the authors would like to take this opportunity to thank V. M. Lobashov, Yu. Ya. Stavisskiĭ, A. N. Tavkhelidze, Dzh. Fidekaro, K. G. Chetyrkin, I. S. Shapiro, and T. Érikson for their interest in this work and for the beneficial discussions.

[1] a_n and $a_{\bar n}$ are complex and their imaginary parts describe the effective absorption of N and $\bar N$.

[2] This effect is completely analogous to the reflection of light from a metallic mirror, which also depends on the reflection of a light wave in a metal.

[3] To suppress this dephasing in the experiments on $N\bar N$ oscillations, we must provide a good

shielding against the earth's magnetic field, and also provide a high vacuum ($N \lesssim 10^{13}$ atoms/cm^3) when working with UCN.

[4]Otherwise, one or both of the components in Eq. (1) may escape from the trap.

[5]Assuming that each event of the $\bar{N}$ absorption is recorded.

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Translated by S. J. Amoretty
Edited by Robert T. Beyer