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Field compensation as an alternative to magnetic shielding in searches for n-$\bar{n}$ transitions

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Application of suitable *additional* intermittent magnetic fields is proposed as an alternative to magnetic shielding in searches for n-$\bar{n}$ transitions. The quenching effect of the Earth's field can be negated by assuring that, within a characteristic time interval, a neutron experiences zero field on average.

If a free neutron can transform[1,2] into an antineutron, the transition must be very slow—since it has never been seen—which means that the responsible $\Delta B=2$ interaction must be very weak. Therefore, to search for such transitions, one must be careful to avoid perturbations which remove the n-$\bar{n}$ degeneracy and suppress the effect of the n-$\bar{n}$ transition potential ϵ, whose magnitude cannot exceed 10^{-21} eV according to the best direct limit[3] on n-$\bar{n}$ transitions. In particular, the energy of an antineutron, whose magnetic moment μ is opposite to that of a neutron, would differ from that of a neutron by a quantity of order 10^{-12} eV in the Earth's magnetic field, almost completely quenching[4] n-$\bar{n}$ transitions. It has been noted[5] that the inhibiting effect of a magnetic field takes time to develop and that, under realistic assumptions about the time ($T \lesssim 10^{-1}$ s) during which one can observe a neutron beam, reduction of the ambient magnetic field to 10^{-3} G suffices to make its inhibiting effect completely innocuous. In the present note, we show that overall magnetic shielding to this level is *not* required, and a suitable arrangement of intermittent corrective field regions along the neutron flight path achieves the same purpose. Since increased sensitivity comes mainly from greater T, and correspondingly longer flight paths, this alternative arrangement may offer advantages over the previously proposed solution of magnetic shielding over the entire region.

As usual, we represent the state of a neutron (with given spin orientation which we take to be along[6] the magnetic-field direction) by a two-component wave function

$$\Psi=\begin{pmatrix}\Psi_n\\ \Psi_{\bar{n}}\end{pmatrix} ,$$

whose time evolution in the interaction representation is given by

$$i\frac{\partial\Psi}{\partial t}=M\Psi \quad , \tag{1}$$

with $\hbar=c=1$, and

$$M=\begin{pmatrix}\Delta & \epsilon\\ \epsilon & -\Delta\end{pmatrix}=\epsilon\rho_x+\Delta\rho_z \quad , \tag{2}$$

where $\Delta=\mu B_0$ and B_0 is the strength of the magnetic field, assumed to be constant[7] over the flight path; the ρ_i are standard Pauli matrices acting in the n-$\bar{n}$ space. According to Eqs. (1) and (2), an initial state Ψ_0 evolves in time τ into

$$\Psi_1=U\Psi_0 \quad , \tag{3}$$

with

$$U\equiv\exp[-i\tau(\epsilon\rho_x+\Delta\rho_z)]\simeq\exp(-i\tau\Delta\rho_z)-i\epsilon\Delta^{-1}\rho_x\sin\tau\Delta$$

to lowest order in ϵ. As noted in Ref. 5, for $\Delta\tau \ll 1$ the amplitude of $\bar{n}$, arising from an initial *neutron* state

$$\Psi_0=\begin{pmatrix}1\\0\end{pmatrix} ,$$

approaches $-i\epsilon\tau$, the same as for $\Delta=0$.

Now suppose that, after time τ, a magnetic field $B_1 \gg B_0$ is applied antiparallel to B_0 for a time $\theta \ll \tau$. For[7] $\theta\to 0$ and $\mu B_1\theta=\phi$, Ψ_1 will be transformed to

$$\Psi_2=\Theta\Psi_1=\Theta U\Psi_0 \tag{4}$$

with

$$\Theta U=\exp(i\phi\rho_z)U\simeq\exp i(\phi-\tau\Delta)-i\rho_n\epsilon\Delta^{-1}\sin\tau\Delta \quad ,$$

to lowest order in ϵ, with $\rho_n=\rho_x\cos\phi-\rho_y\sin\phi$. If the compensating field is adjusted[8] to cancel the phase difference which the magnetic field B_0 has caused to develop between the n and $\bar{n}$ components of Ψ, $\phi=\tau\Delta$, this simplifies to

$$\Xi=I-i\rho_n\epsilon\Delta^{-1}\sin\tau\Delta \quad , \tag{5}$$

which is very similar to the unhindered action of the matrix $M_0=\epsilon\rho_x$, viz., when $\Delta=0$. The only differences are that Ξ represents a rotation about an axis

$$\hat{n}=\hat{x}\cos\phi-\hat{y}\sin\phi$$

instead of $\hat{x}$, and the angle of rotation is reduced by a factor $(\tau\Delta)^{-1}\sin\tau\Delta$, which approaches unity for $\tau\Delta \ll 1$. It is then easy to see that result of repeated applications of Ξ. If a neutron beam, represented initially by Ψ_0, passes through N regions of magnetic field B_0, after each of which a corrective field B_1 applies a phase $\phi\rho_z$, the final "neutron" wave function will be

$$\Psi_N=\Xi^N\Psi_0 \quad ,$$

with

$$\Xi^N\simeq I-i\rho_nN\epsilon\Delta^{-1}\sin\tau\Delta \quad , \tag{6}$$

again to lowest order in ϵ.

Consequently, the amplitude of $\bar{n}$ which develops in time

$T = N\tau$ from

$$\Psi_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

is $(\tau\Delta)^{-1}\sin\tau\Delta$ times the magnitude it would acquire if Δ were negligible. Thus we see that, to avoid the suppressive effect on Δ on n-$\bar{n}$ transitions, one does not necessarily have to eliminate Δ. It suffices to provide a counteractive field which cancels[9] Δ *on average* provided that this is done at time intervals τ satisfying $\Delta\tau << 1$. For Δ arising from the Earth's magnetic field, this requires $\tau << 10^{-3}$ s, so if we consider neutrons with velocity 400 m/s, the corrective fields would have to be applied at intervals of less than 40 cm. If a rough form of magnetic shielding were used to reduce the field seen by the neutrons, the spacing could be correspondingly increased.

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[1]V. Kuzmin, Pisma Zh. Eksp. Teor. Fiz. 12, 335 (1970) [JETP Lett. 12, 228 (1970)].

[2]For a recent review in the context of current theories, see R. N. Mohapatra, in *ICOBAN,* proceedings of the International Conference on Baryon Nonconservation, Bombay, 1982, edited by V. S. Narashinham, P. Roy, K. V. Sarma, and B. V. Sreekantan (Indian Academy of Sciences, Bangalore, 1982).

[3]G. Puglierin reported a preliminary limit of $\tau_{n\bar{n}} > 10^6$ s from the Institut Laue-Langevin experiment at International Conference on Matter Nonconservation, Frascati, 1983 (unpublished).

[4]S. L. Glashow, in *Quarks and Leptons,* proceedings of the Summer Institute, Cargèse, France, 1979, edited by M. Lévy *et al.* (Plenum, New York, 1981).

[5]R. N. Mohapatra and R. E. Marshak, Phys. Lett. 94B, 183 (1980); M. Baldo-Ceolin and R. Wilson (unpublished), cited in Ref. 2.

[6]For the opposite spin orientation, the sign of Δ is simply reversed and the discussion proceeds in exactly the same way.

[7]These assumptions are made only to simplify the mathematical description and are not at all necessary for the validity of the general argument.

[8]Note that the compensation condition $\theta B_1 = \tau B_0$ applies equally for all neutron velocities.

[9]Another way of implementing this was suggested by G. Costa and P. Kabir [Phys. Rev. D 28, 667 (1983)].