Polarization rotation of slow neutrons because of parity nonconservation in a nuclear interaction

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The spin of a neutron will rotate in the plane of its wave vector in a homogeneous medium as a result of parity-nonconserving inelastic processes. The change in the spin component along the momentum is given by a single-parameter Lorentz transformation with a rapidity proportional to the path length in the medium and to a quantity that determines the helical dichroism.

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The amplitude for the forward scattering of a neutron by a spin-zero nucleus in the case of parity nonconservation is

$$f = A + B\vec{\sigma}\mathbf{n} \,, \tag{1}$$

where $\vec{\sigma}$ are the Pauli matrices, and $\mathbf{n}$ is a unit vector along the direction of the neutron's momentum. The parity nonconservation is caused by the second (spin) term in (1).

The rotation of the spin of a slow neutron during coherent scattering with parity nonconservation was studied by Stodolsky,[1] who assumed that the amplitude B was real. Because of this assumption, the spin rotated only in the plane perpendicular to $\mathbf{n}$ (by analogy with the rotation of the linear polarization of light in a gyrotropic medium). Recent experiments,[2] however, have revealed that the energy dependence of the quantity

$$\epsilon = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \,, \tag{2}$$

which is a measure of the helical dichroism ($\sigma_\pm$ are the total interaction cross sections for neutrons with different helicities),[1)] is of a resonance nature. Since the total cross section for slow resoanance neutrons (with an energy on the order of 1 eV) is determined primarily by inelastic processes, the results of Ref. 2 mean that the amplitude B (like the amplitude A) has an imaginary part which does not vanish at low energies.[2)] Specifically, from the unitarity relation we have (the optical theorem)

$$\mathrm{Im}\, B = \epsilon\, \mathrm{Im}\, A \,. \tag{3}$$

Let us assume that the propagation of the neutron wave in the medium is described by a refractive index

$$N = 1 + \frac{2\pi}{k^2}\rho f \,, \tag{4}$$

where k is the wave number and ρ the density of scattering centers. The spinor wave function $|\mathbf{r}\rangle$ of the neutron at the point $\mathbf{r}$ is then given by

$$|\mathbf{r}\rangle = [\exp(ikNx)]\,|0\rangle \,, \tag{5}$$

where

$$x = \mathbf{nr}, \qquad |0> = |\mathbf{r}=0>, \qquad <0|0> = 1. \tag{6}$$

If the neutrons are polarized along the direction of the unit vector $\vec{\nu}$ at $\mathbf{r} = 0$, then

$$< \vec{\sigma}\,\mathbf{n}>_0 \equiv <0|\vec{\sigma}\mathbf{n}|\,0> = \mathbf{n}\vec{\upsilon}\,. \tag{7}$$

We wish to evaluate the quantity

$$<\vec{\sigma}\mathbf{n}>_x = <\mathbf{r}|\vec{\sigma}\mathbf{n}|\mathbf{r}>/<\mathbf{r}|\mathbf{r}>. \tag{8}$$

The exponential function in (5) is given explicitly by

$$\exp(ikNx) = l(x)u(x)\exp(i\kappa x)\,, \tag{9}$$

$$\mathrm{Re}\,\kappa = k\left(1 + \frac{2\pi}{k^2}\rho\,\mathrm{Re}A\right), \qquad \mathrm{Im}\,\kappa = \frac{2\pi}{k}\rho\,\mathrm{Im}\,A, \tag{10}$$

$$u(x) = \exp\left(\frac{i}{2}\vec{\sigma}\,\mathbf{n}\,\omega\,x\right), \qquad \omega = \frac{4\pi}{k}\rho\,\mathrm{Re}B, \tag{11}$$

$$l(x) = \exp\left(-\frac{1}{2}\vec{\sigma}\,\mathbf{n}\,\eta\,x\right), \qquad \eta = \frac{4\pi}{k}\rho\,\mathrm{Im}\,B = 2\epsilon\,\mathrm{Im}\,\kappa\,. \tag{12}$$

The matrix $u(x)$ in (9) causes the spin vector to rotate through an angle ωx around $\mathbf{n}$. The matrix $l(x)$, on the other hand, corresponds to a single-parameter Lorentz transformation for motion along $\mathbf{n}$ with a rapidity ηx. Also using (6) and (7) and noting that the quantities $\langle\mathbf{r}|\vec{\sigma}|\mathbf{r}\rangle$ and $\langle\mathbf{r}|\mathbf{r}\rangle$ constitute a 4-vector, we can write

$$< \sigma\,\mathbf{n} >_x = \frac{-\,\mathrm{v} + \mathbf{n}\upsilon}{1 - \mathrm{v}\mathbf{n}\vec{\upsilon}}\,, \qquad \mathrm{v} = \mathrm{th}\,\eta\,x\,. \tag{13}$$

This is the solution of our problem. In particular, it can be seen from (12) and (13) that the helical dichroism leads to a rotation of the neutron's spin in specifically that plane which contains the wave vector and that this dichroism is not directly related to a rotation of the spin around this wave vector. For an experimental determination of ImB, experiments carried out to measure ϵ and $\langle\vec{\sigma}\mathbf{n}\rangle_x$ would be equivalent, but to find ReB it would be necessary to study the small-angle scattering of polarized neutrons or to measure the coherent spin-rotation angle around the momentum. Curiously, this purpose could be served, in principle, by neutron interferometry, since [as follows from (5), (9), and (11)] the spin rotation around $\mathbf{n}$ due to parity nonconservation corresponds to the same change in the spinor phase as in the precession of the neutron's spin in a magnetic field.[4]

[1)]These experiments were carried out with nuclei having nonzero spins. For brevity, we have assumed in this letter that the spin of the target nucleus is zero; this assumption has no substantial effect on the results.

[2)]It also follows from the experiments of Ref. 3 with thermal neutrons (an energy of 0.03 eV) that ImB is not equal to zero.

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