Test of T invariance in neutron optics

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This paper describes a possible new effect in the propagation of polarized neutrons through a polarized medium. The neutron polarization may precess about, and towards, an axis perpendicular to the plane containing the beam direction and the direction of spin polarization of the medium. Observation of either effect would provide unambiguous evidence of T noninvariance, which has yet to be demonstrated, and indicate the presence of T-noninvariant interactions outside the neutral-kaon system.

Departures from time-reversal symmetry[1] (TRS) are expected on the basis of TCP invariance[2] and the observed CP nonconservation[3] in neutral-kaon decays. Despite many searches,[4] and one definite prediction[5] of an observable effect, no such departure has yet been observed. This paper describes a possible effect in neutron optics, whose observation would conclusively establish the failure of TRS in association with reflection noninvariance outside the neutral-kaon system. Bearing some resemblance to searches for an electric dipole moment of the neutron, the proposed test could conveniently be carried out with a slight modification of those experiments.

The propagation of slow neutrons of wave number k in matter containing a number density N of scattering centers can be described by a refractive index[6]

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

where f is the forward scattering amplitude for the individual neutrons, which depends in general on the neutron polarization and on any other vectors which may characterize the state of the medium. If there are no other vectors in the problem, the only polarization dependence of f consistent with rotational invariance is a parity-nonconserving (PNC) term in f proportional to $(\vec{\sigma}_n \cdot \vec{k})$, which gives rise to an analog of optical activity for polarized neutrons[7] traversing matter. Such a PNC effect has been recently observed,[8] with a magnitude considerably exceeding prior theoretical estimates.[7,9] While this is of interest for the study of PNC interactions between neutrons and the scatterers in the medium, evidently it can tell us nothing about time-reversal symmetry. For that, we require the participation of another vector, which we shall take to be the spin polarization $\vec{S}$ of the scatterers. In that case, one can have a dependence of f on $(\vec{\sigma}_n \cdot \vec{S})$ which gives rise to an analog of the Faraday effect when neutrons traverse matter, but also does not test the question of TRS. On the other hand, a term f_T in f proportional to $\vec{\sigma}_n \cdot (\vec{k} \times \vec{S})$ does reverse sign under motion reversal; consequently its presence would give rise to effects which are noninvariant under time reversal. Likewise, since $\vec{\sigma}_n \cdot (\vec{k} \times \vec{S})$ changes sign under space inversion, its occurrence requires parity nonconservation as well.

Specifically, the presence of a nonvanishing f_T makes a corresponding contribution to the refractive index n [Eq. (1)], causing the neutron polarization to precess about and towards $(\vec{k} \times \vec{S})$. If the scattering centers are polarized transverse to the beam, the component of the neutron polarization in the $(\vec{k}, \vec{S})$ plane will precess in that plane at a rate

$$\chi = \frac{4\pi}{k} N \,\mathrm{Re} f_T \quad . \tag{2}$$

We note that such precession, like the precession of neutron spin in an electric field, would be unambiguous proof of T noninvariance.[10]

The relation of this effect to the existence of a possible electric dipole moment for the neutron can be simply seen as follows. Suppose that a strong magnetic field $\vec{B}$ is the agency for creating the spin polarization $\vec{S}\ (\parallel \vec{B})$ of the scattering centers. An incident neutron sees, in its rest frame, the applied magnetic field $\vec{B}$ partly as an electric field $(\vec{k} \times \vec{B})/m_n c$ and, if it possessed an electric dipole moment, the neutron spin would precess about $(\vec{k} \times \vec{B})$ even if the medium were not there. Thus, the effect which we have considered describes a motion of the neutron spin which has exactly the same kinematic structure as that sought in experiments which aim to establish the neutron's electric dipole moment (EDM); consequently, it is an analogous test of space-time symmetries. The responsible interaction can be called a pseudo-EDM interaction in the same sense that spin-dependent neutron-nucleus interactions were described by Abragam[11] as "pseudomagnetism." Just as spin-dependent nuclear interactions of the neutron are much stronger than its magnetic interactions, the pseudo-EDM interaction of a neutron with matter could be much stronger than that arising from its possible EDM with any realizable electric field.

In addition, the effect of $\mathrm{Im} f_T$ will be to cause differential absorption[12] of neutrons with spin up and down relative to $(\vec{k} \times \vec{S})$, resulting in incremental polarization along this direction amounting to

$$\delta = \frac{4\pi}{k} N \,\mathrm{Im} f_T \tag{3}$$

per unit distance of propagation. Observation of differential absorption proportional to $\vec{\sigma}_n \cdot (\vec{k} \times \vec{S})$, or the equivalent detection of polarization along $(\vec{k} \times \vec{S})$ of the transmitted neutrons, would be equally unambiguous evidence of T noninvariance.

Although the possible occurrence of T-noninvariant terms in the internucleon potential has been noted previously,[13] very little is known about the strength of interactions which could give rise to a scattering amplitude of the form f_T. If we represent it phenomenologically by $\gamma \vec{k} \cdot (\vec{S} \times \vec{\sigma}_n)/m_n^2$, the dimensionless parameter $\gamma = \gamma_R + i\gamma_I$ characterizes the strength of the unknown interaction. According to Eq. (2), the corresponding rate of spin precession would be given by $4\pi N \gamma_R / m_n^2$, which for $N \sim 10^{22}$ cm^{-3} yields a rotation of order $10^{-4} \gamma_R\ \mathrm{cm}^{-1}$. Similarly, according to Eq. (3), the difference in cross sections for spin-up and -down neutrons with respect to $(\vec{k} \times \vec{S})$ will be $4\pi\gamma_I/m_n^2$, of order γ_I mb. The level of precision attained in searches for the neutron's electric dipole moment[14] suggests that a magnitude of γ of 10^{-4} or greater should give rise to observable effects. If the required P- and T-noninvariant interaction arises from a mechanism similar to that believed to be responsible for parity nonconservation in nuclear interactions, one does not expect γ to exceed 10^{-5} at most, but since the interaction we are considering has vanishing spin average its effect on nuclear states could be diminished, and larger values of γ could occur without prior detection.[15] Therefore, a search for the effect which we have described may not be entirely unrewarding.

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[15]In principle, experiments which test TRS in nucleon scattering are directly sensitive to γ, but we do not know of any measurements which attain the requisite precision.