Mechanisms for the enhancement of *P*- and *T*-invariant effects in neutron-nucleus reactions

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It is possible that *T*- and *P*-invariance effects are enhanced in the scattering of slow neutrons by compound nuclei.

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Two recent papers[1,2] discuss the possibility of observing effects of a joint violation of (spatial) parity and time invariance as a polarized neutron beam passes through a polarized target. These effects correspond to a *T*- and *P*-invariant combination of the nuclear spin **I**, the neutron spin $\vec{\sigma}$, and the neutron wave vector **k**: $\vec{\sigma}[\mathbf{k}\times\mathbf{I}]$.

The first effect is the appearance of a precession of the neutron spin around the $[\mathbf{k}\times\mathbf{I}]$ axis. If the target is polarized perpendicular to **p**, the component of the neutron spin in the $(\mathbf{k}\times\mathbf{I})$ plane will rotate through an angle χ which depends on the length of the sample, *z*, and we will have

$$\frac{d\chi}{dz}=\frac{4\pi N}{k}\,\mathrm{Re}\,(f_\uparrow - f_\downarrow), \tag{1}$$

where *N* is the density of nuclei in the target, and $f_\uparrow$ and $f_\downarrow$ are the amplitudes for zero-angle scattering of neutrons polarized respectively along and opposite the $[\mathbf{k}\times\mathbf{I}]$.

The second effect is that the total cross sections for the neutrons polarized along and opposite $[\mathbf{k}\times\mathbf{I}]$ differ by an amount

$$\Delta_T=\frac{4\pi}{k}\,\mathrm{Im}\,(f_\uparrow - f_\downarrow). \tag{2}$$

We will show that for these quantities there are both dynamic and resonant enhancements analogous to the enhancements of parity-violating effects.[3,4]

Using the microscopic theory of nuclear reactions[5] and the approach of Ref. 4 to *P* violation in nuclear reactions, we find the following for slow neutrons in first order in the weak interaction *W* (ignoring a trivial spin factor):

$$\frac{d\chi}{dz}=\frac{4\pi N}{k^2}\,\frac{w(\Gamma_s^n\Gamma_p^n)^{1/2}[(E-E_s)(E-E_p)-\Gamma_s\Gamma_p/4]}{[(E-E_s)^2+\Gamma_s^2/4][(E-E_p)^2+\Gamma_p^2/4]},$$

$$\Delta_T=-\frac{2\pi}{k^2}\,\frac{w(\Gamma_s^n\Gamma_p^n)^{1/2}[(E-E_p)\Gamma_s+(E-E_s)\Gamma_p}{[(E-E_s)^2+\Gamma_s^2/4][(E-E_p)^2+\Gamma_p^2/4}, \tag{3}$$

where *s* and *p* specify the compound resonances, $E_{s,p}$ are the energies of the resonances, Γ and Γ^n are the total and neutron widths of the resonances, and *w* is the matrix element of the weak potential which violates P and T invariance. For our choice of wave-function phases we have $w = -\mathrm{Im}\langle\psi_s|W|\psi_p\rangle$, where $\psi_{s,p}$ are the wave functions of the compound nucleus.

To simplify the analysis, we have incorporated in (3) only two adjacent resonances with identical spin and different parity. We see that $d\chi/dz$ and Δ_T can be linked with the P-noninvariant but T-invariant quantities $d\Phi/dx$ (Φ is the angle through which the polarization of the neutron rotates) and $\Delta_{\mathrm{tot}} = \sigma_- - \sigma_+$ (the difference between the total cross sections for the neutrons with different helicities)[4]:

$$\frac{d\chi}{dz} = \frac{d\Phi}{dz}\frac{w}{\mathrm{v}} , \qquad \Delta_T = \Delta_{\mathrm{tot}}\frac{w}{\mathrm{v}} , \tag{4}$$

where $\mathrm{v} = -\mathrm{Re}\langle\psi_s|W|\psi_p\rangle$ is a P-noninvariant but T-invariant matrix element.

It is customary to examine the derivative $d\Phi/dz$ over the neutron mean free path $l(\Phi)$ and the quantity $P = \Delta_{\mathrm{tot}}/2\sigma_{\mathrm{tot}}$. Analogously, we can introduce

$$\chi = \frac{d\chi}{dz} l = \Phi\frac{w}{\mathrm{v}} , \qquad \eta_T = \frac{\Delta_T}{2\sigma_{\mathrm{tot}}} = P\frac{w}{\mathrm{v}} , \tag{5}$$

where η_T is the relative difference between the cross sections for neutrons polarized along and opposite $[\mathbf{k}\times\mathbf{I}]$.

It can thus be seen from (3) and (4) that two enhancement factors are operating for the P- and T-invariant interaction w, as for v (Ref. 4), in reactions which go through the stage of a compound nucleus. First, there is the dynamic enhancement w/D which results from the proximity of the s and p levels of the compound nucleus ($D = |E_p - E_s|$). Second, there is a resonant enhancement, (D/Γ) for $d\chi/dz$ and $(D/\Gamma)^2$ for Δ_T, which results from the particular nature of the nuclear reactions. The quantities χ and η_T (in contrast with $d\chi/dx$ and Δ_T) "sense" the resonant enhancement only near the p resonance. A corresponding property for Φ and P—in contrast with $d\Phi/dz$ and Δ_{tot}—was noted in Refs. 4.

The quantities Φ and P have been determined experimentally and theoretically (see Ref. 4, for example, and the literature cited there). To find the expected values of $d\chi/dz$ and Δ_T (or χ and η_T) we need to determine $\delta = w/v$. Since we know nothing about the T-noninvariant nucleon–nucleon interaction, we adopt the following hypothesis in order to estimate δ: The ratio of the nuclear interaction matrix elements w and v is equal to the ratio of the constants of these interactions at the nucleon level:

$$\delta = \frac{w}{\mathrm{v}} = \frac{G_T}{G_F} , \tag{6}$$

where G_F is the constant of the T-invariant and P-noninvariant interaction, and G_T is the constant of the P- and T-noninvariant interaction. According to the theories on the spontaneous violation of CP invariance in weak interactions,[6] which give a satisfactory description of experimental data on the decay of K mesons, we have

$$\delta \sim \frac{m_q m_p}{m_H^2} . \tag{6b}$$

where m_q is the quark mass, m_p is the nucleon mass, and m_H is the mass of the Higgs boson responsible for the *CP*-noninvariant interaction with quarks. (A more rigorous estimate will require further calculations, which we intend to undertake in the future.) Substituting in some reasonable values for m_q and m_H, we find $\delta \sim 10^{-2}$–10^{-3}.

Now, using our hypothesis and these estimates of δ, let us estimate, for example, η_T and χ for the 0.75-eV p resonance of ^{139}La, for which the large experimental value $P(\mathrm{La}) \sim 10^{-1}$ has been observed.[7] From (6b) we find

$$\eta_T(\mathrm{La}) \sim 10^{-3} - 10^{-4},$$

$$\chi(\mathrm{La}) \sim 10^{-3} - 10^{-4}\ \mathrm{rad}.$$

The obsrvation of these effects would constitute unambiguous evidence for the existence of a "milliweak" interaction violating T invariance.

It should be noted that the resonant behavior of $d\chi/dz$ and Δ_T makes it possible to distinguish the effect from a possible background from, for example, internal fields in the target.

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