New possibility for the search of *P,T*-noninvariant effects

A. P. Serebrov
B. P. Konstantinov Institute of Nuclear Physics, 188350 Gatchina, Leningrad Oblast, Russia

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A method is proposed for the search of P,T-noninvariant effects as a neutron beam passes through a polarized nuclear target. The idea is to measure the ratio of the asymmetry to the polarization. This method allows one to avoid spurious effects due to a nuclear pseudomagnetism or a weak magnetism.

The observation of a substantial strengthening of P-noninvariant effects at p resonances[1] has spurred several discussions of whether it is possible to observe a P, T-noninvariant effect for an $\mathbf{s}[\mathbf{J}\times\mathbf{k}]$ correlation as a polarized neutron beam passes through a polarized nuclear target[2–8] ($\mathbf{k}$ is the neutron wave vector, s is the neutron spin, and J is the spin of the target nucleus). However, there is the problem of distinguishing the $\mathbf{s}[\mathbf{J}\times\mathbf{k}]$ correlation of interest from the background of effects from $(\mathbf{s}\cdot\mathbf{J})$ and $(\mathbf{s}\cdot\mathbf{k})$ correlations, which are responsible for the strong and weak spin-dependent interactions. The standard method for measuring polarizations or asymmetries is not suitable in this case, since effects stemming from strong and weak interactions are considerably larger than a possible P,T-noninvariant effect. This problem can be resolved by comparing the longitudinal polarization P which arises during the passage of an unpolarized beam through a target and the asymmetry A of the detector count rate which arises when the longitudinal polarization of the beam incident on the target is reversed. A difference between the asymmetry and the polarization can arise for a longitudinal polarization only if there is a violation of temporal parity, and it can arise for a transverse polarization only if there is violation of both spatial and temporal parity.

This proposed method for measuring the ratio of the asymmetry to the polarization might be implemented in the experimental apparatus in Fig. 1. It consists of a polarizer p, an analyzer a, the polarized nuclear target T, two flippers (F_1 and F_2), which reverse the polarization of the neutron beam, and a detector D. The two possible states of the flippers lead to four measurable count rates of the neutron detector: N_{++}, N_{+-}, N_{-+}, and N_{--}. The $+$ and $-$ specify the sign of the current in the first and second coils of the adiabatic flippers.

This layout is the sum of two constituent layouts: one for measuring the asymmetry (the polarizer, flipper F_1, the target, and the detector) and a second for measuring the polarization (the target, flipper F_2, the analyzer, and the detector). To measure the quantity of interest in this layout, it is a simple matter to eliminate the effect of the extraneous elements by combining the results measured with opposite states of the flippers: with flipper F_1 to find the polarization P and with flipper F_2 to find the asymmetry A.

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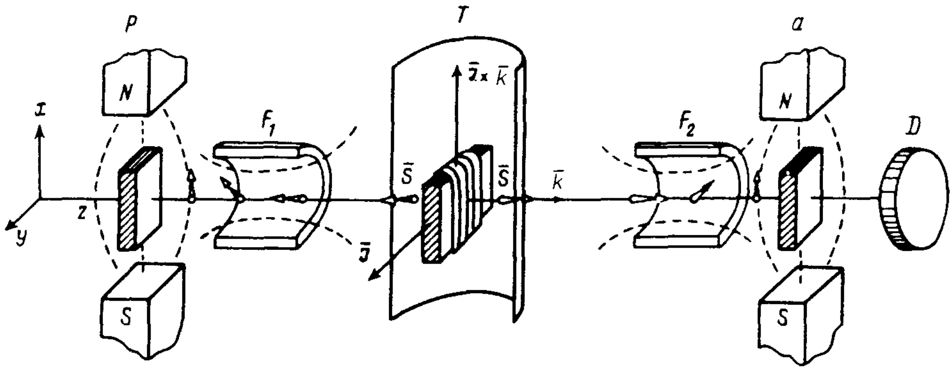

FIG. 1. Experimental layout. p—Polarizer; a—analyzer; T—polarized nuclear target with a solenoid to produce a magnetic field, inside a superconducting magnetic screen; F_1, F_2—flippers of the neutron polarization; D—detector.

It can be shown that the ratio

$$X \equiv \frac{(N_{++}+N_{+-})-(N_{--}+N_{-+})}{(N_{++}+N_{-+})-(N_{--}+N_{+-})} = \frac{pA}{aP} = \frac{p[(T_{11}-T_{22})-(T_{12}-T_{21})]}{a[(T_{11}-T_{22})+(T_{12}-T_{21})]}, \quad (1)$$

measured experimentally, is the ratio of the asymmetry A to the polarization P, corrected for the polarizing power p and the analyzing power a of the polarizer and the analyzer. This ratio can be expressed in terms of the target transmission coefficients without and with changes in the neutron spin state: T_{11}, T_{22}, T_{12}, and T_{21}. These coefficients are given by

$$\begin{pmatrix} J_1^k \\ J_2^k \end{pmatrix} = \begin{pmatrix} T_{11} T_{12} \\ T_{21} T_{22} \end{pmatrix} \begin{pmatrix} J_1^n \\ J_2^n \end{pmatrix}, \quad (2)$$

where J_1^n, J_2^n, J_1^k, and J_2^k are the intensities of the neutron spin components in front of and behind the target. They can be expressed in terms of the wave functions of the corresponding states:

$$J_1^n = \varphi_1(0)\varphi_1^*(0), \quad J_2^n = \varphi_2(0)\varphi_2^*(0), \quad (3)$$

$$J_1^k = \varphi_1(Z_0)\varphi_1^*(Z_0), \quad J_2^k = \varphi_2(Z_0)\varphi_2^*(Z_0). \quad (4)$$

The wave functions constitute a solution of the equations

$$\frac{\hbar^2}{2m}\frac{d^2\psi}{dZ^2} + (E-U-iW-\boldsymbol{\sigma}\mathbf{H})\psi = 0, \quad \psi = \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix}, \quad (5)$$

$$\frac{\hbar^2}{2m}\frac{d^2\varphi_1}{dZ^2} + (E-U-iW-H_z)\varphi_1 - (H_x - iH_y)\varphi_2 = 0, \quad (6)$$

$$\frac{\hbar^2}{2m}\frac{d^2\varphi_2}{dZ^2}+(E-U-iW-H_z)\varphi_2-(H_x-iH_y)\varphi_1=0. \tag{7}$$

Solving Eqs. (6) and (7), and using (2), we find

$$T_{11}-T_{22}=\frac{2}{HH^*}\left[\mathrm{Re}(H_zH^*)\sinh k\frac{\mathrm{Im}\,H}{E-U}Z_0+\mathrm{Im}(H_zH^*)\sin k\frac{\mathrm{Re}\,H}{E-U}Z_0\right]$$
$$\times\exp\left(-k\frac{w}{E-U}Z_0\right), \tag{8}$$

$$T_{12}-T_{21}=\frac{2}{HH^*}\left(\cosh k\frac{\mathrm{Im}\,H}{E-U}Z_0-\cos k\frac{\mathrm{Re}\,H}{E-U}Z_0\right)$$
$$\times(\mathrm{Re}\,H_x\mathrm{Im}\,H_y-\mathrm{Re}\,H_y\mathrm{Im}\,H_x)\exp\left(-k\frac{w}{E-U}Z_0\right), \tag{9}$$

where Z_0 is the target thickness, and H is the effective pseudomagnetic field, which is the vector sum of the magnetic field H_m, the nuclear pseudomagnetic field $\mathbf{H}_n=H_n^0\mathbf{J}/J$, the weak pseudomagnetic field $\mathbf{H}_p=H_p^0\mathbf{k}/k$, and the P,T-noninvariant pseudomagnetic field $\mathbf{H}_t=\mathbf{H}_t^0[\mathbf{J}\times\mathbf{k}]/Jk$. The real part of the effective pseudomagnetic field determines the interaction energy of the neutron spin ($\mu=1$); the imaginary part is responsible for the spin-dependent part of the absorption. The quantity U is the spin-independent real part of the potential of the medium for a neutron, and W is the spin-independent imaginary part of the potential of the medium for a neutron. The Z axis runs along the beam axis, while the Y axis is directed in such a way that the magnetic field of the target lies in the YZ plane. Since the polarization vector of the target and the magnetic field vector coincide, the component H_x of the pseudomagnetic field is due exclusively to the $\mathbf{s}(\mathbf{J}\times\mathbf{k})$ interaction. If there is no such interaction, we have $H_x=0$, $T_{12}=T_{21}$, and $P_z=A_z$.

For a longitudinally polarized beam, the inequality $T_{12}\neq T_{21}$ arises solely from the pseudomagnetic P,T-noninvariant field H_t. A characteristic effect of the $\mathbf{s}(\mathbf{J}\times\mathbf{k})$ interaction is a singularity in the function X near $T_{11}-T_{22}\approx 0$, i.e., near the angle $\vartheta=\pi/2$, which is the angle between the target polarization direction and the beam axis (a transversely polarized target). In the region $+\pi/2>\vartheta>-\pi/2$, the P,T-noninvariant effect is suppressed, and X is determined by the ratio p/a. In this layout, the $(\mathbf{s}\cdot\mathbf{J})$ and $(\mathbf{s}\cdot\mathbf{k})$ effects for the quantity X are canceled by virtue of the equality $P_z=A_z$ for the longitudinal polarization. Figure 2a shows the behavior of the function $X(\vartheta)$ when there is an effect from the $(\mathbf{s}[\mathbf{J}\times\mathbf{k}])$ interaction.

This experiment essentially tests the equality of the forward and inverse processes of neutron spin flip during passage through a transversely polarized target: from a positive helicity to a negative one and vice versa. The vector sum of the magnetic and nuclear pseudomagnetic fields must lead to a spin flip of the neutron. This situation can be arranged by adjusting the current in the transverse solenoid of the target to achieve the maximum effect.

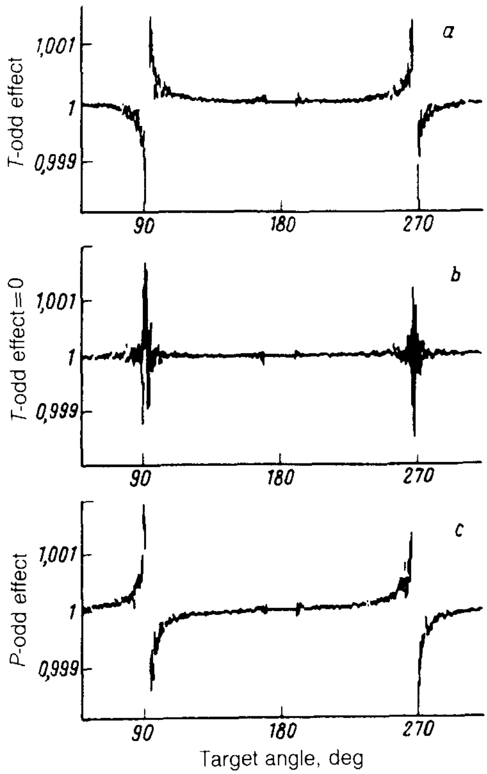

FIG. 2. Modeled behavior of the function $X(\vartheta)$. *a*—The $X(\vartheta)$ dependence in the case in which the effect of interest, $\mathbf{s}[\mathbf{J}\times\mathbf{K}]$, is present, with $\mathrm{Im}H_t^0/\mathrm{Im}H_N^0=3\times10^{-5}$; *b*—$X(\vartheta)$ in the absence of effects, to show the statistical error of the measurements; *c*—the $X(\vartheta)$ dependence due to the $(\mathbf{s}\cdot\mathrm{K})$ effect and the presence of a transverse component of the polarization in the X direction, with $\mathrm{Im}\,H_p^0/\mathrm{Im}_n^0=10^{-1}$ and $P_x=10^{-3}$.

Possible spurious effects could be tested for by rotating the target through 180°, by changing the sign of the vector sum of the magnetic and nuclear pseudomagnetic fields, by carrying out measurements with an unpolarized target, and by studying the energy dependence of the effect near resonance.

Expressions for $T_{11}-T_{22}$ and $T_{12}-T_{21}$ in the case of transverse polarization in the X direction (P_x) can be found from (8) and (9) by making the substitutions $H_x\to H_y,\ H_y\to H_z,\ H_z\to H_x$. In the case of a transverse polarization in the Y direction (P_y), this can be done by making the substitutions $H_x\to H_z,\ H_y\to H_x,\ H_z\to H_y$. A detailed analysis of the relations derived here shows that the main condition for the absence of a spurious effect from the $(\mathbf{s}\cdot\mathbf{k})$ interaction in an experimental search for an P,T-noninvariant $(\mathbf{s}[\mathbf{J}\times\mathbf{k}])$ interaction is that there be no contribution of the transverse polarization in the X direction and that the contribution of the transverse polarization in the Y direction have no effect. A spurious effect, in contrast with a true effect, would not change sign when the target was rotated through 180° (Fig. 2c), so a true P,T-noninvariant effect could be observed by rotating the target or by reversing the resultant field $H_n + H_m$. Developing an experiment on the basis of the method proposed here will require a detailed modeling of the experimental geometry, with allowance for the divergence of the beam and the variations in the magnetic fields which arise near the superconducting screen of the target. The quality of the adiabatic symmetric flippers requires particularly careful scrutiny.

Experiments are being planned in Japan and the US to seek P,T-noninvariant effects.[9,10] A distinguishing feature of the method proposed here is the fundamentally new approach to the suppression of spurious effects, through the use of the equality $P_z = A_z$ and through the introduction of the new measurable quantity $X = A/P$. The latter requires four measurements with various combinations of the states of the two flippers in front of and behind the target.

In this method, the effect of the spin-dependent strong interaction $(\mathbf{s} \cdot \mathbf{J})$ is canceled for any polarization projection, while the effect of the weak interaction $(\mathbf{s} \cdot \mathbf{k})$ is eliminated for the case of the longitudinal polarization. If there is a small transverse polarization component, the P,T-noninvariant effect can be distinguished by reversing the resultant field $H_n + H_m$. This method might be implemented in the beam of the VVR-M reactor with the rotary chopper developed at the Institute of Theoretical and Experimental Physics, at the IBR-30 pulsed reactor, and at other pulsed neutron sources (KEK and LAMPF). The most favorable conditions for such an experiment might be arranged at the hot-neutron source of the ILL reactor in Grenoble.

Preliminary estimates for ^{139}La show that the statistically attainable error of measurements of the ratio H_t^0/H_n^0 is 3×10^{-5}. This figure corresponds approximately to the limitation on the CP-breaking nucleon constant, 2×10^{-4}. The existing experimental limitation, found from the electric dipole moment of the neutron, is $(2\text{–}4) \times 10^{-3}$.

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