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T-VIOLATION AND NEUTRON OPTICS EXPERIMENTS

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The possibility of testing for T-violation in neutron optics experiments is discussed. Three possible schemes of neutron optics experiments to search for T-violation: in dynamic diffraction on a perfect crystal, in a perfect-crystal neutron interferometer, and in the reflection of ultracold neutrons (UCNs) from a material surface are considered. An experiment to search for P-violation in neutron reflection from a material surface is proposed.

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Neutron optics affords the possibility of testing for T-violation by means of a comparison between the forward and backward reactions. This possibility arises due to the neutron spin, in the case when the neutron helicities in the initial and final states are opposite. The probabilities of processes with a change of helicity will differ from each other only in the presence of T-violation. The neutron helicity can be changed in two ways: 1) a change of spin direction in forward scattering; 2) a change of momentum direction (backscattering) with the same spin direction. The two cases are shown in Fig.1, where the first one corresponds to spin-flip in transmission and the second corresponds to backscattering. The right-hand part of the picture can be obtained from the left-hand part by means of the time-reversal operation and rotation. The first case has been discussed many times in connection with a possible experiment in which T-violation is sought in the transmission of polarized neutrons through a polarized target [1 - 3]. The second case is the subject of the present paper.

As is well known, P- and T-violating processes can be significantly increased near p-wave compound nuclear resonances due to the mixing of states with opposite parity. The amplitudes of P,T-violating process can be written in the following form:

$$f_1^{P,T} = \frac{i\lambda(w)\mathbf{s}[\mathbf{P}\times\mathbf{I}]}{(E-E_s+i\Gamma_{s/2})(E-E_p+i\Gamma_{p/2})}, \qquad (1)$$

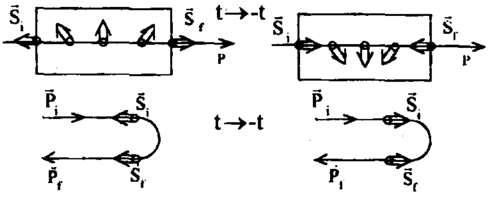

Fig.1. Processes involving a change of neutron helicity in forward scattering and backscattering

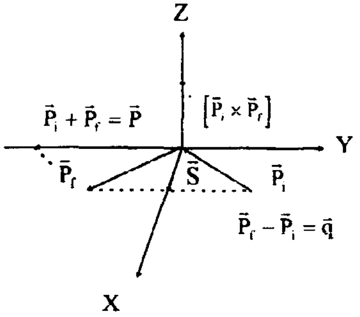

Fig.2. Vector diagram of the scattering process

$$f_2^{P,T} = \frac{i\lambda\langle w\rangle(\mathrm{sq})}{(E - E_s + i\Gamma_{s/2})(E - E_p + i\Gamma_{p/2})}. \tag{2}$$

Formula (1) describes the spin-flip process, and formula (2) the backscattering process. Both amplitudes are proportional to the T-violation parameter $-i\lambda$, the weak-interaction matrix element $\langle w\rangle$, and resonance factor determined by the parameters of the s-wave and p-wave resonances – their energy positions (E_s, E_p) and widths (Γ_s, Γ_p), S is the neutron spin, $\mathbf{P} = \mathbf{P}_i + \mathbf{P}_f$, and $\mathbf{q} = \mathbf{P}_i - \mathbf{P}_f$, where $\mathbf{P}_i$ and $\mathbf{P}_f$ are the initial and final neutron momenta.

It should be mentioned that a polarized nuclear target is not required for determining the T-violating amplitude $f_2^{P,T}$(sq -correlation), a circumstance that is rather attractive experimentally. However, there are the same kinds of problems for (sq)-correlation as for $\mathbf{S}[P \times I]$-correlation because of the presence of other correlations: $\mathbf{S}(\mathbf{P}_i + \mathbf{P}_f)$-correlation, caused by the weak interaction, and $\mathbf{S}[\mathbf{P}_i \times \mathbf{P}_f]$-correlation, caused by the strong interaction. These three correlations are at right angles to each other as shown in Fig. 2.

Any deviations of the neutron polarization vector from the direction of the vector q will cause spurious effects. Fortunately the neutron polarization direction can be oriented with rather high accuracy, namely, an accuracy corresponding to the uniformity of the magnetic field at the target position, for instance, 10^{-4}–10^{-5} rad. If a crystal is chosen as the target, the direction of the momentum transfer q can be oriented to an accuracy within the crystal mosaic (10^{-4}–10^{-5} rad). By changing the direction of polarization (magnetic field) with respect to that of the vector q it is possible to extract the effect of T-violation due to $\vec{\sigma}$q- correlation. A very important circumstance is that the energy dependence of the correlations is different. Since the T-violating amplitude has a factor $i\lambda$, the energy dependence of the real part of the T-violating correlation corresponds to the energy dependence of the imaginary part of P-violating correlation, and vice versa.

In what follows we discuss three possible schemes of neutron optics experiments for searching for T-violation.

I. Crystals of ^{139}La or its compounds can be used to advantage in T-violation experiments because of the possibility of resonance enhancement near the p-wave resonance at 0.74 eV.

The influence of the T-violating (sq)-amplitude in dynamic diffraction on the perfect crystal is a question which should be considered separately. However, the simplest experimental scheme can be proposed for mosaic crystals, when the extinction length and single-crystal thickness in the sample are of the same order of magnitude. This scheme is shown in Fig. 3.

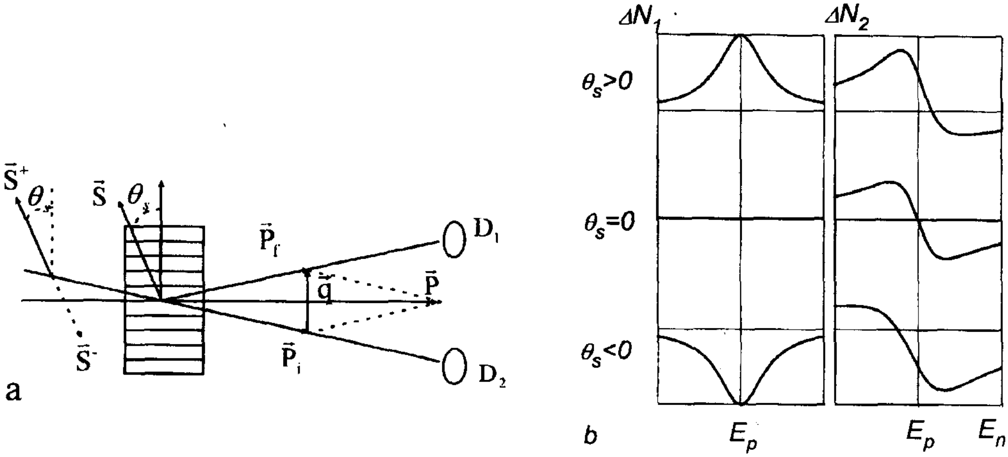

Fig.3. Experiment to search for T-violation in Bragg scattering; a) experimental scheme: D_1 – detector, D_2 – monitor; b) energy dependence of the experimental effect ΔN

The counting rate of the detector D_1 (reflected beam) is measured as the sign of the neutron beam polarization is changed. The polarization vector and the vector normal to the crystal planes should be parallel. Deviation of the neutron polarization vector from the vector normal to the crystal planes brings about an $\mathbf{S}(\mathbf{P}_i + \mathbf{P}_f)$-effect which changes sign upon a change of sign of the polarization. The energy dependence is shown in the left-hand part of Fig. 3b. If a T-violating effect exists, then a distortion of the picture on the left will arise, as shown on the right in Fig. 3b. First, the energy dependence changes sign at the resonance energy, when $\theta_s \simeq 0$; second, there is a deviation from symmetrical form for the P-violating effect at $\theta_s \neq 0$. Unfortunately, the $\mathbf{S}[\mathbf{P}_i \times \mathbf{P}_f]$-correlation has the same energy dependence near the resonance as the T-violating sq-correlation, and therefore only high precision in the orientation of the neutron polarization (guiding magnetic field) with respect to the vector normal to the crystal planes can help to solve this problem.

The expected effects were described by analyzing the energy dependence of the imaginary part of the T-violating amplitude, which governs the transmission effect, while the contribution of the real part of the amplitude was considered as a small correction.

II. Let us consider the possibility of searching for T-violation in neutron optics experiments by means of perfect-crystal interferometers. The classic interferometer scheme, augmented by spin-flippers to work with a polarized beam, is shown in Fig. 4. A simultaneous switching on (off) of the flippers F_1, F_3 or F_2, F_4 allows us to change the sign of the sq-correlation between the upper and lower arms of the interferometer. Flipper F_0 can be used to change the sign of the observed effect.

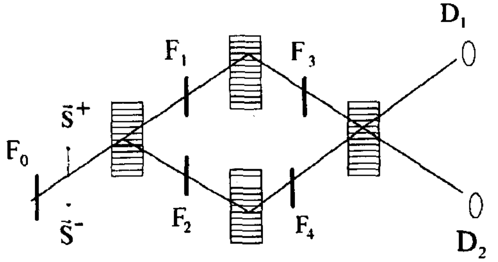

Fig.4. Interferometer scheme based on a perfect crystal. F_0, F_1, F_2, F_3, F_4 – flippers, D_1, D_2 – detectors

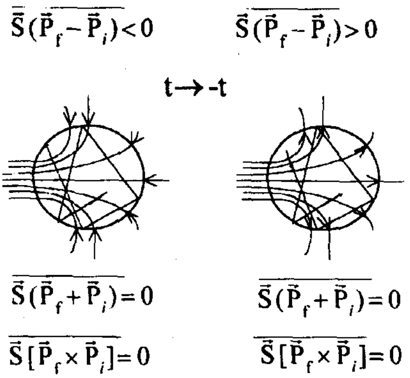

Fig.5. T-violation in the reflection of UCNs; *a*) UCN trap in a magnetic field having a strong divergence; *b*) experimental scheme: *1* – superconducting solenoid; *2* – UCN trap; *3* – UCN detector

This scheme also allows us to study the P-violating $s(\mathbf{p}_i+\mathbf{p}_f)$-correlation and the strong $s[\mathbf{p}_i\times\mathbf{p}_f]$-correlation at a certain direction of neutron polarization. Unfortunately, the experimental scheme is restricted in the choice of materials that can be studied.

IIIA. Finally, let us take a look at the possibility of searching for T-violation in the reflection of ultracold neutrons (UCNs) from a material surface.

Fig.5*a* shows an UCN trap placed in a magnetic field having a strong divergence. The UCN polarization keeps track of the magnetic field during the UCN storage in the trap. The average value of the sq-correlation is nonzero due to the strong divergence of the magnetic field, whereas the average values for the $s(\mathbf{p}_i+\mathbf{p}_f)$- and $s[\mathbf{p}_i\times\mathbf{p}_f]$-correlations are equal to zero because of repeated collisions with the trap walls. Thus the search for a T-violating effect involves the measurement of the UCN storage time in the trap for different signs of the magnetic field (τ_+, τ_-). There is no problem with the spurious effect due to the weak and strong correlations $(s(\mathbf{p}_i+\mathbf{p}_f)$ and $s[\mathbf{p}_i\times\mathbf{p}_f])$, but the momentum transfer q is very small, and this suppresses the expected effects.

The experimental scheme is shown in Fig. 5*b*. A superconducting solenoid polarizes the UCNs coming into the trap. The divergence of the magnetic field at the end of the solenoid simultaneously provides the necessary magnetic field configuration. The dependence of the UCN storage time on the sign of the current in the solenoid (τ_+, τ_-) is measured to observe T-violation.

An estimate of the possible effect due to nuclear absorption shows that the value $(\tau_+-\tau_-)/(\tau_++\tau_-)$ could be about $10^{-5}\lambda$, where λ is the T-violation parameter. The possible experimental accuracy for τ is limited to 10^{-5}, and so the range of interest for the T-violation problem, $\lambda = 10^{-3}$–10^{-4}, is not achievable at present. However, the estimate was made for nuclear absorption, while another part of the UCN losses in the trap is related to the interaction of UCNs with a solid material. T-violation in the interaction of neutrons with a solid state is a question which requires special consideration and is a valid one for direct experimental investigation. The high density of states for the neutron–solid system holds forth the hope for enhancement of the P- and T-violating effects, like the nuclear enhancement mechanism observed experimentally.

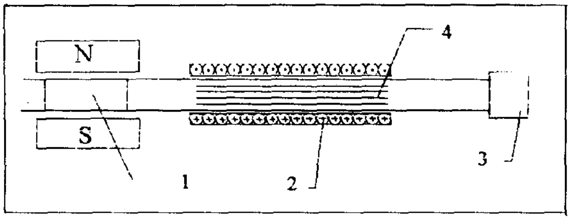

Fig.6. Experimental scheme to search for P-violation in neutron reflection from a material surface: *1* – polarizer, *2* – solenoid, *3* – detector, *4* – multislit neutron guide coated with the material to be studied

IIIB. The experimental search for P-violation in the reflection of neutrons from a material surface can be implemented by the scheme shown in Fig. 6.

A multislit neutron guide system with a coating of the material to be studied is connected to a polarizer with a transverse magnetic field. A solenoid with a longitudinal magnetic field provides the best condition for $S(P_i + P_f)$-correlation. The change of the detector counting rate is measured upon a change in the direction of the current in the solenoid.

In conclusion it should be kept in mind that the problem of P- and T-violation in neutron optics has not received practical development, and the aim of this paper is to call this interesting physics problem to the attention of experts for a more in-depth study of the questions which were touched on here.

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