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SYMMETRY BREAKING IN NEUTRON SCATTERING

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Abstract. It has been shown that the helicity-dependent imaginary part of the weak neutron interaction does not preserve spatial parity and breaks T-invariance. Time reversal symmetry breaking also occurs with a strong spin dependent interaction. The group structure of the spinor transformation in both cases is related to the Lorentz group transformations.

Keywords: *neutron scattering, weak and strong interaction, symmetry, groups SU_2, $SL(2, C)$, T-violation*

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1. INTRODUCTION

In this paper we analyze the properties of discrete symmetries in neutron transmission. The product of discrete symmetries *CPT*, where *C* is the charge conjugation, *P* is the parity transformation, and *T* is the time reversal, is a conserved quantity and constitutes the content of the fundamental theorem of Lüders-Pauli. This theorem is proved on the basis of two fundamental principles: Lorentz invariance and interaction locality. In this case the hermiticity of the Hamiltonian or Lagrangian is not obligatory [1]. By virtue of this theorem discrete symmetries can be broken only in pairs. Further we consider possible cases.

1. If the symmetry at time reversal *T* is preserved, then violations of spatial *P* and charge *C* parities are possible. The combined parity *CP* is also preserved. This property of the weak interaction is shown, for example, at beta decay. At action of transformations *C* and *P* on dynamical variables the helicity is changed and the particle is replaced by an antiparticle, so that the left-polarized particle passes to the right-polarized antiparticle. This property is a reflection of the fact that the weak interaction has divided the world into "left" and "right". The weak interaction involves left-polarized particles or right-polarized antiparticles.

2. At preservation of charge parity *C*, spatial parity *P* and symmetry at time reversal *T* can be broken. In other words, at such a weak interaction the combined *CP*-parity is broken, but *PT*-parity is preserved. The *PT* transformation in this case leaves the momentum direction unchanged but changes the sign of the spin, i.e., the helicity is changed in this transformation. Since antiparticles do not participate in neutron scattering, the change of helicity in neutron scattering is an indication of the violation of *T*-invariance.

3. At preservation of spatial parity *P* there can be charge parity violations *C* and symmetry at time reversal *T*. The strong interaction can possess such property.

This paper is intended to show that the three considered types of broken pair symmetries occur in spin-dependent zero-angle neutron scattering in the target matter. The main attention will be paid to the weak interaction, which in addition to the well-known violation of spatial parity can also lead to symmetry breaking in time reversal. Before considering the symmetries of the spin-dependent interaction of neutrons in the target matter, let us discuss the properties of discrete transformations in the framework of the *CPT*-theorem. Inversions of the coordinate system *P* and charge conjugation *C* represent an example of unitary transformations. The operator *P* changes the coordinate signs to opposite ones, and the operator *C* replaces a particle by an antiparticle. The time reversal operation is a non-unitary operation. When simply replacing $t \to -t$, the spin and momentum of the particle change sign, but the permutation relations between coordinate and momentum $[x, p_x] = i\hbar$, as well as the commutation relations between the spin components $[s_i, s_j] = i\varepsilon_{ijk}s_k$ and other relations containing spin or momentum change. In this case, positive-frequency solutions become negative-frequency solutions in the evolution operator. If the zero-point energy state is taken to be vacuum, the energies become less than vacuum energies, which should not be the case.

In order that the laws of nature do not depend on the direction of time, it is accepted to define the time reversal operator T as the product of the unitary operator U_T by the complex conjugation operation K. Such an operator is called anti-unitary and the result of its action preserves the relations between other operators. The justification of such representation is given in books on quantum field theory by Peskin and Schroeder [2], Weinberg [3] and the structure of the atomic nucleus by Bohr and Mottelson [4]. At such definition, the time reversal operator changes the sign of imaginary unit. Then, if $T(\sigma) = -\sigma$, then $T(i\sigma) = i\sigma$ and $T(\psi(t)) = \psi^*(-t)$.

2. SYMMETRIES OF SPIN-DEPENDENT NEUTRON INTERACTIONS

In the first Born approximation, the forward neutron scattering amplitude is usually represented in the following form:

$$f(0) = a + g_w\left(\sigma \cdot \mathbf{p} / p\right) + g_{str}\left(\sigma \cdot \mathbf{I} / I\right) + d\left(\sigma \cdot [\mathbf{I} \times \mathbf{p}]\right), \quad (1)$$

where s, p, I — the spin, neutron momentum, and angular momentum of the target nuclei, respectively. The coefficients in relation (1) are in general case complex numbers. The constants a and g_{str} determine the strength of the spin-independent and spin-dependent strong interactions. The weak interaction is represented by the second summand in (1), and the last summand in (1) describes the assumed weak interaction of the neutron spin with the vector field created by the vector product of the angular momentum of the nucleus by the neutron momentum.

Over the past 40 years, there has been a strong perception that weak interaction in spin-dependent neutron scattering violates only spatial parity and the degree of such violation is a measure of the scattering asymmetry depending on the neutron helicity. It was also assumed that symmetry breaking in time reversal arises in neutron scattering on the vector field represented by the last summand in (1), and the measure of the T-noninvariant effect is the magnitude of the imaginary part of the coefficient d. This representation is not quite accurate, since the analysis of the symmetry of the scattering amplitude did not take into account the anti-unitary property of the time reversal operation.

Let us consider the symmetries of different summands in expression (1). Let us apply the operator T to the second summand in expression (1), then we have $T(g_w) = g^*_w$. This result means that at time reversal the real and imaginary parts of the amplitude with spirality have different symmetries. The real part remains P-odd and preserves CP-parity, while the imaginary part, responsible for spin-dependent neutron absorption, is P-odd and changes sign upon time reversal, i.e., left-polarized particles change to right-polarized particles, which clearly violates T-invariance or CP-parity. Thus, to measure the effect of symmetry breaking in time reversal, it is sufficient to measure polarization with an unpolarized initial beam passing through an unpolarized target.

Left-polarized particles or right-polarized antiparticles participate in the weak interaction, so left-polarized neutrons are absorbed more strongly than right-polarized ones, and after passing the target the beam acquires the right polarization, i.e., there is a transition from zero polarization to final polarization. According to the optical theorem for an unpolarized target, the total cross section of the process depends on the helicity in the imaginary part of the amplitude (1):

$$\sigma_{\pm} = \frac{4\pi}{k} \operatorname{Im} f_{\pm}(0)$$

where signs indicate helicity, and this cross section is larger for left-polarized neutrons. Another case is also possible, where the passage of neutrons polarized along the momentum and against it is measured sequentially. In both cases, the measured value of asymmetry determines the polarization of the beam and, hence, the degree of violation of T-invariance.

The strong spin-dependent interaction is characterized by the fact that neutrons with spins opposite to the spins of the target nuclei interact more strongly than neutrons whose spins are parallel to the target spins. And while the real part of the interaction (scalar) preserves all discrete symmetries, the imaginary part (imaginary scalar) violates T-invariance and, by virtue of the CPT-theorem, charge parity C. This means that at charge conjugation, i.e. at transition to antiparticles, the absorption will be stronger in the case of parallel spins.

The real part of the interaction, represented by the last summand in (1), breaks the spatial parity and symmetry at time reversal, i.e., it breaks *CP*-parity. The imaginary part violates *P*-parity and preserves *CP*-parity.

Thus, we have shown that all pairwise violations of discrete symmetries allowed by the *CPT*-theorem are possible in neutron scattering.

3. WEAK SPIN-DEPENDENT INTERACTION AND THE LORENTZ GROUP

The scattering amplitude (1) with constant accuracy is a Fourier transform of the potential at zero transferred momentum, the Fourier transform in this case is equal to the mean value of the potential over the volume of the nucleus and is called the Fermi pseudopotential. Therefore, further on we will successively consider spin-dependent interactions corresponding to the summands of the amplitude (1). Then the weak neutron interaction is defined as follows:

$$W = -g_w\left(\sigma \cdot \mathbf{p} / p\right) / 2. \qquad (2)$$

The operator part of expression (2) is a pseudoscalar, i.e., a quantity that does not preserve spatial parity. We substitute (2) into the expression for the evolution operator $U = \exp(-iWt / \hbar)$ and introduce the following parameterization:

$$\vartheta = t\,\mathrm{Re}\,g_w / \hbar, \quad \varphi = -t\mathrm{Im}g_w / \hbar. \qquad (3)$$

The choice of a minus sign before $\mathrm{Im}g_w$ is associated with the fact that in the weak interaction the left-polarized particles participate. On the other hand, at such choice the bispinor column, as it will be seen below, has a traditional form with the right spinor in the upper position of the column. With parameterization (3) the evolution operator will have the following form:

$$U = \exp\left(i\left(\vartheta - i\varphi\right)\left(\sigma \cdot \mathbf{n}\right) / 2\right). \qquad (4)$$

At $\varphi = 0$, the matrix (4) is a unitary group SU(2) of spinor rotations by angle $\vartheta/2$ around the neutron momentum direction defined by the unit vector $\mathbf{n}$. This group has correspondence to the orthogonal group SO(3) of rotations in three-dimensional space by angle ϑ. These groups are homomorphic.

In a general form the operator (4) coincides with the spinor transformation matrix on the group SL(2, C). There is a correspondence of this group with the Lorentz group SO(1,3), where the digits 1, 3 indicate the signature of the Minkowski space. The group SL(2, C) is homomorphic to the group SO(1,3). Information about these groups can be found, for example, in [5].

It is known that the Lorentz proper transformations do not form a group because the boost generators K_i ($i = x, y, z$) in three directions do not have a closed algebra. The closed algebra arises by combining Lorentz transformations with three-dimensional rotations. Three generators of rotations, which are the components of angular momentum J_i, and three generators of boosts K_i, where $i = x, y, z$, give a six-parameter group. Going to the new generators $M_i = (J_i + iK_i)/2$ and $N_i = (J_i - iK_i)/2$, two irreducible representations of the Lorentz group characterized by the generators M_i and N_i, respectively, arise. The commutators for each of the generators are similar to the angular momentum commutators: $[M_x, M_y] = iM_z$ plus cyclic permutations and the same rule for commutators with generators N_i.

In the transition to spinors, two cases are possible. In the first case $M_i = J_i = \sigma_i/2$, $K_i = -i\sigma_i/2$ and $N_i = 0$. This representation is denoted as (1/2, 0) and describes right-handed spinors, since the spin in this case is parallel to the direction of the boost (or momentum of the particle). In the second case (this representation is (0, 1/2)) the spin direction is opposite to the momentum. In this case $M_i = 0$, $N_i = J_i = \sigma_i/2$ and $K_i = i\sigma_i/2$, i.e. the subgroup with N_i generators in this case describes left-handed spinors. Then, denoting by ϑ the three-dimensional rotation angle and by φ the boost angle, we can write the resulting matrix:

$$\begin{pmatrix}\psi_r\\ \psi_l\end{pmatrix} = \begin{pmatrix}\exp(i(\vartheta - i\varphi)(\boldsymbol{\sigma}\mathbf{n})) & 0\\ 0 & \exp(i(\vartheta + i\varphi))(\boldsymbol{\sigma}\mathbf{n}))\end{pmatrix}\begin{pmatrix}\psi_{0r}\\ \psi_{0l}\end{pmatrix} \qquad (5)$$

As already noted, the matrices included in expression (5) represent the group SL(2, C) of spinor transformations on the Lorentz group. The initial spinors are indistinguishable for resting particles or for unpolarized beam particles. Assuming them equal to $\psi_{0r} = \psi_{0l}$, we find the relation for the final spinors and present this relation in matrix form:

$$0 = \begin{pmatrix}-1 & \exp(\varphi(\boldsymbol{\sigma}\mathbf{n}))\\ \exp(-\varphi(\boldsymbol{\sigma}\mathbf{n})) & -1\end{pmatrix}\begin{pmatrix}\psi_r\\ \psi_l\end{pmatrix}$$

Expanding the exponents, we will have the final expression:

$$0 = \begin{pmatrix}-1 & ch\varphi + (\boldsymbol{\sigma}\mathbf{n})sh\varphi\\ ch\varphi - (\boldsymbol{\sigma}\mathbf{n})sh\varphi & -1\end{pmatrix}\begin{pmatrix}\psi_r\\ \psi_l\end{pmatrix} \qquad (6)$$

Here, the following property of Pauli matrices has been used in the derivation:

$$\left(\sigma \cdot \mathbf{n}\right)^{2k} = 1, \quad \left(\sigma \cdot \mathbf{n}\right)^{2k+1} = \left(\sigma \cdot \mathbf{n}\right).$$

The unitary matrices of the SU(2) group of rotating spinors by an angle $\vartheta/2$ at the derivation of equality

(6) are reduced and do not give a contribution to the connection between right and left spinors. As it follows from equality (6), when the coordinate system $\mathbf{n} \to -\mathbf{n}$ is inverted and the spinors change places. The same happens at time inversion, because the sign of the hyperbolic sine changes due to the change of the sign of the angle φ at this operation.

The group approach to the weak interaction (2) allow to make some conclusions. First, at T-noninvariant scattering the imaginary part of the weak potential is negative. The real part of this potential initiates the spinor rotation along the SU2 group, which for three-dimensional spins means spin precession in a pseudo-magnetic field directed along the momentum and equal to $\mathrm{Re}g_w$. The weak interaction violates spatial parity and T-invariance.

Let us note the universality of relation (6). The weak interaction in (6) is represented by the parameterization of the angle φ according to (3). But another parameterization is also possible, for example, relativistic, in which $\mathrm{tg}\varphi = \beta = v/c$, where c is the speed of light and v is the speed of the boost. Assuming the speed of light equal to unity, we have

$$\varphi = \gamma = \left(1 - \beta^2\right)^{-0.5} = E/m$$

and

$$\mathrm{sh}\varphi = \beta\gamma = p/m,$$

where E, m and p are respectively energy, mass and momentum of the particle. Then, using the equality $\mathbf{n}p = \mathbf{p}$, instead of (6) we obtain the Dirac equation written for bispinors:

$$0 = \begin{pmatrix} -m & E + \sigma \cdot \mathbf{p} \\ E - \sigma \cdot \mathbf{p} & -m \end{pmatrix} \begin{pmatrix} \psi_r \\ \psi_l \end{pmatrix}.$$

This is a reflection of the known fact that the transformation of spinors by the Lorentz group leads to the Dirac equation. At transition to 4-spinors and gamma matrices this equation acquires a traditional form in the form of one-line notation.

4. SPIN DENSITY MATRIX, NEUTRON COUNT RATE AND SCATTERING ASYMMETRY

To emphasize the effects of broken symmetries, we will use the spin density matrix formalism described in [6]. Let us refer to the system of equations (5) and calculate the density matrix based on the first equation for the wave function:

$$\rho_f = \psi_r \psi_r^\dagger = \exp\left(\frac{i}{2}(\vartheta - i\varphi)((\boldsymbol{\sigma}\mathbf{n}))\right)\rho_0 \times \times \exp\left(-\frac{i}{2}(\vartheta + i\varphi)((\boldsymbol{\sigma}\mathbf{n}))\right). \quad (7)$$

For the initial matrix we will consider the neutron flux normalized to one. Then this matrix has the following form:

$$\rho_0 = \frac{1}{2}\left(I + \sigma \cdot \mathbf{p}_0\right),$$

where $\mathbf{p}_0$ is the polarization vector, I is a unit matrix and the trace of the density matrix is equal to one. If the polarization of the initial beam is zero, the expression (7) takes the form

$$\rho_f = \frac{1}{2}\exp\left(\varphi(\boldsymbol{\sigma}\mathbf{n})\right) = \frac{1}{2}\left(\mathrm{ch}\varphi + (\boldsymbol{\sigma}\mathbf{n})\mathrm{sh}\varphi\right). \quad (8)$$

At the exit from the target, the beam acquires polarization $\mathbf{p}_f = \mathbf{n}\,\mathrm{ch}\varphi$ and a new intensity normalization equal to $\mathrm{sh}\varphi$. In order to pass to the number of samples, the beam must pass through the analyzer, the density matrix of which is determined by its efficiency

$$\rho_a = \frac{1}{2}\left(I + \sigma \cdot \mathbf{p}_a\right),$$

then for the count rate we have

$$N_\pm = Tr\rho_f\rho_{a\pm}, \quad (9)$$

where the signs indicate the efficiency of polarization measurement along the pulse and against it. Calculating the ratio of the difference in the number of neutron counts with the opposite polarizations to their sum, we obtain the value of asymmetry

$$A_w = (\mathbf{p_a}\mathbf{n})\,\mathrm{th}\,\varphi = -\left(\mathbf{p}_a \cdot \mathbf{n}\right)\mathrm{th}\left(t\mathrm{Im}g_w/\hbar\right). \quad (10)$$

In this expression the pseudoscalar violates spatial parity, and the hyperbolic tangent changes sign at time reversal. As a result, the asymmetry becomes P-odd and T-noninvariant. Because the neutron beam density matrix commutes with the analyzer density matrix, the analyzer device, which we will now call a polarizer, can be placed in front of the target. The asymmetry in this case remains the same.

Let us now calculate the effect of spin precession in the pseudomagnetic field of the weak interaction. For this purpose we will assume that in expression (7) the neutron momentum is directed along the x axis and this direction is given by the unit vector $\mathbf{n}_{px}$, where the index p indicates the momentum, and the initial neutron flux has transverse polarization along the unit pseudovector, e.g., $\mathbf{P}_y = \mathbf{n}_y P_y$. Then in expression (7) the initial density matrix will be equal to

$$\rho_0 = \frac{1}{2}\left(I + \sigma_y \cdot \mathbf{P}_y\right). \tag{11}$$

Neutrons after passing the target enter the analyzer, for which we choose the direction z and the efficiency $\mathbf{P}_{az}$:

$$\rho_z = \frac{1}{2}\left(I + \sigma_z \cdot \mathbf{P}_{az}\right). \tag{12}$$

Here, the polarization pseudovector $\mathbf{P}_z = \mathbf{n}_z P_z$. Then, using expressions (7), (9), (11) and (12), for the magnitude of the effect we can write

$$A = \frac{N_+ - N_-}{N_+ + N_-} = -\frac{\left(\left[\mathbf{n}_{px} \times \mathbf{n}_y\right] \cdot \mathbf{n}_{az}\right) P_{az} P_y \sin\vartheta}{\text{ch}\varphi}. \tag{13}$$

In this expression, the scalar product is a time-dependent pseudoscalar. When time is reversed, the sign of the angle ϑ also reverses, therefore this expression is P-odd and T-invariant, and by virtue of the CPT-theorem, if it is valid, violates the charge parity. CP-parity in in this case is preserved. With decreasing energy p-wave resonance and increasing the target length, the effect of breaking T-invariance according to (10) grows, since the angle φ increases. At the same time, the spin rotation angle ϑ also grows and the value of the sine amplitude in (13) decreases, i.e. the value of the P-odd effect decreases.

The described apparatus is applicable for determination the symmetry properties of the strong interaction. For this purpose, we introduce a new parameterization: $\upsilon = t\,\text{Re}g_{str} / \hbar$ and $\varphi = -t\,\text{Im}g_{str} / \hbar$, and a unitary pseudovector $\mathbf{n}_I$ in the direction of the angular momentum of the nucleus. Then the unitary group SU(2) will correspond to the spin group in three-dimensional space SO(3) describing the spin precession in the pseudomagnetic field, directed along the angular momentum of the nucleus. In polarized targets such fields can be significant [7]. All discrete symmetries are preserved.

With the parameterization by the strong interaction in equation (6), the definition of left and right changes. The scalar product in this equation defines the projection of the neutron spin on the direction of the angular momentum of the nucleus. And for right spinors this projection is positive, and for left spinors it is negative. In the time reversal operation, the spinors change places. This means that the strong spin-dependent interaction has divided the world into "left" and "right". Neutrons are more strongly involved in this interaction with left polarization, and antineutrons with right polarization.

By changing the parameterization in expression (10), we obtain an expression for the scattering asymmetry for the spin-dependent strong interaction:

$$A_{str} = (\mathbf{p}_\mathbf{a}\mathbf{n})\,\text{th}\,\varphi.$$

This expression does not preserve T-invariance, since it changes sign at time reversal. According to the CPT-theorem, the charge parity must be violated also.

Finally, let us consider the symmetries of the interaction of the neutron spin with the vector field $\mathbf{V} = [\mathbf{I}\times\mathbf{p}]$, represented by the last term in the amplitude (1). In accordance with the above approach, the real part of such interaction describes the precession of the spin around this field and this precession is P-odd and T-noninvariant. If there is an imaginary component in the interaction with the vector field, the expression for the asymmetry has the following form:

$$A_V = -\left(\mathbf{p}_a \cdot \mathbf{n}_V\right)\text{th}\varphi,$$

where $\mathbf{n}_V$ is a unit vector in the direction of the vector field. As follows from the form of this expression, the scattering asymmetry is P-odd and T-invariant.

5. DISCUSSION

The weak interaction for small nucleon systems is 7 orders of magnitude smaller than the strong interaction, so it is extremely difficult to observe it. But, as was predicted in [8-11], the effect of spatial parity violation is enhanced by a factor of a million in neutron reactions occurring near the p-wave resonance. This enhancement arises because, when neutrons scatter through the compound state, the weak interaction mixes closely lying levels of the same spin but opposite parity. A state with indeterminate parity arises and the decay of this state leads to a violation of spatial symmetry.

Experiments performed at JINR [12-14] confirmed this prediction and initiated an intensive study of neutron scattering through compound states near the p-wave resonance. The experiments were carried out at PNFI (Gatchina), JINR (Dubna), LANL (Los

Alamos), and KEK (Tsukuba). Detailed information is available in reviews [15, 16]. The same mechanism of the weak interaction enhancement was extended to the effects that do not preserve *CP*-parity due to symmetry breaking in time reversal and spatial parity violation [17-20].

The scope of the research is indicated by 125 references in [21] to papers related to the discussed issue. As noted in the review [21], the parity violation effect was measured at 150 resonances. The asymmetry in neutron scattering with right and left polarizations has magnitudes ranging from a few fractions of a percent to 10%. In La^{139} the effect, according to [22], is 10.2%. This value at neutron energy $E = 0.734$ eV and target length of 10 cm, according to (10), allows us to determine the imaginary part of the interaction $\text{Im} g_w$. By order of magnitude, this value turns out to be equal to 10^{-11} eV.

Combinatorial parity violation or symmetry breaking in time reversal was discovered in 1964 in K_0-meson decays and later in B_0-meson decays. The search for *CP*-parity violation in other physical phenomena, e.g., nuclear reactions, nucleus scattering, atomic and molecular physics, molecules and crystals, has not yet been successful, as well as many years of measurements of the electric dipole moment of the neutron, which give only a constraint on this quantity. But, as shown in this paper, the helicity-dependent zero-angle scattering of neutrons due to the weak interaction has been shown to be a well-measured effect of symmetry non-preservation under time reversal. The real part of this interaction violates the *P*-parity along with the preserving CP-parity, and the imaginary part creates the *P*-odd effect with violation of the *CP*-parity.

The fact that the violation of the *T*-invariance in neutron scattering near the *p*-wave resonance, measured more than 40 years ago in numerous experiments, has not been reported until now should be ascribed to a historical curiosity. Another misconception, lasting about 40 years, is the notion of a way to detect the effect of symmetry breaking in time reversal. It was believed that this effect would be discovered by measuring the magnitude of the interaction of the neutron with the vector field represented by the last term in relation (1).

The values of $\text{Re} d$ and $\text{Im} d$ were not measured, only the schemes of $\text{Im} d$ emission were discussed, since the spin-dependent absorption is easier to measure than the spin precession. A large number of papers have been devoted to the discussion of these schemes, references to which can be found in [23]. Up to now it was considered that the measure of the *T*-noninvariant effect is the value $\text{Im} d$. But this is not true, since at time reversal the value $i\text{Im} d\,(\sigma \cdot [\mathbf{I}\times\mathbf{p}])$ does not change the sign, i.e., is *T*-invariant. For the same reason, the imaginary pseudoscalar $i\text{Im} g_w(\sigma \cdot \mathbf{p})$ and the imaginary scalar $i\text{Im} g_{str}(\sigma \cdot \mathbf{I})$, respectively, are *T*-noninvariant. That is, in this case the study of triple correlation does not make sense.

Another stable stereotype is the statement that in strong interactions all discrete symmetries are conserved separately. But, as it has been shown, the strong spin-dependent interaction of neutrons with polarized nuclei breaks the symmetry at time reversal. The magnitude of such a violation can be quite significant. As an example, let us point to the neutron passage through a polarized medium from He^3. At neutron energies less than 10 eV, the absorption cross section at oppositely directed spins is much larger than the cross section in the case of parallel spins [24]. In this work, the polarization of the neutron beam obtained by passing a polarized He^3, is 25%. This is the maximum value of the effect of *T*-invariance violation.

In K_0-meson decays, the effect of *CP*-parity violation is three cases per thousand, in B_0-meson decays – eight cases per thousand. In neutron scattering, the *T*-noninvariant effect is much stronger. For the isotopes studied, its value ranges from a few fractions of a percent to 10%, but the *T*-noninvariant effect is even more pronounced in the strong interaction.

In conclusion, we note that both in neutron transmission and in the decays of K_0- and B_0- mesons the effects of the *T*-noninvariant are explained by the use of the non-Hermitian Hamiltonians.

Let us point out a close analogy in the explanation of *T*-noninvariant neutron scattering and K-meson decays. In Okun's book [25] it is noted that in the first order of perturbation theory with an effective four-fermion local interaction the effect of *CP*-parity violation is enhanced by about six orders of magnitude due to the small mass difference between K_1- and K_2- mesons. The interaction violating *CP*-parity mixes these states, so that the mixing matrix element is equal to the non-diagonal imaginary mass, which determines the imaginary constant of the interaction and, consequently, the violation of the *T*-invariance. At the quark level, the imaginary part of the interaction arises in the product of current by current when an imaginary phase is introduced into the quark mixing matrix.

In all cases, the primary effect is the *T*-noninvariant effect, which is equivalent to *CP*-symmetry breaking when *CPT*-parity is preserved.

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