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Searching for *T*-Invariance Violation Effects in Spin Observables of *pd*-Scattering

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Abstract—Relationships imposed by the T-invariance on differential spin observables A_y, P_y, K_x^z, and K_z^x of elastic pd-scattering are considered, and the degree to which these relationships are violated is estimated with allowance for the T-odd P-even interaction. The result is compared to a similar estimate for a null test experiment in which it is planned to measure the integral cross section of interaction between transversely polarized protons and aligned deuterons. The spin observables are calculated using a modification of the Glauber theory.

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INTRODUCTION

Discrete symmetries related to the reflection of space (P) and time (T) play a key role in understanding the properties of fundamental interactions. Violation of CP-invariance (or T-invariance under the condition of CPT-symmetry) is necessary to explain the baryon asymmetry of the Universe [1]. At the same time, the effects of T-invariance violation have not been observed in baryon systems, and there are restrictions only on the upper limit of such violations from experiments to measure the electric dipole moment (EDM) of neutrons and neutral atoms, and from some other experiments as well [2]. Detection of a nonzero EDM would indicate the simultaneous violation of T-invariance and P-evenness and could be associated with the θ term of quantum chromodynamics in the standard model.

Along with effects of this kind, it is interesting to look for those in which T-invariance is violated but P-evenness is preserved (TVPC) [3]. This interaction, which is noninvariant with respect to time inversion (T-odd) but preserves spatial evenness (P-even) and flavor, does not occur at the fundamental level in the standard model but can be generated by weak radiation corrections to T-odd P-odd interaction. In this case, however, the magnitude of the corresponding observables is expected to be so low that they cannot be measured at the current state of the experimental technique [2], so searching for TVPC interaction in nuclear experiments in fact means searching for physics beyond the scope of the standard model.

The magnitude of TVPC effects is usually formulated in terms of the ratio of matrix elements of transitions with violation of T-invariance and preservation of P-evenness to matrix elements of the strong interaction α_T. Theoretical estimates based on existing experimental restrictions on the EDM of neutrons and atoms yield very different restrictions on the magnitude of TVPC effects, depending on the scenario of EDM generation (which remains unknown). In one such scenario, the restriction turns out to be very strong [4, 5]. According to another possible scenario [5], the EDM does not lead to restrictions on TVPC. Within this second scenario, restrictions on TVPC can be obtained only by directly searching for TVPC effects and appear to be rather weak. The corresponding results are based on studies of the detailed balance in nuclear reactions [6] ($\alpha_T < 2 \times 10^{-3}$ [7]), five-dimensional correlations in the interaction between polarized neutrons and aligned nuclei ($\alpha_T \leq 7.1 \times 10^{-4}$ [8]), and violation of charge symmetry during np-scattering ($\alpha_T \leq 8 \times 10^{-5}$ [9]). The relative weakness of existing experimental restrictions on the magnitude of TVPC effects gives grounds for expecting the detection of such effects at a ratio of matrix elements on the order of $\alpha_T \sim 10^{-6}$ [10]. Such a restriction on the magnitude of a TVPC signal will presumably be obtained in an experiment [10] planned at COSY to measure the integral cross section of interaction between transversely polarized protons and tensorially polarized deuterons at a beam energy of 135 MeV.

In this work, we consider relationships imposed by T-invariance on differential spin observables A_y, P_y, and K_i^j of elastic pd-scattering and estimate the degree of violation of these relationships with allowance for T-odd and P-even effects depending on phenomenological constants determining the intensity of these interactions [11]. Spin observables of elastic pd-scattering are calculated using the Glauber theory. The corresponding spin formalism of elastic pd-scattering for T-even and P-even NN-interactions was recently developed in [12]. This formalism includes the total spin dependence of elementary spin amplitudes of *pN*-scattering, along with the *S*- and *D*-components of the deuteron wave function. We develop this formalism further and use it to calculate the polarization transfer coefficients and the polarization of particles in the final state, and to consider the contribution from *T*-odd *P*-even *NN*-interactions. The effect *T*-odd *P*-even contributions have on relationships of *T*-invariance between differential observables A_y, P_y, and K_i^j is compared to the corresponding contribution to the null test observable [3] that we plan to measure in an experiment [10].

FORMALISM OF INVARIANT SPIN AMPLITUDES

The amplitude of the $pd \to pd$ transition can be written in the form [13]

$$\langle p'\mu', d'\lambda'|T|\, p\mu, d\lambda\rangle = \varphi^{+}_{\mu'} e^{(\lambda')*}_{\beta} T_{\beta\alpha}(\vec{p}, \vec{p}, \vec{\sigma}) e^{(\lambda)}_{\alpha} \varphi_{\mu}, \quad (1)$$

where φ_μ ($\varphi_{\mu'}$) is the Pauli spinor of the initial (final) proton in a state with spin projection onto quantization axis μ (μ'); $e^{(\lambda)}_{\alpha}$ ($e^{(\lambda')}_{\beta}$) is the polarization vector of the initial *d* (final *d*') deuteron in a state with the spin projection λ (λ'); and $T_{\beta\alpha}$ is a second rank tensor (β, $\alpha = x, y, z$) in which every element depends on the initial ($\vec{p}$) and final ($\vec{p}\,'$) proton momentum. It also contains Pauli matrices $\vec{\sigma}$, i.e., it is an operator acting in the spin state space of an impacting proton. Under the condition of rotational invariance and invariance with respect to the inversion of spatial coordinates, matrix element (1) generally contains 18 invariant amplitudes.

In a coordinate system with axes $OX \uparrow\uparrow \vec{q}$, $OZ \uparrow\uparrow \vec{k}$, $OY \uparrow\uparrow \vec{n}$, where $\hat{\vec{q}} = (\vec{p} - \vec{p}\,')/|(\vec{p} - \vec{p}\,')|$, $\hat{\vec{k}} = (\vec{p} + \vec{p}\,')/|(\vec{p} + \vec{p}\,')|$, $\hat{\vec{n}} = [\vec{k} \times \vec{q}]/|[\vec{k} \times \vec{q}]|$, we find for tensor $T_{\beta\alpha}$ in the most general case independent of specific dynamics

$$\begin{gathered} T_{xx} = M_1 + M_2\sigma_y, \quad T_{xy} = M_7\sigma_z + M_8\sigma_x, \\ T_{xz} = M_9 + M_{10}\sigma_y, \quad T_{yx} = M_{13}\sigma_z + M_{14}\sigma_x, \\ T_{yy} = M_3 + M_4\sigma_y, \quad T_{yz} = M_{11}\sigma_x + M_{12}\sigma_z, \\ T_{zx} = M_{15} + M_{16}\sigma_y, \quad T_{zy} = M_{17}\sigma_x + M_{18}\sigma_z, \\ T_{zz} = M_5 + M_6\sigma_y, \end{gathered} \quad (2)$$

where σ_x, σ_y, and σ_z are Pauli matrices; M_i ($i = 1, \ldots, 18$) are complex amplitudes determined by the dynamics of the process.

Invariance with respect to time inversion operation $t \to -t$ (with simultaneous rearrangement of the initial and final states) leads to the requirement

$$T_{\beta\alpha}(\vec{p}, \vec{p}\,', \vec{\sigma}) = T_{\alpha\beta}(-\vec{p}\,', -\vec{p}, -\vec{\sigma}). \quad (3)$$

In our coordinate system, the requirement of *T*-invariance is reduced to relationships [14]

$$\begin{gathered} M_{13} = -M_7, \quad M_{14} = M_8, \quad M_{15} = -M_9, \\ M_{16} = -M_{10}, \quad M_{17} = -M_{11}, \quad M_{18} = M_{12}. \end{gathered} \quad (4)$$

The same result is obtained in a coordinate system with $OZ \uparrow\uparrow (\vec{p} - \vec{p}\,')$ [13, 14].

In [12], the general spin structure of the $pd \to pd$ transition operator is written in another form. Allowing for *P*-invariance only, the $pd \to pd$ transition operator can be presented as

$$\begin{aligned} M = {} & (A_1 + A_2\vec{\sigma}\hat{\vec{n}}) + (A_3 + A_4\vec{\sigma}\hat{\vec{n}})(\vec{S}\hat{\vec{q}})^2 + (A_5 + A_6\vec{\sigma}\hat{\vec{n}})(\vec{S}\hat{\vec{n}})^2 + A_7(\vec{\sigma}\hat{\vec{k}})(\vec{S}\hat{\vec{k}}) \\ & + A_8(\vec{\sigma}\hat{\vec{q}})\left[(\vec{S}\hat{\vec{q}})(\vec{S}\hat{\vec{n}}) + (\vec{S}\hat{\vec{n}})(\vec{S}\hat{\vec{q}})\right] + (A_9 + A_{10}\vec{\sigma}\hat{\vec{n}})(\vec{S}\hat{\vec{n}}) + A_{11}(\vec{\sigma}\hat{\vec{q}})(\vec{S}\hat{\vec{q}}) \\ & + A_{12}(\vec{\sigma}\hat{\vec{k}})\left[(\vec{S}\hat{\vec{k}})(\vec{S}\hat{\vec{n}}) + (\vec{S}\hat{\vec{n}})(\vec{S}\hat{\vec{k}})\right] \\ & + (T_{13} + T_{14}\vec{\sigma}\hat{\vec{n}})\left[(\vec{S}\hat{\vec{k}})(\vec{S}\hat{\vec{q}}) + (\vec{S}\hat{\vec{q}})(\vec{S}\hat{\vec{k}})\right] + T_{15}(\vec{\sigma}\hat{\vec{q}})(\vec{S}\hat{\vec{k}}) + T_{16}(\vec{\sigma}\hat{\vec{k}})(\vec{S}\hat{\vec{q}}) \\ & + T_{17}(\vec{\sigma}\hat{\vec{k}})\left[(\vec{S}\hat{\vec{q}})(\vec{S}\hat{\vec{n}}) + (\vec{S}\hat{\vec{n}})(\vec{S}\hat{\vec{q}})\right] + T_{18}(\vec{\sigma}\hat{\vec{q}})\left[(\vec{S}\hat{\vec{k}})(\vec{S}\hat{\vec{n}}) + (\vec{S}\hat{\vec{n}})(\vec{S}\hat{\vec{k}})\right], \end{aligned} \quad (5)$$

where $\vec{S}$ is the spin operator of the target deuteron; $\vec{q}$ is the transferred 3-momentum; and A_i are the invariant amplitudes ($i = 1, \ldots, 12$) introduced in [12] for *P*- and *T*-invariant interactions. After inverting spatial coordinates $\vec{r} \to -\vec{r}$, we have $\vec{k} \to -\vec{k}$, $\vec{q} \to -\vec{q}$, $\vec{n} \to \vec{n}$, $\vec{\sigma} \to \vec{\sigma}$, and $\vec{S} \to \vec{S}$. After time inversion operation $t \to -t$ and simultaneous rearrangement of the initial and final states, momenta $\vec{q}$, $\vec{n}$, and $\vec{k}$ and spin operators are transformed in the following manner: $\vec{k} \to -\vec{k}$, $\vec{q} \to \vec{q}$, $\vec{n} \to -\vec{n}$, $\vec{\sigma} \to -\vec{\sigma}$, and $\vec{S} \to -\vec{S}$. Using these properties, we find from expression (5) that operator expressions in front of amplitudes T_i (i = 13, ..., 18) are *T*-odd and therefore differ from zero only in the case of *T*-invariance violation. In a similar manner, we find that amplitudes A_i ($i = 1, \ldots, 12$) are *T*- and *P*-invariant.

We can show that amplitudes M_i are expressed in the form of the following linear combinations of the amplitudes A_i:

$$\begin{gathered} M_1 = A_1 + A_5, \quad M_2 = -(A_2 + A_6), \quad M_3 = A_1 + A_3, \\ M_4 = A_2 - A_4, \quad M_5 = A_1 + A_5 + A_3, \\ M_6 = -(A_2 + A_4 + A_6), \quad M_7 = -iA_7, \quad M_8 = A_8, \\ M_9 = -iA_9, \quad M_{10} = iA_{10}, \quad M_{11} = -iA_{11}, \\ M_{12} = A_{12}, \quad M_{13} = iA_7, \quad M_{14} = A_8, \quad M_{15} = iA_9, \\ M_{16} = -iA_{10}, \quad M_{17} = iA_{11}, \quad M_{18} = A_{12}. \end{gathered} \tag{6}$$

It is evident that invariant amplitudes (6), in which A_i ($i = 1, \ldots, 12$) are taken from [12], satisfy requirements of T-invariance (4).

When terms $T_{13},\ldots,T_{18}$ violating T-invariance are taken into account, an additional term (denoted here as M_i^{TV}) additively complements each of the invariant amplitudes M_i ($i = 1, \ldots, 18$). We can show that these additional terms take the form

$$\begin{gathered} M_1^{TV} = M_2^{TV} = M_3^{TV} = M_4^{TV} = M_5^{TV} = M_6^{TV} = 0, \\ M_7^{TV} = iT_{17}, \quad M_8^{TV} = iT_{15}, \quad M_9^{TV} = T_{13}, \quad M_{10}^{TV} = -T_{14}, \\ M_{11}^{TV} = 0, \quad M_{12}^{TV} = iT_{16}, \quad M_{13}^{TV} = -T_{17}, \quad M_{14}^{TV} - iT_{15}, \\ M_{15}^{TV} = T_{13}, \quad M_{16}^{TV} = -T_{14}, \quad M_{17}^{TV} = -T_{18}, \quad M_{18}^{TV} = 0. \end{gathered} \tag{7}$$

Total amplitude M_i^T with T-invariant and T-noninvariant contributions thus has the form

$$M_i^T = M_i + M_i^{TV}, \tag{8}$$

where M_i are the T-invariant amplitudes presented in formulas (6).

T-INVARIANCE RELATIONSHIPS BETWEEN SPIN OBSERVABLES

Let us obtain expressions for vector analyzing power A_y^p of the process $\vec{p} + d \to p + d$ with a polarized initial proton, and for polarization of the final proton P_y^p in the process $p + d \to \vec{p} + d$ with nonpolarized initial particles:

$$\begin{aligned} A_y^p &= TrM\sigma_y M^+ / TrMM^+ \\ &= \frac{2}{\sum_{i=1}^{18} |M_i|^2} [Re(M_1M_2^* + M_9M_{10}^* + M_3M_4^* + M_{15}M_{16}^* + M_5M_6^*) \\ &\quad - Im(M_8M_7^* + M_{14}M_{13}^* + M_{11}M_{12}^* + M_{17}M_{18}^*)]. \end{aligned} \tag{9}$$

$$\begin{aligned} P_y^p &= TrMM^+\sigma_y / TrMM^+ \\ &= \frac{2}{\sum_{i=1}^{18} |M_i|^2} [Re(M_1M_2^* + M_9M_{10}^* + M_3M_4^* + M_{15}M_{16}^* + M_5M_6^*) \\ &\quad + \mathrm{Im}(M_8M_7^* + M_{14}M_{13}^* + M_{11}M_{12}^* + M_{17}M_{18}^*)]. \end{aligned} \tag{10}$$

In these expressions, we must perform substitution $M_i \to M_i^T$ if contributions (7) violating T-invariance are included. Comparing these expressions to one another, we find that they differ by the sign of the expression representing the imaginary part of the same bilinear combination of invariant amplitudes. Applying the requirement of T-invariance (4), we immediately obtain the familiar relationship [15]

$$P_y^p = A_y^p. \tag{11}$$

The analogous relation $P_y^d = A_y^d$ is valid for vector analyzing power A_y^d of a reaction with a vectorially polarized deuteron $p + \vec{d} \to p + d$ and vector polarization of the final deuteron P_y^d in the reaction $p + d \to p + \vec{d}$.

Let us consider polarization transfer coefficients K_x^z and K_z^x. Using the formalism of invariant spin amplitudes (2), we can show that, in a coordinate system with the OZ axis directed along the vector $\vec{p} + \vec{p}'$, under conditions of T-invariance (4), the following relationships between polarization transfer coefficients are valid:

$$\begin{gathered} K_x^z(p \to p) = -K_z^x(p \to p), \\ K_x^z(p \to d) = -K_z^x(d \to p), \\ K_x^z(d \to p) = -K_z^x(p \to d), \\ K_x^z(d \to d) = -K_z^x(d \to d). \end{gathered} \tag{12}$$

CONSIDERING T-ODD P-EVEN INTERACTIONS

T-odd P-even NN-interactions generally contain 18 different operators [11]. To estimate the degree to which relations (11) and (12) are violated, we consider only the three types of interaction studied in [16]:

$$t_{pN} = h_p[(\vec{\sigma}\cdot\vec{p})(\vec{\sigma}_p\cdot\vec{q}) + (\vec{\sigma}_p\cdot\vec{p})(\vec{\sigma}\cdot\vec{q}) - (\vec{\sigma}_p\cdot\vec{\sigma})(\vec{p}\cdot\vec{q})]$$
$$+ g_p[\vec{\sigma}\times\vec{\sigma}_p]\cdot[\vec{q}\times\vec{p}] + g_p'(\vec{\sigma}-\vec{\sigma}_p)\cdot i[\vec{q}\times\vec{p}][\vec{\tau}_x\times\vec{\tau}_p]_z + (p \leftrightarrow n). \quad (13)$$

In the context of the phenomenological potentials of meson exchanges, the g' term corresponds to ρ-meson exchange and the h term corresponds to axial-vector meson exchange. In the single scattering approximation with allowance for the S- and D-waves of a deuteron, we obtain the following expressions for T-odd amplitudes:

$$T_{15} = [S_0^{(0)}(q/2) + \frac{1}{\sqrt{8}}S_2^{(1)}(q/2)](h_n + g_n + h_p + g_p),$$
$$T_{16} = [S_0^{(0)}(q/2) - \frac{1}{\sqrt{2}}S_2^{(1)}(q/2)](g_n - h_n + g_p - h_p), \quad (14)$$

where $S_0^{(0)}$ and $S_2^{(1)}$ are elastic deuteron form factors corresponding to the S- and D-waves, respectively, in the designations of [12]. Charge-exchange term g' makes no contribution in the single scattering approximation because the matrix element from the isospin operator for this transition disappears. Other T-odd amplitudes for the mechanism under consideration disappear as well: $T_{13} = T_{14} = T_{17} = T_{18} = 0$.

Total Spin-Dependent Cross Section

For the total cross section, we obtain the following expression using the optical theorem with allowance for its dependence on spin [17–19]:

$$\sigma_{\text{tot}} = \sigma_0 + \sigma_1\vec{p}^{\,p}\cdot\vec{p}^{\,d}$$
$$+ \sigma_2(\vec{p}^{\,p}\cdot\hat{\vec{k}})(\vec{p}^{\,d}\cdot\hat{\vec{k}}) + \sigma_3 P_{zz} + \tilde{\sigma}p_y^p P_{xz}, \quad (15)$$

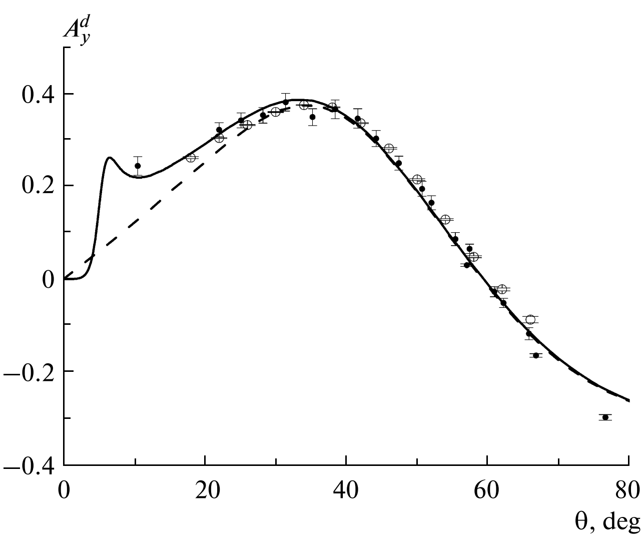

Fig. 1. Vector analyzing power A_y^d of the $pd \to pd$ process at a proton beam energy of 135 MeV as a function of the scattering angle in the center-of-mass system. The curves show the results from our calculations without allowance for Coulomb scattering (dashed curves) and with it (solid curves). The experimental data were taken from [22] (white dots) and [23] (black dots).

where $\vec{p}^{\,p}$ ($\vec{p}^{\,d}$) is the polarization vector of the initial proton (deuteron) and P_{zz} and P_{xz} are the tensorial polarizations of a deuteron. The first four cross sections σ_i ($i = 0, 1, 2, 3$) differ from zero only for T-even P-even interaction. The last term in (15) emerges only if we include the T-odd and P-even contributions to the transition amplitude. This term is the null test signal of T-invariance violation in the presence of P-invariance. Measuring cross section $\tilde{\sigma}$ corresponding to this term is the aim of the TRIC experiment [10]. We can demonstrate that a nonzero result for $\tilde{\sigma}$ is obtained only if we include the mechanism of double scattering [19].

NUMERICAL RESULTS AND DISCUSSION

Numerical results on differential spin observables are presented here for the energy of the planned experiment [10], 135 MeV. The spin amplitudes of elastic pN-scattering were taken from the data in [20] and the deuteron wave function corresponds to the CD Bonn NN-potential [21]. The results from our numerical calculations for nonpolarized cross sections, vector analyzing powers, and spin correlation coefficients at 135 and 250 MeV are in satisfactory agreement with available experimental data at narrow scattering angles ($\theta < 30°$) and/or the results from Faddeev calculations [22, 23]. The calculation results for vector analyzing power A_y^d are compared in Fig. 1 to the experimental data from [22, 23].

In light of T-odd P-even interactions (13), constants h and g were chosen such that the absolute value of total cross section $\tilde{\sigma}$ (the null test signal of the experiment [10]) of interaction between transversely polarized protons and tensorially polarized deuterons is at the limit of the TRIC experiment's capabilities: $\tilde{\sigma}/\sigma_0 = 10^{-6}$. The calculation results for quantities $\left|A_y^p - P_y^p\right|$, $\left|A_y^d - P_y^d\right|$, and $\left|K_x^z + K_z^x\right|$ are presented in Fig. 2. It can be seen from the figure that in the forward hemisphere ($\theta < 50°$), the maximum value of the violation of T-invariance relations at the chosen value of constant h is $2–3 \times 10^{-4}$ for $\left|K_x^z(p \to d) + K_z^x(d \to p)\right|$ one order of magnitude lower for the difference $\left|A_y^p - P_y^p\right| \sim 3 \times 10^{-5}$ and even lower for other considered relationships. The quantity $\left|K_x^z(p \to d) + K_z^x(d \to p)\right|$ is thus greater than $\tilde{\sigma}/\sigma_0$ almost by two orders of magnitude. The null test observable $\tilde{\sigma}$ can nevertheless be measured in the same experiment, while measuring

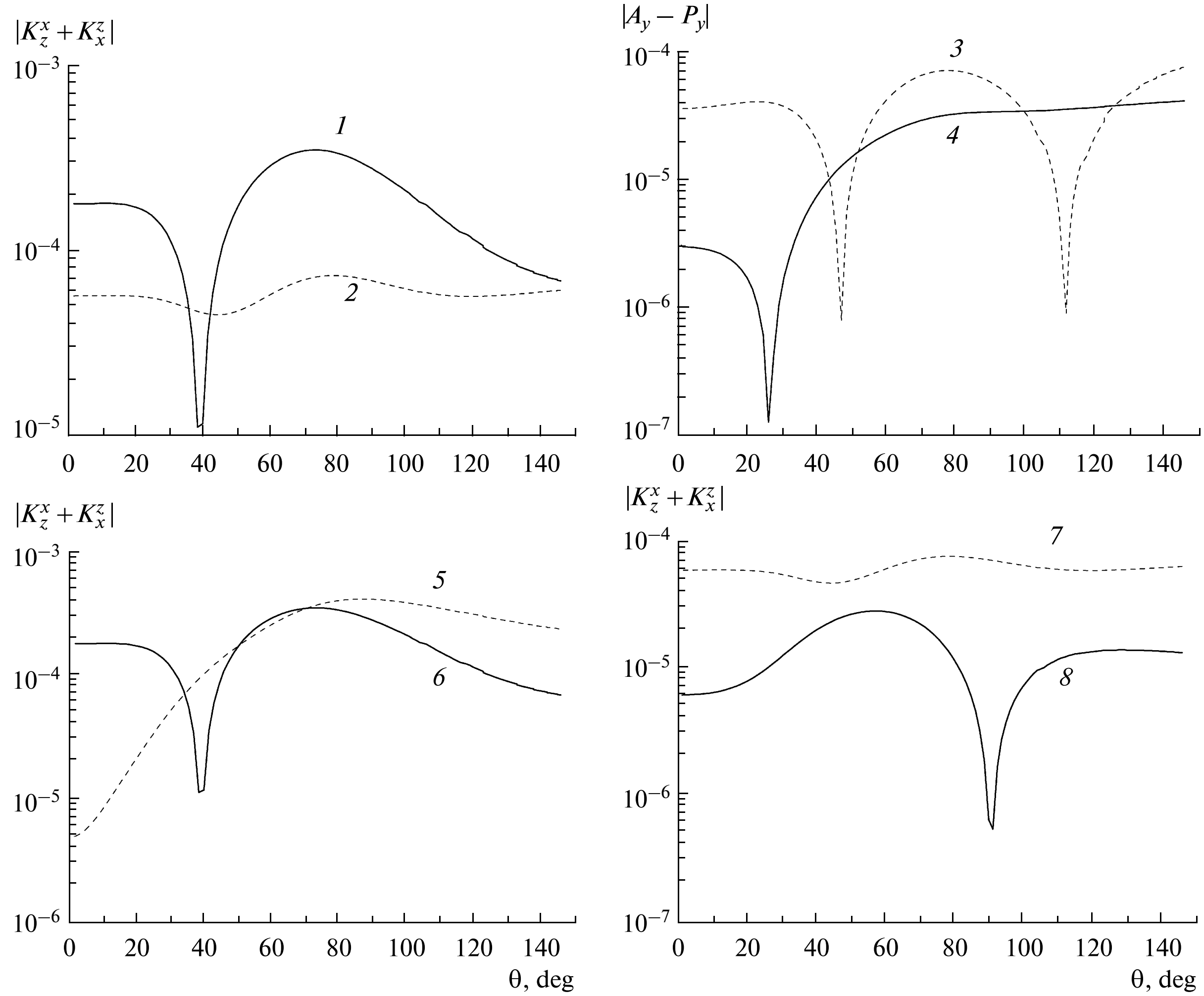

Fig. 2. Results from calculations for relations $\left|A_y^p - P_y^p\right|$, $\left|A_y^d - P_y^d\right|$, and $\left|K_x^z + K_z^x\right|$: *(1)* $\left|K_x^z(p \to d) + K_z^x(d \to p)\right|$, *(2)* $\left|K_z^x(p \to d) + K_x^z(d \to p)\right|$, *(3)* $\left|A_y^p - P_y^p\right|$, *(4)* $\left|A_y^d - P_y^d\right|$, *(5)* $\left|K_x^z(p \to p) + K_z^x(p \to p)\right|$, *(6)* $\left|K_x^z(p \to d) + K_z^x(d \to p)\right|$, *(7)* $\left|K_z^x(p \to d) + K_x^z(d \to p)\right|$, and *(8)* $\left|K_x^z(d \to d) + K_z^x(d \to d)\right|$. The intensity of interactions $h_p = h_n$ and $g_p = g_n$ was chosen such that $\tilde{\sigma}/\sigma_0 = 10^{-6}$.

quantities $\left|A_y^p - P_y^p\right|$ or $\left|K_x^z(pd) + K_z^x(dp)\right|$ requires that we conduct two or more complex polarization experiments with measurements of final particle polarization. The authors of [10] believe that the null test experiment will allow us to obtain stricter limits on the magnitude of TVPC effects than experiments to measure the transfer of polarization or difference $\left|A_y^p - P_y^p\right|$. Without analyzing the specific conditions of each experiment, however, we cannot give prior preference to any one in particular.

CONCLUSIONS

Numerical calculations of the characteristics of elastic *pd*-scattering with T-even P-even NN-forces in comparison to the experimental data show that the Glauber formalism allows us to describe spin observables of this process with reasonable (nuclear) accuracy at the rather low energies of ~100 MeV with which a null test experiment is planned to verify T-invariance [10]. This gives grounds for considering the effect of T-odd contributions within this formalism along with the strong NN-interaction. Searching for the effects of T-invariance violation in differential (bilinear in transition amplitude M_{fi}) observables has its own advantages and disadvantages, compared to the integral cross section (the observable linear in M_{fi}).

One disadvantage is that there is interference between the T-odd part of the amplitude and its predominant T-even part; part is generally known with an accuracy considerably less than the one required to discern T-odd effects against the background of

T-even contributions. One advantage is that for special observables in the rigorous relationships suggested by T-invariance, this interference can considerably amplify the effects of T-invariance violation. It is unimportant that the T-even amplitude itself is known with insufficient accuracy. According to our calculations, the amplification of T-odd effects due to interference from the strong part of the elastic *pd*-scattering amplitude for polarization transfer coefficients can be as high as two orders of magnitude.

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