Double-Polarized pd Scattering and Test of Time-reversal Invariance

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Abstract. The integrated proton-deuteron cross section \( \sigma \) for the case of transversal polarization \( p_y^p \) of the proton and tensor polarization \( P_{zz}^d \) of the deuteron provides a null test signal for time-reversal invariance violating but P-parity conserving effects. The corresponding experiment is planned at COSY to measure the observable \( \sigma \). Here we consider in general case the status of the null-test observable in pd scattering, calculate \( \sigma \) within the Glauber theory of the double-polarized pd scattering at 100 - 1000 MeV and study the contribution of the deuteron S- and D-waves for several type of the T-odd NN interactions.

1. Introduction
Discrete symmetries play an important role in physics of fundamental interactions. In particular, the CP-violation (or T-invariance violation under CPT symmetry) is responsible for the baryon asymmetry of the Universe [1]. However, within the standard model CP-violation effects observed in physics of kaons and B-mesons are far not sufficient to explain this asymmetry [2]. Therefore, other sources of CP violation have to be found. Time-invariance-violating (T-odd) P-parity conserving (P-even) (TVPC) interactions do not arise on the fundamental level within the standard model. This type of interaction can be generated by weak radiative corrections to the T-odd P-odd interaction discovered in physics of kaons and B-mesons. However in such a case its intensity is too small to be observed in experiments at present [3]. Thus, observation of TVPC effects would be considered as indication to physics beyond the standard model.

The total polarized cross section \( \sigma \) of the proton-deuteron scattering with vector polarization of the proton \( p_y^p \) and tensor polarization of the deuteron \( P_{zz}^d \) constitutes a null-test observable for TVPC effects [4]. The dedicated experiment is planned at COSY [5] at proton beam energy 135 MeV. The first analysis of the TVPC null-test signal [6] was done within the nonmesonic deuteron breakup channel pd \( \rightarrow \) ppn estimated in the single scattering approximation. Recently we used the spin-dependent formalism [7] of the Glauber theory to calculate the cross section \( \sigma \) [8] and also ”null-combinations” of some differential spin observables of the pd elastic scattering which deviate from zero only in case of presence of the TVPC effects [9]. The formalism includes full spin dependence of elementary pN-amplitudes and S- and D-components of the deuteron wave function. This formalism allows one to explain existing data on the non-polarized differential cross section and spin observables of the elastic pd scattering [10] at energies of the experiment planned at COSY [5]. We calculated energy dependence of \( \sigma \) for different type of TVPC interactions in the S-wave approximation for the deuteron [8]. Influence of the Coulomb
interaction on the cross section $\tilde{\sigma}$ was found to be negligible [8]. Here we consider in general case the status of the null-test observable in $pd$ scattering and study for several type of the TVPC NN interactions the contribution of the D-wave of the deuteron.

2. Null-test signal of TVPC interactions

Time-reversal symmetry conserving and P-parity conserving (TCPC or T-even P-even) interactions lead to the following transition amplitude of the elastic $pd$ scattering at zero degree [11]

$$
e^\ast_e M(0)_{\alpha\beta}^{TCPC} e_\alpha = g_1[e e'' - (m e')(m e'')] + g_2(m e')(m e'') +$$

$$
i g_3(\sigma[\epsilon \times e'']) - (\sigma m)(m \cdot [\epsilon \times e'']) + i g_4(\sigma m)(m \cdot [\epsilon \times e''])$$,

(1)

where $\epsilon$ ($\epsilon'$) is the polarization vector of the initial (final) deuteron, $m$ is the unit vector along the beam momentum, $\sigma$ is the Pauli matrix, $g_i$ ($i = 1, \ldots, 4$) are complex amplitudes. To the right-hand side of Eq.(1) one can add the TVPC (T-odd P-even) term in a very general form

$$
e^\ast_e M(0)_{\alpha\beta}^{TVPC} e_\alpha = \tilde{g}[\sigma \cdot (m \times \epsilon)](m \cdot e'') + (\sigma \cdot [m \times e'']) (m \cdot e)$$,

(2)

where $\tilde{g}$ is the TVPC transition amplitude.

Using the generalized optical theorem, the total cross section of the $pd$ scattering can be written in the form [10]

$$
\sigma_{tot} = \sigma_0 + \sigma_1 p^p \cdot p^d + \sigma_2(p^p \cdot m)(p^d \cdot m) + \sigma_3 P_{zz} + \tilde{\sigma} p^p P^d_{zz},
$$

(3)

where $p^p$ ($p^d$) is the vector polarization of the initial proton (deuteron) and $P_{zz}$ and $P_{zz}$ are the tensor polarizations of the deuteron. The OZ axis is directed along the proton beam momentum $m$, OY $\uparrow \uparrow p^p$, OX $\uparrow \uparrow [p^p \times m]$. In Eq. (3) the terms $\sigma_i$ with $i = 0, 1, 2, 3$ are non-zero only for T-even P-even interactions corresponding to Eq. (1) and the last term $\tilde{\sigma}$ constitutes a null-test signal of T-invariance violation with P-parity conservation. The generalized optical theorem gives $\tilde{\sigma} = -4\sqrt{\pi} Im \frac{g}{g}[8]$.

Hadronic amplitudes of pN scattering are taken as [7]

$$
M_N(p, q; \sigma, \sigma_N) = A_N + C_N \sigma \hat{n} + C_N' \sigma_N \hat{n} + \sum_{l=n,q,k} B^l_N(q) (\sigma \hat{l})(\sigma \sigma_N \hat{l}),
$$

(4)

where $q$, $\hat{k}$ and $\hat{n}$ are defined as unit vectors along the vectors $q = p - p'$, $k = p + p'$ and $n = [k \times q]$, respectively; $p$ ($p'$) is the initial (final) proton momentum; $\sigma_N$ is the Pauli matrix acting on the spin state of the nucleon $N$. We consider the following terms of the TVPC NN interaction which were under discussion in Ref. [6]:

$$
t_{pN} = h_N(\sigma \cdot k)(\sigma_N \cdot q) + (\sigma_N \cdot k)(\sigma \cdot q) - \frac{2}{3}(\sigma_N \cdot \sigma)(k \cdot q)/m^2_p +$$

$$
+ g_N(\sigma \cdot \sigma_N) \cdot [q \times k]/m^2_p + g'_N(\sigma - \sigma_N) \cdot i [q \times k][\tau \times \tau N]_z/m^2_p.
$$

(5)

Here $\sigma$ ($\sigma_N$) is the Pauli matrix acting on the spin state of the proton (nucleon $N = p, n$), $\tau$ ($\tau_N$) is the corresponding matrix acting on the isospin state; $m_p$ is the proton mass. In the framework of the phenomenological meson exchange interaction the term $g'$ corresponds to $\rho$-meson exchange, and $h$-term provides the axial meson $h_1$ exchange.

The crucial point is the following. The strong (T-even P-even) background is excluded from the null-test observable $\tilde{\sigma}$. This means that when calculating (or measuring at ideal conditions) the observable $\tilde{\sigma}$ one does not deal with a sum of the strong NN amplitude and the weak TVPC NN amplitude. Only products of these amplitudes may appear in $\tilde{\sigma}$ (see below Eq. (6)). Furthermore, uncertainties in our knowledge of the strong amplitudes of the NN-scattering could not affect the final result for $\tilde{\sigma}$ drastically.
Figure 1. The calculated energy dependence of the TVPC cross section $\tilde{\sigma}/\phi_h$ for the $h$-term in units of the unknown $h_1NN$ constant $\phi_h$ for the separate contribution of the deuteron S-wave (dashed line), and total result with the S- and D-wave included (full). The energy dependence for the $g$-term has the same behaviour.

2.1. $g'$ term
As was shown in our papers [8] the $g'$-term give zero contribution to the null-test observable $\tilde{\sigma}$ within the Glauber theory of the $pd$ elastic scattering. The reason for this is the specific spin-isospin structure of the $g'$ term given in Eq. (5) which allows only the charge-exchange double pN-scattering mechanism for the elastic $pd$ scattering amplitude.

2.2. $h$- and $g$-terms and S-D interference
For the single scattering mechanism the amplitude $\tilde{g}$ vanishes within the Glauber theory. This follows from Eq. (5) where all terms are zeros at zero transferred momentum $q = 0$. For double scattering mechanism considered for the $h$- and $g$-terms in Eq. (5) we derived in Ref. [8] a formula for $\tilde{g}$ in the S-wave approximation. Taking into account the D-wave we find for the TVPC amplitude the following result

$$\tilde{g} = \frac{i}{4\pi m_p} \int_0^\infty dq q^2 \left[ S_0^{(0)}(q) - 2\sqrt{2} S_2^{(1)}(q) \right] \left[ C'_n(q)(g_p - h_p) + C'_p(q)(g_n - h_n) \right],$$

where $S_0^{(0)} = \int_0^\infty dr u^2(r) j_0(qr)$ and $S_2^{(1)}(q) = 2 \int_0^\infty dr u(r) w(r) j_2(qr)$ are the elastic form factors of the deuteron including the S-wave $u(r)$ and D-wave $w(r)$ of the deuteron in notations of Ref. [8].

2.3. Numerical results
For the $C'_N$ amplitude of the pN scattering we use the SAID date base [12]. The deuteron wave function is taken in the CD Bonn model. The results of calculation of the observable $\tilde{\sigma}$ for the $h$-term in units of the unknown constant $\phi_h = G_h/G_h$, where $G_h$ ($G_h$) is the TVPC (strong)
coupling constant of the $h_1$ meson and nucleon $hNN$, are shown in Fig. 1 versus the proton beam energy $T_p$. One can see that the D-wave of the deuteron taken into account changes considerably the result for the observable $\bar{\sigma}$ as compared to the S-wave result obtained previously in [8, 13]. The destructive S-D interference diminishes considerably the null-test signal $\bar{\sigma}$ at energies of the planned COSY experiment [5] $\sim 100$ MeV as compared to the pure S-wave contribution and provides an enhancement at 700-800 MeV.

3. Summary
In the first theoretical analysis of the null-test observable $\bar{\sigma}$ performed in Ref. [6] only the single scattering mechanism was considered for the straightforward calculation of the inelastic and elastic $pd$-scattering. We use the optical theorem for calculation of the $\bar{\sigma}$, that requires to get only the forward elastic $pd$ scattering amplitude. On this way we find within the Glauber theory that the single scattering mechanism gives zero contribution to the null-test cross section $\bar{\sigma}$. The double scattering mechanism for the $h$ and $g$ terms of the TVPC NN interaction leads to Eq. (6) for the TVPC amplitude of the $pd$ scattering and shows that the only hadronic $pN$ amplitude $C_N'$ from Eq. (4) modulates the TVPC observable $\bar{\sigma}$. Furthermore, we have shown for the case of the $h$- and $g$-type of interaction that the deuteron D-wave gives a valuable contribution to the null-test signal due to interference between the deuteron S- and D-waves. Of course, there are many other TVPC terms in the NN interaction [14] which we are going to consider later on.

The $g'$-term caused by the $p-$ meson exchange in the TVPC NN-interaction does not contribute to $\bar{\sigma}$ within the Glauber theory with T-even P-even NN-interaction in the deuteron [8]. However, the $g'$-term can give contribution to the null-test signal $\bar{\sigma}$ if this interaction will be included into the deuteron bound state [8]. One-pion exchange is excluded from TVPC NN-interaction [15], however, two-pion exchange probably does contribution [16]. Furthermore, TVPC NN forces can contribute to the electromagnetic $p$-d interaction due to the toroidal quadrupole form factor of the deuteron [17]. Another T-odd P-even effect very similar to the $\bar{\sigma}$ observable in pd-scattering can be observed in inclusive interaction of unpolarized leptons with polarized nucleons [18].

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