Search for T-invariance Violation in the Proton-Deuteron Scattering

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The spin-dependent Glauber theory is used to calculate differential observables and integrated polarized cross sections of the *pd* scattering at proton beam energy 135 MeV. In addition to the pure strong NN interactions, the Coulomb effects and T-invariance violating but P-parity conserving interactions are considered. This study is motivated by the TRIC experiment planned at COSY to test time-reversal symmetry.

1 Introduction

Under assumption of CPT-symmetry, CP violation established in physics of kaons and B-mesons implies existence of T-odd P-odd interactions. These interactions are parametrized in the standard model by CP violating phase of the Cabibbo-Kobayashi-Maskawa matrix. On the contrary, time-invariance-violating (T-odd) P-parity conserving (P-even) flavor conserving (TVPC) interactions do not arise on the fundamental level within the standard model. This type of interaction can be generated by radiative corrections to the T-odd P-odd interaction. However in such a case its intensity is too small to be observed in experiments at present [1]. Thus, observation of TVPC effects would be considered as indication to physics beyond the standard model.

The goal of the TRIC experiment [2] is the measurement of the total polarized cross section $\widetilde{\sigma}$ of the proton-deuteron scattering with vector polarization of the proton p_y^p and tensor polarization of the deuteron P_{xz} (see below Eq. (4)). As it was shown in Ref. [3], this observable constitutes a null-test of TVPC effects. According to [4], the experiment [2] will be done at beam energy 135 MeV. The aim of this experiment is to improve the results of previous measurement [5] on $\vec{n}^{167}$Ho scattering by one order of magnitude. In this case, detailed information on the ordinary T-even P-even spin observables at this energy is required in order to determine magnitude of possible false-effects caused by pure strong and Coulomb interaction due to non-ideal conditions of the experiment. However, experimental data on these observables at this energy are not complete. In the present work we use the Glauber theory to calculate unpolarized differential cross section and spin observables of the elastic *pd* scattering and total polarized *pd* cross sections. The spin-dependent formalism of the pd-elastic scattering is recently developed in Ref. [6]. The formalism includes full spin dependence of elementary pN-amplitudes and S- and D-components of the deuteron wave function. We further develop the formalism to account for Coulomb effects and TVPC interactions.

2 Elements of formalism

Assuming P-invariance the transition operator for the process $pd \to pd$ can be written as [7]

$$\begin{aligned} M = &(A_1 + A_2\boldsymbol{\sigma}\hat{\mathbf{n}}) + (A_3 + A_4\boldsymbol{\sigma}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})^2 + (A_5 + A_6\boldsymbol{\sigma}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{n}})^2 + A_7(\boldsymbol{\sigma}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{k}}) + \\ &A_8(\boldsymbol{\sigma}\hat{\mathbf{q}})\left[(\mathbf{S}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})\right] + (A_9 + A_{10}\boldsymbol{\sigma}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{n}}) + A_{11}(\boldsymbol{\sigma}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{q}}) + \\ &A_{12}(\boldsymbol{\sigma}\hat{\mathbf{k}})\left[(\mathbf{S}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{k}})\right] \\ &+(T_{13} + T_{14}\boldsymbol{\sigma}\hat{\mathbf{n}})\left[(\mathbf{S}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{q}}) + (\mathbf{S}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{k}})\right] + T_{15}(\boldsymbol{\sigma}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{k}}) + T_{16}(\boldsymbol{\sigma}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{q}}) + \\ &T_{17}(\boldsymbol{\sigma}\hat{\mathbf{k}})\left[(\mathbf{S}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})\right] + T_{18}(\boldsymbol{\sigma}\hat{\mathbf{q}})\left[(\mathbf{S}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{k}})\right], \end{aligned} \tag{1}$$

were $\boldsymbol{\sigma}$ is the Pauli matrix acting on the spin state of the proton beam, $\mathbf{S}$ is the spin operator of the deuteron; the unit vectors $\hat{\mathbf{q}}$, $\hat{\mathbf{k}}$, $\hat{\mathbf{n}}$ are defined through initial $\mathbf{p}$ and final $\mathbf{p}'$ momenta as $\hat{\mathbf{q}} = (\mathbf{p} - \mathbf{p}')/|\mathbf{p} - \mathbf{p}'|$, $\hat{\mathbf{k}} = (\mathbf{p} + \mathbf{p}')/|\mathbf{p} + \mathbf{p}'|$, $\hat{\mathbf{n}} = [\hat{\mathbf{k}} \times \hat{\mathbf{q}}]/|[\hat{\mathbf{k}} \times \hat{\mathbf{q}}]|$; $A_1 \div A_{12}$ are T-even P-even invariant amplitudes introduced in Ref. [6], $T_{13} \div T_{18}$ are T-odd P-even (TVPC) amplitudes. The reference frame is defined as $OZ \uparrow\uparrow \hat{\mathbf{k}}$, $OX \uparrow\uparrow \hat{\mathbf{q}}$, $OY \uparrow\uparrow \hat{\mathbf{n}}$. Under T-invariance conditions $T_{13} = T_{14} = T_{15} = T_{16} = T_{17} = T_{18} = 0$ the following relations between spin transfer coefficients are valid [7]

$$\begin{aligned} &K_x^z(\vec{p} \to \vec{p}) = -K_z^x(\vec{p} \to \vec{p}),\ K_x^z(\vec{p} \to \vec{d}) = -K_z^x(\vec{d} \to \vec{p}), \\ &K_x^z(\vec{d} \to \vec{p}) = -K_z^x(\vec{p} \to \vec{d}),\ K_x^z(\vec{d} \to \vec{d}) = -K_z^x(\vec{d} \to \vec{d}). \end{aligned} \tag{2}$$

In addition the relations $A_y^p = P_y^p$ and $A_y^d = P_y^d$ are also valid, where A_y^p (A_y^d) is the vector analyzing power for the proton (deuteron) and P_y^p (P_y^d) is the polarization of the final proton (deuteron) for the case of unpolarized initial particles.

In general case TVPC NN interaction contains 18 different terms [8]. We consider here only following terms which were under discussion in Ref. [4]:

$$\begin{aligned} t_{pN} = &h[(\boldsymbol{\sigma} \cdot \mathbf{p})(\boldsymbol{\sigma}_N \cdot \mathbf{q}) + (\boldsymbol{\sigma}_N \cdot \mathbf{p})(\boldsymbol{\sigma} \cdot \mathbf{q}) - (\boldsymbol{\sigma}_N \cdot \boldsymbol{\sigma})(\mathbf{p} \cdot \mathbf{q})] + \\ &+g[\boldsymbol{\sigma} \times \boldsymbol{\sigma}_N] \cdot [\mathbf{q} \times \mathbf{p}] + g'(\boldsymbol{\sigma} - \boldsymbol{\sigma}_N) \cdot i\,[\mathbf{q} \times \mathbf{p}][\boldsymbol{\tau} \times \boldsymbol{\tau}_N]_z. \end{aligned} \tag{3}$$

Here $\boldsymbol{\sigma}$ ($\boldsymbol{\sigma}_N$) is the Pauli matrix acting on the spin state of the proton (nucleon $N = p, n$), $\boldsymbol{\tau}$ ($\boldsymbol{\tau}_N$) is the corresponding matrix acting on the isospin state, $\mathbf{q} = \mathbf{p} - \mathbf{p}'$. In the framework of the phenomenological meson exchange interaction the term g' corresponds to $\rho-$meson exchange, and h-term provides the axial meson exchange. In the single scattering approximation accounting S- and D- waves of the deuteron we obtain only two non-zero amplitudes: T_{15} and T_{16} [7]. Other TVPC amplitudes vanish in this case: $T_{13} = T_{14} = T_{17} = T_{18} = 0$. The charge-exchange g'-term gives zero-contribution because the corresponding isospin matrix element equals zero for the single scattering mechanism of the $pd \to pd$ process.

In collinear kinematics the transition operator (1) contains only four terms (invariant spin amplitudes) for the case of T-even P-even interaction and one additional term for T-odd P-even interactions. Consequently, the total cross section of the pd interaction takes the form

$$\sigma_{tot} = \sigma_0 + \sigma_1 \mathbf{p}^p \cdot \mathbf{p}^d + \sigma_2(\mathbf{p}^p \cdot \hat{\mathbf{k}})(\mathbf{p}^d \cdot \hat{\mathbf{k}}) + \sigma_3 P_{zz} + \widetilde{\sigma} p_y^p P_{xz}^d, \tag{4}$$

where $\mathbf{p}^p$ ($\mathbf{p}^d$) is the vector polarization of the initial proton (deuteron) and P_{zz} and P_{xz} are the tensor polarizations of the deuteron. The OZ axis is directed along the proton beam

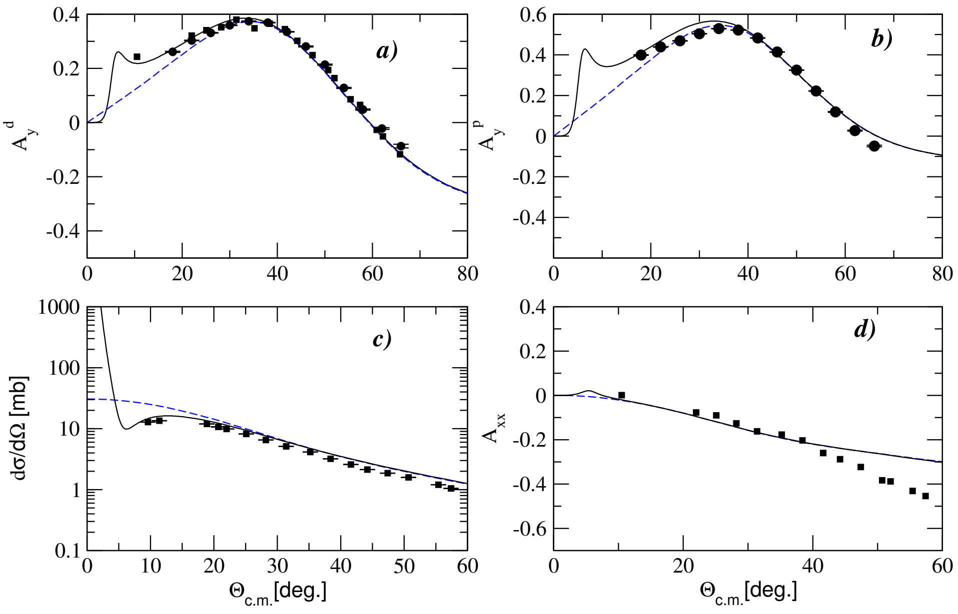

Figure 1: Result of our calculations [10] of spin observables A_y^d(a), A_y^p (b), $d\sigma/d\Omega$ (c) and A_{xx} (d) of the pd elastic scattering in comparison with the data [11] (squares) and [12] (circles) at 135 MeV: without Coulomb (dashed line) and with Coulomb included (full).

momentum. In Eq. (4) the terms σ_i with $i = 0, 1, 2, 3$ are non-zero only for T-even P-even interaction and the last term $\widetilde{\sigma}$ is non-zero if the T-odd P-even interaction effects occur. Thus, this term constitutes a null-test signal of T-invariance violation with P-parity conservation. The total hadronic polarized cross sections σ_1 and σ_3 are calculated using the optical theorem, whereas Coulomb effects are taken into account in the line of Ref. [9].

3 Numerical results and discussion

The detailed formalism for T-even P-even amplitudes $A_1 \div A_{12}$ was developed within the Glauber model in Ref. [6] taking into account single and double scattering mechanisms, S- and D-components of the deuteron wave function and full spin dependence of the elementary pN scattering amplitudes. We use this formalism to calculate spin observables of the pd-elastic scattering at energy of the TRIC experiment, i.e. $T = 135$ MeV. In addition to Ref. [6] we take into account the Coulomb interaction, as explained in [10] within the single scattering mechanism. Some results of numerical calculations performed with the Cd Bonn wave function of the deuteron are shown in Fig. 1. One can see from this figure, that the Glauber model allows to explain data on unpolarized cross section, vector analyzing powers A_y^p, A_y^d and tensor analyzing power in forward hemisphere. Accounting for the Coulomb interaction is very important at these energies and considerably improves the agreement with the experimental data [11, 12] at small c.m.s. scattering angles $\theta_{cm} < 20° - 30°$. We can show [10] that good agreement was obtained also between this theory and the data [12] on spin-correlation coefficients $C_{xz,y}$, $C_{y,y}$,

$C_{x,z}$, and $C_{z,x}$ of the pd elastic scattering at 135 MeV in forward hemisphere.

The constants g and h in Eq. (3) are chosen here in such a way that the absolute value of the integrated cross section $\tilde{\sigma}$ in Eq. (4) would be $\tilde{\sigma}/\sigma_0 = 10^{-6}$. One should note that the aim of the TRIC experiment is to get an upper limit for the TVPC signal $\tilde{\sigma}$ just at this level. We show [7] that in this case the maximal magnitudes of the violation of the relations (2) (in forward hemisphere, $\theta_{cm} < 50^\circ$) are $2 \div 3 \times 10^{-4}$ for $|K_x^z(p \to d) + K_z^x(d \to p)|$, $|A_y^p - P_y^p| \sim 3 \times 10^{-5}$ and much more lower for others relations. Thus, $|K_x^z(p \to d) + K_z^x(d \to p)|$ is by two orders of magnitude higher than $\tilde{\sigma}/\sigma_0$. Nevertheless, the null-test observable $\tilde{\sigma}$ can be measured in one experiment, whereas measurement of $|A_y^p - P_y^p|$ and $|K_x^z(pd) + K_z^x(dp)|$ requires two or more experiments with measurement of polarizations of final particles.

Let us consider possible problems in measurement of the null-test observable $\widetilde{\sigma}$. One source of false-effects is connected with non-zero projection of the vector polarization of the deuteron $p_y^d \neq 0$ onto direction of the vector polarization of the proton beam p_y^p. In this case the term $\sigma_1 p_y^p p_y^d$ in Eq. (4) contributes to the asymmetry $A_{xz,y}$ which is planned to be measured in the TRIC experiment [2] and corresponds to the cases $p_y^p P_{xz}^d > 0$ and $p_y^p P_{xz}^d < 0$. According to our calculation, at beam energy 135 MeV the total cross sections are $\sigma_0 = 78.5$ mb, $\sigma_1 = 3.7$ mb, $\sigma_2 = 17.4$ mb, and $\sigma_3 = -1.1$ mb. Therefore, the ratio $r = \sigma_1/\sigma_0$ is equal to ≈ 0.05. If the TRIC project is going to measure the ratio $R_T = \widetilde{\sigma}/\sigma_0$ with an uncertainty about $\leq 10^{-6}$ (an upper limit for R_T), then one can find from this ratio r that the vector polarization of the deuteron p_y^d has to be less than $\approx 2 \times 10^{-6}$. When making this estimation, we assume that the ratio of the background-to-signal is $p_y^d \sigma_1/\widetilde{\sigma} \sim 10^{-1}$.

4 Summary

We found that the Glauber model with Coulomb interaction taken into account reasonably explains existing data on unpolarized differential cross section and some spin observables of pd elastic scattering at 135 MeV in forward hemisphere. This provides a theoretical basis for estimation of possible false-effects in the TRIC experiment [2] planned at this energy.

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