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STUDY OF *T*-ODD ASYMMETRY IN BACKWARD ELASTIC $\vec{d}\vec{p}$ SCATTERING AS A METHOD TO IDENTIFY THE REACTION MECHANISM

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1 Introduction

Study of polarization effects in backward elastic dp scattering at the maximal available energy is the very effective method to obtain information about the deuteron structure in the region of large internal momenta. The matter is in the framework of the Impulse Approximation (IA) there is one-to-one connection between the only kinematical parameter of the reaction, total energy in the CM system, and the deuteron wave function (DWF) argument in the momentum space, when the deuteron is implied as two nucleon system. That is serious advantage of this reaction (and of the deuteron electrodisintegration also) in comparison with ed elastic scattering, where observables connected with the DWF argument through integral. Usually this reaction is interpreted in the framework of the one nucleon exchange (ONE) mechanism. That is particular case of the IA.

Up to now, apart from cross sections[1], only the analyzing power T_{20} , induced by the initial deuteron tensor polarization[2, 3, 4], and the polarization transfer coefficient from the deuteron to the proton (κ_0)[4] have been investigated. Obtained experimental data, as it is shown in ref[4], are in principal contradictions with such simplified mechanism as ONE.

But this discrepancy does not mean the IA is not valid in principle. For instance, one can try to correct situation taking into account the plenty of NN^*-configurations, arising in the deuteron in the framework of quark count[5], that lead to additional IA diagrams, where the neutron is replaced by N^*.

To distinguish whether the observed effects are induced by the more complicated deuteron structure or more complicated reaction mechanism, it is necessary to measure new polarization observables. In particular, it would be important to find such polarization observables that are especially sensitive to details of the reaction mechanism. As it will be shown below, these are experiments deal with T-odd observables of this process. The investigation of T-odd effects is of great interest because in any kind of the IA they are equal to zero. Therefore, the detection of nonzero values of T-odd polarization characteristics will indicate the necessity of radical revision of mechanism of the considered reaction.

We discuss here the simplest T-odd observable of backward elastic dp scattering, namely the analyzing power, induced by a specific choice of polarization axes of interacting particles relatively each other and the beam direction.

In Section 2, we analyze polarization effects in general form, using the parametrization of the full $d+p \to p+d$ amplitude in terms of four independent complex scalar amplitudes. Such formalism is not connected directly either with the deuteron model or the reaction mechanism. In Section 3, we discuss shortly feasible mechanisms that lead to nonzero T-odd effects. In Section 4, we consider briefly how to measure the discussed analyzing power.

2 Spin Structure of the $d+p \to p+d$ Reaction

The process of elastic dp scattering at an arbitrary angle in general case is defined by 12 independent complex amplitudes[6] and so, at least 23 polarization observables must be measured in the complete experiment.

The problem of the complete experiment is much simpler in case of forward ($\theta = 0^o$) and backward ($\theta = 180^o$) scattering, when the total helicity of interacting particles is conserved. In this case the spin structure of the full amplitude is defined by only four amplitudes (which are different for two mentioned above kinematical conditions).

There are some equivalent sets of amplitudes, suitable for the description of the discussed process. We use here the method of so called scalar amplitudes $g_i(s)$, related with helicity ones $F_{\lambda_d \lambda_p \to \lambda_{d'} \lambda_{p'}}$ by the following way:

$$\begin{aligned} F_{0+\to 0+} &= g_2(s), \\ F_{0+\to +-} &= -\sqrt{2} g_3(s), \\ F_{++\to ++} &= g_1(s) + g_4(s), \\ F_{-+\to -+} &= g_1(s) - g_4(s), \end{aligned} \tag{1}$$

where $\lambda_d(\lambda_p)$ corresponds to the deuteron (proton) spin projection onto the beam direction (+1,0,-1 for deuterons and $\pm\frac{1}{2}$ for protons). It is easy to see from (1), that $g_1(s)$, $g_2(s)$ and $g_4(s)$ do not change the transversal ($g_1(s)$ and $g_4(s)$) or longitudinal ($g_2(s)$) polarization of the initial deuteron, and $g_3(s)$ describes the transition between the transversally (longitudinally) polarized initial deuteron and longitudinally (transversally) polarized final one. In the latter case the proton spin must be reversed.

In terms of scalar amplitudes the full amplitude F has the following form:

$$\mathcal{M} = \chi_2^\dagger F \chi_1, \quad F = A + i\vec{\sigma}\cdot\vec{B}, \tag{2}$$
$$A = g_1(s)[\vec{U}_1\vec{U}_2^* - (\vec{n}\vec{U}_1)(\vec{n}\vec{U}_2^*)] + g_2(s)(\vec{n}\vec{U}_1)(\vec{n}\vec{U}_2^*),$$
$$\vec{B} = g_3(s)[\vec{U}_1 \times \vec{U}_2^* - \vec{n}(\vec{n}\vec{U}_1 \times \vec{U}_2^*)] + g_4(s)\vec{n}(\vec{n}\vec{U}_1 \times \vec{U}_2^*),$$

where $\vec{U}_1(\vec{U}_2)$ is the spin vector of the initial (final) deuteron, $\chi_1(\chi_2)$ is the two-component spinor of the initial (final) proton, $\vec{\sigma}$ are the Pauli matrices, s is the Mandelstam's variable (squared total energy), $\vec{n}$ is the unit vector along the beam direction. That is the most suitable formalism to analyze the problem of the complete experiment in backward dp scattering.

We accept the following parametrization of the initial polarization states. These are

$$\rho = \frac{1}{2}(1 + \vec{\sigma}\vec{P}) \tag{3}$$

for protons, where $\vec{P}$ is 3-vector of proton polarization, and

$$U_i U_j^* = \frac{1}{3}(\delta_{ij} + \frac{3}{2} i\epsilon_{ijl} S_l - Q_{ij}) \tag{4}$$

for deuterons, where pseudovector $\vec{S}$ and symmetrical tensor Q_{ij} characterize the vector and tensor deuteron polarization. We have

$$Q_{ij} = Q_{ji}, \quad Q_{ii} = 0. \tag{5}$$

Here we consider most simple polarization effects induced by the polarization of initial particles (analyzing powers). Substituting relations (2) into the following expression for cross sections

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\mathcal{N} \overline{Sp F(1 + \vec{\sigma}\vec{P}) F^\dagger}, \quad \mathcal{N} = \frac{1}{64\pi^2 s}, \tag{6}$$

one can obtain

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma^{(0)}}{d\Omega}[1 + A_1(Q_{ij}n_i n_j) + A_2 \vec{S}\vec{P} + A_3(\vec{P}\vec{n})(\vec{S}\vec{n}) + A_4 \vec{n} \cdot \vec{Q} \times \vec{P}], \tag{7}$$

where vector $\vec{Q}$ is defined as

$$Q_i = Q_{ij} n_j,$$

$\frac{d\sigma^{(0)}}{d\Omega}$ is the differential cross sections when both the initial proton and deuteron are unpolarized. The cross section and the coefficients $A_1 - A_4$ are related with the scalar amplitudes by the following expressions:

$$3\mathcal{N}^{-1}\frac{d\sigma^{(0)}}{d\Omega} = 2|g_1|^2 + |g_2|^2 + 4|g_3|^2 + 2|g_4|^2, \tag{8}$$

$$3A_1\mathcal{N}^{-1}\frac{d\sigma^{(0)}}{d\Omega} = |g_1|^2 - |g_2|^2 - |g_3|^2 + |g_4|^2, \tag{9}$$

$$A_2\mathcal{N}^{-1}\frac{d\sigma^{(0)}}{d\Omega} = Re[(g_1 + g_2 - g_4)g_3^*], \tag{10}$$

$$(A_2 + A_3)\mathcal{N}^{-1}\frac{d\sigma^{(0)}}{d\Omega} = -Re[(g_3 - g_4)g_3^*], \tag{11}$$

$$3A_4\mathcal{N}^{-1}\frac{d\sigma^{(0)}}{d\Omega} = 2Im[(-g_1 + g_2 - g_4)g_3^*]. \tag{12}$$

As it is evident from (9) - (12), all four sources of asymmetry of the first interaction are independent. The coefficient A_1 determines the effect induced by the tensor polarization of the initial deuteron, firstly considered in ref[7]. The coefficients A_2, A_3 determine the effects induced by the vector polarization of both initial deuteron and proton. The latter source of polarization effects is considered in details in ref.[8]. All mentioned above asymmetries are T-even. And finally, collision of tensor polarized deuterons with polarized protons is characterized by the coefficient A_4. This asymmetry is T-odd.

Not only mentioned, but all T-odd observables are related with amplitudes via expressions like $Im(g_i g_k^*)$. Appearance of imaginary parts of bilinear combinations is the direct consequence of complex conjugation as the necessary attribute of T-transformation in the T-invariant theory. The important property of T-odd observables is their sensitivity to small phase diffferences of scalar amplitudes. Indeed, we have

$$Im(g_i g_k^*) = |g_i||g_k| sin(\delta\phi) \simeq |g_i||g_k|(\delta\phi),$$

in difference with T-even observables, expressed via such combinations as

$$Re(g_i g_k^*) = |g_i||g_k| cos(\delta\phi) \simeq |g_i||g_k|(1 - \frac{(\delta\phi)^2}{2}).$$

3 The Analyses of Sources of the T-odd Asymmetry

The T-odd asymmetry for the total cross-section of dp-scattering characterizes the T-violation and must be small (so called "null"-test[9]). But in case of elastic dp-scattering the coefficient A_4 can be large enough due to nonzero relative phases of different amplitudes. As far as the interaction constant remains real in any kind of the IA (relativistic or nonrelativistic), such complications of the deuteron model as increasing of the number of arguments (up to 6[10]), taking into account such vertexes as $d \to NN^*$[5] or relativistic one $d \to p\overline{n}$[11], does not lead to complexity of amplitudes. Only additional to IA mechanisms of the reaction can provide such property of amplitudes. These are

- excitation of Δ-isobar and so on in the intermediate state;
- excitation of three-nucleon resonances in the direct channel of pd collision;
- exchange by fermion Regge poles.

The complexity of amplitudes is also the inevitable outcome of the unitarity conditions.

Such effects as excitation of Δ-isobar in the intermediate state are considered, for example, in ref.[12]. The amplitude, responsible for this subprocess, can be expressed through the parameters of $NN \to N\Delta$ interaction and some integral over the definite combinations of the S- and D-components of the DWF. It demonstrates quasiresonance behaviour in region of $T_d \simeq 0.75$ GeV. The resulting behaviour of the full amplitude in this region depends essentially on the formfactors of $NN\pi$- and $NN\rho$-vertexes.

The physical reasons for appearance of such objects as three-barion resonances are different. It is enough to mention the possibility of existence of ΔNN-resonance, if the anomalous ΔN-interaction (different from one-pion exchange) exists. The appearance of 3-barion resonances seems absolutely natural in different versions of quark bag model[13].

The reaction $d + p \to p + d$ seems to be most suitable for studying of this problem due to following circumstances:

- the smallness and relatively simple spin structure of the main background amplitude (one-nucleon exchange);
- the sensitivity of the differential cross section energy dependence to the values of spin and space parity of 3-barion resonances.

The most probable interval of 3-barion resonance masses is 3 – 3.5 GeV/c. So, an energy of the primary beam $T_d \leq 1$ GeV is needed to investigate this problem.

At higher energies a possible source of complexity of scalar amplitudes is a fermion Regge poles[14] (FRP) exchange. On quark language it can be interpreted as more general three quark exchange in u-channel, than in case of the ONE. Such an exchange is equivalent to new effective $d \to NR$ vertex (R is a regeon), which allows one to take into account in some sense the quark degrees of freedom in the deuteron. The most interesting peculiarity of FRP is "self-conjugation". That means the existence of two complex-conjugate trajectories with special kind of argument for each Regge pole, namely $\alpha(\sqrt{u})$ and $\alpha^*(\sqrt{u})$, where u is the Mandelstam's variable.

At $u < 0$ a number of reasons leads to the complex contribution of FRP into amplitudes. At $u > 0$ only one of them survives, namely, connected with signature factors[15]

$$1 \pm exp[i\pi\alpha(\sqrt{u})], \quad 1 \pm exp[i\pi\alpha(-\sqrt{u})].$$

At $\theta = 180^o$ u is always positive:

$$u = \frac{(m_d^2 - m_p^2)^2}{s}.$$

It changes its sign at an angle defined by following condition:

$$1 + cos(\theta_0) = \frac{(m_d^2 - m_p^2)^2}{2m_p^2 p_d^2}, \tag{13}$$

or, approximately,

$$\theta_0 \simeq \pi - \frac{3m_p}{p_d}, \tag{14}$$

where p_d is the initial deuteron 3-momentum in the Lab system.

The phenomenology of FRP was very effective for the description of the $\pi + N \to \pi + N$, $\pi + N \to \eta + N$, $\pi + N \to \rho + N$ reactions[16]. It is interesting to note, that the asymptotic Regge regime in reactions with participation of the deuteron is achieved more early in comparison with πN and γN reactions. For instance, the Regge picture $\gamma + d \to n + p$ is began from anomalously small energy, namely, $E_\gamma \geq 400$ MeV.

We mention here, that the contribution of single bosonic Regge poles does not lead to nonzero phases between different amplitudes.

4 How to Measure the T-odd effect

The vector product near the coefficient A_4 can be expressed as follows:

$$\vec{n} \cdot \vec{Q} \times \vec{P} = -\frac{3}{4} Q_{zz} P_y sin(2\beta), \tag{15}$$

where z is the axis of the initial deuteron tensor polarization, $\vec{n}$ lies in the xz-plane and β is an angle between $\vec{n}$ and the x-axis, P_y is a projection of $\vec{P}$ onto the y-axis.

As it is easy to see from (15), this vector product is equal to zero until an angle between the deuteron polarization axis and the beam direction remains 90^o, independently on choice of the initial proton polarization axis.

If we deal with a polarized deuteron beam and a polarized proton target(PPT), the vertical polarization axis of the extracted beam is assumed. If one rotate the deuteron spin with help of a solenoid (90^o), then a spin rotation respectively the beam direction can be achieved due to anomal part of a particle magnetic moment while the beam is deflected by dipoles. The target polarization axis must be vertical in this case. The connection between the summary bending angle of a beam line (φ_0) and spin rotation respectively the beam direction (in the current deuteron rest frame) is expressed by simple formula

$$\varphi_{rot} = \varphi_0 \gamma (\frac{g}{2} - 1), \tag{16}$$

where $\gamma = E/m$, $g = 1.716$.

One can see it is not possible to provide an optimal spin rotation in a wide energy region of the beam having a fixed beam line. Now existing beam line upstream the PPT at Dubna[17] (with the summary beam bending angle in dipoles of 27^o) provides values of $sin(2\beta)$ increasing from 0.25 up to 0.49 while one changes the primary beam momentum from 3 up to 7 GeV/c. Needed for the largest energy magnetic field integral in a solenoid (about 40 Tm), may be, is not realistic. Nevertheless, performing of the experiment in this case is also possible. For example, in case of fixed magnetic field integral about 10 Tm (decreasing with energy spin rotation in a solenoid), $sin(2\beta)$ remains on the level of $\simeq 0.2$ in the mentioned range of primary beam energies. In the latter case a thin alignment of the PPT polarization axis is necessary for each energy of the primary beam.

May be, it is more convenient to investigate this problem using a polarized proton beam and a polarized deuteron target. Such an experiment is feasible at COSY using the spectrometer, advertised in ref.[18]. Keeping in mind that the primary beam polarization is vertical, to have $sin(2\beta) = 1$ one has to orient the deuteron target polarization axis in the horizontal plane at an angle of 45^o to the beam direction.

5 Conclusion

We demonstrated here the importance of study of T-odd polarization effects in backward elastic *dp* scattering as an effective tool of the determination of the reaction mechanism. Nonzero T-odd asymmetry arise only in case the additional to the Impulse Approximation mechanisms are essential. Revealing of nonzero T-odd asymmetry will lead to radical revision of mechanism of this reaction. Only one from four possible asymmetries (for first interaction) is T-odd. Such measurements are realistic.

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