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SPIN OBSERVABLES OF THE DEUTERON BREAKUP REACTION $pd \rightarrow pp(^1S_0)n$ AND SHORT-RANGE NN PROPERTIES

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Analysis of recent ANKE-COSY data on the deuteron breakup $pd \rightarrow (pp)(^1S_0)n$ in a kinematics similar to backward pd elastic scattering shows very high sensitivity of this process to the short-range NN interaction. Employing the CD Bonn potential instead of the RSC or Paris potentials changes all contributions of the deuteron breakup model based on the one-nucleon exchange, single pN scattering and Δ excitation mechanism in the right direction and achieves good qualitative agreement with the measured unpolarized cross section. Spin observables, planned to be measured at ANKE-COSY, are calculated here within the above model.

Показана чувствительность спиновых переменных в реакции развала дейтрона $pd \rightarrow (pp)(^1S_0)n$ к NN -потенциалу. Выбор боннского потенциала вместо парижского меняет вклады всех механизмов в правильном направлении и приводит к хорошему описанию усредненных по спину сечений. Вычислены спиновые переменные, которые должны быть измерены в эксперименте ANKE-COSY.

INTRODUCTION

The structure of the lightest nuclei at short distances is tested mainly by electromagnetic probes at high transferred momenta [1]. The problem here is, however, that a self-consistent picture of electro- and photo-nuclear processes is not yet established due to the unknown strength of the meson-exchange currents. Hadron-nucleus collisions can give additional information. In this case, theoretical analysis of hadron processes is complicated by effects specific for the strong interaction like initial and final state interactions and excitation/de-excitation of nucleons in intermediate states.

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To minimize the complicating effects, it was proposed [2] to study the deuteron breakup reaction $pd \rightarrow (pp)n$ in the kinematics of backward elastic pd scattering with the final pp pair having low excitation energies $E_{pp} \leq 3$ MeV, and thus being predominantly in the spin-singlet (isotriplet) 1S_0 state. This reaction, in contrast to the $pd \rightarrow dp$ process, provides a considerable suppression of the Δ - (and N^*)-excitation amplitudes by the isospin factor 1/3 in comparison with the one-nucleon-exchange (ONE) [3]. Furthermore, the S -wave dominance in the final pp pair displays the node of the half-off-shell $pp(^1S_0)$ scattering amplitude, $t(q, k)$, at the off-shell momentum $q \sim 0.4$ GeV/ c . This node leads to a dip in the unpolarized cross section for the ONE mechanism [2, 4] and results in irregularities in the spin observables at beam energies 0.5–1 GeV [4]. A similar node in the s -wave component of the deuteron wave function $u(q)$ at $q \approx 0.4$ GeV/ c leads to the experimentally observed node in the deuteron monopole charge form factor [5].

The first data on the reaction $pd \rightarrow (pp)n$ at high beam energies 0.6–1.9 GeV were obtained this year at the ANKE spectrometer at COSY [6]. These data were analyzed in Ref. 7 on the basis of relativistic Hamiltonian dynamics [8] and it was found that the deuteron and diproton wave functions are probed in this experiment at internal momenta $q = 0.4$ – 0.65 GeV/ c . The approach [7] includes the coherent sum of the ONE, single pN scattering (SS) and double scattering with excitation of the $\Delta(1232)$ -isobar (Δ). Rescatterings in the initial and final states were taken into account in eikonal DWBA approximation for the ONE mechanism. It was found in [7] that (i) the results of the calculation are very sensitive to the short-range behaviour of the NN interaction; (ii) the CD Bonn, a high accuracy NN potential [9], provides a reasonable description of the data whereas the RSC and Paris potentials fail; (iii) rescatterings in the initial and final states improve significantly the agreement between the model and data. The obtained result points to a softness of the deuteron and diproton $pp(^1S_0)$ at short NN distances.

Furthermore, the data [6] were analyzed in Ref. 10 within the fully covariant Bethe–Salpeter formalism and a conclusion was made about dominant contribution of the relativistic P wave in the diproton. However, only a single mechanism was used in Ref. 10, namely one-nucleon-exchange without taking into account rescatterings in the initial and final states and without excitation of nucleon isobars in the intermediate state.

Both these approaches, Ref. 7 and Ref. 10, describe the data [6] with approximately the same accuracy. Therefore new experimental data, especially for spin observables, and further analysis are necessary to distinguish between these two approaches. We present here the result of calculations performed within the ONE + SS + Δ model for spin observables of the reaction in question for different types of NN -interaction potentials.

1. ELEMENTS OF FORMALISM

Matrix element of the binary reaction of the type $1/2 + 1 \rightarrow 0 + 1/2$, where $0, 1/2, 1$ are the spins of scalar, spinor and vector particles, respectively, can be written in the c.m.s. as

$$M_{fi} = \varphi_f^+ T_\gamma(\mathbf{k}, \mathbf{k}', \boldsymbol{\sigma}) e_\gamma \varphi_i, \quad (1)$$

where φ_i (φ_f) is the Pauli spinor of the initial (final) fermion; \mathbf{T} is the vector operator acting in the spin-1/2 state space; e_γ is the polarization vector of the deuteron ($\gamma = x, y, z$). Using the c.m.s. momenta of the initial proton \mathbf{k} and the final neutron \mathbf{k}' , one can define the following set of the orthogonal unit vectors:

$$\mathbf{l} = (\mathbf{k} + \mathbf{k}')/|\mathbf{k} + \mathbf{k}'|, \quad \mathbf{n} = [\mathbf{k} \times \mathbf{k}']/|[\mathbf{k} \times \mathbf{k}']|, \quad \mathbf{m} = [\mathbf{l} \times \mathbf{n}]/|[\mathbf{l} \times \mathbf{n}]|. \quad (2)$$

We choose the coordinate system with axes $OX \uparrow\uparrow \mathbf{l}, OY \uparrow\uparrow \mathbf{n}, OZ \uparrow\uparrow \mathbf{m}$. In this system one gets $n_y = l_x = m_z = 1$ and all other components of the unit vectors (2) vanish. Using P -parity conservation and rotational invariance of the reaction amplitude, one can find [2] in the above coordinate system

$$T_x = M_1 \sigma_x + M_2 \sigma_z, \quad T_y = M_3 + M_4 \sigma_y, \quad T_z = M_5 \sigma_x + M_6 \sigma_z, \quad (3)$$

where M_1, \dots, M_6 are six scalar (complex) amplitudes that completely describe this reaction.

The polarization coefficients are defined as

$$A_j^p = \frac{\text{Sp } T_\gamma \sigma_j T_\gamma^+}{\text{Sp } T_\gamma T_\gamma^+}, \quad (4)$$

$$A_j^d = \frac{\text{Sp } T_\gamma (\mathcal{S}_j)_{\gamma\beta} T_\beta^+}{\text{Sp } T_\gamma T_\gamma^+}, \quad (5)$$

$$A_{ij} = \frac{\text{Sp } T_\gamma (\mathcal{P}_{ij})_{\gamma\beta} T_\beta^+}{\text{Sp } T_\gamma T_\gamma^+}, \quad (6)$$

$$C_{i,j} = \frac{\text{Sp } T_\gamma \sigma_j (\mathcal{P}_j)_{\gamma\beta} T_\beta^+}{\text{Sp } T_\gamma T_\gamma^+}, \quad (7)$$

$$C_{ij,k} = \frac{\text{Sp } T_\gamma \sigma_k (\mathcal{P}_{ij})_{\gamma\beta} T_\beta^+}{\text{Sp } T_\gamma T_\gamma^+}, \quad (8)$$

where \mathcal{S}_j ($j = x, y, z$) are the Cartesian components of the spin 1 angular momentum operator and \mathcal{P}_{ij} is the symmetric tensor:

$$\mathcal{P}_{ij} = \frac{3}{2}(S_i S_j + S_j S_i) - 2\delta_{ij}. \quad (9)$$

Using Eqs.(3), (4), and (5) we obtain the following formulae for the vector analyzing powers:

$$\begin{aligned}
 A_y^p &= 2B^{-1} \{ \text{Re } M_3 M_4^* - \text{Im } (M_5 M_6^* + M_1 M_2^*) \}, \\
 A_x^p &= A_z^p = 0; \\
 A_y^d &= 2B^{-1} \text{Im } (M_5 M_1^* + M_6 M_2^*), \\
 A_x^d &= A_z^d = 0,
 \end{aligned} \tag{10}$$

where B is defined as

$$B = \sum_{i=1}^6 |M_i|^2. \tag{11}$$

The spin–spin correlation coefficients, resulting from Eqs.(3), (7), and (8), are

$$\begin{aligned}
 C_{y,y} &= 2 [\text{Re } M_2 M_5^* - \text{Re } M_1 M_6^*] B^{-1}, \\
 C_{z,z} &= -2 [\text{Re } M_1 M_4^* + \text{Im } M_3 M_2^*] B^{-1}, \\
 rC_{xz,y} &= 3 [\text{Im } M_1 M_6^* + \text{Im } M_5 M_2^*] B^{-1}.
 \end{aligned} \tag{12}$$

For the tensor analyzing power one finds [2]

$$\begin{aligned}
 T_{20} &= \frac{1}{\sqrt{2}} A_{zz}, \\
 A_{zz} &= \left\{ 1 - \frac{|M_5|^2 + |M_6|^2}{\frac{1}{3}B} \right\}.
 \end{aligned} \tag{13}$$

2. RESULTS AND DISCUSSION

The results of the numerical calculations are presented in Figs.1, 2. For simplicity we neglect here the Coulomb force in the pp pair. As was shown in Ref.7, Coulomb repulsion diminishes the unpolarized cross section by about 20%. Furthermore, we present here the results of calculation only at one magnitude of the excitation energy of the final pp pair, namely $E = 1.14$ MeV. We can show numerically that for unpolarized cross section with the Coulomb force in the pp system switched off, this value is an effective (averaged) magnitude of the excitation energy for the interval $E_{NN} = 0-3$ MeV probed in Ref.6.

We found that the vector analyzing powers are very sensitive even to rather small contributions to the reaction amplitude. We stress that A_y is zero for each mechanism (ONE, SS, Δ), taken separately: $A_y^{\text{ONE}} = A_y^{\text{SS}} = A_y^{\Delta} = 0$. Only the

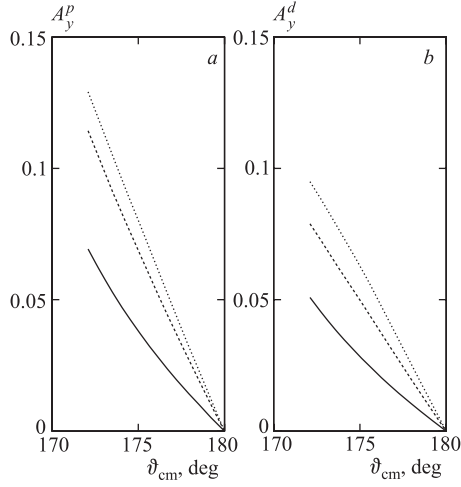


Fig. 1. Vector analyzing powers for the reaction $pd \rightarrow (pn)(^1S_0)p$ at $T_p = 0.5$ GeV and $E_{np} = 1.14$ MeV versus the neutron c.m.s. scattering angle calculated on the basis of the ONE DWBA+SS+ Δ model for different NN potentials: RSC (dotted line), Paris (dashed line), CD Bonn (solid line)

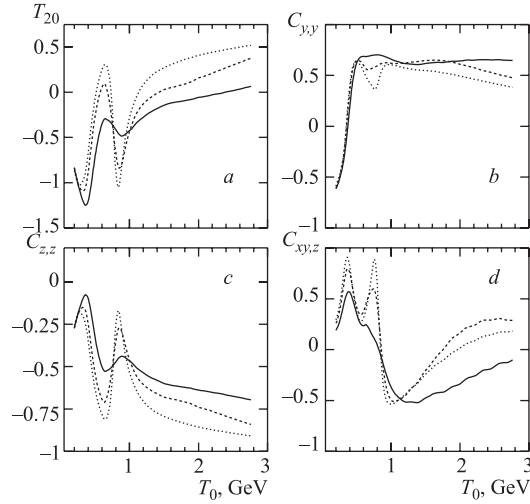


Fig. 2. Tensor polarization T_{20} (a), spin-spin correlation parameters $C_{y,y}$ (b), $C_{z,z}$ (c) and spin-tensor correlation parameter $C_{xy,z}$ (d) for the reaction $pd \rightarrow (pn)(^1S_0)p$ at $E_{np} = 1.14$ MeV, $\theta_n = 178.5^\circ$ versus beam energy. The notations of the curves are the same as in Fig. 1

coherent sum of them gives a nonzero result: $A_y^{\text{ONE+SS+}\Delta} \neq 0$. The slope of A_y (Fig. 1), as a function of the c.m.s. scattering angle of the neutron, depends on the NN model. The positive sign of A_y^p at $T_p = 0.5$ GeV is in agreement with the preliminary data from ANKE [11], but exclusion of the rescatterings and SS

mechanism changes the sign. One can see from Fig. 2 that the CD Bonn NN potential leads to the much smoother behaviour of T_{20} , $C_{y,y}$, $C_{z,z}$ and $C_{xz,y}$ in the region of the ONE dip. This behaviour is caused by the increasing relative contribution of the Δ mechanism for the CD Bonn as compared to the RSC and Paris potentials. This effect (in a similar way) shows up in the unpolarized cross section in the beam energy region 0.5–1 GeV [7], too.

We should note, however, that the ONE + SS + Δ model fails to reproduce the experimental data on T_{20} for the $pd \rightarrow dp$ process, particularly in the Δ region 0.4–8 GeV, while it reasonably explains the unpolarized cross section. This can be attributed to the unknown spin structure of the $NN \rightleftharpoons \Delta N$ amplitudes. Such an assumption is supported by the observation that inclusion of $3N$ -forces, based on the Δ -isobar excitation, into Faddeev calculations of pd -elastic scattering at lower energies 100–200 MeV also improves the agreement with the unpolarized cross section and some spin observables, but increases the disagreement for the spin-tensor observables [12]. Therefore, due to the dominance of the Δ mechanism in the region of the expected ONE dip of the $pd \rightarrow (pp)(^1S_0)n$ reaction one could get more insight into the spin structure of the Δ amplitude.

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