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

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

Yu.N. Uzikov [1†] and H. Seyfarth [2]

(1) *Joint Institute for Nuclear Research, LNP*
(2) *Forschungszentrum Jülich, Jülich, Germany*
† *E-mail: uzikov@nusun.jinr.ru*

Abstract

Analysis of recent ANKE-COSY data on the deuteron breakup $pd \to (pp)(^1S_0)n$ 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.

1. 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.

To minimize the complicating effects, it was proposed [2] to study the deuteron breakup reaction $pd \to (pp)n$ in the kinematics of backward elastic pd scattering with the final pp pair having low excitation energies $E_{pp} \le 3$ MeV, and thus being predominantly in the spin-singlet (isotriplet) $^1S_0$ state. This reaction, in contrast to the $pd \to dp$ process, provides a considerable suppression of the $\Delta-$ (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 formfactor [5].

The first data on the reaction $pd \to (pp)n$ 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.

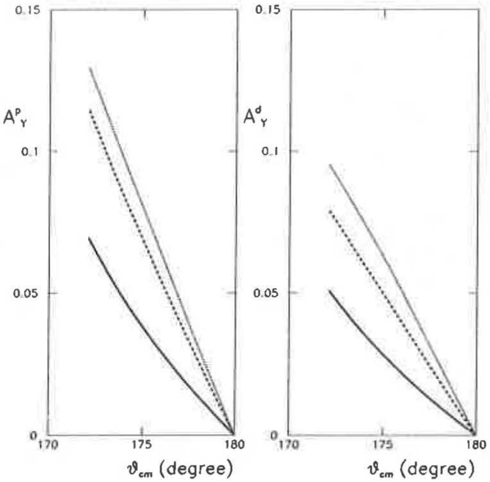

Figure 1: Vector analyzing powers for the reaction $pd \to (pn)(^1S_0)p$ at T_p=0.5 GeV and E_{np}=1.14 MeV versus the neutron c.m.s. scattering angle calculated on the basis of the ONE DWBA+SS+Δ model for different NN-potentials: RSC (dotted line), Paris (dashed), CD Bonn (solid).

Furthermore, the data [6] were analysed 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.

2. Elements of formalism

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

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

where φ_i (φ_f) is the Pauli spinor of the initial (final) fermion, $\mathbf{T}$ is the vector operator acting in the spin-$\frac{1}{2}$ 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

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

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

$$T_x = M_1\sigma_x + M_2\sigma_z, T_y = M_3 + M_4\sigma_y, T_z = M_5\sigma_x + M_6\sigma_z, \tag{3}$$

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

The polarization coefficients are defined as

$$A_j^p = \frac{SpT_\gamma\,\sigma_j\,T_\gamma^+}{SpT_\gamma T_\gamma^+}, \tag{4}$$

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

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

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

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

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:

$$\mathcal{P}_{ij} = \frac{3}{2}(S_iS_j + S_jS_i) - 2\delta_{ij}. \tag{9}$$

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

$$A_y^p = 2B^{-1}\left\{ReM_3M_4^* - Im(M_5M_6^* + M_1M_2^*)\right\}, \tag{10}$$
$$A_x^p = A_z^p = 0;$$
$$A_y^d = 2B^{-1}Im(M_5M_1^* + M_6M_2^*),$$
$$A_x^d = A_z^d = 0,$$

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

$$C_{y,y} = 2\left[ReM_2M_5^* - Re(M_1M_6^*\right]B^{-1}, \tag{12}$$
$$C_{z,z} = -2\left[ReM_1M_4^* + ImM_3M_2^*\right]B^{-1},$$
$$C_{xz,y} = 3\left[ImM_1M_6^* + ImM_5M_2^*\right]B^{-1},$$

For the tensor analyzing power one finds [2]

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

3. 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].

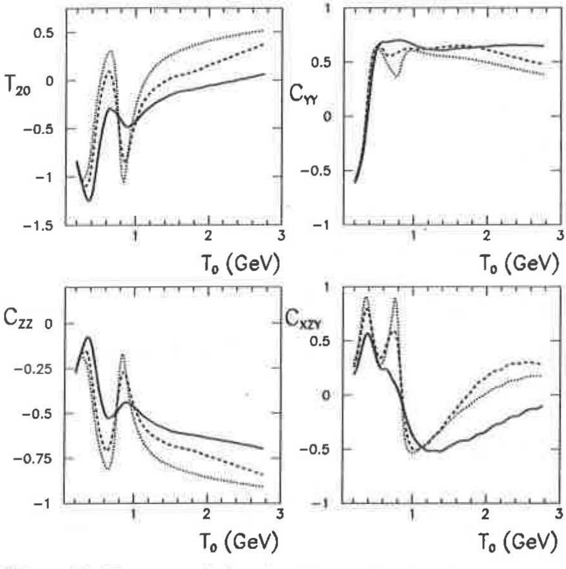

Figure 2: Tensor polarization T_{20}, spin-spin correlation parameters $C_{y,y}$, $C_{z,z}$ and spin-tensor correlation parameter $C_{xy,z}$ for the reaction $pd \to (pn)(^1S_0)p$ at E_{np}=1.14 MeV, $\theta_n = 178.5°$ versus beam energy. The curves notations are the same as in Fig. 1.

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 mechanim (ONE, SS, Δ), taken separately: $A_y^{ONE} = A_y^{SS} = A_y^{\Delta} = 0$. Only the coherent sum of them gives a non-zero result: $A_y^{ONE+SS+\Delta} \neq 0$. 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 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 $pd \to dp$ process, particularly in the Δ region 0.4-8 GeV, while it reasonable 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 [6]. Therefore, due to the dominance of the Δ mechanism in the region of the expected ONE dip of the $pd \to (pp)(^1S_0)n$ reaction one could get more insight into the spin structure of the Δ amplitude.

Acknowledgements. The authors are thankful to V. Komarov and F. Rathmann for stimulating discussions and to J. Haidenbauer for providing the scattering wave functions. This work is supported in part by the BMBF grant KAZ 02/001.

References

[1] R. Gilman, F. Gross, J. Phys. G **28**, R37 (2002).

[2] O. Imambekov and Yu.N. Uzikov, Sov. J. Nucl. Phys. **52**, 862 (1990).

[3] Yu.N. Uzikov, Pisjma v ZhETF **75**, 7 (2002).

[4] Yu.N. Uzikov, J. Phys. G **28**, B13 (2002).

[5] D.M. Nikolenko et al., Phys.Rev. Lett. **90**, 072501 (2003).

[6] V.I. Komarov et al., Phys. Lett. **B553**, 179 (2003).

[7] J. Haidenbauer, Yu. N. Uzikov, Phys. Lett. **B562**, 227 (2003).

[8] B.L.G. Bakker, L.A. Kondratyuk, and M.V. Terentjev, Nucl. Phys. **B158**, 497 (1979).

[9] R. Machleidt, Phys. Rev. **C 63** , 024001 (2001).

[10] L.I. Kaptari, B. Kämpfer, S.S. Semykh, S.M.Dorkin, nucl-th/0212062.

[11] F. Rathmann at al., Proc. 15^{th} Int. Spin Physics Symp., Brookhaven Nat. Lab., Upton, NY, USA, 9-14 September 2002. AIP Conf. Proc. **V. 675**, 553 (2003).

[12] H. Sakai et al. Phys. Rev. Lett. **84**, 5288 (2000).

Discussion

Q. (G.Lykasov, JINR, Dubna): You demonstrated that the reaction $pd \to (pp)(^1s_0)\,n$ is very sensitive to behaviour of NN interaction potential at short distances. Have you checked the CD Bonn NN potential using other pd–breakup data obtained in Dubna.

A. The CD Bonn NN potential is the best one now in describing NN phase shifts. In order to test this potential in off-shell region we have to be sure that the mechanism of pd-interaction is known. It is not so in case of inclusive data from JINR. Our process is more clean as it follows from the analyses of the $pd \to dp$ reaction.

Q. (E.Strokovsky, JINR, Dubna):
1) Will ANKE measure the spin correlation parameters?
2) Because in your model all spin-dependent observables are governed mostly by two components of the wave function, there must exists correlations between spin-dependent observables. Did you consider such correlations? It would be extremely useful to look on such data-to-data correlations experimentally.

A. In collinear kinematics there are only two independent amplitudes describing this process. In principle, a complete polarization experiment can be performed with polarized beam and target by measuring some spin-spin correlations. Such measurements are planned at ANKE-COSY.

Q. (G.Lykasov, JINR, Dubna): Could you check the CD Bonn potential describing the other existing data on $pd \to dp$ and $pd \to ppn$ reactions?

A: To check NN potential by *pd*-interaction one has to know the mechanism of interaction. For pd-elastic and inelastic scattering the mechanisms are known at rather low internal momenta in the deuteron, i.e. in the region where all potentials give almost the same result. At present the CD Bonn potential gives the best fit to the experimental NN-phase shifts as compared to other high accuracy NN-potentials like Nijmengen-II, Argonn-18.

In *ed*-elastic scattering Bonn type of NN-potentials, being based on the one boson exchanges, allow to include meson-exchange currents (MEC) in a self-consistent way. As was shown by Arenhoevel et al. (2000), the deuteron electro-magnetic formfactors and T_{20} can be explained very reasonably up to $Q^2 = 1.5\,(GeV/c)^2$ using the Bonn-Q interaction plus the MEC. For the CD Bonn such a calculations are still absent.