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Short-range NN-properties in the processes $pd \to dp$ and $pd \to (pp)n$

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Abstract. The data from the first measurement, performed at ANKE/COSY, of the unpolarized cross section of the reaction $pd \to (pp)n$ in the kinematics of backward elastic $pd \to dp$ scattering at proton-beam energies between 0.6 and 1.9 GeV are analyzed in a phenomenological approach. The $pd \to (pp)n$ data and the triplet cross section of the reaction $pd \to (pn)p$, calculated from the $pd \to dp$ data on the basis of the Fäldt-Wilkin extrapolation, are used here to derive the ratio ζ of the singlet production matrix element squared to the triplet one. This ratio, defined in our earlier analysis of $pd \to (pn)p$ data in a largely model-independent way, depends on the dynamics of the pd interaction. We find here $\zeta \approx 0.02$ and show that the smallness of this value may point toward softness of the deuteron at short NN distances.

PACS. 13.75.Cs Nucleon-nucleon interactions (including antinucleons, deuterons, etc.) – 25.10.+s Nuclear reactions involving few-nucleon systems

1 Introduction

The structure of the lightest nuclei at short distances in the nucleon overlap region $r_{NN} < 0.5$ fm, *i. e.* at high relative momenta $q_{NN} \sim 1/r_{NN} > 0.4$ GeV/c between the nucleons, is a fundamental problem of nuclear physics. The structure can be tested by electromagnetic probes at high transferred momenta. However, a self-consistent picture of electro- and photo-nuclear processes is not yet developed due to the unknown strength of the meson-exchange currents. Hadron-nucleus collisions can give important independent informations. The theoretical analysis of hadron processes is complicated by initial and final state interactions and the excitation/de-excitation of nucleons in intermediate states. For instance, a large contribution of the double pN scattering with excitation of the $\Delta(1232)$-resonance was found in proton-deuteron backward elastic scattering $pd \to dp$ at ~ 0.5 GeV [1,2,3,4,5]. At higher beam energies the role of heavier baryon resonances is expected to increase. Unfortunately, these contributions are not well controlled in theory due to the rather poor information about the $pN \rightleftharpoons NN^*$and $pN \rightleftharpoons N\Delta$ amplitudes. To some extent these effects are taken into account in the one-pion exchange (OPE) model [1] with a virtual subprocess $pp \to d\pi^+$, but another important contribution, i.e. the one-nucleon-exchange (ONE) amplitude, cannot be included in this model.

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To minimize these complicating effects, it was proposed [6] to study the deuteron breakup reaction $pd \to (pp)n$ in the kinematics of backward elastic pd scattering. For low excitation energies $E_{pp} \leq 3$ MeV, the final pp pair can be assumed to be in the $^1S_0$ spin singlet (isotriplet) state. This feature, in contrast to the $pd \to dp$ process, results in a considerable suppression of the $\Delta-$ (and N^*)$-$ excitation amplitudes by the isospin factor 1/3 in comparison with the one-nucleon exchange (ONE). Recently it was shown [7] that the same suppression factor acts for a broad class of diagrams with isovector meson–nucleon rescattering in the intermediate state including the excitation of any baryon resonance. Furthermore, the node in the half-off-shell $pp(^1S_0)$ scattering amplitude at the off-shell momentum $q \sim 0.4$ GeV/c results in remarkable irregularities in the spin observables and leads to a dip in the unpolarized cross section for the ONE mechanism [6, 8]. In the $pd \to dp$ and $pd \to pX$ processes, the node in the deuteron S wave is hidden by the large contribution of the D wave. The irregularities of the observables allow new studies of (i) the commonly used potentials of the NN interaction at short distances and (ii) possible contributions from N^*- exchanges [9] and exotic three-baryon states [2].

The first data on the reaction $pd \to (pp)n$ at high beam energies $T_p = 0.6-1.9$ GeV with forward emission of a fast proton pair of low excitation energy E_{pp} were obtained at ANKE-COSY [10]. Using a largely model-independent approach based on the Migdal-Watson and the Fäldt-Wilkin

FSI theory, we discuss the relative strength of the measured singlet in comparison to the triplet channel. We present also the results of a calculation of the deuteron breakup cross section performed within the main mechanisms of the $pd \to dp$ process [5].

2 The FSI theory

At excitation energies around 1 MeV, the $pd \to (pn)p$ cross section is strongly influenced by the np FSI. The resulting peak is well described by the Migdal-Watson formulae [11,12] which take into account the nearby poles in the FSI triplet (t) and singlet (s) $pn-$scattering amplitudes

$$d\sigma_{s,t} = FSI_{s,t}(k^2)\, K\, |A_{s,t}|^2. \quad (1)$$

Here $A_{s,t}$ is the production matrix element for the singlet and triplet state, K is the kinematical factor, and $FSI_{s,t}$ is the Goldberger-Watson factor [12]

$$FSI_{s,t}(k^2) = \frac{k^2 + \beta_{s,t}^2}{k^2 + \alpha_{s,t}^2}. \quad (2)$$

Here k is the relative momentum in the pn system at the excitation energy $E_{np} = k^2/m$, where m is the nucleon mass. The parameters α and β are determined by the known properties of the on-shell NN-scattering amplitudes at low energies: $\alpha_t = 0.232$ fm^{-1}, $\alpha_s = -0.04$ fm^{-1}, $\beta_t = 0.91$ fm^{-1}, $\beta_s = 0.79$ fm^{-1} [13]. Information on the $pd \to pnp$ mechanism and the off-shell properties of the NN system is contained in the matrix elements $A_{s,t}$ and their ratio [14]

$$\zeta = \frac{|A_s|^2}{|A_t|^2}. \quad (3)$$

The $pd \to (pp)n$ data, obtained at ANKE/COSY [10], are presented as cms cross sections

$$\overline{\frac{d\sigma}{d\Omega_n}} = \frac{1}{\Delta\Omega_n} \int_0^{E_{max}} dE_{pp} \int\int m \frac{d^3\sigma}{dk^2 d\Omega_n} d\Omega_n, \quad (4)$$

integrated over E_{pp} from 0 to 3 MeV and averaged over the neutron cms angle $\theta_n^* = 172^\circ - 180^\circ$, where

$$\frac{d^3\sigma}{dk^2 d\Omega_n} = \frac{1}{(4\pi)^5} \frac{p_n}{p_i} \frac{k}{s\sqrt{m^2+k^2}} \frac{1}{2} \int\int d\Omega_{\mathbf{k}} \overline{|M_{fi}|^2} \quad (5)$$

and $\Delta\Omega_n$ is the neutron solid angle. In Eq. (5) p_i and p_n are the cms momenta of the incident proton and the final neutron, respectively; M_{fi} is the full matrix element of the reaction. Due to the isospin invariance the following relation holds in the singlet cannel

$$\frac{d\sigma}{d\Omega^*}(pd \to (np)_s p) = \frac{1}{2} \frac{d\sigma}{d\Omega^*}(pd \to (pp)_s n). \quad (6)$$

Using the Fäldt-Wilkin extrapolation [15] for the bound and the scattering S wave functions in the triplet state at short pn distances $r < 1$ fm, and taking into account the short-range character of the interaction mechanism, the triplet cross section $pd \to (pn)_t n$ is obtained as

$$\frac{d\sigma_t}{d\Omega^*} = \frac{p_f}{p_i} f^2(k^2) \frac{d\sigma}{d\Omega^*}(pd \to dp), \quad (7)$$

where

$$f^2(k^2) = \frac{2\pi\, m}{\alpha_t (k^2 + \alpha_t^2)} \quad (8)$$

and $d\sigma/d\Omega^*$ is the $pd \to pd$ cms cross section. After integration over E_{pp} the triplet cross section (7) takes the form

$$\overline{\frac{d\sigma_t}{d\Omega^*}} = \frac{p_f}{p_i} Z \frac{d\sigma}{d\Omega^*}(pd \to dp), \quad (9)$$

where

$$Z = \frac{1}{2\pi} \frac{2}{\alpha_t} \left\{ k_{max} - \alpha_t \arctan\left(\frac{k_{max}}{\alpha_t}\right) \right\}. \quad (10)$$

On the other side, the triplet (t) and singlet (s) cross sections can be obtained by integration of Eq. (1) over E_{pp}. K, $|A_s|^2$, and $|A_t|^2$, being very smooth functions of E_{pp}, can be assumed as constant. A ratio of the integrals $R = y_s/y_t$ can be defined, where

$$y_{s,t} = \int_0^{k^2_{max}} FSI_{s,t}(k)\, k\, dk^2. \quad (11)$$

With this ratio one finally gets the singlet-to-triplet ratio ζ defined by Eq. (3) as

$$\zeta = \frac{1}{2\, R\, Z} \frac{\frac{d\sigma}{d\Omega^*}(pd \to (pp)_s n)}{\frac{d\sigma}{d\Omega^*}(pd \to dp)}. \quad (12)$$

It is obvious that ζ is not a direct ratio of the $pd \to (pp)n$ and $pd \to dp$ cross sections, but contains also the additional factor $1/(2\, R\, Z)$.

3 Results and discussion

For the numerical calculations of ζ, defined by Eq. (12), we use the experimental data on the $pd \to dp$ cross section [16] and the new ANKE/COSY data for the $pd \to (pp)n$ reaction [10]. From the Eqs.(2) and (11) and with the values for α_i and β_i, given above, we get $Z = 0.101$ and $R = 2.29$ for $E_{pp}^{max} = 3$ MeV. With these numbers and assuming systematic uncertainties of 10% for both the $pd \to dp$ cross section and the Fäldt-Wilkin ratio (7), we obtain $\zeta = (2.3 \pm 0.5)\%$ for 0.6, $\zeta = (1.6 \pm 0.3)\%$ for 0.7, and $\zeta = (2.1 \pm 1.2)\%$ for 1.9 GeV beam energy. We find the surprising fact that ζ is constant within the errors over the whole investigated beam-energy range from 0.6 to 1.9 GeV.

The present, model-independent small result for ζ can be compared with $\zeta < 5\%$, obtained recently [14] for the $pd \to (pn)p$ reaction data, measured exclusively at 585 MeV and cms angle $\theta^* = 92^\circ$ [17]. A similar, small value for the singlet admixture of a few percent was found for the reaction $pp \to pn\pi^+$ in the FSI region at beam energies of 492 MeV [18] and 800 MeV [19], too. The smallness of the singlet contribution in the Δ-region of the reaction $pd \to (pn)p$ can be explained by dominance of the OPE mechanism with the subprocess $pp \to (pn)_s\pi^+$ [14].

The singlet-to-triplet ratio can be estimated as $\zeta_{th} = R_S \times R_I \times R_X$. Here $R_S = 1/3$ is the spin statistical factor. The isospin ratio R_I is 1 for the ONE and 1/9 for both the Δ-mechanism and the vector meson–nucleon exchanges [7]. R_X is the ratio of the spatial singlet and triplet amplitudes. For the Δ-mechanism, it reflects the difference of the $^1S_0$ and $^3S_1$ wave functions at $r < 1$ fm. Since ζ according to Eqs. (1) and (2) does not contain the FSI factor, R_X is ≈ 1 for the Δ amplitude. For the ONE it is ≈ 0.5 due to the contribution of the D wave in the triplet and its absence in the singlet state. The calculation using Eqs.(5) and (4) with the Reid-Soft-Core (RSC) NN-potential [20] gives $\zeta_{ONE} = 5-8\%$ for $T_p = 1.4-1.9$ GeV for the ONE which is 3 to 4 times the experimental value. For the Δ mechanism this ratio $\zeta_\Delta = R_S \times R_I = 1/27$ is in better agreement with the experimental value.

Calculations [4,8] with use of the RSC NN potential and the ONE+SS+Δ model [2,5], including single pN scattering (SS), describe the $pd \to (pp)n$ cross section data for the beam energies 0.6 and 0.7 GeV as is seen in Fig. 1. In this region the Δ mechanism dominates due to the nearby minimum of the ONE cross section. At higher energies the strong disagreement with the data is obvious. The data show no indication of the dip around 0.8 GeV, and for $T_p > 1.3$ GeV they are by a factor 2 to 4 below the prediction. A very similar discrepancy is observed for $pd \to dp$ backward elastic scattering, as can be seen from the upper part of Fig. 1. Both the earlier $pd \to dp$ and the recent $pd \to (pp)n$ data show that in the until now used model the contribution by the ONE, dominating for $T_p > 1.3$ GeV, is too strong. On the other side, a calculation, using only the Δ mechanism with a cutoff momentum $\Lambda_\pi = 0.7$ GeV/c allows one to describe the $pd \to (pp)n$ data for $T_p > 0.7$ GeV. This mechanism does not involve such high-momentum components of the NN wave function as the ONE. A possible conclusion would be that the deuteron and the $pp(^1S_0)$ system at short NN distances are softer than modeled by the RSC NN potential. As one should note, the assumption about softness of the deuteron at short NN-distances is supported by (i) rather successful description of the $pd \to dp$ cross section within the OPE-model only [21,5], and (ii) the strong disagreement between the ONE calculations and the T_{20} data [22]. Detailed analyses of this conjecture are in progress.

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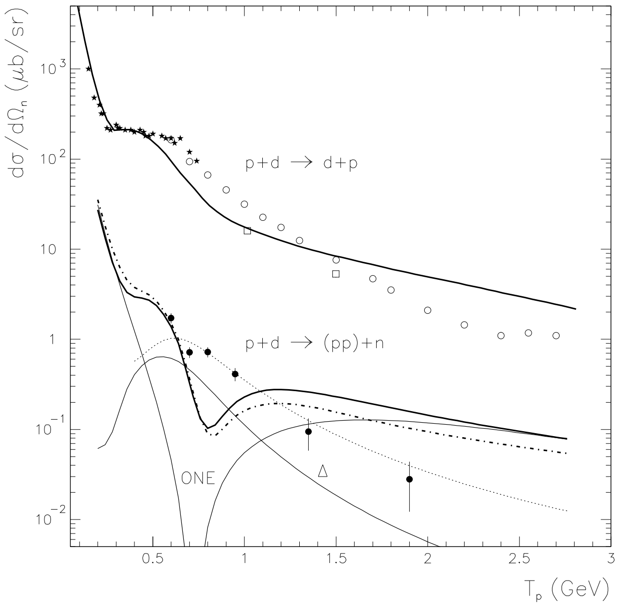

Fig. 1. Experimental cross section of the reactions $pd \to dp$ [16] and $pd \to (pp)n$ [10] as function of the beam energy in comparison with ONE+SS+Δ model calculations (thick full lines) using the RSC potential with cutoff momentum $\Lambda_\pi = 0.53$ GeV/c in the πNN and $\pi N\Delta$-vertices [4]. Inclusion of rescattering in the initial and final states, taken into account within the ONE(DWBA)+SS+Δ model [8], yields the dashed- dotted line. The dotted line results from a calculation using only the Δ mechanism with cutoff momentum $\Lambda_\pi = 0.7$ GeV/c.

References

1. N.S. Craigie and C. Wilkin, Nucl.Phys. **B14** (1969) 477.
2. L.A. Kondratyuk, F.M. Lev, L.V. Schevchenko, Yad. Fiz. **33** (1981) 1208.
3. A. Boudard, M.Dillig. Phys. Rev. **C31** (1985) 302.
4. O. Imambekov and Yu.N. Uzikov, Yad. Fiz. **47** (1988) 1089; O. Imambekov, Yu.N. Uzikov, L.V.Schevchenko, Z. Phys. **A332** (1989) 349.
5. Yu.N. Uzikov, Phys. Part. Nucl. **29** (1998) 583.
6. O. Imambekov and Yu.N. Uzikov, Sov. J. Nucl. Phys. **52** (1990) 862.
7. Yu.N. Uzikov, Pisjma v ZhETF **75** (2002) 7.
8. Yu.N. Uzikov, J. Phys. G: Nucl. Part. Phys. **28** (2002) B13.
9. A.K. Kerman and L.S. Kisslinger, Phys. Rev. **180** (1969) 1483.
10. V.I. Komarov et al., arXiv:nucl-ex/0210017 v2, submitted for publication in Phys. Lett. **B**.
11. K.M. Watson, Phys. Rev. **88** (1952) 1163; A.B. Migdal, Sov. Phys. - JETP **28** (1955) 3.
12. M.L. Goldberger and K.M. Watson. *Collision Theory* (John Wiley, New York, 1964)
13. R. Machleidt, Phys. Rev. **C 63** (2001) 024001.
14. Yu.N. Uzikov, V.I. Komarov, F. Rathmann, H.Seyfarth, Phys. Lett. **B524** (2002) 303.
15. G. Fäldt and C. Wilkin, Phys. Scripta **56** (1997) 566.
16. P. Berthet *et al.*, J. Phys. G: Nucl. Phys. **8** (1982) L111.
17. T. Witten *et al.*, Nucl. Phys. **A254** (1975) 269.
18. V.V. Abaev *et.al.*, Phys. Lett. **B521** (2001) 158.
19. Yu.N.Uzikov, C.Wilkin, Phys. Lett. **B511** (2001) 191.
20. J.R.V. Reid, Ann. Phys. (NY) **50** (1968) 411.
21. V.M. Kolybasov, N.Ya. Smorodinskaya, Yad. Fiz. **17** (1973) 1211.
22. L.S. Azhgirey *et al.*, Phys. Lett. **B391** (1997) 22.