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The reaction $pd \to (pp)n$ at high momentum transfer and short-range NN properties

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Abstract

A recent cross section measurement of the deuteron breakup reaction $pd \to (pp)(0^\circ) + n(180^\circ)$, in the GeV region in a kinematics similar to backward pd elastic scattering, strongly contradicts predictions of a $pd \to dp$ model based on the one-nucleon exchange, single pN scattering and Δ excitation mechanisms, and on the wave functions of the Reid soft core and Paris NN potentials. We show within the same model that for the CD Bonn NN potential there is qualitative agreement with the data. It is attributed to a reduction of the one-nucleon exchange at energies above 1 GeV and an increase of the $\Delta(1232)$-isobar contribution, both related to the short-range properties of the wave functions generated by this potential.

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Keywords: Deuteron breakup; Short-range nucleon–nucleon interaction

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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, can be tested by electromagnetic probes at high momentum transfer [1]. However, a self-consistent picture of electro- and photo-nuclear processes is not yet developed, mainly because of the unknown strength of the meson-exchange currents (MEC). Hadron–nucleus collisions can give, in principle, independent information. On the other hand, here the theoretical analysis is obstructed by initial and final state interactions and by the excitation/de-excitation of nucleons in the intermediate states. For example, a large contribution of double pN scattering with excitation of the $\Delta(1232)$ resonance was found in proton–deuteron backward elastic scattering ($pd \to dp$) at beam energies $T_p \sim 0.5$ GeV [2–7]. At higher energies it is expected that also heavier baryon resonances will play an important role. Like the MEC problem in electro-nuclear interactions, the nucleon-isobar contributions are theoretically not well under control, due to the rather poor information about the $pN \rightleftharpoons NN^*$ and $pN \rightleftharpoons N\Delta$ amplitudes. These difficulties are the main reasons why expectations to consider the reaction $pd \to dp$ as a probe for the

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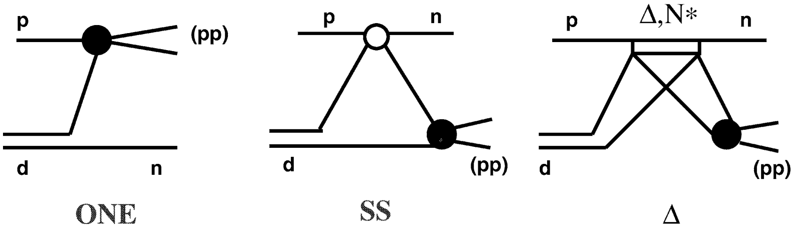

Fig. 1. Mechanisms of the breakup reaction $pd \to (pp)n$. The same mechanisms are used for the reaction $pd \to dp$.

short-range structure of the deuteron could not be realized yet [1].

In order to minimize those complicating effects it was proposed in Ref. [8] to study the deuteron breakup reaction $pd \to (pp)n$ in a kinematics similar to backward elastic pd scattering. For small excitation energies, $E_{pp} \leqslant 3$ MeV, the final pp pair (diproton) is expected to be mainly in the $^1S_0$ spin singlet (isotriplet) state [8,9]. In contrast to $pd \to dp$, the isovector nature of the diproton causes a considerable suppression of the $\Delta-$ (and N^*) excitation amplitude in comparison with the one-nucleon exchange (ONE) contribution, due to the additional isospin factor $1/3$. 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 resonances [10]. Furthermore, the node in the pp ($^1S_0$) half-off-shell reaction amplitude at the off-shell momentum $q \approx 0.4$ GeV$/c$ induces some remarkable features in spin observables and leads to a dip in the unpolarized cross section for the ONE mechanism [8,11]. Though a similar node occurs also in the deuteron S-wave function, its influence in the $pd \to dp$ and $pd \to pX$ processes is, however, hidden by the large contribution of the D-wave component. Thus, the specific features of the $pd \to (pp)n$ reaction mentioned above provide a new testing ground for the pd dynamics at high momentum transfer and, accordingly, for the properties of the commonly used NN potentials at short distances.

In the present Letter we analyze the first data on the reaction $pd \to (pp)n$, obtained recently at ANKE-COSY [12] for beam energies $T_p = 0.6$–1.9 GeV with forward emission of a fast proton pair of low excitation energy of $E_{pp} = 0$–3 MeV.

Existing predictions, produced in the framework of a model which includes the triangle diagram of pN single scattering (SS) in addition to the ONE and Δ-mechanisms (ONE + SS + Δ, cf. Fig. 1), and employing the RSC [13] and Paris [14] NN potentials [8], turned out to be in agreement with the now measured cross section [12] at low energy 0.6–0.7 GeV only. Specifically, the dip of the cross section at around $T_p \approx 0.8$ GeV, suggested by that model calculation [8,11], was not observed in the experiment. Moreover, at higher energies, $T_p > 1$ GeV, the predicted cross section exceeds the data by a factor of 2–3. According to an analysis presented in Ref. [15] those two deficiencies could be a consequence of a too large contribution from the ONE mechanism. Distortions reduce the ONE contribution and, in turn, improve the results somewhat [15], but they do not really remove the disagreement of the model calculation with the data. Therefore, it was argued in Ref. [15] that the high momentum components of the NN wave functions should be much smaller as those of the employed RSC and Paris potentials in order to achieve agreement with the experiment, or in other words those wave functions should be soft. In the present Letter we show, within the ONE + SS + Δ model, that with the use of wave functions generated from the CD Bonn NN potential [16] a qualitative agreement between the calculations and the breakup data can be obtained, especially after taking into account initial and final state interactions for the ONE mechanism.

The cms 3-fold differential cross section of the reaction $pd \to (pp)n$ is given by [9]

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

Here p_i and p_n are the cms momenta of the incident proton and the final neutron, respectively, s is the squared invariant mass of the $p + d$ system, and $\mathbf{k}$ is the relative momentum in the final pp system. The latter is related to the relative energy in the pp system, E_{pp}, by $k^2 = m\,E_{pp}$, where m is the nucleon mass. M_{fi} is the matrix element of the reaction. In Eq. (1) an integration over the directions of the momentum $\mathbf{k}$ is performed. To compare with the COSY data [12] one has to integrate the cross section in Eq. (1) over E_{pp} from 0 to 3 MeV and average over the neutron cms angle in the interval $\theta_n^* = 172°–180°$. For the ONE mechanism the square of the spin-averaged matrix element takes the form

$$\overline{\left|M_{fi}^{\mathrm{ONE}}\right|^2} = \frac{E_d(E_p + E_n)\varepsilon_p(q)}{E_p^2}\frac{m^4}{\pi} \times N_{pp}^2\left[u^2(q) + w^2(q)\right]\left|t\left(q', k\right)\right|^2. \qquad (2)$$

Eq. (2) is derived on the basis of the relativistic Hamiltonian dynamics for the three-body problem [17]. The Lorentz-invariant relative momenta at the vertices $d \to p + n$ and $p + p \to pp(^1S_0)$ are denoted as q and q', respectively. The other notations in Eq. (2) are: E_j is the energy of the deuteron ($j = d$), intermediate proton (p) and neutron (n) in the cms of the $p + d$ system, and $\varepsilon_p(q) = \sqrt{m^2 + q^2}$; $u(q)$ and $w(q)$ are the S- and D-wave components of the deuteron wave function in momentum space, normalized as $\int_0^\infty (u^2(q) + w^2(q))q^2\,dq = (2\pi)^3$. The combinatorial factor $N_{pp} = 2$ in Eq. (2) and also the factor 1/2 in Eq. (1) take into account the identity of the final protons. The half-off-shell t-matrix in the $^1S_0$ pp state is given by

$$t\left(q', k\right) = -4\pi \int_0^\infty \frac{F_0(q'r)}{q'r} V_{NN}(r)\psi^{(-)*}(r)r^2\,dr, \qquad (3)$$

where $F_0(z)$ is the regular Coulomb function for zero orbital momentum $l = 0$ and $\psi^{(-)}$ is the scattering wave function obtained from the solution of the Schrödinger equation for a NN potential (V_{NN}) including the Coulomb interaction (V_C), i.e., $V(r) = V_{NN}(r) + V_C(r)$, and normalized as $\psi^{(-)}(r) \to \frac{\cos\delta}{kr} \times [F_0(kr) + \tan\delta G_0(kr)]$. Here δ is the Coulomb distorted nuclear phase shift and $G_l(kr)$ is the irregular Coulomb function. The pure Coulomb half-off-shell t-matrix, $t^c(\mathbf{q}, \mathbf{k})$, derived in Ref. [18], gives a very small contribution for $|\mathbf{k}| \ll |\mathbf{q}'|$ and is neglected in the present calculation. Further details of the formalism, specifically for evaluating the Δ and SS mechanisms of the breakup reaction $pd \to (pp)n$, can be found in Refs. [7,8,19].

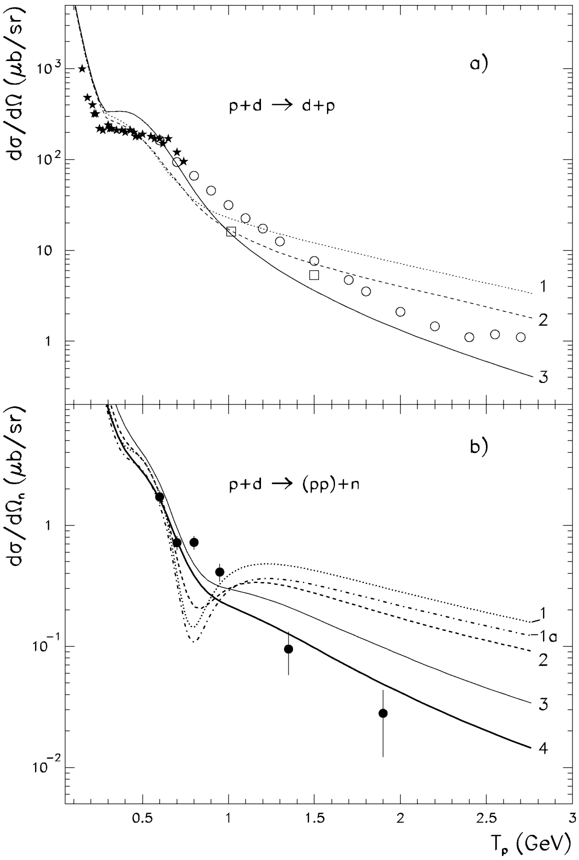

Fig. 2. Cms differential cross sections of the reaction $pd \to dp$ at the proton scattering angle $\theta_p^* = 180°$ (a) and of the reaction $p + d \to (pp) + n$ for neutron scattering angles $\theta_n^* = 172°–180°$ and relative energies $E_{pp} = 0–3$ MeV of the two forward protons (b) as a function of the beam energy T_p. Calculations are performed on the basis of the ONE + SS + Δ model described in the text without (lines 1–3) and with distortions included (4) for the RSC (1), Paris (2) and the CD Bonn (3,4) potentials. The curve 1a shows the result for the RSC potential with Coulomb effects included. Curve 4 is the result for the CD Bonn potential taking into account distortions for the ONE mechanism and also Coulomb effects (by the suppression factor of 20%, cf. text). Data for $pd \to (pp)n$ are from Ref. [12], and for $pd \to dp$ from [21–23].

We start with the reaction $pd \to dp$. Corresponding results are shown in Fig. 2(a). As can be seen, at $T_p < 0.5$ GeV the theoretical predictions describe the shape of the experimental data but overestimate the absolute value. This shortcoming of the model calculation is presumably caused by the neglect of the initial and final state interaction. Indeed the latter effects were used as an argument in Ref. [3] to introduce a phenomenological distortion factor of 0.8 for the ONE amplitude to match the experimental data on the $pd \to dp$ cross section at $T_p < 0.3$ GeV. Actually, the distortion effects are energy dependent, therefore we have refrained from applying such a phenomenological distortion factor to our results for $pd \to dp$ shown in Fig. 2(a). At energies above 1 GeV the results are contradictory. While the calculations based on the RSC and Paris deuteron wave functions lead to an overestimation of the cross section we observe an underestimation for the CD Bonn model. In view of expected substantial contributions of heavy nucleon isobars, which are theoretically not well under control at these energies [7], it is not possible to draw more concrete conclusions from those deviations at the present stage. Therefore, it is much more interesting to look at the reaction $pd \to (pp)n$ because, as we mentioned above, contributions from such isobar states are expected to be suppressed in the breakup channel and, consequently, a comparison of a model calculation with the breakup data should provide a much more conclusive test for the NN interaction models.

Our predictions for the breakup reaction $pd \to (pp)n$ are shown in Fig. 2(b). Let us focus first on the results without Coulomb interaction and without distortion effects. One can see from this figure, the dip becomes less pronounced in the $\mathrm{ONE} + \mathrm{SS} + \Delta$ model calculation when one comes from the RSC (line 1) to Paris (line 2) and then to CD Bonn (line 3) NN potential. At the same time the tail of the cross section at higher energies $T_p > 1$ GeV becomes smaller. As a whole, the model predictions with the CD Bonn wave functions are much closer to the data than for the RSC and Paris potentials. The improvement is caused primarily by the relative softness of the CD Bonn wave functions in the ${}^3S_1$–${}^3D_1$ and ${}^1S_0$ states as compared to those of the RSC and Paris potentials. Because of this feature the relative importance of all mechanisms in question are significantly changed when using the CD Bonn interaction instead of the Paris or RSC models. This is demonstrated more explicitly in Fig. 3, where the separate contributions of the $\mathrm{ONE} + \mathrm{SS} + \Delta$ model are shown for the CD Bonn wave function and also for the Paris potential. Obviously the magnitude of the ONE cross section at $T_p > 0.8$ GeV for the CD Bonn potential is considerably smaller (by factor of 3–4) as compared to the result with the Paris potential (cf. Fig. 3). This reduction of the ONE contribution at higher energies leads to a much better agreement between the $\mathrm{ONE} + \mathrm{SS} + \Delta$ model and the data at $T_p > 1$ GeV for this NN model (see Fig. 2(b)). At the same time the Δ contribution is larger for the CD Bonn interaction as compared to the Paris model. As mentioned above, the CD Bonn wave functions decrease much faster with increasing momentum q as compared to those of the Paris and RSC potentials. This means that, in configuration space, the CD Bonn wave functions provide a higher probability density $|\psi(r)|^2$ for finding the NN system at short distances ($r < 0.5$ fm) as compared to the case of the Paris (or RSC) potentials. Since the amplitude of the Δ mechanism is proportional to the averaged value of r^{-2} [3,8], it is clear that the Δ contribution will be larger for the CD Bonn interaction model than for the Paris potential. This property of the Δ mechanism was demonstrated earlier in Ref. [6] by comparing its contribution to the $pd \to dp$ cross section calculated with the RSC and Paris potentials, respectively. The increase of the Δ contribution to the breakup cross section by approximately 50% for the CD Bonn potential fills in much of the ONE dip [8,9,11] of the cross section (cf. Fig. 2(b)) and, as a result, improves the agreement with data. One can also see from Fig. 3 that for the CD Bonn interaction the Δ mechanism alone describes the measured breakup cross section already rather well at $T_p > 0.8$ GeV, but the interferences between the Δ and the SS mechanisms at around 0.8 GeV and between the Δ and ONE amplitudes for $T_p > 1$ GeV destroy this agreement (see Fig. 2(b)). The SS contribution (not shown in Fig. 3) is relatively small itself. But its contribution to the breakup cross section is also smaller for CD Bonn than for the Paris potential.

For a direct comparision with the experiment let us now also take into account effects of the initial and final state interaction in the ONE contribution. This is done in distorted wave Born approximation (DWBA) as described in Refs. [11,19]. The corresponding result for the CD Bonn model is shown by the thick solid line in Fig. 2(b). In addition, in this calculation the Coulomb effects are included. Since the CD Bonn potential is given only in momentum space it is rather difficult to account for the Coulomb inter-

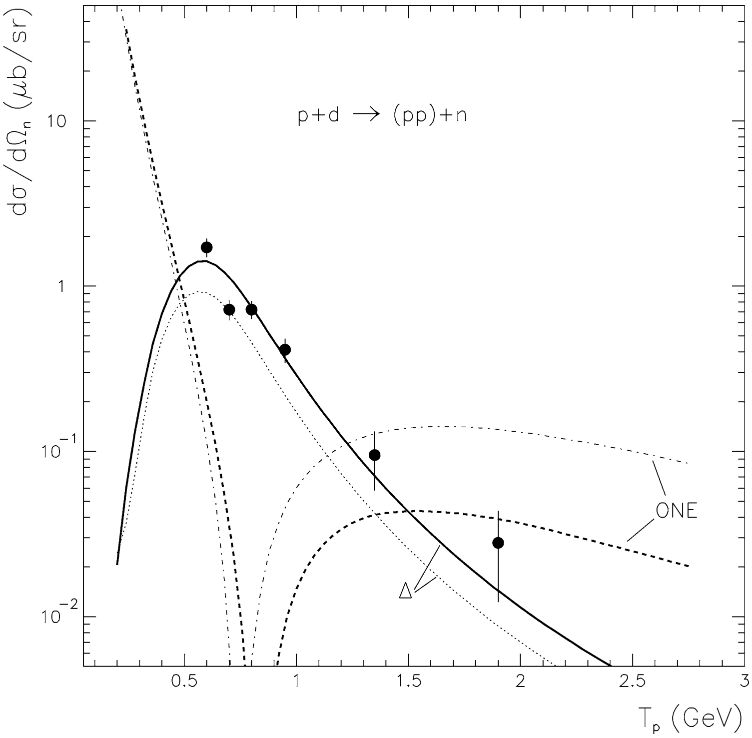

Fig. 3. Contributions of the considered reaction mechanisms to the cms differential cross section of the reaction $p + d \to (pp) + n$ at neutron scattering angle $\theta_n^* = 172°$–$180°$ and relative energies $E_{pp} = 0$–3 MeV of the two forward protons. Results are shown for the Paris (ONE—dash-dotted line, $\varDelta$—dotted line) and CD Bonn (ONE—dashed line, $\varDelta$—solid line) NN potentials. Data are from Ref. [12].

action rigorously [20]. However, by performing corresponding calculations for the RSC and Paris potentials in configuration space we found that inclusion of the Coulomb interaction in the final pp system decreases the ONE + SS + $\varDelta$ cross section by approximately 20% (cf. the curves 1 and 1a in Fig. 2(b) for the RSC potential). Thus, we have assumed here that the Coulomb repulsion produces the same suppression of the cross section also for the CD Bonn NN interaction. Obviously, including both these effects leads to a further reduction of the predicted cross section. In particular, now the total result for the ONE + SS + $\varDelta$ model is already in qualitative agreement with the breakup data.

Let us make some further comments. To begin with, the contribution of the SS mechanism is presumably overestimated. This contribution involves the subprocess of $pn \to pn$ scattering which takes place completely off-shell. However, in the actual calculation the on-shell $pn \to pn$ amplitude is used [3,8]. In addition, double elastic pN scattering, which is not considered in this Letter, should also reduce the influence of the SS mechanism. Actually, as was shown in Ref. [24], the coherent sum of single and double pN scattering produces a $pd \to dp$ cross section which is considerably smaller than that for the SS alone. None the less, we should stress in this context that backward elastic pd scattering is not very sensitive to the details of the SS mechanism. At $T_p < 0.8$ GeV, this reaction is dominated by the ONE and $\varDelta$ mechanisms. Indeed, omitting the SS contribution from the ONE + SS + $\varDelta$ model practically does not change the $pd \to dp$ cross section [4]. The situation is completely different for the breakup reaction $pd \to (pp)n$, specifically around the dip structure because there the contribution of the ONE amplitude is basically zero. Here the ONE + $\varDelta$ result differs significantly from the one based on the ONE + SS + $\varDelta$ amplitude in the region of 0.6–0.9 GeV and as a matter of facts describes the data better in this region (see Fig. 4). Possible non-nucleonic con-

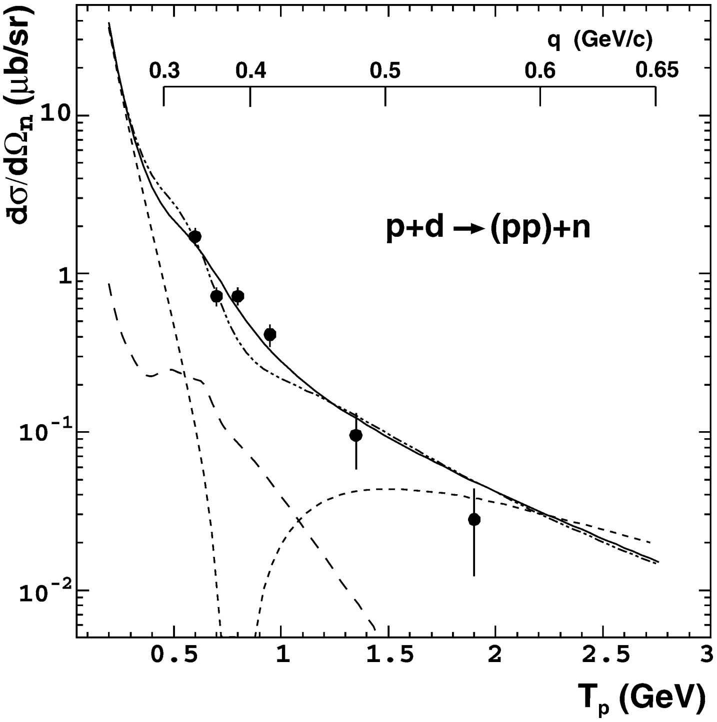

Fig. 4. The same as in Fig. 3, but using the CD Bonn NN potential only. ONE—short-dashed line; SS—long-dashed line; coherent sum of ONE + Δ with Coulomb effects included—solid line; ONE + SS + Δ with Coulomb effects included—dashed-double dotted line. In the latter two cases distortions in the ONE contribution are also included. The upper scale shows the internal momentum of the nucleons in the deuteron for the ONE, cf. Eq. (2).

tributions, like the $\Delta\Delta$ and NN^* components of the deuteron and diproton, can also change the results in the region of the expected dip. The role of the relativistic P-wave component that couples to the $^1S_0$ state was studied recently in Ref. [25] in a covariant Bethe–Salpeter approach. According to Ref. [25] the contribution of this P-wave completely masks the dip of the $pd \to (pp)n$ cross section and makes the pp scattering amplitude properly small to achieve agreement with the experiment at higher energies. However, only the ONE mechanism was discussed in Ref. [25] and, moreover, without rescattering effects. The inclusion of the Δ contribution, may change the result obtained in Ref. [25] significantly. As was shown here and in Ref. [15], already the Δ mechanism alone is sufficient to describe the data.

In conclusion, we analyzed the deuteron breakup data $pd \to (pp)n$ in the framework of the ONE + SS + Δ model that has been previously applied to backward elastic pd scattering in a similar kinematical region. We show that the unpolarized cross section of this reaction is very sensitive to the behaviour of the NN interaction at short distances as reflected in the high momentum components of the deuteron and pp wave functions. Due to the relative smallness of the high momentum component of the CD Bonn wave functions in the $^3S_1$–$^3D_1$ and $^1S_0$ states a much better agreement with the breakup data is achieved than for models with harder wave functions like the RSC or Paris potentials. Future polarization measurements in the reaction $pd \to (pp)n$ can provide a further tests for the present picture of the pd interaction and the NN dynamics at short distances.

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