Proton Induced Deuteron Break-up with Emission of a Fast Forward Proton Pair

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Abstract

A kinematically complete study of the $pd \to (pp)_s n$ reaction with forward emission of an S-wave proton pair $(pp)_s$ has been performed at six beam energies 0.6, 0.7, 0.8, 0.95, 1.35, and 1.9 GeV. The experiment was carried out at the ANKE spectrometer installed at the internal beam of the proton synchrotron COSY (Jülich). 3-momenta of both final state protons have been measured and events with a relative proton energy less than 3 MeV were selected. The differential cross sections of such pair production averaged over the c.m. polar angle of the total momentum of the pair in the range $0° - 8.1°$ have been obtained. A comparison of the result with a theoretical model based on the mechanism of the pd-backward elastic scattering is described as well.

1 Physical motivation

The proton-deuteron interaction at high transferred momenta to both nucleons of the deuteron is well suited to study the short-range nucleon-nucleon interaction and the dynamics of high-momentum transfer in few-nucleon systems. The simplest cases of such interactions are, e.g. elastic pd-scattering at large angles and mesonless deuteron breakup $pd \to pnp$ in a kinematics far from free pN-elastic scattering. The collinear kinematics is favorable here since significant efforts have been already undertaken to comprehend pd backward elastic scattering, $pd \to dp$ (see e.g. review [1] and references therein). The main features of existing data on the unpolarized differential cross section of the $pd \to dp$ process in the region 0.2- 2.0 GeV energy range can be reproduced in a theoretical approach taking into account the coherent sum of three distinct mechanisms, *i)* one nucleon exchange (ONE), *ii)* $\Delta-$excitation in the intermediate state (Δ), and *iii)* single pN-scattering (SS) [2, 3]. The spin coefficient for transfer of the vector polarization of the initial deuteron to the final proton [4] and the tensor analyzing power T_{20} [5] can be also reproduced to some extend. It was noted, however, in Refs. [1, 2, 3] that the dominance of the Δ-isobar excitation at 0.4 - 1.0 GeV and possible excitation of other nucleon isobars N^* at higher energies would mask the short-range NN-properties.

The collinear breakup process with two nucleons emitted in forward direction at low relative energy $E_{NN} < 3$ MeV is kinematically very close to the $pd \to dp$ process. Therefore the same mechanisms (ONE+Δ+SS) can be applied in a theoretical analysis of the breakup process [6]. The reaction

$$p + d \to p(0^\circ) + p(0^\circ) + n(180^\circ) \tag{1}$$

with two forward emitted protons at relative energy $E_{pp} < 3$ MeV is of special interest since in this case the pp-pair is mainly in the $^1S_0$ state. As was shown for the first time in [6] within the ONE+Δ+SS model, the presence of the spin-singlet NN-pair in the final state provides two important new features in comparison with the $pd \to dp$ process. Firstly, the contribution of the Δ-mechanism is essentially suppressed due to isospin invariance. Secondly, the S-wave dominance in the internal state of the forward pp-pair results in remarkable irregularities of the unpolarized cross section and spin observables. These originate from the node of the half-off-shell pp-scattering amplitude, $t(q,k)$ in the $^1S_0$ state at off-shell momentum $q \sim 0.4$ GeV/c. Here $k = \sqrt{E_{pp}m}$ is the relative on-shell momentum, m denotes the nucleon mass. A similar node of the S-wave component of the deuteron wave function in momentum space, $u(q)$, is hidden in the $pd \to dp$ process by the large contribution of the D-wave of the final deuteron wave function. Therefore, the unpolarized differential cross section of the deuteron break-up reaction (1), calculated within the ONE mechanism, exhibits a strong dip at 0.6 - 0.7 GeV followed by and a smooth decrease as a function of incident beam energy in the interval 1 - 3 GeV. The coherent sum of ONE+Δ+SS and elastic rescatterings in the initial and final states do not modify this picture drastically [7]. The process discussed here (1) has not been studied experimentally at intermediate energies in the above described collinear kinematics. The work described here aims at a measurement of the unpolarized differential cross section and a comparison with the energy dependence expected from the ONE+Δ+SS model. For that purpose we have chosen six energies for the measurement: 0.6, 0.7, 0.8, 0.95, 1.35, and 1.9 GeV.

2 Experimental setup and measurements

The experiment was performed at the ANKE spectrometer installed at COSY (Jülich, Germany). The setup is described elsewhere [8]. Figure 1a depicts parts of the spectrometer that are of concern for the present experiment. The protons stored in the COSY ring ($\sim 3.10^{10}$ protons) impinge on a deuterium cluster jet target located 30 cm upstream of the spectrometer dipole D2. A target similar to the one described in Ref. [9] provided a thickness of about $1.3 \cdot 10^{13}$ atoms/cm^2 resulting in a luminosity of $\sim 4 \cdot 10^{29}$cm$^{-2} \cdot$s^{-1}. Charged particles produced in the beam-target interaction pass the D2 magnetic field and intercept a set of three multiwire proportional chambers (MWPC) and a two-plane scintillation counter hodoscope. A small gap of 1 mm between the wires and a total of 12 coordinate planes allowed us to obtain the required momentum resolution ($\sigma(p)/p \approx 1.2\%$ for 2.65 GeV and 1.4% for 0.5 GeV protons) and a reliable separation of the rare two-track events of interest.

The hodoscope, consisting of vertical strips of 4 to 8 cm width, was used for triggering, determination of energy losses, and it enabled us to measure the time differences for particles hitting different strips. Vertical hit coordinates were measured with an accuracy of about 2 cm (rms), using the time difference between the signals from the photomultiplier tubes positioned at both ends of the strips.

The coincidence of the meantimer signals from counters of both planes was used for triggering of the data acquisition system. The two-particle events ($pp, p\pi^+, d\pi^+$, ^{3}Hπ^+) contributed little to the total trigger rate and were selected off-line. The acceptance of the setup is shown in Fig 1.b. Accepted emission angles in the vertical plane are within $\pm 3.5°$. For the polar angle Θ_{pp}^{cm} of the total momentum of the pair in the range from 0° to 5°, the probability to detect the pairs with relative energy $E_{pp} < 3$ MeV varies from 0.52 to 0.37 for T$_p$=0.6 GeV (and from 1.0 to 0.76 for 1.9 GeV). The processes $pp \to pp$, $pp \to d\pi^+$, $pp \to pn\pi^+$ at energies 0.5 GeV and 2.65 GeV were used to calibrate energy losses in the counters and the momentum scale.

The integral beam-target interaction luminosity, L^{int}, for each data set has been measured by counting protons scattered off the deuterons at small laboratory angles between 5° and 10°. The achieved momentum resolution did not allow us to separate events from elastic and quasi-elastic pd-scattering. Thus, the obtained number of counts was related to the sum of elastic and inelastic terms in the diffractive pd-scattering cross section. The cross section was calculated in closure approximation of the Glauber-Franko theory [10]. The errors of the L^{int} values, shown in Table 1, take into account the acuracy of the normalization cross section and the systematic errors.

The proton pairs were selected in arrays of two-particle events by use of the difference Δt between arrival times of the particles measured with an accuracy (rms) of 0.5 ns. A comparison of Δt with the time-of-flight difference calculated for protons of measured momenta provided a clear identification of the proton pairs. The process of interest (1) was identified by missing-mass of the observed proton pairs. The missing-mass spectra at all energies reveal a well defined peak at the neutron mass with an accuracy of 1.7 MeV. The resolution of the setup over the relative energy E_{pp} corresponds to 0.2 MeV at $E_{pp} = 0.5$ MeV and 0.3 MeV at $E_{pp} = 3$ MeV. That allows reliably to select the pairs with $E_{pp} < 3$ MeV. The distributions of the distances between the hits, produced in the wire planes by the proton pairs, are rather wide (4.9 and 3.3 cm rms at 0.6 and 1.9 GeV beam energy, respectively). Therefore, no noticeable correction arrises from the loss of tracks lying too near. For the final analysis the pairs have been taken in the $\pm 2\sigma$ range of the neutron missing mass peak. The signal-to-background ratio was determined for this range.

The limited statistics compels us to deduce the three-fold differential cross section $d^3\sigma/d\cos\Theta_{pp}\cdot d\Phi_{pp}\cdot dE_p$, where Θ_{pp} and Φ_{pp} are polar and azimuthal angles of the total momentum of the proton pair, respectively.

Counting rates at high energies 1.35 and 1.9 GeV were too low to extract even the three-fold cross section from the taken. Therefore, in order to explore the energy dependence of the process in the whole range of beam energies, we report here the cross section integrated over the E_{pp} energy range of $0 - 3$ MeV, over Φ_{pp} in the 2π range and $\cos\Theta_{pp}^{cm}$ from 1 to 0.99. The quantity N_{eff} in Table 1 denotes the total number of proton pairs that satisfy all cuts mentioned above. The quantity N_{eff}^{corr*} gives the number of events corrected for the MWPC efficiency, while N_{eff}^{corr} corresponds to the number corrected in addition for the FD acceptance. The quantity $\overline{d\sigma/d\Omega_{pp}}$ corresponds to the differential cross section $d\sigma/d\Omega_{pp}$ of pairs produced with relative energy less than 3 MeV, averaged over the chosen angular range,

$$\overline{d\sigma/d\Omega_{pp}} = \frac{N_{eff}^{corr}}{L^{int}\cdot\Delta\Omega_{pp}}\cdot\frac{N_{eff}}{N_{eff}+N_{bg}}\cdot f, \tag{2}$$

where, f denotes a correction factor close to unity arising from soft cuts applied during the data analysis.

3 Results and conclusion

The obtained energy dependence of the cross section is shown in Fig. 2 together with calculations performed in the framework of the ONE+Δ+SS model. It is seen that the model with use of both the Reid soft core and the

Paris potential reproduces rather well the cross section value at the lowest energy and its decrease at higher energies. There is no evidence for the expected dip. Elastic rescatterings are taken in account as described in Refs. [7, 11]. The joint theoretical analysis of the backward elastic pd-scattering and the breakup process (1) is in progress.

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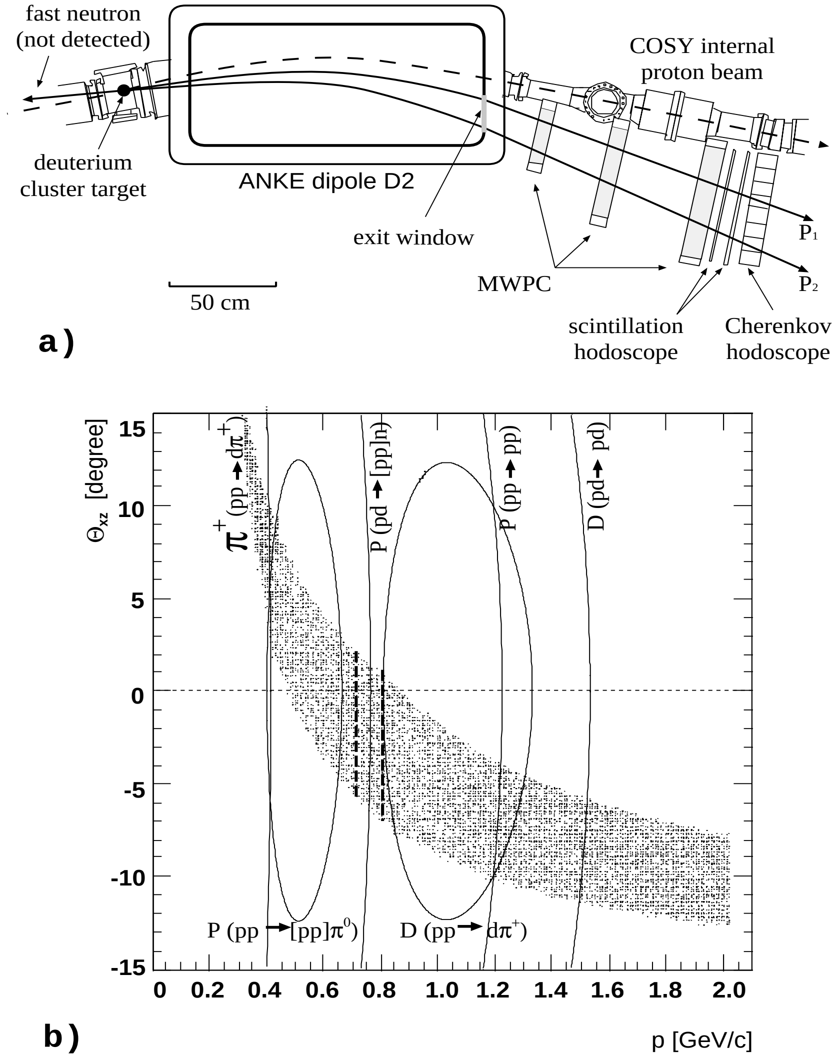
Figure captions

Fig. 1. **a**) Top view of the experimental setup; **b**) Angular-momentum acceptance at 0.6 GeV beam energy. Θ_{xz} gives the polar angle of the emmited particle projected onto the median plane of the setup. The lines show kinematical loci for π^+, p, d from the denoted processes. The symbol [pp] denotes pp-pairs with zero relative energy E_{pp}. The region between the hatched lines corresponds to pp-pairs from process (1) with E_{pp} <3 MeV.

Fig. 2. The measured cross sections of the processes $pd \to dp$ and $pd \to (pp)n$ (E_{pp} = 0 - 3 MeV) in comparison with the results of ONE+SS+Δ model calculations. For the $pd \to dp$ elastic backward scattering the Reid soft core (RSC, dashed-dotted thin line) and the Paris (full thin line) deuteron wave functions (DWF) have been used. For the $pd \to (pp)n$ reaction the calculations have been performed without rescatterings using the RSC (dotted line) and the Paris (dashed line) DWFs. The full thick line shows the result obtained for the ONE with the Paris DWF and with rescatterings.

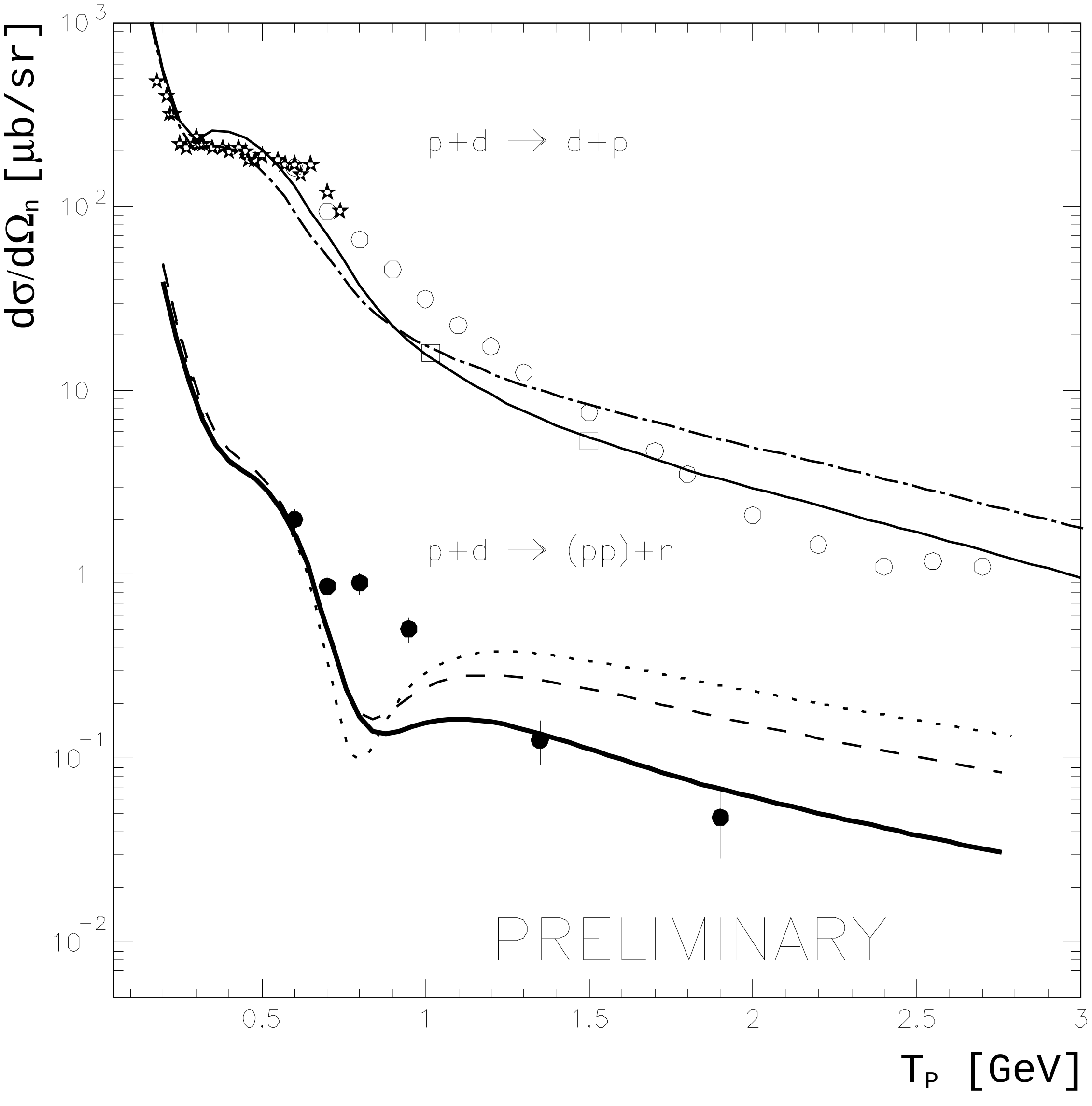
Tp, GeV	L^{int}, $cm^{-2} \cdot 10^{34}$	N_{eff}	N_{eff}^{corr*}	N_{eff}^{corr}	$\frac{N_{eff}}{N_{eff}+N_{bg}}$	$\Delta\Omega_{pp}$, msr	$\overline{d\sigma/d\Omega_{pp}} \pm \sigma^{stat} \pm \sigma^{syst}$ cm^2/sr
0.6	1.41±0.14	266	286	483	0.94	24.4	$(1.48 \pm 0.09 \pm 0.17) \cdot 10^{-30}$
0.7	1.93±0.20	197	211	337	0.87	24.5	$(6.88 \pm 0.49 \pm 0.82) \cdot 10^{-31}$
0.8	2.38±0.25	255	278	405	0.89	24.7	$(6.86 \pm 0.43 \pm 0.78) \cdot 10^{-31}$
0.95	1.28±0.13	89	98	128	0.85	24.7	$(3.85 \pm 0.41 \pm 0.52) \cdot 10^{-31}$
1.35	0.69±0.07	11	12	15	0.79	25.1	$(7.9 \pm 2.4 \pm 2.3) \cdot 10^{-32}$
1.90	0.74±0.08	6	7	8	0.62	25.1	$(2.8 \pm 1.2 \pm 1.3) \cdot 10^{-32}$

Table 1: Summary of the experimental results. (All numbers are still of preliminary character.)



fast neutron
(not detected)
deuterium
cluster target
ANKE dipole D2
COSY internal
proton beam
exit window
MWPC
50 cm
scintillation
hodoscope
Cherenkov
hodoscope
P1
P2
a)
Θxz [degree]
p [GeV/c]
π+ (pp→dπ+)
P (pd→[pp]n)
P (pp→pp)
D (pd→pd)
P (pp→[pp]π0)
D (pp→dπ+)
b)

Figure 1:



dσ/dΩ$_n$ [μb/sr]
10^3
10^2
10
1
10^{-1}
10^{-2}
p+d → d+p
p+d → (pp)+n
PRELIMINARY
0.5
1
1.5
2
2.5
3
T$_P$ [GeV]

Figure 2: