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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 $\rightarrow$ $(pp)_s$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). The 3-momenta of both final state protons have been measured and events with a relative proton energy less than 3 MeV were selected as $^1S_0$ diprotons. 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 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 $\rightarrow$ ppn in a kinematics far from free pN-elastic scattering. The collinear kinematics is favorable here since significant efforts have already been undertaken to understand pd backward elastic scattering, pd $\rightarrow$ dp (see e.g., review [1] and references therein). In the beam-energy range of $T_p = 0.2 \ldots 2.0$ GeV, the main features of the existing data for the unpolarized differential cross section of the pd $\rightarrow$ dp process can be well reproduced by a theoretical approach taking into account the coherent sum of three distinct mechanisms, (*i*) one nucleon exchange (ONE), (*ii*) Δ-excitation in the intermediate state (Δ), and (*iii*) single pN-scattering (SS) [2,3]. The calculated vector polarization transfer coefficient κ_0 (from the inital deuteron to the final proton), Ref. [4], and the tensor analyzing power T_{20} [5] are not in agreement with the data for relative pn momenta above 0.3 GeV/c, while for lower momenta the agreement is quite good. It was noted, however, in Refs. [1–3] that the dominance of the Δ-isobar excitation at $T_p = 0.4$–1.0 GeV and the possible excitation of N^* isobar resonances 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 $\rightarrow$ dp process. Therefore the same mechanisms (ONE + Δ + SS) can be applied in a theoretical analysis of the breakup process [6]. The reaction

$$p + d \rightarrow p(0^\circ) + p(0^\circ) + n(180^\circ) \quad (1)$$

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 Ref. [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 $\rightarrow$ 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 $\rightarrow$ dp process by the large contribution of the D-wave of the final deuteron wave function. Therefore, the

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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 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 change these features significantly [7]. The process (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 1(a) depicts parts of the spectrometer that are of concern for the present experiment. The protons stored in the COSY ring ($\sim 3\cdot 10^{10}$ 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

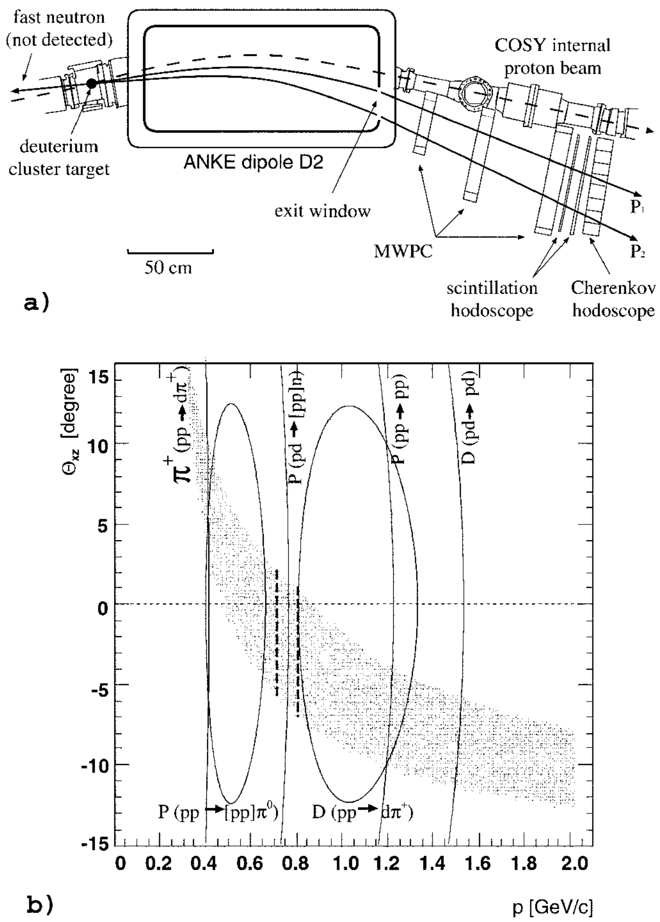

Fig. 1. (a) Top view of the experimental setup; (b) Angular vs. momentum acceptance at 0.6 GeV beam energy. Θ_{xz} gives the polar angle of the emitted particle projected onto the median plane of the setup. The lines show kinematical loci for π^+, p, d from the denoted processes. The symbol [pp] denotes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

of about $1.3\cdot 10^{13}$ atoms/cm^2 resulting in a luminosity of $\sim 4\cdot 10^{29}\,\mathrm{cm^{-2}\,s^{-1}}$. Charged particles from beam-target interactions pass the magnetic field of D2 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 ($\sigma(p)/p \approx 0.8\%$ for 1 GeV/c and 1.2% for 2.7 GeV/c proton ejectile momentum) and a reliable separation of the rare two-track events of interest.

The hodoscope, consisting of vertical scintillation-counter 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, pπ^+, dπ^+, ^{3}Hπ^+) contributed little to the total trigger rate and were identified off-line. The acceptance of the setup is shown in Fig. 1b. 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 8°, 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 $T_p = 1.9$ GeV). The processes pp → pp, pp → dπ^+, and pp → pnπ^+ at energies 0.5 GeV and 2.65 GeV were used to calibrate energy losses in the counters and the momentum scale.

The integrated 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–Franco theory [10]. The errors of the L^{int} values, shown in Table I, take into account the accuracy of the normalization cross section and the systematic errors.

The proton pairs were selected among the 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 pd → ppn was identified by the 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 arises from the loss of hits being too close to each other. For the

Table I. *Summary of the experimental results. (All numbers are still of preliminary character.)*

T_p [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	$(2.8 \pm 1.2 \pm 1.3) \cdot 10^{-32}$

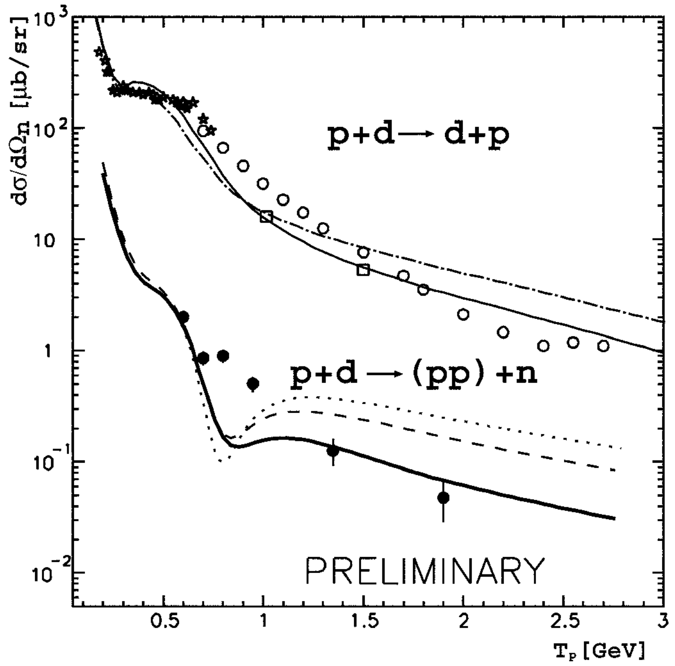

Fig. 2. Measured cross sections of the processes pd → dp and pd → (pp)n ($E_{pp} = 0$–3 MeV) in comparison with results of the ONE + SS + Δ model calculations. The pd → dp experimental data, taken from Refs. [13–15] are labeled by stars, circles, and squares, respectively. The pd → (pp)n data are from the present experiment.

For the pd → dp elastic backward scattering Reid soft core (RSC, dashed-dotted thin line) and Paris (full thin line) deuteron wave functions (DWF) have been used. For the pd → (pp)n reaction the calculations have been performed without rescatterings using RSC (dotted line) and Paris (dashed line) DWFs. The full thick line shows the result obtained for the ONE with the Paris DWF and with rescatterings.

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 $d^3\sigma/d\cos\Theta_{pp} \cdot d\Phi_{pp} \cdot dE_{pp}$, 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 data. 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 I 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,

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

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 results of calculations performed in the framework of the ONE + Δ + SS model. It is seen that the models both for the Reid soft core [11] and the Paris [12] potential reproduce rather well the cross section values at the lowest energy and its decrease at higher energies. There is no evidence for the expected dip. Elastic rescatterings are taken into account as described in Refs. [7,16]. A joint theoretical analysis of the backward elastic pd-scattering and the breakup process (1) is in progress.

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