Measurement of the Analyzing Power in $\vec{p}d \rightarrow (pp)n$
with a Fast Forward $^1S_0$–Diproton

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A measurement of the analyzing power $A_y$ of the $\vec{p}d \rightarrow (pp) + n$ reaction was carried out at the ANKE spectrometer at COSY at beam energies of 0.5 and 0.8 GeV by detection of a fast forward proton pair of small excitation energy $E_{pp} < 3$ MeV. The $S$–wave dominance in the fast di-proton is experimentally demonstrated in this reaction. While at $T_p = 0.8$ GeV the measured analyzing power $A_y$ vanishes, it reaches almost unity at $T_p = 0.5$ GeV for neutrons emitted at $\theta^c_m = 167^\circ$. The results are compared with a model taking into account one–nucleon exchange, single scattering, and $\Delta (1232)$ excitation in the intermediate state. The model describes fairly well the unpolarized cross section obtained earlier and the analyzing power at 0.8 GeV, it fails to reproduce $A_y$ at 0.5 GeV.

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The structure of the lightest nuclei at short distances ($r_{NN} < 0.5$ fm) or high relative momenta ($q > 1/r_{NN} \sim 0.4$ GeV/c), and the closely related nucleon–nucleon (NN) interaction constitute fundamental problems in nuclear physics. Experimental investigations employ processes where the momentum transfer to the nucleus is large ($Q \sim 1$ GeV/c). Most of our present knowledge about the structure of the deuteron has been obtained from electromagnetic probes. The existing data on elastic electromagnetic deuteron form factors for $Q < 1$ GeV/c are in reasonable agreement with NN models based on the exchange of mesons [1, 2]. The situation above $Q \sim 1$ GeV/c becomes much more less clear due to increasing contributions from meson–exchange currents (MEC) in $ed$ interactions and theoretical uncertainties in their treatment. Moreover, meson–exchange models have difficulties to explain photo–disintegration data ($\gamma d \rightarrow np$) for energies $E_{\gamma} > 1$ GeV [3]. Models based on quark degrees of freedom have recently become quite successful in describing the data [4].

Independent information about the short–range structure of nuclei can be obtained from hadronic interactions at large $q$. However, the study of the simplest processes in the GeV region, $pd \rightarrow dp$ [4] as well as inclusive ($dp \rightarrow pX$ [4]) and exclusive ($pd \rightarrow ppm$ [5]) deuteron disintegration turned out to be not conclusive in this respect [6]. It is therefore important to obtain new data under conditions that make the theoretical interpretation more transparent. Recently, the unpolarized cross section of the $pd \rightarrow (pp)n$ reaction was carried out at proton beam energies $T_p = 0.6$ to 1.9 GeV in a kinematics similar to backward $pd$ elastic scattering [3] with formation of a fast diproton in a $^1S_0$ state at low excitation energy ($E_{pp} < 3$ MeV). At high $Q$, near threshold deuteron electro–disintegration $d(e,e')pn$ [6] and single pion production, $pp \rightarrow pp\pi^\pm$ [10] and $pn \rightarrow (pp)\pi^\pm$ [11], constitute prominent examples for the observation that substitution of an ordinary deuteron in the final state by a singlet deuteron or its isoscalar partner, the diproton, will give new insight into the reaction dynamics. In $pd \rightarrow (pp)n$, the diproton provides two new features which are absent for isosinglet nucleon pairs [3, 4, 7]. i) The contribution from three–body forces, related to two isovector meson exchanges, in particular the excitation of $\Delta$ and $N^*$ resonances in the intermediate state, is suppressed by the isospin factor of 3 in the amplitude of this process [12]. This suppression is of relevance, because the theoretical interpretation of three–body effects in hadronic reactions encountered problems similar to those of MEC in electromagnetic processes [12, 13, 14, 15]. ii) The $S$–wave dominates in the internal state of the diproton at $E_{pp} < 3$ MeV. Due to the repulsive $NN$ core, the $^1S_0$ diproton wave function $\psi_{^1S_0}(q)$ has a node at relative $pp$ momenta $q \approx 0.4$ GeV/c [12], leading to a distinct en-

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energy dependence of various polarization observables \cite{17} that helps to identify the dominant reaction mechanisms. The recent analysis \cite{18} of the \(pd \rightarrow (pp)\psi_{NN}n\) cross section, based on a model for the \(pd \rightarrow dp\) process \cite{13}, includes the one–nucleon exchange (ONE), single scattering (SS), and double \(pN\) scattering with excitation of a \(\Delta(1232)\) isobar. This analysis accounts for initial and final state interactions and employs modern \(NN\) potentials, based on the exchange of mesons, e.g. CD–Bonn \cite{14}. A reasonable agreement with our recent data \cite{3} is achieved. In contrast, the widely used \(NN\) potentials like the Paris \cite{20} and especially the Reid Soft Core (RSC) potential \cite{21} lead to a strong disagreement with the data. These potentials apparently overestimate the high–momentum components of the \(NN\) wave function \(\psi_{NN}(q)\). Another approach, using the ONE mechanism only \cite{22}, which is based on relativistic \(P\)–waves in the diproton and deuteron also explains the data \cite{3}.

New information about this reaction can be obtained from measurements of polarization observables. Here we report about the first measurement of the vector analyzing power \(A_v\) at \(T_p = 0.5\) and 0.8 GeV of the reaction

\[
\vec{p} + d \rightarrow (pp)\psi_{NN} + n, \tag{1}
\]

where \((pp)\psi_{NN}\) denotes a fast proton pair emitted in the forward direction with small excitation energy \(E_{pp} < 3\) MeV. The two beam energies were chosen because of the difference in the reaction mechanisms predicted by the model \cite{13}. While at 0.5 GeV the contribution from the \(\Delta\) excitation is comparable to that from ONE, at 0.8 GeV the latter is completely eliminated due to the node in the \(pp\) wave function \(\psi_{pp}(q)\) and hence the process is governed by the \(\Delta\) mechanism. Each mechanism under consideration alone yields an almost vanishing analyzing power. Because of their interference a substantial \(A_v\) arises, which is expected to decrease with increasing beam energy between \(T_p = 0.5\) and 0.8 GeV.

The experiment was performed at the ANKE spectrometer \cite{24} at the internal beam of COSY–Jülich \cite{25} with about \(3 \cdot 10^9\) stored vertically polarized protons. The experimental setup is shown in Fig. 1. The Forward Detector (FD) measured proton pairs from the deuteron breakup and single protons, scattered at small angles from \(pd \rightarrow pX\). The Silicon–detector telescope (SDT) recorded recoil deuterons from small–angle elastic \(pd\) reaction with \(E_{pp} < 3\) MeV at \(E_{pp} = 0.3\) MeV to 3 MeV at \(E_{pp} = 3\) MeV. The SDT \cite{27} consists of three layers of silicon counters in the horizontal plane located inside the vacuum of the ANKE target chamber. Recoil deuterons at angles around \(\theta_{lab} = 90^\circ\) were detected in the SDT in coincidence with elastically scattered protons in the FD. The SDT provided an unambiguous deuteron identification with a detector resolution of 300 keV. The deuteron cluster–jet \cite{28} produced a target density of about \(2 \cdot 10^{14}\) atoms/cm\(^2\) with a target length along the beam of 12 mm and a width of 4.9 mm.

The tracks were reconstructed from the hits in the MWPCs, ensuring that they intercept the 0.5 mm Al exit window. The three–momentum vectors were determined by tracing the particles through the magnetic field of the spectrometer \cite{26}. For two particles hitting different hodoscope counters the correlation of the measured time–of–flight (TOF) difference \(\Delta t_{\text{meas}}\) and \(\Delta t(\vec{p}_1,\vec{p}_2)\), calculated from the measured three–momenta assuming proton masses, allows one to identify charged particle pairs from different reactions (Fig. 2). However, proton pairs from the deuteron breakup can be identified via missing mass without this TOF criterion, as discussed in Ref. \cite{5}. At both energies and for both orientations of the beam polarization, the missing mass peak is observed at the neutron mass \(M_n\), yielding (0.938 ± 0.005) GeV/c\(^2\) \((T_p = 0.5\) GeV\) and (0.935 ± 0.005) GeV/c\(^2\) \((T_p = 0.8\) GeV\). The (rms) peak widths are 16 MeV/c\(^2\) and 20 MeV/c\(^2\), respectively.

The \(S\)–wave dominance in the diproton final state is illustrated in Fig. 3 where the acceptance corrected distribution of events is shown over the cosine of the proton polar angle \((\cos \theta_{\psi_{NN}})\) in the two–proton rest frame with

![Fig. 1: Top–view of the ANKE spectrometer with the forward detector (FD) and the Silicon–detector telescope (SDT, see inset). Diprotons from the breakup reaction stem from the \(pd\) elastic scattering are distributed along the kinematical locus.](image-url)
Careful monitoring of the relative luminosity with every two cycles the orientation of the polarization. Therefore, we measured the analyzing power by reversing the analyzing power from the left–right count rate asymmetry. The spectrometer does not permit one to measure a vector amplitude determined from precise measurements of the beam polarization, oriented along the $\vec{p}$ direction. The absolute value of the beam polarization is given by

$$\Delta \vec{t} = \cos \theta \cdot \frac{1}{P} \cdot (\cos \phi) \cdot \varepsilon \cdot \theta,$$

where $P$ is the polarization of the beam, $\theta$ is the angle between the $\vec{p}$ direction and the c.m. system, $\phi$ is the azimuthal angle, and $\varepsilon$ is the absolute efficiency of the detector.

The absence of azimuthal symmetry of the ANKE spectrometer does not permit one to measure a vector analyzing power from the left–right count rate asymmetry. Therefore, we measured the analyzing power by reversing every two cycles the orientation of the polarization. Careful monitoring of the relative luminosity $L_1/L_\perp$ was achieved by either detecting single particles in the FD at $\theta_{lab} < 1^\circ$ or at $\phi = 90^\circ \pm 5^\circ$ and $\phi = 270^\circ \pm 5^\circ$, where the rates are insensitive to the vertical beam polarization.

The beam polarization at $T_p = 0.800$ GeV was determined from precise $pd$–elastic analyzing power data at 0.796 GeV. The $pd$ elastic scattering angles were determined from the energy deposit of the identified deuterons in the SDT. Since there are no data available at 0.5 GeV, we resorted to the polarization export technique to obtain a calibrated polarization for 0.5 GeV. This was achieved by setting up a cycle with a flat top at energy $T_p = 0.8$ GeV (I), followed by deceleration to a flat top at 0.5 GeV (II), and subsequent re–acceleration to a flat top at 0.8 GeV (III). Avoiding depolarization during crossing of the resonances, the measured beam polarizations $P_I = 0.564 \pm 0.003_{\text{stat.}} \pm 0.004_{\text{syst.}}$ and $P_{III} = 0.568 \pm 0.004_{\text{stat.}} \pm 0.005_{\text{syst.}}$ agree within errors. The systematic errors arise from the statistical uncertainty of the relative luminosity. The weighted average of $P_I$ and $P_{III}$ was used to export the beam polarization to flat top II and to determine the angular distribution of the previously unknown analyzing power of $pd$ elastic scattering at 0.5 GeV. A small angle–independent correction of $-0.0024$ was applied in the export procedure to account for the 4 MeV difference in beam energy, using the energy dependence of $A_y$ between 500 and 800 MeV.

The analyzing power is determined from

$$A_y(\theta) = \varepsilon(\theta) \cdot \frac{1}{P} \cdot (\cos \phi) \cdot \theta,$$

where $P = (P_1 + P_\perp)/2$ and $\varepsilon(\theta)$ is given by

$$\varepsilon(\theta) = \frac{N_1(\theta)/L_1 + N_\perp(\theta)/L_\perp}{N_1(\theta)/L_1 + N_\perp(\theta)/L_\perp}.$$

Here $N_1(\theta)/L_1$ and $N_\perp(\theta)/L_\perp$ denote the number of events in each $\theta$ bin, weighted by the relative luminosity for each orientation of the beam polarization. Events were selected for which $|\phi| \leq 45^\circ$. The average $(\cos \phi) \theta = N_\theta^{-1} \sum N_\phi(\cos \phi) \theta$, where $N_\theta = N_1(\theta) + N_\perp(\theta)$, is determined from the experimental data for each $\theta$ bin. The number of counts $N_1$ and $N_\perp$ were obtained from the neutron missing mass spectra for proton pairs with $E_{pp} < 3$ MeV. The spectra for the two orientations of the beam polarization were fitted separately with a sum of a Gaussian and a linear function to account for the background and the yield was determined within a $\pm 3\sigma$ range around $M_n$. The background was subtracted separately for each reconstructed missing mass value. The obtained values of $A_y$ at 0.5 and 0.8 GeV are shown in Fig. 4 as function of $\theta_{c.m.}$.

The systematic uncertainty of the analyzing power contains contributions from various sources, which were all added in quadrature. An upper limit for the difference of the beam polarization $\Delta P = (P_1 - P_\perp)/2 = 0.013$ was determined from a polarization measurement using the low energy polarimeter of COSY. The analyzing powers change by a factor $(1 + \Delta P \cdot A_y)^{-1}$, thus leading to a systematic error of at most $\pm 0.008$. The systematic effect on $A_y$ due to the uncertainty of the relative luminosity $L_1/L_\perp$ does not exceed $\pm 0.003$. The total systematic error
uncertainty of $A_y$ is smaller than 20% of the statistical error and never exceeds ±0.02 at all angles. Finite–bin corrections to the final $A_y$ amount to at most 0.017, nevertheless they were applied in all $\theta$ bins.

The measured $A_y$ is almost zero at 0.8 GeV, in agreement with the predictions of the ONE+SS+Δ model. At this energy, the calculated $A_y$ is almost insensitive to the spin structure of the Δ–mechanism, which completely dominates the process and produces alone a near zero value of $A_y$. A peculiarity of the data at 0.5 GeV may be related to the short–range structure of the deuteron. Further insight into the short–range structure of the deuteron can be achieved from a measurement of the tensor analyzing power $T_{20}$ in $p\bar{d} \to (pp), S_n, n$, in preparation at ANKE, for which the theoretical predictions are more robust than for $A_y$.

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In summary, a large analyzing power is observed in the $p\bar{d} \to (pp), S_n, n$ process at 0.5 GeV and a value close to zero at 0.8 GeV, significantly differing from the behavior of $A_y$ in $pd$ backward elastic scattering. The observed disagreement of the ONE+SS+Δ model predictions with the measured $A_y$ clearly demonstrates the need to reconsider the spin structure of three–body forces related to the Δ–mechanism. Further insight into the short–range structure of the deuteron can be achieved from a measurement of the tensor analyzing power $T_{20}$.

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FIG. 4: Angular dependence of the analyzing power $A_y$ as function of the neutron polar angle $\theta_n^{\text{cm}}$ for $T_p = 0.5$ (●) and 0.8 GeV (○). The lines show predictions for $A_y$ at 0.5 GeV (solid) and 0.8 GeV (dashed) from the ONE+SS+Δ model [17, 18], with the CD–Bonn potential.
TABLE I: Experimental results of $A_y$ in $\vec{p}d \rightarrow (pp)n$. 

| $\theta_n^c$ [deg] | $(T_p = 0.5$ GeV) | $(T_p = 0.8$ GeV) |
|-------------------|-------------------|-------------------|
| 167               | $0.83 \pm 0.19 \pm 0.02$ | $0.12 \pm 0.19 \pm 0.01$ |
| 169               | $0.56 \pm 0.10 \pm 0.02$ | $0.11 \pm 0.11 \pm 0.01$ |
| 171               | $0.55 \pm 0.08 \pm 0.01$ | $0.06 \pm 0.09 \pm 0.01$ |
| 173               | $0.46 \pm 0.07 \pm 0.01$ | $0.14 \pm 0.08 \pm 0.01$ |
| 175               | $0.35 \pm 0.07 \pm 0.01$ | $0.05 \pm 0.09 \pm 0.01$ |
| 177               | $0.12 \pm 0.09 \pm 0.01$ | $0.03 \pm 0.11 \pm 0.01$ |
| 179               | $-0.07 \pm 0.18 \pm 0.01$ | $0.18 \pm 0.19 \pm 0.01$ |