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

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A measurement of the analyzing power A_y of the $\vec{p}d \to (pp) + n$ 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 diproton is experimentally demonstrated in this reaction. While at $T_p = 0.8$ GeV the measured analyzing power almost vanishes, it rises to nearly unity at $T_p = 0.5$ GeV for neutrons emitted at $\theta_n^{c.m.} = 167°$. The results are compared with a model taking into account one–nucleon exchange, single scattering, and Δ (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 less clear due to increasing contributions from meson–exchange currents (MEC) in ed interactions and theoretical uncertainties in their treatment. In photo–disintegration ($\gamma\, d \to np$) meson–exchange models fail to explain the data for energies $E_\gamma > 1$ GeV [3, 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, $pd \to dp$ [5] as well as inclusive ($dp \to pX$ [6]) and exclusive ($pd \to ppn$ [7]) deuteron disintegration turned out to be not conclusive in this respect [8, 9]. Despite sensitivity to the NN interaction at short range, the current models fail to reproduce the existing data [5–7] badly enough that no particular short range behavior is favored. It is therefore important to obtain new data under conditions that make the theoretical interpretation more transparent by suppressing less well–constrained contributions. In $pd \to (pp)n$, the diproton provides two new features [8] which are absent in the reactions with isosinglet NN pairs studied in Ref. [5–7]. *i)* The contribution from three–body forces, related to two isovector meson exchanges, in particular the excitation of Δ and N^* resonances in the intermediate state, is suppressed by the isospin factor of 3 in the amplitude of this process [10]. 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 [10–13]. *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 $\psi_{pp}(q)$ has a node at relative pp momenta $q \approx 0.4$ GeV/c [8], leading to regions in energy that are dominated by different mechanisms and that can separately test the model ingredients [14]. The recent analysis [9] of the $pd \to (pp)_{^1S_0}n$ cross section, based on a model for the $pd \to dp$ process [11], 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 [15]. A rea-

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sonable agreement with our recent data [16] is achieved. In contrast, the widely used NN potentials like the Paris [17] and especially the Reid Soft Core (RSC) potential [18] lead to a strong disagreement with the data. These potentials apparently overestimate the high–momentum components of the NN wave function $\psi_{NN}(q)$. It is crucially important to confirm the conclusion that the softer core of the CD Bonn interaction is correct by making additional measurements to demonstrate that the current reaction model is valid.

New information about this reaction can be obtained from measurements of polarization observables. Recently, the unpolarized cross section of the $pd \to (pp)n$ reaction was measured at proton beam energies $T_p = 0.6$ to 1.9 GeV in a kinematics similar to backward pd elastic scattering [16] with formation of a fast diproton in a ${}^1S_0$ state at low excitation energy ($E_{pp} < 3$ MeV). Here we report about the first measurement of the vector analyzing power A_y at $T_p = 0.5$ and 0.8 GeV of the reaction

$$\vec{p} + d \to (pp)_{{}^1S_0} + n\,, \tag{1}$$

where $(pp)_{{}^1S_0}$ 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 [9]. While at 0.5 GeV the contribution from the Δ 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 Δ mechanism. Each mechanism under consideration alone yields an almost vanishing analyzing power. Because of their interference a substantial A_y 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 [19] at the internal beam of COSY–Jülich [20] 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 $pd \to pX$. The Silicon–detector telescope (SDT) recorded recoil deuterons from small–angle elastic pd scattering. The FD [21, 22] comprises a set of three multi–wire proportional chambers (MWPCs) and a two–plane scintillation hodoscope, consisting of vertically oriented counters (8 in the first plane, 9 in the second). The acceptance of the setup (Fig. 1) allows one to detect protons from quasi–elastic scattering from $\theta_{\rm lab} = 4.5^\circ$ to 10° at $T_p = 0.5$ GeV and 0.8 GeV. The vertical acceptance corresponds to $\pm 3.5^\circ$. Protons from the breakup reaction with $E_{pp} < 3$ MeV are detected from $\theta_{\rm lab} = 0^\circ$ to 6.5° at both energies, the polar angles of the proton pairs range from $\theta_{pp}^{\rm c.m.} = 0^\circ$ to 14°. The uncertainty in E_{pp} ranges from 0.2 MeV at $E_{pp} = 0.3$ MeV to 0.3 MeV at $E_{pp} = 3$ MeV. The SDT [23] 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 $\theta_{\rm lab} = 90^\circ$ 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 deuterium cluster–jet [24] 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.

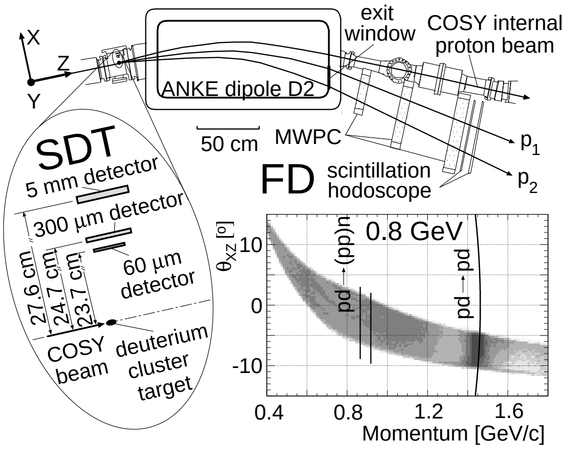

FIG. 1: Top–view of the ANKE spectrometer with the forward detector (FD) and the Silicon–detector telescope (SDT, see inset). Diprotons from the breakup reaction stem from the region indicated in the distribution of the polar angle projection θ_{xz} vs particle momentum (lower right). Protons from pd elastic scattering are distributed along the kinematical locus.

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 [22]. For two particles hitting different hodoscope counters the correlation of the measured time–of–flight (TOF) difference $\Delta t_{\rm meas}$ 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. [16]. 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 ($\cos\theta_k^{c.m.}$) in the two–proton rest frame with respect to the total momentum of the pair.

The spin–dependent yield is given by

$$Y(\theta,\phi)_{\uparrow(\downarrow)} = Y_0(\theta) \cdot [1 \;+\; P_{\uparrow(\downarrow)} \cdot A_y(\theta) \cdot \cos\phi], \tag{2}$$

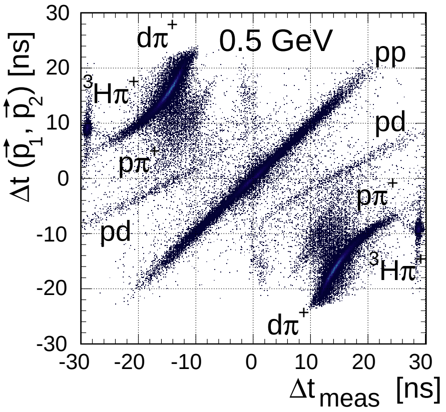

FIG. 2: Proton pairs are identified from the correlation of the TOF differences Δt_{meas} and $\Delta t(\vec{p_1},\vec{p_2})$.

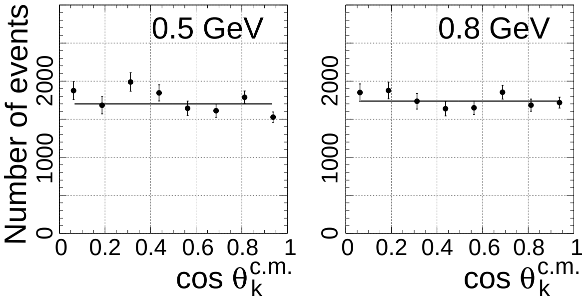

FIG. 3: Acceptance corrected distribution of events as function of $\cos\theta_k^{c.m.}$ for 0.5 GeV (left panel) and 0.8 GeV (right).

where Y_0 denotes the spin–averaged yield and $P_{\uparrow(\downarrow)}$ the absolute value of the beam polarization, oriented along the vertical y–axis. (The coordinate system is shown in Fig. 1.) Polar and azimuthal angles θ and ϕ of the breakup reaction are determined from the neutron momentum in the c.m. system, $\vec{p}_n = -(\vec{p}_1 + \vec{p}_2)$, where $\vec{p}_1$ and $\vec{p}_2$ are the proton momenta.

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 $L_\uparrow/L_\downarrow$ was achieved by either detecting single particles in the FD at $\theta_{\text{lab}} < 1^\circ$ 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 [25] 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 [26] 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

$$A_y(\theta) = \frac{\varepsilon(\theta)}{P} \cdot \frac{1}{\langle\cos\phi\rangle_\theta}\,, \tag{3}$$

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

$$\varepsilon(\theta) = \frac{N_\uparrow(\theta)/L_\uparrow - N_\downarrow(\theta)/L_\downarrow}{N_\uparrow(\theta)/L_\uparrow + N_\downarrow(\theta)/L_\downarrow}\,. \tag{4}$$

Here $N_\uparrow(\theta)/L_\uparrow$ and $N_\downarrow(\theta)/L_\downarrow$ denote the number of events in each θ bin, weighted by the relative luminosity for each orientation of the beam polarization. Events were selected for which $|\phi| \le 45^\circ$. The average $\langle\cos\phi\rangle_\theta = N_\theta^{-1}\sum_i^{N_\theta}(\cos\phi_i)_\theta$, where $N_\theta = N_\uparrow(\theta) + N_\downarrow(\theta)$, is determined from the experimental data for each θ bin. The number of counts $N_\uparrow$ and $N_\downarrow$ 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 the 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 $\theta_n^{c.m.}$ [27].

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 $\Delta P = (P_\uparrow - P_\downarrow)/2 = 0.013$ 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 ± 0.008. The systematic effect on A_y due to the uncertainty of the relative luminosity $L_\uparrow/L_\downarrow$ does not exceed ± 0.003. The total systematic 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 θ 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 Δ–mechanism dominates the process [9] and produces very little sensitivity to the spin of the projectile proton. The peculiarity of the data at 0.5 GeV is the rapid increase of A_y up to a value of 0.8 in a small angular interval from 180° to 167°. The increase of A_y with decreasing energy from 0.8 to 0.5 GeV is expected from the ONE+SS+Δ model, however, the magnitude is grossly underestimated. Different NN–interaction potentials (RSC, Paris) do not improve the description. We recall that the model [9] describes reasonably well the unpolarized cross section [16] (χ^2/d.f. = 1.8) and has no free parameters. Thus we cannot explain our results within the current theoretical framework.

In contrast, in the same angular interval the analyzing power of $pd \to dp$ [28–30] at comparable energies, 0.425, 0.68, 0.8, and 1.053 GeV, never exceeds 0.12.

Perhaps the weakest part of the current model to describe A_y at 0.5 GeV may be related to the spin structure of the Δ–mechanism, given here by the Born term of the $\pi + \rho$ meson exchange in the $NN \to \Delta N$ transition [9, 11]. A three–body force mediated by the Δ has also been applied to pd elastic scattering but at lower energies, where the Δ–contribution is much lower. While it is helpful for the cross section [31], as in the present work, the treatment of polarization observables shows no systematic improvement over ignoring the three–body force completely [13, 32, 33]. Improvements may be achieved by using a coupled channel NN–$N\Delta$ calculation [34].

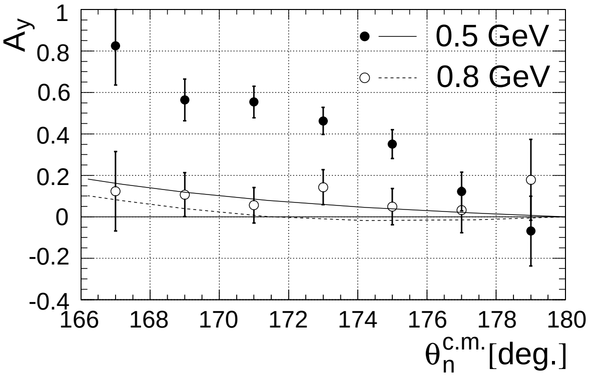

FIG. 4: Angular dependence of the analyzing power A_y as function of the neutron polar angle $\theta_n^{c.m.}$ for $T_p = 0.5$ (●) and 0.8 GeV (○). The lines show predictions for A_y at 0.5 GeV (solid) and 0.8 GeV (dashed) from the ONE + SS +Δ model [9, 14], with the CD–Bonn potential.

In summary, a large analyzing power is observed in the $\vec{p}d \to (pp)_{^1S_0}n$ process at 0.5 GeV and a value close to zero at 0.8 GeV. The large analyzing power disagrees with a ONE+SS+Δ model that does well for the cross section. One possible remedy may be to reconsider the spin structure of three–body forces related to the Δ–mechanism. Further insight into the short–range NN interaction can be achieved from measurements of additional observables in $\vec{p}\vec{d} \to (pp)_{^1S_0}n$, which are in preparation at ANKE.

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