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Analyzing powers in $d(\vec{p}, pp)n$ at intermediate and large scattering angles at 190 MeV

M. Mohammadi-Dadkan^{1,2,a}, H. R. Amir-Ahmadi¹, M. T. Bayat¹, A. Deltuva³, M. Eslami-Kalantari⁴, J. Golak⁵, N. Kalantar-Nayestanaki¹, St. Kistryn⁵, A. Kozela⁶, H. Mardanpour¹, A. A. Mehmandoost-Khajeh-dad^{2,b}, J. G. Messchendorp^{1,c}, A. Ramazani-Moghaddam-Arani⁷, R. Ramazani-Sharifabadi^{1,8}, R. Skibiński⁵, E. Stephan⁹, H. Tavakoli-Zaniani^{1,4}, H. Witała⁵

¹ KVI-CART, University of Groningen, Groningen, The Netherlands

² Department of Physics, University of Sistan and Baluchestan, Zahedan, Iran

³ Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio al. 3, 10222 Vilnius, Lithuania

⁴ Department of Physics, School of Science, Yazd University, Yazd, Iran

⁵ M. Smoluchowski Institute of Physics, Jagiellonian University, 30348 Kraków, Poland

⁶ Institute of Nuclear Physics, PAS, 31342 Kraków, Poland

⁷ Department of Physics, Faculty of Science, University of Kashan, Kashan, Iran

⁸ Department of Physics, University of Tehran, Tehran, Iran

⁹ Institute of Physics, University of Silesia, Chorzow, Poland

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Abstract Understanding of the exact nature of three-nucleon forces is the most challenging topic in the field of nuclear physics. Three-nucleon break-up reaction is a good tool to look into the underlying dynamics of the nuclear force, thanks to its rich kinematical phase space which has different levels of sensitivity to three-nucleon force effects. The recent studies on few-nucleon systems have revealed that the current nuclear force models cannot describe nucleon-deuteron scattering data accurately. In the present work, the analyzing powers of the proton-deuteron break-up reaction obtained using a 190 MeV polarized proton beam will be discussed. We present for the first time the vector analyzing powers for the kinematics in which one of the protons scatters to intermediate and large scattering angles at this energy. The results show a fairly good agreement with various theoretical predictions for both intermediate and large scattering angles of the break-up phase space.

1 Introduction

Since 1932 when Chadwick discovered the neutron as a constituent of atomic nuclei [1], efforts have been made to build a

framework for describing the interaction between nucleons. Yukawa initiated the first systematic approach for describing the nucleon-nucleon (NN) interaction in analogy to the electromagnetic interaction [2]. His formulation of the nuclear force was based on the idea that the proton and neutron are fundamental particles. Therefore, the potentials based on these models solely take the nucleons and mesons as degrees of freedom in the nuclei. Different NN potentials have been developed in the past decades. They usually carry the name of the group which developed them such as AV18 [3], CD-Bonn [4], etc. Each of these models has different parameters and they are fitted to the empirical pp and np scattering database. While these models do a great job in describing two-nucleon systems below the pion-production threshold energy, they fail to describe the systems which have more than two nucleons. There are lots of evidences for this by comparing data and theory for both the nuclear binding energies [5–7] and various scattering observables [8–11]. It has become clear that there are additional underlying dynamics, beyond the NN interaction, playing a role in the nuclear force and which are referred to as many-body force effects. We expect that the three-nucleon force (3NF) is the dominant part in the hierarchy of many-body force effects.

In the past decades, several phenomenological 3NF models such as Urbana-Illinois (UIX) [12, 13] and CD-Bonn+ Δ [14–16] have been developed based on the works by Fujita and Miyazawa [17] and Brown and Green [18] to implement

^a e-mail: m.mohammadi-dadkan@rug.nl (corresponding author)

^b e-mail: mehmandoost@phys.usb.ac.ir

^c e-mail: j.g.messchendorp@rug.nl

3NF effects in the interaction of nucleons. However, different studies have shown that the inclusion of current models of 3NF do not completely fill the gap between data and calculations. For a detailed discussion of the progress of the field at intermediate energies, see Refs. [19,20]. Ever since it was known that nucleons are composed of quarks and gluons, the nuclear force has been considered as residual color force between quarks and gluon. Due to the non-perturbative nature of QCD at low energies, it can, with the present available techniques, only be applied to the nuclear system through an effective field theory (EFT). This fundamental approach for nucleonic systems is known as chiral perturbation theory (ChPT) [21]. To take into account all the effective elements in ChPT calculations, one should extend the calculations to higher orders. The work toward higher orders of ChPT is still in progress. A detailed overview of the present state-of-the-art of the ChPT approach can be found in Refs. [22–26]. Presently, there are no results available from the ChPT calculations for comparison with the data shown in this paper. For a proton beam energy of 190 MeV, higher orders should be included in the calculations before a fair comparison can be made.

In the past decades, the elastic channel in Nd scattering has been investigated experimentally at different beam energies below the pion-production threshold. The results showed that the current 3NF models are not able to describe the discrepancy between measurements and calculations particularly at higher beam energies and at the minimum of the differential cross section as well as at backward angles [11,27]. Moreover, the inclusion of 3NFs into 3N Faddeev calculation has failed to describe the analyzing power A_y at low energies, an effect known in literature as A_y -puzzle [28,29]. The elastic channel has a limited kinematical phase space and one cannot test all the aspects of the theoretical models. To have a systematic and a detailed investigation of 3NFs, the three-body break-up channel is a suitable candidate because of its rich kinematical phase space yielding various degrees of sensitivity to the underlying nucleon-nucleon and three-nucleon forces.

A systematic investigation of 3NFs through elastic and the break-up reaction has been initiated at KVI in a common effort between the Dutch and the Polish groups since the end of the 90s by developing various experimental setups and exploiting high-quality polarized beams [27,30–34]. BINA (big instrument for nuclear-polarization analysis) is the latest experimental setup which was exploited at KVI for few-nucleon scattering experiments. This detection system is capable of measuring the energy and the scattering angles of all the reaction yields of three and four-body final states in coincidence. A series of experiments has been conducted using BINA to study the deuteron break-up channel using polarized proton and deuteron beams in a wide range of energies between 50 and 190 MeV/nucleon [35–39]. In this

article, we present the measurements of the analyzing powers of the proton-deuteron break-up reaction obtained with a proton-beam energy of 190 MeV. A specific part of the phase space of this experiment has already been published [40]. In this work, we focused on the break-up kinematics in which one proton scatters to forward angles ($\theta_1 < 32^\circ$) and the other to backward angles ($\theta_2 > 40^\circ$). The experimental setup will be described in Sect. 2. Then, the analysis method and the results will be presented.

2 Experimental setup

The present experiment was conducted utilizing the AGOR (Accélérateur Groningen-ORsay) cyclotron at KVI delivering a high-quality polarized-proton beam of 190 MeV. For details about the experimental setup, see Ref. [35]. BINA, is a specially designed 4π detection system with which 3NF effects could be studied through the three-body and four-body elastic as well as break-up reactions. The detection system consists of different components which make it capable of measuring energies up to 140 MeV per nucleon, scattering angles between 10° – 160° , and almost a full coverage of azimuthal angles. There are two features that make BINA unique among other detection systems in the field of few-nucleon scattering:

- Detection of all the charged particles in the final-state of the three-body and the four-body reactions in coincidence;
- The almost 4π angular coverage which can probe a large part of the phase space of the break-up reactions.

In general, BINA has two main parts, the forward-wall and the backward-ball. The left part of Fig. 1 illustrates different parts of BINA. The forward-wall consists of a cylindrically-shaped array of scintillators (E -detectors) to measure the energy of charged particles, a MWPC to measure their scattering angles, and a vertical array of ΔE -detectors that is used in combination with E -detectors for particle identification. The forward-wall covers angles which are in the range of $10^\circ < \theta < 35^\circ$. The backward-ball is a ball-shape scattering chamber which consists of 149 pyramid-shaped plastic scintillators. The geometrical design of the backward-ball and its building blocks are similar to the classic soccer ball. The position of each backward-ball scintillator is labeled with a specific θ and ϕ in the laboratory coordinate system. The backward-ball can measure the scattering angles of the particles with a precision of $\pm 10^\circ$. The right panels of Fig. 1 demonstrate the structure of the backward-ball and the positioning of the detector elements. This part of BINA is capable of measuring the energy and the scattering angles of the particles in the range of $35^\circ < \theta < 160^\circ$ except where the target

Fig. 1 The left panel illustrates the structure and the components of BINA (big instrument for nuclear-polarization analysis) together with the angular coverage of each part. The right panel shows the partly-assembled backward-ball (top figure) and the definition of the angles of typical detectors (bottom figure). The centroid of each ball detector is considered as the angular position of that detector; see the black points in the bottom-right figure

holder is attached to the scattering chamber. Therefore, there are no detectors at the part of the phase space with polar and azimuthal angles in the range of $80^\circ < \theta < 120^\circ$ and $70^\circ < \phi < 110^\circ$, respectively. Also, at the angular range of $80^\circ < \theta < 100^\circ$, the scattered protons partially lose their energies in the target-holder ring. Due to the complicated procedure for the energy correction for these protons, we decided to leave out these detectors from the analysis. The detectors which are located at $\theta > 140^\circ$ are excluded from this analysis as well because the expected energy of the break-up protons is lower than the threshold of these detectors. The parts that were used in the analysis cover scattering angles within $40^\circ < \theta < 80^\circ$ and $100^\circ < \theta < 140^\circ$. In the present analysis, we obtained the analyzing powers of the proton-deuteron break-up reaction for the kinematics in which one proton was registered in the forward-wall and the other one in the backward-ball.

3 Analysis method

In the proton-deuteron break-up reaction, there are three particles in the final state, two protons and one neutron. From the kinematic point of view, there are 9 variables (θ_i , ϕ_i , E_i) for this reaction channel which can be measured. Applying energy and momenta conservation reduces the number of degrees of freedom to 5. It is, therefore, sufficient to measure 5 of the 9 variables to have all the information of the reaction. BINA is able to measure the energy and the scattering angles of two protons in coincidence which provides an extra redundancy of one degree of freedom. Conventionally, in the three-body break-up reaction, each kinematical con-

Fig. 2 The scattering diagram of a three-body final-state reaction. $\vec{k}_1$ and $\vec{k}_2$ are the momentum of the two detected particles with scattering angles θ_1 and θ_2 , respectively. ϕ_2 is the angle between the projection of $\vec{k}_2$ on the x - y plane and positive direction of the x -axis. $\hat{s}$ denotes the direction of spin of the projectile. ϕ is the angle between the projection of $\hat{s}$ on the x - y plane and the y -axis. β is the angle between the spin of the projectile and its momentum direction (z -axis). In the present experiment, the polarization of beam is perpendicular to the direction of the beam momentum and, therefore $\beta = 90^\circ$

figuration is defined with $(\theta_1, \theta_2, \phi_{12} = |\phi_2 - \phi_1|)$ which represents the polar scattering angles of protons 1 and 2 and the relative azimuthal angle between them. Figure 2 shows the definition of the scattering angles of two protons in the p - d break-up reaction. There are two conventions for defining the y -axis [41]. In this paper, we use the asymmetric choice for the azimuthal angles, where $\vec{k}_1$ lies in the xz plane, and therefore $\phi_1 = 0$, see Fig. 2. Here, $\vec{k}_1$ is the momentum of the outgoing proton which scattered to smaller polar angle θ . For each kinematical configuration, the energy correlation of

Fig. 3 The kinematically allowed relation of the energies of the two protons of the three-body break-up reaction, so called S -curve, for $(\theta_1 = 25^\circ, \theta_2 = 45^\circ, \phi_{12} = 160^\circ)$ along with the experimental data. In this analysis, we took the minimum of E_2 as the starting point of S -value. The protons which have energies $E_1 > 140$ MeV punch through the E -detectors of the forward-wall and deposit part of their energies in the detectors resulting in a kink in the spectrum. The dashed lines illustrate the definition of a typical S -bin for $S = 127$ MeV. The events within each S -bin were used to extract the asymmetry distributions and the analyzing powers

the two protons is referred to as the S -curve. By employing the S -curve, a variable S is defined as an arc length of the curve with a starting point at the minimum energy of one of the protons. In the present work, we used a convention in which the starting point of S is the minimum value of E_2 and it increases counter-clockwise as it is shown in Fig. 3. Here, E_1 and E_2 correspond to k_1 and k_2 , respectively. Traditionally, the three-body break-up observables are presented as a function of S -value.

To investigate spin effects in the nuclear force, one should measure various spin-related observables such as analyzing powers. The polarized beam (or target) imposes an asymmetry on the cross section of the break-up reaction. In this article, we present a study of the vector analyzing powers, A_x and A_y , in the proton-deuteron break-up reaction. A_x is odd and A_y is even under the parity inversion. Here, the parity inversion corresponds to changing the sign of the azimuthal scattering angle of the two outgoing protons. By exploiting the formulation taken from Ref. [41] for spin- $\frac{1}{2}$ protons, the following expressions can be derived for two parity modes:

$$\gamma^+(\xi, \phi) = \frac{N_p^\uparrow - N_p^\downarrow}{N_p^\downarrow p_z^\uparrow - N_p^\uparrow p_z^\downarrow} = A_y \cos \phi - A_x \sin \phi, \quad (1)$$

$$\gamma^-(\xi, \phi) = \frac{N_m^\uparrow - N_m^\downarrow}{N_m^\downarrow p_z^\uparrow - N_m^\uparrow p_z^\downarrow} = A_y \cos \phi + A_x \sin \phi. \quad (2)$$

where $\gamma^+(\xi, \phi)$ and $\gamma^-(\xi, \phi)$ are the asymmetry terms for two parity modes and ξ represents any appropriate set of kine-

matical variables. $N_p^\uparrow$ ($N_p^\downarrow$) are the number of events for up (down) polarization modes of the (ϕ_1, ϕ_2) setup. Similarly, $N_m^\uparrow$ ($N_m^\downarrow$) are the number of events for up (down) polarization modes of the $(-\phi_1, -\phi_2)$ setup. $p_z^\uparrow$ and $p_z^\downarrow$ are the polarization degrees of up and down modes, respectively. A_x and A_y are the two components of the vector analyzing power and ϕ is the azimuthal angle of the reaction plane. Two asymmetry components can be constructed from $\gamma^+(\phi)$ and $\gamma^-(\phi)$ to extract A_x and A_y independently:

$$g(\xi, \phi) = \frac{\gamma^-(\xi, \phi) - \gamma^+(\xi, \phi)}{2} = A_x \sin \phi, \quad (3)$$

$$h(\xi, \phi) = \frac{\gamma^-(\xi, \phi) + \gamma^+(\xi, \phi)}{2} = A_y \cos \phi. \quad (4)$$

After the energy calibration of the forward-wall detectors [35], each of the backward-ball detectors was calibrated using the energy information of a break-up proton (1) registered in the forward-wall in coincidence with the other proton (2) arriving at one of the backward-ball detectors. Further, the protons with energies larger than 140 MeV ($E_1 > 140$ MeV) punch through the E -detectors of the forward-wall and consequently deposit part of their energies in the detectors, see Fig. 3. The points corresponding to the region of punch through are excluded in the final spectrum. Events were selected for each kinematic of $(\theta_1 \pm 2.5^\circ, \theta_2 \pm 10^\circ, \phi_{12} \pm 10^\circ)$. The S -curve is divided into 15 equally-sized bins and the events within each S -bin are used to reconstruct the missing-mass of the neutron. Figure 3 shows the selected events for configuration

Fig. 4 The reconstructed neutron missing-mass for one of the S -bins. The peak position of the spectrum which is around the expected missing-mass of neutron indicates that the detectors are well calibrated. The interval of $\pm 3\sigma$ was used to obtain the number of break-up events under the peak after subtracting the background. The background was estimated using the sensitive non-linear iterative peak clipping algorithm (red line). The green histogram shows the missing-mass spectrum after background subtraction. The vertical black dash lines illustrate the integration window

of $(\theta_1, \theta_2, \phi_{12}) = (25^\circ, 45^\circ, 160^\circ)$ together with the corresponding S -curve. The number of counts was obtained for each spin state and parity mode using the corresponding missing-mass spectrum after subtracting the background, see Fig. 4. The background mainly stems from uncorrelated protons from two different reactions, either elastically scattered or from a break-up reaction, and accepted by the hardware trigger as candidate break-up events. Figure 4 shows the missing-mass spectrum for the S -bin shown in Fig. 3. The cut on the S -curve induces an artificial correlation between the two time-uncorrelated hits that mainly stem from two protons of the elastic proton-deuteron scattering process and of the break-up reaction. As a consequence, a peaking structure of the background is observed in the missing-mass spectrum for the selected S -bin. The location of this peak depends upon S and is well understood. To account for the background including the one from the elastic channel, we used an algorithm which was developed to estimate background of gamma-rays spectrum [42]. This method allows to separate continuous background from peaks, based on a sensitive non-linear iterative peak clipping algorithm. The algorithm was applied to each neutron missing-mass spectrum to estimate the background shape using an 8th-order polynomial function. The main motivation for employing this method was the complicated shape of the background for each detector and spin state. Figure 4 shows the estimated background shape for a typical missing-mass spectrum. To find the peak position of the missing-mass spectrum, we used an algorithm for peak searching [43]. It allows to automatically identify the peaks in a spectrum in the presence of the continuous background and statistical fluctuations. The algorithm is based on smoothed second differences that are compared to its standard deviations. Therefore, it is necessary to pass a value for the width of the peak (σ) to the peak searching function. The algorithm is selective to the peaks with a given σ . Here, we fixed σ to 7 MeV/ c^2 which is equal to the expected width of the peak in the missing-mass spectrum. Also, to have a consistent counting of events in the four missing-mass spectra, spin up and down and two parity modes, the peak position of one of the spectra was used for the other spectra. The number of counts was obtained by including the events which were located $\pm 3\sigma$ of the peak position. To extract the analyzing powers from Eqs. 3 and 4, the number of counts for each polarization and parity modes are extracted and normalized with the integrated charge from the Faraday cup. The $g(\xi, \phi)$ and $h(\xi, \phi)$ are constructed using the normalized counts as a function of ϕ . To measure the values of analyzing powers, the functions $A \sin \phi + B$ and $C \cos \phi + D$ are fitted to $g(\xi, \phi)$ and $h(\xi, \phi)$, respectively. The parameters A and C represent the analyzing powers A_x and A_y , respectively. The parameters B and D are free parameters to correct for a possible offset of the charge measurement and other normalization factors which we missed during the analysis. Figure 5

Fig. 5 The constructed asymmetry distributions for A_x (top panel) and A_y (bottom panel) for the kinematics $(25^\circ, 45^\circ, 160^\circ)$ and $S = 76$ MeV. The quality of fit and the obtained values of the analyzing powers are shown at the top left of each panel. The statistical errors are obtained using the number of counts before subtracting the background

shows the results of the fits for $g(\xi, \phi)$ and $h(\xi, \phi)$ for one of the analyzed configurations. The quality of the fits for all configurations has been found to be good and an average $\chi^2/\text{ndf} \sim 1$ was obtained.

4 Results and discussion

The proton-deuteron break-up reaction has a rich kinematical phase space. In the present work, we measured the vector analyzing powers for the kinematics in which one proton scatters to forward angles ($\theta_1 < 32^\circ$) and the other to intermediate ($\theta_2 = 45^\circ$) and large ($\theta_2 = 134^\circ$) scattering angles. Due to the low angular resolution in the backward ball, all the theoretical calculations have been averaged over the experimental angular bins. For the averaging, we used the theoretical cross sections and solid angles as weighting factors. For each non-coplanar (coplanar) kinematic, we exploited 125 (75) sub-configurations with a 1° step in θ_1 , 4° step in θ_2 , and 2° step in ϕ_{12} . Figure 6 shows a comparison between

Fig. 6 Comparison of the theoretical predictions (AV18) at the center of the angular bins (red line) and averaged over the angular bins (black line) for some kinematical configurations. The gray lines are the sub-

configurations which are within the detector acceptance and are used to perform averaging

the results of the averaging and the central values for some configurations. Even though the averaging does not show a significant deviation from the calculation based on the central value of the angle of the bin for most kinematics, we performed this procedure for all of them to have a consistent comparison between data and theory.

The measured analyzing powers are presented in Figs. 7, 8, 9 and 10 for a set of configurations at intermediate ($\theta_2 = 45^\circ$) and large ($\theta_2 = 134^\circ$) scattering angles, and compared with Faddeev calculations using various NN and NN+3NF potentials. The red dash and solid lines represent the predictions of CD-Bonn and CD-Bonn+ Δ [15, 16, 44], respectively. The blue dash and solid lines are the predictions of AV18 and AV18+UIX [45–47], respectively. The results of all the calculations are averaged over the experimental angular bins. The Coulomb effect is negligible in the analyzing powers [40]. Therefore, the results of CD-Bonn+ Δ +Coulomb are not included for ease of comparison with the other calculation. The cyan band in each figure represents the systematic uncertainty which consists of three parts. The polarization of the beam was measured by analyzing the elastic proton-deuteron channel with BINA and by using the measurements of the In-Beam Polarimeter (IBP). Typically, the beam polarization varied gradually between 0.5 and 0.7 during the course of the experiment. The associated uncertainties of the polarization values are 6% statistical and 3% systematic [35]. This uncertainty in the polarization causes a systematic error of $\sigma_{pol} \sim 7\%$ in the analyzing power measurement. Another source of systematic uncertainty is identified

to be from residual and unknown asymmetries caused by efficiency variations between the up and down polarization states of the beam, error in charge normalization, etc. All of these will result in a “wrong” model presented in Eqs. 3 and 4. This source of systematic uncertainty was investigated through comparing the results with and without the free parameters of the fitting functions on the asymmetry distributions. We obtained a systematic uncertainty $\sigma_{asymm} \sim 0\text{--}0.1$ for A_x and $\sigma_{asymm} \sim 0\text{--}0.12$ for A_y . The third source of the systematic uncertainty comes from the shape of the background. This part of the systematic uncertainty consists of two components. The first one is the difference between results of full and limited ranges of the background estimation, see Fig. 4. To do this, we keep the polynomial order to be the same but decrease the range of the background estimation. The error from this part was estimated to be in the range of $\sigma_{bg1} \sim 0\text{--}0.04$ for both A_x and A_y . The other component of the error in the shape of the background was obtained using the difference between the results of the background estimation using two different polynomial orders (6 and 8) but keeping the full range. The error from this source was estimated to be in the range of $\sigma_{bg2} \sim 0\text{--}0.04$. The total systematic uncertainty was obtained by a quadratic sum of the four sources of systematic errors, assuming them to be independent. The total systematic uncertainty varies between $0\text{--}0.16$ for A_x and $0\text{--}0.2$ for A_y depending on the configuration. We decided only to present data for which the total systematic uncertainty is less than 0.08 to have a meaningful comparison with the cal-

Fig. 7 Experimental vector analyzing power A_x for $\theta_2 = 45^\circ$ and for various combinations of (θ_1, ϕ_{12}) , as indicated in each panel. Data are compared with predictions of various theoretical approaches based on pairwise NN interactions alone NN (dash lines) as well as with 3NF

included NN+3NF (solid lines); see the legend. The error bars represent statistical uncertainties. The cyan band depicts the systematic uncertainty (2σ) which stems from different sources; see the text

Fig. 8 Same as Fig. 7 but for A_y instead of A_x

culations. This operation only excluded a small fraction of the data points.

Figures 7, 8, 9 and 10 show the results for $\theta_2 = 45^\circ$ and 134° and different combinations of θ_1 and ϕ_{12} . For some

of the configurations where $\theta_2 = 45^\circ$, the data points at $S > 100$ MeV are not presented because we were not able to subtract the background of the uncorrelated elastic break-up events unambiguously. Also, for some S -values in which

Fig. 9 Same as Fig. 7 but for $\theta_2 = 134^\circ$

Fig. 10 Same as Fig. 9 but for A_y instead of A_x

the peak-searching algorithm could not find a peak around the expected missing-mass of neutron and therefore, we are not presenting any data points. For the case of $\theta_2 = 134^\circ$, the data points of the lower values of S ($S < 40$ MeV) are not presented because the S -curve overlapped with the energy threshold of the ball detectors and we could not separate the signal from the noise. Note that our measured values for A_x for coplanar configurations ($\phi_{12} = 180^\circ$) are compatible

with zero. This is consistent with expectations based on parity conservation and, therefore, shows that our analysis method is reliable. The present results correspond to the relatively large values of relative energy, $E_{rel} > 40$ MeV, between two final-state protons. Aside from the slight disagreements for the smaller θ_1 (20° and 25°) and ϕ_{12} (140°), the results reveal a fairly good agreement between data and the theoretical predictions for A_x and A_y , confirming the previous report

on a part of the phase space of this experiment in which two protons scatter to the forward angles with large azimuthal opening angle [40]. It means that the theoretical models provide a good description of analyzing powers for the cases with a large relative energy while they fail to describe the data for lower values of relative energy in proton-deuteron break-up reaction [40].

For some configurations in which $\theta_2 = 134^\circ$, the two 3NF models provide different values of A_y at the intermediate values of S . Considering the statistical and systematic uncertainties, our measurement cannot differentiate between these models.

5 Summary and conclusion

In this article, a study of the vector analyzing powers in the proton-deuteron break-up reaction with an incident polarized proton-beam energy of 190 MeV impinging on a liquid deuterium target is presented. The data were obtained exploiting the almost 4π detection system BINA. The focus was on the part of the phase space at which one of the protons scattered to intermediate and large polar angles. The backward-ball of the BINA is used for the first time to extract break-up observables in coincidence with the forward-wall. We presented the vector analyzing powers, A_x and A_y , for a set of kinematical configurations in which one of the protons scatters to the angles of $\theta_2 = 45^\circ$ and $\theta_2 = 134^\circ$ and the other to forward angles ($12^\circ < \theta_1 < 32^\circ$). This part of the break-up phase space at this beam energy is presented for the first time. At the large scattering angle of the second proton, $\theta_2 = 134^\circ$, the theoretical predictions are in fair agreement with the data. However, the two 3NF models provide different values of analyzing powers at some kinematics. With the precision of the present experiment, one can, however, not distinguish between these models. The 3NF effects are expected to be small at the configurations with $\theta_2 = 45^\circ$ and at large azimuthal opening angles ϕ_{12} . For these configurations the theoretical predictions are also in good agreement with the data. The results presented here mainly correspond to larger values of relative energy between two final-state protons, and the agreement between data and calculations are consistent with earlier measurements for this range of relative energy. On the other hand, a significant disagreement between data and theoretical predictions was reported at this energy for the configurations in which the relative energy is smaller than 10 MeV [40]. The physics behind this discrepancy is not clear yet. A similar, but less pronounced, discrepancy has been observed in the proton-deuteron break-up reaction measured at a proton beam energy of 130 MeV [48]. Further investigation of all parts of the break-up phase space at different beam energies is needed to have a complete picture

of nuclear forces and its dependence on different underlying dynamics.

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