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Analyzing powers of the proton-deuteron break-up reaction at large proton scattering angles measured with BINA at 135 MeV

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Analyzing powers of the proton-deuteron break-up reaction at large proton scattering angles measured with BINA at 135 MeV

PhD thesis

to obtain the degree of PhD at the
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on the authority of the
Rector Magnificus Prof. C. Wijmenga
and in accordance with
the decision by the College of Deans.

This thesis will be defended in public on

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To my dear wife, *Maryam*
and my dear son, *Shayan*

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Chapter 1

Introduction

This chapter starts with a very general review of two and three-nucleon force (2NF and 3NF) models with a brief description of the deficiencies of 2NF models in three-nucleon (3N) systems. Then 3NF force studies in 3N systems with a comparison of data with theoretical predictions based on these models are discussed. With this, we motivate the work presented in this thesis. Finally, the outline of this thesis is presented.

1.1 2NF and 3NF models

The investigation of the forces acting between nucleons, protons and neutrons, is one of the most fundamental issues in the field of nuclear physics. In 1935, Yukawa [1] proposed that the pair-wise nucleon-nucleon (NN) force can be explained by an exchange of a particle. Based on the separation of two nucleons this particle can be a massive meson. One of the basic properties of two-nucleon potentials was found based on the exchange of various mesons by Taketani [2]. In this picture, the central component of the NN potential could be divided into three regions: a long-range part at a distance of about 2 fm between the two nucleons, an intermediate-range part between 0.7 and 2 fm and a repulsive short-range part below 0.7 fm, as shown schematically in Fig. 1.1. The long-range part is described by the exchange of the lightest meson, the pion. The intermediate range is governed by a two-pion (σ -meson) exchange and for the short-range heavier mesons (ρ and ω -mesons) would contribute to the interaction. At present, a number of phenomenological two-nucleon (2N) models based on meson exchanges have been considered [3–7] and all of them describe experimental observables in 2N systems with extreme accuracy below the pion-production threshold.

The application of these high-precision 2N potentials to the 3N system gives a less satisfying result. It is well known that the binding energy (BE) of the triton is significantly

Figure 1.1: Typical nuclear potential (V) and its different parts in the meson-exchange picture as a function of distance (r) between two nucleons. The long-range part is governed by one-pion exchange, the middle-range part by two-pion (σ -meson) exchange and the short-range part by the exchange of heavy mesons.

Figure 1.2: Binding energies of the ground and excited states of light nuclei. The experimental results are compared with the calculations using the Green's function Monte Carlo method based on the Argonne-V18 NN interaction (AV18) and the Illinois-7 (IL7) 3NF. Figure adapted from Ref. [8].

underestimated by these potentials [9]. A similar underbinding occurs for other light nuclei as well [8]; see Fig. 1.2. Here, 2NFs are not sufficient to describe the nuclei accurately. For heavier nuclei, the deviations between the predictions by theory and measured binding energies become even larger. Besides the discrepancies observed in BEs, also deficiencies between calculations and data were observed in cross section and spin observables in three-nucleon scattering processes. An example is the so-called A_y puzzle [10]. Here, rigorous 3N calculations fail to describe the experimentally measured vector analyzing power, A_y , in the Nd scattering reaction at low energies. Similar anomalies were observed for cross section data in the Nd break-up reaction in the space-star configuration [11]. In this configuration, the three outgoing nucleons in the center-of-mass frame have equal energies and are separated by 120° in a plane perpendicular to the beam.

Attempts have been made to understand these discrepancies with the inclusion of a 3NF which is a force between three nucleons that cannot be reduced into pair-wise NN interactions. Fujita and Miyazawa [12] were the first ones who developed a 3NF. In their force all three nucleons interact via a two-pion exchange (TPE) with an intermediate Δ excitation of one of the nucleons as shown in Fig. 1.3.

Apart from the phenomenological approaches, Chiral Perturbation Theory (ChPT) [13] is another framework for the construction of nuclear potentials. ChPT, which is a low-energy approximation of Quantum Chromodynamics (QCD), treats nucleons and pions as the effective degrees of freedom. In the 3N systems, graphs corresponding to 3NFs appear naturally. The first non-vanishing 3NF term is the Next-to-Next-to-Leading Order (NNLO). For more details about the construction of the NN potential within ChPT approach at NNLO see Ref. [14].

1.2 Motivation

The underlying dynamics of 3NF forces is best studied through measurements of differential cross sections and polarization observables (vector and tensor analyzing powers, spin-correlation coefficients and polarization transfer coefficients) for elastic Nd scattering and for break-up of the deuteron in its collision with a nucleon. In the past three decades, many measurements have been carried out at KVI and at other laboratories, like RIKEN, IUCF and RCNP, to obtain high-precision and rich data sets. An overview can be found in recent review articles [15–17].

As a conclusion for Nd elastic scattering measurements at intermediate energies, the importance of 3NFs in the description of the differential cross section at center-of-mass angles, θ_{cm} , at which it is the smallest is notable and grows with increasing bombarding energy [18–30]. For example, Fig. 1.4 shows the results of independent measurements of the differential cross sections as a function of θ_{cm} . For the polarization observables, the discrepancy between the measured data and theory predictions with currently available 3NF models demonstrates that spin-dependent parts of the 3NFs are not completely

Figure 1.3: A schematic representation of a three-nucleon force. The diagram shows the exchange of two pions (π) among three nucleons (N) with a transition of one of the nucleons into an excited state (X). In the Fujita-Miyazawa force, the excited state is a Δ excitation.

understood [19–21, 25, 31–37]. For the description of the cross section for the break-up reactions similar conclusions can be drawn. However, a number of evidences on deviations between the measured analyzing powers and theory predictions were published in Refs. [26, 37–40] even if a 3NF is included in the calculations.

A break-up reaction has a very rich phase space in comparison to the elastic reaction for the investigations of the behavior of 3NF effects. Considering not all the phase space has been analysed so-far, we decided to analyze part of the data of the experiment which was performed in 2006 to study the $\vec{p}d$ break-up reaction at 135 MeV polarized proton beam energy at KVI using BINA, **B**ig **I**nstrument for **N**uclear-polarization **A**nalysis. Figures 1.5 compare the analyzing powers of the earlier analysis [35] of this reaction for $(\theta_1, \theta_2) = (28^\circ, 28^\circ)$ and $(16^\circ, 16^\circ)$ for three different values of ϕ_{12} with some of the theoretical predictions. The dark blue band in the figure, shows the theoretical predictions of various existing NN potentials, namely CDB, Nijmegen-I, Nijmegen-II and AV18 while the red band represents the same NN potentials including the TM³ 3NF. The dotted black, green solid, black solid and the dashed black lines represent predictions of the Faddeev calculations using AV18 potential including the UrbanaIX (UIX) 3NF, CDB+ Δ (3NF), CDB+ Δ +Coulomb and CDB+Relativistic potential, respectively. The errors are statistical and the cyan band depicts the systematic uncertainties. This figure indicates that there is a discrepancy between the data and the theoretical calculations in the analyzing powers, specially for low relative azimuthal scattering angles. In this thesis, we extended the earlier analysis [35] that was done for kinematical configurations at small proton scattering angles (less than 30°) by analyzing configurations at which one of the final-state protons scatters towards the backward part of BINA, namely for polar angles larger than 30° .

Figure 1.4: Differential cross sections as a function of the center-of-mass angle, θ_{cm} . The curves shown are calculations based solely on NN potentials (black band), calculations from AV18+UIX (solid line) and NN+TM' (gray band). The data points from KVI [21] are plotted as open squares. Data are taken from Refs. [22] (135 MeV), [30] (146 MeV), [28] (155 MeV), [29] (198 MeV) and [41] (181 MeV). Figure adapted from [21].

Figure 1.5: The comparison of the results of the analyzing powers measurements for a few selected configurations with several theoretical predictions. The blue band shows the calculations of various existing NN potential, namely CDB, Nijmegen-I, Nijmegen-II and AV18. The red band shows the same NN potentials including the TM' 3NF. The dotted black, green solid, black solid and the dashed black lines represent predictions of the Faddeev calculations using AV18 potential including the UIX 3NF, CDB+ Δ (3NF), CDB+ Δ +Coulomb and CDB+Relativistic potential, respectively. The errors are statistical and the cyan band depicts the systematic uncertainties.

1.3 Outline of the thesis

In the following chapter, a brief theoretical background is given. Two and three-nucleon potential models, three-body scattering formalism, kinematics and observables (cross section and analyzing powers) of the break-up reaction are explained. Chapter 3 covers the experimental setup of this work. A brief description is given on the production of a polarized proton beam and I introduce the most important components of the experimental setup, especially, the backward part, of the BINA detection system are presented. The details of the data analysis for the $\vec{p}d$ break-up reaction with a 135 MeV polarized proton beam are presented in chapter 4. This chapter is mainly devoted to the energy calibration of the detectors and the extraction of analyzing powers. Chapter 5 contains the experimental results and a comparison is made with theoretical predictions. Finally, the summary, conclusions and outlook of this work are presented in chapter 6.

Chapter 2

Theoretical background

The basic theoretical tools to describe the scattering process in the three-body system will be discussed in this chapter. First, an overview for the description of the nuclear force in two and three-nucleon systems is given. This is followed by a discussion of three-body scattering using the Faddeev formalism which is the exact treatment of the three-nucleon scattering problem. Next, the kinematics of a break-up reaction is described and the last section of this chapter introduces the observables of the break-up reaction which are the objective of the presented work.

2.1 Two-nucleon force

In 1935, Yukawa proposed that the force between two nucleons is mediated by the exchange of pions [1]. On the basis of Yukawa's idea, the first generation of the two-nucleon potential models like Hamada-Johnston [42], Yale [43], Reid [44], Paris [45, 46], Nijmegen [47], Bonn [48], Urbana [49], and Argonne [50] were created. In these potentials the force between two nucleons was described, in the leading order, by one-pion exchange. This implies that these 2N potentials only describe the interaction of the two nucleons in isolation. A modification is needed in the case when the nucleons are bound in a nucleus. There are now five modern two-nucleon potentials, which we refer to as realistic potentials: Argonne-V18 [4], charge-dependent (CD) Bonn [3], Reid-93 [6], Nijmegen-I [6] and Nijmegen-II [6]. These potentials are in excellent agreement with NN scattering data below 350 MeV. All five potentials use a local one-pion exchange potential (OPEP) for the long-range part of the NN potential, while they differ in their short and intermediate range parts which are generally non-local. The usual form of the OPEP [44, 51] can be written as

$$V_{OPEP} = \frac{1}{3} g^2 \left(\frac{\mu \hbar}{2Mc} \right)^2 (\vec{\tau}_i \cdot \vec{\tau}_j) \left[\vec{\sigma}_i \cdot \vec{\sigma}_j + S_{ij} \left(1 + \frac{3}{\mu r} + \frac{3}{(\mu r)^2} \right) \right] \frac{e^{-\mu r}}{r}, \quad (2.1)$$

where $S_{ij} = 3(\vec{\sigma}_i \cdot \vec{r})(\vec{\sigma}_j \cdot \vec{r}) - \vec{\sigma}_i \cdot \vec{\sigma}_j$, $\mu = mc/\hbar$ with the pion mass m , g^2 is the pion-nucleon coupling constant determined by data, $M/2$ refers to the reduced mass of nucleons i and j , the Pauli matrices $\vec{\sigma}$ ($\vec{\tau}$) operate in spin (isospin) space on nucleon i or j and $r = |\vec{r}|$ corresponds to the distance between the nucleons. In the following, the realistic potentials are briefly described.

The Argonne-V18 [4] potential contains, in addition to the long-range OPEP, the electromagnetic interaction and short and intermediate-range parts that are phenomenologically implemented. This potential has 14 operators in its charge-independent part which are taken from Argonne-V14 [50], 3 operators for the charge-dependent part and one charge-asymmetric operator. The Argonne-V18 potential is fitted to the Nijmegen pp and np scattering database, to parameters of low-energy nn scattering and to the deuteron binding energy. It contains 40 adjustable parameters to fit 4301 pp and np data in the range 0-350 MeV and the fit minimization resulted in $\chi^2/datum = 1.09$.

The CD-Bonn (CDB) potential [3] is non-local or momentum-dependent and a charge-dependent version of its earlier version of Bonn [3, 48]. The long-range part of this potential is a relativistic OPEP and in the other parts of the potential, the exchange of heavier mesons, like $\rho(770 \text{ MeV})$ and $\omega(782 \text{ MeV})$ is considered [52]. The potential can fit 2932 data points below 350 MeV from pp scattering with χ^2 per datum of 1.01 and it gives a very good fit to the 3058 np experimental data points with $\chi^2/datum = 1.02$. It also uses the deuteron binding energy (2.224575 MeV) in the fit [52]. In this work, we primarily used the CDB potential to compare with our data.

Nijmegen-I and Nijmegen-II [6] potentials are the latest update of the Nijmegen-78 potential [53]. These potentials use the exchange of heavier mesons ρ and ω for their short-range part. Whereas the Nijmegen-II is a totally local potential, Nijmegen-I has some momentum-dependent terms. Nijmegen-I with 41 parameters and Nijmegen-II with 47 parameters give a $\chi^2/datum = 1.03$ using all pp and np scattering data.

The Reid-93 [6] potential is constructed based on the original Reid-93 [44] potential which was not able to describe properly the much more accurate np data. The Reid-93 potential, instead of using meson-exchange for short and intermediate ranges, employs a phenomenological parametrization with 50 parameters. The quality of the fit to data for this potential gives a $\chi^2/datum = 1.03$.

2.2 Three-nucleon force models

The calculations based only on 2NFs are unable to describe the experimental results. For example, none of the realistic potentials can reproduce the binding energy of ${}^3\text{H}$. For these potentials the corresponding values of the binding energy in MeV for ${}^3\text{H}$ are 7.623 (Argonne-V18), 8.012 (CDB), 7.736 (Nijmegen-I) and 7.654 (Nijmegen-II), whereas the experimental value is 8.48 MeV [9]. The most promising and widely-investigated solution has emerged in the form of a three-nucleon force (3NF). The first 3NF was proposed by Fujita and Miyazawa [12] based on two-pion exchange, during which one of the nucleons gets excited to a Δ resonance. In this section, we briefly summarize the most popular 3NF models which are used to study few-nucleon systems.

One of the modern 3NF models is the Tucson-Melbourne (TM) [54] which contains three parts originating from exchanges of $\pi\pi$, $\pi\rho$ and $\rho\rho$ mesons. The $\pi\pi$ part, which is the main ingredient of the TM force due to the long-range contribution, is constricted based on πN scattering amplitude with the pions off their mass shell, i.e. $E^2 \neq p^2 + m^2$, where m is the pion mass. The $\pi\rho$ and $\rho\rho$ components are derived in Ref. [55] for the short-range contributions. The TM-99 (or TM') three-nucleon force is a modification of the TM model which excludes the short-range part to make it compatible with chiral symmetry [56]. This model also has one parameter to regularize its high-momentum behavior. The value of this parameter is adjusted for each specific combination of realistic NN potential and TM-99 3NF.

The Urbana-IX (UIX) [57] 3NF model was introduced for exclusive use with the Argonne-V18 two-nucleon potential. It contains two terms: a two-pion exchange term fitted so that the combination Argonne-V18+UIX reproduce the ${}^3\text{H}$ binding energy and a phenomenological short-range repulsive term adjusted to match the density of nucleon matter [57].

Chiral Perturbation Theory (ChPT) is another approach to calculate the 3NF. Weinberg [58, 59] was the first one who proposed that ChPT can be used to define a nuclear potential. In the framework of ChPT, two types of interactions are assumed: long-range pion exchanges and contact interactions. When we use ChPT for a three-nucleon system, 3NFs appear naturally in the higher-order terms. For the first time a non-vanishing 3NF arises at the Next-to-Next-to-Leading Order (NNLO). For more details about the construction of the NN potential within ChPT approach at NNLO see Ref. [14].

According to the coupled-channel approach, the excitation of a single nucleon to the Δ -isobar yields an effective 3NF from any NN potential. The two-baryon coupled-channel potential CDB+ Δ [60, 61], which was introduced by the Hannover-Lisbon group, couples NN states to $N\Delta$ states. The Δ -isobar is virtual and considered as stable baryon with a mass of 1232 MeV. Similar to the ChPT approach, this approach treats the 3NF in consistent way along with the NN interaction.

2.3 Three-body scattering

The formalism presented in this section is based on Refs. [62–64].

Let us assume that we have three distinguishable spinless particles, numbered 1, 2, and 3, interacting through two-body forces which are of finite ranges. In general three particles can form various arrangements indicated as

$$(1,23); \quad (2,31); \quad (3,12); \quad (1,2,3). \quad (2.2)$$

Each of the first three arrangements is called the two-body fragmentation channel with two particles in a bound state and the third particle is free. The last arrangement is known as the three-body break-up channel with three free particles. It is customary to denote the two-body fragmentation channel by the single free particle. For example the arrangement (1,23) is denoted by channel 1, where particles 2 and 3 are bound to each other while particle 1 is free. Also, the three-body break-up channel is labeled as channel 0. According to this notation, a scattering process can be initiated through each of these 4 channels. For instance, a scattering process initiated by channel 1 (1,23) leads to four possible exit channel as follows:

$$(1,23) \longrightarrow \begin{cases} (1,23) & \text{elastic,} \\ (2,31) & \text{rearrangement,} \\ (3,12) & \text{rearrangement,} \\ (1,2,3) & \text{break-up.} \end{cases} \quad (2.3)$$

We represent the so-called channel Hamiltonian by

$$H_\alpha \equiv H_0 + V_\alpha, \quad (2.4)$$

where H_0 is the kinetic energy operator of the three particles and V_α is, according to the simple rule as for the channels, the two-body potential of the interaction between particle β and γ , with a cyclic permutation of (123) for $(\alpha\beta\gamma)$. If we define the remaining two interactions of particle α with the pair as $V^\alpha \equiv V_\beta + V_\gamma$, the total Hamiltonian operator results:

$$H = H_\alpha + V^\alpha. \quad (2.5)$$

To make this compatible with the break-up channel ($\alpha = 0$) we introduce $V_0 \equiv 0$ and $V^0 \equiv V_1 + V_2 + V_3$. Corresponding to the 4 channels described before, there are 4 types of stationary scattering states [62]

$$|\Psi_\alpha^{(+)}\rangle = \lim_{\epsilon \rightarrow 0} i\epsilon(E + i\epsilon - H)^{-1}|\phi_\alpha\rangle, \quad (2.6)$$

where $|\phi_\alpha\rangle$ is an eigenstate to H_α and E is the energy connected to $|\phi_\alpha\rangle$.

Following the idea of applying resolvent identities to establish the **Lippmann-Schwinger**

Equation (LSE), we define the channel resolvent operators as

$$G_\alpha \equiv (E + i\epsilon - H_\alpha)^{-1} \quad (2.7)$$

and the full resolvent operator as

$$G \equiv (E + i\epsilon - H)^{-1}, \quad (2.8)$$

which satisfy the well-known relation of scattering theory

$$G = G_\alpha + G_\alpha V^\alpha G. \quad (2.9)$$

By inserting this equation into Eq. 2.6 and imposing all the boundary conditions presented in Ref. [62] it can be shown that the following set defines $|\Psi_\alpha^{(+)}\rangle$ uniquely for $\alpha \neq 0$:

$$\begin{aligned} |\Psi_\alpha^{(+)}\rangle &= |\phi_\alpha\rangle + G_\alpha V^\alpha |\Psi_\alpha^{(+)}\rangle, \\ |\Psi_\alpha^{(+)}\rangle &= G_\alpha V^\beta |\Psi_\beta^{(+)}\rangle, \\ |\Psi_\alpha^{(+)}\rangle &= G_\alpha V^\gamma |\Psi_\gamma^{(+)}\rangle. \end{aligned} \quad (2.10)$$

In Eq. 2.6, each scattering state $|\Psi_\alpha^{(+)}\rangle$ initiated by $|\phi_\alpha^{(+)}\rangle$ has to fulfill three different equations. These equations cannot provide a practical algorithm to find $|\Psi_\alpha^{(+)}\rangle$. For this purpose, Faddeev decomposed the total state into 3 parts:

$$|\Psi_\alpha^{(+)}\rangle = \sum_{\mu=1}^3 |\psi_{\alpha\mu}\rangle, \quad (2.11)$$

where $|\psi_{\alpha\mu}\rangle \equiv G_0 V_\mu |\Psi_\alpha^{(+)}\rangle$ is called Faddeev amplitude and $G_0 \equiv (E - H_0)^{-1}$ is the free three-body resolvent operator. By multiplying Eqs. (2.10) with $G_0 V_\alpha$, $G_0 V_\beta$ and $G_0 V_\gamma$ from the left, respectively, we get **Faddeev Equations**:

$$\begin{aligned} |\psi_{\alpha\alpha}^{(+)}\rangle &= |\phi_\alpha\rangle + G_\alpha V_\alpha (|\psi_{\alpha\beta}\rangle + |\psi_{\alpha\gamma}\rangle), \\ |\psi_{\alpha\beta}^{(+)}\rangle &= G_\beta V_\beta (|\psi_{\alpha\gamma}\rangle + |\psi_{\alpha\alpha}\rangle), \\ |\psi_{\alpha\gamma}^{(+)}\rangle &= G_\gamma V_\gamma (|\psi_{\alpha\alpha}\rangle + |\psi_{\alpha\beta}\rangle). \end{aligned} \quad (2.12)$$

In the scattering process, the transition amplitude from channel α to channel β

$$A_{\beta\alpha} \equiv \langle \phi_\beta | V^\beta | \Psi_\alpha^{(+)} \rangle, \quad (2.13)$$

is of importance because it is necessary for the calculation of scattering observables. The transition operator connected to this amplitude is defined by

$$U_{\beta\alpha} |\phi_\alpha\rangle \equiv V^\beta |\Psi_\alpha^{(+)}\rangle. \quad (2.14)$$

Employing Eq. 2.14 and $V_\alpha|\phi_\alpha\rangle = G_0^{-1}|\phi_\alpha\rangle$ in Eqs. (2.10) gives

$$U_{\beta\alpha} = \bar{\delta}_{\beta\alpha}G_0^{-1} + \sum_{\gamma} \bar{\delta}_{\beta\gamma}V_\gamma G_\gamma U_{\gamma\alpha}, \quad (2.15)$$

which are the Alt-Grassberger-Sandhas (AGS) [64] equations for the arrangement amplitudes with $\bar{\delta}_{\beta\alpha} \equiv 1 - \delta_{\beta\alpha}$. With the introduction of the two-body transition operators for particles β and γ via $V_\alpha G_\alpha \equiv t_\alpha G_0$ which obeys the LSE, $t_\alpha = V_\alpha + V_\alpha G_0 t_\alpha$, Eq. 2.15 can be rewritten as

$$U_{\beta\alpha} = \bar{\delta}_{\beta\alpha}G_0^{-1} + \sum_{\gamma} \bar{\delta}_{\beta\gamma}t_\gamma G_0 U_{\gamma\alpha}. \quad (2.16)$$

In nuclear physics, neutrons and protons are treated as identical fermions. One, therefore, needs to antisymmetrize the equations. For later convenience, we consider channel 1 as the initial state, $|\phi_1\rangle$, and assume that it is already antisymmetrized in the two-body sub-system. The antisymmetric scattering state is given by Ref. [63]:

$$|\Psi_a^{(+)}\rangle \equiv \lim_{\epsilon \rightarrow 0} i\epsilon(E + i\epsilon - H)^{-1}(|\phi_1\rangle + |\phi_2\rangle + |\phi_3\rangle) \equiv |\Psi_1^{(+)}\rangle + |\Psi_2^{(+)}\rangle + |\Psi_3^{(+)}\rangle. \quad (2.17)$$

Note that, when each of the three two-fragments configurations is considered as the initial state, the amplitudes for outgoing fluxes are the same since

$$\begin{aligned} \langle\phi_1|V^1|\Psi_a^{(+)}\rangle &= \langle\phi_1|P_{23}P_{12}P_{12}P_{23}V^1|\Psi_a^{(+)}\rangle \\ &= \langle\phi_1|V^2|\Psi_a^{(+)}\rangle \\ &= \langle\phi_1|V^3|\Psi_a^{(+)}\rangle, \end{aligned} \quad (2.18)$$

where P_{ij} is the permutation operator of the two particles i and j . To transform the state $|\phi_1\rangle$ into a fully antisymmetric scattering state $|\Psi_a^{(+)}\rangle$, one introduces the transition operator U_1 by

$$U_1|\phi_1\rangle \equiv \sum_{\alpha=1}^3 U_{1\alpha}|\phi_\alpha\rangle, \quad (2.19)$$

for elastic scattering. Using Eq. 2.16 for $\beta = 1$ and summing over α we get

$$\sum_{\alpha} U_{1\alpha}|\phi_\alpha\rangle = \sum_{\alpha} \bar{\delta}_{\alpha 1}G_0^{-1}|\phi_\alpha\rangle + \sum_{\gamma} \bar{\delta}_{\gamma 1}t_\gamma G_0 \sum_{\alpha} U_{\gamma\alpha}|\phi_\alpha\rangle. \quad (2.20)$$

According to Eq. 2.13 and the properties of the permutation operator $P = P_{12}P_{23} + P_{13}P_{23}$, like $P|\phi_1\rangle = |\phi_2\rangle + |\phi_3\rangle$ and $Pt_1G_0U_1|\phi_1\rangle = t_2G_0U_2|\phi_1\rangle + t_3G_0U_3|\phi_1\rangle$, Eq. 2.20 can be rewritten as a function of U_1 operator with dropping all indices but G to get the transition operator for elastic scattering as:

$$U|\phi\rangle = PG_0^{-1}|\phi\rangle + PT|\phi\rangle, \quad (2.21)$$

where $T \equiv tG_0U$.

The transition amplitude into the break-up channel ($\alpha = 0$) is given by

$$A_0 \equiv \langle \phi_0 | V^0 | \Psi_a^{(+)} \rangle. \quad (2.22)$$

Therefore, the transition operator is defined as follows:

$$U_0 | \phi_1 \rangle \equiv V^0 \sum_{\alpha=1}^3 | \Psi_{\alpha}^{(+)} \rangle. \quad (2.23)$$

Employing the Eq. 2.13 and doing some mathematical operations one can get

$$U_0 | \phi_1 \rangle = \sum_{\alpha} V^{\alpha} | \phi_{\alpha} \rangle + \sum_{\alpha} t_{\alpha} G_0 U | \phi_1 \rangle. \quad (2.24)$$

Because of $V_{\alpha} | \phi_{\alpha} \rangle = G_0^{-1} | \phi_{\alpha} \rangle$, the first terms ($\sum_{\alpha} V^{\alpha} | \phi_{\alpha} \rangle$) in this equation will not contribute to the on-shell amplitude A_0 . After dropping them we have [63]

$$U_0 | \phi_1 \rangle = (1 + P) t_1 G_0 U | \phi_1 \rangle. \quad (2.25)$$

Finally, by dropping the indices on $|\phi\rangle$ and t , the break-up transition operator can be obtained as

$$U_0 | \phi \rangle = (1 + P) T | \phi \rangle. \quad (2.26)$$

The next step is to include the three-body force. If we start from the AGS equations (Eq. 2.15) and repeat all the steps with an additional 3NF indicated by V_4 , the transition operator for elastic scattering will be given by

$$U | \phi \rangle = P G_0^{-1} | \phi \rangle + P T | \phi \rangle + T_4 | \phi \rangle, \quad (2.27)$$

and for the break-up process it will turn out to be

$$U_0 | \phi \rangle = (1 + P) T | \phi \rangle + T_4 | \phi \rangle. \quad (2.28)$$

In both operators $T_4 \equiv t_4 G_0 U$, where t_4 is known as the three-body transition operator and obeys $t_4 = V_4 + V_4 G_0 t_4$. The on-shell matrix elements $\langle \phi | U | \phi \rangle$ ($\langle \phi_0 | U_0 | \phi \rangle$) are used for the calculation of the elastic (break-up) scattering observables as a function of the center-of-mass scattering angle (the arclength along the kinematical curve, S).

2.4 Kinematics of the $\vec{p} + d$ break-up reaction

For the break-up reaction with three free nucleons (two proton and one neutron) in the final state, we need 9 variables to describe the kinematics: three components of each nucleonic momentum vector. Figure 2.1 shows the momenta of the outgoing nucleons and of the incoming proton with other quantities in the helicity frame. The energy and

momentum conservations for the break-up reaction are:

$$\begin{aligned} E_p + E_b &= E_1 + E_2 + E_3, \\ \vec{p}_p &= \vec{p}_1 + \vec{p}_2 + \vec{p}_3, \end{aligned} \quad (2.29)$$

where E is the kinetic energy, $\vec{p}$ refers to the momentum vector, the indices “ p ”, “1”, “2”, “3” show the incoming proton, the outgoing protons “1” and “2” and the neutron, respectively and $E_b = -2.224$ MeV is the binding energy of the deuteron target. The reaction coordinate system (x, y, z) is defined according to Ref. [65]. The beam momentum is along the z -axis. The momentum of outgoing proton “1” is chosen to define the x - z plane with $x > 0$, as illustrated in Fig. 2.1. The y -axis is taken as required to form a right-handed orthogonal coordinate system. The laboratory system (x', y', z'), with z' along the beam momentum and y' vertically upward, is used to define the angular configuration of the outgoing protons.

By measuring the energy, polar and relative azimuthal angles of the outgoing protons, which are in total 5 variables, and by taking into account the conservation laws in Eq. 2.29, the non-relativistic relation [65, 66] between these 5 variables is given as

$$\begin{aligned} &(m_1 + m_3)E_1 + (m_2 + m_3)E_2 + (m_p - m_3)E_p - m_3E_b \\ &- 2\sqrt{m_p m_1 E_p E_1} \cos \theta_1 - 2\sqrt{m_p m_2 E_p E_2} \cos \theta_2 + 2\sqrt{m_1 m_2 E_1 E_2} \cos \theta_{12} = 0, \end{aligned} \quad (2.30)$$

where m_1 and m_2 are the masses of the first and second outgoing protons, respectively, m_3 is the mass of neutron, m_p is the mass of incoming proton and θ_{12} is the opening angle between the outgoing protons with $\cos \theta_{12} = \cos \theta_1 \cos \theta_2 + \sin \theta_1 \sin \theta_2 \cos(\varphi_1 - \varphi_2)$. It is good to mention that Eq. 2.30 represents a 5-dimensional surface, so-called phase-space, in the 9-dimensional momentum space and an ellipse on the $\sqrt{E_1} - \sqrt{E_2}$ plane. The energy correlation of the two outgoing particles for a specific angular configuration, defined by the polar and relative azimuthal angles of those particles, is called S -curve. The corresponding kinematical variable, S , indicates the arc length along the S -curve from a starting point, $S = 0$, and it is expressed in units of energy. The point corresponding to $S = 0$ for angular configurations with $\theta_1 < 90^\circ$ ($\theta_1 \geq 90^\circ$) is defined by $E_2 = 0$ ($E_1 = 0$) with E_1 (E_2) having a larger value. A couple of examples of relativistic S -curves are shown in Fig. 2.2.

2.5 Cross section and analyzing powers

The general formula for the cross section of the break-up reaction induced by an incident polarized beam made up of spin- $\frac{1}{2}$ particles in the Cartesian coordinate system is given by Ref. [65]

$$\sigma(\xi, \phi_{12}) = \sigma_0(\xi, \phi_{12})[1 + p_x A_x(\xi, \phi_{12}) + p_y A_y(\xi, \phi_{12}) + p_z A_z(\xi, \phi_{12})], \quad (2.31)$$

Figure 2.1: A schematic view of the kinematics of the break-up reaction. $\vec{p}_p$, $\vec{p}_1$, $\vec{p}_2$, and $\vec{p}_3$ represent the momentum vectors of the proton projectile, the outgoing protons “1” and “2” and the neutron, respectively. The polar (θ_1 and θ_2) and azimuthal (φ_1 and φ_2) and the relative azimuthal angles $\varphi_{12} = \varphi_1 - \varphi_2$ are defined for the outgoing protons; for details see the text.

where σ_0 is the cross section for the case of an unpolarized beam; p_x , p_y and p_z are the Cartesian components of the beam polarization, A_x , A_y and A_z refer to the analyzing powers, and $\varphi_{12} = \varphi_1 - \varphi_2$ together with $\xi = (\theta_1, \theta_2, S)$ denote all the kinematical variables of the two outgoing particles in the break-up reaction.

To obtain the components of the beam polarization in the Cartesian coordinate system, usually the direction of the spin-quantization axis is described by two angles β and ϕ in the projectile helicity frame: the $\hat{z}$ axis is taken along the direction of the projectile momentum, $\hat{k}_{in}$, the $\hat{y}$ axis is taken along $\hat{k}_{in} \times \hat{k}_{out}$, where $\hat{k}_{out}$ represents the direction of the scattered particle, and $\hat{x}$ axis is chosen to form a right-handed coordinate system. The angle β ($0 \leq \beta \leq \pi$) is taken to be the angle between the beam direction and the spin-quantization axis. The angle ϕ ($0 \leq \phi \leq 2\pi$) is the angle between the Y-axis and the

Figure 2.2: Examples of relativistic correlations between the energies of the two protons for two configurations, as indicated in the legend, in a $\bar{p} + d$ break-up reaction at 135 MeV. The starting point $S = 0$ is indicated and the increase of the variable S along the curve is indicated by the direction of the arrow for each individual configuration.

projection of the spin-quantization axis onto the X-Y plane, see the Fig. 2.3. With these definitions, the components of the beam polarization are:

$$\begin{aligned} p_x &= -p_Z \sin \beta \sin \phi, \\ p_y &= p_Z \sin \beta \cos \phi, \\ p_z &= p_Z \cos \beta, \end{aligned} \quad (2.32)$$

where p_Z indicates the magnitude of the beam polarization with respect to its quantization axis $\hat{s}$.

For $\beta = 90^\circ$, which was the case in our experiment, Fig. 2.3 will be equivalent to Fig. 2.1 and Eq. 2.31 can be rewritten as

$$\sigma(\xi, \phi_{12}) = \sigma_0(\xi, \phi_{12})[1 - \sin \phi p_Z A_x(\xi, \phi_{12}) + \cos \phi p_Z A_y(\xi, \phi_{12})]. \quad (2.33)$$

Parity conservation restricts the analyzing powers in Eq. 2.33 by the following properties:

$$\begin{aligned} A_x(\xi, \phi_{12}) &= -A_x(\xi, -\phi_{12}), \\ A_y(\xi, \phi_{12}) &= A_y(\xi, -\phi_{12}). \end{aligned} \quad (2.34)$$

Consequences of the above properties are: (1) A_x will vanish for coplanar configurations ($\phi_{12} = 180^\circ$) and (2) for the extraction of A_y (A_x) it helps to add (subtract) the data of the configurations with ϕ_{12} to (from) that of the $-\phi_{12}$.

Figure 2.3: The spin-quantization axis in the projectile helicity frame. The angle β is defined as the angle between the quantization axis and the beam direction, and ϕ is the angle between the projection of $\vec{S}$ on the $X-Y$ plane and the Y -axis. This is called the Madison convention and the left, right, up, and down scattering angles are denoted by $\phi = 0^\circ$, $\phi = 180^\circ$, $\phi = 270^\circ$, and $\phi = 90^\circ$, respectively.

Chapter 3

Experimental setup

In this chapter, the most important components of the experimental setup used for the present work will be discussed. The ${}^2\text{H}(\vec{p}, pp)n$ break-up reaction was performed at the **K**ernfysisch **V**ersneller **I**nstituut¹ (KVI). In this experiment, a polarized proton beam produced by **P**OLarized **I**on **S**ource (POLIS) accelerated with the superconducting cyclotron AGOR (**A**ccélérateur **G**roningen **O**Rsay) to 135 MeV. After that, the proton beam impinged a liquid-deuterium target and the reaction products were detected by the **B**ig **I**nstrument for **N**uclear-polarization **A**nalysis (BINA) which inherits a lot of features from its predecessor, **S**mall-Angle **L**arge-Acceptance **D**etector, SALAD [67]. The experimental area is shown in Figure 3.1.

3.1 POLarized Ion Source (POLIS)

POLIS is an atomic-beam source which can produce polarized proton and deuteron beams [68, 69]. In the case of a proton beam, which was used for this work, at first hydrogen gas molecules are dissociated into atoms by a radio-frequency (RF) induced discharge in a Pyrex tube. At this stage, because of the hyperfine splitting², we have atoms in one of the hyperfine states $F = 0, 1$, where

$$\vec{F} = \vec{J} + \vec{I}. \quad (3.1)$$

Here, $\vec{I}$ is the nuclear spin and $\vec{J}$ the spin of the electron. Atoms leaving the dissociation are fed through a hexapole magnet which is able to separate them according to the electron spin. Figure 3.2 shows a Breit-Rabi diagram of the hydrogen atom in a magnetic field.

¹Presently known as KVI-Center for Advanced **R**adiation **T**echnology (KVI-CART).

²The hyperfine splitting comes from the interaction of the magnetic dipole moment of the electron with the magnetic moment of the nucleus.

Figure 3.1: A top view of the KVI experimental facility in 2006. The AGOR accelerator together with POLIS provide polarized and unpolarized beams for the experiments. The BINA detector and the Big Bite spectrometer are shown on top of the picture.

Figure 3.2: Hyperfine states of the hydrogen atom and RF transitions in the magnetic field used in POLIS. The weak field is responsible for $p_z = -1$ and the strong field provides the $p_z = 1$ polarization.

To produce the atoms with a specific spin for protons, we can populate a specific state via the method of the adiabatic transition [70, 71]. By using a weak-field transition, the entire population of the sub-state 1 is transferred to sub-state 3, while the population of sub-state 2 stays the same, therefore, the atoms with protons in the “down” ($\downarrow$) spin state are produced. Similarly, the atoms with protons in the “up” ($\uparrow$) spin state are produced by applying a strong-field transition which transfers the population of sub-state 2 to sub-state 4 while the population of sub-state 1 stays the same. Finally, the electrons are stripped off in an Electron Cyclotron Resonance (ECR) ionizer and the polarized beam is transported to the AGOR cyclotron for acceleration. The polarization degree of a beam of spin- $\frac{1}{2}$ particles, such as a proton beam, is defined as:

$$p_z = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}, \quad (3.2)$$

where $N^\uparrow$ and ($N^\downarrow$) are the number of particles with a particular spin “up” ($\uparrow$) and “down” ($\downarrow$), respectively. Theoretically, the maximum achievable polarization value is $p_z = \pm 1$. In practice, the beam polarizations during the experiment were 50%–70% of these values.

3.2 The AGOR cyclotron

After preparing the proton beam discussed in the previous section, it was accelerated by the AGOR cyclotron to reach the requested energy. AGOR [72] is a superconduct-

ing cyclotron which has been constructed in collaboration with IPN (Institut de Physique Nucléaire) Orsay, France. This cyclotron with a pole diameter of 1.88 m has superconducting coils which can produce magnetic fields with values of up to 4 T. AGOR can accelerate protons, deuterons and heavy ions. For instance, protons can be accelerated by AGOR up to 190 MeV and deuterons up to a maximum energy of 90 MeV/nucleon. Figure 3.3 shows the operating diagram of the AGOR cyclotron. This picture depicts the energy range which can be obtained for a given Q/A -ratio. For the work presented here, a 135 MeV proton beam in $\bar{p}d$ scattering has been used.

Figure 3.3: The maximum available energy in MeV for an ion with a given Q/A -ratio in the AGOR cyclotron. Q and A stand for charge and atomic number of ions, respectively. The colors dots indicate different beams with Q/A that have been accelerated by AGOR. A proton beam with $Q/A = 1.0$, can be accelerated up to 190 MeV and a deuteron or α beam with $Q/A=0.5$ can be accelerated up to 90 MeV/nucleon.

3.3 The In-Beam Polarimeter (IBP)

In our experiment, we used the KVI In-Beam Polarimeter (IBP) [73] for online polarization monitoring. IBP measures the polarization of the proton beam via the reaction $H(\vec{p}, pp)$. This operation can be done by detecting both particles emerging from the scattering reaction in coincidence. IBP consists of sixteen phoswich³ detectors arranged in

³A phoswich (phosphor sandwich) is a combination of scintillators with dissimilar pulse-shape characteristics optically coupled to each other and to a common PMT.

four planes at 0° , 45° , 90° , and 135° (see the setup of the IBP in Figure 3.4). Each plane contains four detectors. Two detectors in each plane can detect final-state particles in coincidence. From the number of detected particles in each plane, the left-right asymmetry can be measured. Using this asymmetry and the known analyzing power of reaction, one can determine the polarization. For details see Ref. [35].

Figure 3.4: Schematic setup of the IBP. The plane containing detectors 1 to 4 coincides with the horizontal plane in the laboratory frame of reference. In this plane, detectors 1 and 2 measure in coincidence both outgoing particles of the scattering reaction of interest for $\varphi = 0^\circ$. Detectors 3 and 4 are mounted in the same way, but for $\varphi = 180^\circ$. The difference of the number of counts between these two detector pairs gives the left-right asymmetry. The detector pairs of the other planes are mounted in the same manner.

3.4 The Lamb-Shift Polarimeter (LSP)

In 2003, because of some IBP disadvantages, it was decided to build a low-energy polarimeter, namely the KVI Lamb-Shift Polarimeter [74] based upon the Lamb-shift principle⁴ [75]. The disadvantages were: (i) setting up and operating the IBP is time consuming, especially for absolute polarization measurements, (ii) expensive cyclotron beam

⁴The Lamb-shift is a small difference in energy between $2s_{1/2}$ and $2p_{1/2}$ levels of the hydrogen or deuterium atoms.

time has to be used for starting and tuning POLIS, using the IBP, and (iii) the analyzing power of the $\vec{d} + p$ reaction is not known for all energies available from AGOR. The LSP enables one to determine the polarization degree of proton and deuteron beams before acceleration within one minute and with a statistical uncertainty of less than 1% by scanning the magnetic field through the resonance peaks. More details can be found in Ref. [74].

3.5 The BINA detector

As a result of a collaboration between KVI and the Vrije Universiteit Amsterdam, the BINA detector was assembled in 2004 and its commissioning experiments were finished in 2005 [33]. During the period 2005-2011, KVI, in collaboration with Polish physicists, provided a large database to study few-body nuclear physics. In 2012, BINA was transported to the Cyclotron Center Bronowice (CCB) in Krakow, Poland [76]. BINA enables us to study break-up and elastic reactions at intermediate energies of up to ~ 200 MeV/nucleon with almost 80% of the full 4π solid angle coverage. As shown in Fig. 3.5, BINA is composed of two main parts, the forward wall which covers scattering angles of 10° - 37° , and the backward ball which covers the rest of the polar angles up to 165° . In the following sections these two parts are briefly described.

3.5.1 The forward wall

The forward wall consists of three parts: a Multi-Wire Proportional Chamber (MWPC), ΔE - and E -scintillators. The forward wall covers the polar angle (θ) in the range of 10° - 32° with full azimuthal-angle (φ) coverage while, due to the corners of the MWPC, the azimuthal-angle coverage is limited for the polar angles from 32° - 37° . When a particle passes through the MWPC, its coordinates are recorded. Subsequently, a small fraction of its energy is deposited when it passes through the ΔE -scintillators. Finally, the particle will stop inside of the E -scintillators if its energy is less than 140 MeV. The type of particle can be identified by a combination of E - and ΔE scintillators. All parts of the forward wall have a central hole for the passage of beam pipe. In the following subsections, these parts are described in more detail.

3.5.1.1 Multi-Wire Proportional Chamber (MWPC)

The MWPC is used for the reconstruction of the interaction point of a charged particle with the detector in nuclear and high-energy physics experiments. The MWPC of BINA with an active area of 38×38 cm² is installed at a distance of 29.5 cm from the target position and it consists of 3 planes, X, Y, and U [77]. These planes are parallel arrays of equally-spaced anode wires which have a 2 mm distance from each other. The anode wire planes are sandwiched between two parallel cathode plates. Cathode plates are made of

Figure 3.5: A side view of BINA. The top panel shows a photograph of BINA side-view and the bottom one presents schematic drawing of the forward wall and the backward ball.

sprayed-graphite coated mylar foils with a thickness of $25\text{ }\mu\text{m}$ and connected to a high voltage of -3250 V . The volume between cathodes is filled with an electro-negative gas with a mixture of CF_4 (80%) and isobutane (20%) and with an over-pressure of about 2-3 mbar. The X (Y) plane has 236 parallel vertical (horizontal) wires, whereas the U plane contains 296 parallel wires placed diagonally at an angle of 45° with respect to the X or Y planes. Charged particles, which pass through the active area of the MWPC, ionize the gas and as a consequence, the avalanche electrons are collected on the wires in the detection region to produce a signal.

3.5.1.2 E - and ΔE -scintillators

The E -scintillators can be divided into two main parts, the cylindrically-shape part whose center coincides with the center of the target and two flat wing-like parts placed above and below the cylindrical part. The latter, which was not used in the present experiment, can be used for detecting the secondary scattered particles in polarization-transfer experiments. The cylindrical part consists of 10 horizontal scintillator bars with a trapezoidal cross section and the dimensions of $((9-10) \times 12 \times 220\text{ cm}^3)$ each. The two central scintillators have a hole in the middle for passage of the beam pipe. The top and bottom wings also contain 10 horizontal scintillator bars with a rectangle-cubic shape and dimensions of $(12 \times 12 \times 220\text{ cm}^3)$ each.

ΔE -scintillators in combination with the E -scintillators are used to identify the particle type (i.e. proton, deuteron etc.) as well as to determine the MWPC efficiency. A detailed

Figure 3.6: The photograph of the forward wall of BINA with various components moved out of the original position for demonstration. From the left to right: E -scintillators without the wings, ΔE scintillators and the MWPC.

Figure 3.7: Details of the engineering design of the forward part of BINA. Here, the E -scintillators, ΔE -scintillators, and the MWPCs (only MWPC 1 is used in the present work) can be seen. Also, the distances between components and their sizes are shown in mm.

Table 3.1: Physical constants of BICRON scintillators. Here, L_t is the light attenuation length, λ_{max} is the peak wavelength of the generated light, H/C is the ratio of Hydrogen to Carbon, ρ is the density of material, and n_c gives the refractive index.

Type	Decay (ns)	λ_{max} (nm)	L_t (cm)	H/C ratio	ρ (g/cm ³)	n_c
BC-408	2.1	425	380	1.104	1.032	1.58
BC-444	180	428	180	1.109	1.032	1.58

description of the efficiency determination of the MWPC can be found in Ref. [35]. The array of ΔE -scintillators is composed of 12 thin slabs ($0.2 \times 3.17 \times 43.4$ cm³) of plastic scintillator which are placed vertically between the E -scintillators and the target. In Figure 3.6, these scintillators are visible.

All E - and ΔE -scintillators are made of BICRON-408 plastic scintillator material. The physical constants of this material are listed in Table 3.1. Due to different energy losses in materials between the target and the E -scintillators, the protons (deuterons) with an initial energy below 20 MeV (25 MeV) will not reach the E -scintillators. The details of the engineering design of the forward wall are shown in Fig. 3.7.

3.5.2 The backward ball

The backward part of BINA is ball-shaped and is made out of 149 phoswich detectors. These detectors cover almost 80% of the full 4π solid angle, polar angle θ in the range of 40° to 165° with a complete azimuthal acceptance (φ) (except at the position of the target holder at $\theta = 100^\circ$). Therefore, the backward ball together with the forward wall allow BINA to cover nearly the complete phase space.

The shape and the construction of the inner surface of the ball is similar to the surface of a soccer ball (which consists of 20 identical hexagon and 12 identical pentagon structures), see Fig. 3.8. Each pentagon (hexagon) is composed of five (six) identical triangles. In the hexagon, all sides of the triangle have the same size while in the pentagon only two sides are the same, see Fig. 3.9. Each triangle is composed of a phoswich detector and covers an angular range as large as $\sim 20^\circ$, in both φ and θ directions. Therefore, the granularity of the backward ball is poor compared to that of the forward wall.

Each detector of the backward ball is composed of a fast plastic scintillator, BICRON BC-408, and a slow phoswich part, BICRON BC-444, which has the same cross section and is glued to the fast component. Physical parameters of BICRON plastics are given in Table 3.1. The slow scintillator part has a thickness of 1 mm, while, because of the energy difference between particles scattered at different polar angles, the thickness of the fast scintillator below $\theta < 100^\circ$ is 9 cm and for the rest is 3 cm. The energy correlation of the fast and slow components can be used for particle identification. All these elements were painted with white color and glued with each other making the ball sphere; see Fig. 3.10.

Figure 3.8: A model of the backward ball. The model is made from a soccer ball and the surface is completed with hexagons and pentagons. Indicated are the target holder entrance, the front exit window, and the direction of the beam.

Figure 3.9: A schematic view of the ball elements; left panel shows the two building blocks of the ball: the penta- and hexagon structures, and the right panel shows the fast (back) and slow (front) parts for a single phoswich detector.

Figure 3.10: The left panel shows the front exit window of the ball and on the right panel the cut pyramid geometry of the scintillators in the incomplete backward ball is shown.

The front exit window of the backward ball, shown in Fig. 3.10, was made of $250\ \mu\text{m}$ thick Kevlar cloth and $50\ \mu\text{m}$ thick Aramica foil [67] which are glued to a metal frame. This thin window is strong enough to hold the vacuum inside the ball (with a value of 10^{-5} mbar for pressure) and it also allows the forward scattered particles to pass through it with a very small energy loss.

The BINA backward ball acts as a scattering chamber with a vacuum that is sufficient to avoid the collection of dirt on the foil of the liquid-deuterium target. Due to the vacuum and the absence of additional material or structure inside the ball, the scattered particles do not suffer as much from energy losses compared to a detection system for which the scattering chamber is separated from the detector. However the target frame, the target window foil and the thin cylindrical aluminum foil used as a thermal shielding around the target cell are obstacles for particles going through them. Due to its construction, the ball detects particles with very low kinetic energies. Other details of the engineering design of the backward ball of BINA are shown in the Fig. 3.11.

3.5.3 Target system

The target system of BINA consists of target materials, a target cell, a holder, a cryogenic system, a heater, a gas-flow system, temperature sensors, and a temperature controller unit. The types of targets materials which were used in our experiments were: solid CH_2 , Zinc Sulphide (ZnS) and liquid deuterium (LD_2). The ZnS target together with an empty cell were used to optimize the beam position and optics. Solid CH_2 was used to make an on-line check of the experimental setup and to optimize the settings. We used mainly LD_2 with the density of $\rho = 169\ \text{mg/cm}^3$ in our experiment because it is pure and, therefore, minimizes background reactions.

The target cell used in this experiment is made of high purity Aluminum to optimize the thermal conductivity and its windows are covered by a transparent foil of Aramid [67] with a thickness of $\sim 4\ \mu\text{m}$; see Fig. 3.12. This thickness increased to 3.85 mm due to

Figure 3.11: Details of the engineering design of the backward ball of BINA. All the sizes are in mm.

bulging of the target because of the pressure inside the cell. In this experiment, the operating temperature and pressure of the LD_2 target were 19 K and 258 mbar, respectively.

The target holder is installed at $\theta_{lab} = 100^\circ$ on top of the backward ball with a slight inclination angle of 10° and could be moved by a pneumatic system. All targets were mounted on a holder to put in the center of the backward ball.

Other components of the target system were used to operate liquid targets. The deuterium gas was transported by a gas-flow system to the cell. Then the cell was cooled by a cryogenic system to liquefy the gas for providing liquid deuterium. The temperature and pressure were kept constant, otherwise the liquid inside the cell can freeze or evaporate which might result in a target explosion. In the present setup, this procedure is constantly monitored by means of a Programmable Logic Controller (PLC) system which measures the temperature and the pressure.

Figure 3.12: Left panel: the target cell. Right panel: the target cell mounted inside the BINA backward ball with liquid deuterium inside it (the target is half filled with deuterium for demonstration). The thin aluminum cylinder around the target cell (the 80 K shield) is used to isolate the cold head from the surrounding environment.

3.5.4 Electronics of BINA

The read-out electronics of BINA, as a main part of data-acquisition (DAQ) system, is responsible for digitizing the information of the detectors. The other parts of the BINA DAQ are: a trigger system which will be described in the next section, a real-time computer to collect the selected data, and a mass storage system which saves the data. Figure 3.13 shows the block diagrams of the DAQ of BINA. A detailed description of the data acquisition can be found in Ref. [33]. The electronics of BINA are divided into the forward wall, the backward ball, and the MWPC electronics. Here, a short description of each part is given.

Figure 3.13: The data acquisition of BINA consists of 4 parts: the read-out electronics to digitize the information from detectors (MWPC, the wall and the ball scintillator signals), a trigger system, a real-time computer to collect the selected data, and the storage unit which saves the data on disk via a connection to the real-time computer. Figure adapted from Ref. [35].

The forward-wall electronics provide signals from 10 E - and 12 ΔE -detectors. Each detector of the forward wall is read out by two PMTs at both ends of it. ΔE -scintillator bars located at the position of the beam pipe are disconnected. The signals from these PMTs are, consequently, independent of each other. As Fig. 3.14 shows, first, each analog signal of all these detectors is split into two via an active splitter; one of the outputs is fed to a constant fraction discriminator (CFD) to produce a logic signal for trigger definition, storing the time information in a Time-to-Digital Converter (TDC) and recording the rates into scalers⁵. The second one is sent to FERA⁶, a Charge-to-Digital Converter (QDC), for the integration of the total charge of each analog signal from the PMTs. The gate for the integration was derived from the trigger. To match the timing of the integration gate, the analog signals were delayed by about 250 ns. The START signal of the TDCs were obtained from the output of the CFDs and the STOP was derived from the trigger.

The backward-ball electronics, shown schematically in Fig. 3.15, are similar to forward-wall electronics. Since the ball detectors are composed of scintillators with slow and fast

⁵The scaler is a unit which counts the number signals fed into as input over a, by hardware set, time interval.

⁶Fast Encoding and Readout ADC

Figure 3.14: The general scheme of the forward-wall electronics of BINA. In this part, signals from 44 ($E, \Delta E$) PMTs are split into two parts via an active splitter. From the second output, the signal is sent to the FERA, after a cable delay of ~ 250 ns. The first output is sent to a CFD to be used as the input to the trigger unit.

Figure 3.15: The electronics of the backward ball of BINA. The splitting unit is of the same type as used for the forward-wall electronics. In order to generate two copies of the output signals of the active splitter, the signals are sent through a passive splitter before going to the FERAs.

responses, the second output is split once more by a passive splitter to provide signals for long-gate and short-gate integration for particle identification purpose.

A sketch of the electronics of the MWPC is shown in Fig. 3.16. As mentioned before, the MWPC has three planes with 236 (X), 236 (Y), and 296 (U) wires in each plane. As each two wires are connected to one read-out channel, a total number of 384 channels were required to cover the read out of the MWPC; 118 channels for the X, 118 channels for the Y plane and 148 channels for the U plane. The signals from the wires are read out via a PCOS-III electronics system (LeCroy's Proportional Chamber Operation System). The read-out signals from the wires are amplified and sent to a discriminator. Then, the logic signal outputs are delayed and registered using a programmable delay and latch unit. The information from the delay and latch unit is collected by a CAMAC⁷ PCOS unit and sent to a VME⁸ memory unit via a hand-shaking protocol. The strobe signal for the PCOS controller is received from the common trigger signal.

⁷Computer-Aided Measurement And Control

⁸Versa Module Eurocard

Figure 3.16: A sketch of the electronics of the MWPC in BINA. The MWPC has three planes with 236 (X), 236 (Y), and 296 (U) wires in each plane. The read-out is based on a PCOS-III data-acquisition system. See the text for more details.

3.5.5 The trigger system of BINA

Our scattering experiment may lead to various outgoing channels such as elastic and break-up channels. Four different trigger conditions were used in this work. These conditions were based on hit multiplicity⁹ in three groups of photo-multiplier tubes (PMTs); all E -detector PMTs (M_E), the PMTs of ΔE -detector ($M_{\Delta E}$), and all ball PMTs (M_{ball}). Based on these multiplicities, used triggers were defined as follow:

1. **Trigger T1** $\equiv (M_E \geq 3) \text{ OR } (M_{\Delta E} \geq 3)$. After the linear addition of the 20 CFD signals from the E -detectors, the corresponding SUM signal was sent to a leading-edge discriminator. In the case that at least three CFD signals were active, the discriminator was generating an output signal. This means that when a signal will be generated if the multiplicity of firing E -PMTs is larger than 2. The same procedure was applied for the 24 CFD outputs of the ΔE -detectors. The two multiplicity signals from the E - and ΔE -detectors were ORed together which gave the so-called T1 trigger. This trigger has been applied to select the break-up reaction at which two charged particles were registered in coincidence in the wall (wall-wall coincidence).
2. **Trigger T2** $\equiv (M_E \geq 1 \text{ OR } M_{\Delta E} \geq 1) \text{ AND } (M_{ball} \geq 1)$. This trigger was made from a coincidence between an OR signal of all the CFD outputs of the forward scintillators and an OR of all the CFD outputs of the backward ball detectors. This trigger covers both elastic and break-up events in which one particle scatters to forward and the other one to backward part of the detector (wall-ball coincidence).
3. **Trigger T3** $\equiv (M_{ball} \geq 2)$. In this trigger, 149 CFD signals of the backward ball detectors were added to each other to make the SUM signal as input to a leading-edge discriminator. When the multiplicity of firing PMTs of ball detectors was larger than one, the discriminator generated an output signal. Trigger T3 is useful

⁹Multiplicity in this experiment is the number of firing PMTs in an event.

for break-up events in which two particles scatter towards the backward ball.

4. **Trigger T4** $\equiv (\mathbf{M}_E \geq 1) \text{ OR } (\mathbf{M}_{\Delta E} \geq 1) \text{ OR } (\mathbf{M}_{ball} \geq 1)$. The trigger T4 covers any type of event and was, therefore, used as a minimum-bias trigger in which at least one particle registered in the whole setup (singles).

All triggers were combined by a dedicated trigger box to produce a common trigger output. The common trigger output was used to generate the gates of the QDCs, the strobe of the PCOS-III system, and the common stop signal of the TDCs. To reduce the bias on triggers with the larger counting rate, the trigger box can pre-scale the individual triggers by a factor of 2^n ($n = 1, 2, 3, \dots$). Table 3.2 gives overview of typical counting rates which were obtained during our scattering experiments.

Table 3.2: A summary of information about the typical counting rates, and their scaling factors and experimental parameters for this experiment:

data-taking rate	15 kHz
T1 rate	8 kHz
T2 rate	42 kHz
T3 rate	85 kHz
T4 rate	280 kHz
T1 downscaling	2^0
T2 downscaling	2^3
T3 downscaling	2^6
T4 downscaling	2^{10}
live time	70%
data-transfer rate	3.0 Mbytes/s
average size of an event	200 bytes
beam current	10-20 pA

3.5.6 Beam luminosity

A Faraday cup at the end of the beam was used for stopping the beam and monitoring its luminosity. A Faraday cup is made of a copper block containing a heavy alloy metal as the actual beam stopper. In this experiment, only for the last day of the experiment, a precision current meter was readout and connected to the Faraday cup. The output of the current meter was converted into logic signals with a frequency proportional to the actual current and read out by the scalers of the DAQ. This action was taken as the normal readout of the system at very low beam currents was showing some fluctuations. For the data taken on the other days, an alternative method was studied as describe in Ref. [35] to obtain the beam current. The beam current was typically 15 pA.

Chapter 4

Analysis of $\vec{p}d$ break-up reaction

In this chapter, the analysis of the $\vec{p}d \rightarrow ppn$ process at a proton-beam energy of 135 MeV on a liquid deuterium target will be discussed. This chapter gives the steps which were applied to extract the analyzing powers and cross sections for some angular kinematic configurations. First, the energy calibration of the detectors will be presented. Then, based on each break-up S -curve, the event selection will be described. Finally, the procedure for obtaining analyzing powers and cross sections. Some results of these observables will be shown as well.

4.1 Energy calibration

The break-up observables are given as a function of S , the arc length along the S -curve. The S -curve is the kinematical curve presenting the energy correlation between two final-state particles of the break-up reaction (see Sec. 2.4). In this work, the forward-backward configurations in which one of the outgoing protons scatters to the forward wall and the second one to the backward part of the setup were selected. To obtain the desired observable, an accurate energy calibration is needed. Both wall and ball scintillators were calibrated for each angular configuration.

From the forward wall four polar angles (16° , 20° , 24° and 28°) were selected, with the bin-size of $\pm 2^\circ$, as demonstrated in Fig. 4.1. In the following sub-sections, the energy correlation procedure of the wall E and ball scintillators is described briefly.

The ball detectors were classified into six rings and then into subrings based on their geometrical orientation. Each subring consists of triangles with similar orientations. In each orientation the centroid of a triangle coincides with a common polar angle. Figure 4.2 shows schematically a Mercator projection, neglecting the bending of lines, for the back-

Figure 4.1: Schematic view of 10 E -scintillators in the forward wall. The polar angles ($\theta = 16^\circ, 20^\circ, 24^\circ$ and 28°) with the bin-size of $\pm 2^\circ$ and selected azimuthal angles ($\phi = 0^\circ, 90^\circ, 180^\circ$ and 270°) are marked.

ward ball. Because of the statistics, we started from the first rings of the backward ball for analysis and only two subrings of the first ring (r1s1 and r1s2) and one subring of the fourth ring (r4s2) were analyzed. Ball elements were partially transparent, although all ball elements were painted with white color to prevent the light leakage from a given ball detector to its neighbors. Therefore, in order to obtain better energy resolution one can consider a cluster instead of a single element in the track reconstruction procedure, described in Ref. [76]. However, the resolution due to the target thickness and the size of ball elements dominate the one from clustering procedure, as a result, we did not perform a clustering procedure and we selected the highest QDC channel of events in the backward ball for the present analysis.

4.1.1 Theoretical kinematic curve at the detector position

For translating the QDC channel into the deposited energy by a particle, we need to have a reference point. We, therefore, decided to convert the theoretical kinematic curve at the target position into the one at the detector position. This conversion is done by determining the energy loss due to the materials between the target and the detector using GEANT3 simulations. Figure 4.3 shows the relation between the deposited and initial energies of the protons in wall E -detectors for different proton polar scattering angles. At different scattering angles, the length of the path in the material is different for a particle traveling from the target towards the detection point. In the inset, the dependence of the energy loss on scattering angle is visible. The diagonal line is drawn to indicate deviation from a linear correlation.

Figure 4.2: A schematic Mercator projection (bending of lines has been neglected) for the backward ball. Each ring has subrings which consist of triangles with similar orientations. In each orientation, the centroid of a triangle coincides with a common polar angle.

The same relation as in Fig. 4.3 is presented in Fig. 4.4 for different ball scintillators with their centroids placed at a common polar angle with different azimuthal angles. Due to a slight inclination (10°) of the target system, the energy loss is different for the particles going to the ball elements at the same polar angle. Because of the vacuum and the absence of additional materials inside the ball, the main sources of energy loss are the target material, target frame, target window foil and thermal shielding. For a particle impinging to the wall E scintillator, components such as the target material, target window foil, the exit window of the ball, the MWPC, ΔE scintillators, wrapping foils and air are responsible for the energy loss.

Figure 4.3: The simulated correlation between the deposited and initial so-called “thrown” energy of protons in the wall E scintillators for different proton polar scattering angles. In the inset, which depicts the correlation at lower energies, one can see that the energy loss depends on the scattering angle. The diagonal line is drawn to indicate deviation from a linear correlation.

Figure 4.4: Same as Fig. 4.3 except for different ball scintillators at the same polar angle. The inclination of the target system causes asymmetric energy losses for ball elements placed in a specific polar angle.

4.1.2 Jitter in the trigger system

Each wall E -scintillator has two photomultiplier tubes (PMTs) at its two ends. The difference in signal strength between the two PMTs depends on the actual position at which a particle hits the detector. This is due to differences in light attenuation which depend upon the distance between the PMT and the point of impact. By obtaining a geometric mean of the left-PMT signal (C_L) and the right-PMT signal (C_R), i.e. $\sqrt{C_L \times C_R}$, most of the position dependence cancels. In the ball, we have one PMT and two kinds of QDC channels (because of the slow and fast parts of the scintillator response, see Sec. 3.5.2) for each element. For the present analysis, we select the highest QDC channel of events from the fast part, the so-called fast response. In the right panels of Fig. 4.5, the geometric mean of the PMTs' responses of the given wall E -detector (#1) versus the fast PMT response of a chosen ball element (#22) for the configuration ($\theta_1 = 50^\circ, \theta_2 = 28^\circ, \phi_{12} = 140^\circ$)

is presented. Most of the events are from the break-up reaction and one would naively expect a smooth dependence between the two QDC values. Clearly this is not the case and two disconnected bands are observed. The origin of this effect has been traced back to an artefact of the trigger system resulting in mismatch in the timing of the charge-integration gate. The left panels in Fig. 4.5 illustrates the RF-timing spectrum for the selected events. As can be observed, in each bunch of this spectrum there are two peaks and each peak is related to a specific response of the trigger system, demonstrating the timing mismatch in the trigger system. The effect of selecting different regions of the time spectrum on the energy correlation is indicated from top to the bottom rows in this figure. In the next step of the analysis, each group of selected events has been calibrated separately.

Figure 4.5: The effect of jitter in the trigger system on the energy correlation of two protons from the break-up reaction. The left column shows the RF-timing spectrum for the selected events and the right one shows the energy correlation. The effect of selecting different region of the RF-time spectrum on the energy correlation is indicated from top to the bottom rows.

4.1.3 Matching channel to deposited energy

To perform the matching of QDC channel to the deposited energy for a particular configuration and for each RF group, one E scintillator from the wall and one scintillator from the ball were selected. The channel numbers were multiplied by a linear calibration factor to match to the expected kinematical curve. Figure 4.6 shows the same data as depicted in the top-right panel of Fig. 4.5 after applying the matching mentioned above. Since we are interested in S at the interaction point, we, therefore, decided to translate deposited energy to initial energy. The procedure is described in the following section.

Figure 4.6: The deposited-energy correlation between two protons: one detected in a chosen ball element (here #22) and the other in the wall E -detector (#1) for a chosen configuration ($\theta_1 = 50^\circ, \theta_2 = 28^\circ, \phi_{12} = 140^\circ$). The solid line is the expected kinematical correlation of deposited energies for this configuration.

4.1.4 Translating deposited energy to initial energy

Because of the energy loss, the deposited energy in the scintillator is less than the initial energy at the reaction point. The relation between deposited and initial energies (as explained in Sec. 4.1.1) was obtained via a GEANT3 simulation for the protons detected in the wall and ball separately. Using these relations, the energy losses were added to the deposited energies to convert them into initial energies at the interaction point or target position and the result is presented in Fig. 4.7.

Figure 4.7: Same as Fig. 4.6 after correction for energy losses. The measured energies of the protons and curve correspond to the values at the target position or interaction point.

4.2 Selection of events

In order to evaluate the cross sections and analyzing powers of the break-up process $\vec{p}(d, pp)n$ for a specific configuration, we selected the two coincident break-up protons in the final state. The angular bins for event integration were chosen to be $\Delta\theta_1 = 20^\circ$ (size of the ball detector), $\Delta\theta_2 = 4^\circ$ and $\Delta\phi = 10^\circ$.

To obtain the observables as a function of S (see Sec. 2.4), the S -curve is divided into slices (S -bin) of equal width of ΔS (10 MeV) along its length, see Fig. 4.8. The projection of the indicated region in Fig. 4.8 onto the D-axis (a line perpendicular to the S -curve) is shown in Fig. 4.9. The background and signal contributions are obtained by fitting a function composed of a polynomial function (red line), representing the background, and a Gaussian distribution (blue line), representing the signal. The black line corresponds to the sum of both contributions. The number of events underneath the main peak of the signal will be referred to as the number of break-up coincidences for each S -bin. The background of accidental coincidences is located on the right side of the main peak in Fig. 4.9 and it is found to be small. The dominant contribution stems from hadronic interactions of the break-up protons inside the detector or in the material between the target and detector. These events are located at the lower part of the main peak and, therefore, it has been estimated by a GEANT3 simulation and corrected for when determining the

cross sections. Also, in some configurations, there was a background from the elastic channel. These configurations were not considered in the present analysis. The following sections will describe the procedure that was taken to extract the cross section and analyzing powers.

Figure 4.8: The energy spectrum of two coincidence protons coming from the break-up reaction and registered at $(\theta_1 = 50^\circ \pm 10^\circ, \theta_2 = 28^\circ \pm 2^\circ, \phi_{12} = 140^\circ \pm 5^\circ)$. The solid line shows the kinematical curve for the central values of the experimental angular bins.

4.3 Determination of the break-up cross section

This section gives the procedure for extracting the break-up cross section for a chosen kinematical point $(\theta_1, \theta_2, \phi_{12}, S)$. After the projection of the events onto the D-axis for each S -bin, as explained in Sec. 4.2, a polynomial representing all backgrounds (accidental coincidences and hadronic contributions) and a Gaussian representing the signal were fitted to the D-distribution. The integral of the histogram in the range of the D-axis between -3σ and $+3\sigma$ from the peak position is referred to as the number of break-up events, after background subtraction (see Fig. 4.9). The break-up cross section can be expressed as follows:

$$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS} = \frac{N}{Q/Z} \cdot \frac{1}{t \cdot \epsilon} \cdot \frac{1}{\Delta\Omega_1 \Delta\Omega_2 \Delta S}, \quad (4.1)$$

where

- N = The number of counts under the Gaussian peak;
- Q = The total integrated charge collected;
- Z = The charge of the projectile;
- t = The number of scattering centers;
- ϵ = The multiplication of all known efficiencies;
- $\Delta\Omega_1(\Delta\Omega_2)$ = The solid angle for the proton detector in the ball(wall);
- ΔS = The selected window for S on the S -curve.

In this analysis, the cross sections are obtained by taking into account the following conditions and parameters:

1. The MWPC efficiency for protons was found to vary between $\sim 80\%$ and $\sim 95\%$ for most of the E - ΔE hodoscopes, but in some regions it fell down to $\sim 75\%$ [35].
2. The inefficiency originating from hadronic interaction imposed a correction factor of $\sim 8\%$, see Tab. 4.1.

Figure 4.9: The projection of the slice chosen in Fig. 4.8 on the D-axis. The background and signal contributions are obtained by fitting a function composed of a polynomial function (red line), representing the background, and a Gaussian distribution (blue line), representing the signal. The black line corresponds to the sum of both contributions.

Table 4.1: The relevant information used in the analysis of the $\bar{p}d$ break-up reaction.

Beam particle	Polarized protons
Energy	135 MeV
Target	Liquid deuterium
Average beam current	15 pA
Target thickness	3.85 ± 0.2 mm
Average efficiency of MWPC for protons	$92\% \pm 1\%$
Average hadronic efficiency for protons	$92\% \pm 3\%$
Average live-time of the data acquisition	70%
Beam polarization	$p_Z^\uparrow = 0.57 \pm 0.02$ $p_Z^\downarrow = -0.70 \pm 0.04$
Polar angle coverage	$40^\circ < \theta_1 < 60^\circ$ $100^\circ < \theta_1 < 120^\circ$ $14^\circ < \theta_2 < 30^\circ$
Azimuthal opening angle coverage	$0^\circ < \phi_{12} < 180^\circ$
Energy acceptance	$E_1 > 15$ MeV and $E_2 > 25$ MeV
Bin sizes	$\Delta\theta_1 = \pm 10^\circ$ $\Delta\theta_2 = \pm 2^\circ$ $\Delta\phi = \pm 5^\circ$ $\Delta S = \pm 5$ MeV
Number of analyzed configurations	105
Number of obtained data points	~ 1800

3. The effective target thickness was 3.85 ± 0.2 mm, including the bulging effect.
4. The average live-time was $\sim 70\%$.
5. The average beam current was ~ 15 pA [35].
6. Protons with an energy of less than 25 MeV (15 MeV) registered in the wall (ball) were discarded.

The relevant information used in the analysis of $\bar{p}d$ break-up reaction are summarized in Tab. 4.1.

Figure 4.10 shows the cross section, $\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS} [\mu\text{b}/(\text{sr}^2\text{MeV})]$, as a function of S [MeV] for a chosen configuration ($\theta_1 = 50^\circ, \theta_2 = 28^\circ, \phi_{12} = 140^\circ$). This configuration corresponds to break-up protons scattered to a subring which consists of 5 ball elements (#2, #7, #12, #17 and #22) with their centroids placed at a common polar angle of 50° , see Fig. 4.2, in coincidence with protons detected at $28^\circ \pm 2^\circ$ in the forward wall. The top panel shows the cross sections for individual ball elements as specified in the legend with different colors and the bottom one presents the weighted average of those cross sections for each S -bin. The variation of the cross sections in the choice of which ball element was selected is quite obvious, as shown in bottom panel of Fig. 4.10. The shape is reasonable,

Figure 4.10: The cross section is plotted as a function of S [MeV] for the kinematical configuration, $(\theta_1, \theta_2, \phi_{12}) = (50^\circ, 28^\circ, 140^\circ)$. The top panel shows the cross sections for individual ball elements as specified in the legend with different colors and the bottom one presents the weighted average of those cross sections for each S -bin. In the top panel the error bars for all symbols represent statistical uncertainties, which in most cases are smaller than the symbol sizes and in the bottom one the size of the error bars shows the maximum variation of the cross sections for each S -bin as seen in the top panel. The red (dash-dotted), blue (dashed), and black (solid) lines show the average of predictions of Faddeev calculations using CDB (NN), CDB+ Δ (3NF) and CDB+ Δ +Coulomb calculations from Deltuva et al. [78–80], respectively.

though. The red (dash-dotted), blue (dashed), and black (solid) lines show the average of predictions of Faddeev calculations over experimental acceptance using CDB (NN), CDB+ Δ (3NF) and CDB+ Δ +Coulomb calculations from Deltuva et al. [78–80], respectively. The error bars for all symbols in the top panel represent statistical uncertainties, which in most cases are smaller than the symbol sizes.

The variation of the cross sections could have several reasons. The “trigger efficiency” between the various ball detectors could be problematic and may vary from detector to detector. Also, geometric definition of solid angles for ball elements, i.e. the ratio of surface area of the ball element to the distance squared, may not be precise and a Monte Carlo simulation is needed. It is worth mentioning that the detector responses for the ball elements were checked and signal-to-background ratios were found to be the same. In conclusion, we were not able to pin down the cause of these deficiencies within the time limits of this project. Thus, our cross section extraction will give huge systematic uncertainties. Taking into account these systematic uncertainties, the experimental data do not have enough precision to differentiate between the different theoretical curves to understand the nature and details of 3NF effects. We, therefore, decided not to follow-up any further the analysis of cross sections at other kinematical configurations. However, the problem of efficiencies drops out for analyzing powers. This was checked by comparison of analyzing powers for several ball elements placed in a specific polar angle. Contrary to the cross sections, no significant differences were observed, as expected.

4.4 Determination of the break-up analyzing powers

As discussed in the previous section, the projection of the events onto the D-axis for each S -bin was done. The range of the D-axis between -10 MeV and $+10$ MeV, corresponding to distances of -3σ and $+3\sigma$ from the peak position, was selected without background subtraction and normalized to the collected charge, corrected for dead time. The obtained numbers of events as a function of the azimuthal scattering angle ϕ of one of the protons was determined.

Following from Eq. 2.33, the ϕ dependence of the number of events $N_{\xi, \phi_{12}}^{\uparrow} (N_{\xi, \phi_{12}}^{\downarrow})$ for the spin-up state, $\uparrow$ (spin-down state, $\downarrow$) and for a kinematical point (ξ, ϕ_{12}) can be written as:

$$N_{\xi, \phi_{12}}^{\uparrow, \downarrow}(\phi) = N_{\xi, \phi_{12}}^0(\phi)[1 - \sin \phi p_Z^{\uparrow, \downarrow} A_x(\xi, \phi_{12}) + \cos \phi p_Z^{\uparrow, \downarrow} A_y(\xi, \phi_{12})], \quad (4.2)$$

where $\xi=(\theta_1, \theta_2, S)$ denotes all the kinematical variables but ϕ_{12} , and $p_Z^{\uparrow}$ and $p_Z^{\downarrow}$ are the polarization of the up and down polarized beam, respectively, with respect to its quantization axis. $N_{\xi, \phi_{12}}^0$ is the number of events for the case of an unpolarized beam. According

to Eq. 4.2, by eliminating the $N_{\xi,\phi_{12}}^0(\phi)$ term, the following formula is obtained.

$$\frac{N_{\xi,\phi_{12}}^\uparrow(\phi) - N_{\xi,\phi_{12}}^\downarrow(\phi)}{p_Z^\uparrow N_{\xi,\phi_{12}}^\downarrow(\phi) - p_Z^\downarrow N_{\xi,\phi_{12}}^\uparrow(\phi)} = -\sin\phi A_x(\xi, \phi_{12}) + \cos\phi A_y(\xi, \phi_{12}). \quad (4.3)$$

By denoting the left side of Eq. 4.3 by $f_{\xi,\phi_{12}}(\phi)$, one can rewrite the Eq. 4.3 as follows:

$$f_{\xi,\phi_{12}}(\phi) = -\sin\phi A_x(\xi, \phi_{12}) + \cos\phi A_y(\xi, \phi_{12}). \quad (4.4)$$

Thus, A_x and A_y values can be extracted, if one uses the following combinations for mirror configurations $(\xi, +\phi_{12})$ and $(\xi, -\phi_{12})$:

$$g_{\xi,\phi_{12}}(\phi) \equiv \frac{f_{\xi,-\phi_{12}}(\phi) + f_{\xi,+\phi_{12}}(\phi)}{2}, \quad (4.5)$$

and

$$h_{\xi,\phi_{12}}(\phi) \equiv \frac{f_{\xi,-\phi_{12}}(\phi) - f_{\xi,+\phi_{12}}(\phi)}{2}, \quad (4.6)$$

which, using the advantage of parity conservations (see Eq. 2.34), can be express as:

$$g_{\xi,\phi_{12}}(\phi) = \cos\phi A_y, \quad (4.7)$$

and

$$h_{\xi,\phi_{12}}(\phi) = \sin\phi A_x. \quad (4.8)$$

Using the beam polarizations $p_Z^\uparrow = 0.57 \pm 0.02$ and $p_Z^\downarrow = -0.70 \pm 0.04$ from the analysis of the proton-deuteron elastic-scattering using BINA [81], A_y and A_x were evaluated from fitting the right-hand side function of Eq. 4.7 to the experimentally determined distribution $g_{\xi,\phi_{12}}(\phi)$ and fitting the right-hand side function of Eq. 4.8 to the experimentally determined distribution $h_{\xi,\phi_{12}}(\phi)$, respectively. Samples of such fits for a particular S -bin in a given configuration are illustrated in Fig. 4.11. In this analysis, analyzing powers are obtained by taking into account the conditions and parameters which are listed in Tab. 4.1. However, the extraction of the analyzing powers relies on determining ratios of rates measured with up and down polarized beams. Therefore, many experimental factors like detection efficiency of MWPC and scintillators, losses due to particle identification, and uncertainties in the determination of the solid angles should cancel. In Fig. 4.12, examples of the two analyzing powers, A_x and A_y , are shown for one chosen kinematical configuration. The error bars reflect only statistical uncertainties.

The fit quality for the extraction of the analyzing powers has been checked by comparing the distribution of the reduced χ^2 , $\chi_r^2 = \chi^2/\text{n.d.f.}$, of the data with the expected χ_r^2 distribution. A reduced χ_r^2 distribution has a mean (or average) of one. Its curve is skewed to the left and get broader for small degrees of freedom and becomes more symmetric as degrees of freedom increases, approaching a Gaussian distribution for large ones. Fig-

Figure 4.11: Examples of asymmetry distributions with fitted curves obtained for configurations with $\theta_1 = 50^\circ$, $\theta_2 = 28^\circ$, $\phi_{12} = \pm 140^\circ$ and $S = 135$ MeV. The two upper (lower) panels depict the asymmetries $f_{\xi, +\phi_{12}}(\phi)$ and $f_{\xi, -\phi_{12}}(\phi)$ ($g_{\xi, \phi_{12}}(\phi)$ and $h_{\xi, \phi_{12}}(\phi)$). The data are represented as open circles and the red lines show the results of a fit through the data. See text for further details.

Figure 4.12: Examples of the analyzing powers A_x and A_y of the proton-deuteron break-up reaction for one kinematical configuration ($\theta_1 = 50^\circ$, $\theta_2 = 28^\circ$, $\phi_{12} = 140^\circ$). Theoretical predictions are shown as lines, as specified in the legend. For the explanation of the lines, see Fig. 4.10.

Figure 4.13 shows the frequency spectra of the obtained reduced χ_r^2 values in comparison with the expected reduced χ_r^2 distributions (solid lines) with n.d.f. = 4 in case of a perfect fit. The left (right) panel of the figure compares the expected χ_r^2 distribution with the results of our fits for A_x (A_y), respectively. This figure demonstrates that the data do not follow very well the expected chi-square distribution. This means that the errors are underestimated. In order to establish the systematic errors, we increased the statistical errors before the fitting procedure in the extraction of analyzing powers in such a way that χ_r^2

distribution follows the expected curve. The new analyzing powers are slightly different from the old ones introducing a new systematic uncertainty. The size of this uncertainty is generally between 10% to 20% of the statistical uncertainties.

Figure 4.13: The left (right) panel shows the observed reduced χ^2 distribution related to the fitting procedure for determination of the analyzing power A_x (A_y) at $(\theta_1 = 50^\circ, \theta_2 = 28^\circ)$. The label “frequency” refers to the number of configurations for the corresponding bin. The solid curves are the predicted reduced χ^2 distributions.

4.5 Error analysis

Experimental results are influenced by two types of uncertainties, namely the statistical and the systematic one. In the following, an estimation of these uncertainties for the observables obtained in this analysis will be presented.

The statistical uncertainties arise mainly from the error in the number of counts obtained for the break-up coincidences. By introducing the abbreviation $\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS} \equiv d\sigma$, the statistical uncertainty in the differential cross section is given by:

$$\Delta d\sigma|_{stat} = \frac{\sqrt{N}}{Q/Z} \cdot \frac{1}{t \cdot \epsilon} \cdot \frac{1}{\Delta\Omega_1 \Delta\Omega_2 \Delta S}. \quad (4.9)$$

The statistical uncertainty in the analyzing powers A_y and A_x was obtained by performing the error propagation to Eq. 4.5 and to Eq. 4.6, respectively, i.e.,

$$\Delta A_y|_{stat} = \Delta A_x|_{stat} = \frac{1}{2} \sqrt{\left(\Delta f_{\xi,+\phi_{12}}(\phi)\right)^2 + \left(\Delta f_{\xi,-\phi_{12}}(\phi)\right)^2}, \quad (4.10)$$

where the statistical uncertainty in $f_{\xi,+\phi_{12}}(\phi)$ and $f_{\xi,-\phi_{12}}(\phi)$ was obtained by performing the error propagation to the left side of Eq. 4.3, i.e.,

$$\Delta f_{\xi,\pm\phi_{12}}(\phi) = \frac{(p_Z^\uparrow - p_Z^\downarrow) \sqrt{(N_{\xi,\pm\phi_{12}}^\uparrow)^2 N_{\xi,\pm\phi_{12}}^\downarrow + (N_{\xi,\pm\phi_{12}}^\downarrow)^2 N_{\xi,\pm\phi_{12}}^\uparrow}}{\left(p_Z^\uparrow N_{\xi,\pm\phi_{12}}^\downarrow(\phi) - p_Z^\downarrow N_{\xi,\pm\phi_{12}}^\uparrow(\phi)\right)^2}. \quad (4.11)$$

For the break-up cross sections, the main known sources of systematic uncertainties were: the uncertainty in the target thickness ($\sim 5\%$), the average correction for the hadronic reaction efficiency for both protons via a GEANT3 simulation ($\sim 6\%$ for two protons) and the uncertainty in the efficiency determination of the MWPC ($\sim 1\%$ for one proton). Also, there were other unknown sources which caused the big variation of the cross sections for individual ball element (see Sec. 4.3). Therefore, we could not estimate the associated systematic uncertainties and did not go further with the analysis of cross sections.

For the analyzing powers, one of the contributions to the systematic uncertainty, which does not cancel in the ratios given by Eq. 4.3 in Sec. 4.4, stems primarily from the measurements of the beam polarizations. The estimated values of uncertainty originating from the measurement of the beam polarization were $\sim 3\%$ and $\sim 6\%$ for up and down-modes, respectively. Altogether, by adding these two systematic uncertainties in quadrature, the maximum systematic uncertainty associated with this effect for analyzing powers was less than 7% .

In addition, the asymmetries coming from other sources else than A_x can cause systematic uncertainty on the analyzing powers. In order to estimate these effects, we studied coplanar configurations ($\phi_{12} = 180^\circ$) at which the analyzing powers are supposed to be zero. The average A_x values with their corresponding errors are calculated for each coplanar configuration, (θ_1, θ_2) , as shown in Fig. 4.14. All numbers are within 2 standard deviations from zero and are well distributed around zero. Based on this, the detector asymmetry effects are found to be very small (0.0027 based on the sigma of the fit). The shaded band represents the result of a straight line fit through the data. The width of the the band corresponds to a 2σ error of the fit.

The analyzing powers A_x and A_y were extracted by selecting events that fall within 3σ around the peak position in the D -spectrum as shown in Fig. 4.9. With this procedure, we induce a systematic error since we take into account as well some small amount of background events in the analysis. To estimate the effect on A_x and A_y of the residual background, we performed an alternative analysis procedure whereby we fit the D -distribution with a Gaussian signal shape combined with a 3^{th} -order polynomial representing back-

ground contributions. Note that the dominant background contribution is due to hadronic interactions, and are, thereby, still events that originate from the break-up channel. By integrating the Gaussian distribution, we obtained for each ϕ -bin the number of signal events $N_{\xi,+\phi_{12}}^{\uparrow}(\phi)$, $N_{\xi,-\phi_{12}}^{\uparrow}(\phi)$, $N_{\xi,+\phi_{12}}^{\downarrow}(\phi)$, and $N_{\xi,-\phi_{12}}^{\downarrow}(\phi)$ and extracted the asymmetries $f_{\xi,-\phi_{12}}(\phi)$ and $f_{\xi,+\phi_{12}}(\phi)$. The resulting analyzing powers differ at most by 0.016 (0.030) for A_y (A_x) compared to the results of the nominal analysis procedure. These differences are taken as a source of systematic uncertainty in the final results.

The other systematic uncertainties contribute to the fitting procedure discussed in Sec. 4.4. In order to estimate the associated systematic error, the analysis is repeated with increased statistical errors before the fitting procedure. The analyzing powers for the two different sizes of the statistical errors yield a systematic uncertainty which is of the order of 10% to 20% of the statistical uncertainties.

Figure 4.14: The average A_x values with their corresponding errors for coplanar configurations, (θ_1, θ_2) . The shaded band represents the result of a straight line fit through the data. The width of the the band corresponds to a 2σ error of the fit.

Chapter 5

Results and discussion

This chapter discusses the experimental results and their comparison with theoretical predictions for the break-up channel in $\vec{p} + d$ scattering at an incident proton beam energy of 135 MeV. First, in order to perform reasonable comparisons of the experimental data with the theoretical models, the averaging of the theoretical predictions over the detector acceptances is explained. Then, the experimental results of analyzing powers (A_x and A_y) are presented for some selected configurations in which one of the final-state protons scatters to the forward wall and the other one to the backward ball of BINA. Next, a systematic comparison between the data and theory is made. Finally, the end of this chapter is devoted to a discussion about the results.

5.1 Averaging of the theoretical predictions over experimental acceptance

As explained in Ch. 4, each ball detector covers a large solid angle. As a consequence, the experimentally-extracted observables are integrated over a large part of the solid angle, and, hence, one cannot simply assume that the results correspond to the central coordinate of the detector. Thus, in order to perform a fair comparison between the data and calculations, averaging [82] of the theoretical values of the observables over the experimental detector has to be applied. The integration procedure of the theoretical predictions is discussed in the following.

Figure 5.1 shows the schematic drawing of the backward and forward angular bins that are used to count exclusively the break-up events. First, for each configuration defined by the central values of angles θ_1^c , θ_2^c and ϕ_{12}^c , the theoretically-determined analyzing powers (A_x and A_y) and cross sections (σ) are obtained for all combinations of angles $\theta_1^c + \delta \frac{\Delta \theta_1}{m}$,

Figure 5.1: Schematic drawing of the angular bins used for event integration at ($\theta_1 = 50^\circ, \theta_2 = 28^\circ$). Indices “1” and “2” represent the backward and forward identities, respectively. The central configuration ($\theta_1^c, \theta_2^c, \phi_{12}^c$) is marked with red and other combinations of angles are shown by purple with m and n taking values of 5 and 6, respectively (specified in the legend). Note that the numbers in the legend are specific for the detector shown here.

θ_2^c and $\phi_{12}^c + \gamma \frac{\Delta \phi_1}{n}$, where m and n are natural and δ and γ are integer numbers (specified in the legend). Only those combinations that fall within the acceptance of the detector are considered without taking into account the size of the forward angular bins; see Fig. 5.1. Then, analyzing-power values are weighted with the product of the 5-fold differential cross section for that value of the angle and the solid angle factor, while the cross section values are only weighted with the solid angle factor. Finally, the weighted observables are placed on the E_1 versus E_2 plane to project them onto the relativistic S -curve calculated for the central angles θ_1^c, θ_2^c and ϕ_{12}^c . In this way, the results of non-relativistic calculations are projected onto relativistic kinematics and, therefore, non-relativistic calculations can be directly compared to the S distributions of the data, without the necessity to correct for difference of arc-lengths calculated along relativistic and non-relativistic S -curves. Note that in this step, the variable S was not used as a reference point for the configurations because S is defined individually for each of them, therefore, the same values of S for different configurations correspond usually to different (E_1, E_2) points.

The importance of the averaging procedure is shown in Fig 5.1. This figure depicts the results of various theoretical predictions based on the coupled channel approach from the Hannover group, including the extended CD-Bonn (NN) potential with a virtual Δ excitation as 3NF and accounting for Coulomb interaction. The theoretical curves marked

with purple refer to various combinations of the θ_1 , θ_2 and ϕ_{12} within the bin-sizes (see Fig. 5.1), which are taken into account in the averaging procedure. The thick red lines represent the calculations for the central configurations, whereas the black ones present the final results of the averaging approach. Differences between the thick red and black lines are clearly observed pointing to the fact that averaging of values of observables for such large detection elements is necessary.

Moreover, it has been checked that employing of more dense grid of angles for averaging has very small influence on the results. In order to estimate the associated effect, the averaging procedure was repeated with more and less combinations of angles. The maximum differences in A_x and A_y are found to be 0.006 and 0.010, respectively.

Figure 5.2: The theoretical calculations which are taken into account in the averaging procedure for the central configuration, $\theta_1^c = 50^\circ$, $\theta_2^c = 28^\circ$ and $\phi_{12}^c = 140^\circ$. The thick red and black lines represent the central and average values of the observable for this configuration, respectively.

5.2 Experimental results

The results of analyzing powers measurements are obtained for forward-backward configurations in which one of the final-state protons scatters to the forward wall and the other one to the backward ball of BINA. For the procedure that was used to select the events, we refer to Ch. 4. An example was given for a specific configuration. Here, we present the results for a large range in which the proton polar angle θ_1 in the backward ball is changed in the range from 40° to 60° and 100° to 120° , for θ_2 in the forward wall a range from 14° to 30° with the step of 4° is selected and azimuthal opening angle ϕ_{12} for the two protons is varied with the step of 20° in the range from 20° to 180° . The values of our observables are extracted for the part of the phase space in which $E_1 > 15$ MeV and $E_2 > 25$ MeV. These cuts include the energy necessary for the protons to reach the detectors, namely 10 and 20 MeV, and the threshold that was used in the CFD which was about 5 MeV. The bin size along the kinematical S -curve is set to be ~ 10 MeV. The analyzing powers for the chosen configurations are presented in Figs. 5.3-5.14. Note that the coplanar configurations $(\theta_1, \theta_2, \phi_{12}) = (107^\circ, 16^\circ, 180^\circ)$, $(107^\circ, 20^\circ, 180^\circ)$ and $(107^\circ, 24^\circ, 180^\circ)$ have been excluded from the analysis, since in those cases, the background from the proton-deuteron elastic channel was overwhelming and could not be reduced significantly by PID.

Experimental results are influenced by two types of uncertainties, namely the statistical and the systematic one. In the figures the error bars represent the statistical uncertainties only. The statistical uncertainties arise mainly from the error in the number of counts obtained for the break-up coincidences.

In Figs. 5.3-5.14, the theoretical predictions (provided by Deltuva et al. [78–80]) were obtained based on realistic NN potential CD-Bonn (CDB) with the inclusion of the Coulomb interaction (CDB+C) and according to the coupled-channel approach with the CDB+ Δ potential and including the Coulomb force (CDB+ Δ +C). To compare them with the experimental data, they are all averaged over the detector acceptance, see Sec. 5.1. The red (dash-dotted), blue (dashed), and black (solid) lines represent the final results of the averaging approach for CDB, CDB+C and CDB+ Δ +C calculations, respectively.

5.3 Systematic comparison of the results with theory

To have other views on the data with higher statistics, two types of quantities are considered [33, 35].

The first one is the average of the observables. In this method, both measured and calculated data points of the analyzing powers (A_x and A_y) for each configuration, $(\theta_1, \theta_2, \phi_{12})$, are averaged over S using the following equation:

Figure 5.3: The analyzing powers at $(\theta_1 = 45^\circ, \theta_2 = 16^\circ)$ as a function of S for different azimuthal opening angles. Error bars shown reflect only statistical uncertainties. The red (dash-dotted), blue (dashed), and black (solid) lines show the average of predictions of Faddeev calculations using CDB (NN), CDB+ Δ (3NF) and CDB+ Δ +Coulomb calculations from Deltuva et al. [78–80], respectively. In some cases, the calculations are not distinguishable.

Figure 5.4: Same as Fig. 5.3 except for $(\theta_1 = 45^\circ, \theta_2 = 20^\circ)$.

Figure 5.5: Same as Fig. 5.3 except for $(\theta_1 = 45^\circ, \theta_2 = 24^\circ)$.

Figure 5.6: Same as Fig. 5.3 except for $(\theta_1 = 45^\circ, \theta_2 = 28^\circ)$.

Figure 5.7: Same as Fig. 5.3 except for $(\theta_1 = 50^\circ, \theta_2 = 16^\circ)$.

Figure 5.8: Same as Fig. 5.3 except for $(\theta_1 = 50^\circ, \theta_2 = 20^\circ)$.

Figure 5.9: Same as Fig. 5.3 except for $(\theta_1 = 50^\circ, \theta_2 = 24^\circ)$.

Figure 5.10: Same as Fig. 5.3 except for $(\theta_1 = 50^\circ, \theta_2 = 28^\circ)$.

Figure 5.11: Same as Fig. 5.3 except for $(\theta_1 = 107^\circ, \theta_2 = 16^\circ)$.

Figure 5.12: Same as Fig. 5.3 except for $(\theta_1 = 107^\circ, \theta_2 = 20^\circ)$.

Figure 5.13: Same as Fig. 5.3 except for $(\theta_1 = 107^\circ, \theta_2 = 24^\circ)$.

Figure 5.14: Same as Fig. 5.3 except for $(\theta_1 = 107^\circ, \theta_2 = 28^\circ)$.

$$\bar{A}_{x(y)}(\xi) = \frac{\sum_{i=1}^N \frac{A_{x(y)}(\xi, S_i)}{(\Delta A_{x(y)}^{exp}(\xi, S_i))^2}}{\sum_{i=1}^N \frac{1}{(\Delta A_{x(y)}^{exp}(\xi, S_i))^2}}, \quad (5.1)$$

where $\xi=(\theta_1, \theta_2, \phi_{12})$ denotes all kinematical variables excluding S_i . N is the number of data points in S for that configuration, $A_{x(y)}(\xi, S_i)$ is the uncertainty of the data point and i is the index for the variable S running from 1 to N . The uncertainty in the average can be evaluated using standard error propagation to be

$$\Delta \bar{A}_{x(y)}(\xi) = \frac{1}{\sqrt{\sum_{i=1}^N \frac{1}{(\Delta A_{x(y)}^{exp}(\xi, S_i))^2}}}. \quad (5.2)$$

Figures 5.15 and 5.16 represent the averages of the analyzing powers A_x and A_y , respectively, as a function of the opening azimuthal angle, ϕ_{12} . The errors are statistical and the cyan bands depict only the systematic uncertainties stemming from beam polarization. The averages of the calculations are presented by the same line colors and styles as were chosen for Figs. 5.3-5.14.

The second quantity is the average difference between the experimental data and the theoretical ones for every configuration, $(\theta_1, \theta_2, \phi_{12})$. Equation 5.3 describes this quantity mathematically for the analyzing powers A_x and A_y ,

$$\text{Deviation } A_{x(y)}(\xi) = \frac{\sum_{i=1}^N \frac{A_{x(y)}^{exp}(\xi, S_i) - A_{x(y)}^{the}(\xi, S_i)}{(\Delta A_{x(y)}^{exp}(\xi, S_i))^2}}{\sum_{i=1}^N \frac{1}{(\Delta A_{x(y)}^{exp}(\xi, S_i))^2}}, \quad (5.3)$$

where $A_{x(y)}^{exp}(\xi, S_i)$ and $A_{x(y)}^{the}(\xi, S_i)$ are the experimental and the theoretical analyzing powers at S_i , respectively, for every kinematical configuration, $(\theta_1, \theta_2, \phi_{12})$, N is the number of S points and $\Delta A_{x(y)}^{exp}(\xi, S_i)$ is the uncertainty of the data point. For the uncertainty in the deviation, Eq. 5.2 is utilized. In Figs 5.17 and 5.18, the average differences between the calculations for A_x and A_y and the data are shown by the same line and color styles as used in Figs. 5.3-5.14. The cyan bands depict only the systematic uncertainties stemming from beam polarization for every panel.

5.4 Discussion

The behavior of the discrepancies observed between data and the theoretical calculation is different at small and large azimuthal opening angles, ϕ_{12} . In this section, the discussion of the experimental results and their comparison with the theoretical predictions are presented with respect to ϕ_{12} .

By taking an overall look at the measured data in Figs. 5.3-5.14, we note that the values of the A_x varies between ~ -0.1 and ~ 0.05 whereas the corresponding values for A_y cover a range from ~ -0.3 to ~ 0.2 as a function of S . Furthermore, A_x is less sensitive to S compared to A_y and the effect of the Coulomb force is expected to be negligible as can be seen from the calculations [35].

From Fig. 5.15, the average A_x values are negative and the their variation as a function of ϕ_{12} are in general rather moderate for $\theta_1 < 90^\circ$. The effect of Coulomb and the 3NF effect is small. The Coulomb effect is even negligible. The predictions appear to overshoot slightly the data, in particular towards smaller ϕ_{12} . The deviations are larger than the error. At large ϕ_{12} , the data are very precise and match very well the calculation. Also, almost all average analyzing powers are at their largest absolute values when the opening azimuthal angle, ϕ_{12} , is around 100° .

From Fig. 5.16, the average A_y values are positive and the their variation as a function of ϕ_{12} are in general rather fluctuating for $\theta_1 > 90^\circ$. The size of A_y is rather large towards small ϕ_{12} . The Coulomb contribution is small in general. The Δ 3NF effects start to appear towards smaller ϕ_{12} at small θ_1 and (also) at large ϕ_{12} for large θ_1 . The full calculations overshoot the data towards large ϕ_{12} . In particular, for $\theta_1 = 50^\circ$, only around $\phi_{12} = 100^\circ$, there seems to be agreement, but no significant deviations appear towards both small and large ϕ_{12} . Even at places where the sensitivity to Δ 3NF effects is predicted to be small, the Δ 3NF is not “helping”, contrary, it makes the comparison even worse, in particular at small ϕ_{12} .

From Fig. 5.17, two distinct features can be observed when comparing the results for large azimuthal opening angles, $\phi_{12} > 100^\circ$, with the data corresponding to small azimuthal opening angles, $\phi_{12} \leq 100^\circ$. At larger azimuthal opening angles, $\phi_{12} > 100^\circ$, no major discrepancy is observed between the data and theoretical predictions. The theoretical calculations, namely CDB, CDB+ Δ and CDB+ Δ +C, predict almost the same value as the experiment provides at these large azimuthal opening angles. For $\phi_{12} \leq 100^\circ$, the full calculation including a 3NF, CDB+ Δ , is slightly worse than predictions based upon a calculation without the inclusion of the Δ . Note that all calculations have the largest deviation with respect to the data for $\theta_1 > 90^\circ$.

From Fig. 5.18, we observe that the results of the analyzing powers A_y for most configurations deviate significantly from all theoretical predictions. The theoretical calculations for $\theta_1 < 90^\circ$ ($\theta_1 > 90^\circ$), predict almost the same (different) value for the analyzing power at large (small) azimuthal opening angles, $\phi_{12} > 100^\circ$ ($\phi_{12} < 100^\circ$). The analyz-

ing power A_y for $\theta_1 < 90^\circ$ ($\theta_1 > 90^\circ$), the predictions of CDB (CDB+ Δ) are closer to the data, although the discrepancies remain significant.

To improve our insight into 3NF effects and controlling the consistency of the results, we decided to do a systematic survey of all experimental analyzing powers which are obtained up to now for the $\vec{p}d$ break-up reaction at 135 MeV with BINA. For the first survey, the average analyzing powers versus the azimuthal opening angle, ϕ_{12} , for backward- and forward-forward configurations is presented in Fig. 5.19 to see how the progression is of the results of analyzing powers going from forward to backward angles. For a fixed angle of one of the protons hitting the forward detector, the progression for the other proton while going towards backward angles shows that the average A_y values become smaller for small ϕ_{12} s. However, for $\theta_1 > 90^\circ$ it becomes larger again and even changes sign.

For an alternative survey of this large database, which covers a wide range of energies for outgoing protons, using invariant coordinates is very useful. The relative energy of the two outgoing protons in the $\vec{p}d$ break-up reaction is one of these invariant coordinates, more details can be found in Refs. [17, 83]. The differences between calculations including a 3NF and the data are shown as a function of the relative energy of the two outgoing protons in Fig. 5.20. In the two upper panels, the differences between calculations including a 3NF and the data for the analyzing power A_x is shown as a function of the relative energy of the two outgoing protons for coplanar and non-coplanar configurations. The bottom panel shows the differences for the analyzing power A_y for all configurations. For these observables, the larger differences between the model predictions and the data come from kinematics for which the relative energy of the outgoing protons is small. The agreement seems to be reasonable at large relative energies. To look at the relative energy progression going from forward to backward angles in order to verify the theoretical calculations, a plot is made, in the same way, for the analyzing power A_y from Ref. [35] for the forward-forward configurations; see Fig. 5.21. Note that the analyzing powers A_x are not extracted for these configurations. It can be concluded that our data fits well in the trend that was observed earlier for the forward-forward configurations.

Figure 5.15: The average of the analyzing power A_x over S for every kinematics configuration (θ_1, θ_2) versus ϕ_{12} . The lines correspond to the same calculations as shown in Figs. 5.3-5.14. The cyan bands depict only the systematic uncertainties stemming from beam polarization for every panel.

Figure 5.16: Same as Fig. 5.15 except for A_y .

Figure 5.17: The average difference between the experimental analyzing power A_x and the theoretical predictions, which are shown by the same line styles as used in Figs. 5.3-5.14, versus ϕ_{12} for a fixed (θ_1, θ_2) . The cyan bands depict only the systematic uncertainties stemming from beam polarization for every panel.

Figure 5.18: Same as Fig. 5.17 except for A_y .

Figure 5.19: The analyzing powers, averaged over S for every kinematics configuration (θ_1, θ_2) versus ϕ_{12} for backward- and forward-forward configurations. The experimental data of forward-forward configurations $(\theta_1 \leq 28^\circ, \theta_2 \leq 28^\circ)$ are taken from Ref. [35]. Similarly, the average analyzing powers for the theoretical predictions are produced and are presented by the same line styles as were chosen for the lines depicted in Figs. 5.3-5.14. The cyan bands depict only the systematic uncertainties stemming from beam polarization for every panel.

Figure 5.20: Results of the calculations are subtracted from all corresponding data points for analyzing powers of the $\bar{p}d$ break-up reaction at 135 MeV for forward-backward configurations. In the two upper panels, the differences between calculations including a 3NF and the data for the analyzing power A_x is shown as a function of the relative energy of the two outgoing protons for coplanar and non-coplanar configurations. The bottom panel shows the differences for the analyzing power A_y for all configurations.

Figure 5.21: Results of the calculations are subtracted from all corresponding data points for analyzing powers of the $\bar{p}d$ break-up reaction at 135 MeV for forward-forward configurations. Data are taken from Ref. [35]. See Fig. 5.20 for a complete description of the plot.

Chapter 6

Summary, conclusions and outlook

6.1 Summary and conclusions

At present, existing NN potentials such as Argonne-V18 [4], CD-Bonn [3], Reid-93 [6], Nijmegen-I [6] and Nijmegen-II [6] provide an excellent description of NN scattering observables and of the properties of the deuteron. However, exact calculations employing 2NFs alone are not sufficient to describe, with similar accuracy as the two-nucleon system, systems consisting of more than two nucleons. For example, none of the NN potentials can reproduce the binding energy of the simplest three-nucleon system, the triton [9]. A similar underbinding occurs for other light nuclei as well [8]. More details can be found in Sec. 1.1. The most promising and widely-investigated solution is often referred to as a three-nucleon force (3NF), a contribution that cannot be reduced to pair-wise forces. The 3NFs arise in the framework of meson exchanges as an intermediate excitation of a nucleon to a Δ -isobar such as Urbana-IX (UIX) [57] and Tucson-Melbourne (TM99) [54] or they appear fully naturally in Chiral Perturbation Theory (ChPT) at a certain order [58, 59]. Alternatively, the 3NFs can appear in the coupled-channel approach with an explicit Δ -isobar excitation like the CD-Bonn+ Δ (NN+3NF) [60, 61].

The importance of 3NF contributions to the dynamics of systems of more than two nucleons was first established in binding energies of few-nucleon states [8]. Further verification of the role of the 3NF has been carried out on the basis of scattering experiments. Various observables were measured in elastic nucleon-deuteron scattering and in the break-up of the deuteron via its collision with a nucleon. An extensive discussion of the present status of our understanding of the three-nucleon system dynamics of the dynamics of the three-nucleon system, based on modern calculations and many precise and rich data sets,

can be found in reviews [15–17]. The 3NF turned out to be very important for improving the description of the cross section for nucleon-deuteron elastic scattering data. At beam energies above 100 MeV per nucleon certain discrepancies between data and calculations still persist, though significantly reduced as compared to predictions based on purely NN potentials. On the other hand, the precise experimental data demonstrate both the successes and the difficulties of the current models in describing cross sections, analyzing powers, spin-transfer and spin-correlation coefficients for Nd elastic scattering [83].

In the past three decades, many measurements have been carried out at KVI and at other laboratories to obtain high-precision data sets to provide a better understanding of the underlying dynamics of the 3NF. The experimental studies of the ${}^2\text{H}(\vec{p}, pp)n$ reaction at 135 and 190 MeV [39, 40] show a large (and growing with beam energy) discrepancy between the measured data and the theoretical predictions for the vector analyzing power. These discrepancies between the measured data and theory predictions with currently available 3NF models demonstrate that spin-dependent parts of the 3NFs are not completely understood [21]. Based on these observations, and considering the rich phase space of the break-up reaction, it was decided to extend the analysis of the data taken in 2006 at KVI. In this work, we extended the earlier analysis [16] that were done for kinematical configurations in which protons scatter to small forward angles up to 35° angles by analyzing configurations at which one of the final-state protons scatters to the backward part of BINA.

BINA is composed of two parts: the (forward) wall and the (backward) ball. The wall consists of a Multi-Wire Proportional Chamber (MWPC) and a segmented hodoscope of thin (2 mm) and thick (12 cm) scintillators for the determination of the energy of the charged reaction products. The wall covers the polar angles, θ , between 10° and 35° , and the full range of the azimuthal angle ϕ . The ball has 149 phoswich scintillator elements which are glued together and cover polar angles between 40° and 160° . These detectors also act as the scattering chamber. A beam of polarized protons produced in an atomic-beam type polarized ion source from the AGOR accelerator impinged on liquid-deuterium target with a thickness of 3.85 ± 0.2 mm which was mounted in the center of the ball of BINA; see Fig. 3.5.

The results of analyzing powers measurements for both A_x and A_y are presented in this thesis. For the event-selection procedure, the proton polar angle θ_1 in the backward ball varies from 40° to 60° and 100° to 120° and θ_2 varies from 14° to 30° with steps of 4° . The azimuthal opening angle φ_{12} for the two protons varied with steps of 20° in the range from 20° to 180° . Spin observables are extracted for part of the phase space in which $E_1 > 15$ MeV and $E_2 > 25$ MeV. The bin size along the kinematical S -curve is set to be ~ 10 MeV. Due to the size of the detector elements at the backward angles, a large variation of theoretical predictions is observed within the angular bins. Thus, in order to perform a fair comparison between the data and calculations, the theoretical values of the observables were averaged over the experimental acceptance.

By taking an overall look at the measured A_x results, we note that the values of A_x vary between ~ -0.1 and ~ 0.05 whereas the corresponding values for A_y cover a range

from ~ -0.3 to ~ 0.2 as a function of S . Generally, A_x varies less with S compared to A_y . The effect of Coulomb and the 3NF effect is small. The Coulomb effect is even negligible. The average A_x values are negative and their variation as a function of ϕ_{12} are in general rather moderate for $\theta_1 < 90^\circ$. The predictions appear to overshoot slightly the data, in particular towards smaller ϕ_{12} . At large ϕ_{12} , the data are very precise and match very well the calculation. Also, almost all average analyzing powers are at their largest absolute values when the opening azimuthal angle, ϕ_{12} , is around 100° . Two distinct features can be observed when comparing the results for large azimuthal opening angles, $\phi_{12} > 100^\circ$, with the data corresponding to small azimuthal opening angles, $\phi_{12} \leq 100^\circ$. At larger azimuthal opening angles, $\phi_{12} > 100^\circ$, no major discrepancy is observed between the data and theoretical predictions. The theoretical calculations, namely CDB, CDB+ Δ and CDB+ Δ +C, predict almost the same value as the experiment provides at these large azimuthal opening angles. For $\phi_{12} \leq 100^\circ$, the full calculation including a 3NF, CDB+ Δ , is slightly worse than predictions based upon a calculation without the inclusion of the Δ . Note that all calculations have the largest deviation with respect to the data for $\theta_1 > 90^\circ$.

For A_y , the average values are positive and their variation as a function of ϕ_{12} are in general rather fluctuating for $\theta_1 > 90^\circ$. The size of A_y is rather large towards small ϕ_{12} . The Coulomb contribution is small in general. The Δ 3NF effects start to appear towards smaller ϕ_{12} at small θ_1 and (also) at large ϕ_{12} for large θ_1 . The full calculations overshoot the data towards large ϕ_{12} . In particular, for $\theta_1 = 50^\circ$, only around $\phi_{12} = 100^\circ$, there seems to be agreement, but no significant deviations appear towards both small and large ϕ_{12} . Even at places where the sensitivity to Δ 3NF effects is predicted to be small. The Δ 3NF is not “helping” resolve the discrepancy; to the contrary, it makes the comparison even worse, in particular at small ϕ_{12} . The results of the analyzing powers A_y for most configurations deviate significantly from all theoretical predictions. The theoretical calculations for $\theta_1 < 90^\circ$ ($\theta_1 > 90^\circ$), predict almost the same (different) values for the analyzing power at large (small) azimuthal opening angles, $\phi_{12} > 100^\circ$ ($\phi_{12} < 100^\circ$). For the analyzing power A_y at $\theta_1 < 90^\circ$ ($\theta_1 > 90^\circ$), the predictions of CDB (CDB+ Δ) are closer to the data, although the discrepancies remain significant.

To compare the data to previously published data for the $\vec{p}d$ break-up reaction at 135 MeV, the differences between calculations including a 3NF and the data are made as a function of the relative energy of the two outgoing protons. For our data, the larger differences between the model predictions and the data come from kinematics for which the relative energy of the outgoing protons is small. The agreement seems to be reasonable at large relative energies. This trend is also observed for previous results corresponding to forward-forward configurations [35].

In conclusion, we measured for the first time A_x and A_y in the proton-deuteron break-up reaction for forward-backward configurations. We, thereby, extended the database of spin observables at intermediate energies, e.g. 135 MeV. The data can be used as a benchmark for testing 3NF effects. Large fluctuations in efficiency or solid angle coverage between the various ball detectors were observed. Since we were not able to pin down the cause of these deficiencies within the time frame of the project, we were, unfortunately, not able to

extract cross section data with respectable systematic uncertainties that would reveal any sensitivity to 3NF effects. To understand completely the nature and details of 3NF effects, a very large database consisting of break-up and elastic-scattering data taken at different beam energies is needed since the size and location of discrepancies between data and theories are energy and angle dependent [35]. The effects of the Coulomb force effects are generally predicted to be very small for the analyzing powers as shown in Figs. 5.3-5.14. It is possible that relativistic and short-range 3NF effects which are not included in the present calculations might be the origin of these discrepancies.

6.2 Outlook

For the break-up reaction, cross sections and analyzing powers have been measured at several energies and for a large range of scattering angles. The database is in good shape for these two observables. However, spin observables cannot always be explained when adding current 3NFs, indicating a defect in the spin-dependent parts of the presently used 3NF models [32]. Therefore, precise data for all kind of spin observables would be needed, for instance spin-correlation and spin-transfer coefficients, in order to pin down 3NF effects.

Spin-transfer and spin-correlation coefficients have been measured only for a couple of energies and in a limited angular coverage. For these observables the spin polarization of more than one of the reactants is measured. If both of the particles whose polarization is known or measured are in the initial channel, or in the final channel, the relevant observable is referred to a ‘spin correlation’ coefficient; if one polarized particle is in the initial and one is in the final channel, the relevant observable is referred to a ‘polarization transfer’ experiment. More details about spin observables can be found in Refs. [63, 65, 84]. It is worth mentioning that these observables are the most difficult ones to measure for a large part of the phase space as one would require a polarimeter in several regions of the phase space. First attempts have been made to measure this observable for a selected kinematics [38]. The extension of these type of measurements might pin down the spin structure of the nuclear forces.

Samenvatting

Momenteel leveren bestaande NN-potentialen, zoals Argonne-V18 [4], CD-Bonn [3], Reid-93 [6], Nijmegen-I [6] en Nijmegen-II [6] een excellente beschrijving van NN-verstrooiingsparameters en de eigenschappen van deutron. Toch zijn exacte berekeningen die enkel berusten op 2NF's niet voldoende om, met eenzelfde precisie als het twee-nucleon-systeem, systemen bestaande uit meer dan twee nucleonen te beschrijven. Zo kan geen van de bestaande NN-potentialen de bindingsenergie van het simpelste drie-nucleon-systeem, een triton, beschrijven [9]. Een vergelijkbare onderschatting bestaat voor andere lichte atoomkernen [8]. Voor meer details zie Sec. 1.1. De meest veelbelovende en onderzochte oplossing wordt vaak de drie-deeltjeskracht genoemd (3NF), een bijdrage die niet kan worden toegeschreven aan paarsgewijze krachten. De 3NF's verschijnen in het kader van mesonuitwisselingen als een tussenexcitatie van een nucleon naar een Δ -isobar, zoals in Urbana-IX (UIX) [57] en Tucson-Melbourne (TM99) [54], of ze verschijnen volledig natuurlijk in chirale verstoringstheorie (ChPT) vanaf een bepaalde orde [58, 59]. Een andere mogelijkheid is dat 3NF's verschijnen in de gekoppelde-kanaal-benadering met een expliciete Δ -isobar excitatie zoals in CD-Bonn+ Δ (NN+3NF) [60, 61].

Het belang van 3NF bijdragen aan de dynamica van systemen met meer dan twee nucleonen is als eerste opgemerkt in de bindingsenergie van toestanden met weinig nucleonen [8]. Verdere verificatie over de rol van 3NF is uitgevoerd op basis van verstrooiingsexperimenten. Verschillende observabelen zijn gemeten in een elastische nucleon-deutronverstrooiing en in het uiteenvallen van het deutron via zijn botsing met een nucleon. Een uitgebreide discussie van de huidige status van het begrip van de dynamiek van een systeem met drie nucleonen, op basis van moderne berekeningen en veel precieze en rijke datasets, is te vinden in reviews [15–17]. De 3NF blijkt erg belangrijk voor een betere beschrijving van de experimentele data over de werkzame doorsnede bij nucleon-deutron elastische verstrooiing. Bij bundelenergieën boven 100 MeV per nucleon blijven bepaalde discrepanties tussen experimentele data en berekeningen bestaan, hoewel deze discrepanties aanzienlijk minder zijn dan bij voorspellingen op basis van pure NN-potentialen. Aan de andere kant tonen de precieze experimentele data zowel de successen als de moeilijkheden van huidige modellen bij het beschrijven van werkzame doorsneden, analyserende vermogens, spinoverdrachts- en -correlatiecoëfficiënten voor Nd elastische verstrooiing [83].

In de afgelopen drie decennia zijn er veel metingen uitgevoerd bij het KVI en in andere laboratoria om zeer nauwkeurige datasets te verkrijgen om daarmee een beter inzicht te krijgen in de onderliggende dynamiek van de 3NF. De experimentele studies van de $^2\text{H}(\vec{p}, pp)n$ reactie bij 135 en 190 MeV [39, 40] tonen een grote discrepantie (die toeneemt voor hogere bundelenergie) tussen de meetgegevens en de theoretische voorspellingen voor het vector analyserend vermogen. Deze verschillen tussen de gemeten gegevens en theoretische voorspellingen met de momenteel beschikbare 3NF-modellen tonen aan dat spinafhankelijke delen van de 3NF's niet volledig begrepen zijn [21]. Op basis van deze waarnemingen, en rekening houdend met de rijke faseruimte van de opsplitsingsreactie, is besloten om de analyse van de data die in 2006 bij KVI is genomen uit te breiden. In dit werk hebben we de eerdere analyse [16], die is uitgevoerd voor kinematische configuraties waarin protonen zich verspreiden naar kleine voorwaartse hoeken tot 35° , uitgebreid door configuraties te analyseren waarbij een van de protonen in de eindtoestand zich naar het achterste deel van BINA begeeft.

BINA bestaat uit twee delen: de (voorwaartse) muur en de (achterwaartse) bal. De wand bestaat uit een proportionele dradenkamer (MWPC) en een gesegmenteerde hodoscoop van dunne (2 mm) en dikke (12 cm) scintillatoren voor de energiebepaling van de geladen deeltjes in de eindtoestand. De muur heeft een bereik van de poolhoek, θ , van 10° tot 35° en heeft het volledige bereik van de azimutale hoek ϕ . De bal heeft 149 phoswich scintillatorelementen die aan elkaar zijn gelijmd en hoeken tussen 40° en 160° bedekken. Deze detectoren werken ook als de verstrooiingskamer. Een straal gepolariseerde protonen, geproduceerd in de gepolariseerde ionenbron van het type atoomstraal van de AGOR-versneller, botst op een vloeibaar deuterium doelwit met een dikte van $3,85 \pm 0,2$ mm die in het midden van de bal van BINA is gemonteerd; zie Fig. 3.5.

De resultaten van metingen van het analyserend vermogen van zowel A_x als A_y , waarbij A_x nieuw is, worden in dit proefschrift gepresenteerd. Voor de datasetselectieprocedure varieert de polaire hoek van het proton, θ_1 , in de achterwaartse bal van 40° tot 60° en 100° tot 120° en θ_2 varieert van 14° tot 30° , beide in stappen van 4° . De azimutale openingshoek φ_{12} voor de twee protonen wordt gevarieerd in stappen van 20° in het bereik van 20° tot 180° . Spin-observabelen worden geëxtraheerd voor het deel van de faseruimte waar $E_1 > 15$ MeV en $E_2 > 25$ MeV. De klassenbreedte van de kinematische S -curve is ingesteld op ~ 10 MeV. Vanwege de grootte van de detectorelementen bij achterwaartse hoeken wordt een grote variatie waargenomen voor de verschillende hoekklassen, waardoor de betreffende datapunten in overeenstemming zijn met de theoretische voorspellingen. Dus, om een eerlijke vergelijking tussen de data en berekeningen uit te voeren, worden de theoretische waarden van de observabelen gemiddeld over de experimentele acceptantie.

Als we de gemeten resultaten van A_x in het algemeen bekijken, zien we dat de waarden van A_x variëren tussen $\sim -0,1$ en $\sim 0,05$ terwijl de overeenkomstige waarden voor A_y een bereik van $\sim -0,3$ tot $\sim 0,2$ als functie van S bereiken. Over het algemeen varieert A_x minder met S wanneer deze wordt vergeleken met A_y . De bijdrage van de Coulombkracht en 3NF zijn klein, de bijdrage van de Coulombkracht is zelfs te verwaarlozen. De gemiddelde A_x waarden zijn negatief en hun variatie als functie van ϕ_{12} zijn over

het algemeen tamelijk gematigd voor $\theta_1 < 90^\circ$. De theoretische voorspellingen lijken enigszins hoger te liggen dan de datapunten, met name voor kleine ϕ_{12} . Bij grote ϕ_{12} is de data zeer nauwkeurig en komt deze zeer goed overeen met de theorie. Bijna alle gemiddelde analyserende vermogens zijn op hun grootste absolute waarden wanneer de azimuthale openingshoek, ϕ_{12} , ongeveer 100° is. Twee verschillende kenmerken kunnen worden waargenomen als de resultaten voor grote azimuthale openingshoeken, $\phi_{12} > 100^\circ$, worden vergeleken met de resultaten voor kleine azimuthale openingshoeken, $\phi_{12} \leq 100^\circ$. Bij grotere azimuthale openingshoeken, $\phi_{12} > 100^\circ$, wordt geen grote discrepantie waargenomen tussen de data en de theoretische voorspellingen. De theoretische berekeningen, namelijk CDB, CDB+ Δ en CDB+ Δ +C, voorspellen bijna dezelfde waarden als gemeten bij deze grote azimuthale openingshoeken. Voor $\phi_{12} \leq 100^\circ$ is de volledige berekening inclusief 3NF, CDB+ Δ , iets slechter dan voorspellingen op basis van een berekening zonder de Δ . Alle berekeningen hebben de grootste afwijking ten opzichte van de data voor $\theta_1 > 90^\circ$.

Voor A_y zijn de gemiddelde waarden positief en hun variatie als functie van ϕ_{12} schommelt over het algemeen nogal voor $\theta_1 > 90^\circ$. De waarden van A_y zijn vrij groot voor kleine ϕ_{12} . De bijdrage van de Coulombkracht is over het algemeen klein. De Δ 3NF-effecten beginnen te verschijnen voor kleinere ϕ_{12} , voor kleine θ_1 en (ook) voor grote ϕ_{12} bij een grote θ_1 . De theoretische waarden zijn hoger dan de datapunten voor grote ϕ_{12} . Met name voor $\theta_1 = 50^\circ$, enkel rond $\phi_{12} = 100^\circ$, lijkt er overeenstemming te zijn, maar er verschijnen geen significante afwijkingen voor zowel kleine als grote ϕ_{12} . Zelfs op plaatsen waar de gevoeligheid voor Δ 3NF-effecten klein is. De Δ 3NF “helpt” de discrepantie niet. Integendeel, het maakt het verschil nog groter, met name voor kleine ϕ_{12} . De resultaten van de analyserende vermogens A_y wijken voor de meeste configuraties aanzienlijk af van alle theoretische voorspellingen. De theoretische berekeningen voor $\theta_1 < 90^\circ$ ($\theta_1 > 90^\circ$), voorspellen bijna dezelfde (verschillende) waarden voor het analyserend vermogen voor grote (kleine) azimuthale openingshoeken, $\phi_{12} > 100^\circ$ ($\phi_{12} < 100^\circ$). Voor het analyserend vermogen A_y met $\theta_1 < 90^\circ$ ($\theta_1 > 90^\circ$), liggen de voorspellingen van CDB (CDB+ Δ) dicht bij de data, hoewel de verschillen aanzienlijk blijven.

Om de data te vergelijken met eerder gepubliceerde data voor de $\bar{p}d$ splitsingsreactie bij 135 MeV worden de verschillen tussen de berekeningen inclusief een 3NF en de data weergegeven als een functie van de relatieve energie van de twee uitgaande protonen. Voor onze data komen de grotere verschillen tussen de modelvoorspellingen en de data uit kinematica waarvoor de relatieve energie van de uitgaande protonen klein is. De overeenkomst lijkt redelijk te zijn bij grote relatieve energieën. Deze trend wordt ook waargenomen voor eerdere resultaten die overeenkomen met voorwaarts-voorwaartse configuraties [35].

Kortom, wij hebben voor het eerst A_x en A_y gemeten in de proton-deuteron splitsingsreactie voor voorwaarts-achterwaartse configuraties. Wij hebben daardoor de database van spinobservaties bij tussenliggende energieën, dat wil zeggen rond 135 MeV, uitgebreid. De data kan worden gebruikt als criterium voor het testen van 3NF-effecten. Grote fluctuaties in efficiëntie en ruimtehoekbedekking tussen de verschillende baldetectoren werden

waargenomen. Omdat we de oorzaak van deze tekortkomingen niet binnen het tijdsbestek van het project konden achterhalen, konden we helaas geen data - met respectabele systematische onzekerheden - van de werkzame doorsnede verkrijgen die een gevoeligheid voor 3NF-effecten zouden onthullen. Om de aard en details van 3NF-effecten volledig te kunnen begrijpen, is een zeer grote database met data van elastische verstrooiings- en splitsingsreacties nodig die bij verschillende bundelenergieën zijn genomen, omdat de grootte en locatie van verschillen tussen de data en de verschillende theorieën afhankelijk zijn van zowel de energie als de hoeken [35]. Over het algemeen wordt voorspeld dat de effecten van de Coulombkracht erg klein zijn voor de analyserende vermogens, zoals weergegeven in figuren 5.3-5.14. Het is mogelijk dat relativistische 3NF-effecten op korte afstand, die niet zijn opgenomen in de huidige berekeningen, de oorzaak kunnen zijn van deze verschillen.

Voor de splitsingsreactie zijn werkzame doorsnedes en analyserende vermogens gemeten bij verschillende energieën en voor een groot bereik van verstrooiingshoeken. De database staat er voor deze twee observabelen goed voor. Spin-observabelen kunnen echter niet altijd worden verklaard wanneer huidige 3NF's worden toegevoegd, wat duidt op een tekortkoming in de spin afhankelijke delen van de momenteel gebruikte 3NF-modellen [32]. Daarom is nauwkeurige data voor alle soorten spin-observabelen nodig, zoals spincorrelatie en -overdrachtscoëfficiënten, om 3NF-effecten vast te stellen.

Spinoverdrachts- en -correlatiecoëfficiënten zijn slechts voor een paar energieën en voor een beperkt hoekbereik gemeten. Voor deze observabelen wordt de spinpolarisatie van meer dan een van de reactanten gemeten. Als beide deeltjes, waarvan de polarisatie bekend of gemeten is, zich in het initiële of laatste kanaal bevinden, wordt de relevante spinobservabele een "spinrelatie"-coëfficiënt genoemd. Als één gepolariseerd deeltje zich in het initiële kanaal bevindt en de ander in het laatste kanaal, dan wordt de relevante spinobservabele een 'polarisatieoverdrachtsexperiment' genoemd. Meer details over spinobservabelen zijn te vinden in Refs. [63, 65, 84]. Het is vermeldenswaardig dat deze observabelen het moeilijkst te meten zijn voor een groot deel van de faseruimte, omdat men een polarimeter nodig zou hebben in verschillende gebieden van de faseruimte. Er zijn eerste pogingen gedaan om dit te meten voor bepaalde kinematica [38]. De uitbreiding van dit soort metingen kan de spinstructuur van de nucleaire krachten vaststellen.

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