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Proton-deuteron break-up studies with BINA and a review of three-nucleon database

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Proton-deuteron break-up studies with BINA and a review of three-nucleon database

PhD Thesis

to obtain the degree of PhD at the
 University of Groningen
 on the authority of the
 Rector Magnificus Prof. C. Wijmenga
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This thesis will be defended in public on

Friday 10 January 2020 at 12:45 hours

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The background picture of the front cover is Nasir al-Mulk mosque in Shiraz, Iran.
The same picture is printed in its original intensity on the back cover.

*To my dear parents, Aliyar and Farideh
and my dear husband, Amin*

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Chapter 1

Introduction

A detailed description of nuclear forces is essential for understanding the properties of nuclei and the dynamics in few-nucleon scattering processes. Although the nucleon-nucleon (NN) interaction has been studied extensively in the past using proton-proton and proton-neutron scattering data, the role of higher-order forces, such as the three-nucleon force (3NF) remains mysterious.

1.1 The two-nucleon systems

In 1935, a theory for a new force was conceived by the Japanese physicist Hideki Yukawa [1], who suggested that the nucleons would exchange particles between each other and this mechanism would create the force. Yukawa constructed his theory in analogy to the theory of the electromagnetic interaction where the exchange of a (massless) photon is the cause of the force. However, in the case of the nuclear force, Yukawa assumed that the "force-makers" (which were eventually called "mesons") carry a mass which is fraction of the nucleon mass [2]. Later, this particle, the pion, was discovered [3–5] and its mass was found to be close to the mass predicted by Yukawa using the finite range of the nuclear force of ~ 2 fm. Based on the exchange of various mesons, the central component of the nucleon-nucleon potential could be divided into three regions: a long-range part at the distance between the two nucleons of about 2 fm, a middle-range part between 0.7 fm and 2 fm and a short-range part below 0.7 fm, as shown schematically in Fig. 1.1. The longest range attractive two-nucleon force (2NF) is due to the exchange of pions and for the shorter ranges, the exchange of two pions and heavier mesons contribute to the interaction [6–8].

Figure 1.1: A sketch of the nucleon-nucleon potential with the various meson-exchange parts. 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 shows a tree level Feynman diagram of the NN interaction within the meson-exchange picture. The most important result of meson exchange is an excellent phenomenology for describing nuclear forces. It allows for the construction of very quantitative models. Therefore, the high-precision NN potentials constructed in the mid-1990s are all based upon meson phenomenology [2]. More generally, the interaction models are based on a meson-exchange theory or created by phenomenology. Two-nucleon potentials, like CD-Bonn (CDB), Argonne-V₁₈ (AV₁₈), Reid93, NijmegenI (NijmI) and NijmegenII (NijmII) are able to predict observables with a very high precision for 2N systems with χ^2 per degree of freedom of ~ 1 . However, with the rise of QCD to the ranks of the authoritative theory of strong interactions, meson exchange is definitively just a model [2]. Although calculations within lattice QCD are being performed and improved, they are computationally very costly, and thus they are useful, in practice, only to explore a few cases [2]. A large part of the interaction between nucleons is described in meson-exchange theories or in the framework of Chiral Perturbation-Theory (ChPT) [9–11]. This is consistent with the fact that ChPT is a low-momentum expansion. ChPT gives validation to and provides a better

Figure 1.2: Nucleon-nucleon interaction between two nucleons by the exchange of mesons.

framework for 3NFs which were proposed more than 80 years ago and modeled five decades ago; it alleviates existing problems in few-nucleon reactions and the spectra of the light nuclei [2].

1.2 The three-nucleon systems

Although, observables in the two-nucleon systems can be calculated with unprecedented precision using modern two-nucleon potentials, the same potentials are not able to describe the three-nucleon systems very accurately. The need for an additional three-nucleon potential became evident when comparing three-body scattering observables and light-nuclei binding energies with the state-of-the-art calculations [12]. For simplest three-nucleon system, the triton, a precise solution of the three-nucleon Faddeev equation employing only two-nucleon force clearly underestimates the experimental binding energy. This indicates that 2NFs are not sufficient to describe the three-nucleon systems and NN potentials fail to describe the experimental data. This discrepancy becomes even more evident when comparing the results of rigorous calculations for the binding energy of light nuclei with data. Figure 1.3 depicts the binding energy of ground and low-lying excited states of light nuclei [13]. The experimental data are compared with the predictions of a Green's Function Monte Carlo calculation based on (AV_{18}) and 2N+3NF ($AV_{18}+IL2$) potentials [13].

Figure 1.3: The binding energy of light nuclei. The experimental results are compared with 2NF (AV₁₈) and 2N+3NF (AV₁₈+IL2) models [13].

Besides deficiencies in the binding energies of nuclei, the need for an additional three nucleon potential became clear as well by studying nucleon-deuteron scattering observables. In particular, the differential cross section in proton-deuteron scattering revealed a huge sensitivity to higher-order contribution that go beyond the pairwise NN interaction [14]. Moreover, Faddeev calculations solely based on state-of-the-art NN potentials of various spin observables in this reaction failed to describe the experiment data [8, 15–27]. Figure 1.4 shows the comparison between the data to theoretical predictions based on modern NN forces and their combinations with 3NF for $\vec{p}d$ elastic scattering at 108 MeV [20].

In 1957, the first 3NF model, based on two-pion exchange, was described by Fujita-Miyazawa [28]. Figure 1.5 illustrates this 3NF that is based on a two-pion exchange with an intermediate Δ resonance.

There are also other approaches to treat the 3NF in a consistent way

Figure 1.4: The comparison between experimental data for $\bar{p}d$ elastic scattering at 108 MeV and theoretical calculations based on NN potentials with (red bands) and without (gray bands) the TM' three-nucleon potential [20].

Figure 1.5: The 3NF based on two-pion exchange.

with the 2NF. One is based ChPT, an approach that relates to the dynamics of low-energy QCD on an effective-field theoretical manner. Weinberg was the first to discuss nuclear three-body forces in the context of ChPT [29].

Another approach originates from the Hannover-Lisbon groups [30, 31]. Their model extends the CDB NN potential with an additional Δ degree-of-freedom, thereby, dynamically generating the 3NF such as the Fujita-Miyazawa force. We refer to this as CDB+ Δ . Besides extending the potential with the Δ , their model is also able to take into account the Coulomb interaction, referred to as CDB+ Δ +Coulomb. The observed discrepancies between data and calculations based solely on 2NFs are usually viewed as an indication of the existence of a 3NF. Indeed, 3NFs which cannot be reduced to pair-wise NN interactions arise naturally in the context of a meson-exchange theory and at the more fundamental level of QCD [12]. For almost all observables in elastic scattering, the calculations which only include 2NFs fail to a large extent to describe the data, and in particular at higher energies. In addition to the elastic channel, the break-up reaction offers a rich kinematics and as such provides a good testing ground for the structure of the nuclear force [12]. Several theoretical formalism have been made, such as a dynamic Δ [31] and the Tucson-Melbourne [32] 3NFs and these have been embedded within rigorous calculations using the Faddeev-type equations by, for example, Bochum-Kraków [32–35] and Hannover-Lisbon [30, 31, 36, 37] theory groups.

To have a complete picture of the ongoing process in three-nucleon forces, a systematic study of the observables of the break-up reaction has been started at KVI. Figure 1.6 indicates the scattering measurements of cross section and vector analyzing power, A_y , for $d(\vec{p}, pp)n$ reaction at 135 MeV for a few selected configurations that was performed at KVI, using BINA [8] with several theoretical predictions. The blue band depicts the calculations of various existing 2N potential, namely CDB, NijmI, NijmII and AV_{18} . The red band shows the same 2N potentials including the 3NF (TM'). The lines represent predictions of the Faddeev calculations using the AV_{18} (2N) potential including the UIX (3N) potential, dotted black, CDB+ Δ (3NF), green solid, CDB+ Δ +Coulomb (3NF), black solid, and CDB (2NF) including the relativistic effects [38–40], dashed black. The errors are statistical and the cyan band in each panel depicts the systematic uncertainties. The inclusion of 3NFs only

Figure 1.6: The comparison of the results of the cross section and A_y measurements for a few configurations with several theoretical predictions. The blue band shows the results of the calculations of various existing 2N potentials, namely CDB, NijmI, NijmII and AV₁₈. The red band shows the same 2N potentials with the addition of TM', 3N potential. The dotted black, green solid, black solid, and dashed black lines represent predictions of the Faddeev calculations using AV₁₈ potential including the UIX 3N potential, CDB+ Δ (3NF), CDB+ Δ +Coulomb and CDB+Relativistic potential, respectively. The errors are statistical and the cyan band in each panel depicts the systematic uncertainties [8].

partly remedies these deficiencies and the disagreement is still significant. Therefore, the origin of this discrepancy must lie in the treatment of 3NF.

Nucleon-deuteron break-up process is one of the sources for studying three nucleon forces. The aim is to significantly extend the reactions which is suitable for the investigation of the world's database in the three-nucleon system as a benchmark to eventually confine the structure of the three-nucleon interaction. The $\bar{p}d$ break-up reaction was performed with a polarized proton beam at a kinetic energy of 135 MeV using BINA at KVI. The first data analysis was performed in 2009 [8]. In this thesis, the component of vector analyzing power, A_y , and the cross

section are reanalyzed. A_x is measured for the first time. Also for the first time, we performed a Dalitz analysis of the rich database of cross sections and vector analyzing powers for two incident energies of 135 and 190 MeV.

1.3 Outline of the thesis

In the next chapter, an overview of the theoretical calculations used to describe three-nucleon systems will be given and nucleon-nucleon, and three-nucleon potential models are presented. The experimental setup of this work, BINA, and all its components, will be explained in Chapter 3. In chapter 4, the data analysis for the $\vec{p} + d$ break-up reaction is described. Results of the $\vec{p} + d$ break-up reaction together with a discussion are presented in chapter 5. Chapter 6 is devoted to a dedicated study of the spin-isospin dynamics of the $\vec{p} + d$ break-up reaction. Finally, a summary and conclusions of the whole thesis will be presented in Chapter 7.

Chapter 2

Theoretical background

Following the development of precise N-body equations using the presentation in momentum or configuration space, the numerical solution of the three- and four- nucleon problems has been one of the most difficult attempts at the nuclear reaction theory from the early 70s of the last century [36]. Direct nuclear reactions of three-body nature provide an important test for models of nuclear dynamics [41].

Most of the models of 2N forces describe the interaction part according to the meson-exchange picture as shown in the left panel of Fig. 2.1. The present generation of 2N potentials reaches an unprecedented accuracy in describing the pp and np observables below 350 MeV, expressed by a fit quality with a reduced χ^2 of ~ 1 . These types of forces are referred to as realistic potentials, and operate on purely nucleonic degrees of freedom as stable objects. Besides NN potentials that are solely based upon the coupling of mesons and nucleons, some extended this via a coupled-channel approach including other baryons as well. The authors of Ref. [31] extended the NN interaction by accounting for $N\Delta$ and $\Delta\Delta$ interactions with the Δ representing the first excitation of the nucleon. Implementation of such dynamics in the calculations of the observables for the 3N system is based on the picture of two-pion exchange between all three nucleons with an intermediate Δ isobar excitation as shown in the middle and right panel of Fig. 2.1 [42].

In a more fundamental approach, the strong forces between the nucleons should be considered as interactions between their constituent quarks and treated by quantum chromodynamics (QCD). The link between QCD and the 2N interaction phenomenology is provided by effective field theories (EFTs). These methods generate approximations which are both efficient in application and allow to reliably estimate their

Figure 2.1: Schematic diagrams of the structure of the nucleon-nucleon interaction (left) and of the three-nucleon force (middle and right) in the meson-exchange picture [42].

uncertainties [43]. EFTs are useful because they provide a systematic expansion that organizes and extends previous phenomenological knowledge about nuclear processes, and they provide a rigorous connection to QCD.

Chiral perturbation theory (ChPT) has been first outlined by Weinberg [29]. In the case of more than two nucleons, one can expect a necessity to include into the description some additional dynamics, which is called three-nucleon force (3NF). In ChPT, when regarding a system of three nucleons, non-vanishing 3NF graphs appear naturally at the next-to-next-to-leading order (NNLO) [43]. The experimental data for the three-nucleon systems cannot be described on the basis of the modern 2NFs alone.

In this chapter, the basic ingredients to describe the scattering formalism and potentials in the two- and three-nucleon system will be discussed.

2.1 The 2N and 3N scattering formalism

The contents described in this section has been extracted from Refs. [24, 44–47].

In the nucleon-nucleon scattering theory, it is assumed that a wave packet which describes the projectile, approaches a wave which describes the target in the laboratory frame. The behavior of the wave packet before and after the interaction is constrained by boundary conditions. In the non-relativistic limit and in the center-of-mass frame, the dynamics

of the wave function before scattering is the solution of the Schrödinger equation

$$i\hbar \frac{\partial}{\partial t} |\phi(\vec{x}, t)\rangle = H_0 |\phi(\vec{x}, t)\rangle, \quad (2.1)$$

where $H_0 = -\frac{(\hbar)^2}{2m} \nabla^2$ is the Hamiltonian of a freely moving particle. The general solution of Eq. 2.1 is

$$|\phi(\vec{x}, t)\rangle = e^{-iH_0 t} |\phi(\vec{x})\rangle, \quad (2.2)$$

where $|\phi(\vec{x})\rangle$ is the time-independent wave function of the unperturbed state.

As soon as the wave packet approaches the interaction region, the time evolution of the state is given by

$$i\hbar \frac{\partial}{\partial t} |\psi(\vec{x}, t)\rangle = H |\psi(\vec{x}, t)\rangle, \quad (2.3)$$

with the Hamiltonian $H = H_0 + V$, where V is the interaction potential. A general solution to this equation is given by

$$|\psi(\vec{x}, t)\rangle = e^{-iHt} |\psi(\vec{x})\rangle, \quad (2.4)$$

In the absence of any potential, the scattering state $|\psi(t \rightarrow 0)\rangle$ must be equal to a free state, i.e., $|\phi(t \rightarrow 0)\rangle$, with the same energy which implies that

$$\lim_{t \rightarrow -\infty} \|e^{-iHt/\hbar} |\psi\rangle - e^{-iH_0 t/\hbar} |\phi\rangle\| = 0. \quad (2.5)$$

The relation between the scattering and the free states can be written as [44]

$$|\psi^\pm\rangle = \lim_{\epsilon \rightarrow 0} i\epsilon \frac{1}{E - H \pm i\epsilon} |\phi\rangle, \quad (2.6)$$

where H is the total Hamiltonian and E the eigen energy of the state ϕ . In the three-body system the Hamiltonian can be decomposed as

$$H = H_0 + V_i + V^i \equiv H_i + V^i, \quad (2.7)$$

where H_0 is the kinetic energy, H_i the so-called channel Hamiltonian with one pair interaction $V_i \equiv V_{jk}$ ($j \neq i, k \neq i$) and V^i the sum of

the remaining two interactions with the i^{th} particle. We shall use this convenient notation to denote a pair by the number of the third particle. Obviously ϕ_i is an eigenstate of H_i with the eigen energy, E . Now, using the resolvent identities, we obtain

$$\begin{aligned} \frac{1}{E - H \pm i\epsilon} &= \frac{1}{E - H_0 \pm i\epsilon} + \frac{1}{E - H_0 \pm i\epsilon} V^i \frac{1}{E - H \pm i\epsilon} \\ &= G_0 + G_0 V^i G, \end{aligned} \quad (2.8)$$

for $i = 1, 2, 3$, where $G_0 = (E - H_0 \pm i\epsilon)^{-1}$ is the free-particle propagator. We can define $G_{\pm} = \frac{1}{E - H \pm i\epsilon}$ as the resolvent or Green's function for the Helmholtz equation

$$(\nabla^2 + k^2)G_{\pm}(\vec{x}, \vec{x}') = \delta(\vec{x} - \vec{x}'). \quad (2.9)$$

By substituting Eq. 2.8 into Eq. 2.6 and knowing that $i\epsilon G_0|\phi\rangle = |\phi\rangle$, we get the *Lippmann-Schwinger Equation* (LSE)

$$|\psi^{\pm}\rangle = |\phi\rangle + G_0 V |\psi^{\pm}\rangle. \quad (2.10)$$

In the region far from the interaction point, the wave function $\langle \vec{x} | \psi^{\pm} \rangle$ is a combination of the incident wave $\langle \vec{x} | \phi \rangle$, and an outgoing (incoming) spherical wave corresponding to the positive (negative) solution.

In the scattering process, we are interested in the transition of the initial state to a final state via the intermediate state, $|\psi^+\rangle$. The transmutation operator, t , is defined by

$$V|\psi^+\rangle \equiv t|\phi\rangle. \quad (2.11)$$

Multiplying the LSE by V from the left results in

$$t = V + V G_0 t. \quad (2.12)$$

The t -matrix can be evaluated iteratively (Born series) by

$$\begin{aligned} t &= V + V G_0 (V + V G_0 t) \\ &= V + V G_0 V + V G_0 V G_0 V + V G_0 V G_0 V G_0 V + \dots \end{aligned} \quad (2.13)$$

This can be shown diagrammatically for a system with two nucleons as shown in Fig. 2.2. The potential V is represented by the wiggled

Figure 2.2: The t operator is represented by the series of diagrams and the potential, V , in terms of meson scattering. Figure is taken from Ref. [47].

lines and can be expanded in terms of meson scattering represented by dashed lines.

The matrix elements of the transition operator in the momentum space are used to obtain the cross section

$$\frac{d\sigma}{d\Omega} \propto |\langle p' | t(E + i\epsilon) | p \rangle|^2. \quad (2.14)$$

The state $|p\rangle$ defines the beam momentum and the state $|p'\rangle$ is defined by the momentum of scattered particle.

Nowadays, exact theoretical descriptions for the 3N system can be obtained by using the Faddeev equations with realistic potentials and with model 3NF interactions. The non-uniqueness of the Lippmann-Schwinger equation (LSE) has been pointed out by Faddeev and he could overcome this problem by splitting up the LSE to three equations with a unique solution [47].

2.2 The nucleon-nucleon potentials

A few 2N potentials in the 70s and 80s of last century were developed based on the meson-exchange theory. These were the Paris [48–50], Bonn [51], Nijmegen-78 [52] and Argonne- V_{14} [53] potentials. The meson-nucleon coupling constants are considered as free parameters and are obtained via fitting the potentials to the world data set of 2N scattering. The quality of the fits was given by a reduced $\chi^2 \gtrsim 2$ which came mostly from a fairly large number of bad data points that were included in the world database. Around 1990, the Nijmegen group developed their energy-dependent phase shift [54, 55] and multi-energy partial-wave analysis (PWA) [6, 56]. The difference to the former phase-shift analysis

was that their phase-shift analysis could use the scattering data in a large range of incident-beam energies and the pion-nucleon coupling constant could be extracted from the scattering data very precisely [57]. So called “bad data” were discarded by a statistical analysis of world’s dataset of 2N scattering experiments. Based on partial-wave analysis, a number of so-called high-quality potentials were developed, namely, Nijmegen-I, Nijmegen-II and Reid93 [7]. In these high-quality potentials, the meson-coupling constants are fitted to the database of experimental nucleon-nucleon scattering for each partial wave separately, except for the pion-nucleon coupling constant. Note that for large angular momenta, only the pion contributes and all partial waves are consistent with that coupling alone. The PWA has 39 parameters and has been fitted to 4301 data points of all pp and np scattering data with the reduced $\chi^2 \simeq 0.99$ and it is possible to calculate rather precisely nucleon-nucleon scattering observables up to energies of ≈ 300 MeV [58]. Also for the Bonn potential, which was built on a meson-exchange principle, a parameterization in each partial wave was used and its successor, Charge-dependent Bonn (CD-Bonn) potential [59], was fitted to the 2N scattering database which also resulted in a reduced $\chi^2 \approx 1$.

The high-quality potentials mentioned here were all constructed with the purpose of calculating two-nucleon scattering observables. Another potential, the AV_{18} [60], was constructed as an input for Green’s function Monte Carlo calculations of nuclear matter, and is built along the same lines as the other potentials. The four additional terms in the AV_{18} potential (as compared with AV_{14}) are charge-independence breaking terms.

All these so-called high-quality potentials, NijmI, NijmII, Reid93, CD-Bonn and AV_{18} contain ≈ 40 fit parameters. The results of all these potentials for two-nucleon observables agree with each other, but the potentials show different off-shell effects. However, these cannot be measured experimentally. Since the coupling constants are fitted in each partial wave, their physical content is meaningless [7] and apart from the one-pion exchange, the potentials are in large part based on phenomenology. A different approach is provided by the Hannover-Lisbon theory group, where the Δ -isobar is treated on the same footing as the nucleon, resulting in a coupled channel potential CD-Bonn+ Δ [30, 31] with pairwise nucleon-nucleon and nucleon-isobar interactions mediated through the exchange of π , ρ , ω , and σ mesons [8].

More recently, another approach, namely the Chiral Perturbation Theory (ChPT) has been developed for studying the NN interactions. In this

framework, all nuclear forces such as 2NF, 3NF, and 4NF are included simultaneously and consistently.

2.3 The three-nucleon potentials

The idea of the existence of a three-nucleon potential already dates back to the 30s of the last century. However, it was not until the 50s of the last century when Fujita and Miyazawa described the 3NF with two-pion exchange (TPE) between three nucleons with an intermediate excitation of one nucleon into its first excited state, the Δ -isobar [28]. Later, more refined ingredients have been added leading to the Tucson-Melbourne (TM) [61] and corrected Tucson-Melbourne (TM' or TM99) 3NFs [62–64] allowing for additional processes contributing to the re-scattering of the mesons. In addition to this, other 3NF models such as Urbana IX were developed. One could also treat the intermediate Δ as a dynamic state to create an effective 3NF. The third approach for describing three-body systems is based on ChPT [9]. In the following, a short description of these potentials is given.

2.3.1 Hannover-Lisbon potential

The Hannover-Lisbon group investigates the correction mechanisms of the microscopic nuclear structure which arise from the internal nucleonic degree of freedom seen in the Δ -isobar excitation to obtain an effective 3NF from any 2NF [30, 31, 36, 37, 65]. In this model, an explicit Δ -isobar is added to the nucleonic Hilbert space of a three-nucleon system [66]. The Δ -isobar is considered as a stable particle rather than a π N system [65]. The Δ -degree of freedom is treated in a coupled-channel approach. This approach emphasizes the need for consistency between the two-nucleon interaction and the correction mechanisms of the microscopic nuclear structure due to Δ -isobar excitation. A two-baryon Coupled-Channel Potential (CCP) was developed which couples two-nucleon states to nucleon- Δ states. The transition potential from 2N to $N\Delta$ states is derived from π - and ρ -exchange. The advantage of CCP is that it treats the 3NF in a consistent way with the 2N interaction via including the short-range (heavier mesons and multi-pion exchange). Within CCP approach, the Hannover-Lisbon group managed to include, for the first time, the (shielded) Coulomb interaction into the calculations of 3N systems [67]. The Coulomb interaction between protons has been

included in the potential in 2005 for the first time [68]. The CD-Bonn+ Δ potential was employed to describe elastic and inelastic 3N scattering processes [31].

2.3.2 Tucson-Melbourne potential

The Tucson-Melbourne (TM) potential was one of the first serious attempts, to build a complete three-nucleon force with the inclusion of short- and long-range parts of the interaction based on two-pion exchange. The TM' 3N force relies on a low momentum expansion of the off-shell π N scattering amplitude, which is a modification of the original version [47, 61] removing a term which was in conflict with chiral symmetry [47, 63]. In order to treat a 3N system, one needs to combine 2N potentials with the three-nucleon force models, for example a 2π -exchange based 3NF, such as TM'. The Bochum-Kraków group used the modified TM' potential as 3NF. They added this 3NF to the 2N models, CD-Bonn, NijmI, NijmII, and AV₁₈ [8].

2.3.3 Urbana-Illinois potential

The matter calculations are less accurate but provide important constraints on the Hamiltonian. The calculations have used the AV₁₈ model of the two-nucleon interaction, V_{ij} , and the Urbana IX (UIX) and Illinois models of the three-nucleon interaction, V_{ijk} [13, 69]. The addition of the UIX model of V_{ijk} fixes the binding energy of ^3H and ^4He and significantly improves the binding of the p -shell nuclei. The UIX potential does not have the TPE s -wave and the three-pion-exchange terms [8, 13].

2.4 Chiral Perturbation Theory (ChPT)

The nuclear forces, according to the Standard Model, are understood as the residual of the strong interaction between quarks inside nucleons, and the associated dynamics is governed by quantum chromodynamics (QCD). However, at low energy, QCD becomes non-perturbative. In other words, due to confinement, the quarks and gluons are no longer the relevant degrees of freedom. In 1990, Weinberg suggested that an effective field theory (EFT), with nucleons and pions as the effective degrees of freedom, can be derived in such a way that terms in the Lagrangian are consistent with the (broken) chiral symmetry (and in fact

Figure 2.3: Hierarchy of nuclear forces in ChPT. Solid and dashed lines denote nucleons and pions, respectively. Solid dots, filled circles and filled squares refer, respectively, to the leading, subleading and sub-subleading vertices in the effective Lagrangian.

all the other symmetries) of QCD. This approach is known as Chiral Perturbation Theory (ChPT). Applying the ChPT Lagrangian to 2N scattering results in an infinite number of Feynmann diagrams [70]. ChPT [9] is an approach for constructing nuclear forces. In this framework, all nuclear forces such as 2NF, 3NF, and 4NF are included simultaneously and consistently. In this approach, the potential among any number of low-energy nucleons is expanded in powers of nucleon momenta, Q/Λ , and the pion mass, m_π/Λ , scaled by a characteristic mass, Λ , of order of 1 GeV.

For energies below the Δ -nucleon mass difference, the Δ can be integrated out. In this case, the three-nucleon terms appear, for the first time, at Next-to-Next-to Leading Order (NNLO). Figure 2.3 shows the ordering and the hierarchy of all diagrams in the Δ -less chiral perturbation theory. The chiral perturbation Lagrangian is organized in powers of ν (chiral order), $\mathcal{L}(\Lambda^{-\nu})$, and is written as a sum of contributions from different orders [8]

$$\mathcal{L}_{eff} = \mathcal{L}^{\nu=0} + \mathcal{L}^{\nu=1} + \mathcal{L}^{\nu=2} + \dots \quad (2.15)$$

The Leading Order (LO) and Next-to-Leading Order (NLO) cover only the two nucleon (2N) force. As the order of expansion increases, the 3NF and 4NF emerge (see Fig. 2.3). Advantages of the ChPT are: (1) the 3NFs are derived and taken into account in a consistent way, i.e. they

emerge naturally in higher-order expansion and, (2) it allows a good control over systematic uncertainties of the predictions. Similar to the case of phenomenological potentials, also in ChPT there are certain free parameters, known as the low-energy constants (LECs), for which, the values are taken from the πN and $2N$ scattering data.

Chapter 3

Experimental setup

In this chapter, the most important instruments and facilities which had been used in the proton-deuteron break-up experiment at the Kernfysisch Versneller Instituut (KVI) are described. The contents described in this chapter along with some pictures have been extracted from Refs. [8, 24, 47].

Figure 3.1 shows the experimental facility at KVI in 2007. The polarized (unpolarized) beam is provided with the atomic **POLarized Ion Source (POLIS)**. The beams of (polarized) protons and deuterons are accelerated (65-190 MeV/nucleon) by the superconducting cyclotron **AG-OR (Accélérateur Groningen ORsay)** at KVI. For these two beams, the beam polarization can be measured in parallel with the actual experiments by the **In-Beam Polarimeter (IBP)**. After 2003, another facility was designed to measure the beam polarization, namely the **Lamb-Shift Polarimeter (LSP)**. The proton-deuteron break-up reaction was studied with the **Big Instrument for Nuclear-polarization Analysis, BINA**, which inherits a lot of its features from its predecessor, the **Small-Angle Large-Acceptance Detector, SALAD** [71]. This detector is particularly suited to study the elastic and break-up reactions at intermediate energies.

In this chapter, we describe the polarized ion source, AGOR, IBP and BINA.

3.1 POLarized Ion Source (POLIS)

The beam of protons and deuterons is produced with **POLarized Ion Source (POLIS)**. It is an atomic-beam-type polarized-ion source. Experimentally, the nominal polarization values for proton and deuteron

Figure 3.1: A schematic top view of the KVI experimental facility in 2007. The AGOR accelerator together with POLIS provides (un)polarized beams for the experiments. The BINA detector was located in the experimental area depicted on top of the picture.

Figure 3.2: A schematic sketch of the POLarized Ion Source (POLIS)

beams delivered to experimental setups are between 60-80% of the theoretical values [72]. For the proton beam, hydrogen (or ^2H) atoms are generated in a dissociator from hydrogen molecules by a radio-frequency discharge in a Pyrex tube as shown in Fig. 3.2. The atoms with the nucleon spin up or down ($\uparrow$ or $\downarrow$) are selected depending on the polarization state requested. The hyperfine interaction is the interaction between the proton spin $\vec{S}_p$, with both the spin of the electron, $\vec{S}_e$, and its orbital angular momentum, $\vec{L}$. In this case, the total angular momentum is:

$$\vec{F} = \vec{L} + \vec{S}_e + \vec{S}_p = \vec{J} + \vec{S}_p. \quad (3.1)$$

For an s -state, $L = 0$, with $S_e = 1/2$ and $S_p = 1/2$, the eigenvalues of $\vec{F}$ are $F = 0, 1$. The Breit-Rabi diagram of the hydrogen atom in a magnetic field is shown in Fig. 3.3. By applying a magnetic field, this degeneracy is removed and the states are split into different energy levels for each m_F . This is called the Zeeman effect and the amount of energy separation is proportional to the magnetic field and the value of the quantum number m_F . For a strong magnetic field, larger than 10 G, the energy separation is not linear and F is not a good quantum number anymore. In

Figure 3.3: The polarization scheme for protons using an atomic-beam-type ion source, atoms with the electron spin up are focused towards the beam-line, whereas atoms with the electron spin down are defocused. The nuclear spin is then aligned appropriately in a radio-frequency transition unit. The weak field is responsible for $p_z = -1$ and the strong field provides $p_z = 1$ polarization [47].

this case, $(m_l + 2m_s)$ is a more appropriate quantum number. Therefore, atoms with electron spin ($\uparrow$) or ($\downarrow$) will be separated in the strong magnetic field [24]. Atoms with the electron spin up are focused towards the beam-line, whereas atoms with the electron spin down are defocused. The nuclear spin is then aligned appropriately in a radio-frequency transition unit.

Atoms leaving the dissociator pass through a hexapole magnet which separates the beam according to the electron spin states, m_s , in Fig. 3.3, atoms in states 1 and 2 (electrons in spin-up state) are focused, and atoms in states 3 and 4 (electrons in spin-down state) are defocused. After this stage, atoms with an electron state ($\uparrow$) pass through a tapered electromagnet which produces a static magnetic field. The static magnetic field with a gradient field is used to selectively populate specific states via the method of adiabatic passage [73,74]. Using the method of adiabatic passage, the entire population of the $(F = 1, m_F = 1)$ state 1 is transferred to the $(F = 1, m_F = -1)$ state 3, while the population of the $(F = 1, m_F = 0)$ state 2 remains the same. Similarly, for a strong-field transition, the population of the $(F = 1, m_F = 0)$ state 2 can be transferred to the $(F = 0,$

Table 1: The polarization states for proton beams which were used in the present experiments. The maximum theoretical values of the vector polarization, p_Z , are given in the table.

Field(s)	p_Z	
WF	-1	vector down
SF	+1	vector up
Off	0	off

$m_F = 0$) state 4. When atoms are leaving this cavity, the electrons are stripped off in an ECR¹ ionizer and the polarized beam is transported to the AGOR cyclotron for acceleration.

The polarization of the proton beam is defined as:

$$p_Z = \frac{N^+ - N^-}{N^+ + N^-}, \quad (3.2)$$

where $N^{+,-}$ are the number of particles with a particular spin (up or down). Therefore, for a proton beam, the maximum polarization value of $p_Z = \pm 1$ can be achieved. The polarization scheme used in our experiment is summarized in Tab. 1.

3.2 The AGOR cyclotron

The Accélérateur Groningen Orsay (AGOR) is built in collaboration with IPN (Institut de Physique Nucléaire) Orsay. The cyclotron magnet is built with superconducting coils [75] that can produce magnetic fields with values of up to 4 T. It is a compact three-sector cyclotron with a pole diameter of 1.88 m, equipped with three accelerating electrodes located in the pole valleys. Figure 3.4 shows the operating diagram of the AGOR cyclotron. This picture depicts the energy range which can be obtained for a given Q/A -ratio.

Protons can be accelerated up to 190 MeV and deuterons or α beam with $Q/A=0.5$ to a maximum energy of 90 MeV/nucleon. After acceleration, the beam is transported to the experimental areas and beams of protons and deuterons are used for the few-body experiments.

¹Electron Cyclotron Resonance

Figure 3.4: The energy of an ion in MeV/nucleon as a function of Q/A in the AGOR cyclotron. Q and A stand for charge and atomic number of ions, respectively. 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 In-Beam Polarimeter (IBP)

The In-Beam Polarimeter (IBP) measures the polarization of proton or deuteron beams [76]. The final state of particles in the $\vec{d}p$ and $\vec{p}p$ elastic scattering reactions are detected by sixteen phoswich detectors arranged in four planes at 0° , 45° , 90° , and 135° as shown in Fig. 3.5. For a chosen center-of-mass angle, two detectors in each plane measure the scattered particles in coincidence.

Each phoswich detector consists of a thin plastic scintillator layer (ΔE) with a fast decay-time, and a thick layer (E) with a slow decay-time. Each detector is read out by one photomultiplier tube (PMT). The characteristics of the scintillators are given in Tab. 3.2.

The signal from the PMT is integrated by two gates: a short gate of about 40 ns to measure mainly the total charge of the ΔE signal, and a long gate of about 400 ns, to measure the charge of both ΔE and E signals.

In our experiment, we only used a polarized proton beam. The polarization of this beam, p_z , has been obtained by measuring the rate of

Figure 3.5: Schematic setup of IBP [24].

Table 3.2: Physical constants of BICRON scintillators used in IBP.

Name	Type	Thickness (mm)	Diameter (mm)	Decay time (ns)
ΔE	NE102A	2	50	2.4
E	NE115	100	50	320

elastically scattered protons, $I(\theta, \phi)$, according to

$$I(\theta, \phi) = I_0(\theta) [1 + A_y(\theta) p_z \cos \phi], \quad (3.3)$$

whereby θ, ϕ are the polar and azimuthal angles of the scattered protons, respectively, $A_y(\theta)$ the known analyzing power of the reaction, and $I_0(\theta)$ the reaction rate for an unpolarized beam. The elastic-scattering rate has been determined at $\phi = 0$ and $\phi = \pi$, corresponding to I_L and I_R , respectively. Therefore, Eq. 3.3 can be simplified to

$$\begin{aligned} (\phi = 0) \rightarrow I_L &= I_{0L}(\theta)(1 + p_z A_y), \\ (\phi = \pi) \rightarrow I_R &= I_{0R}(\theta)(1 - p_z A_y), \end{aligned} \quad (3.4)$$

whereby I_{0L} , I_{0R} correspond to the rates of the left and right detectors, respectively, measured with an unpolarized beam. We define:

$$\begin{aligned} I'_L &= \frac{I_L}{I_{0L}}, \\ I'_R &= \frac{I_R}{I_{0R}}, \end{aligned} \quad (3.5)$$

so that the polarization p_z is obtained via

$$p_z = \frac{1}{A_y} \left(\frac{I'_L - I'_R}{I'_L + I'_R} \right). \quad (3.6)$$

3.4 Lamb-Shift Polarimeter (LSP)

The polarization of proton and deuteron beams could be measured before acceleration in a very short time, (1-2 minutes) with an accuracy of a few percent with the Lamb-Shift polarimeter (LSP). The LSP is based on the properties of a three-level interaction between α , β and e states of the hydrogen (or deuterium) atoms [47]. The measured polarization degree value with the LSP is generally 10-15% higher value than that measured by IBP [8]. It is an excellent tool for fast determination of the polarization, therefore ideal for purposes of optimizing transitions in POLIS and for fast check of polarization degree [77].

3.5 BINA detector

The Big Instrument for Nuclear-polarization Analysis (BINA) is particularly suited to study the $\vec{p}d$, $\vec{d}p$ and $\vec{d}d$ elastic and break-up reactions at intermediate energies of up to ~ 200 MeV/nucleon at KVI. BINA is composed of two major parts, the forward-wall and the backward-ball, as shown in Fig. 3.6. The right side of Fig. 3.6 shows the forward-wall and the left side depicts the backward-ball. The forward-wall measures the energy, the position, the type of the particle at scattering angles in the range of 10° - 37° , and the backward-ball part covers the rest of the polar angles up to 165° . Therefore, BINA detector covers close to 4π kinematic phase space of the break-up and elastic reaction.

Figure 3.6: The top panel shows a photograph of BINA side-view and the bottom one presents a schematic drawing of the forward-wall, the backward-ball, the beam direction and the target position of BINA [70].

Figure 3.7: Energy scintillators of the forward part of BINA. It consists of a cylindrically-shaped array of plastic scintillators to measure the energy of the particles and two arrays of scintillators, up and down (wings), for detecting the secondary scattered particles for polarization-transfer experiments.

3.5.1 Forward-wall

The forward-wall is composed of three main parts, Energy scintillators (E -scintillators), ΔE -scintillators, and a Multi-Wire Proportional Chamber (MWPC). The forward-wall allows to detect a charged particle scattered in the forward direction with a polar angle in the range of 10° - 32° with full azimuthal angle coverage, and extending this range up to 37° with partial azimuthal angle coverage.

Energy scintillators

The forward-wall E -detector of BINA is designed to measure the energy of the scattered particles. It consists of a cylindrically-shaped array of plastic scintillators to measure the energy of the particles and two arrays of scintillators, up and down (wings), for detecting the secondary scattered particles for polarization-transfer experiments (see Fig. 3.7). For the present experiments, these wings were not used.

The cylindrically-shaped array consists of 10 horizontal scintillator bars, as shown in Fig. 3.8. Each scintillator with a trapezoidal cross section has dimensions of $((9 - 10) \times 12 \times 220 \text{ cm}^3)$ and is made of BICRON-408 plastic scintillators. The physical constants of these plastic scintillators are listed in Tab. 3.3.

Table 3.3: 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

The thickness of the energy scintillators (12 cm) is enough to stop protons in the energy range of up to 140 MeV. The details of the engineering design of the forward-wall and the distances are shown in Fig. 3.8. Two scintillator bars in the middle of the detector have a hole in the middle for the passage of the beam pipe. The scintillator bars at the interface of the cylinder and the wings have a different trapezoidal shape to match the two connecting surfaces.

For every scintillator bar, two PMTs² at both ends of the scintillator bar collect the scintillation light. The signals from these PMTs are integrated using a charge-to-digital converter (QCD)³ to measure the energy deposited in the scintillator. The discriminated signals from the Constant Fraction Discriminators (CFDs)⁴ are fed into the trigger system as well as to Time-to-Digital Converters (TDCs)⁵. The time difference between the signals from both ends of the scintillators allows one to determine the impact position of the incoming particle. In addition, information about the Time-of-Flight (TOF) of the particles can be extracted.

ΔE -Scintillators

The ΔE -scintillators are thin slabs of scintillator material made of BICRON plastic, BC-408 (see Tab. 3.3), and are used in combination with the E -scintillators to identify the type of particle. They are installed vertically between the E -scintillators and the target. The array of the scintillators is composed of 12 parallel vertical scintillator bars and the dimensions of each bar are $(0.1 \times 3.616 \times 43.4)$ cm³. Each bar is read-out by

²Photonis: XP4392/B

³LeCroy 4300B ADC FERA (Fast Encoding and Readout ADC)

⁴CAEN 16 channel CFD: Mod.C808, and LeCroy 16 channel CFD: 3420

⁵LeCroy 3377 TDC

Figure 3.8: Details of the engineering design of the forward part of BINA. Here, the E -scintillators, ΔE -scintillators, and the MWPCs can be seen. Also, the distances between components and their sizes are shown in mm.

PMTs⁶ located at the bottom and at the top of the scintillator. Therefore, signals from these two PMTs are correlated. Scintillator bars located at the position of the beam pipe are physically separated into upper and lower parts. The signals from these PMTs are, consequently, independent of each other.

Particles with the same energy and different atomic masses leave different amounts of energy in the ΔE -scintillator bars. To identify the type of particles, the deposited energy in the ΔE -scintillator is combined with the energy in the E -scintillator. For the kinematics covered in the present measurements, it was not necessary to use this feature. Furthermore, the vertical array structure of the ΔE bars can be combined with the horizontal array structure of the energy scintillator to determine the coordinates of particles in the scattering plane, albeit with a poor position resolution (± 1.8 cm).

Multi-Wire Proportional Chambers (MWPC)

Multi-wire proportional chambers are used to measure the positions of charged particles and to construct their trajectories in nuclear and high-energy physics experiments. The size and the precision of the chambers make it possible to cover a wide range of scattering angles.

Our BINA system has a MWPC to track the trajectory of the particles in the scattering process (see Fig. 3.9). It is installed at a distance of 29.5 cm from the target position and has an active area of 38×38 cm². The MWPC of BINA consists of 3 planes, X, Y, and U. These planes are parallel arrays of equally-spaced anode wires to readout the positions of the scattered particles. The anode wire planes are sandwiched between two parallel cathode plates that are connected to a high voltage of -3250 V.

The X plane is made of 236 parallel vertical wires, the Y plane has 236 horizontal wires, and the U plane has 296 parallel wires placed at an angle of 45° with respect to the X or Y planes. The coordinates can, therefore, be calculated from the wire numbers of the X and Y planes. In cases where more than one particle hits the chamber, the U-plane is used to resolve the ambiguities in the determination of the coordinates [78, 79]. Every two wires are electrically connected and act as an individual counter. Wires are made of gold-plated tungsten. They have a diameter of $20 \mu\text{m}$ and can stand up to 100 g force.

⁶Phillips: XP1911/20, and XP1911/08

Figure 3.9: The multi-wire proportional chamber of BINA. It is installed between the target and the E -scintillator at a distance of 29.5 cm from the target position and it has an active area of $38 \times 38 \text{ cm}^2$.

The volume between two cathode planes is filled with the electro-negative counting gas (in our case, CF_4 (80%)+isobutane(20%)). Particles which pass through the MWPC ionize the gas, and the avalanche electrons are collected on the wires. The gas inside the chamber is continuously refreshed with a flow rate of 150 cc/min. The gas flow through the chamber helps the system to get rid of possible dirt and dust which might exist in the system. These dust particles usually collect a static charge and create sparks in the chamber resulting in a failure of the system. In the present setup, the chamber detects particles at angles between 9° and 32° with a resolution of better than 0.8° .

3.5.2 Backward-ball

The backward part of BINA is covered by a ball-shaped detector. The backward-ball is the scattering chamber and a detector at the same time. The incoming beam hits the target which is placed at the center of the ball. The forward going particles are detected by the forward wall, which is placed outside the vacuum, and particles scattering to angles larger than 35° are detected by the ball.

The backward-ball of BINA is made of 149 small cut pyramid-shaped scintillator detectors as shown in Fig. 3.10. These detectors cover almost

Figure 3.10: The left panel shows the backward-ball. On the right panel, the cut pyramid geometry of the scintillators in the backward-ball is shown.

80% of the full 4π solid angle, for $\theta = 32^\circ - 160^\circ$ and a complete azimuthal acceptance, ϕ , except in the corners of the opening frame at $\theta = 37^\circ$ and where the target enters the ball. Together with the forward-wall, BINA covers nearly the complete phase space.

Each detector of the backward-ball is composed of a fast plastic scintillator, BICRON BC-408, and a slow phoswich part which has the same cross section and is glued to the fast component. The slow scintillator part, BICRON BC-444, has a thickness of 1 mm and its physical constants are given in Tab. 3.3. Each plastic scintillator is extended with a light guide and connected to a PMT⁷. The plastic scintillators in the ball come with two different thicknesses. Since the energy of particles that scatter towards forward angles are generally larger than those that scatter to larger angles, elements with a thickness of 9 cm are placed at angles smaller than 100° and elements at backward angles are built with a thickness of 3 cm. The BINA backward-ball as a bulk consists of two building blocks: pentagons and hexagons. The complete ball is made of these two main building blocks but with different sizes and details.

In general, scattering chambers are separated from the detectors, imposing an energy loss in the chamber wall and thereby increasing the energy threshold for particle detection. For BINA, this problem has been solved by using the backward-ball as the scattering chamber. The BINA backward-ball as a scattering chamber consists of a beam pipe, glued scintillators, and the front flange which acts as a thin window to the

⁷Phillips: XP2282B, and XP2020

Figure 3.11: The exit window of the backward-ball of BINA. This opening is covered by a $250\text{ }\mu\text{m}$ thick Kevlar cloth and $50\text{ }\mu\text{m}$ thick Aramica foil [71] which is glued to a metal frame and separates the vacuum, inside the chamber, from the atmosphere outside.

forward-wall. The special design of the ball makes it possible to evacuate the ball volume via the beam-pipe. Exploiting turbo pumps, the pressure inside the ball reaches a value of 10^{-5} mbar, which is good enough to avoid the collection of dirt on the foil of the liquid-deuterium target. The front exit window is built from $250\text{ }\mu\text{m}$ thick Kevlar cloth and $50\text{ }\mu\text{m}$ thick Aramica foil [71] which are glued to a metal frame and separates the vacuum, inside the chamber, from the atmosphere outside. Figure 3.11 shows the front window.

3.5.3 Target

In experiments with BINA, different targets are exploited. The target holder unit is installed at $\theta_{lab} = 100^\circ$ on top of the backward-ball with a slight inclination angle of 10° which brings the target into the center of the ball, as is illustrated in Fig. 3.6. The target holder can carry different targets like: ZnS, empty cell or a solid target, and liquid targets. The liquid-target setup has many different components, such as cryogenic system connections, heaters, gas-flow system, temperature sensors, and a target-moving mechanism. The complete system can move vertically via a pneumatic system.

Figure 3.12: Left panel: the target cell. Right panel: the target 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.

Two types of targets were used in our experiments with BINA: solid targets and liquid targets. Solid targets are hydrocarbons such as CH_2 , CD_2 , and other organic substances. In general, solid targets have the advantage that they are very easy to operate, but the reaction of interest is always accompanied by backgrounds originating from other reactions from the other components of the target material such as Carbon. In contrast, a liquid target is usually pure and, therefore, suffers less from background reactions. However, liquid targets are more difficult to handle during the experiments.

The target cell used in this experiment (see Fig. 3.12) is made of high purity aluminum to optimize the thermal conductivity. The windows are covered by a transparent foil of Aramid [71] with a thickness of $\sim 4 \mu\text{m}$. During this experiment, a liquid-deuterium target cell with a diameter of 15 mm and a thickness of 3.2 mm was used. Because of the pressure difference between the inside and the outside of the target cell, one observes a bulging of the target, increasing the thickness to 3.85 mm for this particular cell. The target cell together with its gas lead were mounted on the cold head of the target holder [8].

In a liquid-target system, the target gas, like D_2 , flows into the target cell. The temperature of the target cell is reduced to a few degrees Kelvin by a cryogenic system. As a consequence, for a certain temperature and pressure inside the cell (around the triple point), the gas liquefies. The

temperature and pressure should be kept constant, otherwise the liquid inside the cell can freeze or evaporate which might result in a target explosion. In the present setup, the system is constantly monitored by a Programmable Logic Controller (PLC) system which measures the temperature and the pressure. In this experiment, the operational region for the liquid deuterium target was: $T = 19$ K, $P = 258$ mbar. The liquid-deuterium density is $\rho_{D_2} = 169$ mg/cm³ [8].

3.5.4 Electronics

A simplified electronics scheme of the setup of BINA is presented in Fig. 3.13. The BINA data-acquisition (DAQ) consists of 4 parts: the read-out electronics to digitize the information of the detectors, a trigger system, a real-time computer to collect the selected data, and a mass storage system which saves the data on disk via a connection to the real-time computer. The detector electronics of BINA are divided into three parts; forward-wall electronics, backward-ball electronics and MWPC electronics.

The forward-wall electronics digitizes the signals from 44 ($E, \Delta E$)-PMTs. Figure 3.14 shows block diagrams of the forward-wall electronics. In this part, signals from 20 E PMTs and 24 ΔE PMTs are split into two parts via an active splitter⁸. The first output is sent to a CFD (Constant Fraction Discriminator). The outputs of the CFDs were used as the input to the trigger unit and as a start for the TDC. Each CFD module has 16 input channels and provides individual logic signals, the sum of all channels (SUM), and OR of all channels. The SUM and OR signals are used to generate the appropriate trigger. From the second output, the signal is sent to charge-integrating QDCs, after a cable delay of ~ 250 ns [8].

The backward-ball electronics supports all 149 detectors of the ball. Figure 3.15 shows the backward-ball electronics. First, signals from 149 detectors are split into two. The same type of splitters were used as for the forward-wall electronics. Since the ball detectors are composed of scintillators with slow and fast responses, the input signals are split once more to provide signals for the inputs of the QDCs with long and short integration times for particle identification. For this, a passive home-made splitter box has been used [8].

⁸Giessen Splitter box

Figure 3.13: A sketch of the readout system of BINA. Figure is modified from [70].

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. The first output is sent to a CFD to be used as the input to the trigger unit. From the second output, the signal is sent to the FERA, after a cable delay of ~ 250 ns.

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 FERA.

Figure 3.16: A sketch of the electronics of the MWPC in BINA. MWPC has three planes with the number of wires of 236, 236 and 296 in X, Y and U planes. Every two wires are coupled to produce a total of 384 read out signals. The read-out is based on a PCOS-III data-acquisition system. See the text for more details.

The MWPC signals are digitized by dedicated MWPC electronics. The MWPC channels are read out by the PCOS-III⁹ electronic system. This system consists of amplifiers, discriminators, delay and latch modules and can encode the MWPC signals as shown in Fig. 3.16. The read-out signals from the wires are amplified and sent to the discriminators. The logic signals are then delayed and registered with a programmable delay and a latch unit. A CAMAC PCOS controller unit collects the information from the delay and latch units and sends the data to a VME memory unit via a hand-shaking protocol. The strobe signal for the PCOS controller is received from a common trigger signal [8]. As mentioned earlier, the MWPC has three planes with the number of wires of 236, 236 and 296 in X, Y and U planes. Since the MWPC has a hub (see Fig. 3.9) in the middle, the wires in this region are disconnected. Therefore, they are read out from both sides. So, the MWPC electronics embeds 118 read-out channels for the X and Y planes and 148 channels for the U plane. Altogether, 384 channels are required to cover the read out of the MWPC.

The trigger system is composed of logic units which combine information from the backward-ball, forward-wall E , and ΔE . In the experiments with BINA, four different trigger conditions were made:

1. T1 = Wall E (Multiplicity¹⁰ ≥ 3) OR Wall ΔE (Multiplicity ≥ 3).

Coincidence of two charged particles registered in wall (wall-wall coincidence).

2. T2 = (Wall E OR) AND (Ball OR).

At least one particle registered in wall and at least particle registered in ball (wall- ball coincidence).

3. T3 = Ball (Multiplicity ≥ 2).

Coincidence of two charged particles registered in ball (ball-ball coincidence).

4. T4 = OR of everything (OR of all detectors).

All triggers coincide in time with the cyclotron radio-frequency signal. Usually, every trigger condition is designed to detect a special reaction channel or phase space. For example, in the $\vec{p} + d$ reaction, the

⁹LeCroy's Proportional Chamber Operating System (PCOS-III)

¹⁰Multiplicity in this experiment is the number of firing PMTs in an event.

T1 trigger (in this setup) is covering the break-up channels with two hits in the forward-wall. The T2 trigger is suitable for any reaction in which one particle scatters to forward direction and the other one to backward angles. This includes the elastic channel and part of the break-up channel. Trigger T3 covers break-up events in which two particles scatter towards the backward-ball. The trigger, T4, covers any type of event and was, therefore, used as a minimum bias trigger.

In general, the cross sections for the different reactions and phase spaces are different. Those reactions or phase spaces that have a larger cross section dominate the trigger rate. Some of the triggers were, therefore, down-scaled by a prescaler trigger box¹¹ to reduce the bias on triggers with the larger counting rate. The typical down-scaling factors were 2^x , x is 0, 3, 6, 10 for the T1, T2, T3 and T4 triggers, respectively.

The individual trigger signals were registered on an event-by-event basis by using a TDC. They were used as a start of each TDC channel with a common stop derived from a coincidence between the global trigger and the radio-frequency signal. This information was further used to sort events off-line by their trigger type [8].

The read-out electronics and real-time computing select the incoming data from the electronics based on the trigger conditions and communicate with the storage unit to send the data to be saved on the disk. After the signals have been digitized in the FERA units, the data are subsequently sent to memory units. During this procedure, the triggers from new events are not accepted, but are counted in scalers and used in the off-line analysis to correct for dead-time losses. The experimental data are saved on a remote storage disk¹². Typical rates for the present experiment are listed in Tab. 3.4 [8].

¹¹TB8000, Trigger box.

¹²daq storage of University of Groningen

Table 3.4: Various triggers, some typical rates and experimental parameters for the present experiment [8].

data-taking rate	15 kHz
T1 rate	8 kHz
T2 rate	42 kHz
T3 rate	85 kHz
T4 rate	280 kHz
T1 down-scaling	2^0
T2 down-scaling	2^3
T3 down-scaling	2^6
T4 down-scaling	2^{10}
Livetime	70%
Beam current	10-20 pA

Chapter 4

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

The $\vec{p}d$ break-up reaction was performed in 2006 with a polarized proton beam with an energy of 135 MeV using BINA. The first data analysis was performed in 2009 [8]. In this thesis, the vector analyzing power, A_y , and the cross section are reanalyzed and A_x is extracted for the first time. Moreover, we performed for the first time a global review of a rich set of cross section and vector analyzing-power data taken with a proton-beam energy of 135 MeV and 190 MeV using a Dalitz analysis. In this chapter, we describe the method to obtain differential cross sections and the components of vector analyzing powers, A_x and A_y , for the $d(\vec{p}, pp)n$ reaction. Part of this chapter is devoted to a description of the energy calibration procedure that was used in the analysis. Then, the procedure for obtaining the vector analyzing powers and cross section will be illustrated. In the last part of this chapter, we discuss the Dalitz analysis procedure applied to the respective observables.

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

In the final state of $\vec{p}d$ break-up reaction, there are three ejectiles, namely two protons and one neutron. Each ejectile can be described by three kinematical variables, therefore the final state is described by nine variables of the three outgoing particles. Four of those can be constrained by momentum and energy conservation:

$$\begin{aligned}\vec{p}_{beam} &= \vec{p}_1 + \vec{p}_2 + \vec{p}_3; \\ E_{beam} &= E_1 + E_2 + E_3 - E_b,\end{aligned}\tag{4.1}$$

Figure 4.1: A projection of a break-up scattering event with its mirror image. The circles show the polar angles of θ_1 and θ_2 of the outgoing particles. A typical bin of 4° in polar angle and 10° in azimuthal direction is chosen to select data. ϕ_{12} depicts the opening azimuthal angle between the two outgoing particles. The numbers in the horizontal rectangles correspond to the scintillation-detector numbers of the forward-wall.

where $\vec{p}_{beam}(E_{beam})$ is the three-momentum (kinetic energy) of the beam. $\vec{p}_1(E_1)$, $\vec{p}_2(E_2)$ and $\vec{p}_3(E_3)$ are the three-momenta (kinetic energies) of the two protons and neutron, respectively. $E_b = -2.224$ MeV is the binding energy of the deuteron. Thus, by measuring five variables, the other four variables are obtained using Eq. 4.1. Four of these variables are chosen to be the scattering angles of the two protons, namely their polar and azimuthal angles, θ and ϕ . An angular configuration for cases in which both protons scatter to the forward-wall (see Sec. 3.5.1) is defined by $(\theta_1, \theta_2, \phi_{12})$ as illustrated in Fig. 4.1. The fifth variable is the energy correlation between the two protons (E_1, E_2) , referred to as S . The kinematic variable S corresponds to the arc-length along the kinematical curve with $S = 0$ at the point where E_1 is minimum. Figure 4.2 shows a few S -curves for several angular configurations. For the forward-wall configurations, θ_1 and θ_2 are between 14° and 30° and the energy of proton is larger than 20 MeV (the energy threshold of BINA).

Figure 4.2: The energy correlation between E_1 and E_2 , referred to as the kinematical S -curve, for different kinematical configurations of $(\theta_1, \theta_2, |\phi_{12}|)$. The curves depicted here correspond to a proton beam energy of 135 MeV.

4.2 Calibration of the E -detectors

To analyze the $\vec{p}d$ break-up reaction and to extract vector analyzing powers and cross sections, a precise energy determination of the final-state protons is required. To obtain these values, the E -scintillators of the forward-wall are calibrated as the first step in the data analysis. For this purpose, we use the scattering angles measured by the MWPC. The calibration of the E -scintillators is done in three steps:

- Background reduction of the break-up reaction;
- Detector calibration using background-reduced data;
- Energy-loss corrections to determine the kinematics of the scattered protons at the target position.

4.2.1 Background analysis of the break-up reaction

In this section, we report on the analysis procedure that was used to identify and to suppress background contributions. When two particles

Figure 4.3: The left panel shows the TOF of the second particle versus TOF of the first particle. The square shows the TOF of prompt events. The right panel shows the relative TOF of two outgoing protons at the scintillators of forward-wall. The region with the highest peak contains the true events.

give signals in the MWPC and in two E -scintillators of the forward-wall within the coincidence time window set by the hardware trigger, the event is accepted as a break-up candidate. The two dominant channels in $\bar{p}d$ scattering are the elastic and break-up reactions. The phase space of the break-up reaction is significantly larger than that of the elastic channel. With the high rate of data taking, there is a high probability for receiving within the coincidence window of the hardware trigger, two uncorrelated events. To reduce the time-uncorrelated background, we exploit the relative time-of-flight information ($TOF_1 - TOF_2$) induced by the two coincidence particles. Here, TOF_1 and TOF_2 refer to the sum of the TDC values of the discriminated signals of the left and right PMTs of the E -scintillators for two particle tracks (1 and 2), respectively. The TOFs are measured with respect to the radio frequency (RF) of the accelerator. The left panel in Fig. 4.3 shows the TOF_2 versus TOF_1 . The events inside the red square present the prompt events. The relative TOF, ($TOF_1 - TOF_2$), between the two particles is shown in the right panel of Fig. 4.3. A clear RF-time structure can be observed, indicating that the arrival times of the two particles can differ. The highest peak in Fig. 4.3 contains mostly the true events from the same beam pulse in

Figure 4.4: The roughly-calibrated deposited energy of particle 2 versus particle 1 for $(\theta_1 = 24^\circ \pm 2^\circ, \theta_2 = 24^\circ \pm 2^\circ, \phi_{12} = 180^\circ \pm 5^\circ)$ at the detector position. The left and the right panels indicate E_2 versus E_1 before and after making a cut shown in Fig. 4.3 on the relative TOF, respectively.

the time window of 25 ns. The neighboring peaks can be explained by two uncorrelated protons from the scattering channels. To reduce the time-uncorrelated background, we apply a cut around the prompt peak with a window of ± 12.5 ns as shown in the right panel of Fig. 4.3.

Two panels in Fig. 4.4 present the rough calibrated energy of proton 2 versus that of proton 1 at the detector position for the configuration $(\theta_1 = 24^\circ \pm 2^\circ, \theta_2 = 24^\circ \pm 2^\circ, \phi_{12} = 180^\circ \pm 5^\circ)$. The left panel corresponds to the spectrum without any cut, whereas the right panel shows the spectrum after applying the cut (shown in Fig. 4.3) on the prompt events within two RF-cycles in the relative TOF spectra. This panel shows the true break-up events that arrived in the expected time window of 25 ns. To calibrate the data, we need the kinematical S -curve as a reference. The data correspond to the proton information at the detector position, whereas the kinematical S -curve is related to the proton energies at the interaction point, hence, at the target position. Therefore, we translate the kinematical S -curve by applying the energy-loss corrections from the target to the detector. In addition, after the calibration, the data will be translated from the detector position to the target position since the theoretical calculations correspond to the kinematics of the protons at the target position (interaction point). For these reasons, we have to determine the energy loss of the protons between the target and detector

Figure 4.5: The simulated relation between deposited and thrown energies of protons. The data are generated using an event generator of the break-up reaction. The particle tracks are propagated using a GEANT-3 model of BINA. The black lines are fits through the simulated data. The left panel presents the deposited energy versus the thrown energy and the right panel shows the thrown energy versus the deposited energy.

positions. The procedure that was used to determine these energy losses will be explained in the next section.

4.2.2 Energy loss of the particles

The kinematical correlation between energy of the first and the second proton, the *S*-curve, is the best reference to use in the calibration procedure. The deposited energies at the detector position differ from the corresponding energies of the protons at the target position. This is due to presence of the material located between the target and detector positions causing the protons to lose part of their energy. The relation between the thrown (at the target) energy and the deposited energy is found by using a Monte Carlo simulation based on GEANT-3. In this simulation, all the components of BINA such as *E*-scintillators, ΔE -scintillators, target holder, MWPC, etc., were modeled. The relation between the deposited and the thrown energies is non-linear and varies with energy as shown in Fig. 4.5.

To obtain the expected energy correlation of the protons at the detector position, we fitted the data on the locus shown in the left panel of Fig. 4.5 with a fifth-order polynomial. The black line depicts the fit result. The underlying function is used to map the kinematical energies at

the target to that of the expected energies at the detector position. The resulting relation is used to calibrate the data. Once the energy calibration is performed (see next section), the measured energies of the break-up events are translated to the corresponding kinematics at the target position. This is done in order to be able to compare the data with the results of theoretical calculations. The function that maps the measured energies at the detector position to that at the target position is found by taking the fit result of the function shown in the right panel of Fig. 4.5.

4.2.3 Energy calibration of the *E*-detectors

There are two PMTs at both ends of each *E*-scintillator in the forward-wall. The energy of the impinging particle is measured by using the information of both of them. To compensate for the light attenuation, the geometrical average, $\sqrt{L_{chan} \times R_{chan}}$, is used as a measure of the deposited energy. L_{chan} and R_{chan} present the deposited energy of the left and right PMTs. For the energy calibration, we translate the raw data, given in units of channels, to energy, in units of MeV, by exploiting the expected kinematical correlation (*S*-curve) as a reference.

As an example we choose a symmetric configuration, ($\theta_1 = 24^\circ$, $\theta_2 = 24^\circ$, $\phi_{12} = 180^\circ$) with a range of θ and ϕ , $\Delta\theta_1 = \Delta\theta_2 = 4^\circ$ and $\Delta\phi_{12} = 10^\circ$, to start the calibration of the *E*-scintillators. Figure 4.6 shows the energy correlation of one scintillator before the energy calibration. The energy calibration procedure is performed for all scintillators by finding a calibration function that minimizes the shortest distance between the measured data points (E_1, E_2) to the kinematical *S*-curve. This is done via an iterative procedure. In the final step of the calibration, we translate the data at the detector position to the target position, as explained in the previous section, to measure the break-up observables. Figure 4.7 illustrates the calibrated energy correlation of two protons at the detector and at the target position. The kinematical *S*-curve in the left panel of Fig. 4.7 is the corrected *S*-curve at the detector position and the kinematical *S*-curve in the right panel of Fig. 4.7 is the kinematical *S*-curve at the target position. As can be observed, the calibration procedure matches nicely the data to the expected curve. Protons with an energy less than 20 MeV do not reach the *E*-scintillators and are subsequently not detected. Therefore, a clear cut off at the target position is observed.

Figure 4.6: The energy correlation between the two outgoing protons for $(\theta_1 = 24^\circ, \theta_2 = 24^\circ, \phi_{12} = 180^\circ)$ before the energy calibration.

Figure 4.7: E_2 versus E_1 for $(\theta_1 = 24^\circ, \theta_2 = 24^\circ, \phi_{12} = 180^\circ)$. The solid line shows the kinematical S-curve. The left and the right panels depict the data and S-curve at the detector and target position, respectively.

4.2.4 Hadronic interaction of particles

If charged particles interact with the medium of the scintillator, they transfer their energy and this process leads to the energy loss of charged particles. In some cases the charged particles transfer their energy to a neutral particle like a neutron and the neutron escapes out of the scintillator without depositing any energy. This hadronic interaction causes a detection inefficiency because the value for S can no longer be measured. The spectra in Fig. 4.7 clearly show the effect of hadronic interactions. The solid line shows the kinematical S -curve. A significant fraction of the data fall below this S -curve which are due to hadronic interactions. For the cross section and the analyzing-power determination, we only counted events which deposited their complete energy into the scintillators. Hence, for the cross-section measurements we need to correct for the fraction of events which undergo a hadronic interaction.

The response of the detection setup to protons is simulated using GEANT-3 and the results are used to correct for the hadronic contribution. To determine the energy dependence of this contribution, we used two-dimensional histograms of the deposited energy versus thrown energy for one proton as illustrated in Fig. 4.5. In this figure, we made some slices for thrown energies between 20 MeV and 120 MeV in steps of 10 MeV. Then, we filled one-dimensional histograms with the difference between deposited and thrown energies interval mentioned above. An example is shown in Fig. 4.8. The data are fitted using a third-order polynomial, representing the hadronic contribution together with a Gaussian representing events which deposit their complete energy. The ratio between the number of break-up events which deposit their complete energy and the total number of events is taken as a measure of the hadronic interaction effects. Figure 4.9 represents the hadronic interaction effects as a function of thrown energy. In general, this number is somewhere between 93-98% of the total number of simulated protons.

4.2.5 The geometrical inefficiency

This section describes how to determine the inefficiencies that originate from the geometrical design of BINA and trigger choices. For example, in the case that two protons of the break-up channel scatter to the same E -scintillator, no trigger signal will be generated and, therefore,

Figure 4.8: The simulated difference between the thrown and deposited energies for a range of thrown energies between 60 MeV to 70 MeV. The red line shows the result of a fit through the data. For the fit, we used a second-order polynomial+Gaussian function. Due to the energy loss, the peak is not around zero.

Figure 4.9: The effect of hadronic interaction as a function of thrown energy.

the event will not be registered. These geometrical inefficiencies (=1-efficiency) were calculated using a GEANT-3 simulation. For the determination of the geometrical inefficiency, proton-deuteron break-up events were simulated excluding hadronic interactions. The resulting geometrical inefficiencies are large for configurations with a small azimuthal angle, ϕ_{12} . For instance, at $\phi_{12} = 20^\circ$ the inefficiency is $\sim 12\%$ for each proton. For larger values of ϕ_{12} , this inefficiency is less than 2% [8].

4.2.6 MWPC efficiency

The MWPC inefficiency comes predominantly from charged particles which induce a signal below the applied threshold. If an event is registered in the $E, \Delta E$ part and not in the MWPC, it implies an inefficiency of the MWPC. Since the E and ΔE -detectors are used as the reference for calculating the MWPC efficiency, the surface of the MWPC is divided into areas corresponding to the $E - \Delta E$ hodoscopes (see Fig. 4.10) [8]. Every hodoscope is composed of a horizontal E -bar and vertical ΔE -bar. With this, it is possible to determine the efficiency at several places in the MWPC. The efficiency for each hodoscope is obtained by the ratio of events for which an $E - \Delta E$ hit was found in coincidence with a corresponding hit in the MWPC to the total number of $E - \Delta E$ hits for the regions where geometrical overlap between the hodoscope and MWPC is perfect. The MWPC efficiency varies between 80% and 96% for most of the hodoscopes. The lower efficiencies come from broken wires in the MWPC or dead channels [8]. More details are discussed in Ref. [8].

4.3 Extraction of the $\vec{p}d$ break-up observables

This section describes the procedure for measuring the break-up observables such as cross sections and vector analyzing powers. The energy correlation between the two outgoing protons, E_2 versus E_1 , after the calibration for a particular configuration is shown in Fig. 4.7. To measure the break-up observables, at the first step, we make several slices along the kinematical S -curve in width of 9 MeV which is larger than the experimental energy resolution. This is illustrated in the left panel of Fig. 4.11. The projection of the indicated region on the line perpendicular to the S -curve (D-axis) is shown in the right panel. The peak around zero corresponds to break-up events. Most of the events on the

Figure 4.10: The MWPC efficiency for elastically-scattered protons with energies larger than 100 MeV. The efficiency is given for every hodoscope element in % [8].

Figure 4.11: The left panel shows E_2 versus E_1 , energies of the two protons at $(\theta_1, \theta_2, \phi_{12}) = (24^\circ \pm 2^\circ, 24^\circ \pm 2^\circ, 180^\circ \pm 5^\circ)$. The solid line shows the kinematical S-curve calculated for the central values of the experimental angular ranges. The right panel is the projection of events along the D-axis for one slice shown in the left panel.

left-hand side of the peak are due to break-up events. In these cases, the protons have lost energy due to hadronic interactions inside the detector; see Sec. 4.2.4. The amount of accidental background is small as can be seen from the small amount of events on the right-hand side of the peak. We fit this spectrum by using a third-order polynomial, representing the hadronic interactions and the accidental background, and a Gaussian function, representing the signal. The extracted number of signal events, N , were corrected by the data-acquisition dead-time and the down-scaling factor Sec. 3.5.4. This number is subsequently used to measure the cross sections and vector analyzing powers.

4.3.1 The cross section of the break-up reaction

The cross section of the break-up reaction can be obtained by (see appendix A for more details):

$$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS} = \frac{N}{\frac{Q}{Z} t \epsilon \Delta\Omega_1 \Delta\Omega_2 \Delta S}, \quad (4.2)$$

with:

- N : The number of break-up events in each slice along the S -curve corrected for the down-scaling factor and the dead-time;
- Q : The total integrated charge;
- Z : The projectile charge ($Z = 1$);
- t : The number of the scattering centers;
- ϵ : The multiplication of all the efficiencies including the MWPC efficiency [8], hadronic correction and geometrical efficiency [8];
- $\Delta\Omega$: The solid angles for the two outgoing protons;
- ΔS : The width of the selected window in each slice along S -curve.

Table 1 shows the experimental features used to extract cross sections and vector analyzing powers. Figure 4.12 depicts the cross section as a function of S for one configuration. The lines in this figure show the results of Faddeev calculations using 2N and 2N+3NF models such as CD-Bonn (dotted red line), CDB+ Δ (dashed-dotted blue line), CDB+TM'

Figure 4.12: The cross section as a function of S for $(\theta_1, \theta_2, \phi_{12} = 24^\circ, 24^\circ, 140^\circ)$. The lines show the predictions of Faddeev calculations that are based on a modern potential such as CD-Bonn (dotted red line), CDB+ Δ (dashed-dotted blue line), CDB+TM' (dashed-double dotted green line), and CDB+ Δ including Coulomb (solid black line).

(dashed-double dotted green line), and CDB+ Δ +Coulomb (solid black line). The error bars in these figures indicate the statistical error and the cyan bands depict the systematic uncertainties. The various sources of systematic errors include:

- Target thickness uncertainty is 5% (3.85 ± 0.2 mm);
- The uncertainty in determining the hadronic interaction effects using GEANT-3 is estimated to be 6% for both protons (3% per proton).
- MWPC efficiency for both protons is 2% (1% for each proton) [8];
- Geometrical inefficiencies using GEANT-3 is 12% for $\phi_{12} = 20^\circ$ and 2% for $\phi_{12} > 20^\circ$ [8].

The total systematic uncertainties for the cross sections at small relative azimuthal angles ($\leq 20^\circ$) is about 14% and for the larger relative azimuthal angles ($> 20^\circ$) is about 9%. For this, we added up, quadratically, the systematic errors of the various sources assuming them to be independent. The data for this particular configuration are larger than

the predictions of the models. Note, however, that the discrepancy is marginal with respect to the CDB+ Δ calculation considering the systematic uncertainties.

4.3.2 The vector analyzing powers

To measure the vector analyzing powers, the number of break-up events were normalized to the collected beam charge for the two polarization states (up and down). The relation between the normalized number of events with the polarized beam, N^s , and unpolarized beam, $N_{\xi, \phi_{12}}^0(\phi)$, is given by [80]:

$$N_{\xi, \phi_{12}}^s(\phi) = N_{\xi, \phi_{12}}^0(\phi)(1 + p_z^s A_y(\xi, \phi_{12}) \cos \phi - p_z^s A_x(\xi, \phi_{12}) \sin \phi), \quad (4.3)$$

where s indicates the spin of the beam. ξ defines a given kinematical point (θ_1, θ_2, S) . The component of the vector polarization of the beam is given by p_z^s and the vector analyzing powers are indicated by A_x and A_y . Here, ϕ is the angle between quantization axis for the polarization and the normal to the scattering plane in the laboratory frame of reference shown in Fig. 4.13. ϕ_{12} is the relative azimuthal opening angle of two protons.

Since the statistics obtained with an unpolarized beam was limited, we extracted the spin observables by solely using $N_{\xi, \phi_{12}}^\uparrow(\phi)$ and $N_{\xi, \phi_{12}}^\downarrow(\phi)$, corresponding to the normalized number of events for the spin-up and spin-down polarized beams, respectively. The analyzing powers A_x and A_y are extracted using the following relation:

$$\begin{aligned} f_{\xi, \phi_{12}}(\phi) &= \frac{N_{\xi, \phi_{12}}^\uparrow(\phi) - N_{\xi, \phi_{12}}^\downarrow(\phi)}{N_{\xi, \phi_{12}}^\uparrow(\phi)p_z^\downarrow - N_{\xi, \phi_{12}}^\downarrow(\phi)p_z^\uparrow} \\ &= A_y(\xi, \phi_{12}) \cos \phi - A_x(\xi, \phi_{12}) \sin \phi, \end{aligned} \quad (4.4)$$

where $p_z^\uparrow$ and $p_z^\downarrow$ are the values of up (0.57) and down (-0.70) beam polarizations. Parity conservation imposes the following restrictions on the components of the vector analyzing powers [80]:

$$\begin{aligned} A_x(\xi, -\phi_{12}) &= -A_x(\xi, \phi_{12}); \\ A_y(\xi, -\phi_{12}) &= A_y(\xi, \phi_{12}), \end{aligned} \quad (4.5)$$

Table 1: The experimental features of the experiments with the proton beam of 135 MeV [8] and 190 MeV [24].

Beam particle	Polarized proton	Polarized proton
Energy	135 MeV	190 MeV
Average beam current	15 pA	10 pA
Target	Liquid deuterium	Liquid deuterium
Target thickness	3.85 mm	6.8 mm
Down-scaling factor of the trigger	1	1
Average live-time	70%	50%
RF-cycle	19 ns	16 ns
Average efficiency of the MWPC for protons	92%	97%
Geometrical efficiency	88% ($\phi_{1,2} = 20^\circ$) 98% ($\phi_{1,2} = 180^\circ$)	80% ($\phi_{1,2} < 20^\circ$) 99% ($\phi_{1,2} = 180^\circ$)
Angular range	$14^\circ \leq \theta_{1,2} \leq 30^\circ$, $0 \leq \phi_{1,2} \leq 360^\circ$	$14^\circ \leq \theta_{1,2} \leq 30^\circ$, $0 \leq \phi_{1,2} \leq 360^\circ$

Figure 4.13: Definition of the coordinate systems for the break-up reaction with transversally-polarized beam: The laboratory system (x', y', z') , with z' along the beam-momentum direction and y' vertically upward, is used to define the angular configuration of the outgoing protons (with momenta p_1 and p_2). The reaction coordinate system, with z along the beam-momentum direction and x obtained by projection of p_1 onto the plane perpendicular to z . The angle ϕ is defined as the angle between the y axis and the spin quantization axis s , which, in the studied case, is vertical (parallel to y') [26,80,81].

where for $\phi_{12} = 180^\circ$, we expect $A_x = 0$. By taking the sum and difference of $f_{\xi, \phi_{12}}(\phi)$ and $f_{\xi, -\phi_{12}}(\phi)$ in combination with the results of Eq. 4.4, the following combination of asymmetries for mirror configurations (ξ, ϕ_{12}) and $(\xi, -\phi_{12})$ can be obtained [26,27]:

$$\begin{aligned}
 g_{\xi, \phi_{12}}(\phi) &= \frac{f_{\xi, \phi_{12}}(\phi) + f_{\xi, -\phi_{12}}(\phi)}{2}, \\
 &= A_y(\xi, \phi_{12}) \cos \phi. \\
 h_{\xi, \phi_{12}}(\phi) &= \frac{f_{\xi, \phi_{12}}(\phi) - f_{\xi, -\phi_{12}}(\phi)}{2}, \\
 &= -A_x(\xi, \phi_{12}) \sin \phi.
 \end{aligned} \tag{4.6}$$

We performed a fit of the experimental distribution $f_{\xi, \phi_{12}}(\phi)$ with A_x and A_y as free parameters according to Eq. 4.4. Examples of such a fit are shown in the upper two panels of Fig. 4.14. In addition, we fitted the distributions $g_{\xi, \phi_{12}}(\phi)$ and $h_{\xi, \phi_{12}}(\phi)$ with A_y and A_x as free parameters according to Eq. 4.6, whereby the kinematical configurations with $\pm\phi_{12}$

Figure 4.14: Examples of asymmetry distributions obtained for two (mirror) kinematical configurations with $\theta_1 = 28^\circ$, $\theta_2 = 24^\circ$, $\phi_{12} = \pm 100^\circ$ and $S = 66$ MeV. In the top two panels, the asymmetries $f_{\vec{\zeta}, \phi_{12}}(\phi)$ for $\phi_{12} = +100^\circ$ and $\phi_{12} = -100^\circ$ configurations are presented. The bottom two panels show the asymmetry distributions for $g_{\vec{\zeta}, \phi_{12}}(\phi)$ and $h_{\vec{\zeta}, \phi_{12}}(\phi)$. The vertical error bars represent statistical uncertainties and the horizontal error bars depict the range of ϕ . The red lines show the results of the fit of the corresponding functions, as described in the text.

are combined together. The results for our example are shown in the bottom two panels in Fig. 4.14. The analyzing-power values, A_x and A_y , are obtained from the fits of Eq. 4.6 for the kinematical configurations.

Figures 4.15 illustrate the extracted A_x and A_y for several values of S obtained from the following distributions: $f_{\xi,\phi_{12}}(\phi)$ with $\pm\phi_{12}$, $g_{\xi,\phi_{12}}(\phi)$ and $h_{\xi,\phi_{12}}(\phi)$. The lines in this figure show the results of Faddeev calculations using 2N and 2N+3NF models such as CD-Bonn (dotted red line), CDB+ Δ (dashed-dotted blue line), CDB+TM' (dashed-double dotted green line), and CDB+ Δ including Coulomb (solid black line). The cyan bands depict the systematic uncertainties. For $f_{\xi,\phi_{12}}(\phi)$ functions, a combined fit with two free parameters is needed, while by fitting $g_{\xi,\phi_{12}}(\phi)$ and $h_{\xi,\phi_{12}}(\phi)$, spectra the best precision is obtained without doing a combined fit, since A_x and A_y are decoupled. We identified two sources that give rise to a systematic uncertainty in the measurements of A_y and A_x . The first one is related to the uncertainty in the beam polarization. The second source relates to induced asymmetries due to small differences in the efficiencies and errors in the charge normalization between the data taken with the spin-up and down polarization states. Below, we discuss separately the procedure that has been used to estimate both sources.

The error of the beam polarization is about 6% [24]. This uncertainty gives rise to a systematic error in A_x and A_y . We estimated this uncertainty by recalculating both analyzing powers with an input polarization that differs by +6% (−6%) for the spin-up (down) mode. The difference with the results using the nominal value of the beam polarizations is used as an estimate of the corresponding systematic error.

The other source of systematic uncertainty (induced detection asymmetries) has been estimated by exploiting data at particular kinematical configurations for which the vector analyzing powers are known or constrained. For A_y , we have analyzed various symmetric configurations for which both protons scatter to the same polar angle with a relative azimuthal angle of 180° . By taking the average vector analyzing power, $\bar{A}_y$, for the covered S -range, one expects a value of zero. Figure 4.16 shows the average values for A_y for several symmetric configurations. We have performed a fit with a free offset value to the data and we used the corresponding offset as a measure of the systematic uncertainty for A_y . Note that we find a very small systematic uncertainty for this source with respect to other errors. To estimate the systematic error for A_x , we analyzed the data for a relative azimuthal angle of 180° for which A_x should be zero, and extracted the corresponding value for A_x as a

Figure 4.15: A_y and A_x as a function of S for $(\theta_1, \theta_2, \phi_{12} = 28^\circ, 24^\circ, 100^\circ)$. These were obtained from fitting the $f_{\vec{\zeta}, \phi_{12}}(\phi)$ distribution for data selected with $+\phi_{12}$ (red squares), $-\phi_{12}$ (blue triangles). The results obtained if A_x and A_y were obtained by fitting the $g_{\vec{\zeta}, \phi_{12}}(\phi)$ and $h_{\vec{\zeta}, \phi_{12}}(\phi)$ distributions are shown by black circles. The lines show the results of Faddeev calculations, CD-Bonn (dotted red line), CDB+ Δ (dashed-dotted blue line), CDB+TM' (dashed-double dotted green line) and CDB+ Δ including Coulomb (solid black line). The cyan bands represent a 2σ systematic error.

Figure 4.16: The average of A_y for symmetric configurations with $\phi_{12} = 180^\circ$. The red line shows the fitted constant line which is taken as a systematic offset and used for the estimation of the systematic uncertainty.

Figure 4.17: The definition of the variables for a three-body decay.

function of S . Subsequently, these results are fitted to a zeroth-order polynomial and its value is used as an estimate for the corresponding systematic error. The two sources of systematic uncertainties are added in quadrature assuming them to be independent. The cyan bands in Fig. 4.15 depict the total systematic uncertainties.

4.4 Dalitz analysis

Traditionally, the break-up reaction has been studied based on producing five-fold differential cross sections and analyzing powers and comparing these data with the results of calculations. Although such a procedure is straight, it lacks the capability to provide a global overview of the dynamics of the reaction. In this work, we performed an analysis that is based on the so-called Dalitz method. With this, we aim to provide a comprehensive study of the large experimental database of cross sections and vector analyzing powers, A_x and A_y , for the $\vec{p} + d$ break-up reaction at different energies.

A Dalitz analysis is an inspection of the general final-state phase-space distribution of a three-body decay named after its inventor Richard Dalitz (1925-2006) who first applied it to the " τ - θ puzzle" [82]. According to the three-body decay, shown in Fig. 4.17, a particle with mass M and four-momentum $P = (M, \mathbf{P})$, decays into three particles with masses, m_i and energies, E_i with four-momenta $p_i = (E_i, \mathbf{p}_i)$, where $i = 1, 2, 3$. The Lorentz invariant variables of interest are defined by the following equations:

$$s_1 = m_{23}^2 = (P - p_1)^2 = (p_2 + p_3)^2; \quad (4.7)$$

$$s_2 = m_{13}^2 = (P - p_2)^2 = (p_1 + p_3)^2; \quad (4.8)$$

$$s_3 = m_{12}^2 = (P - p_3)^2 = (p_1 + p_2)^2. \quad (4.9)$$

These invariants can be worked out further and yield

$$\begin{aligned} m_{ij}^2 &= (p_i + p_j)^2 = m_i^2 + m_j^2 + 2E_i E_j - 2\vec{p}_i \cdot \vec{p}_j \\ &= (P - p_k)^2 = M^2 + m_k^2 - 2ME_k. \end{aligned} \quad (4.10)$$

The three variables are not independent, since summing them up gives the following identity

$$\begin{aligned} m_{12}^2 + m_{13}^2 + m_{23}^2 &= 3M^2 + m_1^2 + m_2^2 + m_3^2 - 2M(E_1 + E_2 + E_3) \\ &= 3M^2 + m_1^2 + m_2^2 + m_3^2 - 2M^2 \\ &= M^2 + m_1^2 + m_2^2 + m_3^2 = \text{constant}. \end{aligned} \quad (4.11)$$

Therefore, we can describe the complete dynamics of the reaction by considering only two of the variables m_{ij}^2 .

Figure 4.18 shows a simulated Dalitz spectrum of the $\vec{p} + d \rightarrow p + p + n$ reaction for a proton beam energy of 135 MeV and 190 MeV. This spectrum has been obtained using a Monte Carlo event generator with a phase-space distribution in 4π and after accounting for the acceptance of the forward-wall. The conditions are applied for polar angle (14° to 30°) and the energies which are large enough to make it to the detector for detection.

4.4.1 Dalitz analysis for the experimental data

In this section, we discuss the procedure that is used to present cross section and vector analyzing power data in terms of a Dalitz spectrum. In Sec. 4.3 we presented the analysis that was used to obtain cross sections and analyzing powers in a five-fold differential configuration characterized by $(\theta_1, \theta_2, \phi_{12}, S)$. To present the data using the Dalitz method, we have to reduce the dimension to two parameters, namely the two invariants m_{pn}^2 and m_{pp}^2 . This requires a different analysis procedure in which we have to integrate the data over the other dimensions. We note

Figure 4.18: Simulated phase-space distribution of m_{pn}^2 versus m_{pp}^2 for the $\bar{p} + d$ break-up reaction at 135 MeV (left column) and 190 MeV (right column). The subscripts p and n refer to the final-state proton and neutron, respectively. The top row shows the distribution for a 4π phase space and the bottom row shows the distribution whereby the two protons of the break-up reaction are accepted by the forward-wall.

Figure 4.19: The reconstructed mass of the missing-neutron spectrum for the $\bar{p} + d$ break-up reaction. The left (right) panel shows the data corresponding to an incident proton beam energy of 135 (190) MeV. The red line shows a Gaussian+third-order polynomial fit function.

that we only consider events in which both protons are registered in the forward-wall of BINA. Moreover, we extend our analysis by considering as well data taken at a proton beam energy of 190 MeV [24].

In the previous method, we used the D spectrum to identify events of the break-up reaction. In the Dalitz method, we exploit the reconstructed mass of the missing neutron to count the number of signal events. The reconstructed mass of the missing neutron is defined by the following equation:

$$p_3^\mu = P - (p_1^\mu + p_2^\mu);$$

$$\text{Reconstructed Neutron Mass} = \sqrt{p_3^\mu p_{3\mu}}. \quad (4.12)$$

where p_i^μ ($i = 1, 2$) is defined as four-momenta of two outgoing protons and p_3^μ is four-momenta of neutron. P is defined as four-momentum of beam and target.

Figure 4.19 shows the reconstructed mass of the missing neutron for

data taken at 135 MeV (left panel) and 190 MeV (right panel). A clear peak around the expected neutron mass of 939 MeV can be observed corresponding to events of the break-up reaction. The data on the left-hand side and the right-hand side of the peak correspond to accidental background and hadronic contributions, respectively. This spectrum is fitted by using a third-order polynomial, representing background and hadronic contributions, and a Gaussian function, representing events of the break-up channel. Events corresponding to the break-up reaction are selected by cutting on the reconstructed mass of the missing-neutron spectrum whereby the selection window is taken around the peak position with a width of $\pm 3\sigma$ as indicated by the vertical lines in Fig. 4.19.

For each event, we applied a kinematic fitting procedure in order to avoid events which might fall outside the allowed region of the Dalitz spectrum and to significantly improve the resolution of the presented mass variables. In this procedure, we modified the measured energies of the protons in such a way that the reconstructed mass of the missing neutron matches its nominal value. The angular information of the protons are not altered since their resolution is significantly better than the energy resolution. The algorithm that was used to perform the kinematic fit can be summarized as follows. Each event is characterized by the two energies of the final-state protons, (E_1, E_2) , together with their scattering angles (θ_i, ϕ_i) whereby i refers to proton 1 and 2. For each event, two new energies, $\tilde{E}_1$ and $\tilde{E}_2$, are numerically calculated by solving the reconstructed mass of the missing neutron equation with as input (E_2, θ_i, ϕ_i) and (E_1, θ_i, ϕ_i) , respectively. This results in two points that both lie exactly on the S -curve with energy labels $(\tilde{E}_1, E_2)$ and $(E_1, \tilde{E}_2)$. The two points are connected by a straight line. The updated energies of the two protons are taken from a point on this line in such a way that the experimental resolution is accounted for as a weight factor. This procedure is repeated till no significant change in energy is observed anymore. As an example, Fig. 4.20 shows E_1 vs E_2 for a specific configuration for data taken at 135 MeV. The left panel depicts the spectrum after cutting on the reconstructed mass of the missing neutron and the right panel indicates the spectrum after cutting on the reconstructed mass of the missing neutron and after applying the kinematic fitting procedure. The number of events, N , that are eventually found are corrected for the down-scaling factor and dead-time corrections. Also note that the accidental background is small for the data taken at 135 MeV, whereas a substantial background contribution is observed for the 190 MeV case.

Figure 4.20: E_2 versus E_1 for $(\theta_1, \theta_2, \phi_{12}) = (28^\circ \pm 2^\circ, 28^\circ \pm 2^\circ, 180^\circ \pm 2^\circ)$ configuration for proton beam at 135 MeV. The left panel shows the energy correlation after cutting on the reconstructed mass of the missing-neutron spectrum. The right panel shows the results after cutting on the reconstructed mass of the missing neutron and after applying the kinematic fitting procedure.

For the data taken at a beam energy of 190 MeV, the accidental background is subtracted using ΔTOF , the difference between the time-of-flight of particles extracted from the information of the TDCs, $(\text{TOF}_1 - \text{TOF}_2)_{\text{TDC}}$, and the time-of-flight calculated using the measured energies and flight paths, $(\text{TOF}_1 - \text{TOF}_2)_E$. For a particle with a total energy, E_{tot} and the rest mass, m , that travels a distance, r , the calculated time-of-flight from the measured energy can be obtained by:

$$\text{TOF}_E = \frac{r}{c \sqrt{1 - \left(\frac{mc^2}{E_{\text{tot}}}\right)^2}}, \quad (4.13)$$

where c is the speed of light. The E -scintillators of the forward-wall have a cylindrical shape with a radius of r_0 . r is the distance between the target and the detection point in the E -scintillators. Figure 4.21 shows the definition of $\vec{r}$ in terms of the polar and azimuthal angles θ and ϕ and in terms of the cylindrical angles Θ and Φ . The unit vector of $\vec{r}$ is:

Figure 4.21: The definition of the polar and azimuthal angles, θ and ϕ , and the two cylindrical angles, Θ and Φ . $\vec{r}$ connects the interaction point at the target to the detection point.

$$\hat{u}_{\vec{r}} = \begin{pmatrix} \sin \theta \cdot \cos \phi \\ \sin \theta \cdot \sin \phi \\ \cos \theta \end{pmatrix} = \begin{pmatrix} \sin \Theta \\ \cos \Theta \cdot \sin \Phi \\ \cos \Theta \cdot \cos \Phi \end{pmatrix}. \quad (4.14)$$

The angles Θ and Φ can be obtained by

$$\begin{aligned} \Phi &= \arctan \left(\frac{\sin \theta \sin \phi}{\cos \theta} \right); \\ \Theta &= \arcsin(\sin \theta \cos \phi). \end{aligned} \quad (4.15)$$

The components of $\vec{r}$ are defined by:

$$\begin{aligned} r_x &= r_0 \tan \Theta; \\ r_y &= r_0 \sin \Phi; \\ r_z &= r_0 \cos \Phi, \end{aligned} \quad (4.16)$$

r_0 is the distance from the center of the cylinder of the E -scintillators to the target, and it has a value of 76.15 cm for the present experiment.

Figure 4.22: ΔTOF as a function of the measured energy at the target position of one of the outgoing protons. The red (middle) rectangle shows the break-up events which include accidental background and two black (top and bottom) rectangles show background events.

Figure 4.22 depicts the ΔTOF as a function of the measured energy at the target position of one of the outgoing protons in $\bar{p}d$ reaction at 190 MeV. The events at ΔTOF around zero (the region indicated by the red rectangular and referred to as prompt) correspond to the break-up events for which a fraction will be accidental. The two sideband regions, indicated by the black rectangles, correspond to events that are solely time-uncorrelated. These events differ about 16 ns from those in the prompt region, matching well the RF timing of the accelerator. The events in the sideband regions are used to estimate the amount and topology of accidental events in the prompt region. For this, we subtract the Dalitz spectrum of the prompt region with that of a spectrum from the normalized sideband regions. Figure 4.23 shows the reconstructed mass of the missing neutron before (the blue line) and after (the green line) subtracting the background. The ratio between signal and background is around 20. Figure 4.24 depicts the Dalitz distribution of the background events (left panel), the measured Dalitz distribution before and after subtracting the background from the prompt events (middle and right panel) for the $\bar{p}d$ reaction at 190 MeV.

Figure 4.23: The reconstructed mass of the missing-neutron spectrum for the $\bar{p} + d$ break-up reaction for proton beam energy of 190 MeV. The blue (green) line shows the data before (after) subtracting the background. The red line shows a Gaussian+third-order polynomial fit function.

Figure 4.24: The measured Dalitz distribution for the phase space covered by the forward-wall phase space for $\bar{p} + d$ break-up reaction at 190 MeV for the background events shown by the black rectangles in Fig. 4.22 (left panel), the measured Dalitz distribution before subtracting the background from the prompt events shown by the red rectangle in Fig. 4.22 (middle panel) and after subtracting the background from the prompt events (right panel).

4.4.2 A Monte Carlo generator of the break-up channel using realistic potentials

To compare the data, presented as Dalitz spectra, with predictions by theory, we developed a Monte Carlo (MC) event generator that is able to simulate the predicted distributions according to a specific model for the two- and three-nucleon potentials. In the following, we describe the working principles of the generator and how it has been used to model the detector response.

The generator is based upon the TGenPhaseSpace class provided by the ROOT software framework [83]. The algorithm that is used by this class originates from the earlier developed GENBOD code which uses the Raubold and Lynch method [84]. The algorithm allows to generate via MC the kinematics (four momenta) of the final-state protons and neutron of the break-up reaction obeying energy and momentum conservations. For each generated event, a weight factor, WT , is calculated which can be used to provide a proper phase space modeling of the reaction. An example of its application has already been illustrated in Fig. 4.18.

To account for a model that incorporates as well the prediction of a specific two- and three-nucleon potential, we developed an algorithm that provides for each generated events the corresponding amplitude, A . By weighting each event by $WT \cdot |A|^2$, we then obtain a generator that produces the distribution according to the predictions of the model of interest. The code that calculates the amplitude for each event has been provided by theory colleagues [36, 85]. Since it turned out to be too computing intensive to calculate the amplitude for each event, we further developed an interpolation method based on a look-up table.

For each model, we created a look-up table by sampling 10^5 events covering the complete phase space of the reaction. For each event, we registered its kinematics and calculated the corresponding amplitude and analyzing powers, and stored all the information in a database. This database was used as input to previously described MC generator. For each event generated with TGenPhaseSpace, we searched for the corresponding elements in the database that are close in kinematics to the generated event. For the algorithm that was used to search through the database, we made use of the approximated nearest-neighbor method provided by the ANN C++ library [86]. This method allows for a fast search by reorganizing the data according to a k -d-tree structure [87, 88].

Figure 4.25: Dalitz distributions weighted by $WT \cdot |A|^2$ using CDB+ Δ +C model for the generated events (left panel), generated events after smearing (middle panel) and generated events after smearing and kinematic fitting (right panel). The final results (right panel) show a similar pattern as the the generated events (left panel).

The amplitude and analyzing powers of the event are calculated by taking an Euclidian-based weighted average of the five nearest neighbors. These values were subsequently used to further process the event to generate the Dalitz spectra of interest. The robustness of the MC method has been tested by varying the size of the database and the number of nearest-neighbors.

Because of computational reasons, our MC simulation in this MC analysis does not make use of GEANT-3, and it, therefore, does not model the scintillators of the forward-wall explicitly. To account for the geometrical inefficiency in this analysis, we propagated the generated momenta of the protons to a virtual plane mimicking the forward-wall and we required that the two protons do not hit the same virtual E -scintillator bar. To find the coordinates of the detectors we used Eq. 4.16. We simulated the energy and angular resolution by modifying the momenta (smearing) of the generated events, then we used the kinematic fitting, the in the same way as was done for the data, to have the same condition as applied to the data. Figure 4.25 shows the MC-simulated Dalitz spectra using CDB+ Δ +C and the beam energy at 135 MeV. The left panel corresponds to MC events within the acceptance of the forward-wall but without taking into account the energy and angular resolutions. The middle panel shows the same data after taking into account the resolutions as well and the right panel depicts the same MC data after applying both the smearing and the kinematic fitting. Note the similarity

Figure 4.26: Dalitz plot of the cross section for the forward-wall phase space for proton beam energy at 135 MeV (left panel) and 190 MeV (right panel).

of the data presented in the left and right panels. This demonstrates that the simulated data after accounting for the detector response and applying kinematic fitting gives a good representation of the original distribution. Moreover, note the various structures in the Dalitz spectrum. These are mostly due to dynamic effects, not observed in the spectra presented in the right column of Fig. 4.18, and are, therefore, related to variations in the amplitude of the reaction.

4.4.3 Dalitz analysis of the cross section

We produced Dalitz spectra for the cross section of the proton-deuteron break-up reaction as a function of two invariant masses and for two incident beam energies of 135 MeV and 190 MeV. To obtain the two-fold differential cross section from the number of events, N , for each bin in (m_{pp}^2, m_{pn}^2) , we apply the following formula:

$$\frac{d^2\sigma}{dm_{pp}^2 dm_{pn}^2} = \frac{N}{\frac{Q}{Z} t \epsilon \Delta m_{pp}^2 \Delta m_{pn}^2}. \quad (4.17)$$

The definition of most of the variables can be found in Sec. 4.3.1. m_{pp}^2 and m_{pn}^2 are the invariant mass squares defined in Eq. 4.7–4.9. Figure 4.26 shows the Dalitz plot of the cross section of the break-up reaction within the acceptance of the forward-wall and within the polar angular range between 14° and 30° with a full azimuthal coverage. The left (right) panel corresponds to the data taken with a proton beam of 135 (190) MeV.

Figure 4.27: The measured and the calculated cross sections as a function of S for the $\bar{p} + d$ break-up reaction at 135 MeV for the kinematical configuration $(\theta_1, \theta_2, \phi_{12}) = (28^\circ \pm 4^\circ, 24^\circ \pm 4^\circ, 100^\circ \pm 10^\circ)$.

In the previous section, we described the numerical method that is used to generate MC events according to a specific model with the aim to provide a simulated Dalitz spectrum. The experimentally obtained Dalitz spectra can be directly compared to the results of the MC method. To also compare the model predictions with the data on an absolute scale, *i.e.* providing two-fold differential cross section in the same units as data, we applied the following procedure to get the required conversion factor for the simulated data. We first used our generator to produce a simulated spectrum as a function of S whereby we constrained the angles of the two outgoing protons within bins similar to what has been done for the presentation of the data in a five-fold differential. Since the calculations also provide the absolute differential cross section for that particular configuration, we determined the scaling factor taking into account as well the number of generated events and bin sizes. This scaling factor is then used further for other comparisons. Figure 4.27 illustrates the results of the MC-simulated cross section for a specific configuration for the $\bar{p}d$ break-up reaction at 135 MeV after applying the scaling factor (gray circles). The black line shows the theoretical prediction of CDB+TM'. The red points correspond to the data that were analyzed in a five-fold differential way according to Eq. 4.2 as explained in Sec. 4.3.1. The black points show the measured cross sections using the method

as explained above (Dalitz method). For the error of these points, the events divided to five parts and for each part the cross sections were extracted. The error corresponds to the standard deviation of these five subsamples divided by $\sqrt{5}$. This figure shows that our present results are in reasonable agreement with the previous analysis. At the same time, it shows the good agreement between the simulated and theoretical calculations.

4.4.4 Dalitz analysis of the vector analyzing powers

In our Dalitz analysis, we extracted the experimental cross sections by adding up the events with equal weight, and, thereby, effectively integrating over the azimuthal angle ϕ . According to Eq. 4.4, the asymmetry effect due to the analyzing powers cancel in that case. To obtain a measure for the analyzing powers, we weighted each event by $\sin \phi$ or $\cos \phi$. With these weights, we are able to extract an average of A_x and A_y , respectively, for each bin in (m_{pp}^2, m_{pn}^2) , as can be seen from the right side of Eq. 4.4.

In the previous section, we described an algorithm that generates events and allows to incorporate a model based on a specific two- and three-nucleon potential. Since for each MC-generated event, we also have access to the predicted analyzing powers, we can extract an average value for A_x and A_y according to the model as well. For this, we weighted each generated event by $WT \cdot |A|^2 \cdot A_x$ or $WT \cdot |A|^2 \cdot A_y$ and normalized the resulting distributions with $WT \cdot |A|^2$ to obtain an average analyzing power for each bin in (m_{pp}^2, m_{pn}^2) .

Figure 4.28 shows A_x and A_y as a function of S for a specific configuration for the $\vec{p} + d$ break-up reaction at 135 MeV. The black points show the measured analyzing powers using the method as explained above (Dalitz method). To estimate the statistical error, we subdivided the data into five parts. The error was derived from the standard deviation of the analyzing powers obtained from the five subsamples divided by $\sqrt{5}$. The red points correspond to the data that were analyzed in a five-fold differential way according to Eq. 4.6 as explained in Sec. 4.3.2. We conclude that the results of the two analysis methods are compatible with each other.

Figures 4.29 and 4.30 depict the Dalitz plots of the extracted vector analyzing powers, for the $\vec{p} + d$ break-up reaction at 135 MeV and 190 MeV.

Figure 4.28: The measured and calculated A_x and A_y as a function of S for the $\vec{p} + d$ break-up reaction at 135 MeV for the kinematical configuration $(\theta_1, \theta_2, \phi_{12}) = (28^\circ \pm 4^\circ, 24^\circ \pm 4^\circ, 100^\circ \pm 10^\circ)$. The top and bottom panels show A_x and A_y , respectively.

Figure 4.29: Dalitz plots of the extracted vector analyzing power, A_x , of the proton-deuteron break-up reaction at 135 MeV (left) and 190 MeV (right) for the phase space covered by the forward-wall.

Figure 4.30: Same as Fig. 4.29 except for A_y .

Chapter 5

Results and discussion

In this chapter, a comprehensive overview of all the cross-section and analyzing-power measurements of the proton-deuteron break-up reaction are presented that were obtained from the data taken with BINA and with incident proton energies of 135 and 190 MeV. For the data taken at 135 MeV, we present five-fold differential results. Our results for the differential cross sections and A_y are compared to the results of a previously performed study reported in Ref. [8]. Moreover, and for the first time, we present data for A_x . The results of state-of-the-art Faddeev calculations that are based on modern NN and 3N potentials are benchmarked to all our measurements.

Besides presenting the data in a five-fold differential manner, we also performed a more global analysis including data taken at 190 MeV. For one of the global analyses we present our results in Dalitz spectra. Also in this case, the data are compared to corresponding predictions based on Faddeev calculations using modern NN and 3N potentials.

5.1 The results of the $\vec{p}d$ break-up reaction at 135 MeV

In this work, we focused on configurations of the break-up reaction in which the two final-state protons are registered by the forward-wall of BINA, hence, scattering to polar angles smaller than 30° and with a relative azimuthal opening angle varying between 20° and 180° . In this section, we present the results for five-fold differential cross sections and vector analyzing powers, A_x and A_y , for the $\vec{p} + d$ break-up reaction taken with an incident polarized proton beam of 135 MeV. The data are compared to the predictions of Faddeev calculations based on modern two-nucleon and three-nucleon potentials.

5.1.1 Cross sections

Figure 5.1 shows cross-section data as a function of S for symmetric and asymmetric configurations at small, intermediate and large relative azimuthal angles. The results of our analysis are indicated as black dots and that of the previous work [8] by gray dots. The error bars indicate statistical uncertainties which are in many cases smaller than the symbol sizes. The cyan bands depict the systematical uncertainty whereby the width corresponds to 2σ . The various lines present the results of Faddeev calculations using 2NF and 2N+3NF models such as CD-Bonn, red (dotted-dashed) line, CDB+ Δ , blue (dotted) line, and CDB+ Δ including Coulomb effect (CDB+ Δ +Coulomb), black (solid) line from the Hannover-Lisbon group [37, 41, 89] and CDB+TM', brown (double dotted-dashed), AV₁₈, green (long dashed) line and AV₁₈+UIX, gray (dashed) line, from the Bochum-Kraków group [33, 85]. There is a small difference between the results of our analysis and the previous work [8] that can be traced back to differences in the energy calibration and in the choice of S -bins. The results show a different behavior between the data and theoretical calculations at small and large relative azimuthal angles. At small azimuthal opening angles the results are closer to the predictions of the theoretical approach that deploy CDB+ Δ +Coulomb potential. This demonstrates that the Coulomb effect is sizeable for this observable at these configurations. Note that in this case the relative energy between the two protons has small values. For large relative azimuthal angles, the model based on the CDB+TM' potential appears to be the closest to the experimental data, albeit that the differences between the various models are in general small. In some cases, the shape of the cross section between data and theoretical calculations differ significantly. This difference is not due to the experimental resolution of S which is better than the chosen bin size. A comprehensive overview of all our cross-section measurements as a function of S is shown in Figs. B.1–B.10 in appendix B.

5.1.2 Vector analyzing powers

Figures 5.2 and 5.3 show the results of the analyzing powers, A_x and A_y , as a function of S for a few configurations at small, intermediate and large relative azimuthal angles. The results of our analysis are indicated as black dots and that of the previous work [8] by gray dots. The error

Figure 5.1: The cross sections at $(28^\circ, 28^\circ)$ (left) and $(28^\circ, 24^\circ)$ (right) as a function of S at small, intermediate and large relative azimuthal angles for data taken with a proton beam of 135 MeV. Error bars show the statistical uncertainties for the data points. The red (dotted-dashed), blue (dotted), black (solid), green (long dashed), gray (dashed) and brown (double dotted-dashed) lines show the predictions of Faddeev calculations using CD-Bonn, CDB+ Δ , and CDB+ Δ including Coulomb, AV_{18} , $AV_{18}+UIX$ and CDB+TM' calculations [33,37,41,85,89], respectively. The cyan bands depict the systematic uncertainties (2σ).

bars indicate statistical uncertainties. The cyan bands depict the systematic uncertainty whereby the width corresponds to 2σ . The lines are from the same models as discussed for the cross sections. For A_y , our data are compatible with the previous work [8]. Small differences can be attributed to differences in the energy calibration, the choice of S -bins, and in the analysis procedure that was applied to extract A_y . In the previous work, only the data of $+\phi_{12}$ were used and it was assumed that the observable A_x is zero. The statistical precision of our result is significantly better than the previous work as we use the data from both parities including $-\phi_{12}$. Our measurements of A_x for relative azimuthal angles of 180° is found to be consistent with zero as expected from Eq. 4.5. This demonstrates that our procedure to extract the analyzing powers does not suffer from experimental asymmetries. This is also confirmed by our estimate of the systematic uncertainty, which is found to be small.

Our polarization observables are reasonably well described by the calculations for kinematical configurations at which the three-nucleon force effect is predicted to be small. However, striking discrepancies are observed at specific configurations, in particular in cases when the relative azimuthal angle between the two protons becomes small. In this range, the measured values of A_y is close to the results of the 2NF calculation. Although, the disagreement is still significant, the effects of the Coulomb force are very small. Therefore, the origin of this discrepancy must lie in the treatment of 3NFs. We present a more detailed study of the observed discrepancy at small relative azimuthal angles in the next chapter. Possibly, the modeling of short-range 3NF can be significantly improved, for which the data presented in this thesis can be used as a benchmark. We also investigated the weighted average of the calculation for CDB+ Δ in the range of the polar ($\pm 2^\circ$) and azimuthal ($\pm 5^\circ$) angles that was selected for the configurations of data.

A comprehensive overview of all our analyzing powers measurements as a function of S is shown in Figs. B.11–B.20 in appendix B.

5.2 A global comparison between data and theory

Figures B.1–B.20 in appendix B show the results of the cross sections and vector analyzing powers as a function of S for about hundred configurations for incident proton energy of 135 MeV. To have a more efficient

Figure 5.2: Same as Fig. 5.1 except for A_x . The red lines in the bottom panels correspond to a zero line.

Figure 5.3: Same as Fig. 5.1 except for A_y .

study and to compare globally the theoretical predictions with the complete data set, we introduce four types of quantities. For the first type, we average the vector analyzing powers and cross sections over S for each configuration. For the second type, we compare data with theory using a chi-square analysis for several (θ_1, θ_2) and as a function of ϕ_{12} ; for the third one, we show the results for all configurations and combination of angles. For the last quantity, we study the cross sections and analyzing powers in a Dalitz analysis based on two-fold differential cross sections and analyzing powers.

5.2.1 Average of cross sections, A_x , and A_y

We take the average of each of the observables over S using

$$\bar{O} = \frac{\sum_{i=1}^N \frac{O_i(S)}{\sigma_i^2}}{\sum_{i=1}^N \frac{1}{\sigma_i^2}}, \quad (5.1)$$

where N is the number of measured data points in S for a given configuration $(\theta_1, \theta_2, \phi_{12})$, the quantity O_i represents one of the spin or cross section observables (A_x , A_y , or $d^5\sigma/d\Omega_1 d\Omega_2 dS$), either from data or theory, and σ_i is the measured statistical error. The index i refers to a data point in S or the theoretical prediction at the corresponding bin in S . The statistical error of the averaged variable $\bar{A}$ has been obtained from:

$$\sigma_{\bar{O}} = \frac{1}{\sqrt{\sum_{i=1}^N \frac{1}{\sigma_i^2}}}. \quad (5.2)$$

Figures 5.4 and 5.5 depict the average cross sections and vector analyzing powers versus ϕ_{12} for data taken with a proton beam of 135 MeV. Similarly, the average cross sections and analyzing powers for the theoretical predictions are produced and are presented by the same line colors and styles as were chosen for Figs. 5.1-5.3. The errors are statistical and the bands depict the average of the systematic uncertainties for every panel. The panels are arranged column-wise and row-wise in such a way that for each row the angle θ_1 is fixed and only θ_2 changes, and for every column the angle θ_2 is fixed and θ_1 varies. By comparing the averaged cross section data with the various models, we observe that

the calculations match well the experimental results within systematic uncertainties. This in contrast to the more differential study, presented earlier, where significant discrepancies are observed.

Figure 5.5 depicts the averages for A_y and A_x for the same configurations as were shown for the cross sections. The model sensitivity, in particular the effect of the 3NF, appears to increase with decreasing ϕ_{12} for the observable $\bar{A}_y$. Surprisingly, for many configurations, calculations that exclude a 3NF describe the data significantly better than the ones including a 3NF effect. The case at which both protons scatter at very small angles of 16° reveals a striking discrepancy towards small ϕ_{12} even for the calculation that is solely based on NN potentials. Towards large ϕ_{12} the calculations match well the data for practically all configurations. Note that for symmetric configurations ($\theta_1 = \theta_2$) one expects a perfect agreement for the $\bar{A}_y$ because of symmetry arguments. This is indeed the case which gives confidence in the methodology that is used to extract this analyzing power from the asymmetry measurements. We also note that our data are compatible with the results of the earlier analysis [8]. For the observable $\bar{A}_x$, we observe a different behavior between data and predictions. At small ϕ_{12} , the calculations match reasonably well the data with a slight preference, albeit not very significant considering the systematic uncertainties, for those excluding 3NF effects. At very large ϕ_{12} , one expects $\bar{A}_x$ to become zero for parity reasons. This is indeed compatible with our data lending confidence to our procedure to extract this observable. Significant deviations between theory and data can be observed for ϕ_{12} between 40° and 140° . This in contrast to what is observed for $\bar{A}_y$. We can, therefore, conclude that the observables A_x and A_y are complementary probes for scrutinizing the underlying potentials. A similar study for $\bar{A}_y$ extracted from data taken with a proton-beam energy of 190 MeV has been performed in the past and its results can be found in Ref. [24].

5.2.2 Chi-square analysis

Although the averaging procedure described above shows interesting patterns when comparing data with theory, it has the disadvantage that some of the details might be averaged out. We, therefore, used a different approach in which we performed a quality study based on a chi-square analysis. The quantity χ^2 per degree of freedom is defined by

Figure 5.4: The average of differential cross sections over S as a function of ϕ_{12} for data taken with a proton beam of 135 MeV. The lines show the average of cross sections for different theoretical predictions. The cyan bands depict the 2σ systematic uncertainties.

Figure 5.5: Same as Fig. 5.4 except for A_y (top panels) and A_x (bottom panels).

$$\chi_m^2/d.o.f = \frac{1}{N} \sum_{i=1}^N \left\{ \frac{O_i - T_i^m}{\sigma_i} \right\}^2, \quad (5.3)$$

where N is the number of measured data points, O_i is one of the observables (A_x , A_y , or $d^5\sigma/d\Omega_1 d\Omega_2 dS$), σ_i is the measured statistical error of data points and T_i^m is the results of the theoretical calculation whereby the sup-index m refers to a specific model, namely, $m = \text{CDB}, \text{CDB}+\Delta, \text{CDB}+\Delta+\text{Coulomb}$ and $\text{CDB}+\text{TM}'$, and the sub-index i refers a specific data point.

Figures 5.6 and 5.7 show the results of $\chi^2/d.o.f.$ versus the angular combination (θ_1 and θ_2) (left panels) and versus ϕ_{12} (right panels) for different observables (A_x , A_y and $d^5\sigma/d\Omega_1 d\Omega_2 dS$) for data taken with a proton-beam energy of 135 MeV and 190 [90], respectively. The investigation of the systematic errors of the cross sections and analyzing powers for data taken with a proton-beam energy of 190 is ongoing [90]. The symbols show the theoretical calculations such as CDB (squares), CDB+ Δ (circles) and CDB+ Δ +Coulomb (solid circles) and CDB+TM' (triangles). The asymmetric error bars reflect the systematic uncertainty of the data with respect to one of the theoretical calculations, namely CDB+ Δ +Coulomb. These errors were obtained by adding and subtracting the estimated total systematic error to and from the data resulting in two alternative chi-square values corresponding to the edges of the error bars.

The large values of $\chi^2/d.o.f.$ for the cross section at specific scattering and relative azimuthal angles are noticeable. We do observe a clear trend of the chi-square as a function of both ϕ_{12} and polar-angle combinations that will persist even when taking into consideration systematic effects. The deviations, independent of the model and beam energy, appear to increase towards small and large values of ϕ_{12} and, in the case of the data taken at 135 MeV, at large scattering angles. For small ϕ_{12} , the calculation based on CDB+ Δ +Coulomb shows a smaller chi-square compared to those that exclude the Coulomb interaction. Hence, our data show sensitivity to the Coulomb effect.

The absolute values of the $\chi^2/d.o.f.$ for the analyzing powers A_x and A_y appear to behave better than the ones for the cross section. However, also here, there are clear trends to be observed in which all the model predictions deviate beyond statistical fluctuations from the data. For A_y , the trend for the polar angle combination looks similar to what is

Figure 5.6: The results of $\chi^2/\text{d.o.f.}$ versus $(\theta_1$ and $\theta_2)$ (left panels) and versus ϕ_{12} (right panels) for different observables (A_x , A_y and $d^5\sigma/d\Omega_1 d\Omega_2 dS$) for data taken with a proton-beam energy of 135 MeV. The error bars reflect the systematic uncertainty. For details, we refer to the text.

Figure 5.7: Same as Fig. 5.6 except for data taken with a proton-beam energy of 190 MeV. The systematic errors are still under study.

observed for the cross section. The models show a larger discrepancy towards larger angles. The trends as a function of ϕ_{12} are vastly different compared to the ones observed in the cross section. Although A_y features a worse agreement towards small ϕ_{12} (and partly large ϕ_{12}), the observable A_x is well predicted at small ϕ_{12} except for CDB+TM'. In general, CDB+ Δ +Coulomb effect is the most compatible with the data compared to all other calculations. For this model, we show the effect of the systematic uncertainty in this model in Fig. 5.6.

By comparing the results between the two energies, *i.e.* Figs. 5.6 and 5.7, in general, similar trends as a function of ϕ_{12} are observed for the cross section and A_y . For the data taken at 190 MeV, CDB+ Δ +Coulomb effect for the cross section shows the worst agreement. The sensitivity to 3NF effects appear to be larger at the higher energy. For both energies, it is clear that the inclusion of a 3NF is by far not sufficient to remedy the observed discrepancies. We also note that the Coulomb effect is much smaller compared to the precision of the data for both spin observables. By globally reviewing the chi-square data, we note that CDB+TM' gives the worst description of the data.

5.2.3 A global comparison for all combinations of angles

In Figs. 5.5–5.7, we compared our data with calculations for specific combinations of angles. To provide a global comparison between data and theory of the break-up reaction for all configurations, we calculated for each configuration the difference between data and the predictions by the Hannover-Lisbon group, based on the modified CDB potential. We considered two cases, namely excluding and including the dynamic Δ degree-of-freedom. Figures 5.8 and 5.9 depict the results for the cross sections (top row) and the vector analyzing powers (middle and bottom rows) for the data taken with a beam energy of 135 MeV and 190 MeV, respectively.

The left panels show the intensity of the number of configurations plotted with respect to the difference between data and calculation with (y-axis) and without (x-axis) the inclusion of the Δ resonance as an effective 3NF. Data that fall close to (0,0) correspond to configurations that are described well by the model and whereby the effect of the 3NF is expected to be negligible. Data points far away from (0,0) show sensitivity to effects that go beyond the NN potential.

Figure 5.8: Left: an intensity spectrum of the (relative) difference between experimental measurements of each five-fold configuration at 135 MeV and the results of calculations based on CDB+ Δ (NN+3N) potential versus the (relative) difference using only CDB (NN) potential. Right: the differences between calculations including a 3NF and the data are shown as a function of invariant mass of the two outgoing protons (M_{pp}) shifted by twice the mass of the proton ($2m_p$). The top row shows the differences for cross sections, the second and third rows, for the proton analyzing powers.

Figure 5.9: Same as Fig. 5.8 except for proton beam at 190 MeV.

For many configurations the cross-section predictions underestimate the data and in some regions the calculations overestimate the data. In general, we observe that the effect of the 3NF in the model is not large enough to bring the majority of the data points to the horizontal axis as one would hope for. For the polarization observables, A_x and A_y , a large number of data points are around $(0, 0)$. For these data points, the 2NF is already sufficient to describe the data reasonably well and the effect of the 3NF is predicted to be small.

In the right panels the deviation between data and calculation is plotted versus the invariant mass of the two outgoing protons shifted by twice the mass of the proton. This invariant mass of the two protons is correlated to ϕ_{12} and also this variable is Lorentz invariant. The differences seen as a function of this variable are, therefore, similar to those shown in the average of observables over S and the chi-square analysis. From this spectrum, we conclude that the largest deficiencies for the vector analyzing powers appear at small relative energies (corresponding to small invariant masses). For the cross section, the deficiencies remain for the all proton-proton invariant masses and there is no clear correlation with this variable.

5.2.4 Dalitz analysis

To study the whole dataset of the $\vec{p} + d$ break-up reaction at 135 MeV and 190 MeV, a Dalitz analysis was used taking into account the scattering polar angles smaller than 30° (two protons seen at the forward-wall) for the full azimuthal angles (0° and 360°). Based on the Dalitz analysis, the final results for the cross section and the vector analyzing powers, A_x and A_y , have been obtained for the both proton-deuteron break-up reactions at incident proton beam energies of 135 MeV and 190 MeV. A comparison between the Dalitz plot for the data and the results of the predictions from Faddeev calculations using 2N and 2N+3NF models such as CD-Bonn, CDB+ Δ , CDB+ Δ including Coulomb and CDB+TM' [33, 37, 41, 85, 89] has been performed. The error corresponds to the standard deviation of five subsamples divided by $\sqrt{5}$.

Figures 5.10 and 5.11 show the results of the Dalitz analysis for the

Figure 5.10: Dalitz plots of the experimental cross sections and 3NF theoretical calculation (CDB+ Δ including Coulomb) for $\bar{p} + d$ break-up reaction at 135 MeV. The top row shows Dalitz plots of the data (left) and the absolute error of the data (right). The bottom row depicts Dalitz plots of the CDB+ Δ +Coulomb calculation (left) and the ratio of the data to the results of CDB+ Δ +Coulomb calculation (right).

measured cross sections (top left panels), the absolute errors of the measured cross sections (top right panels), the theoretical calculations (bottom left panels) and the ratio between the data and calculations (bottom right panels) for proton beam at 135 MeV and 190 MeV, respectively. These figures show the theoretical calculation based on 2N+3NF, CDB+ Δ +Coulomb model. A comparison between more theoretical calculations based on 2N and 2N+3NF are shown in appendix B.

There are structures in the data and the theoretical calculations at more or less the same place, but the structures of data and theoretical calculations differ. The Dalitz plot of the ratio in Fig. 5.11 shows a peak in that part of the phase space where the accidental background is significant, namely at m_{pp}^2 around $3.57 \text{ (GeV/c}^2\text{)}^2$ and m_{pn}^2 around $3.86 \text{ (GeV/c}^2\text{)}^2$; see also Fig. 4.24. Although we subtracted the TOF-sideband data, it appears that it did not fully remove all of accidental

Figure 5.11: Same as Fig. 5.10 except for 190 MeV.

of background.

Table 5.1 shows the fraction (in percentage) of the Dalitz spectrum for which the ratio between data and theoretical prediction falls within the indicated range at 135 MeV and 190 MeV. According to Tab. 5.1 for proton beam at 190 MeV more than 50% and for proton beam at 135 MeV more than 40% of the ratios lie in the range of 0.8-1.2, and the rest of ratios indicate that the predictions overestimate or underestimate the data.

Figures 5.12–5.15 show the results of the Dalitz analysis for the measured analyzing powers, A_x and A_y , (top left panels), the absolute errors of the measured analyzing powers (top right panels), the theoretical calculations (bottom left panels) and the difference between the data and calculations (bottom right panels) for proton beam at 135 MeV and 190 MeV. The model that was used in these figures corresponds to the theoretical calculation based on 2N+3NF (CDB+ Δ +Coulomb) model. Dalitz plots for more theoretical calculations based on other 2N and 2N+3NF are shown in appendix B. According to the figures, there is a

Table 5.1: The fraction, in percentage, of the Dalitz spectrum for which the ratio (difference) between data and theoretical predictions for cross section (analyzing powers) falls within the indicated range. The results refer to the data taken with a beam energy of 135 MeV and 190 MeV. CS stands for cross section.

Observable	E_{beam}	range	CDB	CDB+ Δ	CDB+ Δ +C	CDB+TM'
A_x	135 MeV	-0.03-0.03	46%	44%	44%	45%
		< -0.03	21%	23%	23%	24%
		> 0.03	33%	33%	33%	31%
	190 MeV	-0.03-0.03	36%	35%	34%	34%
		< -0.03	32%	37%	38%	37%
		> 0.03	32%	28%	28%	29%
A_y	135 MeV	-0.05-0.05	52%	53%	54%	54%
		< -0.05	37%	34%	34%	33%
		> 0.05	11%	13%	12%	13%
	190 MeV	-0.05-0.05	43%	41%	42%	38%
		< -0.05	44%	45%	44%	45%
		> 0.05	13%	14%	14%	17%
CS	135 MeV	0.8-1.2	40%	46%	51%	42%
		< 0.8	49%	36%	28%	48%
		> 1.2	11%	18%	21%	10%
	190 MeV	0.8-1.2	61%	64%	62%	57%
		< 0.8	33%	28%	25%	36%
		> 1.2	6%	8%	13%	7%

Figure 5.12: Dalitz plots of A_x for the proton-deuteron break-up reaction at 135 MeV. The top row shows the spectra for the data (left) with an estimate of its absolute error (right). The bottom row depicts a complete theoretical calculation including CDB+ Δ +Coulomb (left) and the difference between data and calculation (right).

significant difference in structure between the A_y data and corresponding theory.

Table 5.1 shows the percentage of the difference between experimental values and different theoretical calculations of A_x at 135 MeV and 190 MeV, respectively. What can be noted is that the fraction of points for which the difference between data and theory is less than 0.03 is slightly larger for 135 MeV ($\sim 45\%$) compared to 190 MeV ($\sim 35\%$) and hardly depends upon the underlying potentials. Table 5.1 also presents the difference between data and theory for A_y . Also here, one observes that, in general, the theory gives a better overall description of the data for 135 MeV than for 190 MeV. The fraction of points for which the calculation differs by less than 0.05 from the data is about 50% for 135 MeV whereas this fraction is only 40% for the 190 MeV case. From the same

Figure 5.13: Same as Fig. 5.12 except for A_y .

Figure 5.14: Same as Fig. 5.12 except at 190 MeV.

Figure 5.15: Same as Fig. 5.12 except for A_y at 190 MeV.

table, we also see that a different behavior is observed for the cross section. In this case, the 190 MeV case appears to provide a better agreement between data and theory compared to the 135 MeV case. The fraction of points for which the ratio between theory and cross section data falls within 0.8 and 1.2 is about 60% for 190 MeV whereas this value is about 40% for the 135 MeV case. A comparison between data and theory of alternative models can be found in appendix B.

Chapter 6

Vector analyzing powers in the $d(p, pp)n$ and $d(p, {}^2\text{He})n$ channels at 135 MeV

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Vector analyzing powers in the $d(\vec{p}, pp)n$ and $d(\vec{p}, {}^2\text{He})n$ channels at 135 MeV

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Abstract. Vector analyzing powers, A_x and A_y , of the proton-deuteron break-up reaction have been measured by using a polarized-proton beam at 135 MeV impinging on a liquid-deuterium target. For the experiment, the Big Instrument for Nuclear-polarization Analysis (BINA) was used at KVI, Groningen, the Netherlands. The data are compared to the predictions of Faddeev calculations using state-of-the-art two- and three-nucleon potentials. Our data are reasonably well described by calculations for the kinematical configurations at which the three-nucleon force (3NF) effect is predicted to be small. However, striking discrepancies are observed at specific configurations, in particular in the cases of symmetric configurations, where the relative azimuthal angle between the two protons is small which corresponds to the $d(\vec{p}, {}^2\text{He})n$ channel. The vector analyzing powers of these configurations are compared to the proton deuteron elastic scattering to study the spin-isospin sensitivity of the 3NF models. The results are compared to the earlier results of the proton-deuteron break-up reaction at 190 MeV proton-beam energy [1]. A disagreement is observed for both proton-beam energies between data and calculations which points to a deficiency in the treatment of spin-isospin part of the 3NF.

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1 Introduction

A detailed description of nuclear forces is essential for understanding the properties of nuclei and the dynamics in few-nucleon scattering processes. A large part of the interaction between nucleons is described in meson-exchange theories or in the framework of Chiral Perturbation-Theory (ChPT) [2–4]. Impressive developments are made in describing the two-nucleon force (2NF) within lattice QCD [5], albeit that they are still computationally very expensive and only applicable in a few cases [6].

The need for an additional 3NF became evident when comparing three-body scattering observables and binding energies of light nuclei with the state-of-the-art calculations [7]. All 2NF models such as CD-Bonn [8], Argonne-V18 (AV18) [9], Reid93, Nijmegen I, Nijmegen II [10] give an excellent description of proton-proton and proton-neutron scattering and the properties of the deuteron, such as its binding energy [11]. For the simplest three-nucleon system, the triton, a precise solution of the three-nucleon Faddeev equations employing only 2NF clearly underestimates the experimental binding energy. Similar discrepancies were observed in the binding energy of even heavier nuclei [12]. The need for an additional 3NF also became clear through studying nucleon-deuteron scattering observables [13]. A first sign came from the differen-

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tial cross section of the proton-deuteron elastic interaction [14], where the description of the minimum of the cross section could only be improved by adding a 3NF to the potential. Unfortunately, the inclusion of 3NF only partly remedies these deficiencies.

Several theoretical formalisms have been developed, such as a dynamic Δ [15] and the Tucson-Melbourne [16] 3NF. These were embedded within the rigorous calculations using the Faddeev-type equations by Kraków and Hannover-Lisbon theory groups.

Another source of information about the three-nucleon systems is the nucleon-deuteron break-up process. In this paper, the specific region that corresponds to the reaction $d(\bar{p}, pp)n$ at 135 MeV is studied where the two final-state protons scatter with a small relative energy and a small opening angle. A comparison is made with data of the $\bar{p}d$ elastic reaction that were measured by BINA at KVI [17]. The aim is to study the spin-isospin dependence of A_x and A_y vector-analyzing powers. Moreover, the results are compared to proton-deuteron break-up data taken at similar configurations at a slightly higher proton-beam energy of 190 MeV [1]. In the latter case, a spin-isospin anomaly in A_y was reported. In this paper, we address the energy dependence of this observation and we present in addition new results for A_x .

2 Experimental setup

The $\bar{p}+d$ break-up reaction was studied using a polarized beam of protons with an energy of 135 MeV impinging on a liquid deuterium target which was located at the center of BINA vacuum chamber. The polarized beam was prepared by POLIS (POLARized Ion Source) and accelerated by AGOR (Accelerateur Groningen ORsay) at KVI, the Netherlands. The momenta of the final-state protons were measured using the various detectors of BINA. The forward-scattered protons of the break-up reaction were detected by the forward wall placed outside the vacuum.

As shown in Fig. 1, the detector system BINA is composed of two main parts, the forward wall and the backward ball. The forward wall can measure the energy, the position, and the type of the particle at the polar scattering angles between $10^\circ - 35^\circ$ and azimuthal angles between $0^\circ - 360^\circ$. It has three parts, namely E -scintillators, ΔE -scintillators, and a Multi-Wire Proportional Chamber (MWPC).

The forward-wall E -detector of BINA consists of a cylindrically-shaped array of plastic scintillators to measure the energy of the particles and two arrays of scintillators, up and down (wings), for detecting the secondary scattered particles for polarization-transfer experiments. For the present experiments, these wings were not used. The array of the ΔE -scintillators is composed of 12 parallel vertical plastic scintillator bars. The MWPC of BINA consists of 3 planes, X, Y, and U. The X plane is made of 236 parallel vertical wires, the Y plane has 236 horizontal wires, and the U plane has 296 parallel wires placed at an angle of 45° with respect to the X or Y planes. Scattered particles with enough energy travel from the target

Fig. 1: A schematic drawing of the forward-wall, the backward-ball, the beam direction and the target position of BINA.

Table 1: The experimental features of this experiment.

Beam particle	Polarized proton
Energy	135 MeV
Average beam current	15 pA
Target	Liquid deuterium
Target thickness	3.85 mm
Energy resolution	5%

to the scintillators. They pass through the MWPC and, as a result, their coordinates are recorded. Subsequently, particles pass through the ΔE -scintillators in which a small fraction of their energy is deposited. Finally, the particle is stopped (for protons with an energy less than 140 MeV) inside the E -scintillators and its deposited energy is measured.

The backward part of BINA is covered by a ball-shaped detector. The backward-ball is the scattering chamber and a detector at the same time. The incoming beam hits the target which is placed at the center of the ball. The particles are detected by the forward wall, which is placed outside the vacuum, and particles scattering to angles larger than 35° are detected by the ball. Tab. 1 shows the experimental features used in this experiment.

3 Data analysis

Analyzing powers have successfully been measured as a function of the arclength, S , along the curve presenting the correlation between the energies of the final-state protons for different combinations of their polar and relative azimuthal angles ($\theta_1, \theta_2, \phi_{12} = \phi_1 - \phi_2$). The kinematic variable S corresponds to the arclength along the kinematic curve with $S = 0$ at the point where E_1 is at minimum. The left panel in Fig. 2 shows the energy correlation between the two forward scattered protons after

Fig. 2: The left panel shows E_1 versus E_2 , spectrum of the two protons registered at $(\theta_1, \theta_2, \phi_{12}) = (24^\circ \pm 2^\circ, 24^\circ \pm 2^\circ, 180^\circ \pm 5^\circ)$. The solid line shows the kinematical curve calculated for the central values of the experimental angular bins. The right panel is the projection of events along the D-axis for one slice shown on the left panel. The red line shows the result of a fit through the data. We refer to the text for more details.

the energy calibration procedure. This procedure is performed by finding a calibration function that minimizes the shortest distance between the measured data points of the $\bar{p}d$ break-up reaction for all scintillators (E_1 , E_2) to the kinematical S -curve. This is done via an iterative procedure. The data correspond to a specific kinematical configuration $(\theta_1, \theta_2, \phi_{12}) = (24^\circ \pm 2^\circ, 24^\circ \pm 2^\circ, 180^\circ \pm 5^\circ)$. The solid line shows the kinematical S -curve calculated for the central values of the angular bins. The right panel in Fig. 2 depicts the projection of events for one slice of $S - \Delta S$ and $S + \Delta S$ with $\Delta S = 4.75$ MeV, along the D-axis taken perpendicular to the S -curve. The peak around zero corresponds to break-up events. Most of the events on the left-hand side of the peak are also due to break-up events, however in these cases, the protons have lost part of their energy due to hadronic interactions of the charged particles with the large material budget of the scintillators.

inside the detector. The amount of accidental background is small as can be seen from the small amount of events on the right-hand side of the peak. We fit this spectrum by using a third-order polynomial, representing the hadronic interactions and accidental background, and a Gaussian function, representing the signal. The extracted number of signal events were corrected by the data-acquisition dead time, and the collected beam charge.

For a given kinematical configuration, the analyzing powers can be obtained from the following relation [18]:

$$N_{\xi, \phi_{12}}^s(\phi) = N_{\xi, \phi_{12}}^0(\phi)(1 + p_z^s A_y(\xi, \phi_{12}) \cos \phi - p_z^s A_x(\xi, \phi_{12}) \sin \phi). \quad (1)$$

Fig. 3: Definition of the coordinate systems for the break-up reaction with transversally-polarized beam: The laboratory system (x' , y' , z'), with z' along the beam-momentum direction and y' vertically upward, is used to define the angular configuration of the outgoing protons (with momenta p_1 and p_2). The reaction coordinate system is shown with z along the beam-momentum direction and x obtained by projection of p_1 onto the plane perpendicular to z . The angle ϕ is defined as the angle between the y axis and the spin quantization axis s , which, in the studied case, is vertical (parallel to y') [18,19].

N^s (N^0) is the normalized number of events for a polarized (unpolarized) beam. The vector polarization of the beam is given by p_z and the vector analyzing powers are indicated by A_x and A_y . Here, ϕ is the angle between

Fig. 4: Asymmetry distributions of $g_{\xi, \phi_{12}}(\phi)$ and $h_{\xi, \phi_{12}}(\phi)$ for the configuration $\xi = (20^\circ, 20^\circ, 103 \text{ MeV})$ and $\phi_{12} = 100^\circ$. The error bars represent statistical uncertainties. The lines show the fit of the corresponding functions.

quantization axis for the polarization and the normal to the scattering plane of the first nucleon in the laboratory frame of reference, with $\phi_1 = 0$. Fig. 3 shows the coordinate system and the scattering plane.

ξ defines a kinematical point (θ_1, θ_2, S) . Since the statistics obtained with an unpolarized beam were limited, we extracted the spin observables by solely using $N^\uparrow$ and $N^\downarrow$, corresponding to the normalized number of events for the spin-up and spin-down polarized beams, respectively. The analyzing powers A_x and A_y are extracted using the following relation:

$$f_{\xi, \phi_{12}}(\phi) = \frac{N_{\xi, \phi_{12}}^\uparrow(\phi) - N_{\xi, \phi_{12}}^\downarrow(\phi)}{N_{\xi, \phi_{12}}^\uparrow(\phi)p_z^\uparrow - N_{\xi, \phi_{12}}^\downarrow(\phi)p_z^\downarrow} \quad (2)$$

$$= A_y(\xi, \phi_{12}) \cos \phi - A_x(\xi, \phi_{12}) \sin \phi,$$

where $p_z^\uparrow$ and $p_z^\downarrow$ are the values of up (0.57 ± 0.03) and down (-0.70 ± 0.04) beam polarization. Parity conservation imposes the following restrictions on the components of the vector analyzing powers [18]:

$$\begin{aligned} A_x(\xi, -\phi_{12}) &= -A_x(\xi, \phi_{12}); \\ A_y(\xi, -\phi_{12}) &= A_y(\xi, \phi_{12}), \end{aligned} \quad (3)$$

where for $\phi_{12} = 180^\circ$, we expect $A_x = 0$. By taking the sum and difference of $f_{\xi, \phi_{12}}(\phi)$ and $f_{\xi, -\phi_{12}}(\phi)$ in combination with the results of Eq. 3, the following combination of asymmetries for mirror configurations (ξ, ϕ_{12}) and $(\xi, -\phi_{12})$ can be obtained [19, 20]:

$$\begin{aligned} g_{\xi, \phi_{12}}(\phi) &= \frac{f_{\xi, \phi_{12}}(\phi) + f_{\xi, -\phi_{12}}(\phi)}{2}, \\ &= A_y(\xi, \phi_{12}) \cos \phi, \\ h_{\xi, \phi_{12}}(\phi) &= \frac{f_{\xi, \phi_{12}}(\phi) - f_{\xi, -\phi_{12}}(\phi)}{2}, \\ &= -A_x(\xi, \phi_{12}) \sin \phi. \end{aligned} \quad (4)$$

By fitting the experimentally extracted polarization observables $g_{\xi, \phi_{12}}(\phi)$ and $h_{\xi, \phi_{12}}(\phi)$ with $A_y \cos \phi$ and $A_x \sin \phi$, respectively, we extracted A_y and A_x .

Fig. 4 illustrates such a fit for the asymmetry distributions for the configuration $\xi = (20^\circ, 20^\circ, 103 \text{ MeV})$ and $\phi_{12} = 100^\circ$. Figs. 5 and 6 show our measurements of A_x and A_y as a function of S for some symmetric configurations ($\theta_1 = \theta_2$) at small, intermediate and large relative azimuthal angle ϕ_{12} . The lines in these figures show the results of Faddeev calculations for point-like kinematical configurations in the middle range of the data using 2NFs and 2NF+3NFs as explained in the figure caption. We also performed the weighted average of the theoretical calculations in the range of the data. The results of this averaging are very close to the central values for the kinematics presented here. We have, therefore, decided to present the latter to ease the future comparisons with our data. The errors are statistical and the band in each panel depicts the systematic uncertainties. We identified two sources that give rise to a systematic uncertainty in the measurements of A_y and A_x . The first one is related to the uncertainty of the beam polarization ($\sim 6\%$). The second source relates to induced asymmetries due to small differences in the efficiencies and errors in the charge normalization between the data taken with the spin-up and down polarization states.

4 Discussion

As observed in Figs. 5 and 6, for all azimuthal opening angles, the predictions based on a 2NFs are closest to the data for both analyzing powers, although, some disagreements are observed at some places. The effects of the Coulomb force are very small for all the configurations studied in this paper. Therefore, the origin of these discrepancies must lie in the treatment of 3NFs. However, when 3NF is added to the calculations, and specifically for the configurations when the azimuthal angle is small, the disagreement becomes even larger. The origin of this behaviour is not understood but was also observed in an earlier experiment with a beam energy of 190 MeV [1].

The analyzing powers of the reaction $d(\vec{p}, pp)n$ were measured for symmetric configurations of two protons, $\theta_1 = \theta_2$, with small opening angle $\phi_{12} = 20^\circ$ and small relative energy of less than 1 MeV at the center of S -curve.

Fig. 5: The analyzing power, A_y , as a function of the kinematical variable S for some symmetric configurations with the different ϕ_{12} . The details of the configuration are indicated in each panel and the values refer to the angles $(\theta_1, \theta_2, \phi_{12})$. The circles are the measured A_y and the errors are statistical only. The cyan bands show the systematic uncertainties. The lines show the Faddeev calculations using the 2NF such as CD-Bonn (dotted line) and AV18 (light gray line) and 2NF+3NF models such as CDB+ Δ (dashed-dotted line), CDB+ Δ including Coulomb (solid line), CDB+TM99 (black line) and AV18+UIX (gray line) [13, 21–25].

These configurations are similar to the configuration of $d(\vec{p}, {}^2\text{He})n$. The analyzing powers for the corresponding reaction, $d(\vec{p}, {}^2\text{He})n$, can be compared to the analyzing powers of the elastic $d(\vec{p}, d)p$ scattering. In the elastic channel, the total isospin of the initial and final state is exclusively $\frac{1}{2}$, whereas in the former case, the final state could couple to an isospin $\frac{3}{2}$ as a consequence of the isospin violating Coulomb force [1]. To obtain the values of A_x and A_y corresponding to $d(\vec{p}, {}^2\text{He})n$ we use a second-order polynomial fit to the measured analyzing powers as a function of S for $\phi_{12} = 20^\circ$. We took the fit value and its error at the central value of S , corresponding to the smallest relative energy. In these cases, since the two protons move very close to each other, the most probable wave function would have an angular momentum $L = 0$ and isospin $I = 1$ [1] lending confidence to the fact that this state carries the quantum numbers of ${}^2\text{He}$. We extracted the corresponding predicted values for A_x and A_y from theory using the central value of S , with the smallest relative energy of two protons. Fig. 7 shows the values of A_x and

A_y as a function of center-of-mass angles corresponding to $d(\vec{p}, {}^2\text{He})n$, $\theta_{cm}^{2\text{He}}$ and $d(\vec{p}, d)p$, θ_{cm}^d . In the top left panel of Fig. 7, one can observe that the measured values of A_x are very close to zero as required for a two-body reaction. The filled circles in the bottom left panel of Fig. 7 show the data for A_y . For center-of-mass angles less than 135° the experimental data points are higher than the values of all 2N+3NF theoretical calculations while for center-of-mass angles larger than 135° , our data fall below that of the calculations, however the overall tendency seems to be well reproduced. Fig. 8 compares our results for A_y for $d(\vec{p}, {}^2\text{He})n$ with those taken at the higher beam energy. The circles and squares depict the data points of A_y at 135 MeV and 190 MeV, respectively. The solid and dashed lines show the CDB+ Δ +Coulomb predictions at 135 MeV and 190 MeV proton beam energies, respectively. For both proton beam energies there is a disagreement between the data and the calculations including a 3NF.

Fig. 6: Same as Fig. 5 except for A_x . Note that for $\phi_{12} = 180^\circ$, the analyzing power must be exactly 0 due to parity conservation.

Fig. 7: The analyzing powers, A_x and A_y , as a function of the center-of-mass angles for $d(\vec{p}, {}^2\text{He})n$, $\theta_{cm}^{2\text{He}}$ and $d(\vec{p}, d)p$, θ_{cm}^d , at 135 MeV proton beam energy. On the left panel, the circles show the data points for A_x and A_y and the curves represent the results of different break-up calculation with kinematics very close to the $d(\vec{p}, {}^2\text{He})n$ reaction. The right panel depicts the measured A_y [17] and the calculations for the $\vec{p}d$ elastic reaction at 135 MeV proton beam energy.

Fig. 8: A_y versus the center-of-mass angles for $d(\vec{p}, {}^2\text{He})n$ reaction at two proton beam energies. The circles and squares depict the data points of A_y for proton beam at 135 MeV and 190 MeV, respectively. The solid and dashed lines show the CDB+ Δ +Coulomb predictions at 135 MeV and 190 MeV proton beam energies, respectively.

5 Summary and conclusion

The need for an additional 3NF became clear through studying three-nucleon scattering processes. To investigate systematically 3NF effects in three-nucleon scattering processes, the $\vec{p} + d$ break-up reaction was studied using a polarized beam of protons impinging on a liquid deuterium target. Our main priority was to study configurations in which both protons scatter to polar angles smaller than 30° and with a small, intermediate and large relative azimuthal opening angle. Analyzing powers have successfully been measured and are presented as a function of S for different combinations of $(\theta_1 = \theta_2, \phi_{12})$. The major discrepancies between the data and the theoretical calculations arise at small azimuthal opening angles, $\phi_{12} = 20^\circ$, which corresponds to $d(\vec{p}, {}^2\text{He})n$. In this range, the predictions based a 2NF are close to the data, although, the disagreement is still significant. The inclusion of 3NFs increases the gap between data and predictions.

The results of $d(\vec{p}, {}^2\text{He})n$ for 135 MeV proton beam energy are compared to the results using a proton beam with an energy of 190 MeV [1]. A comparison between two proton beam energies of 135 MeV and 190 MeV in Fig. 8 shows that the spin-isospin deficiency that was observed before does not diminish at lower energies.

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Chapter 7

Summary, conclusion and outlook

7.1 Summary and conclusion

Finding a suitable theory of nuclear forces is one of the main goals in subatomic physics. The need for an additional three-nucleon potential became evident when comparing three-body scattering observables and light-nuclei binding energies with state-of-the-art calculations [13]. The two nucleon force models such as CDB, AV_{18} , Reid93, Nijmegen I and Nijmegen II are able to describe the two-nucleon systems very well. The aim is to significantly extend the world database in the three-nucleon scattering system as a benchmark to eventually have a better understanding of the structure of the three-nucleon interaction. Several theoretical formalisms have been developed, such as a dynamic Δ [66] and the Tucson-Melbourne [61] 3NF. Besides these phenomenological approaches, also two- and three-nucleon forces 3NF have been constructed from chiral perturbation theory (ChPT). The leading 3NF in ChPT shows significant contributions to the nuclear force. This approach provides a self-consistent framework for the description of many-body forces include 3NFs [2]. The proton-deuteron break-up is a suitable reaction to study three nucleon systems. In this thesis, the reaction $d(p, pp)n$ is studied where the two final-state protons scatter with a small azimuthal angles.

The $\bar{p}d$ break-up reaction was studied at KVI in 2006 using a polarized proton beam of 135 MeV. The (un)polarized beam was provided by the atomic POLarized Ion Source (POLIS) and accelerated (65-190 MeV/nucleon) by the superconducting cyclotron AGOR (Accélérateur Groningen ORsay). The beam polarization was measured using the

In-Beam Polarimeter (IBP). The reaction was studied with BINA, the **B**ig **I**nstrument for **N**uclear-polarization **A**nalysis, which inherits a lot of its features from its predecessor, the **S**mall-**A**ngle **L**arge-**A**cceptance **D**etector, SALAD [71]. This detector is particularly suited to study the elastic and break-up reactions at intermediate energies. BINA is composed of two major parts the forward-wall and the backward-ball. The forward-wall measures the energy and the position of final-state protons or deuterons at scattering angles in the range 10° – 37° . The backward-ball part covers the rest of the polar angles up to 165° . Therefore, the BINA detector covers almost the complete phase space of the break-up and elastic reactions.

The first data analysis of $\bar{p}d$ break-up reaction, taken with a proton-beam energy of 135 MeV, was carried out in 2009 [8]. In the present thesis, the vector analyzing power, A_y , and the cross section are reanalyzed and A_x is extracted for the first time. Moreover, we performed for the first time a global review of a rich set of cross section and vector analyzing-power data taken with a proton-beam energy of 135 MeV and 190 MeV using a Dalitz analysis. The results were compared with theoretical calculations from Faddeev calculations using 2N and 2N+3NF models such as CD-Bonn, CDB+ Δ , CDB+ Δ including Coulomb and CDB+TM' [32,34,35,37,41,89] for the kinematics in which both protons scatter to polar angles smaller than 30° and with a relative azimuthal opening angle varying between 20° and 180° in steps of 20° . The results of cross sections and analyzing powers (A_x and A_y) as a function of S for different configurations (θ_1 , θ_2 , ϕ_{12}) are shown in Figs. 5.1–5.3 and Figs. B.1–B.20. The results of the cross sections and A_y were compared with previous results [8]. The results show a small difference in comparison to the previous study that can be traced back to differences in the energy calibration and in the choice of S -bins.

For most of the configurations, the results at small and large relative azimuthal angles show a different behavior when comparing data with theory. At small azimuthal opening angles, the calculation, which is based on the extended CDB+ Δ and with Coulomb corrections, CDB+ Δ including Coulomb, shows a smaller discrepancy with the data than the other calculations. The results show that there is a general disagreement between the data and the calculations including a 3NF. In particular, predictions for the vector analyzing powers show a systematic deficiency at small relative azimuthal angles, which corresponds to small relative energies or small proton-proton invariant masses. In this range, the data of

A_y is closest to the three-body calculation that based on a 2N potential excluding a 3NF. To provide a more detailed analysis of the observed anomaly, we studied the vector analyzing powers, A_x and A_y , for symmetric configurations at small relative azimuthal angles corresponding to the $d(p, {}^2\text{He})n$ channel and compared them to the proton-deuteron elastic reaction. The aim is to study the spin-isospin sensitivity of the 3NF models for a proton beam at energy of 135 MeV. The results are compared to the results of data taken with a 190 MeV proton beam [25] for the configurations corresponding to the $d(p, {}^2\text{He})n$ channel. For both proton beam energies we observe a discrepancy between data and theory pointing to a spin-isospin deficiency in the present description of the 3NF. We note, though, that in general the state-of-the art calculations describe reasonably well the experimental break-up data taking into account its precision. The discrepancies show only up at some parts of the kinematical phase space.

Besides the five-fold differential study of the break-up reaction, we also performed a more global comparison of our data with theoretical calculations using four types of quantities. For the first quantity, we average the vector analyzing powers and cross sections over S for each configuration. Figures 5.4 and 5.5 depict the averaging results for the cross sections and vector analyzing powers versus ϕ_{12} for data taken with a proton beam of 135 MeV. the results of the cross sections are well described considering the systematic errors for this quantity. The results of A_y show that at small ϕ_{12} the theoretical predictions underestimate the experimental result.

For the second quantity, we performed a chi-square analysis for several (θ_1, θ_2) and as a function of ϕ_{12} . Figures 5.6 and 5.7 show the results of $\chi^2/\text{d.o.f.}$ for data taken with 135 MeV and 190 MeV, respectively. The results show very large values of $\chi^2/\text{d.o.f.}$ for the cross sections at specific scattering and relative azimuthal angles. The deviations, independent of the model and beam energy, appear to increase towards large values of ϕ_{12} . This implies that the present models are not able to provide a reasonable description of the data. The absolute values of the $\chi^2/\text{d.o.f.}$ for the analyzing powers A_x and A_y are smaller than the ones for the cross section. However, also for these observables no satisfactory agreement is found for all angular combinations (θ_1, θ_2) and ϕ_{12} .

The first and the second quantities mentioned above deal with specific configurations. To show the results for all configurations and combination of angles, the third quantity was developed. In Figs. 5.8 and 5.9,

the results of a global analysis for the break-up reaction at 135 MeV and 190 MeV for all combination of angles (all configurations) are shown. For the cross section, the calculations underestimate the data in most parts of phase space and in some regions the calculations overestimate the data. For A_x and A_y , the results show that the 2NF is already sufficient to describe the data reasonably well and the effect of the 3NF is predicted to be small. For small relative azimuthal opening angles, the addition of 3NF makes the agreement even worse.

For the last quantity, we explored a Dalitz analysis in terms of two Lorentz invariant quantities for the cross sections and analyzing powers. In this study, we selected events for which the polar angles of the two protons are less than 30° corresponding to the part of the forward wall with a full azimuthal coverage. Based on the Dalitz analysis, the final results for the cross section and the vector analyzing powers, A_x and A_y , have been measured for the proton-deuteron break-up reaction for an incident proton-beam energy of 135 MeV and 190 MeV. Figures 5.10–5.15 and Figs. B.21–B.38 show the results of the Dalitz analysis for the cross section and the vector analyzing powers in comparison to the prediction of different theoretical models. Table 5.1 shows the fraction (in percentage) of the Dalitz spectrum for which the ratio between data and theoretical prediction for cross section falls within an indicated range at 135 MeV and 190 MeV. This table also shows the percentage of the difference between experimental values and different theoretical calculations of A_x and A_y at 135 MeV and 190 MeV. According to Tab. 5.1 for the cross section, more than 50% of the ratios lie in the range of 0.8-1.2 indicating a good agreement with theory. For analyzing powers, more than 50% of the difference values lie in the range of -0.03 - 0.03 (-0.05 - 0.05) for A_x (A_y), and the rest indicates that the predictions overestimate or underestimate the data.

Summarizing all the observations, one can conclude that although, a good agreement is observed between data and the theoretical calculations for a fraction of phase space, a large fraction of the kinematical phase space is not well described by the theoretical calculations. In particular, regions with small relative azimuthal opening angles shows large discrepancies for A_y , while the cross section behaves differently at intermediate values of this variable. Finally, A_x behaves differently at small and large opening angles. The bulk of the data provided with the present analysis should provide a good base for examining the theoretical calculations.

7.2 Outlook

This thesis describes a global comparison between data and theoretical calculations for proton-deuteron break-up data at which the two final-state protons scatter to the forward wall of BINA. In particular, we demonstrated that a Dalitz analysis is feasible to perform for the break-up reaction. However, in order to complete such an analysis, it is necessary to add data corresponding to other scattering angles as well. The BINA setup has the potential to cover a much larger phase space than presented in this thesis. The results of the analysis of break-up configurations at other angles at 135 MeV and 190 MeV will soon be published [81, 90]. These data will complement the results presented in this thesis and will allow to provide a 4π analysis of the break-up process leading eventually to a comprehensive database that can be used as a benchmark for further theoretical developments. Once available, we envision that a 4π study of the Dalitz spectrum and a partial-wave analysis of the break-up data become feasible. The ultimate goal would be to construct high-precision 3N potentials, thereby, providing the basis to significantly improve the microscopic description of nuclei.

Samenvatting

Het vinden van een geschikte kernkrachttheorie is een van de hoofddoelen in de subatomaire fysica. De behoefte aan een extra drie-nucleon-potentiaal werd duidelijk bij het vergelijken van drie-nucleon verstrooiingsobservabelen en de bindingsenergie van lichte kernen met geavanceerde berekeningen [13]. De twee-nucleon kracht (2NF) modellen zoals CDB, AV_{18} , Reid93, Nijmegen I en Nijmegen II kunnen de twee-nucleon systemen zeer goed beschrijven. Het doel is om de wereldbank in het drie-nucleon verstrooiingssysteem aanzienlijk uit te breiden om uiteindelijk een beter inzicht te krijgen in de structuur van de drie-nucleon interactie. Verschillende theoretische formalismes zijn ontwikkeld, zoals een dynamische Δ [66] en de Tucson-Melbourne [61] 3NF. Naast deze fenomenologische benaderingen zijn ook twee- en drie-nucleon krachten geconstrueerd uit chirale perturbatie theorie (ChPT). De eerste order 3NF in ChPT levert een significante bijdrage aan de kernkracht. Deze benadering biedt een zelfconsistent raamwerk voor de beschrijving van veel-nucleonkrachten, waaronder 3NF's [2]. De proton-deuteron splitsing is een geschikte reactie om drie-nucleon systemen te bestuderen. In dit proefschrift wordt de reactie $d(\vec{p}, pp)n$ bestudeerd, waar de twee eindtoestand-protonen zich verspreiden met kleine azimutale hoeken.

De $\vec{p}d$ -splitsingsreactie is in 2006 bij het KVI bestudeerd met behulp van een gepolariseerde protonbundel van 135 MeV. De (niet) gepolariseerde bundel werd geleverd door de atomaire gepolariseerde-ionenbron (POLIS) en versneld (65-190 MeV/nucleon) door de supergeleidende cyclotron AGOR (Accélérateur Groningen ORsay). De bundelpolarisatie werd gemeten met behulp van de in-bundel polarimeter (IBP). De reactie werd bestudeerd met BINA (Big Instrument for Nuclear-polarization Analysis) het grote instrument voor kern-polarisatie analyse dat veel van zijn kenmerken overneemt van zijn voorganger, de kleine-hoek grote acceptantie detector SALAD (Small-Angle Large-Acceptance Detector)

[71]. BINA is met name geschikt om de elastische en splitsingsreacties bij intermediate energieën te bestuderen. Deze detector bestaat uit twee hoofdonderdelen: de voorwaartse wand en de achterwaartse bal. De voorwaartse wand meet de energie en de positie onder verstrooiingshoeken in het bereik 10° – 37° . De achterwaartse bal bedekt de rest van de polaire hoeken tot 165° . Daardoor bestrijkt de BINA-detector bijna de volledige faseruimte van de splitsings- en elastische reacties.

De eerste data-analyse van de $\bar{p}d$ -splitsingsreactie, gemeten met een protonbundelenergie van 135 MeV, werd uitgevoerd in 2009 [8]. In dit proefschrift worden het vector analyserend vermogen A_y en de werkzame doorsnede opnieuw geanalyseerd en wordt A_x voor het eerst geëxtraheerd. Bovendien hebben we, met behulp van een Dalitz-analyse, voor het eerst een globale evaluatie uitgevoerd van een rijke set aan data in de werkzame doorsnede en het vector analyserend vermogen die zijn gemeten met een protonbundelenergie van 135 MeV en 190 MeV. De resultaten zijn vergeleken met de theoretische berekeningen van Faddeev-berekeningen met behulp van 2N- en 2N+3NF-modellen zoals CD-Bonn, CDB+ Δ , CDB+ Δ inclusief Coulomb en CDB+TM' [32, 34, 35, 37, 41, 89] voor de kinematica waarbij beide protonen verstrooien tot polaire hoeken kleiner dan 30° en met een relatieve azimuthale openingshoek variërend tussen 20° en 180° in stappen van 20° . De resultaten van de werkzame doorsnede en analyserende vermogens (A_x en A_y) als functie van S voor verschillende configuraties (θ_1 , θ_2 , ϕ_{12}) worden getoond in Figs. 5.1–5.3 en Figs. B.1–B.20. De resultaten van de werkzame doorsnede en A_y zijn vergeleken met eerdere resultaten [8]. De resultaten laten een klein verschil zien in vergelijking met voorgaande resultaten. Dit verschil kan worden teruggevoerd op verschillen in de energiekalibratie en in de keuze van S -bin.

Voor vele kinematische combinaties, komen de data overeen met de resultaten van de theoretische berekeningen. Echter, bij kleine en grote relatieve azimuthale hoeken vertonen de resultaten van de berekeningen een ander gedrag wanneer ze met de data vergeleken zijn. Bij kleine azimuthale openingshoeken vertoont de berekening, die is gebaseerd op de uitgebreide CDB+ Δ en, met Coulomb-correcties, CDB+ Δ inclusief Coulomb, een kleinere discrepantie met de data dan de andere berekeningen. Voor deze configuraties laten de resultaten zien dat er een algemene onenigheid bestaat tussen de data en de berekeningen die een

3NF meenemen. In het bijzonder, voorspellingen voor de vector analyserende vermogens vertonen een systematische deficiëntie bij kleine relatieve azimuthale hoeken, ofwel kleine relatieve energieën (invariante massa van de twee uitgaande protonen (M_{pp}) verschoven met tweemaal de massa van het proton ($2m_p$)). In dit bereik komt de data van A_y het dichtst in de buurt van de berekening van het drie-nucleon systeem die is gebaseerd op een potentieel van 2NF *exclusief* een 3NF. Voor een meer gedetailleerde analyse van de waargenomen afwijking hebben we de vector analyserende vermogens A_x en A_y bestudeerd voor symmetrische configuraties bij kleine relatieve azimuthale hoeken die overeenkomen met het $d(p, {}^2\text{He})n$ -kanaal en vergeleken met de proton-deuteron elastische reactie. Het doel is om de spin-isospin-gevoeligheid van de 3NF-modellen voor een protonbundel met een energie van 135 MeV te bestuderen. De resultaten zijn vergeleken met de resultaten van data die zijn gemeten met een 190 MeV protonbundel [25] voor de configuraties die overeenkomen met het $d(p, {}^2\text{He})n$ -kanaal. Voor beide protonbundelenergieën zien we een discrepantie tussen data en theorie die wijst op een spin-isospin deficiëntie in de huidige beschrijving van de 3NF. We merken echter op dat de geavanceerde berekeningen over het algemeen redelijk goed de experimentele verstrooiingsdata beschrijven, rekening houdend met de nauwkeurigheid ervan. De verschillen zijn alleen aanwezig in een aantal delen van de kinematische faseruimte.

Naast de vijfvoudige differentiële studie van de splitsingsreactie hebben we met behulp van vier soorten grootheden ook een meer globale vergelijking van onze data met theoretische berekeningen uitgevoerd. Voor de eerste grootheid nemen we van de vector analyserende vermogens en de werkzame doorsnede voor elke configuratie het gemiddelde over S . Figuren 5.4 en 5.5 tonen de gemiddelde resultaten voor de werkzame doorsnede en de vector analyserende vermogens tegen ϕ_{12} voor data gemeten met een protonbundel van 135 MeV. De resultaten van de werkzame doorsnede worden goed beschreven, rekening houdend met de systematische fouten voor deze grootheid. De resultaten van A_y laten zien dat bij kleine ϕ_{12} de theoretische voorspellingen het experimentele resultaat onderschatten. Voor de tweede grootheid voerden we een chi-kwadraattoets uit voor verschillende (θ_1, θ_2) en als functie van ϕ_{12} . Figuren 5.6 en 5.7 tonen de resultaten van χ^2 , gedeeld door het aantal vrijheidsgraden (d.o.f.), voor data gemeten met respectievelijk 135 MeV en 190 MeV. De resultaten tonen zeer grote waarden van $\chi^2/\text{d.o.f.}$ voor de werkzame doorsnede bij specifieke verstrooiing en

relatieve azimuthale hoeken. De afwijkingen, afhankelijk van het model en de bundelenergie, lijken toe te nemen naar grote waarden van ϕ_{12} . Dit houdt in dat de huidige modellen geen redelijke beschrijving van de data kunnen geven. De absolute waarden van de $\chi^2/\text{d.o.f.}$ voor de analyserende vermogens A_x en A_y zijn kleiner dan die voor de werkzame doorsnede. Maar ook voor deze observabelen is geen bevredigende overeenstemming gevonden voor alle hoekcombinaties (θ_1, θ_2) en ϕ_{12} .

De eerste en de tweede hierboven genoemde grootheden hebben betrekking op specifieke configuraties. Om de resultaten voor alle configuraties en combinaties van hoeken te tonen, werd de derde grootheid ontwikkeld. In Fig. 5.8 en 5.9 worden de resultaten van een globale analyse voor de splitsingsreacties bij 135 MeV en 190 MeV voor alle combinaties van hoeken (alle configuraties) getoond. Voor de werkzame doorsnede onderschatten de berekeningen de data in de meeste delen van de faseruimte en in sommige regio's overschatten de berekeningen de data. Voor A_x en A_y laten de resultaten zien dat de 2NF al voldoende is om de data redelijk goed te beschrijven en de voorspelling is dat het effect van de 3NF klein is. Voor kleine relatieve azimuthale openingshoeken maakt de toevoeging van 3NF de discrepantie nog groter. Voor de laatste grootheid hebben we een Dalitz-analyse uitgevoerd in termen van twee Lorentz-invariante grootheden voor de werkzame doorsnede en de analyserende vermogens. In deze studie hebben we data geselecteerd waarvoor de polaire hoeken van de twee protonen kleiner zijn dan 30° , overeenkomend met het deel van de voorwaartse wand met een volledige azimuthale dekking. Op basis van de Dalitz-analyse zijn de eindresultaten voor de werkzame doorsnede en de vector analyserende vermogens A_x en A_y gepresenteerd voor de proton-deuteron splitsingsreactie voor een invallende protonbundelenergie van 135 MeV en 190 MeV. Figuren 5.10–5.15 en Figs. B.21–B.38 tonen de resultaten van de Dalitz-analyse voor de werkzame doorsnede en de vector analyserende vermogens in vergelijking met de voorspelling van verschillende theoretische modellen. Tabel 5.1 toont de fractie (in percentage) van het Dalitz-spectrum waarvoor de verhouding tussen data en theoretische voorspelling voor de werkzame doorsnede binnen het aangegeven bereik valt bij 135 MeV en 190 MeV. Deze tabel toont ook het percentage van het verschil tussen experimentele waarden en verschillende theoretische berekeningen van A_x en A_y bij 135 MeV en 190 MeV. Volgens Tab. 5.1 ligt voor de werkzame doorsnede meer dan 50% van de verhoudingen in het bereik van 0.8-1.2, hetgeen een goede overeenstemming met de

theorie aangeeft. Voor de analyserende vermogens ligt meer dan 50% van de verschilwaarden in het bereik van -0.03 - 0.03 (-0.05 - 0.05) voor A_x (A_y). De rest geeft aan dat de voorspellingen de data overschatten of onderschatten. Alle waarnemingen samenvattend kan worden geconcludeerd dat een grote fractie van de kinematische faseruimte niet wordt beschreven door de theoretische berekeningen. In het bijzonder vertonen gebieden met kleine relatieve azimuthale openingshoeken grote verschillen voor A_y , terwijl de werkzame doorsnede zich anders gedraagt bij tussenliggende waarden van deze variabele. Ten slotte gedraagt A_x zich anders bij kleine en grote openingshoeken. De grote hoeveelheid data die bij de huidige analyse zijn verstrekt biedt een goede basis voor het toetsen van de theoretische berekeningen.

Dit proefschrift beschrijft een globale vergelijking tussen data en theoretische berekeningen voor proton-deuteron-splitsingsdata waarbij de twee eindtoestand-protonen zich verspreiden naar de voorwaartse wand van BINA. We hebben met name aangetoond dat een Dalitz-analyse van de splitsingsreactie uitvoerbaar en nuttig is. Om een dergelijke analyse te voltooien is het echter noodzakelijk om ook data toe te voegen die gemeten zijn voor andere verstrooiingshoeken. De BINA-opstelling kan een veel grotere faseruimte bestrijken dan in dit proefschrift wordt gepresenteerd. De resultaten van de analyse van splitsingsconfiguraties onder andere hoeken bij 135 MeV en 190 MeV zullen binnenkort worden gepubliceerd [81, 90]. Deze data zullen een aanvulling vormen op de resultaten die in dit proefschrift zijn gepresenteerd en zullen het mogelijk maken om een 4π analyse van het splitsingsproces uit te voeren, wat uiteindelijk zal leiden tot een uitgebreide databank die kan worden gebruikt voor verdere theoretische ontwikkelingen. We voorzien dat een 4π studie van het Dalitz-spectrum een partiële-golf analyse van de splitsingsdata mogelijk zal maken. Het uiteindelijke doel zal zijn om uiterst nauwkeurige $3N$ -potentialen te construeren, waardoor de basis wordt gelegd om de microscopische beschrijving van kernen aanzienlijk te verbeteren.

Appendix A

Extracting the cross sections

A general form for the differential cross section is

$$\frac{d\sigma}{d\Omega} \left[\frac{\text{mb}}{\text{sr}} \right] = \frac{N_{\text{out}}}{I[\text{nC}]/Z} \cdot \underbrace{\frac{1}{N[1/\text{mg}] \delta x[\text{mg}/\text{cm}^2]}}_{\equiv t[1/\text{mb}]} \cdot \frac{1}{\Delta\Omega[\text{sr}]}, \quad (\text{A.1})$$

where N_{out} is the number of outgoing particles, I is the total integrated charge in nC, Z is the charge per projectile, δx is the target thickness in mg/cm^2 , N is the number of scattering centers per mg of the target and $\Delta\Omega$ is the solid angle in sr. The target thickness is obtained from

$$t[1/\text{mb}] = \delta x[\text{mg}/\text{cm}^2] \cdot \frac{n_{\text{atoms}}}{m_{\text{target}}^{\text{mol}}[\text{u}]} \cdot N_A \cdot 10^{-3} \cdot 10^{-27} \left[\frac{\text{cm}^2}{\text{mb}} \right],$$

where N_A is Avogadro's number, n_{atoms} is the number of atoms per compound molecule, and $m_{\text{target}}^{\text{mol}}(\text{u})$ is the target weight in atomic units, with $1\text{u} = 10^3\text{mg}/1\text{mol}$.

$$\begin{aligned} \frac{1}{e} \cdot 10^{-9} \cdot \underbrace{10^{-3} \cdot N_A \cdot 10^{-27}}_{N\delta x[\text{cm}^2/(\text{mb} \cdot \text{mol})]} \cdot \underbrace{10^{-3}}_{\Delta\Omega} &= \frac{N_A}{e} \cdot 10^{-42} \left[\frac{\text{cm}^2}{\text{mb} \cdot \text{C} \cdot \text{mol}} \right] \\ &\approx 3.75872 \left[\frac{\text{cm}^2}{\text{mb} \cdot \text{C} \cdot \text{mol}} \right] \end{aligned} \quad (\text{A.2})$$

where e is the elementary charge. Inserting these relations into (A.1) leads to the formula used during this work to calculate the cross sections:

$$\frac{d\sigma}{d\Omega} \left[\frac{\text{mb}}{\text{sr}} \right] = \frac{e \cdot 10^{42}}{N_A} \cdot \frac{N_{\text{out}}}{I[\text{nC}]/Z} \cdot (\delta x[\text{mg}/\text{cm}^2] \cdot \frac{n_{\text{atoms}}}{m_{\text{target}}^{\text{mol}}[\text{u}]})^{-1} \cdot \frac{1}{\Delta\Omega[\text{msr}]} \quad (\text{A.3})$$

For scattering of protons, $Z = 1$, on deuterons using a liquid deuterium target during the experiments in this work, $n_{\text{atoms}} = 2$ and $m_{\text{target}}^{\text{mol}}(\text{u}) = 4.028$ and equation (A.3) results in:

$$\frac{d\sigma}{d\Omega} \left[\frac{\text{mb}}{\text{sr}} \right] = \frac{1}{3.75872} \cdot \frac{N_{\text{out}}}{I[\text{nC}]} \cdot \left(\frac{1}{\delta x[\text{mg}/\text{cm}^2] \cdot 0.496} \right) \cdot \frac{1}{\Delta\Omega[\text{msr}]}.$$

Appendix B

Results of the cross sections and analyzing powers

The results of the two- and five-fold differential cross sections and analyzing powers are shown in this appendix.

Figure B.1: The cross sections at $(28^\circ, 28^\circ)$ as a function of S at different azimuthal angles. Error bars show the statistical uncertainties for the data points. The red (dotted-dashed), blue (dotted), black (solid), green (long dashed), gray (dashed) and brown (double dotted-dashed) lines show the predictions of Faddeev calculations using CD-Bonn, CDB+ Δ , and CDB+ Δ including Coulomb, AV_{18} , $AV_{18}+UIX$ and CDB+TM' calculations [33, 37, 41, 85, 89], respectively. The cyan bands depict the systematic uncertainties (2σ).

Figure B.2: Same as Fig. B.1 except for $(\theta_1, \theta_2) = (28^\circ, 24^\circ)$. Figure B.3: Same as Fig. B.1 except for $(\theta_1, \theta_2) = (28^\circ, 20^\circ)$.

Figure B.4: Same as Fig. B.1 except for $(\theta_1, \theta_2) = (28^\circ, 16^\circ)$. Figure B.5: Same as Fig. B.1 except for $(\theta_1, \theta_2) = (24^\circ, 24^\circ)$.

Figure B.6: Same as Fig. B.1 except for $(\theta_1, \theta_2) = (24^\circ, 20^\circ)$. Figure B.7: Same as Fig. B.1 except for $(\theta_1, \theta_2) = (24^\circ, 16^\circ)$.

 Figure B.8: Same as Fig. B.1 except for $(\theta_1, \theta_2) = (20^\circ, 20^\circ)$.

 Figure B.9: Same as Fig. B.1 except for $(\theta_1, \theta_2) = (20^\circ, 16^\circ)$.

Figure B.10: Same as Fig. B.1 except for $(\theta_1, \theta_2) = (16^\circ, 16^\circ)$.

Figure B.11: Same as Fig. B.1 except for A_x and A_y . The red lines in the bottom panels correspond to a zero line.

Figure B.12: Same as Fig. B.11 except for $(\theta_1, \theta_2) = (28^\circ, 24^\circ)$.

 Figure B.13: Same as Fig. B.11 except for $(\theta_1, \theta_2) = (28^\circ, 20^\circ)$.

Figure B.14: Same as Fig. B.11 except for $(\theta_1, \theta_2) = (28^\circ, 16^\circ)$.

 Figure B.15: Same as Fig. B.11 except for $(\theta_1, \theta_2) = (24^\circ, 24^\circ)$.

Figure B.16: Same as Fig. B.11 except for $(\theta_1, \theta_2) = (24^\circ, 20^\circ)$.

 Figure B.17: Same as Fig. B.11 except for $(\theta_1, \theta_2) = (24^\circ, 16^\circ)$.

Figure B.18: Same as Fig. B.11 except for $(\theta_1, \theta_2) = (20^\circ, 20^\circ)$.

 Figure B.19: Same as Fig. B.11 except for $(\theta_1, \theta_2) = (20^\circ, 16^\circ)$.

Figure B.20: Same as Fig. B.11 except for $(\theta_1, \theta_2) = (16^\circ, 16^\circ)$.

Figure B.21: Dalitz plots of the experimental cross sections and 3NF theoretical calculation (CDB+Δ) for $\bar{p} + d$ break-up reaction at 135 MeV. The top row shows Dalitz plots of the data (left) and the absolute error of the data (right). The bottom row depicts Dalitz plots of the CDB+Δ calculation (left) and the ratio of the data to the results of CDB+Δ calculation (right).

Figure B.22: Same as Fig. B.21 except for CDB+TM'.

Figure B.23: Same as Fig. B.21 except for CDB.

Figure B.24: Same as Fig. B.21 except at 190 MeV.

Figure B.25: Same as Fig. B.24 except for CDB+TM'.

Figure B.26: Same as Fig. B.24 except for CDB.

Figure B.27: Dalitz plots of A_x for the proton-deuteron break-up reaction at 135 MeV. The top row shows the spectra for the data (left) with an estimate of its absolute error (right). The bottom row depicts a complete theoretical calculation including CDB+ Δ (left) and the difference between data and calculation (right).

Figure B.28: Same as Fig. B.27 except for CDB+TM' (135 MeV).

Figure B.29: Same as Fig. B.27 except for CDB (135 MeV).

 Figure B.30: Same as Fig. B.27 except for A_y (135 MeV).

Figure B.31: Same as Fig. B.30 except for CDB+TM' (135 MeV).

Figure B.32: Same as Fig. B.30 except for CDB (135 MeV).

Figure B.33: Same as Fig. B.27 except at 190 MeV.

Figure B.34: Same as Fig. B.33 except for CDB+TM' (190 MeV).

Figure B.35: Same as Fig. B.33 except for CDB (190 MeV).

Figure B.36: Same as Fig. B.33 except for A_y (190 MeV).

Figure B.37: Same as Fig. B.36 except for CDB+TM' (190 MeV).

Figure B.38: Same as Fig. B.36 except for CDB at 190 MeV.

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