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A comprehensive study of the analyzing powers of the proton-deuteron break-up reaction at 190 MeV with BINA

Mohammadi-Dadkan, Maisam

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University of Sistan
 and Baluchestan

A comprehensive study of the analyzing powers of the proton-deuteron break-up reaction at 190 MeV with BINA

Ph.D. thesis

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

and

to obtain the degree of Ph.D. at the
 University of Sistan and Baluchestan
 on the authority of the
 President Prof. Gh. Rezaei
 and in accordance with
 the decision by the College of Deans.

Double Ph.D. degree

This thesis will be defended in public on
 Monday 4 May 2020 at 14:30 hours

by

Maisam Mohammadi Dadkan

born on 3 February 1987
 in Iranshahr, Iran

Supervisors

Prof. N. Kalantar-Nayestanaki

Prof. A. A. Mehmandoost-Khajeh-Dad

Co-supervisor

Dr. J. G. Messchendorp

Assessment committee

Prof. E. Epelbaum

Prof. Calvin R. Howell

Prof. M. Mahjour-Shafiei

Prof. R. G. E. Timmermans

Front cover:

A conceptual design depicting the experimental setup, symmetry, and asymmetry.

Back cover:

A photo of the beautiful and unique needleworking art from Baluchestan. This art is used for thousands of years in this region to make women's dresses and other things.

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To my dear family
and
my teachers

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1. Introduction

To have a solid framework for describing properties of atomic nuclei, nuclear reactions, and nuclear matter, we need to understand all aspects of the nuclear force. A lot of effort has been made to establish a theoretical framework for the nucleon-nucleon (NN) interaction, since Chadwick discovered the neutron as a constituent of atomic nuclei [1]. Based on Yukawa’s meson-exchange model [2], several semi-phenomenological models have been developed in the last decades for the NN interaction [3–6]. All these models deploy a residual interaction of the underlying strong force between quarks and gluons according to the theory of Quantum Chromodynamics (QCD). The Chiral Perturbation Theory (ChPT), an effective field theory of QCD for nucleon-meson degrees of freedom, provides a fundamental approach for formulating the nuclear force. Both the phenomenological two-nucleon models and ChPT accurately describe NN scattering database with $\chi^2/ndf \sim 1$.

While the NN models provide excellent predictions of the large NN scattering database, they fail to describe the binding energy (BE) of $A > 2$ nuclei [7,8]. Figure 1.1 compares the measured binding energies and the Green’s Function Monte Carlo Calculations (GFMC), see Ref. [9] and references therein, performed with only a two-nucleon potential. This comparison demonstrates that as the number of nucleons in the nuclei increases, the deviation between the calculation based on AV18 NN potential (blue lines) and the measurements (green lines) increases. Furthermore, a large discrepancy has been observed between predictions of NN models and the nucleon-deuteron elastic scattering data [10–12]. These evidences confirmed that there are additional underlying mechanisms which are playing a role in the nuclear force and they are not incorporated within the NN potentials. These effects are referred to as many-body force effects. The three-nucleon force (3NF) is considered as the most dominant one of these effects.

In the past decades, several phenomenological 3NF models have been developed based on the works by Fujita and Miyazawa [13] and Brown and Green [14] to implement 3NF effects in the existing calculations [15–19]. For the case of the binding energy (see Fig. 1.1), the inclusion of a 3NF in the calculations (red lines) improves the agreement between data and calculations. For observables in elastic Nd scattering at higher energies and large scattering angles, the inclusion of 3NF effects does not completely fill the gap between data and calculations. Figure 1.2 demonstrates this by showing a comprehensive comparison between data and theory of vector analyzing power (A_y) and cross section (σ) in elastic proton-deuteron scattering at several beam energies between 100-200 MeV. It seems that the present approaches of adding phenomenological 3NFs to NN models do not provide a complete framework of the nuclear force. Based on binding energy studies, the available 3NF do a very reasonable job. This means that the 3NF can describe the main features in nuclei that are dominated by low-momentum components of the wave function. Via scattering experiment, which are more sensitive to the high-momentum components, one does see still large discrepancies, and hence high-momentum components are not well understood. On the other hand, the predictions from different 3NF models are not in

Figure 1.1: GFM C energies of ground and excited states of light nuclei for the AV18 and AV18+IL7 Hamiltonians compared to experimental values [9]. For a description of the colored lines, see the legend.

agreement with each other. For instance, a large difference in the predictions of the cross sections at intermediate energies can be seen between two different treatments of a 3NF in combination with the CD-Bonn NN model; see Fig. 1.3. Therefore, there is a large ambiguity in the 3NF between theoretical approaches. Data are required to constrain the modeling of 3NF effects.

In the past decades, the elastic channel of Nd scattering has been investigated experimentally at different beam energies below the pion-production threshold. The results revealed that the current 3NF models are not able to explain the discrepancy between measurements and calculations particularly at higher beam energies and at the minimum of the differential cross section at backward angles [10, 11, 20]. Also, the elastic scattering process cannot provide any further information about the dynamics of the 3NF effects due to its limited phase-space coverage. The break-up reaction, on the other hand, has a rich kinematical phase space to investigate the nuclear force in much more details. To have a systematic and detailed investigation of 3NFs, the three-body break-up channel is a suitable candidate because of its rich kinematical phase space and having various degrees of sensitivity to the three-nucleon forces and other underlying dynamics depending on the kinematic. In contrast to the elastic channel, the Nd break-up reaction has three particles in the final state. This provides a richer phase space, but also imposes a complexity with respect to the detection of the break-up reaction. This makes the break-up experiments more challenging compared to studying the elastic channel. In the break-up case, there are two methods to design and carry out these kinds of the experiments. In the

Figure 1.2: The deviation of various theoretical calculations from pd elastic scattering measurement at different energies. The left panels depict the deviation for the vector analyzing powers A_y at different energies. The right panels show the deviation for cross sections in [%]. It is clear that the deviations for both observables increase at higher beam energies and large θ_{CM} . For a description of the lines, see the legends. The data are taken from Ref. [21].

first method, one selects specific kinematics and places the detectors at the corresponding angles. Another method, which is more challenging technically, is to exploit a large acceptance detector to measure the kinematical variables of all the particles in the final state for a large part of the available phase space.

The investigation on the 3NF through the break-up channel has started since the 70s by measuring cross sections and spin-dependent observables. Later measurements of this kind have been performed for limited parts of the break-up phase space at low energies and it was shown that the effect of 3NF is rather small at these energies [23–25]. Still, there are notable discrepancies between nucleon-deuteron break-up data and rigorous 3N calculations at low energies. For example, the space star anomaly [26–30] in nucleon-deuteron break-up and the neutron-neutron quasi-free scattering problem [31–33]. Also, a significant discrepancy in A_y between data and calculations was observed at low energies. This anomaly is also known as the A_y -puzzle [34]. Also, at intermediate energies below 100 MeV, several measurements were performed and the results show a similar trend as was observed at low energies except for a few configurations [35–37]. A comparison between those results and measurements for a few configurations at 200 MeV [38] showed

Figure 1.3: The relative difference between the predictions of Bochom-Crakow (BC) and Hanover-Lisbon (HL) groups for proton-deuteron elastic scattering cross sections as a function of θ_{CM} for incident nucleon energies between 50 and 200 MeV. The left panel depicts the differences between the models for the case when only the two-nucleon CD-Bonn potential has been used. In the right panel, two different 3NFs have been included in the calculations. The TM' and Δ 3NFs are used for BC and HL calculations, respectively. The results are separated into two groups, one for 50–120 MeV with black squares and the other for 120–200 MeV with red squares. Figure is taken from Ref. [22].

a mixed picture and one cannot make a conclusion based on these results. Generally, we expect that spin and isospin effects, relativistic effects [39–41], and Coulomb force [42] play a role in the properties of nuclei. In the three-body break-up reaction, the sensitivity to each of these effects depends strongly on the selected kinematics and energies involved. To perform a broad investigation of the nuclear force through the break-up reaction, it would be advantageous to probe the complete kinematical phase space.

Many theoretical and experimental investigations have been carried out in the past and they have opened doors improving our understanding of the nature of the nuclear force [22, 43–45]. In contrast to the available rich database in the *Nd* elastic scattering channel, the number of experiments in the *Nd* break-up reaction is very limited. Figure 1.4 illustrates the existing database of various observables of *Nd* elastic and break-up channels. It is clear that the dataset of the break-up observables is still very poor. The ultimate goals of the present research are to perform a systematic investigation of the nuclear force in three-nucleon systems through the break-up channel at relatively high energies below the pion-production threshold, and also to improve the database of the three-body break-up observables.

Figure 1.4: The database of the observables as measured at various laboratories till 2013. The red circles represent the experiments which are performed with neutron beam and the blue circles are data from the experiments using proton and deuteron beams at different beam energies (in units of MeV per nucleon). The size of each circle or square roughly represents the angular coverage for a particular observable at a given energy. A large circle or square refers to a (nearly) complete angular coverage, whereas for a small circle or square only a limited angular range was measured. Open circles refer to data that are presently being analyzed and not published till 2013. Figure is taken from Ref. [22].

1.1 Study of the nuclear force at KVI

A systematic investigation of the nuclear force through various few-body scattering processes has been initiated at KVI in a common effort between the Dutch and the Polish groups since the end of 90s by developing various experimental setups and exploiting high-quality polarized beams [21, 42, 46–58]. Several reaction channels at different beam energies have been studied in the past two decades. Besides the comprehensive study of the radiative capture, bremsstrahlung, and elastic-scattering processes, the main focus in the last phase of the experimental campaign was on the three and four-body break-up channels. BINA¹ is the last experimental setup which was exploited at KVI for few-nucleon scattering experiments. This detection system is capable of measuring the energy

¹ Big Instrument for Nuclear-polarization Analysis

and the scattering angles of all the reaction products of three and four-body final states in coincidence. Since 2005, various experiments were carried out using BINA and a polarized proton or deuteron beam. Key examples are the study of the proton-deuteron process at 190 MeV [50] and 130 MeV [51] beam energies. Further, different channels in deuteron-proton and deuteron-deuteron scattering have been investigated using BINA with a polarized deuteron beam at an energy of 65 MeV/nucleon [52].

The large angular coverage and the large variety of final states provided a rich dataset. Only part of the acquired data were so-far analyzed and published. The work presented in this thesis is a complementary analysis of the proton-deuteron break-up reaction at 190 MeV. This experiment is a suitable tool to study the high-momentum components of the nuclear force. The first goal of the work presented in this thesis is to reproduce the results that were obtained in the previous analysis [50]. The previous analysis has been done for the part of the phase space at which two protons scatter to the forward angles ($\theta_{1,2} < 40^\circ$). The results of that analysis showed that there is a significant disagreement between data and various theoretical predictions of the analyzing power (A_y) at some kinematics which corresponds to small relative energies of two protons and a relatively good agreement at other kinematics; see Fig. 1.5. The second and primary goal is to complement the previous analysis by providing a complete set of vector analyzing powers and cross sections of the proton-deuteron break-up reaction at 190 MeV. For this, we analyzed the part of phase space at which one proton scatters to angles less than 40° and the other one to angles larger than 40° . Finally, we combined all the results that have been obtained in this and the previous analysis to systematically investigate 3NF effects in the proton-deuteron break-up reaction below the pion-production threshold with the aim to provide new insights in our understanding of the nuclear force.

1.2 Outline of the thesis

Chapter 2 of this thesis is devoted to describing the theoretical frameworks that are used to model NN and 3NF. Several theoretical approaches for calculating break-up observables will be discussed in this chapter. In Chapter 3, the experimental facility which has been used for the present research will be discussed. All the components of the detection system and its specifications will be described. A brief description of the electronic and the data acquisition system will be explained in this chapter. The analysis methods used to extract the break-up observables will be discussed in Chapter 4. The final results for most of the break-up configurations are presented in Chapter 5. Furthermore, a comprehensive comparison between the experimental results and various theoretical predictions will be provided. At the end, the present analysis will be summarized, followed by concluding remarks and an outlook in Chapter 6.

Figure 1.5: The comparison of the results of the analyzing power measurements for a few selected configurations with different theoretical predictions. The NN band (light gray) is composed of various existing two-nucleon calculations. The 3N band (dark gray) shows the same NN potentials including the TM (3N) potential. The lines are described in the legend. The errors are statistical and the cyan band in each panel depicts the systematic uncertainties (2σ). Figure is taken from Ref. [50].

2. Theoretical framework of the nuclear force

The exact nature of the nuclear force has been one of the main points of investigation in nuclear physics since Chadwick discovered the neutron as a constituent of atomic nuclei in 1932 [1]. It then became clear that the neutron and the proton are the building blocks of the atomic nuclei. After that, people started to answer the question on how the nucleons are bound in the atomic nuclei. Yukawa proposed the first systematic approach for the nuclear force in 1935 [2] in analogy to the electromagnetic interaction where the photon is the force carrier. Due to the short range of the nuclear force, Yukawa proposed that the force carrier between nucleons should be a particle with a mass of ≈ 130 MeV. After a few years, the particle which Yukawa had proposed was discovered and called pion [59].

Since 1935, when Yukawa initiated his model for the describing nucleon-nucleon interaction, the nuclear force has evolved and different approaches have been developed to find a consistent description for the interaction between nucleons. The primitive attempt to formulate the nuclear force was based on the idea that the proton and neutron are fundamental particles. Therefore, the potentials based on these models solely take the nucleons and mesons as degrees of freedom in the nuclei. While these models do a great job in describing two-nucleon systems, they fail to describe the systems which have more than two nucleons. It has become clear that there are additional underlying dynamics, beyond the NN interaction, which are playing a role in the nuclear force, generally referred to as few-nucleon force effects. To implement these effects in the nucleon-nucleon potentials, various phenomenological 3NF models have been developed in combination with two-nucleon potentials.

Ever since it was known that nucleons are composed of quarks and gluons, the nuclear force has been considered as a residual color force between quarks and gluons. Due to the non-perturbative nature of QCD at low energies, it can be applied to the nuclear system only through an Effective Field Theory (EFT). This fundamental approach for nucleonic systems is known as Chiral Perturbation Theory (ChPT) [60,61]. To have higher precision, one should extend the calculations to the higher orders. Three-, four- and more-nucleon forces start contributing at third, fourth and sixth orders, respectively [62].

In this chapter, we will briefly describe the scattering theory and Faddeev equations. Then, three phenomenological NN potentials, as representative examples, will be discussed. Furthermore, two different 3NF models will be discussed as well. Then, chiral perturbation theory and its latest successes in the field of the nuclear force will be discussed.

2.1 Scattering theory and Faddeev equations

The non-relativistic scattering theory is based on the well-known Lippmann-Schwinger equation (LSE). Solving this equation is essential for calculating observables in scattering processes. For nucleon-nucleon scattering, this equation can be written as:

$$|\Psi^\pm\rangle = |\phi\rangle + \lim_{\epsilon \rightarrow 0} \frac{1}{E \pm i\epsilon - H_0} V |\Psi^\pm\rangle, \quad (2.1)$$

where $|\phi\rangle$ is the eigenstate of the operator $H_0 = -\frac{1}{2m}\nabla^2$ with the eigenvalue E . $|\Psi^+\rangle$ ($|\Psi^-\rangle$) is the outgoing (incoming) wave functions in a scattering process. V is the interaction potential between two systems in the scattering process. In the scattering experiments, the observables associated with $|\Psi^+\rangle$ are measured. The transition operator, t , is defined by:

$$V|\Psi^\pm\rangle \equiv T|\phi\rangle. \quad (2.2)$$

Multiplying V from the left side of Eq. 2.1 results in

$$T = V + VG_0T, \quad (2.3)$$

where $G_0 \equiv \frac{1}{E \pm i\epsilon - H_0}$. Using the Born approximation, Eq. 2.3 can be expanded as a series of G_0 and V to evaluate the T -matrix. The cross section is proportional to the square of the transition amplitude of $|A_{q_i \rightarrow f}|^2$ from q_i to q_f :

$$A_{q_i \rightarrow f}(t) = \langle \psi_{q_f}^0 | \Psi(t) \rangle. \quad (2.4)$$

Therefore, in nucleon-nucleon scattering process, the cross section is proportional to $|T_{i \rightarrow f}|^2$.

In contrast with two-nucleon scattering, in three-nucleon scattering, there are three LS equations of the process which cannot be solved using the Born approximation. These three equations originate from different possible channels in three-body scattering approximation and are defined by:

$$\begin{aligned} |\Psi_\alpha^{(+)}\rangle &= |\phi_\alpha\rangle + G_\alpha V^\alpha |\Psi_\alpha^{(+)}\rangle, \\ |\Psi_\alpha^{(+)}\rangle &= G_\beta V^\beta |\Psi_\alpha^{(+)}\rangle, \\ |\Psi_\alpha^{(+)}\rangle &= G_\gamma V^\gamma |\Psi_\alpha^{(+)}\rangle. \end{aligned} \quad (2.5)$$

α , β , and γ indicate different rearrangement channels of the three-nucleon system, $\beta \neq \alpha \neq \gamma$, and $V^\alpha \equiv V_\beta + V_\gamma + V_4$. For three-nucleon scattering, an exact solution can be obtained iteratively through the Faddeev equations [63]. In this approach, the total state is decomposed into 3 parts in such a way that the sum of the amplitudes of the decomposed parts gives the total amplitude. Therefore, one obtains:

$$\begin{aligned} |\psi_{\alpha,\alpha}\rangle &= |\phi_\alpha\rangle + G_\alpha V_\alpha (|\psi_{\alpha,\beta}\rangle + |\psi_{\alpha,\gamma}\rangle), \\ |\psi_{\alpha,\beta}\rangle &= G_\beta V_\beta (|\psi_{\alpha,\gamma}\rangle + |\psi_{\alpha,\alpha}\rangle), \\ |\psi_{\alpha,\gamma}\rangle &= G_\gamma V_\gamma (|\psi_{\alpha,\alpha}\rangle + |\psi_{\alpha,\beta}\rangle), \end{aligned} \quad (2.6)$$

where $|\psi_{\alpha,\mu}\rangle \equiv G_0 V_\mu |\Psi_\alpha^{(+)}\rangle$. The resolvent operator G for the three-nucleon system can be expanded as a series of G_0 and V_μ ,

$$G = G_0 + G_0 \sum_{\mu} V_{\mu} G_0 + G_0 \sum_{\mu} V_{\mu} G_0 \sum_{\gamma} V_{\gamma} G_0 + \dots \quad (2.7)$$

The application of this method in three-nucleon systems is comprehensively discussed in Refs. [64, 65].

2.2 Phenomenological NN potentials

The existing NN potentials give us a superb quantitative description of two-nucleon systems such as the deuteron binding energy and also cover the complete proton-proton and neutron-proton scattering database. Different NN potentials have been developed in the past decades. They usually carry the name of the group which developed them such as Reid [3], Nijmegen [4], AV18 [5], CD-Bonn [6], etc.. Each of these models has different parameters and they are fitted to the empirical pp and np scattering database. These potentials are for a large part constructed in the spirit of the meson-exchange theory. In the following, the elements of three of these NN potentials used in this thesis for theoretical predictions, will be discussed.

Generally, the NN potentials contain a strong short-range repulsion, an intermediate-range attraction, and a long-range part which are shown in Fig. 2.1. Commonly, for the long-range part of the NN potentials, the one-pion exchange (OPE) mechanism is applied. For the short and the intermediate ranges, each model exploits different phenomenological approaches to parametrize them.

2.2.1 Nijmegen potentials

A lot of effort has been made by the Nijmegen group to develop NN potentials since 1975 [4, 66–69], followed up by a partial-wave analysis (PWA) of the experimental scattering data [70, 71]. The interplay between constructing NN potentials and PWA resulted in series of so-called high-quality potentials [72, 73]. These new potentials are categorized as three new NN potential models: a non-local Reid-like Nijmegen potential (Nijm I), a local version (Nijm II), and an updated regularized version (Reid 93) of the Reid soft-core potential. These three high-quality potentials were constructed based on the Nijm78 potential [4]. The Nijm I potential was constructed from the Nijm78 potential by allowing the parameters of the Nijm78 potential to be adjusted in each partial wave separately. The Nijm II potential is similar to the Nijm I potential, but all non-locality in each partial wave was removed [73]. The Reid93 potential is an updated version of the old Reid potential [73]. The main difference between the Reid93 potential and the Nijmegen potentials is the form factors. In the Nijmegen potentials an exponential form factor is used. The parameters of these potentials were obtained by fitting on existing pp and np scattering database at that time with a nearly optimal χ^2 per datum and can therefore be considered

Figure 2.1: The typical form of NN potential. The potential can be divided in three parts: long-, intermediate-, and short-range with different mechanisms contributing to each part.

as alternative partial-wave analysis [73].

2.2.2 Charge-Dependent Bonn potential

The CD-Bonn is a charge dependent, One-Boson Exchange (OBE) and non-local NN potential which was introduced in 2001 [6] as a new version of the Bonn potential [74]. Despite the fact that the full Bonn model includes multi-meson exchange, the CD-Bonn potential is solely based on the OBE framework. Also, for avoiding the potential to be energy-dependent, the CD-Bonn model was based on the OBE framework. The energy-dependent NN potentials cause conceptual and practical problems when they are applied in nuclear many-body systems. Generally, the OBE models include mesons with masses below the nucleon mass. Also, the OBE models usually use scalar mesons like π , η , ρ and ω . In this model, however, scalar-isoscalar bosons, which are denoted by σ , are also included. One of the Feynman diagrams which introduce the CD-Bonn model is shown in Fig. 2.2. The first-order contributions are the one-pion and the one-omega exchanges. In the CD-Bonn model, the π -meson determines the long-range part and the ω -meson determines the short-range repulsive and the spin-orbit interaction of the potential. Moreover, the intermediate-range in the CD-Bonn model is described by a 2π -

Figure 2.2: The first order of the Feynman diagram of the OBE in the full Bonn model.

exchange mechanism. The potential is derived from a covariant Feynman amplitude which is non-local. Consequently, the off-shell behavior of the CD-Bonn potential differs in a characteristic way from commonly used local potentials and leads to larger binding energies in nuclear few and many-body systems, where under-binding is a persistent problem [6]. For a detailed discussion about the impacts of the non-local nature of the nuclear potential on the nuclear structure, see Ref. [75].

Despite the differences between the CD-Bonn and the Bonn potential, the new version inherited the charge-dependence and non-relativistic nature from the old one. There are two charge symmetries that play an important role in the nuclear force; charge-independence and charge-symmetry. By definition, charge-independence is invariant under any rotation in isospin space. A violation of this symmetry is known as charge-dependence or charge-independence breaking (CIB). On the other hand, charge symmetry is invariant under a rotation by 180° around y -axis in isospin space whereby the positive z -direction is associated with the positive charge. The violation of this symmetry is known as charge symmetry breaking (CSB).

In the strong NN interaction, CIB means that in the case of isospin $T = 1$, the interaction of three combinations of nucleons are a bit different even after electromagnetic effects have been removed. From the isospin point of view, the proton-proton ($T_z = +1$), neutron-proton ($T_z = 0$) and neutron-neutron ($T_z = -1$) strong interactions are not the same regardless of their charge. CSB is related to a difference between proton-proton and neutron-neutron interactions. Based on the current understanding of the hadrons, the main source of CIB in the NN interaction is the pion-mass splitting. CSB is generated mainly from the mass difference between up and down quarks and the electromagnetic interaction between them. For a comprehensive discussion about the charge-dependence of the NN interaction, see Ref. [76]. Regarding all the features which were discussed above, the CD-Bonn model proposes three NN potentials for neutron-neutron, neutron-proton and proton-proton which are not independent but are slightly different due to the CIB and CSB. The potentials were fitted to the world proton-proton data below 350 MeV with $\chi^2/\text{datum} = 1.01$ and proton-neutron data with $\chi^2/\text{datum} = 1.02$. In this thesis, we refer to the CD-Bonn model as CDB.

2.2.3 The Argonne potential (AV18)

The Argonne potentials are a series of modern phenomenological NN potentials which are developed by a group of theoreticians at Argonne National Laboratory. The last version of these series is called AV18 [5] which has 18 parameters and it is a developed version of the AV14 potential [77]. In this section, the general structure of the AV14 potential will be discussed, and then the AV18 potential and its characteristics will be explained.

The Argonne V14 (AV14) is an NN potential with 14 operator terms which has a similar form as the Urbana model [78]. This potential is written as the sum of the following operator components:

$$v_{14,ij} = \sum_{p=1}^{14} [v_{\pi}^p(r_{ij}) + v_I^p(r_{ij}) + v_S^p(r_{ij})] O_{ij}^p, \quad (2.8)$$

where the operators (O_{ij}^p) are:

$$O_{ij}^{p=1,14} = 1, \vec{\tau}_i \cdot \vec{\tau}_j, \vec{\sigma}_i \cdot \vec{\sigma}_j, (\vec{\sigma}_i \cdot \vec{\sigma}_j)(\vec{\tau}_i \cdot \vec{\tau}_j), S_{ij}, S_{ij}(\vec{\tau}_i \cdot \vec{\tau}_j), (\vec{L} \cdot \vec{S}), (\vec{L} \cdot \vec{S})(\vec{\tau}_i \cdot \vec{\tau}_j), \vec{L}^2, \vec{L}^2(\vec{\tau}_i \cdot \vec{\tau}_j), \vec{L}^2(\vec{\sigma}_i \cdot \vec{\sigma}_j), \vec{L}^2(\vec{\sigma}_i \cdot \vec{\sigma}_j)(\vec{\tau}_i \cdot \vec{\tau}_j), (\vec{L} \cdot \vec{S})^2, (\vec{L} \cdot \vec{S})^2(\vec{\tau}_i \cdot \vec{\tau}_j). \quad (2.9)$$

Here,

$$S_{ij} = 3(\vec{\sigma}_i \cdot \hat{r}_{ij})(\vec{\sigma}_j \cdot \hat{r}_{ij}) - \vec{\sigma}_i \cdot \vec{\sigma}_j$$

is a tensor operator, $\vec{L}$ is the relative orbital angular momentum, and $\vec{S}$ is the total spin of the pairs of nucleons. $\vec{\sigma}$ and $\vec{\tau}$ are the spin and isospin operators, respectively. The first eight operators of Eq. 2.9 are essential to fit S and P -waves. The four L^2 operators provide differences between S and D waves, and P and F waves. $(\vec{L} \cdot \vec{S})^2$ provides an extra way of splitting the triplet states with different J values in addition to the S_{ij} and $(\vec{L} \cdot \vec{S})$ operators. The radial part of the potential consists of three parts: the long-range OPE part $v_{\pi}^p(r_{ij})$, the intermediate-range part $v_I^p(r_{ij})$, and the short-range part $v_S^p(r_{ij})$. The long-range part has a shape which we expect from the Yukawa potential. In the intermediate-range, the most dominant process is Two-Pion-Exchange (TPE). The short-range part has a Woods-Saxon shape whereby the parameters are taken from the Urbana model [78].

The AV18 potential is an updated version of AV14 with three additional charge-dependent and one charge-asymmetric operators. The potential has been fitted directly to the Nijmegen pp and np scattering database, low-energy nn scattering parameters, and deuteron binding energy with 40 parameters and it gives χ^2 per datum of 1.09 for pp and np data in the energy range of 0-350 MeV [5]. The four additional operators which are responsible for the CIB effects are given by

$$O_{ij}^{p=15,18} = T_{ij}, (\sigma_i \cdot \sigma_j)T_{ij}, S_{ij}T_{ij}, (\tau_{zi} + \tau_{zj}), \quad (2.10)$$

where $T_{ij} = 3\tau_{zi}\tau_{zj} - \tau_i \cdot \tau_j$ is the iso-tensor operator which is defined in analogy to the S_{ij} operator. For the details of the operators and the fitting procedure of the AV18 potential, see Refs. [5, 77]. Figures 2.3-2.5 show the trend of each part of the potential as a function

of relative distance between the nucleons. The left panel of Fig. 2.3 shows the first four components of the potential. The L^2 components are shown in the left panel of Fig. 2.3. The left panel of Fig. 2.4 shows the tensor and tensor-isospin parts of the AV18 potential. The spin-orbit and quadratic spin-orbit terms are shown on the right panel of Fig. 2.4. The charge-dependence and charge-asymmetry are depicted in Fig. 2.5. Comparing to the older AV14 potential, the present model has a weaker tensor force, which will generally lead to more binding in the light nuclei, and less rapid saturation in the nuclear matter [5].

Figure 2.3: The left panel shows the central (c), isospin (τ), spin (σ), and spin-isospin ($\sigma\tau$) components of the AV18 potential. The right panel shows the L^2 components of the potential. Figures are taken from Ref. [5].

Figure 2.4: The left panel is the tensor (t) and tensor-isospin ($t\tau$) parts of the AV18 potential. Also, the OPE contribution to the tensor-isospin potential, and for comparison, an OPE potential with a monopole form factor containing a 900 MeV cutoff mass are shown. The right panel shows spin-orbit and the quadratic spin-orbit components of the AV18 potential. Figures are taken from Ref. [5].

Figure 2.5: The charge-dependent (T , σT , tT) and the charge-asymmetric (τz) components of the AV18 potential. $C1(pp)$ is the static Coulomb potential for comparison. Figure is taken from Ref. [5].

2.3 Three nucleon force (3NF) models

The many-body effects appear in different interactions and this is well-known in the gravitational and the electromagnetic forces. The importance of the many-body forces in the field of interaction between nucleons in the nuclei was perceived at the early days of nuclear physics [79]. It is accepted that the most dominant part of the many-body forces in this type of the interactions is 3NF. Regarding the fact that the majority of the NN potentials were developed in the pion field theory, the first attempts were made to construct the 3NF from the same theory as was used to construct the NN interaction. Nevertheless, it has become clear that it is not possible to get a quantitative model for the 3NF due to the lack of a systematic expansion parameters in the present NN models. Therefore, it was tried to develop the 3NFs by using basic theoretical ideas from pion field theory together with phenomenological approaches.

The prime example of three-nucleon interaction is described by Fujita and Miyazawa [13, 80] which is mainly based on TPE and the excitation of one of the nucleons to the $\Delta(1232)$ resonance. In this scenario, besides the NN interaction, a πN interaction should be taken into account. Figure 2.6 illustrates a diagram of this extra contribution for a three-nucleon system. The today's most commonly 3NF models have been developed based on the Fujita-Miyazawa force (FMF). Besides FMF, some other groups have developed 3NFs using different approaches [81, 82]. These 3NF models are unrelated to the NN interaction, which cause in a strong model-dependence from the predictions based on combining such 3NFs and different NN interactions. In this section, we will discuss only the phenomenological 3NF models which we use in this thesis. For a comprehensive review of 3NF models from early models to ChPT, see Ref. [83].

Figure 2.6: Three-nucleon force arising from virtual excitation of a Δ (1232). Solid (dashed) lines indicate nucleons (pions).

2.3.1 The Urbana-Illinois 3NF model

The Urbana-Illinois 3NF models are a series of potentials which are developed in the last decades mainly to describe the properties of the nuclear matter and the light nuclei. The first version of this series was introduced in 1981 in combination with a realistic NN potential in the variational calculation of the asymmetric nuclear matter [84, 85]. The NN potential which was used in the first version v_{14} did not give a satisfactory description of the properties of the nuclear matter. The combination of $v_{14}+3NF$ model gave the correct energy, density, and compressibility of the nuclear matter. This 3NF potential can be divided into two parts. One of them generates a density-dependent repulsive two-nucleon interaction which is added to the v_{14} interaction in the nuclear matter calculations. The contribution of the other part is attractive, and it is represented as a function of density. Despite some successes, this preliminary 3NF model had major problems, specially in the description of nuclear matter [17].

The new generation of Urbana 3NF models was introduced in combination with AV18 NN potential in 1995 to calculate properties of light nuclei using Green's Function Monte Carlo (GFMC) calculation method [86]. This potential has two main parts. A two-nucleon interaction part v_{ij} which is the same as the AV18 potential and it was discussed in section 2.2.3, and a three-nucleon part V_{ijk} . The Hamiltonian is in the form of

$$H = \sum_i -\frac{\hbar^2}{2m_i} \nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}, \quad (2.11)$$

where the first term is kinetic, and the second and the third terms are two and three-

Figure 2.7: Three-body force Feynman diagrams. The first is the Fujita-Miyazawa (a), (b) is two-pion S -wave, (c) and (d) are three-pion rings with one Δ in intermediate states.

nucleon interaction potentials. The AV18 two-nucleon potential generally contains v^π , the OPE potential with a short-range cutoff, v^R representing all other strong interaction terms, and v^γ takes care of the electromagnetic interaction:

$$v_{ij} = v_{ij}^\pi + v_{ij}^R + v_{ij}^\gamma. \quad (2.12)$$

In 2001, five different 3NF models have been developed to parametrize the V_{ijk} potentials on the same footing as the Urbana 3NF potential. These models are known as Illinois models and they are labeled as Illinois-1 to -5 (IL1 to IL5) [87]. In this thesis, we use a combined version of Urbana and Illinois 3NF potentials in conjunction with AV18 potential, which is known as Urbana-Illinois X (UIX). The V_{ijk} term of the UIX potential is derived with the following components:

$$V_{ijk} = A_{2\pi}^{PW} O_{ijk}^{2\pi, PW} + A_{2\pi}^{SW} O_{ijk}^{2\pi, SW} + A_{3\pi}^{\Delta R} O_{ijk}^{3\pi, \Delta R} + A_R O_{ijk}^R, \quad (2.13)$$

where each term represents different contributions in the three-nucleon potential. The first term represents $V_{2\pi}^{PW}$ with a strength of $A_{2\pi}^{PW}$ which comes from the Fujita-Miyazawa mechanism for the nucleon- Δ excitation. The Feynman diagram of this term is shown in Fig. 2.7 (a). To parametrize this term of the potential, the kinetic energy of nucleon and Δ are neglected. Generally, this term is included in most of the 3NF models, but it is treated slightly different.

The second term in the Eq. 2.13 expresses the $V^{2\pi, SW}$ which describes πN and S -wave scattering. Figure 2.7 (b) shows the Feynman diagram of this term. The parameters of this term are discussed in Ref. [17]. This term gives rather small contributions to nuclear energies, and it is difficult to extract its strength $A_{2\pi}^{SW}$ from the nuclear data. However, it is assumed that the strength of this term is around 1 MeV [87].

The $O_{ijk}^{3\pi, \Delta R}$ is modeled based on the three-pion exchange ring diagrams which are shown in Figures 2.7 (c) and 2.7 (d). Only one Δ is included at a time at the intermediate states. The total $V_{3\pi, \Delta R}$ is approximated from the sum of the two associated potential terms of Figures 2.7 (c) and 2.7 (d) which can be referred as $V_1^{3\pi, \Delta R}$ and $V_2^{3\pi, \Delta R}$, respectively. The value of $A_{3\pi}^{\Delta R}$ is estimated from the observed values of the constants, and

neglecting the kinetic energies, is ~ 0.002 MeV. In all the Illinois models, the $A_{3\pi}^{\Delta R}$ is determined by fitting the nuclear binding energies.

The pion-exchange three-nucleon interactions are attractive, and lead to a significant over-binding and large equilibrium density of the nuclear matter. Therefore, there must be other three-nucleon interactions to compensate the attraction from $V^{2\pi}$ in the nuclear matter at large densities [87]. The V^R term in the Urbana models of V_{ijk} was designed to approximate these effects. It has been retained in the Illinois models with a spin-isospin independent operator.

2.3.2 Hannover-Lisbon Δ model

The Hannover-Lisbon model follows a different approach which is not used in the conventional models like UIX or other phenomenological potentials. This method is based on folded-diagram expansion which permits one to obtain an energy-independent potential where the computational problem of evaluating the many-body theory is simplified comparing to the case of the energy-dependent interactions [88]. The NN phase shift of this model at low energies (below $E_{lab} \approx 150$ MeV) are in good agreement with those obtained using the full Bonn model [74]. The results of the binding energy of triton based on the NN folded-diagram expansion were different from the empirical values and it means that the 3NFs must be important.

For taking into account 3NFs, a new version of folded-diagram approach were introduced in 1993 with a coupled-channel involving the Δ -isobar [89]. In this method, the Δ is treated on the same footing as the nucleon which is advantageous because of two main reasons. One is by including the Δ , the important part of the three-nucleon effects automatically appears. The second one is that by exploiting this formalism, one can use Faddeev method in few-body systems including nucleons and Δ . Furthermore, to perform quantitative studies of NN scattering above the pion-production threshold, the coupled-channel of NN, $N\Delta$ and $\Delta\Delta$ channels will be required. In the coupled-channel approach, besides NN potential, there are an $N\Delta$ and $\Delta\Delta$ potentials and also, transition potentials between NN, $N\Delta$, and $\Delta\Delta$ states. Figures 2.8 (a), 2.8 (b), and 2.8 (c) show one-meson-exchange boxes of the transition potentials for $NN \leftrightarrow N\Delta$, $NN \leftrightarrow \Delta\Delta$, and $N\Delta \leftrightarrow \Delta\Delta$, respectively.

In this thesis, we use a version of the coupled-channel models of 3NF which was developed specially for the nucleon-deuteron scattering calculations for the elastic and the break-up reactions [90–92]. This potential couples two-nucleon states and the states in which one nucleon is excited to the Δ -isobar. Below the pion-production threshold, the Δ -isobar is virtual but it is assumed as a stable baryon with a mass of 1232 MeV and spin and isospin $\frac{3}{2}$. The excitation of the Δ -isobar yields an effective three-nucleon force. In this model, the three-particle scattering equations are solved employing a separable expansion of the two-baryon transition matrix. However, the model could not resolve all the discrepancies between the experimental results and the calculations, specially in some spin observables at higher energies. Part of this disagreement is due to using an outdated two-nucleon potential (Paris potential) in combination with the Δ -isobar channel [92].

A new version of this model was introduced in 2003 [93] with two main differences

Figure 2.8: One-meson-exchange contributions to the transition potentials $NN \leftrightarrow N\Delta$, $NN \leftrightarrow \Delta\Delta$ and $N\Delta \leftrightarrow \Delta\Delta$. Figures are taken from Ref. [89].

compared to the earlier version. The first one is that the two-dimensional Chebyshev expansion was used in the new version rather than the real-axis integration using a separable expansion of the two-baryon transition matrix which was used in the older version. The Chebyshev expansion is systematic and it was found to be highly efficient when it is used for interpolation. Furthermore, the new method allows us to use directly any two-nucleon potential and the coupled-channel extension of them as a dynamic input for the description of the three-nucleon bound states and the three-nucleon scattering. Secondly, in the new version, the CD-Bonn potential was used as the two-nucleon reference potential. It means that the CIB and CSB effects are included in the potential and they are important for the nucleon-deuteron break-up at some specific kinematics. In spite of the effective improvements of the 3NF potential which were mentioned above, it suffers from an unrealistic assumption of the phase in-equivalence which becomes unacceptable in the three-nucleon scattering at intermediate energies below the pion-production threshold. This deficiency has been corrected and discussed in Ref. [19]. The potential was constructed by starting from the two-baryon coupled-channels and then adding the three-baryon coupled-channels to them. The NN and $N\Delta$ channels for isospin-triplet partial waves are depicted in Fig. 2.9. Also, some of the three-baryon channels are illustrated in Fig. 2.10.

Figure 2.9: Four channels of the two-baryon coupled-channel potential. The thin vertical lines denote nucleons and the thick vertical lines denotes the Δ -isobar.

Figure 2.10: Some channels of the three-baryon coupled-channel potential. The definition of lines is the same as those shown in Fig. 2.9.

For the rest of this thesis, we refer to this potential as CDB+ Δ . In some proton-deuteron break-up kinematics in which two protons scatter to the forward angles, the effect of the Coulomb interaction between the two protons becomes important and cannot be ignored. Although, adding the Coulomb effect in the three-nucleon systems with two charged particles is a challenging work, the Hannover-Lisbon group resolved it for the first time [94, 95]. The inclusion of Coulomb effects shows a significant change in predicted pd break-up cross section specially at the configurations where the relative energy of the two outgoing protons is low [95]. This effect is partially responsible for lowering the peak in the cross section in the configuration $(15^\circ, 15^\circ, 40^\circ)$ in Fig. 2.11, where the relative pp energy is rather low at the peak. The relative pp energy increases considerably as one changes the azimuthal angle to 160° ; by adding the Coulomb effect, the cross section increases [95]. Moreover, this model has been extended to four-nucleon systems below and above the break-up threshold [96–98]. In this thesis, we refer to the model including the Coulomb effects as CDB+C and the model including both the Δ and the Coulomb effects as CDB+ Δ +C.

2.4 Chiral Perturbation Theory (ChPT)

The nuclear force models, which were explained in the previous sections, were for a large part developed around or after the time when the theory of quantum chromodynamics (QCD) was formulated. The main drawback of these phenomenological models is that they provide a very loose connection to QCD. After QCD was initiated and accepted as a fundamental framework for interaction between hadrons, one would expect that the nuclear force can be derived in terms of this new theory. The main problem with deriving the nuclear force from QCD is the non-perturbative nature of it in the low-energy regime and, therefore, obtaining direct solutions becomes very difficult.

When the effective field theory (EFT) was introduced, a major breakthrough occurred in the field of low-energy QCD. The general idea of EFT, which is based on 'folk theorem'

Figure 2.11: Differential cross section for pd break-up at 130 MeV deuteron lab energy. Results for CDB+ Δ potential including the Coulomb interaction (solid curves) are compared to results without Coulomb (dashed curves) together with experimental measurement. Figure is taken from Ref. [95].

by Weinberg [99], is that one has to write the most general Lagrangian consistent with the assumed symmetry principles, specially the chiral symmetry of QCD. At the nucleon level, or low-energy QCD, the effective degrees of freedom are pions, a Goldstone boson of the broken symmetry, and nucleons instead of quark and gluons. At this point, it seems that we have started again from Yukawa theory except with some constraints. The chiral symmetry breaking is the main core of the EFT application in QCD for nucleonic systems [61, 100]. The current understanding is that this symmetry originates from relatively small masses of the up and down quarks and the electromagnetic interactions [101].

To use EFT, it is important to determine a separation of scales. For applying EFT in the low-energy QCD, a soft scale is assumed as the pion mass, $Q \sim m_\pi$, and rho mass is assumed as a hard scale $\Lambda_\chi \sim m_\rho = 0.78 \text{ GeV} \approx 1 \text{ GeV}$, which is known as a chiral-symmetry breaking scale. Thus, the expansions are done in terms of the soft scale over the hard scale, Q/Λ_χ . Generally, the EFT approach for nuclear physics includes the following steps:

1. Determining the soft scale, the hard scale, and the proper degrees of freedom for the nuclear physics;
2. Determining the symmetries of the low-energy QCD and checking which of them are

broken;

3. Formulating the most general Lagrangian with regard to the symmetries and the symmetry breaking;
4. Choosing an appropriate expansion method and calculate the Feynman diagrams for each case with a desired accuracy including terms at higher orders in the expansion.

The most important feature of QCD in the low-energy regime is the spontaneous chiral-symmetry breaking which allows us to treat the low-energy QCD perturbatively. In other words, since the interaction of the Goldstone bosons must vanish at zero momentum transfer and the chiral limit ($m_\pi \rightarrow 0$), the low energy expansion of the Lagrangian can be arranged in powers of the derivatives and pion masses. In this formalism, the effective Lagrangian can be written as,

$$\mathcal{L}_{eff} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \cdots, \quad (2.14)$$

where the $\mathcal{L}_{\pi\pi}$ describes the dynamics of the pions, $\mathcal{L}_{\pi N}$ stands for the pion-nucleon interactions, $\mathcal{L}_{NN}$ includes the terms of the nucleon contact Lagrangian and ellipsis stands for the terms that involve two nucleons plus pions and three or more nucleons with or without pions. Each of the parts of the $\mathcal{L}_{eff}$ consists of expansion terms. For instance, for $\mathcal{L}_{\pi N}$ we have [101]:

$$\mathcal{L}_{\pi N} = \mathcal{L}_{\pi N}^{(1)} + \mathcal{L}_{\pi N}^{(2)} + \mathcal{L}_{\pi N}^{(3)} + \cdots, \quad (2.15)$$

where the superscripts refer to the number of derivatives or pion-mass insertions (chiral dimension), and the ellipsis stands for the terms of the higher dimensions.

In principle, effective Lagrangians have infinitely many terms, and an unlimited number of Feynman diagrams can be calculated from them. Therefore, we need a mechanism that makes the theory manageable and calculable. A solution for this challenge was proposed by Weinberg in a series of papers [60, 102] and it is known as chiral perturbation theory (ChPT). This scheme tells us how to distinguish between the large (important) and the small (unimportant) contributions. In ChPT, the importance of the diagrams are checked with $(Q/\Lambda_\chi)^\nu$ factor. Determining the power ν (chiral order) is known as power counting. The definition of ν is not unique and it differs from one case to another.

ChPT and its power counting mechanism imply that the nuclear forces come out as a hierarchy which is controlled by the chiral order ν . The $\nu = 0$ order is named as the leading order LO and the higher orders are referred to as next-to-leading order NLO, next-to-next-to-leading order N²LO and so on. Figure 2.12 illustrates the hierarchy of the nuclear forces which are derived from ChPT. Note that, in the order $\nu = 1$, all the contributions vanish because of the parity and time-reversal invariance.

Based on the ChPT formalism, the chiral NN full potential can be written as,

$$V = V_{1\pi} + V_{2\pi} + V_{ct}, \quad (2.16)$$

where $V_{1\pi}$ represents the one-pion exchange, $V_{2\pi}$ represents the two-pion exchange which denote the long and the intermediate-range of the potential, respectively. V_{ct} stands for the NN contact interactions which provides the short-range part of the potential. Each

Figure 2.12: The hierarchy of the nuclear forces in ChPT. The solid and dashed lines represent nucleons and pions, respectively. Different shapes of the vertices indicate the different levels of $\pi\pi$, ϕN , $\pi\pi NN$ and $\cdots$ interactions. Figure is adopted from Ref. [101].

term can be expanded to an allowed chiral order. For $V_{2\pi}$ and V_{ct} , the expansion is in the following order,

$$V_{2\pi} = V_{2\pi}^{(2)} + V_{2\pi}^{(3)} + V_{2\pi}^{(4)} + \cdots, \quad (2.17)$$

and

$$V_{ct} = V_{ct}^{(0)} + V_{ct}^{(2)} + V_{ct}^{(4)} + \cdots, \quad (2.18)$$

where the superscripts denote the chiral orders. Therefore, the NN potentials for each

order are given by:

$$\begin{aligned} V_{LO} &= V_{1\pi} + V_{ct}^{(0)}, \\ V_{NLO} &= V_{LO} + V_{2\pi}^{(2)} + V_{ct}^{(2)}, \\ V_{NNLO} &= V_{NLO} + V_{2\pi}^{(3)}, \\ V_{N^3LO} &= V_{NNLO} + V_{2\pi}^{(4)} + V_{ct}^{(4)}. \end{aligned}$$

As shown in Fig. 2.12, the most important feature of ChPT is that the 3NFs appear on an equal footing as NN force from NNLO upwards. The leading chiral 3NF (that appears at NNLO) is sizable, improves predictions, but also leaves unresolved problems. The chiral 3NF at N³LO involves only leading vertices and most likely does not produce sizable contributions. Sizable contributions are expected from the sub-leading one-loop 3NF diagrams that occur at N⁴LO [101]. The long- [103] and the intermediate-range [104] contributions to the three-nucleon force at N⁴LO have been investigated a few years ago.

Even though the ChPT is a consistent and fundamental method in the field of few-nucleon systems, for the energies used in this thesis, the higher chiral orders are necessary to produce predictions with adequate accuracy which can be compared with data. Details of the ChPT and its latest progresses can be found in Refs. [101, 105–107]. Results of the higher chiral orders for 190 MeV were not available at the time of the analysis and, therefore, we will not compare the results of this theory with our data in this thesis.

2.5 Observables of the pd break-up reaction

In this section we will explain the main features of the kinematics of the reaction channel studied in the present thesis, namely the $\vec{p} + d \rightarrow p + p + n$ reaction. This will provide some insights of the three-body break-up reaction and its observables as an introductory to the following experimental chapters.

The kinematics of a reaction with a three-body final state is more complicated compared to the two-body final state. In the two-body final state and for a fixed beam energy, if one has the information of either the scattering angle or the energy of one of the outgoing particles, all the kinematical information of the system can be obtained through the energy and momentum conservation laws. But, this is not as straightforward in the three-body final state. In the three-body break-up reaction, three kinematical values can be measured for each particle: the energy E , the polar scattering angle θ , and the azimuthal scattering angle ϕ . Therefore, we have 9 measurable quantities of the system. In addition, we have 4 relations between these 9 parameters from the energy and momentum conservation laws which reduce the kinematical degrees of freedom from 9 to 5. In the present experiment, we are able to measure the three kinematical variables (E, θ, ϕ) of the two protons in the final state. Therefore, we measure one variable more than the minimum that we need to suppress or estimate background contributions.

We follow the non-relativistic formalism from Refs. [108, 109] which is compatible with the common conventions of the three-body scattering within the community of few-body

Figure 2.13: The scattering diagram of the three-body final state. $\vec{k}_1$ and $\vec{k}_2$ are the momenta of the two detected protons with scattering angles θ_1 and θ_2 , respectively. ϕ_2 is the angle between the projection of $\vec{k}_2$ on the x - y plane and the positive direction of the x -axis. $\hat{s}$ denotes the direction of spin of the projectile. ϕ is the angle between the projection of $\hat{s}$ on the x - y plane and the y -axis. β represents the angle between the spin of the projectile and its momentum direction (z -axis). In the present experiment, the polarization of the beam is perpendicular to the direction of the beam momentum and, therefore $\beta = 90^\circ$.

physicists. Here, we denote the projectile parameters with subscript p , the two detected protons with 1 and 2, and the neutron with subscript 3. Figure 2.13 shows the definition of the scattering angles only for the detected particles in a three-body break-up reaction. There are two conventions for defining the y -axis [109]. In this thesis, we use the asymmetric choice for the azimuthal angles, where $\vec{k}_1$ lies in the xz plane, and therefore $\phi_1 = 0$, see Fig. 2.13. Here, $\vec{k}_1$ is the momentum of the outgoing proton which scattered to smaller polar angle θ . According to the energy conservation law we have:

$$E_p = E_1 + E_2 + E_3 - Q, \quad (2.19)$$

where Q is the Q -value of the reaction. From the momentum conservation law, we have:

$$\mathbf{k}_p = \mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3, \quad (2.20)$$

where $\mathbf{k}_p$ and $\mathbf{k}_i$ are the momenta of the proton beam and the three particles at the final state, respectively. Using Eqs. 2.19 and 2.20, we obtain a relation between the parameters of the initial and the final state of the break-up reaction in the non-relativistic regime,

$$\begin{aligned} (m_1 + m_3)E_1 + (m_2 + m_3)E_2 - 2(m_p m_1 E_p E_1)^{1/2} \times \cos \theta_1 \\ - 2(m_p m_2 E_p E_2)^{1/2} \times \cos \theta_2 \\ + 2(m_1 m_2 E_1 E_2)^{1/2} \times \cos \theta_{12} \\ - m_3 Q + E_p (m_p - m_3) = 0. \end{aligned} \quad (2.21)$$

where θ_{12} is the angle between $\vec{k}_1$ and $\vec{k}_2$ which is defined as:

$$\cos \theta_{12} = \cos \theta_1 \cos \theta_2 + \sin \theta_1 \sin \theta_2 \cos(\phi_2 - \phi_1), \quad (2.22)$$

and

- m_P = mass of projectile,
- m_1 = mass of observed particle 1,
- m_2 = mass of observed particle 2,
- m_3 = mass of unobserved particle 3,
- E_P = energy of projectile,
- E_1 = energy of observed particle 1,
- E_2 = energy of observed particle 2,
- θ_1 = polar angle of observed particle 1,
- θ_2 = polar angle of observed particle 2,
- ϕ_1 = azimuthal angle of observed particle 1,
- ϕ_2 = azimuthal angle of observed particle 2.

For each combination of the scattering angles of the two detected protons ($\theta_1, \theta_2, \phi_{12} = \phi_2 - \phi_1$), Eq. 2.21 gives a curve in the E_1 - E_2 space. This curve is known as S -curve in this kind of reactions. Regarding the S -curve, a parameter S is defined as the arc length of the curve, and it represents the energy correlation between the two detected protons. Generally, the observables of the break-up reaction are presented as a function of S -value. The origin of S ($S = 0$) is defined as a minimum of the energy of one of the detected particles. In this thesis, $S = 0$ is defined as the minimum of the energy of the second proton, E_2 . Figure 2.14 shows the S -curves for some kinematical configurations of proton-deuteron break-up reaction at 190 MeV.

The observables of interest in this thesis can be extracted from the full expression of the cross section for the spin $\frac{1}{2}$ projectile [109]:

$$\sigma(\xi) = \sigma_0(\xi)[1 - \sin \beta \sin \phi p_z A_x(\xi) + \sin \beta \cos \phi p_z A_y(\xi) + \cos \beta p_z A_z(\xi)], \quad (2.23)$$

where $\sigma_0(\xi)$ is the cross-section for an unpolarized beam, p_z is the polarization of the beam with respect to its quantization axis $\hat{s}$. A_x , A_y , and A_z are the analyzing powers of the reaction. ξ represents all the kinematical variables which, in the three-body final state reactions, can be taken as $\xi(E_1, E_2, \theta_1, \theta_2, \phi_{12} = \phi_2 - \phi_1)$. Other parameters are defined in the caption of Fig. 2.13. In the present experiment, we have $\beta = 90^\circ$ and therefore, the Eq. 2.23 can be simplified to

$$\sigma(\xi) = \sigma_0(\xi)[1 - \sin \phi p_z A_x(\xi) + \cos \phi p_z A_y(\xi)]. \quad (2.24)$$

In this thesis, a break-up kinematic configuration is defined by fixing the scattering angles of two protons and the relative azimuthal angle between them which is written in the form of $(\theta_1, \theta_2, \phi_{12})$. The differential cross-section of each kinematic combination

Figure 2.14: The energy correlation of two outgoing protons for some typical kinematical configurations which are denoted by $(\theta_1, \theta_2, \phi_{12} = |\phi_2 - \phi_1|)$ in the legend. The solid lines are the S -curves of the forward-forward and the dash lines are the S -curves of the forward-backward configurations.

of E_1 and E_2 , is defined as:

$$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS} = \frac{N}{Q/Z} \cdot \frac{1}{t \cdot \epsilon} \cdot \frac{1}{\Delta\Omega_1 \Delta\Omega_2 \Delta S}, \quad (2.25)$$

where N is the number of break-up events, Q is the total integrated charge, Z is the charge of the projectile, t is the target thickness, and ϵ includes all the inefficiencies of the system. $\Delta\Omega_1$ and $\Delta\Omega_2$ are the solid angles of the detector elements used to detect the two protons and ΔS is the size of the S -bin. For studying spin effects of the nuclear force, one can use Eq. 2.24 to extract the vector analyzing powers A_x and A_y as the spin-dependent observables. In this research, due to difficulties in calculating all the efficiencies needed for the extraction of cross sections (see section 4.4), it was decided to primarily focus on the analyzing powers in order to investigate the spin part of the nuclear forces.

3. The experimental setup

This chapter is dedicated to describe the experimental facility and the detection system with which we used to conduct the $\vec{p} + d$ scattering experiment at KVI. Comprehensive measurements of the proton-deuteron elastic and the break-up scattering observables were initiated at KVI since the end of the 90s to study properties of the nuclear force through different reaction channels by exploiting various experimental setups [11, 42, 53–56, 58, 110]. In 2004, a new 4π detection system was installed at KVI to measure the break-up observables of $\vec{p} + d$, $\vec{d} + d$ and $\vec{d} + p$ reactions using polarized and unpolarized beams at intermediate energies. Figure 3.1 depicts the experimental facility at KVI in 2007. The experimental facility at KVI consists of three main parts. The POLarized Ion Source (POLIS) which can produce high-quality polarized and unpolarized ion beams, the AGOR cyclotron which can accelerates ions up to 190 MeV for protons, and the detection system BINA to measure the energy as well as the scattering angles of the reaction yields in coincidence. The ions are produced in POLIS and they are injected into the AGOR cyclotron. The accelerated beam is transferred through the beam lines to the experimental area where the target is located.

3.1 POLarized Ion Source (POLIS)

POLIS is designed to produce polarized atomic beams using the Zeeman effect and the hyperfine structure of the atoms. For polarized proton beams, POLIS separates different quantum states of the hydrogen atoms using a gradient magnetic field. Figure 3.2 shows the splitting mechanism of the hyperfine states of spin $\frac{1}{2}$ particles in a magnetic field. The atomic hydrogen has a total angular momentum which is defined as:

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

where $\vec{L}$ is the orbital angular momentum of the atomic electron and $\vec{S}_e$ and $\vec{S}_p$ are the spin values of the electron and the proton, respectively. For $\vec{L} = 0$ (s -state) and for two spin $\frac{1}{2}$ particles, $\vec{F}$ has two eigenvalues $F = 0, 1$. The state $F = 1$ has a degeneracy of 3 which can be removed when the hydrogen atom passes through the weak field, as shown in Fig. 3.2.

After the hydrogen atom passes through the weak field, the four sub-states are divided into two groups in the strong field. Each group represents one of the electron spin states $m_s = \pm\frac{1}{2}$. After this stage, all the four sub-states are inserted into a hexapole magnet and the states with $m_s = +\frac{1}{2}$ are selected. Furthermore, a static magnetic field $B_z(x)$ is used to increase the population of one of the polarization states of the protons. At the final step, the electrons are removed from the atom and the polarized protons are injected

Figure 3.1: Experimental facility at KVI in 2007. The AGOR cyclotron and POLIS are illustrated in the bottom of the figure. BINA is located in the main experimental hall which is shown at the top of the picture. Figure is taken from Ref. [50].

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

into the AGOR cyclotron to be accelerated to the desired energy.

The polarization value of the proton beam is defined as:

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

where $N^{\uparrow,\downarrow}$ are the number of particles with a spin up ($\uparrow$) or down ($\downarrow$). For protons, POLIS provides polarization values around 60-80% of the maximum value $p_z = \pm 1$. POLIS also provides polarized deuteron beams with similar techniques. The beams used for the present experiment were only polarized protons.

3.2 AGOR

AGOR (Accélérateur Groningen ORsay) is the result of the cooperation between KVI, Groningen, and IPN, Orsay, France. Its design was a joint effort of both institutes; building took place in France. After testing, it was disassembled and moved to the Netherlands in 1994. Since the beginning of 1996, AGOR has produced heavy and light ion beams for experimental use. Figure 3.3 shows the possible beams which the cyclotron can produce

Figure 3.3: The operating diagram of the AGOR cyclotron. The lines represent the limits of the machine, the dots are actual beams produced up to 2014. Figure is taken from Ref. [111].

and the limits of the machine for the operation diagram. The operation diagram represents the charge over mass (Q/A) ratio versus the energy per mass unit (E/A) of all the possible beams with the AGOR cyclotron. AGOR is capable of accelerating protons up to 190 MeV and deuterons up to 90 MeV/nucleon. In the present experiment, the maximum capability of the AGOR has been used to produce protons up to 190 MeV to study the $\vec{p}+d$ break-up reaction.

3.3 BINA

The Big Instrument for Nuclear-polarization Analysis, BINA, is a specially designed 4π detection system for the study of nuclear forces through the three-body and four-body elastic as well as break-up reactions. BINA was designed in 2000 and it was installed at KVI in 2004. The first test experiment was done in 2005. The detection system,

Figure 3.4: A sketch of BINA. Different parts of BINA and the angular coverage of each part are indicated in the figure. The forward-wall covers angles which are in the range $10^\circ < \theta < 35^\circ$. The backward-ball of BINA is capable of measuring the energy and the scattering angles of the particles in the range of $35^\circ < \theta < 160^\circ$.

BINA, consists of different components which make it capable of measuring energies up to 140 MeV/nucleon, scattering angles between $10^\circ - 160^\circ$, and almost a full coverage of azimuthal angles. There are two features that make BINA unique among other detection systems in the field of few-nucleon scattering:

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

In general, BINA has two main parts, the forward-wall and the backward-ball. Figure. 3.4 illustrates different parts of BINA. The forward-wall consists of a cylindrically-shaped array of scintillators (E -detectors) to measure the energy of charged particles, a MWPC to measure their scattering angles, and a vertical array of ΔE -detectors that is used in combination with E -detectors for particle identification. The backward-ball is a ball-shape scattering chamber as well as a detector. In this section, all parts of BINA will be explained together with a brief description of its electronic and the DAQ system.

3.3.1 E -detector of the forward-wall

To measure the energy of the scattered particles in the range of the polar angle, 10° - 35° , a cylindrically-shaped array of scintillators is designed. The array consists of ten plastic scintillator bars each of which connected to two PMTs at both ends of each scintillator.

Figure 3.5: The cylindrically shaped E -scintillators of the forward-wall of BINA. The array consists of 10 scintillator bars which are positioned horizontally and distributed vertically. Each scintillator bar is connected on both sides to PMTs. The wings are shown on the bottom and the top of the figure but were not used in the present experiment. The ΔE detectors and the MWPC were removed in order to obtain a clear view of the E -scintillators..

Table 3.1: The 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 the 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 dimensions, Width $\times$ Thickness $\times$ Length, of each scintillator bar are $10 \times 12 \times 220$ cm³, respectively. Moreover, two flat arrays (wings) of plastic scintillators are added to the top and the bottom of the E -scintillators to measure the polarization-transfer coefficients of the scattered particles. These wings were not used in the present experiment. Figure 3.5 shows a view of the E -detector of the forward-wall. A hole in middle of the array is created for connecting the beam-line to the Faraday cap. All the E -scintillators are made of BICRON-408 plastic scintillator. The properties of this type of plastic scintillator are listed in Table 3.1. When the particles hit each scintillator, the generated light propagates inside the scintillator bar. The two PMTs which are connected to both ends of each bar collect the generated light and convert it to an electrical signal. The design of the E -detectors allows us to measure the energy and the Time-Of-Flight (TOF) of the scattered particles.

3.3.2 ΔE -detector

The ΔE -detector of BINA is composed of a horizontally distributed array of 12 BC-408 thin plastic scintillator bars with a thickness of 0.1 cm. This array is located between the backward-ball and the E -detector. Two PMTs are connected on both ends (top and bottom) of each ΔE -scintillator bar. Except for the two bars in the middle of the array, the signals of each pair of the PMTs are correlated. The ΔE - and E -detector together are capable for particle identification. Moreover, the horizontal distribution of the ΔE -scintillators and vertical distribution of E -scintillators allow us to track the scattered particles with a position resolution of ± 1.8 cm. This position measurement can be used to reject the uncorrelated events between MWPC and the E -detector as well as to determine the MWPC efficiency. Figure 3.6 shows the ΔE -detector and its position with respect to E -detector. In the present experiment, we did not use the ΔE -detector for particle identification.

3.3.3 Multi-Wire Proportional Chamber (MWPC)

The Multi-wire proportional chambers are used to measure the position and the trajectory of the charged particles. Commonly, MWPCs are made of two or three planes of wires which are placed in an electro-negative gas-filled chamber.

The MWPC of BINA is made of 3 planes, X, Y and U with an active area of 38×38 cm².

Figure 3.6: The position of the ΔE -detector of BINA. The ΔE -detector was used together with E -detector to identify the type of the particles and to determine the hit position of the particles using ΔE - E hodoscopes.

Each plane is composed of equally-spaced array of anode wires, and all the planes are placed between two cathode plates. The X and Y planes have 95 parallel wires which are perpendicular to each other. The wires of the U plane are placed at an angle of 45° with respect to the other planes. The U plane is used to resolve the ambiguities in the determination of the coordinates as well as to increase the resolution of the position detection of the charged particles [112]. Figure 3.7 shows the MWPC of BINA and its location in the setup.

The mechanism of the charged-particles tracking in MWPCs is based on gas ionization inside the chamber. When the charged-particles pass through the MWPC, they ionize the gas inside the chamber and the avalanche of the electrons is collected by the wires of each plane which are close to the ionization point. For all the wires, the collected charge is read from one end of the wires except those that are placed in the middle of the MWPC, because they are disconnected due to the central hole of the MWPC. For these wires, the collected charge is read by two channels from the both ends of the wires. The track of the charged particles can be reconstructed using the distance of each plane of the MWPC to

Figure 3.7: The position of the MWPC in BINA. The MWPC is installed between the backward-ball and the ΔE -detector.

the reaction point. In the present experiment, we were not able to use the X-plane of the MWPC due to a technical problem [50]. The X-coordinate of the registered particles is reconstructed using the information of the U and the Y wires.

3.3.4 The backward-ball

In order to detect low-energy particles, the scattering chamber should be a detector as well. The backward-ball of BINA is a spherical array of plastic scintillators with the capability of working simultaneously as a scattering chamber and a detector. The backward-ball covers polar angles larger than 35° up to 160° and almost a full coverage of azimuthal angle ϕ . The target is placed at the center of the backward-ball.

The backward-ball is made of 149 pyramid-shaped plastic scintillators each of which having a triangle surface. The geometrical design of the backward-ball and its building blocks are the same as the classic soccer ball; see Fig. 3.8. Each group of the scintillators

Figure 3.8: The structure of the classic soccer ball with pentagons and hexagons building blocks are illustrated in the left panel. The right panel shows the partly-assembled backward-ball with pyramid shape scintillators with a triangle surface forming the pentagons and hexagons.

builds two bigger blocks. A combination of 5 smaller detectors build a pentagon and 6 bigger ones build a hexagon shape. At the end, a ball shape structure is constructed by putting together these two main segments. The right panel of Fig. 3.8 shows the partly assembled and the geometrical structure of the backward-ball. The angular coverage of the backward-ball is complete in the angular range of $35^\circ < \theta < 160^\circ$ except where the target holder is attached to the scattering chamber. This corresponds to $80^\circ < \theta < 120^\circ$ and $70^\circ < \phi < 110^\circ$. As a detector, the backward-ball consists of 149 plastic scintillator elements. Each element consists of two parts, a thick fast BC-408 plastic scintillator and a 1 mm slow BC-444 phoswich which are glued together. Each detector is connected to a specific PMT which collects the generated light inside the scintillator material and converts it to an electric signal. The idea of using the fast and the slow scintillator materials together was for particle identification but this turned out not to work properly during the experiment because the light collected by the PMTs from the thin (slow) part was too small to significantly influence the signal shape. Due to lack of time, this was not further investigated as it was not needed for the present experiment. The fast scintillator elements of the backward-ball have two different thicknesses of 3 cm and 9 cm. The scintillators with 9 cm thickness were used for the forward part ($35^\circ < \theta < 100^\circ$) of the backward-ball. This thickness was enough to stop protons with energies up to 115 MeV; see Fig. 3.9. The scintillators with 3 cm thickness were used for the back part of the backward-ball, which was enough to stop protons with energies up to 60 MeV. Each detector is labeled with a number and located at a specific θ and ϕ position in the laboratory coordinate system. Therefore, the backward-ball can measure the energy as well as the scattering angles of charged particles with a resolution of $\Delta\theta = \pm 10^\circ$ and $\Delta\phi = \pm 10^\circ$. The right panel of Fig. 3.10 shows an illustration of the angular position of the scintillators in the backward-ball.

As a scattering chamber, all the detector elements are glued to each other to keep

Figure 3.9: The structure of one of the scintillators of the backward-ball. Each backward-ball detector is made of two layers of plastic scintillators. A thin BC-444 with 1 mm thickness which is glued to a thick BC-408 with two different thicknesses. For the front part of the backward-ball, 9 cm thick plastic scintillators were used to stop scattered particles with relatively high energy. Since the scattered particles at larger scattering angles have lower energies, for the backward part of the ball the 3 cm thick plastic scintillators were used. Each detector is individually connected to a PMT.

Figure 3.10: The angular position of the backward-ball. The right panel demonstrates the angular resolution of the detectors in the backward-ball. The black dots are the centroids of the triangles which are taken as the angular position of each detector.

Figure 3.11: The left panel shows the position of various external connectors of the backward-ball. The exit flange of the backward-ball which is covered by a thin layer of Kevlar and Aramida is shown on the right panel.

the vacuum inside up to 10^{-6} mb. The entrance of the beam, the target holder arm, and the forward-window are attached to the backward-ball. The state-of-the-art design of the backward-ball allows us to measure the energy of the particles with a very low energy threshold. Figure 3.11 shows different external components of the backward-ball. The exit flange of the backward-ball is composed of thin but strong material to minimize the energy loss of the forward-scattered particles and also be stable enough to tolerate the large difference between the inside vacuum and the atmospheric pressure outside the chamber. To do that, a $250\text{ }\mu\text{m}$ thick Kevlar foil together with a $50\text{ }\mu\text{m}$ thick Aramida foil are glued to a metal frame which was used as the exit flange of the backward-ball [113]. The right panel of Fig. 3.11 depicts the exit window of the backward-ball.

3.3.5 Target

Some scattering experiments, including the one presented in this thesis, require the use of various of targets. The target holder of BINA has been designed to handle different targets and to be able to switch between them during the experiment. The target holder was mounted on the scattering chamber at a position which corresponds to $\theta = 100^\circ$ and $\phi = 90^\circ$ with a small tilt of 10° to ensure that the interaction point is localized at the center of the backward-ball. The target holder arm was connected to a pneumatic system and it can move vertically.

In the present experiment, a liquid-deuterium target was used for the proton-deuteron break-up experiment. In this type of target, the D_2 gas flows inside a high purity aluminum ring which we call target cell. The target cell has a diameter of 15 mm and a thickness of 6 mm which was covered by a thin layer of $4\text{ }\mu\text{m}$ Aramid to keep the liquid inside the target cell. The temperature of the target cell was fixed around few Kelvins by using a cryogenic system which was connected to it. As a result, when gas flows inside the cell at a certain temperature, which depends on the pressure at the target place, the gas liquefies

and fills the volume inside the cell. The expected target thickness was 6 mm but due to the pressure difference between inside and outside the target cell, the target inflated up to 6.8 mm. The target-cell was shielded with a thin layer of aluminum for isolating it from the environment and for protecting the liquid target from temperature shocks. Figure 3.12 shows the structure of the target which was used in this experiment. For details about the target, see Ref. [50].

Figure 3.12: In the left panel, the components of the target are shown before filling the target cell with liquid deuterium. The right panel depicts the target which is partly filled with liquid deuterium.

3.3.6 The electronics and data acquisition of BINA

The electronics of BINA consists of three main parts:

1. Forward-wall electronics,
2. Backward-ball electronics,
3. MWPC electronics.

The ΔE - E readout electronics digitizes the signals of 44 PMTs of E and ΔE detectors. All the signals from this part are split into two parts using an active splitter. From the second output, the signal is sent to charge-integrating QDCs (FERAs), after a cable delay of ~ 250 ns. The first output is sent to a CFD which output was used as the input to the trigger unit and as a start for the TDC, see Fig. 3.13. The backward-ball electronic is responsible for digitizing the signals of 149 PMTs of the backward-ball. The same as the forward-wall, signals from 149 detectors are split into two branch. Since the ball detectors are composed of slow and fast response scintillators, the input signals were split once more to provide signals for the inputs of QDCs with a long and short integration time for particle identification.

Figure 3.13: A schematic view of the logic of the data acquisition of BINA.

The MWPC channels are read out by the PCOS-III electronic system. The signals of the wires from the X, Y and U plane are handled by the MWPC electronic system. This system consists of amplifiers, discriminators, delay and latch modules and can encode the MWPC signals. The read-out signals from the wires were amplified and sent to the discriminators. The logic signals are then delayed and registered with a programmable delay and latch unit. The strobe signal for the PCOS controller is received from a common trigger signal. The MWPC has three planes with the number of wires of X(96), Y(96) and U(135) in each plane. Since the MWPC has a hub in the middle, the wires in this region are disconnected and, therefore, they are read out from both sides. So, there are 118 read-out channels for the X and Y planes and 148 channels for the U plane.

The data acquisition system (DAQ) of BINA is responsible for collecting the electric signals from the detectors, processing, digitizing and saving them in the storage device. Figure 3.13 shows the logic of the BINA-DAQ together with different electronic components of BINA. Briefly, all the signals from E , ΔE , backward-ball, and MWPC are divided into two parts using the splitters. One branch of the E and ΔE signals is sent to FERA where the ADC converts the analog signal to a digital value as a measure of the energy of the registered particle. The MWPC's signals are sent to the PCOS-III system for digitizing and placing a delay on them. The other branch of the E and ΔE signals are sent to CFD and they are used as a start signal for time measurement as well as input to the trigger unit. As soon as one of the defined trigger conditions are satisfied, the trigger unit sends a signal for opening the gate and the digitized data from FERA, PCOS-III, and TDC will be sent further to be saved in the storage device.

The information from CFDs of BINA after pre-processing are used as inputs for the trigger unit to make a decision whether to accept or reject the event. Four different trigger conditions were defined in the experiment with BINA:

1. $T1 = E$ (Multiplicity ≥ 3) OR ΔE (Multiplicity ≥ 3),
2. $T2 =$ Coincidence of (OR E) AND (OR Ball),
3. $T3 =$ OR Ball (Multiplicity ≥ 2),
4. $T4 =$ OR of everything.

These trigger conditions are designed to cover various channels of the $\vec{p} + d$ scattering reaction. The trigger conditions are in coincidence with the RF of the cyclotron. The T1 trigger covers the break-up channel in which two hits are registered in the forward-wall. The T2 trigger is capable of accepting events in which two hits are registered in coincidence, one in the forward-wall and the other in the backward-ball. Therefore, trigger T2 is suitable to cover the elastic as well as the break-up in which one proton scatters to the forward-wall and the other to the backward-ball. The trigger T3 is suitable for the part of the reaction phase space in which two particles are registered in the backward-ball. The trigger T4 is OR of everything and it means it accepts any combinations of the hits during the experiment. The T3 and T4 were not used in the present analysis.

The trigger rate will be dominated by that part of the kinematics in which the cross sections are large. To have all the triggers without a bias, the trigger with a higher rate were down-scaled. In the present experiment, the trigger T2 had a high count rate because it covers a large part of the elastic channel. Therefore, the trigger T2 was downscaled by a factor of 4. The trigger signals were recorded event-by-event. The TDC starts with a signal from the trigger unit and the stop signal comes from a coincidence between global trigger and RF signal. This information was further used to choose events offline sorted by their trigger type.

The read-out electronics and real-time computing play a crucial role in the BINA-DAQ. They select the incoming data from the electronics based on the trigger conditions and communicate with the storage device to send the data to be saved on the disk. For each defined trigger, a gate-generator unit provides the integration signals for the FERAs, the common stop signal for the TDCs, and the strobes for the PCOS-III system. At the same time, the FERAs receive data from the splitters, with a cable delay of ~ 250 ns. These data are integrated in the charge integrating FERAs within the gate that was provided by the gate generator unit.

After digitizing data in the FERA units, the data are sent to memory units afterward. During this procedure, the triggers from the new events are not accepted, but their amount is stored in scalers and used in the offline analysis to correct for dead-time losses. The rate of data saving is limited due to several parameters such as: the communication link between the memory units and the storage unit, the elapsed time to write events on the disk, the response time of the electronics modules, and the processing time by the CPU. Altogether, they impose a maximum data-taking rate of 15 kHz with a dead-time of 50%. The electronic and DAQ system of BINA have been explained in detail in Ref. [50].

4. Analysis of the proton-deuteron break-up reaction

This chapter is dedicated to describe the analysis method that was applied to the data taken with BINA and a polarized proton beam with energy of $E_p = 190$ MeV impinging on a liquid deuterium target. The aim of the analysis is to select events from the $p + d$ break-up reaction and to extract cross sections and spin observables for exclusive kinematics. After a short introduction to the three-body break-up kinematics, the analysis method to obtain the cross sections and the vector analyzing powers will be discussed for the forward-forward and the forward-backward configurations separately. In this chapter, we use the forward-forward phrase to refer to configurations in which both protons scatter to $\theta_{1,2} < 40^\circ$ and the forward-backward phrase to refer to configurations in which one proton scatters to $\theta_1 < 40^\circ$ and the other scatters to $\theta_2 > 40^\circ$. The observables are extracted for various parts of the three-body break-up phase space and are compared with calculations with and without 3NF effects.

4.1 The three-body break-up kinematics

In the proton-deuteron break-up reaction, there are three particles in the final state, the two outgoing protons and one neutron. For this three-body final state, there are 9 variables (θ_i, ϕ_i, E_i) that can be measured to have a complete description of the kinematics of the system. Using the conservation of energy and momentum, the number of degrees of freedom decreases to 5. Therefore, it is sufficient to measure 5 out of the 9 variables to obtain the full information of the reaction. BINA is capable of measuring the energy and the scattering angles of charged particles in coincidence, which provides an extra redundancy of one degree of freedom. A measurement of this extra variable can be used to identify the channel of interest and to suppress background. Conventionally, in the three-body break-up reaction, a kinematical configuration is defined by $(\theta_1, \theta_2, \phi_{12} = |\phi_2 - \phi_1|)$ which are the polar scattering angle of proton 1, the polar scattering angle of proton 2, and the relative azimuthal opening angle between them, respectively. The left panel of Fig. 4.1 illustrates the definition of these angles.

For each kinematical configuration, the energy correlation of the two outgoing protons is referred to as the S -curve. The right panel of Fig. 4.1 depicts the S -curve for a typical break-up configuration. Using the S -curve, a variable S is defined as the arc length of the curve with the starting point at the minimum value of the energy of the protons. In the present work, we used the convention in which the starting point of S is the minimum value of E_2 and it increases counter-clockwise as it is shown in the right panel of Fig. 4.1. Traditionally, the break-up observables are presented as a function of S .

Figure 4.1: A diagram of the scattering angles of the two outgoing protons in the proton-deuteron break-up reaction (left) and their energy correlation for $(\theta_1 = 30^\circ, \theta_2 = 45^\circ, \phi_{12} = 160^\circ)$ (right).

4.2 Energy calibration

In this section, energy calibration methods for E -scintillators of the forward-wall and the backward-ball will be discussed. The forward-wall of BINA can be calibrated with good precision since the coordinate of the track is well known. The information of deuterons from the elastic reaction or protons from the break-up reaction has been used for the energy calibration of the detectors of the forward-wall. In this thesis, we used the energy information of protons of the break-up channel to perform the energy calibration of the E -scintillators of the forward-wall. The backward-ball scintillators are calibrated by using the information of protons from the elastic and break-up reactions. Depending on the position of the detector, one of the calibration methods was used for the energy calibration of the detectors of the backward-ball. The generated light in the E -scintillators of the forward-wall was collected by two PMTs at both ends of each scintillator bar. The E -scintillators of the forward-wall have a large length and the light attenuation affects the signal of the PMTs. To have a position independent calibration and also partly to compensate for the light attenuation, the quantity

$$E_{response} = \sqrt{L_{PMT} \times R_{PMT}} \quad (4.1)$$

was used as a measure for energy of the detected particles. L_{PMT} and R_{PMT} are the signal strengths of the left and right PMTs, respectively. In the present experiment, protons from the elastic reaction have energies larger than 140 MeV. The thickness of the E -scintillators of the forward-wall is not enough to stop these high-energy protons. Consequently, these protons punch through the scintillators and deposit a fraction of their energies there. Figure 4.2 shows the Geant-3 simulation of the response of the E -detectors of the forward-wall to the protons from the elastic channel. Therefore, it becomes more complicated to use the energy information of the protons from the elastic channel to do the energy calibration. Also, there is a possibility of using the energy information of deuterons from

Figure 4.2: Results of a Geant-3 simulation of the response of the scintillators of the forward-wall to the protons from the elastic reaction, E_p , as a function of the scattering angle of the proton, θ_p . The black curve is the expected energy for protons from the elastic reaction. All the protons from the elastic reaction punch through the detectors of the forward-wall and consequently, deposit part of their energies in the detectors.

the elastic channel to calibrate the detectors. However, to use this calibration method one needs to correct for the quenching effect in order to use the deuteron calibration functions for protons. In this thesis, we chose not to use this method to calibrate the detectors for analyzing the break-up reaction.

4.2.1 Energy calibration of the E -scintillators of the forward-wall

The other option is to use the energy information of the protons from the break-up channel to do the energy calibration. In this method, to perform the calibration for all the 10 E -scintillators of the forward-wall, the configuration $(\theta_1, \theta_2, \phi_{12}) = (28^\circ, 28^\circ, 180^\circ)$ was used due to the high statistics and full coverage of the forward-wall. Figure 4.3 depicts the structure of the E -scintillators of the forward-wall and illustrates the case whereby the two outgoing protons hit the two scintillators at the opposite sides of the forward-wall. The calibration factors for each E -scintillator are obtained by comparing the simulated S -curve with data. For the simulations, we made use of Geant-3 and we used the same conditions as applied to the data. The left panel of Fig. 4.4 shows the signal of the two outgoing protons in the two opposite detectors, detector numbers 2 and 9. The right panel of Fig. 4.4 shows the response of the scintillators as a result of Geant-3 simulation for $(28^\circ, 28^\circ, 180^\circ)$. This simulated result is used to calibrate the detectors of the forward-wall. Moreover, the materials between the interaction point and the E -scintillators cause the protons to lose part of their energies before they reach the scintillators. As a result, the deposited energy

Figure 4.3: An illustration of the forward-wall scintillators together with the hit positions of the two outgoing protons on two opposite scintillator bars, numbers 2 and 9, for the configuration $(28^\circ, 28^\circ, 180^\circ)$. The same colors show the opposite detectors. The numbers on the left and the right side of the figure indicate the numbering of the left and the right PMTs, respectively.

Figure 4.4: The left panel shows the correlation of the signals of two scintillators for the configuration $(28^\circ \pm 2^\circ, 28^\circ \pm 2^\circ, 180^\circ \pm 5^\circ)$ whereby one of the protons hits detector number 2 (y -axis) and the other one hits detector number 9 (x -axis). The right panel shows the deposited energy of the protons in the scintillators as simulated by Geant-3 for the same configuration. The solid line shows the expected energy correlation of the two outgoing protons at the interaction point (target position). The deviation between the deposited energy and the expected E -correlation is due to the energy loss of the protons when they pass through the materials between the interaction point and E -scintillators of the forward-wall.

Figure 4.5: The correlation of the deposited energy of the two break-up protons in scintillator numbers 2 and 9 for the configuration $(28^\circ, 28^\circ, 180^\circ)$. The deposited energies of the two outgoing protons are less than the expected energy by the S -curve due to the energy loss of the protons while passing through the materials between the interaction point and the scintillators.

Figure 4.6: The left panel shows the simulated correlation between the deposited energy ($E_{deposit}$) and the energy at the interaction point (E_{thrown}) of the protons. The right panel shows the measured energy correlation of the two break-up protons for $(28^\circ, 28^\circ, 180^\circ)$ after correcting for the energy loss. The solid black curve is the S -curve for the corresponding configuration.

in the scintillators is less than the expected energy from the 3-body relativistic S -curve as illustrated in Fig. 4.5. The simulation data of the correlation between the energy of the protons at the interaction point and deposited energy in the scintillators are used to obtain a function to convert the deposited energy to the energy at the interaction point for the break-up protons, as shown on the left panel of Fig. 4.6. The right panel of Fig. 4.6 shows a perfect agreement between the energy correlation of the break-up protons and the S -curve after correcting for the energy loss. However, for energies close to 140 MeV and

higher, data start to deviate from the S -curve. This is because of the punch through of the protons in the detectors at this range of energies; see the edges of the S -curve in the right panel of Fig. 4.6. This calibration procedure was applied for all the 10 scintillators of the forward-wall.

4.2.2 Energy calibration of the backward-ball scintillators

The backward-ball is used as a scattering chamber and a detector simultaneously. The calibration procedure of the backward-ball is more challenging than the forward E -scintillators because of some backgrounds originating from the components inside the chamber such as the target cell and the target holder. Furthermore, unlike the forward-wall which has a relatively high angular resolution ($\Delta\theta = \Delta\phi = \pm 1^\circ$), the backward-ball has an angular resolution around ($\Delta\theta = \Delta\phi = \pm 10^\circ$), coming from the size of the detectors. This makes the calibration more difficult and obviously, the energy correlation of the two protons gives us a broader S -curve compared to the forward-forward configurations. There are 149 detectors in the backward-ball. Figure 4.7 shows the angular position of the detectors of the backward-ball. Each detector is labeled with a number which we refer to as detector number.

Figure 4.7: An illustration of the angular positions of the backward-ball scintillators. The data are generated using a Geant-3 simulation. Each color represents the group of detectors which are almost at the same polar angle (θ). Each scintillator is labeled with a number which we refer to as detector number. The white area around $\theta = 100^\circ$ and $\phi = 90^\circ$ is the position where the target holder connects to the chamber and, therefore, there are no scintillators in that part. The white area between $\theta = 160^\circ$ and $\theta = 180^\circ$ is the position of the entrance of the beam pipe to the backward-ball chamber and, therefore, there are again no detectors in that region.

Figure 4.8: The left panel depicts the energy correlation of the two outgoing protons where one of them scatters to the detector number 1 of the backward-ball in units of channels [chan.] (E_2) and the other one scatters to the forward-wall in units of [MeV] (E_1) for the configuration ($25^\circ \pm 2^\circ, 45^\circ \pm 10^\circ, 160^\circ \pm 10^\circ$). The kink in the spectrum at the lower values of E_2 is due to the punch through of protons where $E_1 > 140$ MeV and only a part of their energies is deposited in the forward-wall E -detector. The right panel shows the energy correlation of the two break-up protons as calculated by the Geant-3 simulation for the same configuration as the left panel. E_1^{thrown} and E_2^{thrown} are the energies at the interaction point of the scattered protons to the forward-wall ($\theta_1 = 25^\circ$) and the detector number 1 in the backward-ball ($\theta_2 = 45^\circ$), respectively.

To calibrate the backward-ball scintillators, we divided the backward-ball into three regions:

1. Region 1 corresponds to $40^\circ < \theta < 80^\circ$ and detector numbers 1 to 55;
2. Region 2 corresponds to $80^\circ < \theta < 100^\circ$ and detector numbers 56 to 82;
3. Region 3 corresponds to $100^\circ < \theta < 140^\circ$ and detector numbers 83 to 134.

The scintillators in region 1 are calibrated by using the data selected for break-up protons whereby one of the protons scatters to one of the detectors of the backward-ball and the other to the forward-wall. The energy information of the protons which are registered in the forward-wall was used to find a calibration function to convert [chan.] to [MeV]. The left panel of Fig. 4.8 shows the energy of the scattered protons of detector number 3 in the backward-ball in units of channels [chan.] versus the energy of the scattered protons to the forward-wall in units of [MeV] for the configuration ($25^\circ \pm 2^\circ, 45^\circ \pm 10^\circ, 160^\circ \pm 10^\circ$). The information from the Geant-3 simulation, which is shown on the right panel of Fig. 4.8, is used to find a calibration function for this detector of the backward-ball. This calibration procedure has been performed for all the backward-ball scintillators which are located in region 1. Figure 4.9 shows the presented example and depicts the result for detector number 3 after calibration.

The detectors in regions 2 and 3 are calibrated using the protons from the elastic channel. In this method, a calibration function is obtained to convert [chan.] to [MeV] for each detector using the well-known kinematics of the elastic reaction. Figure 4.10 shows

Figure 4.9: The energy correlation between protons registered in the detector number 1 in the backward-ball (E_2) and those registered in the forward-wall (E_1) for the configuration $(25^\circ \pm 2^\circ, 45^\circ \pm 10^\circ, 160^\circ \pm 10^\circ)$. The solid curve is the expected kinematical S -curve. The deviation between data and the S -curve for $E_2 < 40$ MeV is due to the punch-through of the protons which have energies larger than 140 MeV in the forward-wall.

Figure 4.10: The result of the calibration of detector number 119 in Region 3 for $(20^\circ \pm 2^\circ, 127^\circ \pm 10^\circ, 160^\circ \pm 10^\circ)$. The solid curve is the expected kinematical S -curve for this configuration.

Figure 4.11: The left panel shows the response of the detector number 67 to the protons from the elastic channel. The right panel shows the calibrated version of the left panel and it shows that the energy loss for 50 MeV protons is around 20 MeV when they pass through the target cell (the peak on the left).

the result of the calibration for scintillator number 119 in region 3 for the configuration ($20^\circ \pm 2^\circ, 127^\circ \pm 10^\circ, 160^\circ \pm 10^\circ$). Moreover, because of the shadow of the target cell, the protons which scattered to region 2 have different energy losses. Part of the protons pass through the target cell and lose more energy than those that do not pass through the target cell. Figure 4.11 shows the shadow effect of the target cell for protons of the elastic channel. Those protons that pass through the target cell lose almost 20 MeV more than the other protons which do not pass through the target cell. Also, some of the detectors in regions 1 and 3 are in the shadow area. These detectors and the entire region 2 were excluded from the present analysis.

4.3 Background analysis of the break-up reaction

This section is dedicated to the discussion of the structure of the background of the break-up reaction. Events that originate from the break-up channel can be identified since one expects them to follow the S -curve. Background, on the other hand, can be identified by those events that do not show a clear correlation with the S -curve. An important source of background stems from the proton-deuteron elastic channel due to its high cross section. Therefore, there is a high probability that the trigger unit accepts two uncorrelated elastic-elastic or elastic-break-up events. Moreover, the punch-through threshold for protons in the scintillators of the forward-wall is around 140 MeV and for the scintillators in region 1 of the backward-ball is around 110 MeV. Accordingly, all the protons originating from the elastic channel which scattered to these regions deposit only part of their energy in the detectors. As a consequence, the structure of the background in the forward-forward break-up configurations is different from that in the forward-backward configurations. We will, therefore, discuss both configurations separately.

Figure 4.12: The background structure of the break-up reaction for the forward-forward configuration ($28^\circ, 28^\circ, 180^\circ$). The elastic-elastic accidental events are the most challenging background because they partly interfere with the break-up S -curve.

4.3.1 Background analysis of the forward-forward configurations

The signal and background structures of one of the break-up configurations at which both protons scatter to the forward-wall are shown in Fig. 4.12. The most important part of the background, in this case, is the accidental events from two time-uncorrelated events which are very close to the break-up S -curve at most of the configurations. Part of this background can be suppressed by putting a gate on the relative time-of-flight (TOF) of the two outgoing protons as illustrated in Fig. 4.13. the TOF was obtained using the TDC information of the two detected particles from the left and right PMTs of the forward-wall detectors. At small and large values of S , one of the protons punches through the scintillators and, therefore, their energy does not follow the S -curve. Events from these parts of the S -curve are excluded from the analysis. Figure 4.12 also shows events from the break-up reaction whereby one (or both) of the protons had a hadronic interaction with the scintillator material. Consequently, those events do not follow the S -curve as well since the measured energy is less than what is expected. Since we have no measure of S for those events, we do not count them in order to be able to perform a fully exclusive extraction of observables. The fraction of events that suffer from hadronic interactions has been obtained using simulated data from Geant-3. According to this simulation, 7-8%

of the particles for the energy range of 30-140 MeV undergo a hadronic interaction in the scintillator material of the forward-wall [50].

Figure 4.13: An illustration of the identification of time-uncorrelated events using the time-of-flight (TOF) of the forward-wall scintillators. The first column shows the relative TOF of the two protons and the second column shows the energy correlation between them. Each row shows the effect of various TOF cuts on the energy correlation of the two outgoing protons. TDC_1 and TDC_2 are the TDC information of the two protons. The second row shows the effect of the prompt TOF cut, including three RF-cycles, which partly removes accidental background. The third row shows the events outside the prompt TOF cut.

4.3.2 Background analysis of the forward-backward configurations

The background structure of the break-up configurations whereby one proton has been registered in the forward-wall and the other in the backward-ball will be discussed next. For the forward-backward configurations the event selection is different than the forward-forward configurations. For some neighboring scintillators of the backward-ball, due to poor shielding, generated light in one scintillator can cross to the other detectors and, therefore, more than one detector fired in each event of trigger T2. We performed a preliminary clustering on the detectors of the backward-ball and for each event we took the highest signal among all the signals of the detectors in each cluster. In the case that after clustering the number of hits in the backward-ball for each event was more than 1, we took the highest signal as a break-up candidate.

In region 1 of the backward-ball, there is a high probability of finding a proton or deuteron of the elastic-scattering process. Elastically-scattered deuterons will deposit their full energy in the backward-ball scintillators, whereas for elastically-scattered protons, one will observe a punch-through characteristics for those with an energy larger than 110 MeV. Figure 4.14 depicts the simulation results of the elastic protons in region 1 of the backward-ball. As a result, it is impossible to eliminate the background that originated from the accidental elastic-elastic protons only by using the energy information.

Furthermore, in region 1 of the backward-ball, there is a high probability that the trigger unit accepts time-uncorrelated events from the elastic and break-up reactions. For

Figure 4.14: The simulated response of region 1 of the backward-ball to elastically-scattered protons. The protons with an energy $E > 110$ MeV punch through the scintillator and only deposit part of their energy in the detector. For the elastic channel, this corresponds to scattering angles of $40^\circ < \theta < 58^\circ$. The black solid curve is the expected E - θ correlation of the protons of the elastic channel.

Figure 4.15: The uncorrelated elastic-break-up background before TOF-cut for the configuration $(20^\circ \pm 2^\circ, 45^\circ \pm 10^\circ, 120^\circ \pm 10^\circ)$. The background of the uncorrelated elastic-break-up events appear around $80 \text{ MeV} < E_1 < 100 \text{ MeV}$ and they dominate the middle part of the S -curve.

the smaller values of ϕ_{12} , the background becomes significantly larger than the signal of break-up events. An example is shown in Fig. 4.15 for the configuration $(20^\circ, 45^\circ, 120^\circ)$. In this thesis, the configurations in which $\phi_{12} < 140^\circ$ of region 1 of the backward-ball are not analyzed. The accidental elastic-breakup background of the forward-backward configurations can be partly suppressed by using the TDC information of the two outgoing protons. Here, we used the TDC information from the right PMT of the detectors of the scattered proton in the forward-wall (TDC_1) and the TDC information from the OR of the ball detectors of scattered protons in the backward-ball (TDC_2). Figure 4.16 shows the effect of the relative TDC cut on the E_1 - E_2 spectrum. For larger scattering angles of θ_2 , the intensity of the time-uncorrelated background decreases. This can be clearly seen in Fig. 4.10.

4.4 Break-up cross sections

In this section, the method to extract the break-up cross section will be discussed. The break-up observables are given as a function of S value. In order to extract the observables as a function of S , the data for each kinematical configuration are divided into equal S -bins along the S -curve and then for each S -bin the number of break-up events has been obtained. For the forward-forward and the forward-backward configurations, we used two different approaches to extract the number of counts for each S -bin. In the following sections, the methods of extracting cross sections will be discussed together with procedure to estimate systematic and statistical uncertainties for forward-forward and forward-backward configurations.

Figure 4.16: The effect of various TDC cuts on the E_1 - E_2 spectrum. The first column shows the TDC cuts and the second column shows the effect of the TDC cut on E_1 - E_2 spectrum. The second row depicts the effect of the prompt relative TDC cut on the energy correlation of the two outgoing protons.

4.4.1 Cross sections for the forward-forward kinematics

In the forward-forward break-up configurations, the data for each kinematical configuration were divided into 25 equal S -bins along the S -curve. For each S -bin, the data were projected onto the axis perpendicular on the S -curve, which is called D-axis. The projected data were used to count the number of break-up events in each S -bin. The width of the S -bins for these configurations is 8-10 MeV depending on the configuration. Figure 4.17 shows the energy correlation for the configuration $(28^\circ, 28^\circ, 180^\circ)$ together with the projection of events of one of the S -bins on the D-axis. For obtaining the true break-up events, we estimated and subtracted background from the main peak of the D-spectrum for each S -bin. The main source of the background in the forward-forward configurations is the accidental events. The TOF-window cannot suppress all the background of the time-uncorrelated events from the D-spectrum. In some configurations, these events overlap with the break-up S -curve at intermediate S values. The background was subtracted in two steps. Firstly, for each configuration, a ratio was obtained by comparing the data of the TDC window ($|\Delta TOF| < 49$) and anti-TDC window ($|\Delta TOF| > 49$); see Fig. 4.13. To do this, the following variable was defined:

$$R = N_{TDC}/N_{anti-TDC}, \quad (4.2)$$

where N_{TDC} and $N_{anti-TDC}$ are the number of events within a range of E_1 and E_2 where only accidental events are expected for TDC and anti-TDC cuts, respectively. The ratio R multiplies the number of counts in the D-spectrum corresponding to the data within the

Figure 4.17: The energy correlation of the two outgoing protons for the configuration $(28^\circ \pm 1^\circ, 28^\circ \pm 1^\circ, 180^\circ \pm 5^\circ)$. The D-axis for one of the S -bins is shown on the S -curve. The top-right panel shows the projection of events of one of the S -bins on the D-axis.

Figure 4.18: The left panel shows the signal and the estimated background of the uncorrelated elastic-elastic events using the information of the anti-TDC cut in the TOF spectrum for the configuration $(28^\circ, 20^\circ, 140^\circ)$ and $S = 111$ MeV. The right panel shows the D-spectrum of the left panel after subtracting the background. A 4th-order polynomial plus a Gaussian (blue line) was fitted to take into account the break-up events, the events from the hadronic interaction (left side of the spectrum), and the remaining accidental background (right side of the spectrum) to get the best chi-square and true values of the mean and the sigma of the main peak. The events that fall within three standard deviations ($\pm 3\sigma$) of the final D-spectrum are taken as true break-up events for extracting the cross section.

anti-TDC condition. Then, the obtained histogram was subtracted from the D-spectrum of the TDC cut. The left panel of Fig. 4.18 shows a sample spectrum before subtraction and the right panel shows the result after subtraction. The background subtracted spectrum was subsequently fitted to a function composed of a Gaussian, representing the break-up signal, and a 4th-order polynomial as a model of the remaining background (right side of the spectrum) and the events from the hadronic interaction (left side of the spectrum). The right panel of Fig. 4.18 illustrates the result of such a fit. For extracting the cross section, events are taken that fall within three standard deviations ($\pm 3\sigma$) of the main peak. This method was applied for all the forward-forward kinematics. Figure 4.19 shows the reduced chi-square distribution for the fits of the D spectra of configurations for which the number of degrees of freedom (ndf) equals 35. The agreement between the obtained and the expected chi-square distributions shows that the fitting procedure of the D-spectra is under control.

Generally, the break-up cross section is calculated from the number of counts (N) and the experimental parameters such as beam current, target thickness, etc.. Furthermore, all the inefficiencies of the system have been taken into account as much as we know them. For a typical break-up configuration $\xi = (E_1, E_2, \theta_1, \theta_2, \phi_{12})$, the differential cross section is defined as:

$$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS} = \frac{N}{Q/Z} \cdot \frac{1}{t \cdot \epsilon} \cdot \frac{1}{\Delta\Omega_1 \Delta\Omega_2 \Delta S}, \quad (4.3)$$

Figure 4.19: The reduced chi-square (χ_r^2) distribution of the results of fits on the D-spectrum for the kinematics in which $\text{ndf} = 35$. The solid curve is the expected reduced chi-square distribution for $\text{ndf} = 35$.

where N is the number of break-up events, Q is the total integrated charge, Z is the charge of the beam particle, t is the target thickness, and ϵ represents the efficiencies of the system. $\Delta\Omega_1$ and $\Delta\Omega_2$ are the solid angles of the two outgoing protons and ΔS is the size of the S -bin. For inefficiencies of the system, we take into account the inefficiency of MWPC, geometrical inefficiencies of the forward-wall and the effect of hadronic interactions in the forward-wall. The average efficiency of MWPC for protons is $\sim 97\%$. A correction factor of $\sim 8\%$ per particle was obtained for hadronic interactions. The typical beam current is ~ 10 pA, and the live-time is typically around 50%. The target thickness is 6.8 mm, including 0.8 mm due to bulging of the target. All these numbers are discussed in Ref. [50]. Figure 4.20 shows the differential cross section for the configuration $(28^\circ, 25^\circ, 140^\circ)$ together with calculations based on CDB and AV18 potentials with and without 3NF effects. The data from Ref. [50] are also shown in Fig. 4.20. Both results are from a same experiment. The present results are extracted using a larger data sample and, therefore, the statistical errors are smaller than the results from Ref. [50]. Both results are in a fair agreement with each other taking into account the differences in estimating the systematic errors caused by the background between this analysis and previous work. However, the theoretical predictions are not in agreement with data especially at larger S values.

For the cross sections, the systematic uncertainty is defined using 5 independent sources which are presented in Table 4.1. The uncertainties of target thickness, MWPC efficiency, hadronic interaction, and geometrical inefficiency are taken from Ref. [50]. The fifth source of the systematic uncertainty comes from the background subtraction method. This part of the systematic uncertainty was obtained using the maximum difference between the results of the background estimation using three different polynomial orders (2, 4, and 5) and the average value of them. The estimated background from this source varies in the range

Figure 4.20: Break-up cross sections for the configuration $(28^\circ \pm 1^\circ, 25^\circ \pm 2^\circ, 140^\circ \pm 5^\circ)$. The lines represent the results of different calculations which are described in the legend. The filled circles are the results of the present analysis and the open squares are the results of the same data which are taken from Ref. [50]. The gray band represents the systematic uncertainty which stems from the background model (2σ). The cyan band represents the total systematic uncertainty (2σ); see the text for further details.

Table 4.1: The values of different components of the systematic uncertainty for the cross sections. The first four values were taken from Ref. [50].

Systematic error	Value
Target thickness	5%
MWPC efficiency	2%
Hadronic interaction	6%
Geometrical inefficiency	2-7%
Background model	0-30%

of 0-30%. However, only a small fraction of data points have a systematic uncertainty larger than 20%. The total systematic uncertainty varies in the range of 8-30%. To have a meaningful comparison with the calculations, we decided to present data for which the total systematic uncertainty is less than 25%. This requirement only excluded a small fraction of the data points ($\sim 1.5\%$).

Figure 4.21: The reconstructed missing-mass for one of the S -bins for detector number 1 of the backward-ball indicating that the detectors are well calibrated. The interval of $\pm 3\sigma$ was used to obtain the number of break-up events under the peak after subtracting the background. The background was estimated using the sensitive non-linear iterative peak-clipping algorithm (red dashed line). The green histogram shows the missing-mass spectrum after background subtraction. The vertical black dashed lines illustrate the integration window of $\pm 3\sigma$ around the peak.

4.4.2 Cross section of the forward-backward kinematics

For the forward-backward configurations, we used a different approach to extract the number of break-up events in the S -bins. In this method, the S -curve is divided into 15 equal S -bins and the reconstructed mass of the undetected neutron (which we refer to as the missing mass) is obtained by using the reconstructed energy and momentum information of the two registered protons. The missing-mass for the pd break-up reaction is defined as:

$$P_n^\mu = (P_p^\mu + P_d^\mu) - (P_1^\mu + P_2^\mu);$$

$$Missing-mass = \sqrt{P_n^\mu P_{n\mu}}, \quad (4.4)$$

where P_p^μ and P_d^μ are the 4-momenta of the proton beam and the deuteron target, respectively. P_1^μ and P_2^μ are the 4-momenta of the two detected protons and P_n^μ is the 4-momenta of the undetected neutron in the final-state. The *Missing-mass* is obtained as the invariant mass of P_n^μ . Consequently, we observe a spectrum with a peak around 940 MeV/ c^2 , the mass of neutron, as expected. This is shown for one S -bin in Fig. 4.21.

The number of break-up events (N) are obtained for each S -bin from the missing-mass spectrum after background subtraction. The background mainly stems from uncorrelated protons from two different reactions, either elastically scattered or from a break-up reac-

Figure 4.22: The top panel shows the energy correlation of the two outgoing protons of the break-up reaction for the configuration $(25^\circ, 45^\circ, 160^\circ)$. The solid black curve is the expected kinematical S -curve. The dashed lines which are labeled with 1 and 2 show two different cuts on the S -curve for $S = 93$ MeV and $S = 127$ MeV, respectively. The bottom panels are the corresponding missing-mass spectra for the two cuts shown in the top panel. The data presented in spectra 1 and 2 are fitted using a line-shape model composed of two Gaussians describing the signal (solid black lines) and the elastic background (green dashed lines) and a second-order polynomial describing other background sources and hadronic interactions. The red dashed lines and the solid blue lines represent total background and total fit, respectively. The fit parameters which are labeled with 1 (2) correspond to the break-up signal (elastic background).

tion, and accepted by the hardware trigger as candidate break-up events. To account for the background, we used an algorithm which was developed to estimate background of gamma-rays spectrum [114]. This method allows to separate continuous background from peaks, based on a sensitive non-linear iterative peak-clipping algorithm. The algorithm was applied to each missing-mass spectrum to estimate the background shape using the following input parameters:

- Number of iterations = 30,
- Direction = kBackDecreasingWindow,
- Filter order = kBackOrder8.

For a detailed description of the parameters, see Ref. [115]. The main motivation for employing this method was the complex shape of the background for each detector. Figure 4.21 shows the estimated background shape for a typical missing-mass spectrum. The background, which mainly comes from time-uncorrelated elastic-breakup events, is distributed vertically and it overlaps with the breakup events at larger values of S ($S > 100$ MeV), see the top panel of Fig. 4.22. The cut on the S -curve induces an artificial correlation between the two time-uncorrelated hits that mainly stem from two protons of the elastic proton-deuteron scattering process and of the break-up reaction. As a consequence, a peaking structure of the background is observed in the missing-mass spectrum for the selected S -bin. The peak position of this background depends strongly on S and its width is nearly S -independent. To show the moving of the background from one S -bin to another, we used two different cuts (labeled with 1 and 2) on the S -curve shown in Fig. 4.22 to construct the missing-mass spectrum. The two missing-mass spectra are shown in the bottom panels of Fig. 4.22. The data presented in spectra 1 and 2 are fitted using a line-shape model composed of two Gaussians (describing the signal and the elastic background) and a second-order polynomial (describing other background sources and hadronic interactions). It is clear that the position of the elastic background in the missing-mass spectra moves to the left and for $S = 127$ MeV, it interferes with the breakup S -curve. The data used in the bottom-right panel of the Fig. 4.22 are the same as those in Fig. 4.21. We, therefore, believe to have a sufficient understanding of the background features observed in the data.

To find the peak position of the missing-mass spectrum, we used an algorithm for peak searching [116]. It allows to automatically identify the peaks in a spectrum in the presence of the continuous background and statistical fluctuations. The methods of peak searching are sensitive to the width of the expected peak (σ). Therefore, it is necessary to pass a value for the width of the peak to the peak searching function. For further details, see Ref. [115]. Here, we fixed σ to $7 \text{ MeV}/c^2$ which is equal to the expected width of the peak in the missing-mass spectrum of the forward-backward kinematics. The number of counts was obtained by including the events which were located $\pm 3\sigma$ around the peak position.

The break-up cross section for the forward-backward kinematics can be obtained using Eq. 4.3. Figure 4.23 shows the preliminary results of the break-up cross sections for the configuration ($25^\circ, 45^\circ, 160^\circ$) together with different theoretical predictions. The efficiencies of the MWPC and the hadronic interaction effects for the protons scattered to the

Figure 4.23: Break-up cross sections for the configuration $(25^\circ, 45^\circ, 160^\circ)$ for detector number 1 of the backward-ball. Data are compared with predictions of various theoretical approaches of pairwise NN (dashed lines) and NN+3NF (solid lines); see the legend. The error bars represent statistical uncertainties. The deviation between experimental results and calculations are present mostly because of unknown inefficiencies of the backward-ball.

forward-wall were taken into account to extract the cross section. We observe a significant deviation between theory and data, although the one naively expects the 3NF to be very small at this kinematics. Moreover, note that the measured shape of the cross section matches reasonably well the predictions. We, therefore, suspect that the deviation is likely due to unknown inefficiencies of the backward-ball. Obtaining all these inefficiencies for all detectors of backward-ball needs further analysis and simulations. Due to the lack of time we only show the feasibility of extracting cross sections for the forward-backward kinematics from these data.

4.5 The break-up analyzing powers

In this section, the methodology of extracting the vector analyzing powers of the proton-deuteron breakup reaction will be discussed. In general, the beam (target) polarization causes an asymmetry on the cross section in terms of azimuthal angle ϕ which for the spin- $\frac{1}{2}$ particles is defined as:

$$N(\xi, \phi) = N_0(\xi, \phi)(1 - A_x(\phi)p_z \sin \phi + A_y(\phi)p_z \cos \phi), \quad (4.5)$$

where:

N = number of break-up events for a polarized beam,

- N_0 = number of break-up events for an unpolarized beam,
- p_z = the beam polarization,
- A_x = x component of the vector analyzing power,
- A_y = y component of the vector analyzing power,
- ϕ = azimuthal angle of the reaction plane,
- ξ = all kinematical variables ($E_1, E_2, \theta_1, \theta_2, \phi_{12}$).

We used two different approaches to obtain the vector analyzing powers for the forward-forward and forward-backward configurations.

4.5.1 Analyzing powers of the forward-forward configurations

In order to extract both A_x and A_y for break-up reaction, the data taken with both up and down beam polarization have been used. Moreover, for each kinematical configuration there are two mirror configurations which are referred to $+\phi_{12}$ and $-\phi_{12}$. A_x is odd and A_y is even under parity operation and, therefore, for the two different mirror configurations and beam polarizations the asymmetry distribution are related to:

$$\Upsilon^+(\xi, \phi) = \frac{N_p^\uparrow - N_p^\downarrow}{N_p^\downarrow p_z^\uparrow - N_p^\uparrow p_z^\downarrow} = A_y \cos \phi - A_x \sin \phi, \quad (4.6)$$

$$\Upsilon^-(\xi, \phi) = \frac{N_m^\uparrow - N_m^\downarrow}{N_m^\downarrow p_z^\uparrow - N_m^\uparrow p_z^\downarrow} = A_y \cos \phi + A_x \sin \phi. \quad (4.7)$$

where $\Upsilon^+(\xi, \phi)$ and $\Upsilon^-(\xi, \phi)$ are the asymmetry terms for the two parity modes and ξ represents any appropriate set of kinematical variables. $N_p^\uparrow$ ($N_p^\downarrow$) are the number of events for up (down) polarization modes of the (ϕ_1, ϕ_2) setup. Similarly, $N_m^\uparrow$ ($N_m^\downarrow$) are the number of events for up (down) polarization modes of the $(-\phi_1, -\phi_2)$ setup. $p_z^\uparrow$ and $p_z^\downarrow$ are the polarization degrees of up and down modes, respectively. A_x and A_y are the two components of the vector analyzing power and ϕ is the azimuthal angle of the reaction plane. We used a convention that the proton with the smaller scattering angle (proton 1) lies in the x - z plane and, therefore, $\phi_1 = 0$. Indeed, the ϕ of the reaction plane is equal to the azimuthal scattering angle of the proton 2 (ϕ_2). Two asymmetry components can be constructed from $\Upsilon^+(\phi)$ and $\Upsilon^-(\phi)$ to extract A_x and A_y independently:

$$h(\xi, \phi) = \frac{\Upsilon^-(\xi, \phi) - \Upsilon^+(\xi, \phi)}{2} = A_x \sin \phi, \quad (4.8)$$

$$g(\xi, \phi) = \frac{\Upsilon^-(\xi, \phi) + \Upsilon^+(\xi, \phi)}{2} = A_y \cos \phi. \quad (4.9)$$

To extract the analyzing powers from Eqs. 4.8 and 4.9, the number of counts for each polarization and parity modes are extracted and normalized with the integrated charge from the Faraday cup. $h(\xi, \phi)$ and $g(\xi, \phi)$ are constructed using the normalized counts as a function of ϕ . To extract the values of analyzing powers, the functions $A \sin \phi + B$ and $C \cos \phi + D$ are fitted to $h(\xi, \phi)$ and $g(\xi, \phi)$, respectively. The parameters A and

Figure 4.24: The constructed asymmetry distributions for A_x (left panel) and A_y (right panel) for the kinematics $(25^\circ, 25^\circ, 60^\circ)$ and $S = 91$ MeV. The quality of the fit and the obtained values of the analyzing powers are shown at the top of each panel.

C represent the analyzing powers A_x and A_y , respectively. The parameters B and D are free parameters to correct for a possible offset of the charge measurement and other normalization factors which we may have missed in the analysis. Figure 4.24 shows the fit result of $h(\xi, \phi)$ and $g(\xi, \phi)$ for the kinematic $(25^\circ, 25^\circ, 60^\circ)$ and $S = 91$ MeV. Figure 4.25 presents the analyzing powers for the kinematic $(25^\circ, 25^\circ, 60^\circ)$ as a function of S together with various calculations.

The systematic uncertainty for the analyzing powers stems mainly from uncertainties in the measurement of the beam polarization. The associated uncertainties of the polarization values are 6% statistical and 3% systematical [50]. This uncertainty in the polarization causes a systematic error of $\sigma_{pol} \sim 7\%$ in the analyzing power measurement. Another source of systematic uncertainty is identified to be from residual and unknown asymmetries caused by efficiency variations between the up and down polarization states of the beam, an error in charge normalization, etc.. All of these will result in a wrong model presented in Eqs. 4.8 and 4.9. This source of systematic uncertainty was investigated by comparing the results with and without the free parameters (B and D) of the fitting functions for the asymmetry distributions. Figure 4.26 depicts the distribution of the parameters B and D . The results show the same range for both parameters. The total systematic uncertainty was obtained from a quadratic sum of the two sources of systematic errors. The total systematic uncertainty varies between 0-0.08 for both A_x and A_y .

The procedure of extracting the analyzing powers through fitting on the asymmetry distributions has been done for all the kinematics. To check the quality of the fits, the chi-square distribution was extracted of the fits for asymmetry distributions in which $ndf = 34$. Figure 4.27 shows the chi-square distribution of the fits on the two asymmetry distributions which are used to extract A_x and A_y . The good agreement between the obtained chi-square distribution and the expected chi-squares shows that the fitting on the asymmetry distribution for extracting the analyzing powers is reliable.

Figure 4.25: The results of the analyzing powers A_x and A_y for $(\theta_1, \theta_2, \phi_{12}) = (25^\circ, 25^\circ, 60^\circ)$ as a function of S . Data are compared with predictions of various theoretical approaches of pairwise NN (dashed lines) and NN+3NF (solid lines); see the legend. The error bars represent statistical uncertainties. The cyan band depicts the systematic uncertainty (2σ) which stems from different sources; see the text. For A_y , the results of a different analysis method using the same data from Ref. [50] are shown with open squares.

Figure 4.26: The obtained parameters B and D of the fitted functions for the asymmetry distributions $g(\xi, \phi)$ and $h(\xi, \phi)$. The left and right panels show the distribution of parameters B and D , respectively.

Figure 4.27: The left and the right panels show the chi-square distributions of the fits for $g(\xi, \phi)$ and $h(\xi, \phi)$, respectively. The black curves are the expected chi-square distributions for $\text{ndf} = 34$.

4.5.2 Analyzing powers of the forward-backward configurations

In this section, the analysis method to extract the analyzing powers for the configurations in which one proton scatters to the forward-wall and the other one scatters to the backward-ball will be discussed. For the forward-backward configurations, we used Eqs. 4.6-4.9 to construct the asymmetry distributions. For each S -bin and the backward-ball detectors, the reconstructed missing-mass spectrum is obtained to extract the number of break-up events for each polarization state and each parity mode. The number of counts was obtained for each spin state and parity mode using the corresponding missing-mass spectrum after subtracting the background. We used the same method for estimating the background as we discussed in Sec. 4.4.2 for the forward-backward break-up cross section. To extract the analyzing powers from Eqs. 4.8 and 4.9, the number of counts for each polarization and parity modes are extracted and normalized by the integrated charge from the Faraday cup. Also, to have a consistent counting of events in the four missing-mass spectra, spin up and down and two parity modes, the peak position of one of the spectra was used for the other spectra. This increased the reliability of having the right peaks for all different modes, in particular when the number of counts were small. The number of counts was obtained by including the events which were located $\pm 3\sigma$ around the peak position. The $g(\xi, \phi)$ and $h(\xi, \phi)$ are constructed using the normalized counts as a function of ϕ . Here, ϕ is the azimuthal angle of the detector of the backward-ball in which one of the two outgoing protons arriving there. To measure the analyzing powers, the functions $A \sin \phi + B$ and $C \cos \phi + D$ are fitted to $g(\xi, \phi)$ and $h(\xi, \phi)$, respectively. As before, the parameters A and C represent the analyzing powers A_x and A_y , respectively. The parameters B and D are free parameters for the correction of charge offset or other normalization factors which may have been missed in the analysis. Figure 4.28 shows the results of the fits for $g(\xi, \phi)$ and $h(\xi, \phi)$ for one of the analyzed configurations.

Figure 4.28: The constructed asymmetry distributions for A_x (left panel) and A_y (right panel) for the kinematics $(25^\circ, 45^\circ, 160^\circ)$ and $S = 76$ MeV. The quality of the fit and the obtained values of the analyzing powers are shown at the top of each panel. The statistical errors are obtained using the number of counts before subtracting the background.

Figure 4.29 shows the measured analyzing powers A_x and A_y for $(25^\circ, 45^\circ, 160^\circ)$ together with various calculations. The cyan band in each figure represents the systematic uncertainty which consists of three parts. The definition of two of them are similar to the forward-forward configurations. The uncertainty in the polarization measurement causes a systematic error of $\sigma_{pol} \sim 7\%$ in the analyzing power measurement. Another source of systematic uncertainty is identified to be from residual and unknown asymmetries which will result in a wrong model presented in Eqs. 4.8 and 4.9. This source of systematic uncertainty was investigated through comparing the results with and without the free parameters of the fitting functions on the asymmetry distributions. The distribution of

Figure 4.29: The results of the analyzing powers A_x and A_y for the configuration $(25^\circ, 45^\circ, 160^\circ)$ as a function of S . Data are compared with predictions of various theoretical approaches of pairwise NN (dashed lines) and NN+3NF (solid lines); see the legend. The error bars represent statistical uncertainties. The cyan band depicts the systematic uncertainty (2σ) which stems from different sources; see the text.

Figure 4.30: The obtained parameters B and D of the fitted functions for the asymmetry distributions $g(\xi, \phi)$ and $h(\xi, \phi)$. The left and the right panels show the distribution of parameters B and D , respectively.

the obtained free parameters are shown in Fig. 4.30. It can be seen that the free parameter distribution is different for B and D . It is around 0 for B and -0.05 for D . We obtained a systematic uncertainty $\sigma_{asymm} \sim 0-0.1$ for A_x and $\sigma_{asymm} \sim 0-0.12$ for A_y from this source. The third source of the systematic uncertainty comes from the shape of the background. This part of the systematic uncertainty consists of two components. The first one is the difference between results of full and limited ranges of the background estimation; see Fig. 4.21. To do this, we kept the order of the background estimation algorithm to be the same but decreased the range of the background estimation. The

Figure 4.31: The left and the right panels show the chi-square distributions of the fits of $g(\xi, \phi)$ and $h(\xi, \phi)$, respectively. The red curves are the expected chi-square distributions for $ndf = 11$.

error from this part was estimated to be in the range of $\sigma_{bg1} \sim 0-0.04$ for both A_x and A_y . The other component of the error in the shape of the background was obtained using the difference between the results of the background estimation using two different orders of the background model (6 and 8) but keeping the full range. The error from this source was estimated to be in the range of $\sigma_{bg2} \sim 0-0.04$. The total systematic uncertainty was obtained by a quadratic sum of the four sources of systematic errors, assuming them to be independent. The total systematic uncertainty varies between 0-0.16 for A_x and 0-0.2 for A_y depending on the kinematics.

To check the quality of the fits, the chi-square distribution of part of the fits of the asymmetry distributions in which $\text{nfd} = 11$ was investigated. Figure 4.31 shows the chi-square distribution of the fits for the two asymmetry distributions which are used to extract A_x and A_y . The good agreement between the obtained chi-square distributions and the expected chi-squares shows that our analysis procedure for extracting the analyzing powers is reliable.

5. Results and discussion

This chapter is dedicated to the presentation of the results of the measurement of the proton-deuteron break-up reaction taken with a proton beam with an energy of 190 MeV impinging on a deuterium target. In this chapter we will present and discuss the result of analyzing power measurements. For each break-up configuration, the analyzing powers are presented as a function of the kinematical S parameter. To compare the experimental measurements with various theoretical models for configurations in which $\theta_2 > 40^\circ$, the calculations are averaged within the angular bins of the experimental measurement. The averaging procedure will be discussed in this chapter. Also, to have a global comparison between the data and different theoretical calculations, two average quantities will be exploited to compare data and theory. One is the results of averaging over S values for each set of (θ_1, θ_2) as a function of ϕ_{12} . Another one is the average of the results for each set of (θ_1, ϕ_{12}) as a function of θ_2 . At the end, all the results will be compared with NN and NN+3NF calculations as a function of relative energy between the two outgoing protons. A comprehensive discussion on the results and the theoretical predictions will be presented at the end.

5.1 Analysis of the theoretical predictions

The kinematic variables, such as S , produced by the theoretical calculations are derived using a non-relativistic basis. To have a realistic comparison of data with theory, we need to convert the non-relativistic S -curve of the theoretical calculations to the relativistic one. For the kinematics in which $\theta_{1,2} < 40^\circ$, it was already shown that the difference between the relativistic and non-relativistic S -curve is less than 2 MeV, and in comparison with the experimental bin size of S ($\simeq \pm 5$ MeV), it is negligible [50]. On the other hand, a different trend at large scattering angles ($\theta_2 > 100^\circ$) can be observed. The results show that the difference between the two S -curves is about 9 MeV, which is more than the experimental resolution of S which is around 7 MeV. Figure 5.1 shows the energy of proton 2 (E_2) as a function of S value for relativistic and non-relativistic regimes for configuration $(30^\circ, 127^\circ, 180^\circ)$. To proceed, a conversion between the two was performed by finding the closest point of (E_1, E_2) of the non-relativistic S -curve to a given relativistic (E_1, E_2) . Figure 5.2 shows one of the theoretical prediction before and after the relativistic correction of S . In this thesis, we performed the relativistic correction on S -curves of the theoretical calculations for the configurations in which $\theta_2 > 40^\circ$.

The experimental results are sorted in angular bins of $\Delta\theta$ and $\Delta\phi$. It is common to use the prediction at the central values of the angular bins to compare with the experimental results. This strategy is valid if the angular bins are small and the predictions do not vary significantly within the experimental bin sizes. In principle, one has to average the

theoretical predictions over the experimental bins. For the cases that $\theta_{1,2} < 40^\circ$, the average of the theoretical calculations does not show a significant difference from the calculations taking the center of the bin and, for most cases, this difference is less than 1% [50]. Figure 5.3 shows the results of averaging over the angular bins for some typical

Figure 5.1: The relativistic effect on the S -curve for configuration $(30^\circ, 127^\circ, 180^\circ)$. The energy of the scattered proton to $\theta = 127^\circ$ (E_2) is plotted as a function of S value for relativistic (black line) and non-relativistic (red line) calculations. In this configuration, the maximum difference in S between the two curves is about 9 MeV, which is larger than our experimental resolution of S .

Figure 5.2: The effect of the difference between non-relativistic and relativistic S -curves on the value of A_y with respect to S for configuration $(30^\circ, 127^\circ, 180^\circ)$. The red and black lines represent the results of A_y versus the non-relativistically and relativistically calculated values of S , respectively.

Figure 5.3: The averaged theory curves obtained by averaging over the experimental bin for a few kinematical configurations. For every panel, the red solid line shows the averaged cross section of the theoretical calculations and the black solid line represents the theoretical predictions for the center of the bin. The black curve is overlapping with the red one almost everywhere. Also, the predictions for some of the neighboring kinematics which are used in the averaging procedure are shown with different line styles. Figure is taken from Ref. [50].

configurations in which $\theta_{1,2} < 40^\circ$. Since the differences are significantly smaller than the experimental precision, we decided to use the calculations at the center of bins for these configurations. On the other hand, the angular resolution of the backward-ball is $\Delta\theta \approx \pm 10^\circ$ and $\Delta\phi \approx \pm 10^\circ$. Therefore, for the part of the phase space at which one proton scatters to the backward-ball, due to the wide angular bin sizes, the calculations based on the central points of the bins do not represent the data accurately. To perform averaging over the angular bins for calculations, we used a step size of 1° for θ_1 , 4° for θ_2 and 2° for ϕ_{12} . Considering the fact that the detectors of the backward-ball have a triangle surfaces, we defined each combination of (θ_2, ϕ_{12}) as a point on the surface of detectors. To avoid the effect of the geometrical shape on the averaging procedure, the number of points for each set of θ_2 are taken to be proportional to the width of the detector (ϕ) at each θ . Figure 5.4 illustrates the sub-configurations within a typical detector of the backward-ball. Therefore, for each non-coplanar (coplanar) kinematic, we exploited 125 (75) sub-configurations with a 1° step in θ_1 , 4° step in θ_2 , and 2° step in ϕ_{12} to perform the averaging.

For each sub-configuration, we obtained the results of the different theoretical models.

Figure 5.4: A sketch of the definition of sub-configurations or meshes within the angular acceptance of a typical detector of the backward-ball. Each red point represents a specific (θ_2, ϕ_{12}) . There are 25 points for each detector, and in combination with the 5 points in the range of $\theta_1 \pm 2.5^\circ$, we have 125 (75) sub-configurations for a non-coplanar (coplanar) configuration.

Then, for each value of S , the analyzing powers of the sub-configurations were averaged using a weighting factor of the cross section σ_n and the solid angle $\Delta\Omega_n$. In practice, we used the following formula to get the average of analyzing powers for each S value:

$$\bar{A}(\theta_1, \theta_2, \phi_{12}, S) = \frac{\sum_{n=1}^N A_n(\xi_n) \cdot \sigma_n(\xi_n) \cdot \Delta\Omega_n}{\sum_{n=1}^N \sigma_n(\xi_n) \cdot \Delta\Omega_n}, \quad (5.1)$$

where $\bar{A}$ is the average value of analyzing powers for a given $(\theta_1, \theta_2, \phi_{12}, S)$, $A_n(\xi_n)$ and $\sigma_n(\xi_n)$ are the values of analyzing power and differential cross section of the sub-configuration $\xi_n = (\theta_1^i, \theta_2^j, \phi_{12}^k, S)$, respectively. N is a number of sub-configurations of each main configuration. $\Delta\Omega_n$ is the solid angle of each sub-configuration. Figure 5.5 shows the result of averaging for four configurations at intermediate and large scattering angles of θ_2 . The top panels show A_y values at the center of angular bins together with the results of averaging. The sub-configurations which we used to get the average of A_y are shown using gray lines. The bottom panels are the corresponding cross sections of the configurations displayed in the top panels. It is clear that from Fig. 5.5 for the configuration $(30^\circ, 45^\circ, 180^\circ)$, the values of A_y and the cross section vary significantly within the angular

bins. Therefore, the calculations at the center of the angular bins differ from the average values of the results. On the other hand, the variation of the theoretical predictions for other cases in Fig. 5.5 is small, and the results of the averaging are in agreement with

Figure 5.5: A comparison between the results of the calculations using AV18 at the center of the angular bins and the results of averaging them over the angular bins for some typical configurations. The top four panels show A_y values and the bottom four panels show the corresponding cross sections. The red and black curves are the results of the calculations at the center of the angular bins and the average values, respectively. The values of the cross sections together with the cross angles are used as weighting factors for averaging the analyzing powers. The configuration $(30^\circ, 45^\circ, 180^\circ)$ is an example showing a significant variation of the theoretical prediction over the angular bin. For most of the cases of the phase space, the variation is smooth and the average values do not differ remarkably from the results of the calculations at the center of the angular bins.

Figure 5.6: The effect of the Coulomb interaction on the prediction of CDB+ Δ for A_y . The red line shows the prediction of CDB+ Δ and the green line shows the prediction of CDB+ Δ +C. The effect of the Coulomb interaction is smaller than the experimental precision for the configurations shown here.

the predicted values at the center of the angular bins. Although for most of the configurations there is not a significant difference between the average value and the one taken at in the center of the angular bins, we performed the averaging for all forward-backward configurations to have a consistent comparison between the data and the calculations.

In the present analysis, we do not compare the experimental results with a calculation based on CDB+ Δ +C potential due to the small effect of the Coulomb interaction on the analyzing powers. Figure 5.6 shows a comparison between CDB+ Δ and CDB+ Δ +C for some typical configurations in which $\theta_2 > 40^\circ$.

5.2 Analyzing powers

The experimental setup, BINA, covers a large part of the angular phase space of the break-up reaction. We obtained the analyzing powers for various kinematics at small, intermediate, and large scattering angles. The analyzing power A_y has already been extracted and reported using a different approach than the one we used here for a part of the phase space in which $\theta_{1,2} < 40^\circ$ [50]. In the present analysis, for the same part

of the phase space, the analyzing powers A_y and A_x are extracted using data from two polarization modes of the proton beam. Furthermore, the analyzing powers for the part of the phase space at which one proton scatters to forward angles ($\theta_1 < 40^\circ$) and the other to intermediate ($\theta_2 > 40^\circ$) and large scattering angles ($\theta_2 > 100^\circ$) are extracted for the first time in proton-deuteron break-up reaction at a beam energy of 190 MeV. Here, we will present the results in two parts. In the first part, all the analyzing powers of the configurations in which $\theta_{1,2} < 40$ (wall-wall coincidences) will be presented. In the second part, the results of the configurations in which $\theta_1 < 40^\circ$ and $\theta_2 > 40^\circ$ (wall-ball coincidences) will be presented.

Table 5.1 shows the parameters which are used to extract the analyzing powers of the break-up configurations in which $\theta_{1,2} < 40^\circ$. Figures 5.7-5.16 show the results of this part

Table 5.1: The experimental parameters and efficiencies which are used in the extraction of the break-up analyzing powers in the part of the phase space in which $\theta_{1,2} < 40^\circ$.

Beam particle	Polarized proton
Energy	190 MeV
Average beam current	10 pA
Average beam up-pol $p_z^\uparrow$	0.6
Average beam down-pol $p_z^\downarrow$	0.7
Target	Liquid deuterium
Target thickness	6.8 mm
Average efficiency of the MWPC for each proton	$97\% \pm 1\%$
Average live-time of the acquisition system	50%
Average hadronic reaction correction for each proton	$8\% \pm 3\%$
Angular coverage	$13^\circ < \theta_{1,2} < 30^\circ$
Geometrical inefficiencies caused by geometrical effects calculated using Geant-3,	
$\phi_{12} < 20^\circ \rightarrow$	$20\% \pm 7\%$
$\phi_{12} = 180^\circ \rightarrow$	$1\% \pm 2\%$
Bin sizes	
S bin size	$\Delta S = \pm 5$ MeV
Angular bin sizes	
$\theta_{1,2} < 28^\circ \rightarrow$	$(\Delta\theta = \pm 2^\circ, \Delta\phi = \pm 4^\circ)$
$\theta_{1,2} = 28^\circ \rightarrow$	$(\Delta\theta = \pm 1^\circ, \Delta\phi = \pm 4^\circ)$

of the break-up phase space. Each figure shows the analyzing powers for various relative azimuthal angles (ϕ_{12}) and fixed θ_1 and θ_2 . The top and the bottom panels of each figure show A_x and A_y as a function of S -value, respectively. For some configurations, we were not able to remove the background from the uncorrelated elastic-elastic and elastic-break-up unequivocally. These data points, which are generally located at $100 < S < 150$ MeV, were removed. To have a meaningful comparison with the calculations only data are presented for which the total systematic uncertainty is less than 0.08. This requirement

only excludes a small fraction of the data points ($\sim 0.2\%$). All the presented error bars are statistical. For the case of A_y , the results from Ref. [50] are shown in Figures 5.7-5.16 with open squares to enable a comparison between the results of the two different approaches. The main differences between the present analysis and the analysis from Ref. [50] are the size of the data sample, the method of obtaining the statistical errors, and the method that was used to extract the analyzing power A_y . For the extraction of the analyzing powers, most of the inefficiencies cancel out, and, we, therefore, can neglect the corresponding systematic uncertainties. In the present analysis, the beam polarization values for up and down modes are taken from Ref. [50]. Theoretical predictions of NN and NN+3NF from different models are presented in each panel together with the experimental measurements. The red solid (dashed) line represents CDB+ Δ (CDB) [19,92,93], and the blue solid (dashed) line represents AV18+UIX (AV18) [117–119]. For each configuration, all the theoretical calculations are obtained in the center of the angular bins.

Figure 5.7: The analyzing powers at $(\theta_1, \theta_2) = (15^\circ, 15^\circ)$ for a set of relative azimuthal angles, ϕ_{12} . The top and the bottom figures show A_x and A_y , respectively. The filled circles are the results of the present analysis. For A_y , the open squares are the data from Ref. [50] which we refer to as KVI_2007. The red solid and the red dashed lines show the results of the predictions of Faddeev calculations using CDB+ Δ and CDB [19, 92, 93], respectively. The blue solid and the blue dashed lines represent the results of the predictions of Faddeev calculations using AV18+UIX and AV18 [117–119], respectively. The experimental data points are obtained as a function of the relativistic values of S . However, the S values of the calculations are non-relativistic. The difference between non-relativistic and relativistic S value is less than 2 MeV which is negligible. The cyan band shows the systematic uncertainty (2σ).

Figure 5.8: Same as Fig. 5.7 except for $(\theta_1, \theta_2) = (20^\circ, 15^\circ)$.

Figure 5.9: Same as Fig. 5.7 except for $(\theta_1, \theta_2) = (20^\circ, 20^\circ)$.

Figure 5.10: Same as Fig. 5.7 except for $(\theta_1, \theta_2) = (25^\circ, 15^\circ)$.

Figure 5.11: Same as Fig. 5.7 except for $(\theta_1, \theta_2) = (25^\circ, 20^\circ)$.

Figure 5.12: Same as Fig. 5.7 except for $(\theta_1, \theta_2) = (25^\circ, 25^\circ)$.

Figure 5.13: Same as Fig. 5.7 except for $(\theta_1, \theta_2) = (28^\circ, 15^\circ)$.

Figure 5.14: Same as Fig. 5.7 except for $(\theta_1, \theta_2) = (28^\circ, 20^\circ)$.

Figure 5.15: Same as Fig. 5.7 except for $(\theta_1, \theta_2) = (28^\circ, 25^\circ)$.

Figure 5.16: Same as Fig. 5.7 except for $(\theta_1, \theta_2) = (28^\circ, 28^\circ)$.

The second part of the results corresponds to the configurations in which one proton scatters to the forward-wall and the other to the backward-ball. Since the angular resolution of the backward-ball is much worse than the MWPC of the forward-wall, we used different bin sizes to select data for this part of the break-up phase space. Table 5.2 shows the parameters that we used to extract the analyzing powers for the break-up configurations in which $\theta_1 < 40^\circ$ and $\theta_2 > 40^\circ$. Figures 5.17-5.24 show the analyzing powers as a

Table 5.2: The experimental parameters and efficiencies which are used to extract the analyzing powers for the break-up reaction in the part of the phase space in which $\theta_1 < 40^\circ$ and $\theta_2 > 40^\circ$. The other experimental parameters are presented in Table 5.1.

Down-scaling factor of the trigger T2	4
Angular coverage	$10^\circ < \theta_1 < 37^\circ$ $37^\circ < \theta_2 < 160^\circ$
Bin sizes:	
S bin size	$\Delta S = \pm 7.5 \text{ MeV}$
Angular bin sizes	
$\theta_1 \rightarrow$	$\Delta\theta = \pm 2.5^\circ$
$\theta_2 \rightarrow$	$\Delta\theta = \pm 10^\circ$
$\phi_{12} \rightarrow$	$\Delta\phi = \pm 10^\circ$

function of S value for the break-up configurations in which one of the protons scatters to $\theta_2 > 40^\circ$. Each figure shows the results of one of the ring in θ of the backward-ball and for different combinations of θ_1 and ϕ_{12} .

For $\theta_2 < 80^\circ$, we did not analyze the configurations in which $\phi_{12} < 140^\circ$ due to the dominant background from time-uncorrelated elastic-break-up events. These data points are generally located in the range of $100 < S < 150 \text{ MeV}$ depending on the configuration. Also, for some of the S values, the peak searching algorithm could not find a peak around the neutron mass. These data points are also not presented here. Moreover, the data points with systematic errors larger than 0.08 are not presented. The data points which are at the punch-through region are not presented either. These are located at $S < 50 \text{ MeV}$ for the configurations in which $\theta_2 < 80^\circ$.

For $\theta_2 > 100^\circ$, the configurations in which $\phi_{12} < 120^\circ$ are not analyzed because the S -curve goes below the energy threshold of the backward-ball detectors (15-20 MeV). Moreover, some of the coplanar configurations ($\phi_{12} = 180^\circ$) are not presented because the S -curve overlaps with the proton-deuteron elastic region, and therefore the break-up S -curve is dominated by events from the hadronic interaction of the elastic channel. The data points in which $S < 40 \text{ MeV}$ are close to the energy threshold of the backward-ball detectors and they are not presented here. To have a meaningful comparison with the calculations only data are presented for which the total systematic uncertainty is less than 0.08. This requirement only excludes a small fraction of the data points ($\sim 3\%$).

Figure 5.17: The analyzing powers for $\theta_2 = 45^\circ$ and different combinations of θ_1 and ϕ_{12} . The top and the bottom figures show the results of A_x and A_y , respectively. Each row shows the results for a specific θ_1 , and each column shows the result for a specific ϕ_{12} . The red solid and the red dashed lines show the results of the predictions of Faddeev calculations using CDB+ Δ and CDB [19, 92, 93], respectively. The blue solid and the blue dashed lines represent the results of the predictions of Faddeev calculations using AV18+UIX and AV18 [117–119], respectively. A relativistic correction is applied on S values of the calculations as it was described in section 5.1. The results of all the calculations were averaged over the experimental angular bins. The cyan band represents the systematic uncertainty (2σ).

Figure 5.18: Same as Fig. 5.17 except for $\theta_2 = 52^\circ$.

Figure 5.19: Same as Fig. 5.17 except for $\theta_2 = 67^\circ$.

Figure 5.20: Same as Fig. 5.17 except for $\theta_2 = 74^\circ$.

Figure 5.21: Same as Fig. 5.17 except for $\theta_2 = 106^\circ$.

Figure 5.22: Same as Fig. 5.17 except for $\theta_2 = 113^\circ$.

Figure 5.23: Same as Fig. 5.17 except for $\theta_2 = 127^\circ$.

Figure 5.24: Same as Fig. 5.17 except for $\theta_2 = 134^\circ$.

5.3 Global comparison between the data and theoretical predictions

Figures 5.7-5.24 present the results of measurements of the vector analyzing powers of proton-deuteron break-up reaction at a proton beam energy of 190 MeV. Since our detection system, BINA, has an almost 4π acceptance, we were able to measure fully exclusively the break-up reaction channel. We measured analyzing powers for 193 kinematical configurations and compared with the results of four different theoretical predictions with and without the inclusion of 3NF effects. In total, more than 2000 data points were obtained. To have a systematic comparison between data and calculations, we defined two global variables. The first one is the result of averaging over S values for both data and calculations for each set of $\xi = (\theta_1, \theta_2, \phi_{12})$ using the following formula:

$$\begin{aligned}\overline{A_x}(\xi) &= \frac{\sum_{i=1}^N w_i A_x^i(\xi)}{\sum_{i=1}^N w_i}, \\ \overline{A_y}(\xi) &= \frac{\sum_{i=1}^N w_i A_y^i(\xi)}{\sum_{i=1}^N w_i},\end{aligned}\tag{5.2}$$

where N is the number of the measured data points in each configuration and $A_x^i(\xi)$ and $A_y^i(\xi)$ are the measured analyzing powers at a specific S -value of that kinematic. w_i is the weighting factor, which corresponds to the squared inverse of the statistical uncertainty of each measured value of the analyzing powers ($\frac{1}{\sigma_i^2}$). This procedure was performed for averaging of the theoretical predictions with the same weighting factor, to have a realistic comparison between data and theory. The results of the averaging procedure are presented as a function of ϕ_{12} in Figures 5.25-5.27. The top and the bottom panels of Fig. 5.25 show the average values of A_x and A_y versus ϕ_{12} for the configurations in which $\theta_{1,2} < 40^\circ$, respectively. Similarly, Figures 5.26 and 5.27 show the average values of A_x and A_y for the configurations in which $\theta_1 < 40^\circ$ and $\theta_2 > 40^\circ$. In all the figures, the error bars are statistical. In each panel, the cyan band represents the systematic uncertainty. The lines depict the results of the same averaging procedure for the theoretical predictions as was performed for the experimental data points.

Another global variable is the average difference between data and different theoretical predictions. We obtained this variable for the analyzing powers by exploiting the following formulas:

$$\begin{aligned}\Delta A_x(\xi) &= \frac{\sum_{i=1}^N (A_x^{exp}(\xi, S_i) - A_x^{theo}(\xi, S_i)) w_i}{\sum_{i=1}^N w_i}, \\ \Delta A_y(\xi) &= \frac{\sum_{i=1}^N (A_y^{exp}(\xi, S_i) - A_y^{theo}(\xi, S_i)) w_i}{\sum_{i=1}^N w_i},\end{aligned}\tag{5.3}$$

where $A_x^{exp}(\xi, S_i)$ and $A_x^{theo}(\xi, S_i)$ are the experimental and theoretical values of A_x at S_i for each combination of $\xi = (\theta_1, \theta_2, \phi_{12})$, respectively. $A_y^{exp}(\xi, S_i)$ and $A_y^{theo}(\xi, S_i)$ are the experimental and theoretical values of A_y at S_i for each combination of $\xi = (\theta_1, \theta_2, \phi_{12})$, respectively. N is the number of data points for each configuration. $\Delta A_x(\xi)$ and $\Delta A_y(\xi)$ are the average differences between data and theory for A_x and A_y , respectively. The data are plotted in Figures 5.28-5.30 as a function of ϕ_{12} for each set of (θ_1, θ_2) . The lines depict the average deviation of each theoretical prediction from the experimental results. The error bars are shown only for CDB+ Δ , which are the same for all the other lines. The cyan band represents the systematic uncertainty (2σ).

Figure 5.25: The average of the analyzing powers over the S values for the part of the phase space in which $\theta_{1,2} < 40^\circ$. The top and the bottom figures show the results of A_x and A_y , respectively. The different lines show the average results of various theoretical predictions which are described in the legend. The error bars are statistical, and the cyan band shows systematic uncertainty (2σ). Each row shows the results for a fixed θ_1 and varying θ_2 , and each column shows the results for a fixed θ_2 and varying θ_1 .

Figure 5.26: Same as Fig. 5.25 except for $40^\circ < \theta_2 < 80^\circ$.

Figure 5.27: Same as Fig. 5.25 except for $100^\circ < \theta_2 < 140^\circ$.

Figure 5.28: The average deviation between data and various theoretical predictions for the part of the phase space in which $\theta_{1,2} < 40^\circ$. The top and bottom figures show the results of A_x and A_y , respectively. Each line represents the deviation from each model that is described in the legend. The statistical error bars are only shown for CDB+ Δ and they are the same for the other lines. The cyan band depicts systematic uncertainty (2σ). The horizontal green line shows the zero line.

Figure 5.29: Same as Fig. 5.28 except for $40^\circ < \theta_2 < 80^\circ$.

Figure 5.30: Same as Fig. 5.28 except for $100^\circ < \theta_2 < 140^\circ$.

5.4 Discussion

In the previous section, we presented a large set of analyzing powers of the proton-deuteron break-up reaction at a proton-beam energy of 190 MeV together with the results of various theoretical calculations. In this section, we will give a global comparison between the experimental results and the theoretical predictions.

For the kinematical configurations in which $\theta_{1,2} < 40^\circ$, the agreement between data and theory for A_x and A_y is different. The results reveal a relatively good agreement between data and the theoretical predictions for A_x for most of the kinematics of this part of the phase space; see the top panels of Fig. 5.25. However, for some kinematics, the two 3NF models provide different values for A_x at the intermediate values of ϕ_{12} ; see the top panels of Fig. 5.28. Considering the statistical and systematic uncertainties, our measurement cannot differentiate between these models. On the other hand, the data and calculations of A_y do not agree with each other especially at smaller values of ϕ_{12} . One can see this trend in the bottom panel of Fig. 5.25. Also, at small values of ϕ_{12} , the theoretical models predict a large 3NF effect. But the inclusion of these 3NFs increases the disagreement between data and calculations for A_y compared to calculations of pairwise NN models. At larger values of ϕ_{12} where the 3NF effects are expected to be small, the theoretical predictions are in relatively good agreement with data. This effect was also observed in the earlier analysis and also for a proton beam energy of 130 MeV [50, 51].

At intermediate scattering angles ($40^\circ < \theta_2 < 80^\circ$), the results reveal an agreement between data and the theoretical predictions for A_x at larger values of θ_1 and ϕ_{12} ; see the top panels of Fig. 5.26. For the kinematics at which $\theta_1 < 25^\circ$ and $\phi_{12} < 180^\circ$, the data and the theoretical predictions for A_x are not in agreement. Also, for most of the kinematics at which $\theta_1 < 25^\circ$, the data and the theoretical predictions for A_y are not in agreement; see the bottom panels of Fig. 5.26. At larger values of θ_1 , the agreement between data and theory becomes better.

For most of the presented configurations at large scattering angles ($\theta_2 > 100^\circ$), the results show a good agreement between data and the theoretical predictions for A_x ; see the top panels of Fig. 5.27. At this part of the phase space, the 3NF effects are expected to be small for A_x according to the CDB+ Δ model. However, in some cases, the AV18+UIX shows a larger 3NF effect. For A_y , the 3NF effects are predicted to be larger than for A_x . For some kinematics in which $\theta_2 = 106^\circ$, the inclusion of 3NFs improves the agreement between data and calculations for A_y ; see the first row of the bottom panel of Fig. 5.27. For kinematics at which $\theta_2 = 127^\circ$, the two different 3NF models predict different values for A_y at this part of the phase space; see the third row of the bottom panel of Fig. 5.27. However, the predictions of AV18+UIX show a better agreement with data for A_y compared to the other presented theoretical predictions. Figure 5.31 illustrates comprehensively the analyzing powers measurements for pd break-up reaction at a beam energy of 190 MeV. All the results are averaged over S -value and presented as a function of ϕ_{12} .

Figure 5.31: The average of the analyzing powers over S as a function of ϕ_{12} for all the analyzed configurations in the present work.

Figure 5.32: The results of averaging of the analyzing powers as a function of θ_2 . The top (bottom) figure shows the results of A_x (A_y). The filled circles represent the data. The red (blue) dashed lines show the predictions of CDB (AV18) and the red (blue) solid lines depict the predictions of CDB+ Δ (AV18+UIX). The error bars are only statistical. The cyan band represents the systematic uncertainty (2σ).

To study the variation of analyzing powers as a function of θ , the results from averaging are extracted as a function of θ_2 for different sets of (θ_1, ϕ_{12}) , as it is shown in Fig. 5.32. For A_x , the theoretical predictions are in agreement with the data except for $\theta_1 < 25^\circ$ and intermediate angles of θ_2 ; see the top panel of Fig. 5.32. For A_y , the theoretical predictions are in agreement with the data except for a few parts of the phase space. At intermediate values of θ_2 for $(\theta_1 = 15^\circ, \phi_{12} = 140^\circ)$ and $(\theta_1 = 15^\circ, \phi_{12} = 160^\circ)$, data and theory differ from each other; see the first row of the bottom panel of Fig. 5.32. Generally, the agreement between data and theoretical predictions becomes better at larger values of ϕ_{12} and θ_1 .

A global comparison between data and theory as a function of relative energy between two outgoing protons (E_{rel}^{pp}) is shown in the left panels of Fig. 5.33. The relative energy

Figure 5.33: The differences between data and calculations for all extracted data points of the proton-deuteron break-up reaction taken with a proton beam of 190 MeV. All the deviations are weighted using the statistical uncertainties (σ) of each data point. In the left panels, the deviations between data and AV18+UIX are plotted as a function of relative energy between the two outgoing protons for A_x (top-left panel) and A_y (bottom-left panel). In the right panels, the difference between experimental data and calculations are shown with only AV18 as a 2NF example (x -axis) and with AV18+UIX as a NN+3NF example (y -axis). The top-right and the bottom-right panels show the results for A_x and A_y , respectively. For the discussion of the figures, see the text.

between two outgoing protons for pd break-up reaction is defined as:

$$\begin{aligned} S_{pp} &= (P_1 + P_2)^2; \\ E_{rel}^{pp} &= \sqrt{S_{pp}} - 2m_p, \end{aligned} \quad (5.4)$$

where S_{pp} is the total 4-momenta of the two outgoing protons. P_1 and P_2 are the 4-momenta of the two protons. m_p is the mass of the proton beam and E_{rel}^{pp} is the relative energy between two outgoing protons. The deviation between data and theory is normalized using the statistical errors (σ) of the data points. The result reveals that the deviation between data and theory becomes larger at the lower values of relative energies between the two outgoing protons for A_y . Also, there is a deviation between data and theory at larger values of relative energy between the two outgoing protons ($E_{rel}^{pp} > 50$ MeV). These part of the data corresponds to intermediate and large scattering angles of θ_2 .

A global comparison between the effect of adding 3NF in calculations are presented in the right panels of Fig. 5.33. For A_x , a large number of data points reside around (0,0) indicating that the 2NF is already sufficient to describe the data reasonably well and that the effect of the 3NF is small; see the top-right panel of Fig. 5.33. A fraction of the data points are distributed at the lower part of the diagonal line which means that both NN and NN+3NF calculations overestimate the data. A fraction of the data points reside on the upper part of the diagonal line close to crossing point and bend off from the diagonal indicating that the addition of the 3NF makes the agreement better. However, at lower part of the crossing point, the band bend away from the diagonal line towards the vertical line indicates that the 3NF makes the agreement even worse.

For A_y , a large number of data points reside around (0,0) indicating that the 2NF is already sufficient to describe the data reasonably well and that the effect of the 3NF is small; see the bottom-right panel of Fig. 5.33. A fraction of the data points are distributed at the lower part of the diagonal line which means that both NN and NN+3NF calculations overestimate the data. According to the present models, the effect of the 3NF is predicted not to be large, however, there is a slight tendency towards repairing the deficiencies. A fraction of the data points reside on the upper part of the diagonal line close to the crossing point, and bend away from the diagonal line indicating that the addition of the 3NF makes the agreement even worse.

To perform a statistical analysis of the overall (dis)agreement between data and theory, the presented data in the left panels of Fig. 5.33 are projected onto the y -axis. We also performed a similar analysis using the model based on CDB+ Δ . Figure 5.34 shows the result of this projection for A_x and A_y and the two different NN+3NF models. These distributions are subsequently fitted to a function composed of two Gaussians to extract their means, widths and strengths. For both A_x and A_y , one observes that a fraction of the data can be well described by a Gaussian with the expected mean close to zero and a standard deviation close to one, representing the configurations for which the model is doing a good job within the statistical error that has been achieved by the experiment. This also lends confidence to our understanding of statistical and systematical uncertainties of the measurements. Moreover, the fraction of the configurations that are not well described by the model estimated and represented by the second Gaussian, is remarkably different between A_x and A_y . Taking the fraction of configurations which fall within $\pm 3\sigma$ of the

Figure 5.34: The normalized differences between data and the results of two different NN+3NF models. A function of two Gaussians is fitted to the points. The curves represent the best fit results, whereby the green (red) curves correspond to the first (second) Gaussian. The blue curves is the sum of both. The top (bottom) panels show the results of A_x and A_y for AV18+UIX (CDB+ Δ). The fit parameters of the two Gaussians are shown in the top right of each panel.

peak position (of the main Gaussian), one can observe that a very large fraction ($\approx 97\%$) of the configurations are well described by the model for A_x . For A_y , this fraction amounts to 90%, indicating that for a large number of configurations ($\approx 10\%$), there are significant deviations between the data and the model predictions. This conclusion is independent of the model used in the analysis. It appears that the model deficiencies show up predominantly in A_y and not in A_x . The A_y -puzzle at low energies observed earlier, confirmed by these data at other configurations, are not seen in A_x . This should be further investigated by the theorists to see which terms in their potentials are sensitive to A_y and lack sensitivity in A_x . From an experimental point of view, the new data provide new constraints that help in updating future 3NFs.

6. Summary and outlook

In this thesis, we reported on the results of a comprehensive study of the proton-deuteron break-up reaction using a polarized proton beam with an energy of 190 MeV to explore the three-nucleon force effects. This is part of a systematic effort to understand the nuclear force through measuring nucleon-nucleon, nucleon-deuteron, and deuteron-deuteron scattering observables at KVI [11, 42, 53, 54, 57, 110]. Beyond the NN interaction, other dynamics such as three-nucleon force (3NF), relativistic, and Coulomb effects are predicted to play a role in the studies of the nuclear force. The elastic channel has a limited kinematical phase space and one cannot test all the aspects of the theoretical models. In spite of its limitations, several measurements of the elastic scattering observables have revealed that the present models of the nuclear force are not able to describe data at large center-of-mass scattering angles and at higher energies [10–12]. To have a systematic and a detailed investigation of 3NFs, the three-body break-up channel is a suitable candidate because of its rich kinematical phase space yielding various degrees of sensitivity to the three-nucleon forces and other underlying dynamics. On the other hand, conducting this kind of experiments is difficult. First of all, calculating break-up observables forms a challenge on the theoretical side. Secondly, to have a complete picture of the nuclear force through the break-up reaction, one needs to probe the whole kinematical phase space of this reaction channel which imposes an experimental challenge.

A systematic investigation of 3NFs through the break-up reaction has been initiated at KVI in a common effort between the Dutch and the Polish groups in the middle of 1990s by developing various experimental setups and exploiting high-quality polarized beams [11, 55, 56, 58, 120, 121]. BINA¹ is the latest experimental setup which was exploited at KVI for few-nucleon scattering experiments. It consists of two main parts, the forward-wall which covers the forward angles $10^\circ < \theta < 35^\circ$ and the backward-ball which covers the backward angles in which $\theta > 40^\circ$. The setup has an almost full coverage of the azimuthal angle, ϕ . In the forward-wall, the scattering angles of the particles are measured using a multi-wire proportional chamber with a high resolution resulting in a precision of $\pm 0.5^\circ$. The backward-ball is a spherical array of 149 pyramid shape plastic scintillators with a triangle surface. Each scintillator is connected to a photomultiplier tube. All the detectors are glued to each other with a special technique to tolerate the high vacuum inside. The position of each detector is associated with a θ and ϕ in the laboratory coordinate system. Therefore, the scattering angles of particles impinging the backward ball can be measured with a precision of $\pm 10^\circ$.

Various measurements on pd and dd break-up reactions have been conducted using BINA at different polarized beam energies to extract the cross sections and the analyzing powers [50–52]. In this work, we focused on the break-up kinematics in which one proton scatters to forward angles ($\theta_1 < 40^\circ$) and the other to backward angles ($\theta_2 > 40^\circ$).

¹ Big Instrument for Nuclear-polarization Analysis

Moreover, we reanalyzed the part of the phase space in which $\theta_{1,2} < 40^\circ$. This part of the phase space was already analyzed [50] but only for A_y and the cross section. Here, we used a different approach to extract both A_x and A_y . The results of this part of the phase space are presented in Figures 5.7-5.16. The fair agreement between the present results and those from Ref. [50] indicates the reliability of our analysis procedure. Except for the symmetric configurations ($\theta_1 = \theta_2$) and small relative azimuthal angle ($\phi_{12} \leq 20^\circ$), the data and theory are in agreement with each other. Moreover, the cross sections are also extracted for this part of the phase space and compared with those from the previous analysis. Here, we used a different model to subtract the background compared to the procedure that was used in the previous analysis. [50]. Our analysis showed a sensitivity of the measured cross sections to the choice of the background model resulting in an additional systematic uncertainty that was not considered in the previous study. An overview of the obtained cross sections are presented in Appendix A.

To extend the analysis of break-up reaction to the intermediate and large scattering angles, all the constituent detectors of the backward-ball were calibrated. Some of the detectors which were disconnected or noisy were excluded from the analysis. For each configuration, the events are selected within the angular bins of $(\theta_1 \pm 2.5^\circ, \theta_2 \pm 10^\circ, \phi_{12} \pm 10^\circ)$. Each S -curve was divided into 15 equal sized S -bins and the number of events in each S -bin are used to extract the observables. We limited our analysis to the part of the backward-ball which corresponds to $40^\circ < \theta < 80^\circ$ and $100^\circ < \theta < 140^\circ$. This part of the break-up phase space at this beam energy is analyzed for the first time. The part of the backward-ball corresponding to $80^\circ < \theta < 100^\circ$ is excluded from the analysis due to the shadow of the target holder. The main focus of our analysis was on the large relative azimuthal angles between the two outgoing protons ($\phi_{12} > 100^\circ$). For the forward-backward break-up kinematics, we analyzed 97 configurations to extract the vector analyzing powers. Figures 5.17-5.24 show the results together with theoretical predictions based on various NN and NN+3NF potentials. We compared data with the theoretical predictions of CDB, CDB+ Δ , AV18, and AV18+UIX which were averaged over the experimental angular bins. Note that our measured values for A_x for coplanar configurations ($\phi_{12} = 180^\circ$) are compatible with zero. This is consistent with expectations based on parity conservation and, therefore, shows that our analysis method is reliable. The feasibility of extracting the cross section for these configurations was also investigated. To extract cross sections with sufficiently good accuracy, one needs to perform a thorough efficiency study using extensive Monte Carlo simulations and a dedicated analysis. Due to the lack of time, we did not extract the cross sections for this part of the phase space.

Our results revealed different degrees of (dis)agreement between data and theory at different parts of the phase space. The 3NF effects are expected to be small at configurations in which $40^\circ < \theta_2 < 80^\circ$ and at large azimuthal opening angles ϕ_{12} . For these configurations, the theoretical predictions are also in good agreement with the data. The results presented here mainly correspond to larger values of the relative energy (> 50 MeV) between the two final-state protons. At large scattering angles of the second proton, $\theta_2 > 100^\circ$, the theoretical predictions are in agreement with the data. The two 3NF models predict different analyzing powers at some kinematics. With the precision of the present experiment, one can, however, not distinguish between these models. The proton-deuteron break-up analyzing powers at intermediate and large scattering angles at this

energy are presented for the first time. We probed almost all the phase space of the pd break-up reaction to investigate the 3NF effects.

In the analysis, we faced some problems which stem from the features of BINA. For the configurations in which $40^\circ < \theta_2 < 80^\circ$, a major fraction of the protons resulting from the break-up reaction scattered to the forward-wall with energies larger than 140 MeV. Since the thickness of the E-scintillators of the forward-wall is not enough to stop these high-energy protons they deposit part of their energies in the scintillators and punch through from the detectors. Because of the complication of correcting the energies of these protons, the results of this part of the kinematics are not presented in this thesis. These events belong mainly to $S < 50$ MeV. The defined trigger for the forward-backward break-up configurations is the same as we used for the elastic channel. Because of that, the trigger unit has a high probability to accept time-uncorrelated elastic-break-up elastic events. These events create a strong background in the configurations in which $40^\circ < \theta_2 < 80^\circ$ and for lower values of ϕ_{12} . Therefore, we excluded the configurations in which $\phi_{12} < 140^\circ$ from the analysis. For larger values of ϕ_{12} , this background appears at the middle of S -curve. We also excluded this part of the S -curve from the analysis for some of the configurations. Another challenge that we faced during the analysis was to determine the effect of the target holder and other equipments in the backward-ball on the energy measurement of particles. We exploited Geant-3 simulations to check which parts of the backward-ball are affected by the target holder. We found that the protons that hit a large fraction of detectors in the region $80^\circ < \theta < 100^\circ$ suffered from two distinct energy losses whereby some of the protons passed the target holder and some not. This made it impossible to perform an energy calibration for those detectors. Also, a few detectors in the regions of $60^\circ < \theta < 80^\circ$ and $100^\circ < \theta < 110^\circ$ suffered from the same problem. These detectors were, therefore, excluded from the analysis.

The present analysis provides an almost 4π study of the proton-deuteron break-up reaction studied at a beam energy of 190 MeV. Due to the lack of experimental data of break-up observables, this set of data enhances the database of the three-body break-up observables and provides a unique basis to examine theoretical approaches in the field of nuclear force studies. Our measurements indicate that the present models cannot describe the spin observables at the part of the break-up phase space which corresponds to the low relative energies between the two outgoing protons. The phenomenological 3NF models, which we used in this thesis, improve the comparison between data and calculations at some kinematics and at some cases worsen it. Performing comprehensive studies to measure different break-up observables at different beam energies can lead to a better understanding of the nuclear force. On the experimental part, we still need to measure the cross sections of the break-up reaction at the intermediate and large scattering angles. Also, due to technical constraints at the time that the experiment was conducted, we could not analyze part of the data in which one of the protons scattered to $80^\circ < \theta_2 < 100^\circ$. One needs to investigate this part of the break-up phase space as well. Moreover, the data from the part of the pd break-up phase space in which both protons scatter to the intermediate and large scattering angles are lacking. In the present experiment, we had no suitable trigger to cover this part of the phase space. Designing experiments in such a way that one can investigate this part of the phase space is recommended.

Nederlandse samenvatting

Het begrijpen van de exacte aard van de drie-nucleon interactie is één van de meest uitdagende problemen binnen de kernfysica. De drie-nucleon splijtingsreactie is een goede manier om inzicht te krijgen in de onderliggende principes van de sterke kernkracht. Dit komt door de grote kinematische fase-ruimte, die verschillende niveau's van gevoeligheid kent voor de verschillende effecten van de drie-nucleon interactie. De recente onderzoeken van atoomkernen met slechts een paar nucleonen hebben aangetoond dat de huidige modellen voor de sterke kernkracht ontoereikend zijn in het nauwkeurig voorspellen van experimenteel gemeten observabelen in nucleon-deuteron verstrooiing. In dit proefschrift worden de analyserende vermogens besproken van een door middel van een 190 MeV gepolariseerde-proton geïnduceerde proton-deuteron splijtingsreactie. De vector analyserende vermogens van deze reactie worden voor het eerst gepresenteerd voor de situatie waar één van de protonen verstrooit naar middelgrote en grote hoeken.

Yukawa presenteerde de eerste systematische methode voor het beschrijven van de nucleon-nucleon (NN) interactie naar het model dat wordt gebruikt voor het beschrijven van de elektromagnetische interactie [2]. Zijn methode was gebaseerd op het idee dat protonen en neutronen fundamentele deeltjes zijn. Om die reden bevatten Yukawa's potentialen binnen de atoomkern alleen vrijheidsgraden voor nucleonen en voor mesonen. Verschillende NN potentialen zijn gedurende de laatste decennia ontwikkeld. Deze zijn vaak vernoemd naar de onderzoeksgroep die ze heeft ontwikkeld, zoals de Nijmegen [4], AV18 [5], CD-Bonn [6], etc.. Elk van deze modellen bevatten verschillende parameters die experimenteel moeten worden vastgesteld met behulp van de pp en np verstrooiings database. Deze modellen werken goed voor twee-nucleon systemen beneden de pion-productiegrens, maar falen voor systemen met meer dan twee nucleonen. Het is nu duidelijk dat er in zulke systemen meer aan de hand is dan slechts een optelsom van de nucleon-nucleon interacties. Deze effecten staan bekend als veel-lichamen interacties. Wij verwachten dat de drie-nucleon interactie (3NF) de grootste bijdrage levert aan deze veel-lichamen interacties. Gedurende de laatste decennia zijn verschillende fenomenologische 3NF modellen ontwikkeld, zoals Urbana-Illinois (UIX) [17, 18], CD-Bonn+ Δ [90, 92, 93], en TucsonMelbourne [16, 122]. Deze modellen zijn gebaseerd op het werk van Fujita en Miyazawa [13] en op dat van Brown en Green [14] door de 3NF effecten te implementeren in de nucleon interacties.

Gedurende de afgelopen decennia is de elastische Nd verstrooiingsreactie bestudeerd voor verschillende bundelenergieën lager dan de pion-productiegrens. Deze resultaten tonen aan dat de huidige 3NF modellen het verschil tussen de meetwaarden en de theoretische

voorspellingen niet kunnen verklaren. Vooral de situaties voor hogere bundelenergieën, rond het minimum van de differentiële dwarsdoorsnede en voor verstrooiingshoeken richting 180° zijn moeilijk te beschrijven met deze modellen. De elastische reactie heeft een begrensde kinematische faseruimte, waardoor niet alle aspecten van de theoretische modellen kunnen worden getoetst. Voor een gedetailleerde en systematische studie van de 3NF is een drie-lichaam splijtingsreactie beter geschikt. Deze reactie heeft een rijke kinematische fase-ruimte met vele gradaties voor het meten van de onderliggende nucleon-nucleon en drie-nucleon interacties.

Een systematische studie van de 3NF door middel van het bestuderen van elastische reacties en splijtingsreacties is opgezet door het KVI in samenwerking met Nederlandse en Poolse onderzoeksgroepen sinds het eind van de negentiger jaren van de vorige eeuw. Onderdeel van dit samenwerkingsverband is het ontwikkelen van verschillende experimentele opstellingen die gebruik maken van hoogwaardige gepolariseerde bundels [11, 55, 56, 58, 120, 121]. BINA (Big Instrument for Nuclear-polarization Analysis) is de nieuwste experimentele setup ontwikkeld en gebruikt door het KVI voor het bestuderen van verstrooiingsreacties waar slechts enkele nucleonen bij betrokken zijn. BINA is ontworpen als een 4π detectiesysteem voor het bestuderen van de sterke kernkracht in (kleine) atoomkernen door middel van de volledige detectie van drie-nucleon en vier-nucleon verstrooiingsreacties en splijtingsreacties. BINA bestaat uit twee hoofdonderdelen: de voorwaartse muur en de achterwaardse bol. Het linker gedeelte van Fig. 1 toont deze verschillende delen van BINA. De voorwaartse muur bestaat uit een verzameling van scintillatoren (E -detectoren) die een gedeelte van een cylinder vormen, voor het meten van de energie van geladen deeltjes, uit een MWPC voor het meten van hun verstrooiingshoeken met een precisie van $\pm 0.5^\circ$ en uit een verticale verzameling van ΔE -detectoren. De ΔE -detectoren worden gebruikt voor de identificatie van de deeltjes in combinatie met de E -detectoren. De achterwaardse bol is een bolvormige verstrooiingskamer die bestaat uit 149 piramide-vormige plastic scintillatoren. Het geometrische ontwerp van de bouwstenen van de achterwaardse bol (de scintillatoren) lijkt erg op dat van een traditionele voetbal. De positie van elke scintillator in de achterwaardse bol wordt gemarkeerd door een specifieke waarde van θ en ϕ in het LAB coördinatenstelsel. De achterwaardse bol kan de verstrooiingshoek van de deeltjes meten met een precisie van $\pm 10^\circ$. Het rechter gedeelte van Fig. 1 toont de structuur van de achterwaardse bol en van de posities van de individuele detector elementen daarin.

De proton-deuteron splijtingsreactie geeft een eindtoestand van drie deeltjes: twee protonen en een neutron. De eindtoestand wordt kinematisch beschreven door negen variabelen: (θ_i, ϕ_i, E_i) (i markeert het deeltjes in de eindtoestand). Behoud van energie en impuls reduceert dit aantal tot vijf onafhankelijke variabelen. Deze dienen allemaal gemeten te worden om de eindtoestand volledig te beschrijven. BINA is in staat om de energie en de verstrooiingshoek van beide protonen tegelijk te meten. Dat betekent dat de proton-deuteron splijtingsreactie nog een ongespecificeerde vrijheidsgraad over heeft. In een splijtingsreactie die leidt tot drie deeltjes, wordt de configuratie van de eindtoestand traditioneel gespecificeerd als $(\theta_1, \theta_2, \phi_{12} = |\phi_2 - \phi_1|)$. ϕ_{12} staat hier voor de azimutale hoek tussen deeltje 1 en 2 (proton 1 en 2 in onze situatie). Volgens het formalisme van de S -curve wordt er nu een variabele S gedefinieerd als de booglengte langs de curve van toegestane waarden van de ongespecificeerde vrijheidsgraad. Het startpunt van S is het

punt op de curve waar één van beide protonen een minimale kinetische energie heeft. In dit proefschrift wordt een conventie gehanteerd waarbij het startpunt (minimale S -waarde) ligt bij een minimale energie E_2 en toeneemt in de tegengestelde richting van de klok (dit wordt geïllustreerd in Fig. 2). Het aantal meetpunten is verkregen voor elke spin- en pariteitstoestand door gebruik van het corresponderende spectrum van ‘vermiste’ massa nadat de achtergrond is verwijderd (zie het bovenste gedeelte van Fig. 2).

Wij hebben de analyserende vermogens A_x and A_y gemeten voor 193 verschillende kinematische configuraties, waaronder kleine, middelgrote en grote verstrooiingshoeken en we hebben deze vergeleken met verschillende theoretische voorspellingen. Voor sommige voorspellingen zijn de 3NF effecten meegenomen en voor andere niet. In totaal zijn meer dan 2000 datapunten verkregen. Vanwege dit grote aantal hebben we een globale analyse uitgevoerd om deze datapunten te vergelijken met de theoretische voorspellingen. Het verschil tussen de datapunten en de voorspellingen is bestudeerd als functie van het relatieve energieverschil tussen de twee protonen in de eindtoestand. Dit relatieve energieverschil is gedefinieerd als:

Figuur 1: Het linker gedeelte toont de structuur en onderdelen van BINA (Big Instrument for Nuclear-polarization Analysis), samen met de verstrooiingshoeken die met die onderdelen kunnen worden gemeten. Het rechter gedeelte toont de gedeeltelijk gemonteerde achterwaartse bol (boven) en de hoekdefinitie horende bij een typische detector uit de achterwaartse bol (onder). De centroide van elke detector in de achterwaartse bol wordt beschouwd als de positie van die detector (zie de zwarte punten in de figuur rechtsonder).

Figuur 2: De kinematisch toegestane relatie tussen de energieën van de twee protonen van de drie-deeltjes splijtingsreactie: de S -curve. De getoonde curve correspondeert met $\theta_1 = 25^\circ, \theta_2 = 45^\circ, \phi_{12} = 160^\circ$ in de experimentele data. In deze analyse hebben we het minimum van E_2 genomen als het startpunt van de S -curve. De protonen met een energie lager dan 140 MeV dringen door de E-detectors van de voorwaartse muur heen en deponeren slechts een deel van hun energie in deze detectors. Dit resulteert in een knik in het spectrum. De gestreepte lijn toont de definitie van een typisch S -bin voor $S = 127$ MeV. Het gedeelte rechtsboven toont het gereconstrueerde ‘vermiste’ massaspectrum voor de metingen binnen dit S -bin. De blauwe lijn toont het totale spectrum en de rode lijn toont de geschatte achtergrond. De groene lijn toont de metingen van de splijtingsreactie na verwijdering van de achtergrond. De verticale gestreepte zwarte lijnen tonen het integratie-interval.

$$\begin{aligned} S_{pp} &= (P_1 + P_2)^2; \\ E_{rel}^{pp} &= \sqrt{S_{pp}} - 2m_p, \end{aligned} \tag{1}$$

waar S_{pp} staat voor het de som van de vierdimensionale impulsvectoren van de twee protonen. P_1 en P_2 staan voor de afzonderlijke vierdimensionale impulsvectoren van deze protonen. m_p staat voor de massa van het proton en E_{rel}^{pp} staat voor het relatieve energieverval tussen de twee protonen in de eindtoestand. Het genormaliseerde verschil tussen de datapunten en de theoretische voorspellingen wordt getoond in het linker gedeelte van

Figuur 3. Een globale vergelijking tussen het wel en niet toevoegen van de 3NF effecten in de theoretische voorspellingen wordt getoond in het rechter gedeelte van Figuur 3.

Voor het uitvoeren van een statistische analyse op het globale verschil tussen de datapunten en de theoretische voorspellingen wordt de getoonde data in het linkergedeelte van Figuur 3 geprojecteerd op de y -as. Een vergelijkbare analyse is uitgevoerd voor het model gebaseerd op CDB+ Δ . Figuur 4 toont het resultaat van deze projectie voor A_x en A_y en de twee verschillende NN+3NF modellen. De uitkomsten zijn vervolgens gefit aan de som van twee Gaussische verdelingen en de gemiddelden, standaardafwijkingen en oppervlaktes van deze Gaussische verdelingen zijn bepaald. Voor zowel A_x als A_y blijkt dat een deel van de data goed beschreven kan worden door één Gaussische verdeling met een gemiddelde dicht bij nul en een standaardafwijking dicht bij één. Dit gedeelte van de data is het deel waar de theoretische voorspelling binnen de statistische foutenmarge van de experimentele datapunten valt. Deze conclusie wekt vertrouwen dat onze afschattingen van de statistische en systematische foutmarges in de metingen realistisch zijn. Daarnaast kan het deel van de data dat niet onder de eerste Gaussische verdeling valt goed worden beschreven met een tweede Gaussische verdeling. Deze tweede Gaussische verdeling is opvallend verschillend voor A_x en A_y . Als we kijken naar het deel van de data binnen een interval van $\pm 3\sigma$ rond de piek-positie (het gemiddelde van de eerste Gaussische verdeling), dan kunnen we de conclusie trekken dat een zeer groot deel van de data (ongeveer 97%) goed wordt beschreven door de theoretische voorspellingen voor A_x . Voor A_y is dit ongeveer 90%, wat suggereert dat voor een groot deel van de data een significantie afwijking bestaat tussen de datapunten en de theoretische voorspellingen. Deze conclusie is onafhankelijk van de het model dat in de analyse is gebruikt. Het lijkt er daarom op dat de tekortkomingen van de theoretische modellen zich vooral manifesteren in A_y en niet in A_x . Deze A_y -puzzel die ook bij lage energieën is geconstateerd, is bevestigd door onze data in andere configuraties en manifesteert zich niet voor A_x . Dit verschijnsel dient verder te worden bestudeerd by theoretici, zodat zijn kunnen vaststellen welke termen in hun potentialen wel bijdragen aan A_y , maar niet aan A_x . Vanuit een experimenteel oogpunt levert onze data nieuwe richtlijnen op waar toekomstige 3NF modellen aan zullen moeten voldoen.

Figuur 3: De verschillen tussen de data en de theoretische voorspellingen voor alle verkregen datapunten in de proton-deuteron splijtingsreactie geïnduceerd door een protonenbundel van 190 MeV. Alle afwijkingen zijn gewogen met de statistische onzekerheden (σ) van elk punt. In de linker figuren worden de afwijkingen tussen de data en AV18+UIX getoond als functie van de relatieve energie tussen de twee protonen in de eindtoestand. Het figuur linksboven toont A_x en het figuur linksonder toont A_y . In de rechterfiguren wordt het verschil tussen de datapunten en de theoretische voorspellingen op basis van alleen AV18 (x -as), als voorbeeld van een 2NF voorspelling, geplot tegen het verschil met AV18+UIX als voorbeeld van een NN+3NF voorspelling (y -as). Het figuur rechtsboven toont A_x en het figuur rechtsonder toont A_y . Voor de details over deze figuren, zie de tekst.

Figuur 4: Het genormalizeerde verschil tussen de data en de voorspellingen van twee verschillende NN+3NF modellen. De punten zijn gefit aan de som van twee Gaussische verdelingen. De curves tonen de beste fit, waarbij de groene (rode) curve correspondeert met de eerste (tweede) Gaussische verdeling. De blauwe curve toont de som van beide verdelingen. De parameters van de fits staan in de rechter bovenhoek van de figuren.

A. Cross sections of pd break-up reaction at 190 MeV

In this appendix, we present the measured cross section of the configurations in which both protons scatter to the forward angles ($\theta_{1,2} < 40$). This analysis aims to double-check this results of this measurement with those from Ref. [50]. In the present work, we compare our data with various theoretical predictions of CDB+ Δ , CDB [19, 92, 93], AV18+UIX, and AV18 [117–119]. The Coulomb and relativistic effects are already discussed for this part of the phase space in Ref. [50]. Figures 1–5 show the results of the present analysis (filled circles) and those from Ref. [50] (open squares). The red solid (dashed) lines represent the calculation of CDB+ Δ (CDB). The blue solid (dashed) lines represent the calculations of AV18+UIX (AV18). The cyan band represents the systematic uncertainty (2σ). Both results are in a fairly good agreement except for a few data points due to the statistical fluctuations. The results for kinematics in which we could not subtract the background from signal unambiguously are not presented. This operation only excluded a small fraction of the data points which are mainly correspond to the intermediate values of S . We only present data for which the total systematic uncertainty is less than 25%. Also, the kinematics in which the geometrical inefficiency is larger than 50% are not presented.

To perform a global comparison between data and theory, the average of the cross sections over the S value was obtained for each configuration. The average value for each set of $\xi = (\theta_1, \theta_2, \phi_{12})$ was obtained using the following formula:

$$\bar{\sigma}(\xi) = \frac{\sum_{i=1}^N w_i \sigma(\xi, S_i)}{\sum_{i=1}^N w_i}, \quad (1)$$

where N is the number of the measured data points in each configuration and $\sigma(\xi, S_i)$ is the measured cross section at a specific S -value of the configuration $\xi = (\theta_1, \theta_2, \phi_{12})$. The w_i is the weighting factor, which is correspond to the one over the power of two of statistical uncertainty ($\frac{1}{\sigma_i^2}$) of each measured value of the cross section. This procedure were performed for averaging of the theoretical predictions with the same weighting factor, to have a realistic comparison between data and theory. The results of this averaging are presented in the top panel of Fig. 6 as a function of ϕ_{12} .

To observe the deviation between data and different theoretical prediction, another global quantity was employed. This quantity is defined as a difference between data and theory which is normalized to the theoretical value at each data point. Equation 2 describe

this quantity,

$$\Delta\sigma(\xi) = \frac{\sum_{i=1}^N w_i (\sigma^{exp}(\xi, S_i) - \sigma^{theo}(\xi, S_i)) / \sigma^{theo}(\xi, S_i)}{\sum_{i=1}^N w_i}, \quad (2)$$

where $\sigma^{exp}(\xi, S_i)$ and $\sigma^{theo}(\xi, S_i)$ are the experimental and theoretical values of cross section at S_i for each combination of $\xi = (\theta_1, \theta_2, \phi_{12})$, respectively. w_i is the wighting factor which is the same as Equation 1. N is the number of data points of each configuration. $\Delta\sigma(\xi)$ is the average difference between data and theory for Crows section. These data are plotted as a function of ϕ_{12} for each set of (θ_1, θ_2) in the bottom panel of Fig. 6. The lines depict the average deviation of each theoretical prediction from the experimental results. The error bars are shown only for CDB+ Δ , which are the same for all the other lines. The cyan band represents the systematic uncertainty.

Figure 1: The cross section for $(\theta_1, \theta_2) = (15^\circ, 15^\circ)$, top panel, and $(\theta_1, \theta_2) = (20^\circ, 15^\circ)$, bottom panel, for a set of relative azimuthal angles. The filled circles are the result of the present analysis and the open squares are the result from Ref. [50] which we refer them to as KVI_2007. The red solid and red dashed lines show predictions of Faddeev calculations using CDB+ Δ and CDB [19, 92, 93]. The blue solid and blue dashed lines show predictions of AV18+UIX and AV18 [117–119]. The experimental data points are obtained as a function of the relativistic value of S but the calculations use non-relativistic kinematic for S . The difference between non-relativistic and relativistic S value is less than 1-2 MeV and is negligible. The center of S -bins is taken as S value for the experimental data points. The cyan band represent systematic uncertainty.

Figure 2: Same as Fig. 1 except for $(\theta_1, \theta_2) = (20^\circ, 20^\circ)$, top panel, and $(\theta_1, \theta_2) = (25^\circ, 15^\circ)$, bottom panel.

Figure 3: Same as Fig. 1 except for $(\theta_1, \theta_2) = (25^\circ, 20^\circ)$, top panel, and $(\theta_1, \theta_2) = (25^\circ, 25^\circ)$, bottom panel.

Figure 4: Same as Fig. 1 except for $(\theta_1, \theta_2) = (28^\circ, 15^\circ)$, top panel, and $(\theta_1, \theta_2) = (28^\circ, 20^\circ)$, bottom panel.

Figure 5: Same as Fig. 1 except for $(\theta_1, \theta_2) = (28^\circ, 25^\circ)$, top panel, and $(\theta_1, \theta_2) = (28^\circ, 28^\circ)$, bottom panel.

Figure 6: The top panel shows the average of the cross section over the S value for the part of the phase space in which $\theta_{1,2} < 40^\circ$. The different lines show the average results for various theoretical predictions which are described in the legend. The error bars are statistical, and the cyan band shows systematic uncertainty (2σ). Each row shows the results for a fixed θ_1 and varying θ_2 , and each column shows the results for a fixed θ_2 and varying θ_1 . The bottom panel depicts the average deviation between data and various theoretical predictions for the part of the phase space in which $\theta_{1,2} < 40^\circ$. Each line represents the deviation from one of the calculations that are described in the legend. The statistical error bars are only shown for CDB+ Δ and it is the same for the other lines. The cyan band depicts systematic uncertainty (2σ). The horizontal green lines shows the zero point.

B. Extracting the Cross Sections

A general form for the differential cross section is

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

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 $1\text{u} = 10^3\text{mg}/1\text{mol}$.

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

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

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

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 (3) results in:

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

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