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Measurement of spin observables in three-body break-up in deuteron-deuteron scattering at 130 MeV

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Measurement of spin observables in three-body break-up in deuteron- deuteron scattering at 130 MeV

PhD thesis

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

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To my dear Elham and Alisina,
and my parent.

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1. Introduction

The strong nuclear force is a fundamental building block in nuclear physics. According to the standard model of particle physics, the strong nuclear force is the result of the strong interactions between quarks and gluons. Analog to the Van der Waals force being an effective Coulomb interaction between electron clouds and the core of atoms, the nuclear force is an effective interaction of the underlying strong force. Similar to the short-range behavior of the Van der Waals force, the nuclear force also acts on a short range on the scale of the nuclear radius.

It is common to interpret the interactions between nucleons by the exchange of mesons. Analog to the exchange of massless photons describing successfully the electromagnetic interaction, the meson-exchange theory developed by Yukawa in 1935 successfully describes the interaction between two nucleons with the exchange of virtual mesons between them [1]. The discovery of the pion and subsequently heavier mesons stimulated researchers to develop boson-exchange models to describe nucleon-nucleon interactions. To date, several phenomenological nucleon-nucleon (NN) potentials have been derived based on Yukawa's model. Some of them are successfully linked to the fundamental theory of quantum chromodynamics (QCD) through chiral perturbation theory (χ PT). Precision measurements obtained from nucleon-nucleon scattering data are strikingly well described by these modern NN potentials, albeit with several parameters of the potentials fitted to the data.

1.1 Three-nucleon force in three-body systems

Applying high-precision NN potentials to describe systems composed of at least three nucleons shows some discrepancies between theoretical calculations and experimental data for different observables. For instance, rigorous Faddeev calculations based on high-precision NN potentials for the binding energy of triton, which is the simplest three-nucleon system, underestimate the experimental data [2] by 10%. In addition, *ab-initio* calculations of the differential cross section in elastic nucleon-deuteron scattering show large discrepancies with experimental data in the minimum of the cross section. These observations show that calculations based solely on high-precision NN potentials are not sufficient to describe systems that involve more than two nucleons. These

Figure 1.1: Comparison of experimental data for the binding energies of light nuclei and those for theoretical calculations using Green’s function Monte Carlo calculations based on the AV18 NN potential with (red) and without (blue) the IL7 three-nucleon potential [8].

discrepancies, to some extent, could be attributed to relativistic effects [3]. But, relativistic effect cannot explain the discrepancies in all experiments [4,5].

To remedy the observed discrepancies, the so-called three-nucleon force (3NF) has been introduced. This force was already proposed in the early days of nuclear physics by Primakoff and Holstein [6]. Green’s function Monte Carlo calculations based on the AV18 NN potential complemented with the IL7 three-nucleon potential give a better description of the experimental data for the binding energies of light nuclei; see figure 1.1 [7,8]. The inclusion of 3NF effects can partly resolve the deficiencies observed in the differential cross section in elastic Nd scattering as well [9,10]. The top left panel of figure 1.2 shows the results of the differential cross section of the pd elastic process at 108 MeV. The inclusion of the Tucson-Melbourne potential (TM’) as a 3NF clearly gives a better agreement with experimental data. However, by including this

Figure 1.2: Top panels (bottom panels): comparison between experimental data for the differential cross sections (analyzing powers) of the pd elastic scattering at 108 and 190 MeV and theoretical calculations based on NN potentials with (red bands) and without (gray bands) the TM' three-nucleon potential [10].

3NF at higher energies, the discrepancy between data and theory cannot be completely resolved. The top right panel of figure 1.2 illustrates this for cross section data taken at 190 MeV. The addition of a 3NF for the analyzing power, A_y , shows a different trend as illustrated in the bottom panels of figure 1.2. For example, the discrepancy between data and theory becomes even worse while adding a 3NF as shown for the 108 MeV case. These are only a few of all evidences demonstrating that 3NF effects are presently not well understood.

This thesis presents a study of the nuclear force in a four-nucleon scattering system. The role of many-nucleon effects in systems with more than three nucleons has been qualitatively addressed using chiral-perturbation theory [11, 12]. The results of these studies revealed the existence of a hierarchy

in the many-body forces, *i.e.* the 2NF force is stronger than the 3NF and the 3NF is stronger than the four-nucleon force (4NF) and so on. Therefore, one expects that the 4NF plays less of a role than the 3NF in four-nucleon systems.

1.2 Three-nucleon force in four-body systems

Three-body systems are the simplest ones for the study of 3NF effects, as only NN and 3N forces are involved in such systems and observables can be obtained through *ab-initio* calculations. But the drawback is that the influence of 3NF effects are in general small in a three-body system. Only at specific parts of the phase space in three-nucleon scattering processes, 3NF effects become significant. A well-known example for this case is the scattering angles corresponding to the minimum of the differential cross section in elastic Nd scattering [9, 13]; see figure 1.2. From an experimental point of view, it is challenging to find reaction channels that are sensitive enough to study 3NF effects. An alternative approach, which is the focus of this thesis, is to investigate the four-nucleon (4N) system where 3NF effects are expected to be larger than those in 3N systems [14]. This can be intuitively understood by the fact that the number of three-nucleon combinations increases with the number of nucleons involved and, thereby, enhancing the sensitivity to 3NF effects. A naive estimation is that 3NF is three times larger in 4N systems due to a combination of various geometrical configurations coming from the permutation of the particles in 4N systems. Deuteron-deuteron scattering, as a 4N system, is one of the best systems to study 3NF effects because of its variety of reaction channels, observables, and kinematical configurations. The experimental data available for 4N systems are very limited compared to those for 3N systems. Most of the 4N data cover the very low-energy regime, below the three- and four-body break-up threshold [15–17]. At low energies, calculations are very reliable but the effect of 3NF is very small. However, above break-up thresholds and below the pion-production limit, namely at intermediate energies, there are not much data for 4N processes. Observables measured here are often differential cross sections and analyzing powers [18–21]. The main theoretical challenge stems from singularity structures in momentum space for the break-up configurations which hamper making predictions. Rigorous theoretical calculations for four-nucleon systems are still limited to the low-energy regime, below the three-body break-up threshold. So far, for 4N observables at intermediate energies, there are no *ab-initio* calculations. For this region, calculations are performed using approximations [21].

In summary, deuteron-deuteron scattering as a four-nucleon system is a

good laboratory to investigate few-nucleon forces (in particular 3NF), since 3NF effects are expected to be larger in 4N systems compared to those in 3N systems. The presented analysis of deuteron-deuteron scattering expands the experimental database for future *ab-initio* calculations. This analysis also extends the previous analysis done on the elastic deuteron-deuteron channel [22]. In addition, we present cross section and analyzing power data of the three-body break-up reaction in deuteron-deuteron scattering. Partly, we reanalyzed configurations of an earlier study and found a normalization mistake in the cross section data. Moreover, we extended this study by measuring additional spin observables and by extending the phase space by registering, for the first time, the final-state neutron. Finally, we present the results of a detailed analysis of the three-body break-up channel in the vicinity of the quasi-free process.

1.3 The scope of the thesis

Even though many different aspects of the nuclear force in the few-body regime, from the emergence of the few-nucleon forces to the development of different theoretical models, have already been investigated, the nuclear force is not thoroughly understood, yet. The aim of this thesis is to provide a comprehensive database for studying the 3NF effects through the analysis of different channels in deuteron-deuteron scattering at 130 MeV to provide more insight into many-body interactions. Below the pion-production threshold, the deuteron-deuteron scattering is classified into five different hadronic reaction channels:

- Elastic channel, $\vec{d} + d \rightarrow d + d$;
- Proton-transfer channel, $\vec{d} + d \rightarrow {}^3\text{He} + n$;
- Neutron-transfer channel, $\vec{d} + d \rightarrow {}^3\text{H} + p$;
- Three-body break-up final-state, $\vec{d} + d \rightarrow d + p + n$;
- Four-body break-up final-state, $\vec{d} + d \rightarrow p + n + p + n$.

For convenience, in this thesis, the three- (four-) body break-up final state is referred to as the three- (four-) body break-up. All the five hadronic channels were observed in the data and we extracted cross sections and spin observables of both the elastic and three-body break-up channels.

The next chapter gives a brief explanation about the required theoretical background for few-body systems. The scattering theory of two-, three-, and

four-nucleon interactions is described and the related observables from this analysis such as the differential cross section and various vector and tensor analyzing powers are derived. The third chapter introduces step-by-step the experimental setup used to obtain the data. It starts from the process of producing the polarized deuteron beam to the detection of the final particles by the detector system, BINA, after impinging the beam on the liquid deuterium target. The fourth chapter gives an overview of the analysis techniques that were used to analyze data of the $\vec{d}d$ scattering process. In particular, this chapter gives a thorough description of the methods that were applied to analyze the elastic ${}^2\text{H}(\vec{d}, d)d$ channel. The results of the measured differential cross sections and three related analyzing powers are presented. To cross check the analysis procedure, we also extracted various observables of the well-known elastic $\text{H}(\vec{d}, d)p$ channel using the same methods as applied for the analysis of the ${}^2\text{H}(\vec{d}, d)d$ process. In addition, the chapter describes in detail the analysis procedure of the three-body break-up channel, ${}^2\text{H}(\vec{d}, dp)n$. The energy calibration procedure and the particle identification are explained. Also, the procedure that was used to extract the differential cross section and five analyzing powers for 192 configurations is presented. Moreover, the feasibility of neutron detection by BINA is evaluated, followed by a thorough description of the analysis of the three-body break-up channel ${}^2\text{H}(\vec{d}, dn)p$. The method that is used to extract the energy of the outgoing neutron using the available measured variables is explained. The fifth chapter presents the final results. More specifically differential cross sections and analyzing powers for ${}^2\text{H}(\vec{d}, d)d$, ${}^2\text{H}(\vec{d}, dp)n$ and ${}^2\text{H}(\vec{d}, dn)p$ are presented and compared with each other. Also, the recent publication on the quasi-free domain in deuteron-deuteron scattering is presented. In the end, conclusions and an outlook are given.

2. Theoretical and experimental states of Nd and dd scattering

2.1 Introduction

Inspired by the first scattering experiment done by Rutherford, the nucleon-nucleon scattering technique is commonly used to study the properties of the nuclear force. Many observables, like cross sections, analyzing powers, spin-correlations, and polarization-transfer coefficients may be obtained via scattering experiments. Each of these observables reveal specific aspects of the nuclear force. More specifically, the progress made in nuclear and particle physics would not be possible without scattering experiments.

Various theoretical approaches are exploited to model to understand the unknown aspects of the nuclear force. A partial wave analysis, as a general approach to describe nuclear potentials, were implemented to fit the experimental observables with a high accuracy [23]. Realistic potentials can describe the experimental observables with a reduced chi-square very close to one [24–28]. There are pros and cons to each of the techniques, and none of them can explain all properties of the nuclear force since they are all based on phenomenology. A more rigid and model independent approach could, in principle, be derived from the fundamental theory of QCD. Within this framework, the interaction between quarks is mediated by color charges. At the low energy regime, which is the domain of this work, the quarks are confined within the hadronic systems, and are color-neutral. In this non-perturbative regime, it is practically impossible yet to describe the interaction between the nucleons. However, it is shown to be possible to use an effective field theory in the low-energy regime by applying chiral perturbation theory, as suggested originally by Weinberg [29,30]. Chiral perturbation theory (χ PT) provides the most general Lagrangian involving pions and low-energy nucleons consistent with spontaneous symmetry breaking [31–33]. In essence, one constructs a Lagrangian that is consistent with the underlying symmetries of QCD such as the chirality, parity, and charge conjugation symmetries. Significant progress has been made using this method as described in Refs. [34,35].

In this chapter, a detailed description is given of the scattering theory for the two-nucleon interaction. Then, interactions within two-, three-, and few-body systems are introduced. The extraction of the experimental observables

are discussed as well.

2.2 Scattering theory

In this section, the prerequisites of the theoretical formalism for the nucleon-nucleon scattering in quantum mechanics are outlined to obtain the Lippmann-Schwinger equation (LSE). Also, it is shown how we can express the cross section via a given potential in this formalism. Next, the nucleon-nucleon scattering problem generalizes to the three-nucleon scattering problem. Finally, the LSE formalism is extended to the three-nucleon scattering process to obtain Faddeev equations. The derivations and notations are mainly taken from Refs. [36–39].

2.2.1 Formalism of two-nucleon scattering

In non-relativistic quantum mechanics, the scattering of a nucleon from another nucleon is described by the interaction of two wave packets. The dynamics of the wave packet, $|\psi_0\rangle$, before the interaction is given by the non-relativistic Schrödinger equation as

$$i\hbar \frac{\partial}{\partial t} |\psi_0\rangle = H_0 |\psi_0\rangle, \quad (2.1)$$

where $H_0 = -\frac{\hbar^2}{2m} \nabla^2$ is the free Hamiltonian operator. The wave function of a free particle is obtained from a general solution of Eq. 2.1 which is given by

$$|\psi_0(t)\rangle = e^{-iH_0 t/\hbar} |\psi_0\rangle. \quad (2.2)$$

The time evolution of the wave function when the potential V is felt by the wave packet is given by

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

where the Hamiltonian is given by

$$H = - \sum_i \frac{\hbar^2}{2m_i} \nabla_i^2 + V. \quad (2.4)$$

Here, i represents the i^{th} particle involved in the interaction. One solution of Eq. 2.3 is $|\psi(t)\rangle = \exp^{-iHt/\hbar} |\psi\rangle$, where $|\psi\rangle$ is a time-independent state. To link the two states, $|\psi(t)\rangle$ and $|\psi_0(t)\rangle$, we can look at the asymptotic level by assuming the absence of the potential V :

$$\lim_{t \rightarrow -\infty} \|\exp^{-iHt/\hbar} |\psi\rangle - \exp^{-iH_0 t/\hbar} |\psi_0\rangle\| = 0. \quad (2.5)$$

Using Eq. 2.5, the relation between the scattered and the free states can be expressed as

$$|\psi^\pm\rangle = \lim_{\epsilon \rightarrow 0} i\epsilon \frac{1}{E - H \pm i\epsilon} |\psi_0\rangle, \quad (2.6)$$

where, $G_\pm = \frac{1}{E - H \pm i\epsilon}$ is defined as the resolvent or the Green's function for the Helmholtz equation

$$(\nabla^2 + k^2)G_\pm(\vec{x}, \vec{x}') = \delta(\vec{x} - \vec{x}'). \quad (2.7)$$

The Green's operator for the undisturbed system is given by

$$G_0 = (E - H_0 \pm i\epsilon)^{-1}, \quad (2.8)$$

which is known as the free-particle propagator. Applying algebraic manipulations, the Green's function, G , for a system in which the particles interact with potential V is given by

$$G = \frac{1}{E - H \pm i\epsilon} = \frac{1}{E - H_0 \pm i\epsilon} + \frac{1}{E - H_0 \pm i\epsilon} V \frac{1}{E - H \pm i\epsilon} = G_0 + G_0 V G. \quad (2.9)$$

By inserting Eq. 2.9 into Eq. 2.6 and using the fact that $i\epsilon G_0 |\psi_0\rangle = |\psi_0\rangle$, we obtain the *Lippmann-Schwinger Equation* (LSE)

$$|\psi^\pm\rangle = |\psi_0\rangle + G_0 V |\psi^\pm\rangle. \quad (2.10)$$

In a scattering experiment, the initial and final probabilities are experimentally accessible. The probability for the transition from the initial state, $|\psi_0\rangle$, to the final state, $|\psi^+\rangle$, is expressed as an observable, namely the cross section. Therefore, if we define t as the transition operator

$$V|\psi^+\rangle \equiv t|\psi_0\rangle. \quad (2.11)$$

Multiplying the LSE, Eq. 2.10, by the potential V from the left side, one obtains

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

Now, we can relate the cross section to the matrix element of the transition operator, *t-matrix*, in the momentum space

$$\frac{d\sigma}{d\Omega} \propto |\langle p' | t(E + i\epsilon) | p \rangle|^2, \quad (2.13)$$

where the initial (final) state, $|p\rangle$ ($|p'\rangle$), gives the energy and the direction of the beam (detected particles in the final state). The *t-matrix* can be evaluated by the Born series iteratively

$$t = V + V G_0 V + V G_0 V G_0 V + V G_0 V G_0 V G_0 V + \dots \quad (2.14)$$

This can be shown diagrammatically for a system with two interacting particles, see figure 2.1. The potential V is shown by the wiggled lines. Also, the potential V can be expanded in terms of the exchange of mesons shown by the dashed lines representing pions.

Figure 2.1: The t operator as a series of diagrams in which the potential, V , is shown as wiggled lines. The potential can also be expanded in terms of the exchange of mesons represented by the dashed lines. The figure taken from Ref. [39]

2.2.2 Three- and four-nucleon scattering

In a three-body reaction like nucleon-deuteron scattering, particles interact with each other in different combinations depending on the binding energy of the bound states. Because the nuclear interactions have a finite range, there is no interaction between three particles beyond a specific distance determined by the range of the nuclear force. The three particles can have various geometrical configurations. For instance, two particles can construct a bound state while the third particle is separated from the pair. This arrangement gives three different channels, namely two-body rearrangement channels obtained from the permutation of the labels of particles shown as

$$1, 23; 2, 31; 3, 12. \quad (2.15)$$

For example, channel 1, 23, represent the configuration in which particle 1 is a well-separated particle while particles 2 and 3 form a bound state. The elastic and transfer channels belong to this category. The three-body break-up channel in which there is no bound state between final particles is expressed as

$$1, 2, 3. \quad (2.16)$$

It is common to express a two-body rearrangement channel by a single channel number using the label of the single particle. For example, channel 1 denotes the arrangement; 1, 23; etc.. Also, the same simple rule is applied for the pair

of interactions as introduced for the channels. For example, $V_1 = V_{23}$, etc.. So, the pair of interaction V_α binds two particles in channel α . In this case, the particle α is well-separated and does not interact. The channel state related to channel α is defined as

$$|\phi_{q\alpha}\rangle = |\varphi_\alpha\rangle|q_\alpha\rangle, \quad (2.17)$$

where $|\varphi_\alpha\rangle$ is the wave function of the bound state and $|q_\alpha\rangle$ is the state of the free motion of the particle α with respect to the bound-pair. The state of Eq. 2.17 is an eigenstate of the channel Hamiltonian

$$H_\alpha = H_0 + V_\alpha. \quad (2.18)$$

Here, we have

$$H_\alpha|\phi_{q\alpha}\rangle = E_{q\alpha}|\phi_{q\alpha}\rangle. \quad (2.19)$$

There are other eigenstates of H_α corresponding to a break-up configuration. In other words, there is no bound state between final states. These eigenstates are defined as

$$|\phi_\alpha\rangle^{(+)} = |p_\alpha\rangle^{(+)}|q_\alpha\rangle. \quad (2.20)$$

To obtain the total Hamiltonian operator, we add the interaction of the particle α to H_α with the pair, $V^\alpha \equiv V_\beta + V_\gamma + V_4$, $\alpha \neq \beta \neq \gamma$. V_4 is the three-body force which goes beyond the interaction pairs. Therefore, the total Hamiltonian is

$$H = H_0 + V_\alpha + V^\alpha = H_\alpha + V^\alpha. \quad (2.21)$$

In this convention, the break-up channel is denoted by index 0 and introduced as

$$\begin{aligned} V_0 &\equiv 0, \\ V^0 &\equiv V + V_4. \end{aligned} \quad (2.22)$$

Now the second equality of Eq. 2.21 is used for all four channels with $\alpha = 0, 1, 2, 3$.

To obtain the LSE for a system with three nucleons, we utilized the same approach for the two-body interaction discussed in the previous section. The scattering process can be initiated through each of these 4 channels. The channel resolvent operator for a three-body system is written as

$$G_\alpha(z) \equiv \frac{1}{z - H_\alpha}, \quad (2.23)$$

and the full resolvent operator is

$$G(z) \equiv \frac{1}{z - H}. \quad (2.24)$$

There is a relation between the two resolvents as

$$G(z) = G_\alpha(z) + G_\alpha(z)V^\alpha G(z) = G_\alpha(z) + G(z)V^\alpha G_\alpha(z). \quad (2.25)$$

Using the channel resolvent operator, Eq. 2.23, we can obtain the LSE

$$|\psi_\alpha^{(+)}\rangle = \phi_\alpha + \lim_{\varepsilon \rightarrow 0} \frac{1}{E_\alpha + i\varepsilon - H_\alpha} V^\alpha |\psi_\alpha^{(+)}\rangle, \quad \alpha = 0, 1, 2, 3. \quad (2.26)$$

It can be proven that the scattering state $|\psi_\alpha^{(+)}\rangle$ with $\alpha \neq 0$ is also an eigenstate in addition to another state of the LSE expressed in Eq. 2.26 with homogeneous equations

$$|\psi_\alpha^{(+)}\rangle = \lim_{\varepsilon \rightarrow 0} G_\beta(E_\alpha + i\varepsilon) V^\beta |\psi_\alpha^{(+)}\rangle, \quad \beta \neq \alpha. \quad (2.27)$$

It seems that there is no unique solution of the state $|\psi_\alpha^{(+)}\rangle$ for the Lippmann-Schwinger equation (Eq. 2.26). Using the homogeneous and inhomogeneous solutions, Eqs. 2.26 and 2.27, we obtain a set of equations that give a unique definition for the state $|\psi_\alpha^{(+)}\rangle$

$$\begin{aligned} |\psi_\alpha^{(+)}\rangle &= \phi_\alpha + G_\alpha V^\alpha |\psi_\alpha^{(+)}\rangle, \\ |\psi_\alpha^{(+)}\rangle &= G_\beta V^\beta |\psi_\alpha^{(+)}\rangle, \\ |\psi_\alpha^{(+)}\rangle &= G_\gamma V^\gamma |\psi_\alpha^{(+)}\rangle. \end{aligned} \quad (2.28)$$

It is obvious that every solution of this set should satisfy the Schrödinger equation. The next step is finding a practical algorithm to obtain coupled equations for the three-body problems. For simplicity in the following, we neglect the effects of three-body force, V_4 . With decomposing the total state into three parts, we obtain

$$|\psi_\alpha^{(+)}\rangle = \sum_{\mu=1}^3 G_0 V^\mu |\psi_\alpha^{(+)}\rangle \equiv \sum_{\mu=1}^3 |\psi_{\alpha\mu}^{(+)}\rangle. \quad (2.29)$$

By multiplying Eqs. 2.28 from the left side with $G_0 V_\alpha$, $G_0 V_\beta$, and $G_0 V_\gamma$, we obtain

$$\begin{aligned} |\psi_{\alpha,\alpha}\rangle &= \phi_\alpha + G_\alpha V_\alpha (|\psi_{\alpha,\beta}\rangle + |\psi_{\alpha,\gamma}\rangle), \\ |\psi_{\alpha,\beta}\rangle &= G_\beta V_\beta (|\psi_{\alpha,\gamma}\rangle + |\psi_{\alpha,\alpha}\rangle), \\ |\psi_{\alpha,\gamma}\rangle &= G_\gamma V_\gamma (|\psi_{\alpha,\alpha}\rangle + |\psi_{\alpha,\beta}\rangle), \end{aligned} \quad (2.30)$$

where $|\psi_{\alpha,\mu}\rangle \equiv G_0 V^\mu |\psi_\alpha^{(+)}\rangle$. This is a set of three coupled equations known as the Faddeev equations for a three-body system. According to Eq. 2.26, the

sum of the amplitudes of $|\psi_{\alpha,\varepsilon}\rangle$ with $\varepsilon = 1, 2, 3$, gives the total state $|\psi_{\alpha}^{(+)}\rangle$.

In the case of the four-nucleon system, the theoretical calculation is more challenging because of the increase in the number of degrees of freedom involved due to the presence of the fourth particle compared to a three-body system. It needs to be emphasized that the four-body system offers the possibility to investigate the four-nucleon force. Also, it is expected to be a good laboratory to study the three-nucleon force effects because it is enhanced in magnitude compared to same effects in the three-body systems. Up to now, there are some theoretical calculations available whereby the majority has been performed at energies below the three- and four-body break-up threshold. In other words, at intermediate energies, that is the range of energy for the present study, no *ab-initio* calculations exist. Recently, theoretical calculations have been done for the three-body break-up channel of the deuteron-deuteron scattering based on a rough approximation, namely the single-scattering approximation, SSA, that may have reasonable results near the quasi-free scattering, (QFS), conditions at energies above 100 MeV. The SSA, as a first estimation, uses the lowest-order term in the Neumann series expansion of the Alt, Grassberger, and Sandhas (AGS) equations for the break-up operator. The SSA just considers the scattering of one nucleon due to the break-up of one of the deuterons from the deuteron and exploits the full three-nucleon operator which sums up all orders of the NN scattering involving the corresponding three particles. The same kind of approximation can be used for the elastic channel of the deuteron-deuteron scattering at intermediate energies.

At first, the four-nucleon scattering equations and transition amplitudes are obtained exactly. Then, they are simplified using single-scattering approximation. Also, in the isospin formalism, nucleons are considered to be identical. So, it leads to two two-cluster parts, 3+1 and 2+2. The cluster 3+1 is divided again to (2+1)+1. With four particles with the labels 1, 2, 3, and 4, they construct the clusters, (12,3)4 and (12)(34), respectively. Now, it is supposed that the target deuteron breaks up and its proton interacts with the deuteron beam with all possible interactions. In this case, the neutron acts as a spectator. By considering the first term of the single-scattering break-up amplitude in the calculation, there will be four contributions for the $d + p + n$ final state. Two contributions are graphically shown in figure 2.2. The other two contributions that arise due to the symmetrization of the initial $d + d$ state are not shown in this figure. Here, we assume the right-hand side deuteron as the target and the left as the beam. So, diagram (a) shows the interaction between the deuteron beam and the proton of the deuteron target without any interaction with the neutron. In other words, it corresponds to the deuteron-proton quasi-free scattering. Analogously, diagram (b) shows the deuteron-neutron

Figure 2.2: Two contributions of the single-scattering break-up amplitude. The three-nucleon transition operator is represented by the black boxes. The left (right) diagram belongs to the deuteron-proton quasi-free scattering (deuteron-neutron quasi-free scattering).

quasi-free scattering. The calculations based on just the contribution of figure 2.2 (a) are called SSA-1 while those including all of the four-contributions are called SSA-4. In the regions that the contribution of diagram (a) is dominant, the results of SSA-1 and SSA-4 agree with each other [40–42].

2.3 Experimental overview of Nd scattering

In the last decades, many nucleon-deuteron elastic [43–60] and break-up [61–67] scattering experiments, done by various laboratories at intermediate energies below the pion-production threshold, have provided us a good database to study 3NF effects. The addition of the 3NF, in particular the contribution of the Δ resonance, reduces significantly the discrepancies between the experimental data and the theoretical calculations in the differential cross section. The situation for the spin observables is vastly different. For instance, the inclusion of 3NF effects for the vector analyzing power of the elastic channel at the intermediate energies gives a better agreement between the data and theory, while for the tensor analyzing power, $Re(T_{22})$, the discrepancies are not removed by adding 3NF effects in the model [14]. There are even cases where including 3NF effects to the calculations increases the discrepancies between the experimental observations and theoretical calculations, for instance for the vector analyzing power of the proton in the proton-deuteron break-up reaction at configurations that correspond to small relative energies between the two outgoing protons [14]. These observations imply that spin-dependent

parts of the 3NF effects are not yet well understood [14].

To expand the experimental database, various scattering experiments [10, 43–45, 47, 59, 60, 65] were carried out at KVI, Kernfysisch Versneller Instituut, including experiments to study the deuteron-deuteron elastic and inelastic scattering reactions. These have provided an extended experimental database to investigate various aspects of the 3NF effects, especially its spin-dependent part. Despite the fact that *ab-initio* calculations are still in the development stage in this energy regime, the prospects of studying the structure of 3N forces, and possibly higher-order four-nucleon force effects, look promising [68, 69].

2.4 Cross section and spin observables in a scattering experiment with a polarized beam

The notations used in this section are taken from Refs. [70, 71].

The cross section is one of the most important observables in scattering experiments. In a scattering process with a polarized beam of a spin-1 projectile, the cross section is expressed as

$$\begin{aligned} \sigma(\xi) = \sigma_0(\xi) & \left(1 + \frac{3}{2} [p_x A_x(\xi) + p_y A_y(\xi) + p_z A_z(\xi)] \right. \\ & + \frac{2}{3} [p_{xy} A_{xy}(\xi) + p_{yz} A_{yz}(\xi) + p_{xz} A_{xz}(\xi)] \\ & \left. + \frac{1}{3} [p_{xx} A_{xx}(\xi) + p_{yy} A_{yy}(\xi) + p_{zz} A_{zz}(\xi)] \right), \end{aligned} \quad (2.31)$$

where σ (σ_0) is the cross section of the reaction with polarized (unpolarized) beam and ξ represents the kinematical variables involved in the scattering. For instance, the kinematical variables for the three-body break-up channel of the deuteron-deuteron scattering with three final particles are the energies, polar, and azimuthal angles of two detected particles, namely, E_1 , E_2 , θ_1 , θ_2 , ϕ_1 , and ϕ_2 . The variables p_x , p_y , and p_z are the Cartesian components of the vector polarization of the beam and p_{xy} , p_{yz} , p_{xz} , p_{xx} , p_{yy} , and p_{zz} are the Cartesian components of the tensor polarization of the beam. Similarly, the variables A_x , A_y , and A_z (A_{xy} , A_{yz} , A_{xz} , A_{xx} , A_{yy} , and A_{zz}) represent the Cartesian components of the vector (tensor) analyzing powers.

To describe the polarization of the beam in the Cartesian coordinate system, the positive Z axis is chosen along the direction of the beam (projectile) momentum, $\vec{K}_p$. Some of the applicable unit vectors are defined as following:

$$- \hat{k} = \frac{\vec{K}_p}{|\vec{K}_p|}, \text{ unit vector in the } +Z \text{ direction;}$$

- $\hat{n}$ = unit vector in the +Y direction;
- $\hat{I} = \hat{n} \times \hat{k}$ unit vector in the +X direction;
- $\hat{s}$ = unit vector representing the direction of the spin.

As shown in figure 2.3, the direction of $\hat{s}$ is generally determined by two angles: the angle between the direction of $\hat{s}$ and the beam, denoted as β (with $0^\circ \leq \beta \leq 180^\circ$) and the angle between the direction of Y axis and the projection of $\hat{s}$ on the XY plane, denoted by ϕ (with $0^\circ \leq \phi \leq 360^\circ$). Therefore,

$$\begin{aligned}\cos \beta &= \hat{s} \cdot \hat{k}, \\ \cos \phi &= \hat{s} \cdot \hat{n} / \sin \beta, \\ \sin \phi &= -\hat{s} \cdot \hat{I} / \sin \beta.\end{aligned}\tag{2.32}$$

The experiment discussed in this thesis used a polarized spin-1 deuteron beam. Thus, the polarization of the polarized deuteron consists of two parts, the vector and tensor polarization. By using the definitions of the unit vectors, Eq. 2.32, the Cartesian components of the vector polarizations are defined as:

$$\begin{aligned}p_x &= -p_Z \sin \beta \sin \phi, \\ p_y &= p_Z \sin \beta \cos \phi, \\ p_z &= p_Z \cos \beta.\end{aligned}\tag{2.33}$$

In the same manner, the Cartesian components of the tensor polarization are defined as

$$\begin{aligned}p_{xy} &= -\frac{3}{2} \sin^2 \beta \cos \phi \sin \phi p_{ZZ}, \\ p_{yz} &= \frac{3}{2} \sin \beta \cos \beta \cos \phi p_{ZZ}, \\ p_{zx} &= -\frac{3}{2} \sin \beta \cos \beta \sin \phi p_{ZZ}, \\ p_{xx} &= \frac{1}{2} (3 \sin^2 \beta \sin^2 \phi - 1) p_{ZZ}, \\ p_{yy} &= \frac{1}{2} (3 \sin^2 \beta \cos^2 \phi - 1) p_{ZZ}, \\ p_{zz} &= \frac{1}{2} (3 \cos^2 \beta - 1) p_{ZZ},\end{aligned}\tag{2.34}$$

where p_Z (p_{ZZ}) is the vector (tensor) polarization of the beam with respect to its quantization axis, $\hat{s}$. Because in the present scattering experiment,

Figure 2.3: Geometry of the kinematics of the outgoing particles with a polarized beam. The angle between the direction of $\hat{s}$ and the beam is denoted by β (with $0^\circ \leq \beta \leq 180^\circ$) and ϕ represents the angle between the direction of the y axis and the projection of the $\hat{s}$ on the XY plane (with $0^\circ \leq \phi \leq 360^\circ$).

the quantization axis is perpendicular to the beam direction, the Cartesian components of the vector and tensor polarizations are only ϕ dependent. The substitution of Eqs. 2.33 and 2.34 into Eq. 2.31 and using the fact that $\beta = 90^\circ$, results in:

$$\begin{aligned} \sigma(\xi) = \sigma_0(\xi) & \left(1 - \frac{3}{2} \sin \phi P_Z A_x(\xi) + \frac{3}{2} \cos \phi P_Z A_y(\xi) \right. \\ & - \cos \phi \sin \phi P_{ZZ} A_{xy} + \frac{1}{2} \sin^2 \phi P_{ZZ} A_{xx}(\xi) \\ & \left. + \frac{1}{2} \cos^2 \phi P_{ZZ} A_{yy}(\xi) \right). \end{aligned} \quad (2.35)$$

Here we made use of the over-completeness of the Cartesian tensors as given by

$$A_{zz}(\xi) = -A_{xx}(\xi) - A_{yy}(\xi). \quad (2.36)$$

Therefore, there are five analyzing powers that can be extracted in the break-up channel in the deuteron-deuteron scattering. Moreover, parity conservation

imposes some constraints on the components of the analyzing powers, namely

$$\begin{aligned}
A_x(\phi_1, \phi_2) &= -A_x(-\phi_1, -\phi_2), \\
A_y(\phi_1, \phi_2) &= A_y(-\phi_1, -\phi_2), \\
A_z(\phi_1, \phi_2) &= -A_z(-\phi_1, -\phi_2), \\
A_{xy}(\phi_1, \phi_2) &= -A_{xy}(-\phi_1, -\phi_2), \\
A_{xz}(\phi_1, \phi_2) &= A_{xz}(-\phi_1, -\phi_2), \\
A_{yz}(\phi_1, \phi_2) &= -A_{yz}(-\phi_1, -\phi_2), \\
A_{xx}(\phi_1, \phi_2) &= A_{xx}(-\phi_1, -\phi_2), \\
A_{yy}(\phi_1, \phi_2) &= A_{yy}(-\phi_1, -\phi_2), \\
A_{zz}(\phi_1, \phi_2) &= A_{zz}(-\phi_1, -\phi_2).
\end{aligned} \tag{2.37}$$

Using the above equations for the channels with two final-state particles such as the elastic and transfer channels which, *i.e.* with $\phi_{12} = 180^\circ$, Eq. 2.35 simplifies to:

$$\begin{aligned}
\sigma(\xi) = \sigma_0(\xi) &\left(1 + \frac{3}{2}p_Z A_y(\theta) \cos(\phi) - \frac{1}{4}p_{ZZ} A_{zz}(\theta) \right. \\
&\left. + \frac{1}{4}p_{ZZ}(A_{zz}(\theta) + 2A_{yy}(\theta)) \cos(2\phi) \right),
\end{aligned} \tag{2.38}$$

In some applications, the Cartesian components of the analyzing powers are converted to those in the spherical coordinate. The relation between these two frameworks for the components of the analyzing powers are [70, 71]

$$\begin{aligned}
Re(iT_{11}) &\equiv \frac{\sqrt{3}}{2} A_y, \\
Im(iT_{11}) &\equiv -\frac{\sqrt{3}}{2} A_x, \\
T_{20} &\equiv \frac{1}{\sqrt{2}} A_{zz}, \\
Re(T_{21}) &\equiv -\frac{1}{\sqrt{3}} A_{xz}, \\
Re(T_{22}) &\equiv \frac{1}{2\sqrt{3}} (A_{xx} - A_{yy}), \\
Im(T_{22}) &\equiv \frac{1}{\sqrt{3}} A_{xy}.
\end{aligned} \tag{2.39}$$

Using these relations, the cross section of Eq. 2.35 can be rewritten as

$$\begin{aligned} \sigma(\xi) = \sigma_0(\xi) & \left(1 + \sqrt{3}p_Z \operatorname{Re}(iT_{11}(\xi)) \cos(\phi) + \sqrt{3}p_Z \operatorname{Im}(iT_{11}(\xi)) \sin(\phi) \right. \\ & - \frac{1}{\sqrt{8}}p_{ZZ}T_{20}(\xi) - \frac{\sqrt{3}}{2}p_{ZZ}\operatorname{Re}(T_{22}(\xi)) \cos(2\phi) \\ & \left. - \frac{\sqrt{3}}{2}p_{ZZ}\operatorname{Im}(T_{22}(\xi)) \sin(2\phi) \right). \end{aligned} \quad (2.40)$$

For the coplanar configurations in the break-up channel, the terms with the imaginary part of the analyzing powers are expected to be zero. This has been experimentally verified; see section 5.2.1.

3. Experimental setup

The text of this chapter is based on the information given in Refs. [22,39,72,73].

One of the most common approaches to investigate different aspects of the nuclear force is via scattering a few-nucleon system as a projectile off a nucleus as the target at rest. For this thesis, the deuteron-deuteron scattering experiment as a four-body system is analyzed and its different channels are identified. The data were obtained in a series of scattering experiments performed at the **K**ernfysisch **V**ersneller **I**nstituut (KVI) with the aim to investigate few-body systems, particularly to understand three-nucleon force (3NF) effects. This chapter describes the major components of the facility used in the experiment. The whole process will be introduced starting from the production of the polarized deuteron beam, its acceleration to a kinetic energy of 65 MeV/nucleon, the measurement of the polarization of the beam before and after acceleration, and the detection of the scattered particles after bombarding the beam on a deuterium target using a 4π -detection system.

Figure 3.1 represents an overview of the whole facility at KVI. The **P**olarized **I**on **S**ource (POLIS) produced the required polarized beam of the deuterons (and also protons for other scattering experiments). The polarized beam was then accelerated by the superconducting cyclotron, AGOR (**A**ccélérateur **G**roningen **O**Rsay) up to a few hundred MeV. For the scattering process of interest, the polarized deuteron beam was accelerated to 65 MeV/nucleon. Beam-lines were responsible to guide the polarized beam to reach the target mounted in the detection system, BINA (**B**ig **I**nstrument for **N**uclear-polarization **A**nalysis). The beam polarization was measured with the **L**amb-**S**hift **P**olarimeter (LSP) [74] before, and BINA after acceleration. The following subsections describe each part of the facility in detail.

3.1 The Polarized Ion Source, POLIS

POLIS is an ion source which is used to produce polarized atomic beams of deuterons and protons [76]. The nominal polarization value of the polarized deuteron or proton beam is around 60-80% of the theoretical maxima. As it was mentioned already, the beam of the deuterons was used in this scattering reaction. Therefore, here the deuteron beam polarization process is described in details. The procedure to measure the proton-beam polarization

Figure 3.1: An overview of the experimental facility at KVI in 2007. POLIS provided the polarized beam of deuterons. The AGOR accelerator provided the beam with an energy of 130 MeV for the present experiment. The BINA detection system was mounted at the end of one of the beam-lines.

Table 3.1: The schematic of producing various polarizations of the deuteron which are used in this experiment.

Field(s)	p_Z	p_{ZZ}	
WF	$-2/3$	0	pure-vector down
SFI+SFII	$+2/3$	0	pure-vector up
WF+SFII	0	-2	pure-tensor down
WF+SFI	0	$+1$	pure-tensor up
off	0	0	unpolarized

is described in Refs. [22, 72].

The following steps are taken to select and to separate deuterons with various polarizations. First of all, deuterium molecules are dissociated into atoms by means of a radio-frequency (RF)-induced discharge. The hyperfine structures of the deuterium atoms in the S -state, $l = 0$, appear in the following two states, $F = 1/2, 3/2$ that come from the spin of the electron with $S = 1/2$ and the spins of the proton and neutron in the nucleus which make $J_{nucleus} = 0, 1$. In the next step, these atoms are passed through two hexapole lenses where the atoms with the positive electron polarization, $m_j = +1/2$, are focused toward the RF transition units whereas the atoms with the negative electron polarization, $m_j = -1/2$, are defocused. Next, the atoms are all electronically polarized. As shown in figure 3.2, an external magnetic field breaks the hyperfine structure degeneracy, such that transitions between sub-states become feasible using an appropriate RF field. More specifically, $F = 1/2$ ($F = 3/2$) state splits into two (four) sub-states. At this stage, inducing appropriate transitions leads to the desired combinations of the sub-states.

A spin-1 deuteron beam has a polarization with two parts, the vector and tensor polarizations. The vector and tensor polarizations are defined by the following equations:

$$p_Z = \frac{N_+ - N_-}{N_+ + N_- + N_0}, \quad (3.1)$$

$$p_{ZZ} = \frac{N_+ + N_- - 2N_0}{N_+ + N_- + N_0}, \quad (3.2)$$

where N_+, N_0 , and N_- are the numbers of particles in the sub-state $m = 1, 0$, and -1 , respectively. The two extremum values for p_Z are ± 1 and for p_{ZZ} are -2 and 1 . In the case one desires a pure-vector polarization, the variable p_{ZZ}

must be zero. As a consequence, the extremum values for p_Z will be $\pm 2/3$. Figure 3.2 shows that if we use a weak field with a frequency of 7 MHz, the pure-vector polarization of $-2/3$ with $p_{ZZ} = 0$ is generated, while applying a combination of two strong fields of 455 MHz and 331 MHz, so called SFI and SFII respectively, a pure-vector polarization of $+2/3$ with $p_{ZZ} = 0$ is produced. In addition, using a weak field along with a strong field transition gives a pure-tensor polarization with $p_Z = 0$ [77]. The unpolarized deuteron beam is obtained by switching off both transition units and hexapoles. Table 3.1 gives a summary of the polarization scheme used in the present experiment. In the last step, the electrons of the deuterium atoms are stripped off in an ECR ionizer and then the polarized ions are transferred to the AGOR cyclotron to get accelerated.

Figure 3.2: Illustration of the hyperfine structure and transitions of the deuterium atom shown as a function of magnetic field. A weak field transition gives a pure-vector polarization of $-2/3$ while applying a combination of two strong fields of SFI and SFII provides a pure-vector polarization of $+2/3$. Furthermore, applying a weak field along with a strong field gives a pure-tensor polarization.

3.2 Polarization measurement equipment

The polarization of the deuteron (proton) beam was measured before acceleration with the **Lamb-Shift Polarimeter (LSP)** and after acceleration with BINA. The Ion-Beam Polarimeter, IBP, in the high-energy beam-line is used to measure the polarization degree of the deuteron and proton beam, simultaneously with experiments that are running in the experimental area [79], by exploiting $H(\vec{d}, p)d$ and $H(\vec{p}, p)p$, respectively. For a detailed description of measuring the polarization of proton and deuteron beams with the IBP, we refer to [80]. In the analysis discussed in this thesis, the IBP information was not used.

At the low energy part of the beam line the polarization is measured using

Figure 3.3: The Breit-Rabi diagram for the deuterium atoms that shows the behavior of the $2S_{1/2}$ and $2P_{1/2}$ states in the presence of a magnetic field. Atoms with electrons of spin-up (spin-down) are labeled with α and e (β and f). Applying an appropriate magnetic field leads to a small increase in the α and e states with a small decrease in the β and f states. The lamb-shift polarimeter works based on the lamb-shift principle with employing a resonant three-level interaction between the α , β , and e states of the deuterium (hydrogen) atoms.

a setup called Lamb-Shift Polarimeter, LSP [73]. This compact polarimeter, which works based on the Lamb-Shift principle, was built to measure the polarization of the proton and deuteron in the low-energy beam-line. The lamb-shift principle comes from the tiny difference in the energy of $2S_{1/2}$ and $2P_{1/2}$ states of the hydrogen or deuterium atoms. The $2S$ -state atoms are metastable with a lifetime of around 1.7 s, while in $2P$ -state have a short lifetime of 1.6 ns. Figure 3.3 shows the behavior of the $2S_{1/2}$ and $2P_{1/2}$ states of the deuterium atoms in the presence of a magnetic field, the so-called Breit-Rabi diagram. In the presence of a magnetic field, energies of the spin-up states, namely α and e , increase whereas those for spin-down states, namely β and f , decrease. The lamb-shift polarimeter employs a resonant three-level interaction between the α , β , and e states in the $n = 2$ states of the hydrogen or deuterium atoms [81]. The polarization of the deuteron (proton) beam could be measured in a very short time, around 1-2 minutes, in the low-energy beam-line with an accuracy of 1%. The LSP was mainly used to optimize the polarization without the need to have AGOR available.

At the high-energy beam line, the polarization of the deuteron beam was extracted using ϕ -asymmetry measurements of the dp elastic process based on its well-known analyzing powers [85]. Note that the same experimental setup is used also for the deuteron-deuteron scattering experiment. Fig. 2 in Ref. [85] shows the results of the LSP measurements as well as polarization values obtained by BINA as a function of time. To achieve this, the polarization of the deuteron beam was monitored for different periods of the experiment and found to be stable within statistical uncertainties.

3.3 The superconducting AGOR cyclotron

The polarized deuteron beam (or other ions of interest) produced by POLIS with an energy of a few keV is injected to the AGOR cyclotron to be accelerated up to the desired kinetic energy of about one hundred MeV. This cyclotron, with superconducting coils, was built in a collaboration with IPN (Institut de Physique Nucléaire) Orsay, France. It has three compact sectors equipped with three accelerating electrodes, which can produce magnetic fields up to 4 T [78]. The electrodes are located in a pole valley with a diameter of 1.88 m. The operating diagram of AGOR cyclotron is shown in figure 3.4. Different ions are accelerated in a range of energy per nucleon depending on their charge to mass (Q/A) ratio. For example, protons are accelerated up to 190 MeV while deuterons can be accelerated up to 90 MeV/nucleon. However, pushing the beam energy up to the maximum value leads to a reduction of the luminosity in many cases. For this experiment, the deuteron beam was

delivered at the kinetic energy of 65 MeV/nucleon. Since the cross sections of interest are rather high, the intensity of the beam was not an issue for the present experiment.

Figure 3.4: The operating diagram of the AGOR cyclotron in 2007 for different ions. The diagram shows that protons could be accelerated up to 190 MeV and deuterons with $Q/A = 0.5$ could be accelerated up to 90 MeV/nucleon.

3.4 Detection system, BINA

After two outstanding campaigns of the previous generations of detection systems mounted at KVI, namely the **Big-Bite Spectrometer (BBS)** which is shown in figure 3.1, and the **Small-Angle Large-Acceptance Detector (SALAD)**, the new detection system, **Big-Instrument for Nuclear-Polarization Analysis (BINA)** was designed, manufactured and installed at KVI; see figure 3.1. BINA has the advantage of approximately a full coverage of the phase space (4π solid angle), higher precision in the measurement of relevant observables (specially at the forward angles), and the possibility for detecting the backward-scattered particles. In addition, BINA has the capability of detecting particles at intermediate energies up to around 190 MeV. A series of scattering experiments, such as $\vec{p}d$, $\vec{d}p$, and $\vec{d}d$, was already performed by

BINA to investigate different aspects of the few-nucleon potentials specially the three-nucleon force (3NF) effects. As illustrated in figure 3.5, BINA consists of two main parts: the forward wall and the backward ball of BINA. The two following subsections give a brief description of these two parts. A more detailed description can be found in Ref. [72].

Figure 3.5: A cross-view of BINA is shown with its main parts. The forward wall of BINA consists of the **M**ulti-**W**ire **P**roportional **C**hamber (MWPC), the twelve thin ΔE scintillators, and the ten horizontally-placed, in a cylindrical shape, E scintillators. There are also two rows of scintillators on the top and bottom of the cylindrical-shaped scintillators that were not used in the present experiment. The backward ball of BINA with 149 phoswich scintillators is used as a scattering chamber and detector system. Furthermore, the position of the target in the center of the backward ball and the direction of the incoming beam are shown.

3.4.1 The forward wall of BINA

The forward wall of BINA was designed to measure the energy, time-of-flight (TOF), position, and the type of particles that are scattered to the forward direction. The angular coverage of the forward wall of BINA is $10\text{-}31.5^\circ$ for a full azimuthal coverage and up to 37° for a limited azimuthal coverage. The forward wall of BINA consists of three parts: the **Multi-Wire Proportional Chamber (MWPC)**, twelve segmented hodoscopes of vertically-placed thin ΔE scintillators, followed by ten horizontally-placed E scintillator bars. The particles scattered off the target pass through the MWPC where their positions (polar and azimuthal angles) are measured. Next, the particles deposit a fractions of their energy in the ΔE scintillators and finally they are stopped in the E scintillators. Particle identification (PID) can be performed by combining the information of the ΔE - E plastic scintillators.

Multi-wire proportional chamber

The MWPC was installed at a distance of 29.7 cm from the position of the target and it has an active area of $38 \times 38 \text{ cm}^2$. It has three parallel planes, X, Y, and U. Each plane consists of a parallel array of equally-spaced anode wires to read-out the position of the scattered charged particles. The X plane has 118 output channels that are aligned vertically to read-out the x position. In the same way, the Y plane has 118 output channels that are aligned horizontally and give the y position. Finally, the U plane has 148 output channels and its anode wires are aligned with an angle of 45° with respect to the X and Y planes [82]. The U plane is used to resolve the ambiguity in the position measurement of two or more particles hitting the MWPC at the same time. A hole was embedded in the center of the MWPC to allow the dominantly un-deviated beam particles to pass through. The detection efficiency of the MWPC for the protons and deuterons is 97% and 99%, respectively [22].

ΔE and E scintillators

The ΔE detectors consist of twelve segmented hodoscopes of thin plastic scintillator bars with a thickness of 2 mm. These scintillators were made of a BICRON plastic, BC-408. They are embedded between the MWPC and E scintillators. There are two Photo-Multiplier-Tubes, PMTs¹ mounted on both sides of each bar. The signals from the two PMTs are correlated except for those surrounding the beam pipe. Since the amount of the deposited energy by each particle depends on the atomic number of the particle, the information

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¹ Phillips: XP1911/20, and XP1911/08

of the ΔE detectors along with the E detectors can be used to distinguish between deuterons, protons, and other particles. In our analysis, we have only used the ΔE detectors to determine the MWPC efficiency. For particle identification, these detectors were found not to be very efficient. The low light production of the ΔE scintillators led to a drop in statistics of the particles for some hodoscope elements. In fact, the ΔE detector response of all hodoscopes was not as was expected. In a visual inspection after the experiment, these scintillators were observed to be damaged. Therefore, the $\Delta E - E$ detectors could not provide the PID information for all scattering angles.

The E detectors consist of ten plastic scintillator bars that are mounted horizontally in a cylindrical shape. The position of the target is in the center of this cylindrically-shaped scintillators. The radius of this cylinder is 75.2 cm. These scintillators, with a thickness of 12 cm, were made of the BICRON plastic, BC-408. The thickness of these scintillators is sufficient to stop all the protons and deuterons with energies less than 140 MeV. The majority of the neutrons pass through and deposit a fraction of their energy in the E scintillators. Above and below the cylindrically-shaped detectors, two rows of 5 scintillators are mounted that are used to detect secondary-scattered particles in the polarization-transfer experiments. These were not used in the present experiment.

On the left and right side of each E scintillator bar, a PMT² is installed to collect the scintillation light from the deposited energy of the particles. By using a QDC³, the scintillation lights are integrated to measure the energy deposited in the scintillator. The discriminated signals from the Constant Fraction Discriminators, CFDs⁴, are fed to the Time-to-Digital Converter, TDCs⁵. By using TDCs, the time-of-flight (TOF) of the particles can be extracted. In addition, the time difference between the TDC signals from the left and right hand-side PMTs gives the arrival position of the particles in the scintillator bar. By exploiting this information, we can reconstruct the position of the incoming particles that are not detected by the MWPC, such as neutrons.

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² Photonis: XP4392/B

³ LeCroy 4300B ADC FERA

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

⁵ LeCroy 3377 TDC

3.4.2 The backward ball of BINA

As figure 3.5 shows, the backward ball of BINA has a beam pipe for the incoming particles to reach the target, a feed-through for mounting the target at the center of the ball, and phoswich scintillators. There are 149 pyramid-shape phoswich scintillators that are glued together to construct the required scattering chamber. The backward ball is used to detect particles with scattering angles in the range $40\text{--}165^\circ$ with an approximately full azimuthal coverage, except where the target holding-system is placed. Each pyramid-shape scintillator consists of two main parts, a fast plastic scintillator (made of BICRON BC-408) glued to a thin slow scintillator (with a thickness of 1 mm) from its face surface, made of BICRON BC-444. These two parts can be used for particle identification in the backward ball. The pyramid-shape scintillators are the building blocks of two cluster detectors, pentagonal and hexagonal shapes that are used to construct the backward ball. In our analysis, the backward ball of BINA is only used for selecting the coincidence particles in the elastic channel of the deuteron-deuteron scattering process.

3.4.3 Targets

Different targets were utilized in the liquid or solid state during the different scattering experiments with BINA such as the Zinc Sulfide, (ZnS), empty cell, solid CH_2 , and the liquid deuterium target. The ZnS target accompanied with the empty cell were used to align the beam position optically and to minimize the beam halo, respectively. The solid CH_2 and liquid deuterium targets are used for different scattering experiments. As illustrated in figure 3.5, the target holder unit was installed at the top of the backward ball with a tilt angle of 10° respect to the vertical axis.

The solid CH_2 , with a thickness of $\rho = 13.75 \pm 0.24 \text{ mg/cm}^2$, was used as a proton target for the deuteron-proton scattering experiment while the liquid deuterium, LD_2 , was used as a deuteron target for the proton-deuteron and deuteron-deuteron reactions. The advantage of the solid target is not only the ease of operation but also the lack of bulging of the target that increases the systematic uncertainties. The drawback of the solid target is that there is a huge background accompanied with the interesting reaction that comes from the carbon in CH_2 . In other words, the liquid target is usually pure and therefore suffers less from the background reactions. The drawback of the liquid deuterium is that it is more difficult to handle during the experiment. It has many different components, such as cryogenic system connections, heaters, gas-flow system, temperature sensors, and target-moving machinery. The complete setup can move vertically by a pneumatic system.

The target cell used in this experiment is made of a high purity aluminum

Figure 3.6: The target cell is shown in the left picture while the right one shows the target inside the backward ball of BINA with the liquid deuterium inside it. In this picture, the target cell is half-filled with the liquid deuterium. Also, the empty cell is shown, which is mounted below the liquid target cell. The thin aluminum cylinder around the target cell (the 80 K shield) is used to isolate the cold head from the surrounding environment.

to optimize the thermal conductivity; see figure 3.6. The target window is a transparent foil of Aramid with a thickness of around $4\ \mu\text{m}$ [83]. The typical operating temperature for the deuterium was 17 K and the pressure was about 256 mbar. The thickness of the liquid deuterium was 3.3 mm with a bulging around 0.65 mm. This bulging is due to a pressure difference between the inside and outside of the target cell. The actual target thickness was obtained by comparing the cross section measurements at KVI between the solid and liquid targets [22].

3.5 Beam current monitoring

Using a Faraday cup that is mounted at the end of the beam-line after BINA, the beam current was monitored during the experiment. The Faraday cup is made of a copper block containing a heavy alloy metal that acts as a complete beam stopper. The current meter connected to the Faraday cup was calibrated with a precision current source, KEITHLEY 263 calibrator/source, with an uncertainty of 2%. Typical beam currents for the deuteron-proton and deuteron-deuteron scattering experiments were 4 pA. An offset of 0.28 ± 0.13 pA was observed in the beam current during the deuteron-deuteron scattering experiment by comparing the measured T_{22} with BINA and that with the BBS setup at KVI. A summary of the experimental conditions is presented in table 3.2.

Table 3.2: An overview of the experimental parameters that were used in the $\vec{d}\vec{d}$ scattering experiments.

Average beam current	4 pA
Energy	65 MeV/nucleon
Live-time	40%
Target	Liquid deuterium
Target thickness	$67.6 \pm 3.4 \text{ mg/cm}^2$

3.6 Electronics

The electronic is one of the main parts of the BINA data acquisition, referred to as BINA-DAQ. In this thesis, a brief description of the electronics is presented; for a detailed explanation of BINA-DAQ, see Ref. [72]. The raw signals provided by the PMTs and MWPC are digitized and stored in BINA-DAQ. BINA-DAQ consists of four main parts: the read-out electronics to digitize the information of the detectors, a trigger system which is used to pre-select the events of interest, a real-time computer to collect the selected information, and a mass storage system located at the computing center of the University of Groningen to store the data. The electronics of the detectors of BINA can be divided into three subsections: the forward wall of BINA, backward ball of BINA, and MWPC.

The forward wall contains of ΔE and E detectors with 44 PMTs. Figure 3.7 shows the block-diagram of the forward wall electronic. Signals from the 20 PMTs of the E detectors accompanied with the 24 PMTs of the ΔE detectors are used as the input of an active splitter⁶. Using the active splitter, the signals are split into two equal parts without any amplification factor. The first output signals are fed to a discriminator, CFD⁷. The logic output signals of the CFDs are used as inputs of a trigger unit to generate triggers. Also, the signals are sent to a CAMAC-based time-to-digital Converter, TDC⁸. The TDCs were used in a common-stop mode in which the start signal of TDCs was made by the discriminator of the individual PMT signals. The stop signal was produced by the trigger signal. The second output signals are passed

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⁶ Giessen Splitter box

⁷ CAEN. 16 CH C808 CFD

⁸ LeCroy 3377 TDC

Figure 3.7: The general scheme of the forward-wall electronics of BINA is shown. Signals from the 20 PMTs of the E detectors accompanied with the 24 PMTs of the ΔE detectors are used as the input of an active splitter. The first output is sent to the CFD to be used as the input to the trigger unit as well as the TDCs. The second output is sent to the FERA after a cable delay of ~ 250 ns.

through the delay cables to reach a delay of around 250 ns and are then sent to a charge-integration QDCs unit⁹. The integration gate of the QDC comes from the trigger signal. The electronics of the backward ball of BINA depicted in figure 3.8, is similar to the forward wall of BINA except for the input signals which come from the 149 PMTs belonging to each backward ball scintillator. Also, the second output of the active splitter is fed to a passive splitter box which splits the signal up for a long-gate and short-gate integration.

The signals produced by the three planes of the MWPC are read-out by the PCOS-III¹⁰ electronic system. A block-diagram of the MWPC electronics is depicted in figure 3.9. The read-out signals from a total of 384 output channels, 118 read-out channels for the X plane, 118 read-out channels for the Y plane and 148 read-out channels for the U plane, are amplified and sent to the discriminator. Subsequently, the logic signals are delayed and registered with a programmable delay and latch unit. The information from the delay and latch unit are collected by a CAMAC PCOS controller unit and sent to a VME memory unit via a hand-shacking protocol.

⁹ LeCroy 4300B FERA

¹⁰ LeCroys Proportional Chamber Operating System (PCOS-III)

Figure 3.8: The block diagram of the BINA backward-ball electronics. The splitter box is the same type as used for the forward-wall electronics. In order to generate two copies of the output signal of the active splitter, the signal is sent to a passive splitter before going to the FERA.

Figure 3.9: The block diagram of the MWPC electronics. The signals produced by the three planes of the MWPC are read-out by the PCOS-III electronic system. The MWPC has three planes with the number of wires of X(118), Y(118) and U(148) in each plane and the read-out signals from a total of 384 output channels are amplified and sent to the discriminator system.

3.7 Trigger

For the $\vec{p}d$, $\vec{d}p$ and $\vec{d}d$ scattering experiments, three triggers were designed to pre-select specific reaction channels. As mentioned already in section 3.6, the input of the trigger unit comes from the detectors of the backward ball, and the E and ΔE scintillators of the forward wall of BINA. All the triggers are in coincidence with the cyclotron radio-frequency (RF) signal. These three triggers are defined as:

- T1 or break-up trigger is made to select the break-up events in which

both charged particles are detected in the forward wall. To achieve this, at least three PMTs in the forward wall of BINA should be firing. In other words, the multiplicity¹¹ of the OR¹² signals of the E and ΔE scintillators of the forward wall should be larger than 3 (Multiplicity ≥ 3).

- T2 or coincidence trigger is used to select the elastic events as well as the transfer channels and the break-up events in which one particle is detected in the forward wall in coincidence with another particle detected in the backward ball of BINA. This trigger is made from a coincidence between an OR signal of all the CFD signals of the forward scintillators and an OR of all the CFD output signals of the backward ball detectors.
- T3 or “single” trigger is used to select any event of different reaction channels. In fact, this trigger is used as a minimum-bias trigger and corresponds to an OR of all the CFD signals from all the scintillators in BINA including the forward wall and the backward ball. Furthermore, the “single” trigger is used to determine the efficiencies of the two other triggers.

A prescaler trigger box¹³ was used to combine the triggers and to produce a common trigger output (main trigger). The common trigger output was used to generate the gates of the QDCs, the strobe of the PCOS-III system, and the common stop signal of the TDCs. Since, cross sections for different reactions are different, the reactions with a larger cross sections dominate the trigger rate. To compensate for this effect, some of the triggers were down-scaled by the trigger box to reduce the bias on triggers with a larger count rate. The trigger box has the possibility to down-scale the individual triggers by a factor of 2^n ($n = 0, 1, 2, \dots$) or to disable them completely. Table 3.3 shows the typical counting rates of these three triggers [22, 72].

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¹¹ Multiplicity in this experiment is the number of firing PMTs in an event.

¹² The OR'd signal from all CFD outputs of the E -detector of the forward wall.

¹³ TB8000, Trigger box.

Table 3.3: The typical counting rates and down-scale factors of each individual trigger for different scattering experiments performed with BINA.

Reaction	$\vec{p}d$	$\vec{d}p$	$\vec{d}d$
T1 rate [kHz]	3.8	18	27
T1 down-scaling factor	2^2	2^0	2^0
T2 rate [kHz]	21	27	36
T2 down-scaling factor	2^1	2^1	2^1
T3 rate [kHz]	198	148	160
T3 down-scaling factor	2^9	2^8	2^8

4. Analysis techniques of $\vec{d}d$ scattering at 65 MeV/nucleon

4.1 Introduction

To investigate the three-nucleon force effects, 3NF, in the few-body systems, a series of scattering experiments has been done at KVI, such as proton-deuteron, deuteron-proton, and deuteron-deuteron scattering. Although the three-nucleon (3N) system is the cleanest system to study the 3NF effects since only the NN and 3N forces can contribute and observables can be calculated *ab-initio*, the influence of the 3NF effects are in general small in a 3N system. Only at specific parts of the phase space of the three-nucleon scattering processes, the 3NF effects become significant. Alternatively, one may look for 3N effects by assessing 4N systems where the 3N effects are enhanced due to a larger number of combinations of three interacting bodies.

Below the pion-production threshold, the deuteron-deuteron scattering process leads to five different hadronic reaction channels; see Chap. 1. This chapter presents the analysis procedure that was used to obtain differential cross sections and spin observables for the elastic, ${}^2\text{H}(\vec{d}, d)d$, and two different combinations of the three-body break-up channel, namely the ${}^2\text{H}(\vec{d}, dp)n$ and ${}^2\text{H}(\vec{d}, dn)p$ processes for a deuteron-beam energy of 65 MeV/nucleon. The data were obtained by making use of a vector- and tensor-polarized deuteron beam that was provided by the AGOR facility at KVI in Groningen, The Netherlands. Two experimental setups, located at two different beam-lines, were used to measure independently the various observables in the ${}^2\text{H}(\vec{d}, d)d$ scattering, namely the Big-Bite Spectrometer (BBS) and the Big Instrument for Nuclear-Polarization Analysis (BINA). This chapter addresses primarily the analysis of the data taken with BINA. Details related to the analysis of the BBS data can be found in Ref. [84]. The results presented here are the most precise and accurate data of the deuteron-deuteron scattering as a four-body system at intermediate energies and extend the overall database in the 4N system below the pion-production threshold to intermediate energies. The aim is to produce data that are sensitive to the details of few-nucleon forces, thereby allowing to study the role of 3N and 4N forces in the few-body systems in more detail. Besides studying the ${}^2\text{H}(\vec{d}, d)d$ channel, we also collected data of the $\text{H}(\vec{d}, dp)$ process by simply changing the liquid deuterium target to a

solid CH₂ target while keeping the rest of the system unchanged. As a result, the experimental conditions of both experiments were the same except for the targets. Furthermore, the data of both experiments were analyzed in the same way.

This chapter presents a description of the analysis procedure and the results of the measurement of the differential cross sections and a rich set of spin observables for a large portion of the phase space of the ${}^2\text{H}(\vec{d}, dp)n$ three-body break-up. This work extends the results of an earlier study reported in Ref. [85]. The results of coplanar configurations are compared with the recent available theoretical calculations based on the Single-Scattering Approximation, SSA; see Sec. 5.2.1.

For the ${}^2\text{H}(\vec{d}, dn)p$ reaction only analyzing powers were obtained since the neutron detection efficiency of the E plastic scintillators of the forward wall is around 10% with a large systematic uncertainty for determining cross sections. To achieve this goal, the feasibility of the neutron detection using BINA setup is investigated. By considering the fact that MWPC is just applicable for the charged particles such as deuterons and protons, the timing information of the E scintillators of the forward wall were used to measure the position and scattering angle of the detected neutrons. The energy of neutrons are reconstructed by using the information of their TOF. The discrimination between deuterons and protons is required in this situation and also here we made use of the TOF information. The analysis of ${}^2\text{H}(\vec{d}, dn)p$ and ${}^2\text{H}(\vec{d}, dp)n$ break-up reaction data was carried out in a consistent way. The only difference in the analysis of these reactions is related to detection of the proton/neutron scattering to forward angles. At the end of this chapter, the results of both reactions are discussed by making a comparison between them. In the next section, the event-selection procedure for the elastic and three-body break-up channels among other channels will be described.

4.2 Event selection

4.2.1 Event selection in the elastic channel

The kinematic of the elastic event as a two-body final state is described by six variables, namely the polar and azimuthal angles of the deuterons and their kinetic energies, denoted by θ_{d_i} , ϕ_{d_i} , E_{d_i} , respectively. The subscript $i = 1, 2$ is used to label the two final-state deuterons. We note that the kinematics of the elastic channel can be fully described by only measuring two of the six variables, since the other variables are determined by energy and momentum conservation. Before going into any detailed description of the data analysis,

it is necessary to specify the accessible kinematical phase space provided by BINA. Then, the process of identifying the elastic events will be presented. In the next sections, differential cross sections, vector and tensor analyzing powers are extracted in terms of the center-of-mass angle, $\theta_{c.m.}$, after correcting for detection efficiencies.

Figure 4.1 shows the accessible phase space based on the angular coverage of the wall and ball detectors in BINA. The left panel shows the energy of one of the deuterons in the final state as a function of its scattering angle. In this figure, the energy of the deuterons measured by the forward wall in terms of their scattering angles is shown by the red curve. The blue curve shows the region where one of the deuterons ends up in the backward ball. The energy calibration of the ten scintillator bars in the forward wall has been done by the kinematical loci presented by the red-line. This calibration was directly employed for the elastic channel, and as a primary calibration for the three-body break-up channel. The middle curve, colored in black, is called the ball-ball coincidence. In this part of the phase space, both deuterons are detected in the backward ball detectors of BINA. The right panel of figure 4.1 shows the correlation between the scattering angles of the two deuterons in the final state. The magenta line represents the region of the wall-ball coincidence in which one deuteron scatters to the forward wall in coincidence with another deuteron detected in the backward ball of BINA.

Besides evaluating the available phase space by BINA of the elastic scattering process, we also studied various methods (hardware and software) to suppress the background mostly from other hadronic channels such as the break-up and transfer channels. As mentioned in chapter 3, during data taking, various hardware triggers with different down-scale factors were implemented that were dedicated to a specific hadronic final-state in the deuteron-deuteron scattering. For the selection of events originating from the elastically-scattered deuterons, two triggers were used. First, the so-called coincidence trigger, which was down-scaled by a factor two, is formed with at least one signal from the forward wall scintillators in coincidence with at least one signal from the backward ball scintillators. The detector thresholds were typically set around 1 MeV. Although, with the coincidence trigger we were able to cover a large part of the angular distribution of the $^2\text{H}(\vec{d}, d)d$ reaction, whereby both deuterons in the final state were detected, we observed a significant drop in the detection efficiency for low-energetic deuterons that scatter towards the backward ball due to energy losses of those particles in the liquid-deuterium target. The data selected with the coincidence trigger were used to extract the spin observables, since detection inefficiencies cancel out in the analysis. To extract the differential cross section, we exploited a second trigger, the

Figure 4.1: Left panel: the energy of one of the deuterons in the final state as a function of its scattering angle. The red-line shows the part of the phase space in which one deuteron is detected in the forward wall. The blue-line belongs to the corresponding deuteron detected in the backward ball in coincidence with the detected deuteron in the forward wall. Right panel: the correlation between the scattering angles of the two elastic deuterons in the final state. The wall-ball coincidence is shown with the magenta line.

so-called “single” trigger. This trigger, down-scaled by a factor 256, was built from a logical OR of all the discriminated signals of the scintillators of BINA, and, thereby, not biased on the response of the backward ball. Therefore, the available phase space will be enhanced to extract the differential cross section without compensating for the inefficiencies in the backward ball.

The data from the coincidence trigger were calibrated and further pre-processed by requiring that the relative angles of the reconstructed particles hitting the forward wall and backward ball match the correlation that is expected from kinematical considerations for the elastic deuteron-deuteron scattering process; see figure 4.1. More specifically, the opening angle between the outgoing deuterons has to be 90° , and the momentum of the deuterons in the final state has to be in the same plane as the beam. The latter condition is called coplanarity. These conditions are applied to the data in the form of two cuts. After applying these angular cuts with a window of $\pm 20^\circ$, a major reduction of the background from other hadronic final states, such as the break-up and nucleon-transfer reactions, was obtained.

Figure 4.2 shows the correlation between the energy and scattering angle of deuterons detected in the forward wall of BINA after applying the afore-

Figure 4.2: The correlation between the energy and the scattering angle of the reconstructed particles that were detected in the forward wall of BINA with coincidence requirement with the backward ball after the application of the appropriate conditions (see text). The simulated Monte Carlo points shown by black dots represent the kinematical locus for the elastic deuteron-deuteron scattering process. The data below the elastic events belong to the neutron-transfer channel.

mentioned cuts. Events that originate from elastically-scattered deuterons can easily be observed and distinguished from the background. The dashed line represents the expected kinematical locus for the elastic deuteron-deuteron scattering. The data below the elastic events reveal another clear correlation which has been identified as events belonging to the neutron-transfer channel, $d + d \rightarrow {}^3\text{H} + p$.

The energy of the particles in the elastic reaction does not change in the center-of-mass frame, therefore, the energy spectrum of the elastic channel will be angular independent. In other words, transforming the energy spectrum of figure 4.2 to this frame facilitates the event selection for each interval of the scattering angle. Furthermore, the data were corrected for the recoil effects when each event is transformed to the center-of-mass frame. Therefore, to count the number of events that originate from the elastic-scattering process, the center-of-mass energy for each reconstructed particle is calculated from its energy deposit and scattering angle.

Figure 4.3 shows the correlation between the center-of-mass energy and scattering angle of events that were detected in the forward wall. As expected, the center-of-mass energy of the elastically-scattered deuterons is constant as

Figure 4.3: The correlation between the center-of-mass energy ($E_{c.m.}$) and the scattering angle (θ) of the reconstructed particles that were detected in the forward part of BINA with a coincidence requirement with the backward ball. Comparing the data with the dashed line demonstrates that the reconstructed center-of-mass energy remains constant as a function of the scattering angle of the deuteron.

indicated by the dashed line. To extract the number of counts, the data presented in figure 4.3 were projected to the Y-axis in intervals of 2° of the scattering angle and separated for various polarization states of the beam. The value of 2° for each interval is significantly larger than the resolution of the experimental setup.

Figure 4.4 depicts the center-of-mass energy distribution that has been obtained using data obtained from the “single” trigger. The upper spectrum shows the raw response after calibration and for particles that scatter to $26 \pm 1^\circ$ with no further conditions. For the lower spectrum, a coincidence with the backward ball was required in addition using the kinematical cuts discussed earlier but from data taken with the “single” trigger. The solid lines are the result of a fit through the data based on a Gaussian-distributed signal combined with a 5th-order polynomial representing the backgrounds. The background component of the fit is indicated by the dashed lines. A clear peak can be observed in both cases, corresponding unambiguously to the channel of interest. The coincidence requirement reduces significantly the background contribution. Monte Carlo simulations showed that the remaining background

is mostly due to hadronic interactions of elastically-scattered deuterons in the scintillator. The full-width-at-half maximum ($FWHM$) of the lower spectrum is found to be around 2 MeV which gives an estimate for the energy resolution of the detectors in the forward wall of BINA. The number of counts under the peak after background subtraction is used to extract the cross section via “single” trigger. The cross section was extracted also via coincidence requirements and it is found to be consistent with those extracted via “single” trigger within the uncertainties. The analyzing powers also extracted using coincidence requirements.

Figure 4.4: Spectrum of the center-of-mass energy of particles hitting the E detectors of the forward wall. Data are obtained using the “single” trigger. The scattered particles are confined to polar angles of $26 \pm 1^\circ$. For the lower spectrum, a coincidence condition is imposed in the event selection. The solid lines show the results of a least- χ^2 fit based on a Gaussian (signal) and a 5th-order polynomial (background) distribution. The background contribution is indicated by the dashed lines. The reduced χ^2 of the fit is 1.4 for the upper spectrum and 1.2 for the lower one.

4.2.2 Event selection in the three-body break-up channel

In the analysis of the three-body break-up channel, we would like to find the correlation between the energy of the deuteron and the proton for the desired configuration, $(\theta_d, \theta_p, \phi_{12})$. In totally, there are nine variables involved in the three-body break-up process, namely θ_i , ϕ_i , and E_i where i refers to the deuteron, proton, and neutron. Considering the momentum and energy con-

Figure 4.5: Energy correlation between the deuterons and the protons detected in coincidence in the forward wall of BINA at the target position for some configurations of the three-body break-up indicated in the inset. The kinematics of each configuration, $(\theta_d, \theta_p, \phi_{12})$, is defined by the scattering angle of the deuteron, θ_d , scattering angle of the proton, θ_p , and the relative azimuthal angle of the two particles, ϕ_{12} .

servation laws, measuring the variables of two particles are enough to obtain the other kinematical variables unambiguously. As a result, the kinematics of each configuration of the three-body break-up channel are specified by the scattering angle of the deuteron, θ_d , the scattering angle of the proton, θ_p , the difference between azimuthal angle of the deuteron and proton, $\phi_{12} = |\phi_d - \phi_p|$, and the correlation between the energies of the two particles, E_d and E_p . For convenience in the analysis, the energies of the deuteron and proton are also expressed by two new variables, namely S and D . The variable S is the arc-length along the S -curve with the starting point at the minimum energy of the deuteron. The variable D is the distance between the point (E_d, E_p) and the kinematical S -curve. Figure 4.5 shows the theoretical S -curves of some configurations in the three-body break-up channel. For instance, the configuration $(20^\circ, 90^\circ, 180^\circ)$ indicates that the scattering angle of the first particle (the deuteron) is $20^\circ \pm 2^\circ$, the scattering angle of the proton is $90^\circ \pm 2^\circ$, and the

difference between the azimuthal angle of the two particles is $180^\circ \pm 5^\circ$. This energy correlation is used to calibrate the energy response of the scintillators for breakup events. In addition, it is used to distinguish between signal and background contributions.

4.3 Energy calibration of the E scintillators

The prerequisites of any analysis on the three-body break-up channel is the energy calibration of the ten E scintillator bars in the forward wall of BINA and the particle identification. First, a pre-calibration is done by using the deuterons from the elastic channel of the deuteron-deuteron scattering and the protons from the elastic channel of the deuteron-proton scattering. Then, we find the correlation between the energies of the deuteron and proton for the desired configuration, $(\theta_d, \theta_p, \phi_{12})$. In this step, two methods for energy calibration have been exploited to investigate the sensitivity of the final results to the energy calibration procedures. For the first calibration method, we followed the procedure given in Ref. [22]. In this method, the detector response has been parametrized by a three-parameter fit-function. The measured cross sections that were reported in Ref. [22] using this method of calibration were preliminary and the data have not been published. Moreover, we found that these cross sections were underestimated by a factor 2000 due to a mistake which will be discussed later.

In the second method, we increased the number of degrees-of-freedom in the fit to five parameters for the calibration function to match the experimental data points to the theoretical S -curve. The average of the obtained results based on the two energy calibration procedures was considered as the final result for each data point; see chapter. 5. The difference between these two results for each data point gives a systematic uncertainty attributed to different calibration procedures. In the following, the second energy calibration procedure used in the present analysis is described in detail.

The amount of energy deposited in each E scintillator of the forward wall is proportional to the multiplication of the ADC information coming from the left and right PMTs mounted on the both sides of each scintillator. First of all, a pre-calibration was done by using the dd (dp) elastic events to convert the energy deposited of the deuterons (protons) in the unit of ADC channel number to the unit of MeV. As an example, the result of the pre-calibration for the kinematical configuration $(\theta_d = 25^\circ, \theta_p = 25^\circ, \phi_{dp} = 180^\circ)$ is shown in figure 4.6. The solid line represents the expected kinematical locus for the desired configuration at the detector position, or in the other words, after correcting the energy losses of the particles in the medium between the target

Figure 4.6: The result of the pre-calibration procedure for the kinematical configuration ($\theta_d = 25^\circ, \theta_p = 25^\circ, \phi_{dp} = 180^\circ$). The solid line represents the expected kinematical locus for the same configuration at the detector position.

and the forward E detectors. The deuteron is heavier than the proton and, therefore, its energy loss is more than the proton. The amount of scintillation light produced by the impinging particles in each scintillator depend on the type of particle which could have different quenching factors.

The next step is to match the experimental data points to the expected kinematic locus (the solid line in figure 4.6). To achieve this goal, we have found a gain factor for each experimental data point for the proton (the X-axis) and deuteron (the Y-axis) separately based on the minimum distance between each point of the experimental locus and that for the theoretical locus. Then two fourth-order polynomial calibration functions for the proton and deuteron are separately extracted from fitting the obtained gain factors. Figure 4.7 shows the same data as presented in figure 4.6 after applying the two calibration functions.

In the final step, the energy of the particles at the E -detector position should be converted to the energy at the target position. For this purpose, the energy loss due to materials between the target and E detectors was esti-

Figure 4.7: The same data as shown in figure 4.6 after applying the calibration functions as described in the text. The solid line represents the expected kinematical locus for the same configuration at the detector position.

mated by a GEANT3 simulation. The correlation between the energy at the detector position (E_{dep}) and that energy at the target position (E_{tar}) for the proton (the deuteron) is presented in the left panel (right panel) of figure 4.8. The diagonal lines in both panels represent the scenario in which no energy loss takes place, *i.e.* $E_{\text{dep}} = E_{\text{tar}}$. Figure 4.9 shows the energy correlation between the registered deuteron and proton after calibration and energy-loss corrections.

4.4 Reconstruction of the kinematics of the neutron

4.4.1 The reconstruction of the hit positions of the neutron

Neutrons are not seen by the MWPC due to lack of any energy deposit in it. Therefore, its position (the X- and Y-coordinates) is extracted from the time-of-flight (TOF) information and hit positions registered by the scintillators of the forward wall. The difference between the left (TDC_L) and right (TDC_R)

Figure 4.8: The correlation between the energy at the detector position (E_{dep}) and that energy at the target position (E_{tar}) for the proton (left panel) and the deuteron (right panel). The diagonal lines correspond to $E_{\text{dep}}=E_{\text{tar}}$.

TDC signals coming from the PMTs for each detector is used to extract the X coordinate of the hit; $\Delta TDC = TDC_L - TDC_R$ is proportional to the X coordinate. To find this proportionality, the hit positions of the charged particles in the MWPC are used. Thus, the correlation between the X coordinate using the MWPC for the charged particles and that using ΔTDC gives the corresponding X coordinate in the E scintillator position. Figure 4.10 shows this correlation for the E scintillator number 1. The solid line which is obtained by a line fit through the middle of the spectrum is used to extract the X coordinate of the detected particles. The resolution of the reconstructed X coordinate has been found to be around 2.9 cm. To extract the Y coordinate, the middle Y position of each scintillator is used as the Y coordinate of the hits that were detected in that scintillator. Since the width of the horizontal E scintillators is 9 cm, the resolution of the Y coordinate is around 4.5 cm.

By knowing the X and Y coordinate of each hit, the polar and azimuthal angles can be calculated. To check the reliability of the polar and azimuthal angle determination via the reconstructed MWPC via TOF information of the hits, the obtained scattering angles of the charged particles are compared with those derived from the information of the MWPC; see figure 4.11. This figure demonstrates that the two measurements (one obtained by the TOF information and the other obtained using the MWPC) for the polar angle (left panel) and the azimuthal angle (right panel) agree with each other. The solid lines

Figure 4.9: The same data as presented in figure 4.7 after correcting for the energy losses between the target and the scintillator. The reconstructed energies correspond to the values at the target position. The solid line represents the expected kinematical locus at the target position.

show the bisector line. The angular resolution of both reconstructed polar and azimuthal angles are around 2° . The agreement between the two methods for charged particles is very good lending confidence to apply the TOF-based position determination for neutrons.

4.4.2 The energy reconstruction of the neutron using conservation laws

The detection efficiency for neutrons of the E scintillators is relatively small. Moreover, the majority of these neutrons cannot deposit their whole energy in the scintillators. Therefore, the energy of the detected neutrons cannot be measured by using the ADC signals of the PMTs mounted on both sides of each scintillator. One of the feasible methods to reconstruct the energy of the neutron is using the energy and momentum conservation laws.

The nine kinematical variables involved in the three-body break-up chan-

Figure 4.10: The X coordinate of the MWPC versus the difference between the left (TDC_L) and the right (TDC_R) TDC signals of the E scintillator number 1. The solid line is a line fit through the middle of the spectrum.

Figure 4.11: The left (right) panel shows the comparison of the measured polar (azimuthal) angle using the TOF information of the E scintillators of the forward wall and those measured by the MWPC. The solid lines are the bisector line.

nel are the polar and azimuthal angles and energies of the deuteron, proton, and neutron. By considering the energy and momentum conservation laws, the kinematic of the reaction is completely determined by measuring just five kine-

Figure 4.12: The energy of the proton at the target position (E_p) measured by BINA after energy calibration versus the reconstructed energy of the proton ($E_{p_{Rec.}}$) using the conservation laws. The solid line is the bisector line. The tail under the bisector line belongs to events in which a particle has undergone a hadronic interaction.

mathematical variables involved. In this reaction, the kinematical variables (energy and scattering angles) of the deuteron are measured directly using the detector components of BINA. Also, the polar and azimuthal angle of the neutron can be obtained by the reconstruction of the neutron position, as discussed in the previous section. Then, solving the four equations, corresponding to the four conservation laws, the numerical package (TMinuit) in ROOT leads to the other kinematical variables such as the energy of the neutron.

To check the validity of our energy reconstruction procedure, we refer again to the proton case in the ${}^2\text{H}(\vec{d}, \vec{dp})n$ reaction by supposing that the proton acts like the neutron in the ${}^2\text{H}(\vec{d}, \vec{dn})p$ reaction. Figure 4.12 shows the energy of the proton at the target position (E_p) measured by BINA after energy calibration versus the reconstructed energy of the proton ($E_{p_{Rec.}}$) using the conservation laws. It indicates that the reconstructed energy is compatible with the measurement done by BINA. Moreover, the energy reconstruction

Figure 4.13: The left panel shows the normal S -curve of the configuration ($\theta_d = 28^\circ, \theta_p = 28^\circ, \phi_{dp} = 180^\circ$) for the ${}^2\text{H}(\vec{d}, dp)n$ reaction where both energies of the proton and deuteron are measured with BINA. The solid line shows the expected kinematical locus for this configuration. The right panel shows the corresponding reconstructed S -curve. In this case, the energy of the deuteron (E_d) is measured by BINA after energy calibration and the energy of the proton ($E_{p_{Rec.}}$) is obtained using the conservation laws.

procedure can be considered as a validation of our energy calibration procedure. The solid line is the bisector line. The tail under the bisector line belongs to the hadronic interactions involved in the reaction.

By knowing the energy of the neutron, the S -curve of the deuteron-neutron case can be reconstructed. Also here, we exploited the alternative proton-reconstruction method of the ${}^2\text{H}(\vec{d}, dp)n$ reaction as a check. The right panel in figure 4.13 represents the reconstructed S -curve of the configuration ($\theta_d = 28^\circ, \theta_p = 28^\circ, \phi_{dp} = 180^\circ$) for the ${}^2\text{H}(\vec{d}, dp)n$ reaction. The solid line shows the expected kinematical locus for this configuration. In this case, the energy of the deuteron (E_d) is measured by BINA after energy calibration and the energy of the proton ($E_{p_{Rec.}}$) is obtained using the conservation laws. The left panel of figure 4.13 shows the conventional method that is used to obtain the S -curve of the ${}^2\text{H}(\vec{d}, dp)n$ reaction for the same configuration. The results shown in the right panel of figure 4.13 demonstrate that we correctly applied energy and momentum conservation to each event. Also note that the data do not perfectly fall on top of the expected S -curve (solid line). This is because the data are selected for a finite bin in each configuration whereas the conservation laws are applied for each event. With this energy-reconstruction method, we are also able to extract S for each event. We can, therefore, present our results of the ${}^2\text{H}(\vec{d}, dn)p$ reaction in the same way as we do for the ${}^2\text{H}(\vec{d}, dp)n$ reaction.

4.5 Particle identification of the channel using TOF information

The next step is to describe the technique that is used to identify the type of particle, namely proton or deuteron, in the ${}^2\text{H}(\vec{d}, dp)n$ reaction. Particle identification is performed by comparing the measured relative TOF of the registered particles and their theoretical results of what we expect from the kinematics of the three-body break-up reaction. This procedure was checked with the information of the missing mass of the undetected particle, namely the neutron, and it shows a clear peak around the mass of the neutron for correctly identified particles [85].

The Time-to-Digital Converter (TDC) outputs corresponding to the PMTs of the left (TDC_L) and right (TDC_R) side of each scintillator are added for each event. The TDCs are utilized in a common-stop mode. The start signal of the TDC comes from the individual PMT signal and the stop signal is produced by the signal coming from the trigger. The sum of the left and right TDCs ($TOF_i = (TDC_L)_i + (TDC_R)_i$) is independent of the hit position. The index i is referred to the deuteron and proton hit in the scintillators in the forward wall. Then, the difference between the measured TOF of the deuteron and proton from the information of the TDCs, $(TOF_d - TOF_p)_{TDC}$, and that calculated from the energies and path lengths of the particles assuming that the first particle is a deuteron and the second is a proton, $(TOF_p - TOF_d)_E$, is used to define the variable ΔTOF . In this process, ΔTOF , is in the first order, independent of the value of S :

$$\Delta TOF = (TOF_d - TOF_p)_{TDC} - (TOF_p - TOF_d)_E. \quad (4.1)$$

Figure 4.14 shows the ΔTOF as a function of the energy of the particle we supposed to be deuteron before the particle identification and for a specific configuration. The scattering angles of the two particles are fixed to be $25^\circ \pm 2$ with the relative azimuthal angle of $180^\circ \pm 5$. There are three concentrations of data in the spectrum that are distinguishable. For the calculation of $(TOF_p - TOF_d)_E$ in Eq. 4.1, we assumed that the first particle is a deuteron and the second particle is a proton. It should be emphasize that another assumption where the first particle is proton and the second particle is deuteron is considered in the event selection as well. Also, we used the energy of the deuteron and proton at the interaction point, thereby, not taking into account energy losses while traveling to the detector. For those particles satisfying this assumption, the variable ΔTOF should be around zero, the bottom band. Deviation from zero in the band at the bottom (also for other bands), is due to

Figure 4.14: ΔTOF as a function of the energy of the particle we supposed to be the deuteron. The scattering angles of the two particles are fixed to be $25^\circ \pm 2$ with the relative azimuthal angle of $180^\circ \pm 5$. The data concentrated in the bottom (top) band correspond to the three-body break-up channel for which the first particle is a deuteron (proton) and the second one is a proton (deuteron) of the dp combination (pd combination). The middle ones correspond to the four-body break-up channel whereby the two detected particles are protons (the pp combination). The solid line is used as a graphical cut to select the desired combination.

energy losses of the particles when traveling from the target to the detector, while we assumed that energy of the particle is unchanged for the calculation of the TOF.

Figure 4.15 shows the energy correlation between the deuteron and proton for the configuration $(\theta_d, \theta_p, \phi_{12}) = (25^\circ \pm 2, 25^\circ \pm 2, 180^\circ \pm 5)$ after particle identification. The tail on the left-hand side of the S -curve is dominated by events which have undergone hadronic interactions. The solid line represents the expected kinematical S -curve. The S -curve is divided to S -bins with a width of 10 MeV. One of those bins are indicated in the figure by the dashed lines and used to count the number of events inside the S -bin. To count the number of break-up events in the interval of $S - \frac{\Delta S}{2}$ and $S + \frac{\Delta S}{2}$, the events are projected on a line perpendicular to the S -curve for each S -bin with the value of ΔS with a width of ± 5 MeV. The result of projected events for a particular

Figure 4.15: The energy correlation between deuteron and proton for the configuration $(\theta_d, \theta_p, \phi_{12}) = (25^\circ \pm 2, 25^\circ \pm 2, 180^\circ \pm 5)$ after particle identification. The solid line represents the expected kinematic S -curve originating from the kinematical calculation. The dashed lines indicate one of the S -intervals. The inset figure shows the result of projected events for this S -interval.

S -bin is presented in the inset of figure 4.15. This spectrum consists of a peak around zero which belongs to the break-up events with a negligible amount of accidental background. The peak shows that the majority of the break-up events deposit all their energies in the scintillator. The tail on the left-hand side of the peak corresponds to events which have undergone hadronic interactions inside the scintillator. The tail on the right-hand side of the peak comes from accidental backgrounds. The solid line in the inset of the figure 4.15 is the result of a fit through the data based on a Gaussian-distributed signal combined with a third-order polynomial representing the hadronic interactions contribution. The number of events under the peak is used for further analysis. The contribution of hadronic interactions is estimated by a GEANT3 simulation. The data are corrected for the loss of break-up events due to hadronic

interactions for the extraction of the differential cross section. The average hadronic inefficiency for the deuteron (proton) is $16\% \pm 2\%$ ($10\% \pm 2\%$) [85].

4.6 Particle identification in ${}^2\text{H}(\vec{d}, dn)p$ process

The neutron gives no trace in the MWPC but it can be seen through the E scintillators of the forward wall. Therefore, one can use the MWPC as a veto to identify neutrons. The average MWPC inefficiency for protons and deuterons is measured to be around 3% and 1%, respectively. This implies that when we label the particles which have no trace in the MWPC as neutral particles, they are sometimes mislabeled by those charged particles that are not seen by MWPC. It is obvious that charged particles dominantly deposit all their energy in the E scintillators while just around 10% of the neutrons have a trace in the scintillator where they often deposit a fraction of their energy in the scintillator. By making use of this knowledge, it is possible to identify and separate neutrons from charged particles.

Figure 4.16 shows the energy correlation between the particles seen by MWPC (Y-axis) and those particles which had no trace in the MWPC (X-axis). It shows that the majority of events involve neutrons since the spectrum peaks towards lower neutron energies corresponding to events for which a small fraction of energy is deposited and not registered by the MWPC. Only a few percent of all candidate neutron events deposited a large energy in the E scintillator. These events correspond to charged particles for which the MWPC was inefficient. Therefore, by utilizing a graphical cut we can exclude most of the misidentified charged particles not seen by the MWPC for a further analysis.

The neutron as a neutral particle is distinguishable from other charged particles because the neutron gives no trace in MWPC. To identify a deuteron from a proton, particle identification is required. The procedure of the particle identification for the three-body break-up channel in which neutron is seen as well as one additional charged particles is approximately the same as we applied for the ${}^2\text{H}(\vec{d}, dp)n$ reaction. As discussed in Sec. 4.5, the variable ΔTOF is defined as the difference between the measured TOF of the deuteron and neutron from the information of the TDCs, $(TOF_d - TOF_n)_{TDC}$, and the one calculated from the energies and path lengths of the particles, $(TOF_n - TOF_d)_E$. The energy of the neutron in this case is obtained by solving numerically the four energy and momentum conservation laws. Figure 4.17 shows the correlation between the variable ΔTOF and the energy of the particle that is supposed to be deuteron. The concentration of the data in the figure clearly shows events corresponding to deuteron-neutron coincidences of

Figure 4.16: The energy correlation between the particles seen by MWPC (Y-axis) and those particles which had no trace in the MWPC (X-axis). The solid line shows the graphical cut used to exclude misidentified charged particles not seen by the MWPC. “MeVee” indicates that the X-axis is proportional to the light output.

the three-body break-up channel in ${}^2\text{H}(\vec{d}, dn)p$.

The process of the particle identification using the reconstructed energy of the neutron is also checked with ${}^2\text{H}(\vec{d}, dp)n$ reaction by assuming that the proton acts like the neutron. Figure 4.18 shows the calculated ΔTOF as a function of the energy of the particle which is supposed to be the deuteron before the particle identification and for a specific configuration in the ${}^2\text{H}(\vec{d}, dp)n$ reaction for the configuration indicated in the caption. The left panel shows the normal calculated ΔTOF using the measured energy of the proton via BINA detection system while the right panel shows the calculated ΔTOF using the reconstructed energy of the proton (assuming the proton is similar to the neutron in the reaction ${}^2\text{H}(\vec{d}, dn)p$). It indicates that our interesting region, namely the dp combination of the three-body break-up, remains unchanged and therefore it can be easily selected for further analysis. Therefore, we can conclude that the process of particle identification is also applicable for the ${}^2\text{H}(\vec{d}, dn)p$ reaction to distinguish the dn combination from the pn combination.

Figure 4.17: The variable ΔTOF as a function of the energy of the particle which is supposed to be a deuteron before particle identification and for the configuration $(\theta_d = 25^\circ \pm 2, \theta_n = 25^\circ \pm 2, \phi_{dn} = 180^\circ \pm 5)$, in the ${}^2\text{H}(\vec{d}, dn)p$ reaction. The interesting concentration of data is shown as dn combination of the ${}^2\text{H}(\vec{d}, dn)p$ reaction.

4.7 Extraction of cross sections and analyzing powers

4.7.1 Observables in the elastic channel

To measure the cross section, the extracted number of counts from the elastic events should be corrected for efficiencies and other parameters of the system. To experimentally determine the cross section, we make use of the following relation:

$$\frac{d\sigma}{d\Omega} \left[\frac{mb}{sr} \right] = \frac{Nq}{LT \epsilon Q[nC] \Delta\Omega[sr] n[1/mg] t[mg/cm^2] N_A}, \quad (4.2)$$

Figure 4.18: The variable ΔTOF as a function of the energy of the particle which is supposed to be a deuteron before particle identification and for a specific configuration in the ${}^2\text{H}(\vec{d}, dp)n$ reaction. The scattering angles of the two particles are fixed to be $25^\circ \pm 2$ with the relative azimuthal angle of $180^\circ \pm 5$. The left panel shows the normal calculated ΔTOF using the measured energy of the proton via BINA while the right panel shows the calculated ΔTOF using the reconstructed energy of the proton (assuming the proton is similar to the neutron in the reaction ${}^2\text{H}(\vec{d}, dn)p$).

where

- N = The measured number of counts under the peak after background subtraction;
- q = The charge of the projectile (deuteron);
- A = The atomic mass of the target (2);
- LT = The electronic live-time of the setup;
- ϵ = The efficiencies of the MWPC, losses due to hadronic interaction. etc.;
- Q = The total integrated charge collected in the Faraday cup;
- $\Delta\Omega$ = The solid angle covered by the detector;
- t = The target thickness;
- N_A = The Avogadro's number;
- n = The number of scattering centers of the target per mole
(In this experiment, $n \equiv 2$).

The thickness of the liquid deuterium target was 67.6 ± 10.98 mg/cm² including the bulging in the $\vec{d}d$ scattering experiment. For the $\vec{d}p$ scattering experiment, a solid CH₂ target was used with an effective thickness of 13.75 ± 0.24 mg/cm².

For a scattering experiment in which neither the beam nor the target are polarized, the extracted cross section is independent on the azimuthal angle. In other words, there is an axial symmetry for the cross section with respect to the direction of the beam. However, by using a polarized beam, the spins of the beam particles are aligned in a preferred direction and, therefore, the cross section is not azimuthal independent any more. In fact, the interaction of a polarized beam with an unpolarized target produces an azimuthal asymmetry in the cross section. This asymmetry ratio is proportional to the product of the magnitude of polarization of the beam particles and another observable, namely the analyzing power. Utilizing the vector and tensor polarized beam in our experiment gives the possibility of measuring the analyzing powers. As mentioned in chapter 2, the cross section of any reaction with a polarized beam under the parity conservation for a coplanar two-body final state is given by:

$$\sigma(\theta, \phi) = \sigma_0(\theta) [1 + \sqrt{3} p_Z \text{Re}(iT_{11})(\theta) \cos(\phi) - \frac{1}{\sqrt{8}} p_{ZZ} T_{20}(\theta) - \frac{\sqrt{3}}{2} p_{ZZ} \text{Re}(T_{22})(\theta) \cos(2\phi)]. \quad (4.3)$$

It is convenient for further analysis to rewrite Eq. 4.3 by:

$$\begin{aligned} \frac{\sigma(\theta, \phi)}{\sigma_0(\theta)} = k [1 + \frac{3}{2} p_Z A_y(\theta) \cos(\phi) - \frac{1}{4} p_{ZZ} A_{zz}(\theta) \\ + \frac{1}{4} p_{ZZ} (A_{zz}(\theta) + 2A_{yy}(\theta)) \cos(2\phi)], \end{aligned} \quad (4.4)$$

where θ and ϕ are polar and azimuthal angles of the scattered deuteron, respectively. Further, p_Z and p_{ZZ} are vector and tensor polarizations, respectively. A_y is the vector analyzing power, while A_{zz} and A_{yy} are the tensor analyzing powers. k is the normalization factor and should be equal to one for a perfect normalization. The cross section ratio is determined experimentally by taking the ratio of the charge-normalized counts of the polarized beam over that of the unpolarized beam. Since, the other variables like the target thickness, inefficiencies (except the polarization), and solid angle, are the same for the cross section of the reaction with polarized beam ($\sigma(\theta, \phi)$) and those for unpolarized beam ($\sigma_0(\theta)$), they cancel out when obtaining analyzing powers. We used the data collected with the coincidence trigger to extract the analyzing powers because of high statistic in the event selection without worrying about

inefficiencies. The procedure of the event selection for extracting analyzing powers is the same as that of the cross section except for using the coincidence trigger.

We have extracted the analyzing powers with two different methods resulting in final numbers which are compatible with each other within the statistical uncertainties. In the first method, we suppose that the polarized beam of the deuteron is a pure-vector or a pure-tensor polarized beam during each experiment. The normalization factor, k , should be equal to one, so we constrain $k = 1$. If we consider k as a free parameter, we have a small fluctuation of about 3% ($k = 1.00 \pm 0.03$) which is considered as a systematic uncertainty for the normalization procedure. Then, as it is shown in Eq. 4.4, the asymmetry ratio of the cross section for a polarized over unpolarized beam as a function of azimuthal angle shows a $\cos \phi$ shape if a pure-vector polarized beam of deuteron is used and a $\cos 2\phi$ shape when a tensor polarized beam of deuteron is used; see figure 4.19. The amplitude of the observed $\cos \phi$ oscillation in this figure corresponds, according to Eq. 4.4, to $\frac{3}{2}p_Z A_y(\theta)$. The measured value for the vector polarization of the deuteron beam was $p_Z = -0.601 \pm 0.029$ [85]. The vector analyzing power, A_y is then extracted from the amplitude of $\cos \phi$. In the same way, the amplitude of the $\cos 2\phi$ in the lower panel is $+\frac{1}{4}p_{ZZ}(A_{zz}(\theta) + 2A_{yy}(\theta))$. In addition, there is an offset from one, as illustrated in the lower panel, for the $\cos 2\phi$ function which is equal to $-\frac{1}{4}p_{ZZ}A_{zz}(\theta)$. The measured value for the tensor polarization of the deuteron beam was $p_{ZZ} = -1.517 \pm 0.032$ [85]. Therefore, the tensor analyzing powers A_{zz} and A_{yy} are extracted from the offset of $\cos 2\phi$ from one and its amplitude, respectively.

In the second method, the assumption is that the pure-vector (tensor) polarized beam is not actually a pure-vector (tensor). In other words, the pure-vector (tensor) polarized beam is contaminated with another polarization, say the tensor (vector) polarization. Here, the normalization factor, k , is multiplying each term in Eq. 4.4 and the whole equation is used as a fit-function with four free parameters. So, the asymmetry ratio of the cross section for the polarized over unpolarized beam as a function of azimuthal angle simultaneously shows a $\cos \phi$ and $\cos 2\phi$ shapes. As described before then, the analyzing powers can be extracted from the amplitudes of the $\cos \phi$ and $\cos 2\phi$ functions as well as the offset of $\cos 2\phi$ function from one. The results of both methods agree with each other within the statistical errors as mentioned before.

Figure 4.19: The asymmetry ratio of the cross sections for a polarized over unpolarized beam as a function of ϕ for a pure-vector polarized beam (top panel) and a pure-tensor polarized beam (bottom panel). Here, we used the entire Eq. 4.4 as the fit-function. The scattering angle of the elastically scattered deuteron is $26 \pm 1^\circ$. The $\chi^2/89$ for the top (bottom) panel is 1.04 (0.97).

4.7.2 Differential cross section in the three-body break-up

To measure the cross section for each configuration, the extracted number of counts is corrected for efficiencies of the system such as live-time, MWPC efficiencies, losses due to hadronic interactions, and down-scale factor that was used in the hardware trigger. The differential cross section for each kinematical S -bin ($\theta_d, \theta_p, \phi_{dp}, S$) is defined by:

$$\frac{d^5\sigma}{d\Omega_d d\Omega_p dS} = \frac{Nq}{LT} \frac{A}{\epsilon Q n t N_A} \cdot \frac{1}{\Delta\Omega_d \Delta\Omega_p dS}. \quad (4.5)$$

Here

dS = The size of the energy window along the S -curve in units of MeV;

$\Delta\Omega_i$ = The solid angle covered by the detector for the i^{th} particle,

where i stands for the proton and deuteron. The rest of the variables are the same as defined for Eq. 4.2. The effective target thickness of the liquid deuterium was around 67.6 mg/cm^2 . The detection efficiency of the forward wall scintillators was estimated by a GEANT3 simulation. The detection inefficiency originates mainly from the hadronic interactions. The typical beam current in this experiment was $\sim 5 \text{ pA}$.

4.7.3 Asymmetry ratio and analyzing powers in the three-body break-up channel

In general, the cross section of any reaction with a polarized beam is defined as:

$$\begin{aligned} \sigma(\xi, \phi) = \sigma_0(\xi) & [1 + \sqrt{3}p_Z \text{Re}(iT_{11}(\xi)) \cos(\phi) \\ & + \sqrt{3}p_Z \text{Im}(iT_{11}(\xi)) \sin(\phi) \\ & - \frac{1}{\sqrt{8}}p_{ZZ}T_{20}(\xi) \\ & - \frac{\sqrt{3}}{2}p_{ZZ}\text{Re}(T_{22}(\xi)) \cos(2\phi) \\ & - \frac{\sqrt{3}}{2}p_{ZZ}\text{Im}(T_{22}(\xi)) \sin(2\phi)], \end{aligned} \quad (4.6)$$

where σ (σ_0) is the five-fold differential cross section of the reaction with polarized (unpolarized) beam and ξ represents the kinematical variables of each configuration, $(\theta_d, \theta_p, \phi_{12}, S)$. p_Z and p_{ZZ} are the vector and tensor polarizations, respectively. $\text{Re}(iT_{11})$ and $\text{Im}(iT_{11})$ ($\text{Re}(T_{20})$, $\text{Re}(T_{22})$, and $\text{Im}(T_{22})$) are the vector (tensor) analyzing powers and ϕ is the azimuthal scattering angle of the deuteron. All five analyzing powers were extracted by analyzing the three-body break-up channel.

To extract the whole set of analyzing powers, we define:

$$f^{\tilde{\xi}, \phi_{12}}(\phi) = \frac{\sigma(\xi, \phi)}{\sigma_0(\xi)}, \quad (4.7)$$

where $\xi \equiv (\tilde{\xi}, \phi_{12})$, i.e. $\tilde{\xi}$ defines all kinematical variables excluding $\phi_{12} \equiv \phi_d - \phi_p$. Mirror configurations are those kinematical configurations that differ only in the sign of the relative azimuthal angle ϕ_{12} . The imaginary parts of analyzing powers in Eq. 4.6 are odd under parity conservation while the other three analyzing powers are even. So, by using Eq. 4.7, the mirror configurations $(\tilde{\xi}, \phi_{12})$ and $(\tilde{\xi}, -\phi_{12})$ are used to construct two asymmetry combinations:

$$g^\xi(\phi) = \frac{f^{\tilde{\xi}, \phi_{12}}(\phi) + f^{\tilde{\xi}, -\phi_{12}}(\phi)}{2}, \quad (4.8)$$

and

$$h^\xi(\phi) = \frac{f^{\tilde{\xi}, \phi_{12}}(\phi) - f^{\tilde{\xi}, -\phi_{12}}(\phi)}{2}, \quad (4.9)$$

where $g^\xi(\phi)$ and $h^\xi(\phi)$ are:

$$\begin{aligned} g^\xi(\phi) = & 1 + \sqrt{3}p_Z \text{Re}(iT_{11}(\xi)) \cos(\phi) \\ & - \frac{1}{\sqrt{8}}p_{ZZ}T_{20}(\xi) \\ & - \frac{\sqrt{3}}{2}p_{ZZ}\text{Re}(T_{22}(\xi)) \cos(2\phi), \end{aligned} \quad (4.10)$$

and

$$\begin{aligned} h^\xi(\phi) = & + \sqrt{3}p_Z \text{Im}(iT_{11}(\xi)) \sin(\phi) \\ & - \frac{\sqrt{3}}{2}p_{ZZ}\text{Im}(T_{22}(\xi)) \sin(2\phi). \end{aligned} \quad (4.11)$$

Figure 4.20 (top two panels) shows the data for $g^\xi(\phi)$ as a function of ϕ for the kinematic point $\xi \equiv (\theta_d, \theta_p, \phi_{12}, S) = (25^\circ, 20^\circ, 180^\circ, 240 \text{ MeV})$ for a pure-vector polarized beam (top panel) and a pure-tensor polarized beam (second panel). Using data obtained from a pure-vector polarized beam, ($p_{ZZ} = 0$), the $\text{Re}(iT_{11})$ is extracted from the amplitude of the $\cos \phi$ -shape of the fit-function of Eq. 4.10; see the top panel of figure 4.20. Data extracted from a pure-tensor polarized beam, ($p_Z = 0$), produce a $\cos 2\phi$ -shape of the azimuthal asymmetry with an offset from one due to the term, $\frac{1}{\sqrt{8}}p_{ZZ}T_{20}(\xi)$, in Eq. 4.10; see the second panel of figure 4.20. The amplitude of the $\cos 2\phi$ -shape yields $\text{Re}(T_{22})$ and the offset from one gives $\text{Re}(T_{20})$.

Figure 4.20 (bottom two panels) shows the data for $h^\xi(\phi)$ as a function of ϕ for a pure-vector polarized beam (third panel) and a pure-tensor polarized beam (bottom panel) for the kinematic configuration $\xi \equiv (\theta_d, \theta_p, \phi_{12}, S) = (25^\circ, 20^\circ, 160^\circ, 230 \text{ MeV})$. In the same way, using data obtained from a pure-vector polarized beam, $p_{ZZ} = 0$, the $\text{Im}(iT_{11})$ can be extracted from the amplitude of the $\sin \phi$ -shape fit-function of Eq. 4.11; see the third panel of figure 4.20. Also, the analyzing power, $\text{Im}(T_{22})$, is extracted from the amplitude of the $\sin 2\phi$ -shape fit-function of Eq. 4.11 via using the pure-tensor polarized beam, $p_Z = 0$; see the bottom panel of figure 4.20.

4.8 $\vec{d}p$ scattering experiment at 65 MeV/nucleon

To investigate the compatibility of our approach for the measurement of the differential cross section and analyzing powers of the elastic channel in $\vec{d}d$

Figure 4.20: Top two panels (bottom two panels), the data for $g^\xi(\phi)$ ($h^\xi(\phi)$) as a function of ϕ for a pure-vector polarized beam (top and third panels) and a pure-tensor polarized beam (second and forth panels) for the kinematic configuration $\xi \equiv (\theta_d, \theta_p, \phi_{12}, S) = (25^\circ, 20^\circ, 180^\circ \text{ (} 160^\circ \text{)}, 240 \text{ MeV (} 230 \text{ MeV)})$. The values of $\chi^2/35$ are 0.97, 0.91, 1.099, and 1.14, from the top to the bottom spectrum, respectively.

scattering, we measured the differential cross section and analyzing powers for the elastic channel of the reaction $H(\vec{d}, dp)$ via the coincidence trigger in exactly the same manner as for the elastic channel of reaction ${}^2H(\vec{d}, d)d$. The

target used in this experiment was a solid CH_2 . It should be emphasized that the experimental setup for the $\vec{d}p$ scattering experiment was exactly the same as that for the $\vec{d}d$ scattering experiment. Also, the systematic uncertainties for both scattering experiments were the same as well as the beam energy (65 MeV/nucleon). An overview of general information about the $\vec{d}p$ scattering experiment is presented in table 4.1. The data of the deuteron-proton scattering experiment were taken during the deuteron-deuteron scattering experiment.

Figure 4.21 shows the results of the differential cross section and analyzing powers for the reaction $\text{H}(\vec{d}, dp)$ for the forward angles as a function of the center-of-mass angle, $\theta_{c.m.}$. In each panel, the results of the present analysis are shown as filled circles with statistical uncertainties. The open triangles show the results of the differential cross section taken at RCNP [56]. The open circles and filled triangles show the analyzing power data taken earlier at KVI, [55, 59], and open rectangles are those taken at RIKEN [54]. The solid curves show the results of a coupled-channel calculation by the Hannover-Lisbon theory group based on the CD-Bonn potential including the Coulomb interaction and an intermediate Δ -isobar [40]. The dashed lines represent the results of a similar calculation but excluding the Δ -isobar. Our measured observables for this reaction were found to be in a good agreement with the existing experimental data set and state-of-the-art calculations and show that the procedure of our data analysis and experimental setup are well understood.

Table 4.1: General information of $\vec{d}p$ scattering experiment.

$\vec{d}p$ scattering experiment	
Average Beam Current	30 pA
Energy	65 MeV/nucleon
Target	Solid CH_2
Target thickness	$13.8 \pm 0.2 \text{ mg/cm}^2$
Average efficiency of MWPC for deuterons	$98\% \pm 1\%$
Average efficiency of hadronic interaction for deuterons	$84\% \pm 2\%$
Average live-time of the data acquisition	45%

4.9 Systematic uncertainties and efficiency corrections

Based on Eq. 4.2 (4.5), the number of counts extracted from the data as explained in Sec. 4.2.1 (4.5) should be corrected for various efficiencies of the

Figure 4.21: Differential cross section and analyzing powers of the elastic channel of the reaction $H(\vec{d}, dp)$ are shown with the same beam energy as for the reaction ${}^2H(\vec{d}, d)d$ ($E_d^{lab} = 65$ MeV/nucleon). In each panel, the results of the present analysis are shown as filled circles with statistical uncertainties only. The open circles show the same data but analyzed independently [59]. The open triangles show the results of the cross sections measured at RCNP [56]. The filled triangles show the analyzing power data measured earlier at KVI, [55], and open rectangles are those measured at RIKEN [54]. The gray bands show the systematic uncertainties (2σ). The solid curves show the results of a coupled-channel calculation by the Hannover-Lisbon theory group based on the CD-Bonn potential including the Coulomb interaction and an intermediate Δ -isobar [21]. The dashed lines represent results of a similar calculation but excluding the Δ -isobar.

system. First of all, the number of counts were corrected with the live-time of the system. The average live-time of the data acquisition of BINA for this reaction is around 40%. Second, the number of counts are corrected by the down-scaling factor coming from the trigger system. As mentioned in Sec. 3.7, each trigger has its own down-scaling factor. Other corrections for the number of counts are the detection efficiency of the MWPC for the deuteron and

proton which were 99% and 97% respectively, and correction for the losses due to hadronic interactions.

Events that are away from the kinematical loci are background events coming from other hadronic channels and some good events that undergo hadronic interactions inside the scintillators. Since hadronic interactions are not distinguishable easily from the other background, their contribution is estimated by analyzing part of the data which is roughly background-free or by using the results of a GEANT3 simulation. The average hadronic losses (events falling outside the loci) of the deuteron (proton) is $16\% \pm 2\%$ ($10\% \pm 2\%$).

For the extraction of the differential cross section, one of the main uncertainties of the system comes from the thickness of the liquid-deuterium target due to the bulging effect and it is around 5%. Other systematic uncertainties come from the determination of beam luminosity that was continuously monitored during the experiment via a Faraday cup mounted at the end of the beam line (2%), error in the efficiency of the MWPC for the deuteron (proton) of 1% (3%), and errors in determining the amount of hadronic losses for the deuterons with 2%. Furthermore, a systematic uncertainty is considered due to the calibration procedure that is dominant in the extraction of the differential cross section. This uncertainty is included for each data point of the measured differential cross sections. A detailed description of the systematic uncertainty coming from the calibration procedure is presented in Sec. 4.3.

In the case of measuring the analyzing powers, one of the main uncertainties comes from the determination of polarization, which is about 4%. The polarization of the deuteron beam was extracted using ϕ -asymmetry measurements of the dp elastic process based on its well-known analyzing powers [85]. Note that the same experimental setup is used also for the deuteron-deuteron scattering experiment. Figure 2 in Ref. [85] shows the results of the LSP measurements as well as polarization values obtained by BINA as a function of time. To achieve this, the polarization of the deuteron beam was monitored for different periods of the experiment and found to be stable within statistical uncertainties. Another systematic uncertainty comes from the beam luminosity, which is about 2%.

An additional systematic error has been identified that stems from uncertainties in the measurement of the beam current using a Faraday cup. A small offset of 0.28 ± 0.13 pA in the readout of the current was observed. The offset has been determined by calculating the minimum reduced χ^2 for different values of the offset using the comparison between the results of the $Re(T_{22})$ from the elastic dd scattering process and from an independent measurement using the BBS setup [84]. The error is obtained by evaluating the χ^2 distribution as a function of offset. The intersection points of this distribution with a χ^2

Table 4.2: Systematic uncertainties for $d\vec{d}$ scattering experiment.

[illegible]

(*) The data of the elastic channel are used to extract the average error due to the offset of beam current. Therefore, this error is not presented.

value that is one unit larger than its minimum has been used to determine the uncertainty in the offset. This offset imposes a shift on both polarized and unpolarized cross sections in the same direction. Such a shift causes an additional offset in the ratio of σ/σ_0 , and therefore, imposes remarkable systematic uncertainties on $Re(T_{20})$. However, the effect of the offset in σ/σ_0 is very marginal on $Re(iT_{11})$ and $Re(T_{22})$, since these observables are primarily sensitive to the amplitude of the $\cos\phi$ and $\cos 2\phi$ oscillations.

In the ${}^2\text{H}(\vec{d}, dn)p$ reaction, a systematic uncertainty is considered in addition due to the background effect. Low-efficiency detection of the neutrons leads to a drop in the statistics of the neutrons in each bin of the S -curve that makes it practically impossible to determine the background efficiently. Therefore, the effect of background is estimated by averaging the surrounding background around the signal of interest for each bin. The difference between the results of the analyzing powers with and without subtracting the background is considered as the systematic uncertainty (2σ) due to the background. Such a systematic uncertainty is dominant in the extraction of the analyzing powers while other systematic uncertainties are negligible. An overview of the systematic uncertainties and efficiency corrections for $\vec{d}d$ and $\vec{d}p$ scattering experiments are presented in table 4.2 [22].

5. Results and discussion

In this chapter, the results of differential cross sections and a rich set of analyzing powers for the elastic and three-body break-up channels of the deuteron-deuteron scattering process are presented. In Sec. 5.1, the measured observables for the elastic channel with a two-body final state are presented and discussed. This work extends and also confirms the results that were obtained from a previous analysis [22]. At small center-of-mass angles, the backward scattered deuterons have a large probability to be stopped before they reach one of the backward ball detectors. The fraction of those events that gave a signal in the backward ball is hard to determine. To be able to obtain reliable cross section measurements in this part of the phase space, we used the data taken with the down-scaled “single” trigger to avoid a bias on the backward ball of BINA. The analyzing-power measurements were extracted from data taken with the coincidence trigger to optimize the statistical precision while minimizing the background. Section 5.2 presents the results of the three-body break-up reaction. This section is composed of two parts. In the first part, we discuss the results of the ${}^2\text{H}(\vec{d}, dp)n$ reaction and in the second part the ${}^2\text{H}(\vec{d}, dn)p$ channel. Our results are compared to those of a previous analysis of the ${}^2\text{H}(\vec{d}, dp)n$ reaction. Our measurements of the differential cross section differ by a factor of 2000 from those reported in Ref. [22]. The difference is now understood and point to a trivial error in the previous analysis that affected the absolute normalization of the cross section data. Our data of several analyzing powers agree well with earlier studies reported in Ref. [22]. Moreover, we extended these measurements by extracting for the first time the imaginary parts of the analyzing powers. The second part of the section is devoted to a presentation and a discussion of our results of the ${}^2\text{H}(\vec{d}, dn)p$ reaction for which we reconstructed for the first time the information of forward-scattered neutrons.

5.1 Results for the elastic deuteron-deuteron scattering process

The results of the differential cross section and analyzing powers for the elastic deuteron-deuteron scattering process, ${}^2\text{H}(\vec{d}, d)d$, as a function of the center-of-mass angle, $\theta_{c.m.}$, are summarized in figure 5.1. Our results are shown as

Figure 5.1: Differential cross sections and analyzing powers for the ${}^2\text{H}(\vec{d}, d)d$ elastic reaction. The error bars represent only the statistical errors for each point. The results of this work are shown by filled circles. These results are compared with the previous analysis of the KVI data which are shown by open rectangles [22] and the results of the previous data analysis from the BBS setup at KVI are shown by open circles. The solid lines are the results of calculations based on the lowest-order terms in the Born series expansion of the Alt-Grassberger-Sandhas (AGS) equation for four-nucleon interactions using the CD-Bonn+ Δ potential [21, 41, 42]. The total systematic uncertainty is 7% for the differential cross sections and 5% for the analyzing powers and its size (2σ) is indicated by the gray bands.

filled circles, while the results of the previous analysis of KVI data are presented as open rectangles [22]. Also, the results of the analysis of BBS data by the group at IUCF are shown by the open circles. The results are pre-

sented only with their statistical errors that are smaller than symbol sizes for some data points. The total systematic uncertainty for the differential cross section is 7% and for the analyzing power is 5%. The systematic uncertainty is indicated by a gray band in each panel. The solid lines come from a rough approximation based on the lowest-order terms in the Born series expansion of the Alt-Grassberger-Sandhas equation for four-nucleons interactions using the CD-Bonn+ Δ potential [21, 41, 42].

In order to verify the validity of our approach to obtain the observables of the ${}^2\text{H}(\vec{d}, d)d$ reaction, the same approach was employed to extract the well known observables of the $\text{H}(\vec{d}, dp)$ reaction with a CH_2 target. The results of this study were presented in figure 4.21. A very good agreement was found between our data, earlier published datasets, and the results of state-of-the-art calculations based on modern NN+3N forces, demonstrating the validity of our analysis procedure.

In summary, we have analyzed the elastic deuteron-deuteron scattering process at 65 MeV/nucleon. Data were taken with the BINA setup. The measured observables were compared to data taken with a completely different setup than BINA, namely the BBS, and an excellent agreement within uncertainties between both datasets were observed. At present, there is no model available that is even close to give a reasonable description of the data at these energies.

5.2 Results for the three-body break-up channel

5.2.1 ${}^2\text{H}(\vec{d}, dp)n$ reaction

The differential cross sections and five different analyzing powers for the three-body break-up channel in ${}^2\text{H}(\vec{d}, dp)n$ have been extracted as a function of S for various configurations. Two energy calibration methods were applied to extract the observables discussed earlier in Sec. 4.3. For the results presented in figures 5.2-5.31, the average of the two methods is used. The differences between the two methods are indicated by a gray band for each configuration that is dominant in the total systematic uncertainty. The contribution of the other systematic uncertainties are around 7% (5%) of each measured value of the differential cross sections (analyzing powers). The kinematical variables of each configuration are indicated in each figure. For instance, the scattering angle of the deuteron is indicated in the caption of each figure. The scattering angles of the proton for each panel (configuration) are shown at the right-hand side of each figure. The absolute values of the relative azimuthal angles, ϕ_{12} , are indicated at the top of each figure. The preliminary results of Ref. [22]

underestimated the differential cross sections by a factor of 2000 due to a unit error and a factor two because of missing half of the statistics while performing PID which were found during the re-analysis of the data in the present work.

The recent theoretical calculations based on the single-scattering approximation (SSA) by using the CD-Bonn+ Δ potential are represented for the other three analyzing powers and cross sections of the coplanar configurations; see figures 5.2-5.21. In SSA, the break-up amplitude is calculated using the first term in the Neumann series expansion of the corresponding exact four-nucleon equations. The single-scattering break-up amplitude consists of four terms, two of which come from the break-up of the deuteron target and the two others come from their counterparts, namely the break-up of the deuteron beam. In SSA1, only the term related to the deuteron-target break-up with neutron acting as a spectator is included while in SSA4, all four terms are included [40–42].

We note that the validity of SSA is limited to the quasi-free domain. Therefore, we have left out the results of the calculations for non-coplanar configurations. Very large discrepancies are indeed found between data and theory for non-coplanar cases as shown in Ref. [87]. We expect, however, that the single-scattering approximation provides a reasonable estimate of the observables of the three-body break-up reaction in the quasi-free configurations. The red dashed-dotted (black solid) line represents SSA1 (SSA4) in each panel. The blue dashed lines indicate the energy of the neutron as the third particle in unit of MeV. We define the quasi-free scattering (QFS) region by those configurations at which the energy of the neutron is less than 300 keV that corresponds to the Fermi motion of nucleons inside the deuteron. In general, there is a good agreement between the data and the theoretical calculations in the QFS region. Note that the QFS region corresponds to the part of phase space at which the cross section peaks according to the SSA1 and SSA4 calculations. At those configurations, the results of SSA1 and SSA4 give similar predictions indicating that the SSA1 term dominates in the more extended SSA4 calculations.

Figures 5.2-5.6 show that the single-scattering approximation for the differential cross sections follows the experimental data very well within the systematic uncertainties in the QFS region particularly in the regions where the energy of the neutron is very close to zero. Also, comparing the experimental spin observables and the theoretical estimations reveals a general agreement, particularly in the QFS region. But a more detailed inspection, *e.g.* Figs. 5.7-5.11 show that the SSA underestimates the vector analyzing power ($\text{Re}(iT_{11})$) for the configurations with smaller scattering angles of proton while it agrees perfectly with the data for the configurations with large scattering angles of

the proton. This can be related to Coulomb effects being stronger when the particles move close to each other. Also, it can be concluded that the regions for which SSA1 (red dashed-dotted line) and SSA4 (black solid line) meet each other, the SSA follows the data very well. By comparing the results of the tensor analyzing power ($\text{Re}(T_{20})$), figures 5.12-5.16, a general agreement can be observed between the results of SSA and the data in the QFS region especially for the configurations in which the scattering angle of the proton is less than 30° . In some configurations, a systematic shift can be observed between the predictions by the SSA and the data. Figures 5.17-5.21 show the results for another tensor analyzing power, namely ($\text{Re}(T_{22})$). It interestingly shows a very good agreement between SSA and the data in most of the configurations in the QFS region. It should be stated again that in the regions where SSA1 (red dashed-dotted line) and SSA4 (black solid line) meet each other, there is a perfect agreement between SSA and the data. The two imaginary parts of the analyzing powers, namely $\text{Im}(iT_{11})$ and $\text{Im}(T_{22})$, should be zero for coplanar configurations due to the parity conservation. Our data agree well with this prediction as can be seen from the results shown in figures 5.22-5.31.

As a general conclusion, despite the fact that SSA is as a rough approximation for a four-body interaction, the single-scattering approximation generally produces observables for a four-body interaction with respectable quality. A thorough investigation on the quasi-free behaviour of the data indicates that in identifying regions of kinematics for the study of the quasi-free reaction, one should not only constrain the momentum of the spectator neutron to low values, but also consider the momentum transfer between the beam projectile and the ejectile in the analysis. Chapter 6 presents a dedicated study addressing this aspect in more detail. These results are published in European Journal of Physics A.

Figure 5.2: The results of differential cross sections as a function of S [MeV] for the three-body break-up channel of the reaction ${}^2\text{H}(\vec{d}, dp)n$ for the configurations for which $\theta_d = 15^\circ$. Other kinematical variables are shown at the top and right side of the figure. The gray bands show the systematic uncertainty (2σ) coming from the calibration procedure, which is dominant in the total systematic uncertainty. The contributions of the other systematic uncertainties are around 7% of each measured value. The red dashed-dotted (black solid) line shows the results of the SSA1 (SSA4) approximation using CD-Bonn+ Δ potential and the blue dashed line indicates the neutron energy using the same scale with a unit of MeV. This line is not visible in all plots.

Figure 5.3: Same as figure 5.2 except for $\theta_d = 20^\circ$.

Figure 5.4: Same as figure 5.2 except for $\theta_d = 25^\circ$.

Figure 5.5: Same as figure 5.2 except for $\theta_d = 28^\circ$.

Figure 5.6: Same as figure 5.2 except for $\theta_d = 30^\circ$.

Figure 5.7: The results of $\text{Re}(iT_{11})$ with the same information of figure 5.2 except that the contributions of the other systematic uncertainties are around 5% of each measured value.

Figure 5.8: Same as figure 5.7 except for $\theta_d = 20^\circ$.

Figure 5.9: Same as figure 5.7 except for $\theta_d = 25^\circ$.

Figure 5.10: Same as figure 5.7 except for $\theta_d = 28^\circ$.

Figure 5.11: Same as figure 5.7 except for $\theta_d = 30^\circ$.

Figure 5.12: The results of $\text{Re}(T_{20})$ with the same information of figure 5.7.

Figure 5.13: Same as figure 5.12 except for $\theta_d = 20^\circ$.

Figure 5.14: Same as figure 5.12 except for $\theta_d = 25^\circ$.

Figure 5.15: Same as figure 5.12 except for $\theta_d = 28^\circ$.

Figure 5.16: Same as figure 5.12 except for $\theta_d = 30^\circ$.

Figure 5.17: The results of $\text{Re}(T_{22})$ with the same information of figure 5.7.

Figure 5.18: Same as figure 5.17 except for $\theta_d = 20^\circ$.

Figure 5.19: Same as figure 5.17 except for $\theta_d = 25^\circ$.

Figure 5.20: Same as figure 5.17 except for $\theta_d = 28^\circ$.

Figure 5.21: Same as figure 5.17 except for $\theta_d = 30^\circ$.

Figure 5.22: The results of $\text{Im}(iT_{11})$ as a function of S [MeV] for the three-body break-up channel of the reaction ${}^2\text{H}(d, dp)n$ for the configurations for which $\theta_d = 15^\circ$. Other kinematical variables are shown at the top and right side of the figure. The solid lines represent the zero line. The gray bands show the systematic uncertainty coming from the calibration procedure.

Figure 5.23: Same as figure 5.22 except for $\theta_d = 20^\circ$.

Figure 5.24: Same as figure 5.22 except for $\theta_d = 25^\circ$.

Figure 5.25: Same as figure 5.22 except for $\theta_d = 28^\circ$.

Figure 5.26: Same as figure 5.22 except for $\theta_d = 30^\circ$.

Figure 5.27: The results of $\text{Im}(T_{22})$ with the same information of figure 5.22.

Figure 5.28: Same as figure 5.27 except for $\theta_d = 20^\circ$.

Figure 5.29: Same as figure 5.27 except for $\theta_d = 25^\circ$.

Figure 5.30: Same as figure 5.27 except for $\theta_d = 28^\circ$.

Figure 5.31: Same as figure 5.27 except for $\theta_d = 30^\circ$.

In summary, we have presented a thorough analysis of the three-body break-up reaction of ${}^2\text{H}(\vec{d}, dp)n$, at 65 MeV/nucleon. The experiments were conducted at the AGOR facility at KVI using the BINA 4π -detection system. The three-body break-up reaction has been identified by using the information of TOF, scattering angles, and energies of the particles. We provided a rich set of measured cross sections and analyzing powers for various configurations. The results of coplanar configurations of two imaginary parts of analyzing powers were consistent with zero within statistical uncertainties, demonstrating that our data do not suffer from unknown detector or reconstruction asymmetries. The results of the coplanar configurations for the cross sections and three analyzing powers are compared with the recent theoretical calculations based on the Single-Scattering Approximation (SSA) [40–42]. The data are reasonably well described by the model in the case where the neutron energy becomes very small. Together with future state-of-the-art *ab-initio* calculations, these data will provide further insights into the dynamics of three- and four-nucleon forces in few-nucleon systems.

5.2.2 ${}^2\text{H}(\vec{d}, dn)p$ reaction

The results of analyzing powers for the three-body break-up channel in the ${}^2\text{H}(\vec{d}, dn)p$ reaction have been extracted as a function of S for those configurations in which the full azimuthal coverage is available, see figures 5.33–5.46. The results of the ${}^2\text{H}(\vec{d}, dn)p$ reaction are shown by blue circles while those for the ${}^2\text{H}(\vec{d}, dp)n$ reaction are shown as black circles. The gray bands show the systematic uncertainty due to the background effects which is estimated using the ratio of the signal to the surrounding background; see Sec. 4.9. Other systematic uncertainties were found to be negligible. The theoretical calculations based on the SSA1 (SSA4) are also shown with the red dashed-dotted (black solid) lines. These results are the first measurements in the channels in which neutrons are detected as well as the charged particles. This allows us to investigate the isospin dependence of the reaction by comparing the results of the ${}^2\text{H}(\vec{d}, dp)n$ reaction with those of the ${}^2\text{H}(\vec{d}, dn)p$ reaction. Also, the Coulomb effects can be investigated by comparing these two results.

The number of points presented in each configuration (panel) of the ${}^2\text{H}(\vec{d}, dn)p$ reaction is usually less than that for the ${}^2\text{H}(\vec{d}, dp)n$ reaction because of the lower statistics in the dn case due to the large neutron detection inefficiency (around 90%). Another consequence of this large inefficiency is the lower signal-to-background ratio which results in a larger systematic uncertainty compared to the ${}^2\text{H}(\vec{d}, dp)n$ reaction (the gray band in each panel).

Figure 5.32: The results of the calculations performed by KSU code for the neutron detection efficiency as a function of neutron energy for different energy thresholds of the neutron detection, 8.0 MeV (dashed line), 10.4 (solid line), and 12.4 MeV (dashed-dotted line). Another calculation with SCINFUL code was done for the 10.4 MeV energy threshold of neutron detection which is shown as dotted line. The calculation is done by assuming the thickness and the type of the scintillator are 112.5 mm and NE102 that are approximately compatible with the detectors of BINA. Figure taken from Ref. [88].

Figure 5.32 shows the simulation of the response of the E scintillators to neutrons as a function of neutron energy for different energy thresholds [88]. It indicates that roughly 10% of the neutrons from the ${}^2\text{H}(\vec{d}, dn)p$ reaction are detected. Also, we estimated the applied fraction of neutrons for extracting the analyzing powers by comparing the yield of dn combination of the ${}^2\text{H}(\vec{d}, dn)p$ reaction with that of the corresponding dp combination of the ${}^2\text{H}(\vec{d}, dp)n$ reaction and assuming that their cross sections are similar. From this analysis, we obtain a neutron reconstruction efficiency varying between 3-7% depending upon the energy of neutron. We note that this value is smaller than 10% because of the additional constraints we impose in the dn analysis to reduce the background as discussed in the previous chapter.

Comparing the results of the analysis of the ${}^2\text{H}(\vec{d}, dn)p$ channel with that of the ${}^2\text{H}(\vec{d}, dp)n$ reaction shows us that there is an overall agreement between them within the uncertainties. However, at some specific configurations, a

systematic and significant shift between the two datasets can be observed. For example, the results of the $\text{Re}(iT_{11})$ in the configurations that protons scatter into the 25° and the scattering angle of the deuteron is less than 25° . It is very interesting to compare the ${}^2\text{H}(\vec{d}, dn)p$ with ${}^2\text{H}(\vec{d}, dp)n$ reaction in the QFS region because of high statistics. The QFS region can be identified by those configurations at which the energy of the spectator neutron becomes very small as indicated by the blue dashed lines. Comparing the analyzing powers for the ${}^2\text{H}(\vec{d}, dn)p$ and ${}^2\text{H}(\vec{d}, dp)n$ reactions in this region indicates that differences are generally within the uncertainties except for some configurations where the results of ${}^2\text{H}(\vec{d}, dn)p$ reaction are in better agreement with SSA calculations compared to the ${}^2\text{H}(\vec{d}, dp)n$ reaction. The observed (small) differences in the analyzing powers between the two reactions could point to an isospin dependency or Coulomb effects. To systematically investigate these effects, *ab-initio* calculations are needed that include both isospin and Coulomb effects. Moreover, these results show that we can go one step forward and analyze the four-body break-up channel in which the measurements of the kinematical variables of the neutron is required as well as the deuteron and proton to fully fix the kinematics of this channel.

In summary, we have presented the first measurement of the analyzing powers for the three-body break-up reaction of ${}^2\text{H}(\vec{d}, dn)p$, at 65 MeV/nucleon. To achieve this, the neutrons are detected as well as the protons and deuterons to recognize the kinematical variables of this reaction. The results of analyzing powers for more than 60 configurations of the ${}^2\text{H}(\vec{d}, dn)p$ reaction are presented and compared with those for the ${}^2\text{H}(\vec{d}, dp)n$ reaction. Globally, the measured analyzing powers of both reactions are very close to each other as one would naively expect. However, significant deviations have been observed at specific configurations. Also, the results of the recent theoretical predictions based on Single-Scattering Approximation (SSA) [40–42] are presented as well.

Figure 5.33: The blue points show the results of $\text{Re}(iT_{11})$ as a function of S [MeV] for the three-body break-up channel of the reaction ${}^2\text{H}(\vec{d}, dn)p$ for the configurations with the kinematical variables shown at the top and the right side of the figure. The black points show the corresponding results for the ${}^2\text{H}(\vec{d}, dp)n$ reaction. The gray bands show the systematic uncertainty due to the background. The systematic uncertainty of the dp channel is much smaller compared to that of the dn channel and is, therefore, not presented. The red dashed-dotted (black solid) line is the results of SSA1 (SSA4) calculations using the CD-Bonn+ Δ potential and the blue dashed line indicates the neutron energy in the unit of MeV. This line is not visible in all plots.

Figure 5.34: Same as figure 5.33 but for other kinematical configurations indicated on the right.

Figure 5.35: Same as figure 5.33 but for other kinematical configurations indicated on the right.

Figure 5.36: Same as figure 5.33 but for other kinematical configurations indicated on the right.

Figure 5.37: Same as figure 5.33 but for other kinematical configurations indicated on the right.

Figure 5.38: The results of $\text{Re}(T_{20})$ with the same information of figure 5.33.

Figure 5.39: Same as figure 5.38 but for other kinematical configurations indicated on the right.

Figure 5.40: Same as figure 5.38 but for other kinematical configurations indicated on the right.

Figure 5.41: Same as figure 5.38 but for other kinematical configurations indicated on the right.

Figure 5.42: Same as figure 5.38 but for other kinematical configurations indicated on the right.

Figure 5.43: The results of $\text{Re}(T_{22})$ with the same information of figure 5.33.

Figure 5.44: Same as figure 5.43 but for other kinematical configurations indicated on the right.

Figure 5.45: Same as figure 5.43 but for other kinematical configurations indicated on the right.

Figure 5.46: Same as figure 5.43 but for other kinematical configurations indicated on the right.

Figure 5.47: Same as figure 5.43 but for other kinematical configurations indicated on the right.

6. Investigation of the quasi-free domain in deuteron-deuteron break-up using spin observables

This chapter presents the results of an investigation which has been published in European Journal of Physics A [\[89\]](#). The inclusion of this paper in the present thesis is done with the permission of the co-authors and the publisher.

Investigation of the quasi-free domain in deuteron-deuteron break-up using spin observables

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Abstract. Precision measurements of vector and tensor analyzing powers of the $^2\text{H}(d, dp)n$ break-up process for configurations in the vicinity of the quasi-free scattering regime with the neutron as spectator are presented. These measurements are performed with a polarized deuteron-beam with an energy of 65 MeV/nucleon impinging on a liquid-deuterium target. The experiment was conducted at the AGOR facility at KVI using the BINA 4π -detection system. Events for which the final-state deuteron and proton are coplanar have been analyzed and the data have been sorted for various momenta of the missing neutron. In the limit of vanishing neutron momentum and at large deuteron-proton momentum transfer, the data agree well with the measured and theoretically predicted spin observables of the elastic deuteron-proton scattering process. The agreement deteriorates rapidly with increasing neutron momentum and/or decreasing momentum transfer from the deuteron beam to the outgoing proton. This study reveals the presence of a significant contribution of final-state interactions even at very small neutron momenta.

The study of the properties of nuclei and their interactions based on first principles is an important field of ongoing research. Break-throughs in this field came from an interplay between harvesting precision data in few-nucleon scattering processes and the successful development of *ab initio* theoretical frameworks and mathematical tools to rigorously solve the many-body problem. A key example in this context is the development of boson-exchange models [1] that led to several phenomenological nucleon-nucleon (NN) potentials. These potentials are able to provide an excellent description of the interaction between two nucleons and fit perfectly the rich NN database. Also in the three-nucleon (3N) sector, major progress has been made in the past few decades. Exact Faddeev predictions that were based upon these NN potentials combined with

sophisticated models of the three-nucleon force (3NF) describe reasonably well precision data in the elastic and break-up channels in nucleon-deuteron scattering. In general, the inclusion of (3NF) effects helps to describe the data, although discrepancies are still observed in various spin observables pointing to a deficiency in the spin treatment of the 3NFs [2–8]. More recently, NN and 3N potentials are derived from the basic symmetry properties of the fundamental theory of Quantum Chromodynamics (QCD) [9,10]. An extensive review of the experimental and theoretical progress in the 3N sector up to energies just below the pion-production threshold can be found in refs. [11,12].

Compared to 3N systems, there is a limited experimental database for four-nucleon (4N) systems in the low-energy regime below the three- and four-body break-up thresholds [13–15]. At these low energies, the calculations are very reliable, but the effect of many-body forces is very small and hard to measure. Above the break-up thresholds

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and below the pion-production threshold, namely at intermediate energies, the 4N database becomes even more scarce [16–22]. To enrich the experimental database in few-body systems, various scattering experiments were carried out at Kernfysisch Versneller Instituut (KVI), including a study of the deuteron-deuteron elastic and inelastic scattering processes. This has provided an extended experimental data-base to study various aspects of 3NF and possibly higher-order effects in 4N systems.

In this paper, we present the results of an investigation of various spin observables of the $^2\text{H}(d, dp)n$ break-up process for a deuteron-beam energy of 65 MeV/nucleon. We describe a follow-up analysis of earlier work published in ref. [23] where we compared a small data set selected at a kinematical regime very close to the quasi-free deuteron-proton scattering process with data of the elastic deuteron-proton channel. It was found that the quasi-free results for the spin observables iT_{11} and T_{22} agree well with the data of the elastic channel. A small, but significant, discrepancy was found for T_{20} pointing to a break-down of the quasi-free assumption. In this work, we present a more detailed study by extending the kinematical regime of investigation. For the first time, we compare the momentum distributions of the neutron with the results of a Monte Carlo (MC) study using a neutron-spectator model [34], and we systematically compare the analyzing powers for various bins in neutron momentum with the elastic deuteron-proton data and with the predictions of state-of-the-art 3N calculations. The motivation is to provide a thorough and model-independent study of the validity of the quasi-free assumption in the 4N scattering process.

The data were obtained by making use of a vector- and tensor-polarized, as well as unpolarized deuteron beams that were provided by the AGOR facility at KVI in Groningen, the Netherlands. Deuteron beams were produced by the atomic Polarized Ion Source (POLIS) with nominal polarization values of 60% and 80% for vector and tensor polarization, respectively [24–26]. The beam was accelerated up to 130 MeV by a superconducting cyclotron and impinged a (3.85 ± 0.19) mm thick liquid deuterium target [27] mounted inside the scattering chamber of the Big Instrument for Nuclear-polarization Analysis (BINA). The scattering angles and energies of the final-state protons and deuterons were measured in coincidence with the multi-wire proportional chamber and plastic scintillators of the forward wall of BINA. The time-of-flight information from the scintillators was used to perform particle identification. Details of BINA can be found in refs. [26, 28, 29]. The beam current varied, depending on the polarization state, from 2.73 to 4.08 pA and the duration of the experiment was about 51 hours with beam on target.

The polarization of the deuteron beam was monitored with a Lamb-Shift Polarimeter (LSP) [30] at the low-energy beam line and measured with BINA after the beam acceleration using the deuteron-proton elastic scattering process [31]. The polarization of the deuteron beam was obtained by measuring the ϕ -asymmetry of the dp elastic process and by taking into account the corresponding

analyzing powers. Note that for the polarization measurement, we used the same setup that was used for measuring the spin observables in the deuteron-deuteron scattering experiment. The polarization measurement of the LSP was found to be compatible with the one obtained with BINA [31]. The vector and tensor polarizations of the deuteron beams were found to be $p_Z = -0.601 \pm 0.029$ and $p_{ZZ} = -1.517 \pm 0.032$, respectively, whereby the errors include uncertainties in the analyzing powers in elastic deuteron-proton scattering. The polarization of the deuteron beam was monitored for different periods of the experiment and found to be stable within statistical uncertainties.

The spin observables of the three-body break-up process have been measured in a nearly-background-free experiment. The identification of the three-body break-up channel from other hadronic channels was made possible by using the information of the energy, scattering angle, and time-of-flight of the detected particles. Events were selected with two reconstructed tracks corresponding to a proton and a deuteron, both scattered towards small angles, from 15° to 35° , in the forward wall of BINA giving at least two hits in the wire chamber each with a corresponding signal in two different scintillator bars.

The spin observables of the three-body break-up channel were studied with respect to two kinematical variables, namely the reconstructed momentum of the undetected neutron, p_n , and the square of the four-momentum transfer between the incident deuteron and the final-state proton which is referred to as u . To achieve this, we measured the polar and azimuthal angles, and the energy of the final-state proton and deuteron, (θ_i, ϕ_i, E_i) , respectively, where the index i refers to the proton or deuteron. The four-momentum of the missing neutron is subsequently obtained by applying energy and momentum conservation of the complete reaction. The scattering angles (θ_i, ϕ_i) of the proton ($i = p$) and deuteron ($i = d$) were obtained from the information of the multi-wire proportional chamber. The energies E_p and E_d were extracted from the scintillator data. The scintillator response was calibrated for each configuration by matching the data to the expected energy correlation between E_p and E_d for the break-up channel and for various combinations of scattering angles. The energy losses between the interaction point and the scintillators were accounted for via MC simulations using a model of BINA implemented in GEANT3 [32].

The four-momenta of the proton and deuteron are obtained from measured kinetic energies and scattering angles whereby their masses are taken from the Particle Data Group [33]. Then, the missing four-momentum of the neutron is obtained by taking the difference between initial four-momentum of the beam plus target and that of the sum of the final-state proton and deuteron. The absolute three momentum, p_n , is obtained by taking the square root of the quadratic sum of the momentum components of the four-momentum vector. In this way, we exploit both the energy and angular measurements of the proton and deuteron to reconstruct the missing neutron information. Note that we do not impose a mass-constraint fit on the

Fig. 1. The reconstructed mass of the neutron as the missing particle. A peak around the mass of the neutron (939.50 ± 0.05 MeV) belongs to the break-up events. The tail on the right-hand side of the peak corresponds to the accidental background as well as the events which undergo hadronic interactions inside the scintillator. The red solid line is the result of a fit through the data using four Gaussian functions representing the responses for the break-up channel and backgrounds. The dashed blue lines show the gate used for the event selection and represent a $\pm 3\sigma$ enclosure of the peak.

reconstructed neutron information. The quality of the calibration procedure and the remaining background contributions have been studied via an analysis of the missing mass of the neutron. Figure 1 shows the reconstructed missing-mass distribution of the neutron after calibration and particle identification. The spectrum reveals a peak at a missing mass of 939.50 ± 0.05 MeV that matches very well with the mass of the neutron [33]. The tail on the right-hand side of the peak corresponds to the accidental background as well as the events which undergo hadronic interactions inside the scintillator. The red solid line in the figure is the result of a fit through the data based on four Gaussian-distributed signals representing the responses for the break-up channel and backgrounds. To suppress the background and to select events for which the neutron momentum can be well determined, we placed a cut around the nominal neutron mass with a window of $\pm 3\sigma$ as indicated by the dashed blue lines.

The top panel of fig. 2 shows the correlation between the reconstructed neutron momentum and the Mandelstam variable, u , for the part of the phase space within the wall acceptance (15° – 35°) and with a coplanarity requirement of the outgoing proton-deuteron pair, $\phi_{12} = |\phi_d - \phi_p| = 180^\circ \pm 5^\circ$. Figure 2 shows that the data have distinct features. In particular, the neutron-momentum distribution shows a dependence on the variable u . The neutron momentum peaks around 30 MeV/c for u less than 0.81 [GeV/c] ^{2} without a strong dependence on u . As u increases the peak position drops to lower values of neutron momentum and a strong correlation between the two parameters can be observed. At even larger values of u , the momentum distribution of the neutron shifts towards higher values.

Fig. 2. Top panel: the correlation between the reconstructed momentum of the neutron and the Mandelstam variable, u , defined as the four-momentum transfer from the deuteron beam to the outgoing proton, is shown for the part of the phase space limited by the wall acceptance between 15° – 35° . The dashed lines show different regions that are selected to extract analyzing powers. Bottom panel: the results of the PLUTO simulation for the correlation represented in the top panel.

The bottom panel of fig. 2 shows the QF model of this correlation using a PLUTO simulation with the same condition as explained for the top panel. For the simulations we made use of a QFS model implemented in PLUTO, a versatile package for MC simulations of hadronic interactions in C++ compatible with ROOT analysis environment [34,35]. To parametrize the deuteron wave function, the Paris potential is used in the PLUTO simulation. Also, the resolution of the experimental setup was incorporated in the simulation. To zeroth order, there is hardly any correlation between u and p_n . This is understood, since the neutron is supposed to be a spectator. However, there are some kinematical correlations which show up strongly at the edges in u , but they are of higher orders. The data show that there are two regions. The first one can be seen at small values of u . This region shows hardly any correlation with p_n , hence compatible with the QF model predictions. The other region reveals a strong anti-correlation between u and p_n . It starts around $u = 0.8$ [GeV/c] ^{2} with relatively high values of p_n around 40 MeV/c and it drops rapidly to very low neutron momenta with increasing u . Such a behavior is not seen in the QF-based MC simulations. The latter structure in the data clearly deviates from the naive QF picture due to neutron interacting with another particle. Because of this, we expect that for the events in this region, the neutron participated actively in the reaction. We refer to this as final-state interactions (FSI). We note that large values of u correspond to a small

momentum transfer to the final-state proton. The FSI effects should increase at smaller momentum transfers. It is not clear why this region shows an anti-correlation ending up with neutron momenta that are even smaller than that of the QF case. A detailed four-body calculation would be necessary to provide further insights in this observed phenomena.

To investigate the dependence of the extracted analyzing powers on p_n and u , the data presented in fig. 2 are subdivided into four regions with different intervals in neutron momentum and the corresponding spin observables are analyzed as a function of u . The neutron momenta of these regions are 0.0–16.8, 16.8–23.7, 23.7–29.1, and 29.1–33.6 MeV/c, respectively. The bin sizes correspond to the neutron-momentum resolution obtained in the experiment. These regions are distinguished by the dashed lines in fig. 2. The bin size in u is set to 4 [MeV/c]², corresponding to its reconstruction resolution.

Vector- and tensor-polarized beams give the possibility to measure various analyzing powers by studying the azimuthal asymmetry in the differential cross section. The cross section of our reaction with a polarized beam for coplanar configurations is defined as [36,37]

$$\sigma(\xi, \phi) = \sigma_0(\xi) \left[1 + \sqrt{3} p_Z \operatorname{Re}(iT_{11}(\xi)) \cos(\phi) - \frac{1}{\sqrt{8}} p_{ZZ} T_{20}(\xi) - \frac{\sqrt{3}}{2} p_{ZZ} \operatorname{Re}(T_{22}(\xi)) \cos(2\phi) \right], \quad (1)$$

where σ (σ_0) is the two-fold differential cross section of the reaction with polarized (unpolarized) beam in the quasi-free limits and ξ represents the kinematical variables involved in the event selection, (E_n, u, ϕ_{12}) . p_Z and p_{ZZ} are the vector and tensor polarizations, respectively. $\operatorname{Re}(iT_{11})$ ($\operatorname{Re}(T_{20})$, $\operatorname{Re}(T_{22})$) are vector (tensor) analyzing powers and ϕ is the azimuthal scattering angle of the deuteron.

Using data obtained from a pure vector polarized beam, ($p_{ZZ} = 0$), the $\operatorname{Re}(iT_{11})$ is extracted from the amplitude of the $\cos\phi$ -shape of the fit function given by eq. (1). Data extracted from a pure tensor polarized beam, ($p_Z = 0$), produce a $\cos 2\phi$ -shape of the azimuthal asymmetry with an offset from one due to the term, $\frac{1}{\sqrt{8}} p_{ZZ} T_{20}(\xi)$. The amplitude of the $\cos 2\phi$ -shape yields $\operatorname{Re}(T_{22})$ and the offset from one gives $\operatorname{Re}(T_{20})$. Figure 3 shows an example of the asymmetry ratio of σ/σ_0 as a function of ϕ for a pure-vector polarized beam (top panel) and a pure tensor polarized beam (bottom panel) for the kinematical variables, $0.0 < p_n$ [MeV/c] < 16.8 and $0.790 < u$ [GeV/c]² < 0.794 . The uncertainty of the beam polarization results in a 5% systematic uncertainty in the analyzing powers. A detailed investigation of this type of systematical error can be found in refs. [31,38]. An additional systematic error has been identified that stems from uncertainties in the measurement of the beam current using a Faraday cup. A small offset of 0.28 ± 0.13 pA in the readout of the current was observed. The offset has been determined by calculating the minimum reduced χ^2 for different values of the offset using the comparison between the results of the $\operatorname{Re}(T_{22})$ from the elastic dd scatter-

Fig. 3. The ratio of σ/σ_0 as a function of ϕ for a pure-vector polarized beam (top panel) and pure tensor polarized beam (bottom panel) obtained in the limits of the kinematical variables, $0.0 < p_n$ [MeV/c] < 16.8 and $0.790 < u$ [GeV/c]² < 0.794 . The data are shown as filled circles whereby the length of the horizontal bar corresponds to the bin size. The error bars in vertical direction represent the statistical uncertainty. The solid lines are the result of a fit through the data using eq. (1). The $\chi^2/18$ for the top (bottom) panel is 1.3 (1.5).

ing process and from an independent measurement using the BBS setup [39]. The error is obtained by evaluating the χ^2 distribution as a function of offset. The intersection points of this distribution with a χ^2 value that is one unit larger than its minimum has been used to determine the uncertainty in the offset. This offset imposes a shift in the same direction on both polarized and unpolarized cross sections. Such a shift causes an additional offset in the ratio of σ/σ_0 . The uncertainty in the offset gives rise to a substantial systematic uncertainty for T_{20} . Its effect on the measurement of $\operatorname{Re}(iT_{11})$ and $\operatorname{Re}(T_{22})$ is marginal, since these observables are primarily sensitive to the amplitude of the $\cos\phi$ and $\cos 2\phi$ oscillations. The total systematic uncertainty is obtained by the quadratic sum of the two individual sources of systematic errors.

We are interested in identifying the quasi-free domain with the neutron as the spectator in the ${}^2\text{H}(\mathbf{d}, dp)n_{\text{spec}}$ reaction. To proceed, the reconstructed momentum distribution of the missing neutron for different intervals of the Mandelstam variable, u , is compared with the expected momentum distribution of the nucleon derived from the wave function of the deuteron. Figure 4 shows the results of a comparison between the normalized projections of the data presented in fig. 2 for different intervals of u (indicated in each panel) and the normalized results of the MC simulation of the ${}^2\text{H}(\mathbf{d}, dp)n_{\text{spec}}$ reaction. The regions where the reconstructed momentum distribution of the missing neutron matches well with the expected momentum distribution of the neutron inside the deuteron are labeled as the quasi-free regions. The comparison in fig. 4 shows that for large values of u [GeV/c]², the data do not follow a quasi-free description even at small neutron momenta. It indicates that the QF domain corresponds to the first peak till about 50 MeV/c in neutron momentum which reveals itself strongly for u smaller than 0.81 [GeV/c]² but deteriorates at larger values of u .

Fig. 4. The results of the normalized projection of the data presented in the spectrum of fig. 2 for different intervals of u are presented as the black dots. The results of the PLUTO simulation of the ${}^2\text{H}(d, dp)n_{\text{spec}}$ reaction with the same conditions in the analysis procedure are shown as the red dots.

Fig. 5. The vector and tensor analyzing powers for the break-up reaction presented as a function of u for four different intervals of the neutron momentum (black circles). The dark gray bands show the total systematic uncertainty (2σ). Also shown are the experimental results of the dp elastic scattering (open circles), the coupled channel calculation using CD-Bonn potential including the Δ excitation without (with Coulomb effect) for dp elastic scattering [40, 41] as the dashed lines (solid lines), and the calculation including the Tucson-Melbourne three-nucleon force [42] as the light gray band.

To investigate the validity of this definition for the QF domain, the results of the measured analyzing powers are presented as a function of u in fig. 5 for four different intervals of the neutron momentum. The neutron momentum ranges are shown at the top of the figure. The results of this work are compared with dp elastic data [43] as well as with theoretical calculations of the dp elastic scattering process based on NN potentials with and without including 3NF effects. The total systematic uncertainty is represented as the dark gray bands. By comparing our results of iT_{11} with previously published dp elastic data [23], a very good agreement can be observed for neutron momenta smaller than 17 MeV/c. Increasing the neutron momentum deteriorates this agreement for higher values of u . This is compatible by the observation shown in fig. 4. The QF domain appear to be dominant in the region with the neutron momentum around 34 MeV/c for $u < 0.810$ [GeV/c]². Similar conclusions can be drawn for tensor analyzing powers, although the disagreements here are slightly outside the systematic uncertainties. The results of the tensor analyzing power, T_{20} , also show the same pattern as the other two analyzing powers and agree reasonably well with dp elastic data within the systematic uncertainties. Increasing the neutron momentum (right panels) clearly destroys the agreement with the elastic data at larger values of u . Also, this trend is consistent with the study of the momentum distribution of the neutron inside the deuteron as shown in figs. 2 and 4.

In conclusion, in a careful analysis of the break-up reaction in the $d + d$ system, it has been shown that in identifying regions of kinematics for the study of the QF reaction, one should not only constrain the momentum of the spectator neutron to low values, but also consider the momentum transfer between the beam projectile and the ejectile in the analysis. Our data show that at small momentum transfer, the effects of final-state interactions involving the neutron play an important role. A detailed four-body calculation is required to provide further insights in the underlying reaction dynamics that appear at this part of the phase space.

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7. Summary and outlook

7.1 Summary and conclusions

Although three-nucleon force effects have been well investigated in the three-body systems, they are not yet well understood. There are two strong motivations to go beyond the three-body systems and to analyze the deuteron-deuteron scattering as a four-body system: First, 3NF effects are generally enhanced in magnitude in the four-body systems; and, second, in spite of a good experimental database for the three-body systems, the amount of data of four-nucleon scattering processes is very limited [14]. Therefore, enriching the experimental database can aid to a better understanding of the nuclear potential in the upcoming state-of-the-art theoretical calculations in the four-nucleon systems. Moreover, the deuteron-deuteron scattering provides a large variety of different reaction channels which can be used to probe different aspects of the nuclear force. In the following, a summary of the experimental setup is presented. Then the analysis procedure of the elastic and three-body break-up channels of dd scattering process is summarized and, in the end, the results of the measurements of the observables for these channels are briefly discussed.

A measurement of spin observables of various hadronic channels in the deuteron-deuteron scattering, specifically elastic and three-body break-up channels, requires a 4π detection system capable of identifying particles and measuring their position and energy. Such a detection system has been constructed and brought in operation in the past and carries the name BINA. BINA consists of two main parts: the forward wall and the backward ball. The forward wall of BINA consists of a MWPC which measure the positions of the charged particles, 12 vertically-mounted ΔE and 10 horizontally-mounted E scintillators. The E scintillators are mounted in a cylindrical shape in the center of which the target is embedded. The thickness of the liquid deuterium target cell used for the present measurements was 3.85 mm including the bulging with an uncertainty of 5%. The polarized deuteron beam was produced by POLIS and accelerated to 65 MeV/nucleon by the superconducting cyclotron AGOR. The polarization values for the vector and tensor polarizations of deuteron were $p_Z = -0.601 \pm 0.029$ and $p_{ZZ} = -1.517 \pm 0.032$, respectively. The MWPC covers scattering angles between 10° and 32° with a full coverage of azimuthal angle and up to 37° with a limited coverage of azimuthal angle. The MWPC has

a resolution of 0.4° for the polar angle and between 0.6° and 2.0° for the azimuthal angle depending on the scattering angle. The efficiency of the MWPC for the deuteron (proton) was $99 \pm 1\%$ ($97 \pm 1\%$). The thickness of the forward E scintillators (12 cm) was sufficient to stop all the charged particles for this experiment (the energy of proton should be less than 140 MeV to stop in the forward wall). But, the majority of the neutrons left no trace in the forward E scintillators. More specifically, approximately 10% of the neutrons deposit a fraction of their energy in the E scintillator bars. The energy of the neutrons were obtained through energy and momentum conservation laws. The backward ball of BINA consists of 149 phoswich scintillators that are glued together to construct the scattering chamber. The target position was embedded in the center of the backward ball of BINA. For a complete overview of the experimental setup, refer to Chapter 3

In this thesis, we mainly focused on the presentation of the analysis of the deuteron-deuteron scattering. The identification of the two-body final states among other hadronic channels have been done and a thorough analysis of the elastic channel of ${}^2\text{H}(\vec{d}, d)d$ reaction was presented. The cross section was extracted using the trigger with the minimum bias, namely the “single” trigger, to avoid correcting for detection inefficiencies of the low-energy deuterons that scatter to the ball. On the other hand, the inefficiencies of the backward ball only effect the statistical uncertainties of the spin observables as they cancel out when taking ratios. Therefore, the less-downscaled coincidence trigger was used to extract the analyzing powers to reduce the effects of background. To obtain cross sections, we corrected for various factors, such as the inefficiency of the MWPC, the live-time of the DAQ, losses due to hadronic interactions, and the down-scale factor that was set by the hardware triggers. We managed to control the systematic uncertainty of the differential cross section measurement to about 7% whereby the largest contribution is due to the uncertainty of the target thickness (5%). The total systematic uncertainty of the various polarization observables were estimated to be about 5%.

To investigate the compatibility of our approach for measuring the differential cross section and analyzing powers in ${}^2\text{H}(\vec{d}, d)d$ reaction, we also measured the differential cross section and analyzing powers for the elastic channel of $\text{H}(\vec{d}, d)p$ reaction using a solid CH_2 target with the same method used for the elastic channel of ${}^2\text{H}(\vec{d}, d)d$ reaction. The experimental setup and subsequently systematic uncertainties and the beam energy were exactly the same for these two experiments. An excellent agreement is found between our measurements and published data. In addition, *ab-initio* calculations based on modern NN+3N potentials provide a very good description of the data.

In addition to the elastic channel, a thorough analysis has been done for

the two combinations of the three-body break-up channel of the deuteron-deuteron scattering, namely ${}^2\text{H}(\vec{d}, dp)n$ and ${}^2\text{H}(\vec{d}, dn)p$ reactions. To achieve this, the energy calibration of 10 E scintillator bars in the forward wall was performed using the ADC signals of the PMTs mounted on both sides of each scintillator bar. Also, an excellent particle identification was applied to reduce the majority of the background that comes from the other hadronic channels. To do so, the information of the time-of-flight (TOF) of the particles were used. Because of the low light production of the ΔE -scintillators, the ΔE - E technique was not used for Particle IDentification (PID). We counted the number of events for each configuration in terms of the S value with bins in S of 10 MeV after applying particle identification. The number of break-up events for each S -bin is extracted after subtracting the background from the projected events on the axis perpendicular to the S -curve. The extracted number of counts is corrected for efficiencies of the system as mentioned above.

To extract the analyzing powers, the spectrum of the ratio of the cross section of the reaction using a pure-vector (tensor) polarized deuteron beam to the cross section of an unpolarized beam as a function of ϕ was used to fit a $\cos \phi$ -dependence ($\cos 2\phi$ -dependence with a possible offset from one) of the azimuthal asymmetry. The amplitude of $\cos \phi$ ($\cos 2\phi$) is proportional to the $\text{Re}(iT_{11})$ ($\text{Re}(T_{22})$). Also, $\text{Re}(T_{20})$ is proportional to the offset from one for the $\cos 2\phi$ azimuthal asymmetry.

In the case of the ${}^2\text{H}(\vec{d}, dn)p$ reaction, we investigated the feasibility of neutron detection by the forward wall of BINA. Because the neutron is not seen by MWPC, we constructed a virtual MWPC using the time-of-flight information of the scintillators in the forward wall. The energy of the neutron cannot be measured directly by the scintillators, but it has been obtained by making use of energy and momentum conservation. Moreover, we exploited the relative time-of-flight between the deuteron and neutron for particle identification (PID). The analysis procedure has been verified by studying the deuteron-proton coincidence whereby the proton mimics the neutron. Finally, the analyzing powers were extracted in the same way as for the ${}^2\text{H}(\vec{d}, dp)n$ reaction. The details of the analysis can be found in Chapter 4.

The results of differential cross sections and analyzing powers of the elastic and the three-body break-up channel in ${}^2\text{H}(\vec{d}, dp)n$, and the results of the analyzing powers of the ${}^2\text{H}(\vec{d}, dn)p$ reaction were presented in the previous chapter. Our data are compared to the results of an earlier study and extend these with a larger angular coverage. Moreover, our results are compared with data obtained using another experimental setup, namely BBS, which was a completely different setup with a different analysis procedure. The comparison shows a very good agreement between all available datasets. Also, the

results of a theoretical predictions based on the lowest-order terms in the Born series expansion of the Alt-Grassberger-Sandhas equation for four-nucleon interaction using the CD-Bonn+ Δ potential are shown in figure 5.1. It indicates that, at present, there is no model available that is even close to give a reasonable description of the data at these energies. The work on the three-body break-up channel of ${}^2\text{H}(\vec{d}, dp)n$ reaction also extends and corrects the results of a previous analysis of the same data. The preliminary results presented in Ref. [22] underestimated the differential cross section by a factor of 2000 due to a unit error and a factor two because of missing half of the statistics while performing PID. For the first time, we have extracted the imaginary components of the analyzing powers. Also, our data for coplanar configurations are compared with recently-available theoretical calculations based on the single-scattering approximation, SSA, by using the CD-Bonn+ Δ potential (see Sec. 5.2.1). The experimental data are in a reasonable agreement with the SSA predictions near the QFS region. A more detailed study has been carried out via a dedicated analysis of vector and tensor analyzing powers of the ${}^2\text{H}(\vec{d}, dp)n$ break-up reaction in the vicinity of the QFS regime using the neutron as a spectator and the Mandelstam variable u as a square of the four-momentum transfer between the incident deuteron and the final-state proton. To achieve this, events for which the final-state deuteron and proton are coplanar have been analyzed and the data have been sorted for various momenta of the missing neutron. In the limit of vanishing neutron momentum and at large deuteron-proton momentum transfer, the data agree well with the measured and theoretically-predicted spin observables of the elastic deuteron-proton scattering process. The agreement deteriorates rapidly with increasing neutron momentum and/or decreasing momentum transfer from the deuteron beam to the outgoing proton. This study reveals the presence of a significant contribution of final-state interactions even at very small neutron momenta. The results are published in European Journal of Physics A [89].

Besides studying the ${}^2\text{H}(\vec{d}, dp)n$ break-up reaction, we also performed a study of the ${}^2\text{H}(\vec{d}, dn)p$ channel. The analysis of the ${}^2\text{H}(\vec{d}, dn)p$ reaction indicates that we can go beyond the detection of the charged particles in the experiments done by BINA and look for configurations in which the neutron is detected in the forward wall. The results of the analyzing powers for the ${}^2\text{H}(\vec{d}, dn)p$ reaction for the part of the phase space where the systematic uncertainties are comparable with the statistical uncertainties are presented and compared with those from the ${}^2\text{H}(\vec{d}, dp)n$ reaction. Also, the theoretical calculations based on the SSA are presented as the most recent theoretical calculations for this channel.

7.2 Outlook

The analysis of the ${}^2\text{H}(\vec{d}, dn)p$ reaction has demonstrated that the neutron signal in the plastic scintillators is reliable enough to study that part of the phase space in which the neutron is detected in coincidence with other particles. Future analysis of the four-body break-up channel could, for instance, benefit from the neutron detection. To fully determine the kinematics of this channel, it is not sufficient to only measure the energy and scattering angles of the two protons. The information of at least one of the neutrons needs to be obtained as well. Another application could be the analysis of the proton-transfer channel, ${}^2\text{H}(\vec{d}, {}^3\text{He } n)$.

The high energy and angular resolution of the forward wall led us to focus on the part of the phase space of the three-body break-up in which both deuteron and proton are detected in coincidence in the forward wall of BINA. In the future, one may focus on the part of the phase space of the three-body break-up channel in which one particle is detected in the forward wall in coincidence with another particle detected in the backward ball of BINA. But we should remember the fact that the angular resolutions of the detectors in the backward ball ($\Delta\theta = \pm 10^\circ$ and $\Delta\phi = \pm 10^\circ$) are not as good as those in the forward wall making the comparison with the theoretical calculations more difficult as one needs to fold the response of the detector into the calculations.

Samenvatting

Hoewel de drie-nucleon krachtheffeten (3NF-effecten) goed zijn onderzocht in systemen met drie lichamen, zijn ze nog steeds niet goed begrepen. Dit proefschrift beschrijft de analyse van een vier-deeltjes deuteron-deuteron verstrooiingsexperiment. Er zijn twee belangrijke motivaties voor dit experiment waarbij er verder gekeken wordt dan systemen met drie lichamen. Ten eerste zijn 3NF-effecten over het algemeen groter van omvang in systemen met vier lichamen en, ten tweede, ondanks een goede experimentele database voor systemen met drie lichamen is de hoeveelheid gegevens van vier-nucleon-verstrooiingsprocessen zeer beperkt. Daarom kan het verrijken van de experimentele database bijdragen tot een beter begrip van de nucleaire potentiaal in de toekomstige theoretische berekeningen in vier-nucleon-systemen. Bovendien biedt deuteron-deuteron-verstrooiing (dd verstrooiing) een grote verscheidenheid aan verschillende reactiekanalen die kunnen worden gebruikt om verschillende aspecten van kernkrachten te onderzoeken. Hieronder volgt een samenvatting van de analyseprocedure van het elastische en de drie-lichaam opsplitsingskanalen van het dd verstrooiingsproces en vervolgens worden de resultaten van de metingen van de observabelen voor deze kanalen kort besproken.

Een meting van spin-observabelen van verschillende hadronische kanalen in de deuteron-deuteron-verstrooiing, in het bijzonder het elastische en de drie-lichaam opsplitsingskanalen, vereisen een 4π detectiesysteem dat in staat is deeltjes te identificeren en hun positie en energie te meten. Een dergelijk detectiesysteem is gebouwd en in het verleden in gebruik genomen en draagt de naam BINA. BINA bestaat uit twee onderdelen: de voorwaartse wand en de achterwaartse bal. De voorwaartse wand van BINA bestaat uit een proportionele dradenkamer (MWPC) die de posities van de geladen deeltjes meet, uit 12 verticaal gemonteerde ΔE en uit 10 horizontaal gemonteerde E scintillatoren. De achterwaartse bal van BINA bestaat uit 149 phoswich scintillatoren die aan elkaar zijn gelijmd om een verstrooiingskamer te construeren. De positie van de trefplaat was in het midden van de achterwaartse bal van BINA. De

gepolariseerde deutronstraal werd geproduceerd door POLIS en versneld tot 65 MeV/nucleon door het supergeleidende cyclotron AGOR.

In dit proefschrift hebben we ons vooral gericht op de presentatie van de analyse van de deutron-deutron verstrooiing. De identificatie van twee hadronische kanalen tussen de uiteindelijke toestanden is uitgevoerd en een grondige analyse van het elastische kanaal van ${}^2\text{H}(\vec{d}, d)d$ reactie is gepresenteerd. De werkzame doorsnede is verkregen met behulp van de trigger met een minimale bias, namelijk de “enkele” trigger. Op deze manier wordt de detectie-inefficiëntie van de bal voor laag-energetische deutronen omzeilt in de bepaling van de werkzame doorsnede. Aan de andere kant hebben de inefficiënties van de achterwaartse bal alleen effect op de statistische onzekerheden van de spin-observabelen, aangezien ze elkaar opheffen bij het nemen van ratio's. Daarom werd de minder verkleinde coïncidentie-trigger gebruikt om de analyserende vermogens te bepalen en zo de effecten van de achtergrond te verminderen. Om de werkzame doorsneden te verkrijgen hebben we gecorrigeerd voor verschillende factoren, zoals de inefficiëntie van de MWPC, de live-tijd van de DAQ, verliezen door hadronische interacties en de schaalverlaging die is ingesteld door de hardware-triggers.

Naast het elastische kanaal is een grondige analyse uitgevoerd voor de twee combinaties van twee specifieke drie-lichaam opsplitsingskanalen van de deutron-deutron-verstrooiing, namelijk de ${}^2\text{H}(\vec{d}, dp)n$ en ${}^2\text{H}(\vec{d}, dn)p$ reacties. Om dit te bereiken werd de energiekalibratie van de 10 E scintillatorstaven in de voorwaartse wand uitgevoerd met behulp van de ADC-signalen van de PMT's gemonteerd aan beide zijden van elke scintillatorstaaf. Ook werd een uitstekende deeltjes identificatie (PID) toegepast om het grootste deel van de achtergrond te verminderen die afkomstig is van de andere hadronische kanalen. Hiervoor werd de informatie van de vluchttijd (TOF) van de deeltjes gebruikt. Vanwege de lage lichtproductie van de ΔE -scintillatoren is de $\Delta E - E$ techniek niet gebruikt voor de PID. Voor elke configuratie hebben we het aantal incidenten na toepassing van de PID geteld in termen van de S -waarde, met een bingrootte in S van 10 MeV. Het aantal opsplitsingsincidenten voor elk S -bin is geëxtraheerd na aftrekking van de achtergrond van de incidenten geprojecteerd op de as loodrecht op de S -kromme. Het verkregen aantal incidenten wordt gecorrigeerd voor de efficiëntie van het systeem zoals hierboven is vermeld.

Om de analyserende vermogens te extraheren, is de verhouding van de werkzame doorsnede van de reactie met behulp van een zuivere vector (tensor) gepolariseerde deutronbundel ten opzichte van de werkzame dwarsdoorsnede van een niet-gepolariseerde bundel gebruikt als functie van ϕ , om zo een $\cos \phi$ -afhankelijkheid ($\cos 2\phi$ -afhankelijkheid met een mogelijke offset van één) van

de azimuthale asymmetrie af te leiden. De amplitude van $\cos \phi$ ($\cos 2\phi$) is evenredig met de $\text{Re}(iT_{11})$ ($\text{Re}(T_{22})$). Ook is $\text{Re}(T_{20})$ evenredig met de offset van één voor de $\cos 2\phi$ azimuthale asymmetrie.

In het geval van de ${}^2\text{H}(\vec{d}, dn)p$ reactie hebben we de haalbaarheid van neutronendetectie door de voorwaartse wand van BINA onderzocht. Omdat het neutron niet wordt gezien door de MWPC, hebben we een virtuele MWPC geconstrueerd met behulp van de vluchttijd-informatie van de scintillatoren in de voorwaartse wand. De energie van het neutron kan niet rechtstreeks door de scintillatoren worden gemeten, maar is verkregen door gebruik te maken van energie- en impulsbehoud. Bovendien hebben we voor de PID gebruik gemaakt van de relatieve vluchttijd tussen het deutron en het neutron. De analyseprocedure is geverifieerd door de deutron-proton situatie te bestuderen waarbij het proton het neutron nabootst. Tot slot zijn de analyserende vermogens op dezelfde manier verkregen als voor de ${}^2\text{H}(\vec{d}, dp)n$ reactie. De details van de analyse zijn te vinden in hoofdstuk 4.

De resultaten van de differentiële werkzame doorsneden en analyserende vermogens van het elastische drie-lichaam opsplitsingskanaal ${}^2\text{H}(\vec{d}, dp)n$ in de deutron-deutron verstrooiing en de resultaten van de analyserende vermogens van de ${}^2\text{H}(\vec{d}, dn)p$ reactie zijn gepresenteerd in hoofdstuk 5. Onze gegevens zijn vergeleken met de resultaten van een eerdere studie en breiden deze uit met een groter hoekbereik. Bovendien zijn onze resultaten vergeleken met gegevens die zijn verkregen met een ander experiment, die gebruik maakte van de BBS, wat een compleet andere opstelling is met een andere analyseprocedure. De vergelijking toont een zeer goede overeenkomst tussen alle beschikbare datasets. Ook de resultaten van theoretische voorspellingen op basis van de laagste-orde termen in de Born-serie expansie van de Alt-Grassberger-Sandhas-vergelijking voor een vier-nucleon interactie met behulp van de CD-Bonn + Δ potentiaal wordt getoond in figuur 5.1. Het geeft aan dat er op dit moment geen model beschikbaar is dat zelfs maar een redelijke beschrijving geeft van de data bij deze energieën. Het werk aan het drie-lichaam opsplitsingskanaal ${}^2\text{H}(\vec{d}, dp)n$ in de deutron-deutron verstrooiing breidt ook de resultaten van een eerdere analyse van dezelfde data uit en corrigeert deze. De voorlopige resultaten gepresenteerd in Ref. [22] onderschatten de differentiële werkzame dwarsdoorsnede met een factor 2000 vanwege een eenheidsfout en een factor twee vanwege het missen van de helft van de statistiek tijdens het uitvoeren van de PID. Voor de eerste keer zijn de imaginaire componenten van de analyserende vermogens geëxtraheerd. Ook is onze data voor coplanaire configuraties vergeleken met recente theoretische berekeningen op basis van een enkele verstrooiingsbenadering (SSA) met behulp van de CD-Bonn + Δ potentiaal (zie hoofdstuk 5.2.1). De experimentele

data komt redelijke overeen met de SSA-voorspellingen in de buurt van de QFS-regio. Een meer gedetailleerd onderzoek is uitgevoerd aan de hand van een specifieke analyse van de vector en tensor analyserende vermogens van de ${}^2\text{H}(\vec{d}, dp)n$ opsplitsingsreactie in de nabijheid van de QFS-regio met het neutron als toeschouwer en de Mandelstam-variabele u als een kwadraat van de vierimpuls overdracht tussen het initiële deutron en het proton in de uiteindelijke toestand. Om dit te bereiken zijn botsingen waarvoor het deutron en het proton in de eindtoestand coplanair zijn geanalyseerd, en de gegevens zijn gesorteerd voor verschillende impulswaarden van het ontbrekende neutron. In de limiet van een verwaarloosbare neutronen impuls en bij grote deutron-proton impulsoverdracht komen de gegevens goed overeen met de gemeten en theoretisch voorspelde spin-observabelen van het elastische deutron-proton verstrooiingsproces. De overeenkomst verslechtert snel met toenemende neutronenimpuls en/of afnemende impulsoverdracht van de deutronbundel naar het uitgaande proton. Deze studie onthult de aanwezigheid van een significante bijdrage van eindtoestand-interacties, zelfs bij zeer kleine neutronenimpuls. De resultaten zijn gepubliceerd in het tijdschrift *European Journal of Physics A* [89].

Naast het bestuderen van de ${}^2\text{H}(\vec{d}, dp)n$ opsplitsingsreactie hebben we ook een studie van het ${}^2\text{H}(\vec{d}, dn)p$ kanaal uitgevoerd. De analyse van de ${}^2\text{H}(\vec{d}, dn)p$ reactie geeft aan dat we in experimenten uitgevoerd door BINA verder kunnen gaan dan de detectie van de geladen deeltjes en kunnen zoeken naar configuraties waarin het neutron gedetecteerd wordt in de voorwaartse wand. De resultaten van de analyserende vermogens voor de ${}^2\text{H}(\vec{d}, dn)p$ reactie voor het deel van de faseruimte waar de systematische onzekerheden vergelijkbaar zijn met de statistische onzekerheden zijn gepresenteerd en vergeleken met die uit de ${}^2\text{H}(\vec{d}, dp)n$ reactie. Ook worden de theoretische berekeningen op basis van de eerder genoemde SSA-benadering gepresenteerd als de meest recente theoretische berekeningen voor dit kanaal.

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