Chapter 5

Analysis of deuteron-deuteron scattering at 65 MeV/nucleon

5.1 Introduction

In this chapter the analysis procedure for the deuteron-deuteron scattering data will be described. The elastic channel, one of the transfer channels, and all break-up channels were identified. For this thesis, cross sections and analyzing powers were obtained for the elastic and three-body break-up channels. A further analysis of the other observed channels will be performed in the future. The elastic channel has been analyzed by applying a similar procedure as was performed for the $\vec{p}d$ and $\vec{d}p$ elastic scattering as discussed in Ch. 4. Therefore, this chapter is devoted mainly to the analysis of the three-body final-state break-up reaction.

5.2 Channel identification

Deuteron-deuteron scattering leads to 5 possible final states with a pure hadronic signature, namely

1. Elastic channel: $\vec{d} + d \rightarrow d + d$;

2. Neutron-transfer channel: $\vec{d} + d \rightarrow p + t$;

3. Proton-transfer channel: $\vec{d} + d \rightarrow n + ^3\text{He}$;

4. Three-body final-state break-up: $\vec{d} + d \rightarrow p + n + d$;

5. Four-body final-state break-up: $\vec{d} + d \rightarrow p + n + p + n$.

The $dd$ three-body final-state break-up (the four-body final-state break-up) is further referred as the three-body break-up (four-body break-up) in this work. The identification of these final states is described in the following two subsection.
5.2.1 Channels with two particles in the final state

The elastic and neutron-transfer channels have been identified by detecting the particles in the forward wall of BINA in coincidence with the detected particles in the backward ball of BINA with a high efficiency. The detection efficiency of all particles in the third channel is very low because the efficiency of neutron detection with the plastic scintillators used in our setup is poor and not easy to determine. Therefore, the analysis of the data with BINA was mainly focused on the final states involving charged particles.

Figure 5.1: The correlation between the measured energies of the forward-scattered particles that interact with one of the $\Delta E$-E hodoscopes ($E_1$) and the deposited energy of particles which scatter to one of the detectors in the backward ball ($E_2$). The “blob” on the right-hand side corresponds to elastically-scattered deuterons at $35^\circ \pm 1^\circ$ in coincidence with deuterons detected at $55^\circ \pm 2^\circ$. The “blob” on the left-hand side kinematically matches to the neutron-transfer channel in which tritons are scattered to $35^\circ \pm 1^\circ$ in coincidence with protons scattering to $55^\circ \pm 2^\circ$.

Figure 5.1 shows the correlation between the measured energies of the forward scattered particles that interact with one of the $\Delta E$-E hodoscopes and the deposited energy of particles which scatter to one of the detectors in the backward ball. The “blob” on the right-hand side corresponds to elastically-scattered deuterons at $35^\circ \pm 1^\circ$ in coincidence with deuterons detected at $55^\circ \pm 2^\circ$. The “blob” on the left-hand side kinematically matches to the neutron-transfer channel in which tritons are scattered to $35^\circ \pm 1^\circ$ in coincidence with protons scattering to $55^\circ \pm 2^\circ$. Note that the energy calibration for both
elements was performed assuming that the scattered particle is a deuteron.

The measured time of flight (TOF) of the forward scattered particles is another possible variable for the identification of the reaction channel. This time has been measured relative to the RF of the cyclotron in which the start signal was provided from an E-detector and the stop signal from the RF. Figure 5.2 shows the TOF of events detected in one of the \( \Delta E-E \) hodoscopes in coincidence with particles that scatter to one of the backward ball detectors. The peak on the right-hand side corresponds to elastically-scattered deuterons at \( 35^\circ \pm 1^\circ \), and the peak on the left-hand side to scattered tritons at \( 35^\circ \pm 1^\circ \) that originate from the neutron-transfer channel. Each TDC channel is equivalent to 500 ps.

Figure 5.2: The TOF of the particles detected in one of the \( \Delta E-E \) hodoscopes in coincidence with particles that scatter to one of the backward ball detectors. The peak on the right-hand side corresponds to elastically-scattered deuterons at \( 35^\circ \pm 1^\circ \) and the peak on the left-hand side to scattered tritons at \( 35^\circ \pm 1^\circ \) which originate from the neutron-transfer channel. This identification is confirmed with the \( E_1-E_2 \) correlation information as shown in Fig. 5.1. The analysis of the elastic channel performed in this work. However, the analysis of the neutron-transfer and four-body break-up channels will not be covered in this thesis.

### 5.2.2 Break-up channels

The two break-up channels in \( \bar{d}d \) scattering provide very rich kinematics to study few-nucleon force effects. Both break-up channels have been identified using particle identification (PID). The deposited energy in the E detectors, the time-of-flight, TOF, and the
measured position of scattered particles were used in this work to identify the type of particle.

### 5.2.3 PID using $\Delta E$ and E-detectors

When a particle like a proton or a deuteron for the reactions and energies discussed in this thesis passes through the $\Delta E$ and E-detectors, it will deposit a fraction of its energy in the $\Delta E$ and the rest of its energy in the E-detector. According to the Bethe-Bloch formula, the deposited energy in the $\Delta E$-detector depends on the incident energy and the type of the particle. The energy and the type of the particle can be extracted from the correlation between the deposited energy in these two detectors. Figure 5.3 shows the deposited energy of forward-scattered particles in the $\Delta E$-detector versus their deposited energy in the E-detector for two different hodoscopes in the forward-wall. The top (bottom) panel is the response of a hodoscope with good (bad) performance. The top (bottom) band in the top panel corresponds to forward-scattered deuterons (protons). The window for selecting protons is shown with solid line.

![Figure 5.3: The deposited energy of forward-scattered particles in the $\Delta E$-detector versus their deposited energy in the E-detector for two different hodoscopes in the forward-wall. The top (bottom) panel is the response of a hodoscope with good (bad) performance. The top (bottom) band in the top panel corresponds to forward-scattered deuterons (protons). The window for selecting protons is shown with solid line.](image)
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top panel corresponds to forward scattered deuterons (protons). The break-up channels can be identified by requiring a coincidence between hits in the $\Delta E$-$E$ hodoscope. For the identification of the three-body break-up reaction, one of the hits in the hodoscope should fall inside the deuteron band, e.g. outside the marked area in Fig. 5.3, whereas the other hit should fall inside the proton band, e.g. inside the marked area in Fig. 5.3. In the case for which both hits fall in the proton band, the event originates most probably from the four-body break-up reaction. However, the response of all hodoscopes was not as was expected as it is illustrated in the bottom panel of Fig. 5.3. It turned out that the $\Delta E$ scintillators were damaged after a while for so-far unknown reasons. Therefore, the $\Delta E$-$E$ detectors could not provide the PID information for all scattering angles and we made, instead, use of the time-of-flight for PID.

5.2.4 PID using time-of-flight (TOF)

We determined the TOF of protons and deuterons by two different methods. The first method measured the TOF directly by making use of the output of the TDCs of the scintillators of the forward wall. In the second method, we extracted the TOF of the particles from their measured energies and scattering angles. A comparison between these two methods allows for particle identification. The following two subsections describe these two methods.

Measuring the TOF from the TDC outputs

The registered time for each hit in the E-detector, TOF, is the sum of three time intervals, $t_1, t_2, \text{ and } t_3$ which are defined as:

\[ t_1 = \frac{Ed}{pc^2}, \]

\[ t_2 = \frac{nx}{c}, \]

\[ t_3 = t_{RF}, \]

(5.1)

where $E$ and $p$ are the total energy and absolute magnitude of the momentum of the detected particle at the point of interaction, respectively, and $d$ is the distance between the interaction point and the detection point. Variable $x$ is the effective distance the photon travels from the interaction point in the scintillator to the PMTs, $c$ is the speed of light in vacuum, and $n$ is the index of refraction of the plastic scintillator, $n = 1.58$. The timing was clocked with respect to the RF of the cyclotron, which gives rise to the time, $t_{RF}$. Each E-detector was read out with two PMTs connected to the two edges of the scintillator. Therefore, the registered times for a detected particle in a detector by the
PMTs on the left- and right-hand sides of the detector are:

$$\text{TOF}_L = t_1 + \frac{n x}{c} + t_{RF},$$
$$\text{TOF}_R = t_1 + \frac{n(L - x)}{c} + t_{RF},$$

(5.2)

where $L$ is the length of the detector. From those, one can obtain the position where the particle hits the detector and $t_1$.

The TDCs for the forward scintillators were used in a common-stop mode and the start of the TDC signal was made by the discriminator output of the individual PMT signal. The stop signal was produced by the trigger signals, derived from the RF of the cyclotron. In general, the measured time between the left and right PMTs are different except for the particles which arrive in the middle of the E-detector. Figure 5.4 shows the correlation between $\text{TOF}_L - \text{TOF}_R$ and the measured position in the MWPC for the detected particles in the E detector number 4. The data can be described by a straight line.

![Figure 5.4: The difference between the measured TOF by the PMT on the left-hand side and the PMT on the right-hand side for the detected particles in the E detector number 4 as a function of measured position in the MWPC. The straight line presents a fit through the data. Each channel is equivalent to 0.2 cm and 500 ps for x and y axes, respectively.](image)

The difference in arrival time between the PMTs on the left- and right-hand sides of the detector could be used to determine the interaction point of a particle in the detector. This is illustrated in the left-hand side panel of Fig. 5.5 where the X coordinate of detected hits in the MWPC, $X_{MWPC}$, is plotted versus the reconstructed X coordinate using the $\text{TOF}_L$ and $\text{TOF}_R$, $X_{TOF}$. The reconstructed position resolution (FWHM), by the TOF has been found to be 2.9 cm by analyzing the spectrum, $X_{MWPC} - X_{TOF}$, as depicted in the right-hand side of Fig. 5.5. Note that the obtained position depends on the location where
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Figure 5.5: On the left-hand side, the reconstructed X coordinate using the TOF derived from the left and right PMTs is plotted versus the X coordinate of the detected particles in the MWPC. The spectrum of $X_{MWPC} - X_{TOF}$ is shown in the panel on the right-hand side.

the MWPC is located. The wire chamber resolution plays a minor role in determining this spatial resolution.

For the analysis of the break-up data, the TDC output corresponding to the left- and right-hand side PMTs, $TOF_L$ and $TOF_R$, were added together for each event. This addition cancels out the position dependence of the TOF information for a hit in a scintillator. We call this sum $TOF_i$ and label it by the hit number $i$, labeling the different particles that hit the forward wall.

The identification of the break-up channels proceeds by looking at the difference between the $TOF_1$ and $TOF_2$ values of two coincidence hits in two different E-detectors. Also note that the RF time $t_{RF}$ cancels in such a coincidence requirement. Figure 5.6 shows the $TOF_1 - TOF_2$ for one $S$-bin, $190 \text{ MeV} < S < 200 \text{ MeV}$ of the configuration ($\theta_1 = 25^\circ$, $\theta_2 = 25^\circ$, $\phi_{12} = 180^\circ$). The detected particle in each hit can be a proton or a deuteron. Three clear peaks can be recognized corresponding to proton-deuteron, proton-proton, and deuteron-proton coincidences. The identification of the peaks were confirmed using the $\Delta E-E$ responses as illustrated in Fig. 5.3. The distance between the peaks agrees with the TOF differences calculated based on the particle type and their energies. Therefore, the three-body break-up events can be selected by placing a gate around the left- or right-hand side peak in the TDC spectra. The middle peak (proton-proton coincidences) comes from the four-body break-up reaction. This demonstrates that also the identification of the four-body break-up reaction is feasible using the TDC information. The events outside the three peaks stem mainly from hadronic interactions and there is a small contribution from accidental coincidences. The events which are used in the analysis of a particular $S$-bin (see Fig. 5.24), also contain events with protons or deuterons, such those below the expected kinematical correlation, which have undergone a hadronic
interaction and may have originated from another $S$-bin. Therefore, the TOF difference, $\text{TOF}_1 - \text{TOF}_2$, will differ from the expected value for the selected $S$-bin. This effect was subsequently corrected for as described in Sec. 5.6.

**Extracting the TOF from the energy and scattering angles**

The position of the peaks in Fig. 5.6 depends on the value of $S$ and the scattering angles of the final-state particles. This makes selection of the reaction of interest by placing a window on $\text{TOF}_1 - \text{TOF}_2$ difficult to perform, since it requires a dynamic cut which depends upon $S$, $\theta$ and $\phi$. We, therefore, decided to introduce a new variable, $\Delta\text{TOF}$, which compares the measured TOF difference of the two particles with that calculated from the measured energy and scattering angles of the particles for each event.

The TOF can be extracted from the measured energy and distance traveled by the particle. For a particle which has a total energy, $E_{tot}$, travels over a distance, $r$, the TOF can be obtained by

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

where $c$ is the speed of light and $m$ is the rest mass of the particle.

The polar and azimuthal angles, $\theta$ and $\phi$, of the scattered particles hitting the E-detectors are measured by the MWPC. The E-detectors of the forward wall are a part of a cylinder with a radius of $r_0$. The vector $\vec{r}$ connects the target to the detection point in the E-detectors. Figure 5.7 shows how to define $\vec{r}$ in terms of $\theta$, $\phi$, and in terms of two
new cylindrical angles $\Theta$ and $\Phi$. The unit vector of $\vec{r}$ is

$$
\hat{u}_r = \begin{pmatrix} 
\sin \theta \cdot \cos \phi \\
\sin \theta \cdot \sin \phi \\
\cos \theta 
\end{pmatrix} = \begin{pmatrix} 
\sin \Theta \\
\cos \Theta \cdot \sin \Phi \\
\cos \Theta \cdot \cos \Phi 
\end{pmatrix}. 
$$  \hfill (5.4)

From this we obtain the angles $\Theta$ and $\Phi$ by

$$
\Theta = \arcsin(\sin \theta \cos \phi), \quad \Phi = \arctan \left( \frac{\sin \theta \sin \phi}{\cos \theta} \right). 
$$  \hfill (5.5, 5.6)
and the Cartesian components of \( \vec{r} \) are

\[
\begin{align*}
  r_x &= r_0 \tan \Theta, \\
  r_y &= r_0 \sin \Phi, \\
  r_z &= r_0 \cos \Phi.
\end{align*}
\]

Figure 5.8 represents the magnitude of \( |\vec{r}| = \sqrt{(r_x)^2 + (r_y)^2 + (r_z)^2} \) for several scattering angles as a function of the azimuthal angle. Note that the distance from the center of the cylinder of the E-detector to the target is 75.2 cm. For the break-up analysis, the difference between the TOF of particles 1 and 2 measured by TDCs, \((\text{TOF}_1 - \text{TOF}_2)_{\text{TDC}}\), and that extracted from the energies and the scattering angles, \((\text{TOF}_1 - \text{TOF}_2)_{\text{E}}\), has been used to define the variable \( \Delta \text{TOF} \). The left panels of Fig. 5.9 show the value of \( \Delta \text{TOF} \) as a function of azimuthal angle, \( \phi \), and the right panels show the corresponding projected spectra. For the top panels, we assumed that the length of the vector \( \vec{r} \) is identical to \( r_0 \), the minimum distance from the target to the forward wall, independent of \( \phi \). The cylindrical design of the forward wall can clearly be observed by the dependence of \( \Delta \text{TOF} \) on \( \phi \) for the band around 0, as a consequence of the effects illustrated in Fig. 5.8. For the bottom panels, the extracted values of \( |\vec{r}| \) were used that successfully resulted in a \( \Delta \text{TOF} \) which is independent of \( \phi \). In addition, we note that \( \Delta \text{TOF} \) does not depend upon \( S \). We
assumed that the first particle is a deuteron and the second one a proton. If our assumption is correct the average value of $\Delta$TOF will be zero. The peaks on the right-hand side of that belong to proton-proton and proton-deuteron combinations.

In this thesis, we focus on the analysis of the three-body break-up channel. The top-left panel of Fig. 5.10 represents the correlation between the energy of two particles that are detected in coincidence in the forward wall. The scattering angle of both particles is fixed to be $25^\circ \pm 2^\circ$ and the difference between the azimuthal angles of the two particles is $180^\circ \pm 5^\circ$. This spectrum contains events from two different reactions, namely three- and four-body break-up reactions. The proton-deuteron or deuteron-proton coincidences from the three-body break-up reaction can be separated by choosing events corresponding to the peak of interest as shown in the panel on the right-hand side of Fig 5.9. The results are shown in the top-right and bottom-right panels. The bottom-left panel contains events which correspond to the peak in the middle of the panel on the right-hand side of Fig 5.9. They originate from the four-body break-up channel.
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Figure 5.10: The correlation between the calibrated energy of the two outgoing particles (proton or deuteron) in the deuteron-deuteron break-up process is shown for the coplanar configuration, \((\theta_1, \theta_2, \phi_{12}) = (25^\circ, 25^\circ, 180^\circ)\) before PID (top left panel) and after PID (other panels). The bottom-panel on the left-hand side depicts events from the four-body break-up reaction and the two panels on the right-hand side correspond to the three-body break-up channels. The solid curves represent the relativistic \(S\)-curve that are calculated from energy and momentum conservation for the selected configuration.

5.3 Measurement of the beam polarization

The polarization of the deuteron beam was measured in the low-energy beam line with LSP as well as in the high-energy beam line with BINA. The procedure for the polarization measurement with LSP and BINA is explained in this section.

5.3.1 Measurement of the beam polarization with the LSP

A beam of polarized deuterons delivered by POLIS was decelerated and focused onto the LSP detection system. Figure 5.11 depicts the results of the scanning of the magnetic field around the three resonances between 52 and 63 mT as described in Ch. 3. Figure 5.11 shows the distribution of the different spin states of the deuteron for a tensor polarized beam (top panel) and for a vector polarized beam (bottom panel). The number of deuterons in the spin-up state, \(N_+\), spin-zero state, \(N_0\), and spin-down state, \(N_-\), were
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Figure 5.11: Spin-state distributions for a beam of deuterons with pure tensor (top panel) and with a vector polarization (bottom panel). The solid curves represent a fit of the spectrum using three Gaussian functions combined with a 2nd-order polynomial representing the background.

extracted from the number of events under the peaks on the left, middle and right-hand sides of each spectrum, respectively. The solid curve represents a fit of the spectrum using three Gaussian functions combined with a 2nd-order polynomial representing the background. The vector and tensor polarizations of the beam were calculated by employing Eqs. 3.2 and 3.3.

5.3.2 Measurement of the beam polarization with BINA

The polarization of the beam of deuterons can be measured at the high-energy beam line employing BINA via the $^1\text{H}(\vec{d},\vec{dp})$ reaction. A few $\vec{dp}$ scattering runs have been performed during the $\vec{dd}$ scattering experiment by switching from the liquid target to a CH$_2$ target. The procedure of event selection for the elastic $\vec{dp}$ reaction is discussed in Ch. 4. The asymmetry ratio, $\sigma/\sigma_0$, as a function of the azimuthal angle, $\phi$, was obtained for several polar scattering angles. The value of the analyzing power for each angle was obtained from a fit through the available data at an energy of 65 MeV/nucleon [22,23,95] as it is illustrated in Fig. 5.12 at forward angles. The same procedure has been performed for the backward center-of-mass angles. The open squares are data from Ref. [22], the
filled squares are data from [23], and the open circles from Ref. [95]. The shaded band represents the result of a fit through the data points. The width of the band corresponds to a 2σ error of the fit. The polarization of the beam of deuterons has been measured using different scattering angles and as a function of run number (time) discussed in the following section.

### 5.3.3 Results of the beam polarization measurement

Figure 5.13 represents the results obtained for the vector (top panel) and tensor (bottom panel) polarizations of the deuteron beam by BINA as a function of center-of-mass angle. The shaded bands represent the result of a constant-line fit through the data, which yields $p_Z = -0.601 \pm 0.029$ and $p_{2Z} = -1.517 \pm 0.032$. A small point-to-point uncertainty of $\sim 4\%$ was added to the statistical uncertainty for each point such that the reduced $\chi^2$ equals 1. The width of the band corresponds to a 2σ error of the fit. The total uncertainties of the polarizations was estimated by adding quadratically the statistical error and the systematic
5.3 Measurement of the beam polarization

The systematic uncertainty stems from the uncertainty in the analyzing powers, and was found to be 6% and 5% for the vector and tensor polarizations, respectively.

![Graph showing vector and tensor polarizations](image)

**Figure 5.13:** The vector (top panel) and tensor polarizations (bottom panel) of the deuteron beam as a function of center-of-mass, $\theta_{\text{c.m.}}$. The shaded bands represents the result of a constant-line fit through the data. The width of the band corresponds to a $2\sigma$ error of the fit.

The polarization of the beam of deuterons has been studied as function of time to check the stability of polarization during the measurement. Also, the obtained polarization values by BINA were compared with the obtained values by LSP. The obtained results for the vector (top panel) and tensor (bottom panel) polarizations of the deuteron beam by BINA and LSP are shown in Fig. 5.14 as a function of time. Each filled circle shows the average value of the obtained polarizations from different scattering angles with BINA. The polarization values at different scattering angles were found to be constant within the statistical uncertainties. The values of the polarization obtained with LSP at two time intervals are shown as filled squares. A comparison between the results demonstrates that the beam polarization was stable during the experiments and that there is a good agreement between the measured values at the low-energy beam line (LSP) with those measured at the high-energy beam line (BINA). The shaded bands represent the results of a straight line fit through the data including the results obtained with BINA and LSP. The width of the band corresponds to a $2\sigma$ error of the fit.
5.4 Analysis of the elastic channel

A similar data-analysis procedure as was used for the elastic $\vec{dp}$ and $\vec{pd}$ scattering reactions, described in Ch. 4, was also applied for the elastic $\vec{dd}$ scattering reaction. Figure 5.15 depicts the correlation between the scattering angle and the deposited energy for events registered in the forward part of BINA. The data were taken using a deuteron beam with an energy of 65 MeV/nucleon, impinging on a liquid-deuterium target. The solid curve represents the expected kinematical correlation for a scattered deuteron of the elastic deuteron-deuteron reaction. For the event selection, a coincidence with the backward part of BINA was requested. Events coming from the reaction $^2\text{H}(\vec{d}, \vec{dd})$ can clearly be identified in the spectrum. The events below the elastic band originate from the neutron-transfer and break-up reactions. Elastically-scattered deuterons at small angles, $10^\circ \leq \theta \leq 18^\circ$, have energies between 126 MeV and 117 MeV. The corresponding deuterons scatter to the backward ball with energies between 4 MeV and 13 MeV at the target position. These low-energy deuterons can hardly be detected by the backward detector due to the thres-
5.4 Analysis of the elastic channel

Figure 5.15: The correlation between the deposited energy and the scattering angle for events registered in the forward part of BINA in coincidence with a particle registered in the backward ball. The data correspond to a deuteron beam with an energy of 65 MeV/nucleon impinging on a liquid-deuterium target. The solid curve represents the expected kinematical correlation for a scattered deuteron in the elastic deuteron-deuteron reaction.

old of the detector combined with the possibility of not reaching the detector since all its energy is lost in the target material.

The extraction of the vector- and tensor-analyzing powers was based on Eq. 4.2. Figure 5.16 shows the ratio $\sigma / \sigma_0$, with $\sigma$ as the spin-dependent cross section and $\sigma_0$ as the spin-independent cross section, for a pure vector-polarized deuteron beam (top panel) and a pure tensor-polarized deuteron beam (bottom panel) for the $^2\text{H}(\vec{d}, dd)$ reaction at 65 MeV/nucleon. The amplitude of the $\cos \phi$ modulation in the top panel equals $\sqrt{3}p_{ZiT_{11}}$ and that of the $\cos 2\phi$ modulation in the lower panel equals $-\frac{\sqrt{3}}{2}p_{ZTT_{22}}$. The offset from 1 in the lower panel equals $-\frac{1}{\sqrt{6}}p_{ZZT_{20}}$. The polarization values extracted from a linear fit through the measured values with BINA and LSP in Sec. 5.3 were used to extract the analyzing powers.

To check for additional systematic uncertainties, the experimental data are divided into small portions of one day. The value of $p_{ZiT_{11}}$, $p_{ZTT_{20}}$ and $p_{ZTT_{22}}$ for every day and for different scattering angles are obtained. Figure 5.17 shows the value of $p_{ZiT_{11}}$, $p_{ZTT_{20}}$ and $p_{ZTT_{22}}$ for $\theta_{c.m.} = 54.8^\circ$ as a function of time for $\vec{d}d$ elastic scattering.
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Figure 5.16: The ratio $\sigma/\sigma_0$, with $\sigma$ being the spin-dependent cross section and $\sigma_0$ the spin-independent cross section, for a pure vector-polarized deuteron beam (top panel) and a pure tensor-polarized deuteron beam (bottom panel) for the $^2\text{H}(d,dd)$ reaction at 65 MeV/nucleon.

65 MeV/nucleon. The fluctuations of the $p_{Z1}T_{11}$, $p_{ZZ}T_{20}$ and $p_{ZZ}T_{22}$ in the course of the experiment are very well within the statistical errors. A constant-line fit gives a $\chi^2/NDF \sim 1$ for each angle for the entire experiment.

5.5 Analysis of the three-body break-up channels

One of the main goals of this thesis is the study of the three-body break-up reaction in $dd$ scattering. In the following subsections, we discuss the various analysis procedures which have been applied in the data analysis.

5.5.1 Three-body break-up kinematics and the $S$-curve

For the analysis of the three-body break-up data we follow the conventions as has been used in the past in the proton-deuteron break-up. The convention is to measure the energies, polar and azimuthal angles of the two coincident, emitted particles. Using the
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Figure 5.17: The value of $p_{ZiT_{11}}$, $p_{ZZT_{20}}$ and $p_{ZZT_{22}}$ for $\theta_{c.m.} = 54.8^\circ$ as a function of time for $\vec{d}d$ elastic scattering at 65 MeV/nucleon.

measured variables and considering momentum and energy conservation, all the other kinematical variables of the reaction can be obtained unambiguously. The kinematics of the three-body break-up reaction is determined by using the scattering angles of the proton and the deuteron ($\theta_d, \theta_p, \phi_{12} = |\phi_d - \phi_p|$) and the correlation between their energies presented by the kinematical curve which is called the $S$-curve. The energies of the proton, $E_p$, and deuteron, $E_d$, were described as a function of two new variables, $D$ and $S$ where $S$ is the arc-length along the $S$-curve with the starting point chosen arbitrarily at the point where $E_d$ is minimum and $D$ is the distance of the $(E_p, E_d)$ point from the kinematical curve. The $S$-curves for several kinematical configurations are shown in Fig. 5.18. Each $S$-curve is labeled by three numbers. For example, the label $(20^\circ, 30^\circ, 180^\circ)$ shows a coincidence between a deuteron that scatters to $20^\circ$ and a proton that scatters to $30^\circ$, and the azimuthal opening angle, $\phi_{12}$, between the deuteron and the proton is $180^\circ$.

5.5.2 Energy calibration of the forward E-scintillators

The energy calibration of each E-scintillator has been performed using the response of the left and right PMTs, connected to both sides of the scintillator. In general, the strength of the signals of the PMTs on the left-hand and right-hand sides of the scintillator are different due to a different light attenuation of the scintillation light. By multiplying the
Figure 5.18: The energy correlation between protons and deuterons in coincidence for the three-body break-up reaction in $^3d + d$ scattering is shown as $S$-curves for several kinematical configurations. The kinematics are defined by $(\theta_d, \theta_p, \phi_{12})$, the polar scattering angles of the proton and deuteron, respectively, and the relative azimuthal angle.

collected charges from the left and right PMTs, one can obtain a parameter which hardly depends on the position at which a particle hits the detector. This parameter represents the amount of deposited energy in the scintillator in units of channel number of the ADC.

Five symmetric $\Delta E$-E hodoscope pairs covering ten E-scintillators of the forward wall have been chosen and the following steps were performed to calibrate each scintillator for protons and deuterons:

1- At first, the E-detectors were pre-calibrated using the calibration parameters which were used for the elastic $^3d$ reaction. Figure 5.19 shows the result for two hodoscopes in which two hits were detected in coincidence by two different scintillators. The expected kinematical energy correlation for the chosen configuration $(\theta_p = \angle^\circ, \theta_d = \angle^\circ, \phi_{12} = 180^\circ)$ is shown as a solid curve in Fig. 5.19. The second band that appears above the real band comes from mis-identification of the hits in the hodoscopes. The energy values of this curve correspond to the energies at the E-detector, e.g. corrected for the loss of energy due to the materials between the target and the detectors. The energy loss of the particles while traveling from the target towards the detection point depends on the particle type, particle energy and the type of materials between target and detector. The deuteron is heavier than proton and as a result loses more energy than proton. Figure 5.20 shows the correlation between the deposited and thrown energies of the proton (left panel) and
5.5 Analysis of the three-body break-up channels

Figure 5.19: Results for two hodoscopes in which two hits were detected by two different scintillators. The expected kinematical energy correlation for the chosen configuration ($\theta_p = 21^\circ$, $\theta_d = 21^\circ$, $\phi_{12} = 180^\circ$) is shown as a solid curve. The energy values of this curve correspond to the energies at the E-detector, e.g. including the loss of energy due to the materials between target and detectors.

deuteron (right panel) obtained via a GEANT3 simulation. A diagonal solid line is drawn in each panel to indicate the locus where the energy deposited for protons and deuterons is equal to the thrown energy. The tail under a very dense part of data points in the left panel (right panel) corresponds to protons (deuterons) which have undergone a hadronic interaction inside the forward scintillators.

2- Two calibration functions for protons and deuterons were found by combined fitting of the data to the kinematical curve for the selected $\Delta E$-$E$ pair. The calibration functions obtained for protons and deuterons have been used to calibrate the pre-calibrated detector for the detected protons and deuterons in the E-detector, respectively. Figure 5.21 represents the obtained calibration functions for protons and deuterons which show the correlation between the pre-calibrated and the final calibrated values. Each curve represents the calibration function for one of the E-detectors. The obtained functions for protons and deuterons are different due to the difference in their quenching effects and
Figure 5.20: The correlation between the deposited and thrown energies of protons (left panel) and deuterons (right panel). A diagonal solid line is drawn in each panel to indicate the locus where the energy deposited for protons and deuterons is equal to the thrown energy. The “thrown” energy refers to the energy of the particle at the vertex position.

The fact that calibration parameters are energy dependent. Figure 5.22 shows the same data as Fig. 5.19 after applying the calibration procedure as described in the text. The values correspond to the energies at the detector position.

3- The final step is to translate the energy at the detector position to the energy at the target position. The energy losses of the protons and deuterons have been added to their energies at the detector position and the result is shown in Fig. 5.23.

5.5.3 Event selection

The first step in the event selection for the three-body break-up channel is to find the energy correlation between the final-state protons and deuterons for a particular kinematical configuration $(\theta_p, \theta_d, \phi_{12})$, where $\theta_p$ and $\theta_d$ are the polar angles of the proton and the deuteron, respectively, and $\phi_{12}$ is the difference between their azimuthal angles. The number of break-up events in an interval $S - \Delta S/2$ and $S + \Delta S/2$ was obtained by projecting the events on a line perpendicular to the $S$-curve ($D$-axis).

Figure 5.24 depicts the correlation between the energy of protons and deuterons in coincidence for the kinematical configuration, $(\theta_p, \theta_d, \phi_{12}) = (25^\circ, 25^\circ, 180^\circ)$. The solid curve is the expected correlation for this configuration. One of the many $S$-intervals and the corresponding $D$-axis are also shown. The result of the projection of events on the $D$-axis for a particular $S$-bin is presented in the inset of Fig. 5.24. This spectrum consists of mainly break-up events with a negligible amount of accidental background. Particles for most of the break-up events deposit all their energy in the scintillator, which gives rise to a peak around zero for the variable $D$. Particles in a part of the break-up events undergo a hadronic interaction inside the scintillator or in the material between the target and the
detector. For these events the value of $S$ is ill-defined and, therefore, considered as background (primarily to the left-hand side of the main peak in Fig. 5.24). All the background events were subtracted by fitting a polynomial representing the background and a Gaussian representing the signal to the projected spectrum. The fraction of break-up events which did not deposit their complete energy has been estimated by a GEANT3 simulation and corrected for when determining the cross section. This procedure is explained in Sec. 4.4.

### 5.6 The break-up cross section

In this section, we calculate the cross section directly from the number of counts and the experimental parameters such as the beam current and the target thickness together with the different efficiencies of the system. For a given kinematical configuration, $\xi(S, \theta_p, \theta_d, -
Chapter 5. Analysis of deuteron-deuteron scattering at 65 MeV/nucleon

Figure 5.22: Same as Fig. 5.19 after applying the calibration procedure as described in the text. The values correspond to the energies at the detector position.

\( \phi_{12} \), the break-up cross section is defined as:

\[
\frac{d^5\sigma}{d\Omega_p d\Omega_d dS} = \frac{N}{Q/Z} \cdot \frac{1}{t \cdot \epsilon} \cdot \frac{1}{\Delta\Omega_p \Delta\Omega_d \Delta S},
\]

(5.10)

where, \( N \) is the number of break-up events, \( Q \) is the total integrated charge, \( Z \) is the charge of the projectile, \( t \) is the number of the scattering centers per unit area, and \( \epsilon \) stands for all efficiencies in the system. The parameters \( \Delta\Omega_p \) and \( \Delta\Omega_d \) are the solid angles for the proton and deuteron, respectively, and \( \Delta S \) is the size of the energy window placed on the \( S \)-curve.

The cross sections are determined by taking into account the following parameters and conditions:

1. The efficiencies of the MWPC for protons and deuterons have been determined for a region defined by \( \Delta E-E \) hodoscopes. The average efficiencies of the MWPC for protons and deuterons are \( \sim 97\% \) and \( \sim 99\% \), respectively.
5.6 The break-up cross section

Figure 5.23: Same as Fig. 5.22 but now the energies of the protons and deuterons correspond to the values at the target position. The expected kinematical correlation at the target position is also calculated and shown as a solid curve.

2. The detection efficiency of particles in the forward wall has been obtained at the GEANT3 simulation for each configuration as a function of $S$. The detection inefficiency originates mainly from hadronic interactions of the particles in the scintillator. A small part of the inefficiency is due to the trigger condition and the detection thresholds. Figure 5.25 depicts the obtained efficiency for three different configurations in which the lines are results of a linear fit through the obtained data points.

3. The effective target thickness was 67.6 mg/cm$^2$, including bulging of the target.

4. The beam current and the live-time were read out and determined every second during the course of the experiment. The typical beam current was \( \sim 5 \) pA, and the live-time was typically around 40%.

The relevant information used in the analysis of the $\bar{d}d$ experiment are summarized all in Tab. 5.1.
Table 5.1: The relevant information used in the analysis of the $\vec{d}\vec{d}$ experiment.

<table>
<thead>
<tr>
<th>General information</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Beam particles</td>
<td>Polarized deuterons</td>
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<tr>
<td>Energy</td>
<td>130 MeV</td>
</tr>
<tr>
<td>Target</td>
<td>Liquid deuterium</td>
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<tr>
<td>Average beam current</td>
<td>4 pA</td>
</tr>
<tr>
<td>Target thickness</td>
<td>$67.6 \pm 3.4 \text{ mg/cm}^2$</td>
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<tr>
<td>Average efficiency of MWPC for deuterons</td>
<td>$99% \pm 1%$</td>
</tr>
<tr>
<td>Average efficiency of MWPC for protons</td>
<td>$97% \pm 1%$</td>
</tr>
<tr>
<td>Average hadronic efficiency for deuterons</td>
<td>$84% \pm 2%$</td>
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<tr>
<td>Average hadronic efficiency for protons</td>
<td>$90% \pm 2%$</td>
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<tr>
<td>Average live-time of the data acquisition</td>
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<table>
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<th>Various estimated systematic uncertainties</th>
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<tr>
<td>Target thickness (liquid deuterium)</td>
<td>$5%$</td>
</tr>
<tr>
<td>Current meter</td>
<td>$2%$</td>
</tr>
<tr>
<td>Efficiency of coincidence hardware trigger</td>
<td>$2%$</td>
</tr>
<tr>
<td>Efficiency of MWPC for deuterons</td>
<td>$1%$</td>
</tr>
<tr>
<td>Efficiency of MWPC for protons</td>
<td>$1%$</td>
</tr>
<tr>
<td>Efficiency of hadronic interaction for deuterons</td>
<td>$2%$</td>
</tr>
<tr>
<td>Efficiency of hadronic interaction for protons</td>
<td>$2%$</td>
</tr>
<tr>
<td>Geometrical acceptance</td>
<td>$2%$</td>
</tr>
<tr>
<td>Beam polarization</td>
<td>$4%$</td>
</tr>
<tr>
<td>Total systematic uncertainty for analyzing powers</td>
<td>$4.5%$</td>
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<tr>
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<td>Polar angle coverage</td>
<td>$20^\circ &lt; \theta_{\text{lab}} &lt; 35^\circ$</td>
</tr>
<tr>
<td></td>
<td>$40^\circ &lt; \theta_{\text{c.m.}} &lt; 70^\circ$</td>
</tr>
<tr>
<td>Total systematic uncertainty for the cross section</td>
<td>$6%$</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Specific for the three-body break-up reaction</th>
<th></th>
</tr>
</thead>
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<tr>
<td>Polar angular coverage</td>
<td>$15^\circ &lt; \theta_{1,2} &lt; 28^\circ$</td>
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<tr>
<td>Azimuthal opening angle coverage</td>
<td>$140^\circ &lt; \phi_{12} &lt; 180^\circ$</td>
</tr>
<tr>
<td>Bin sizes</td>
<td>$(\Delta \theta = \pm 2^\circ, \Delta \phi = \pm 5^\circ, \Delta S = \pm 5 \text{ MeV})$</td>
</tr>
<tr>
<td>Number of analyzed configurations</td>
<td>48</td>
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<tr>
<td>Number of obtained data points</td>
<td>$\sim 500$</td>
</tr>
<tr>
<td>Total systematic uncertainty for the cross section</td>
<td>$7%$</td>
</tr>
</tbody>
</table>
5.7 Scattering asymmetry and analyzing powers

The interaction of a polarized beam with an unpolarized target produces an azimuthal asymmetry in the scattering cross section. The magnitude of this asymmetry is proportional to the product of the polarization of the beam and an observable that is called the analyzing power. The procedure for obtaining the analyzing power in the break-up channel is similar to that for the elastic channel. For every kinematical point, $\xi$, the azimuthal distribution of the scattered particles for a polarized beam is normalized to that of the unpolarized beam. The analyzing power of the break-up reaction is presented in a similar way as was done for the analyzing power in the elastic reaction, namely:

$$
\sigma(\xi) = \sigma_0(\xi) \left[ 1 + \sqrt{3} p_Z i T_{11}(\theta) \cos \phi - \frac{1}{\sqrt{8}} p_Z Z T_{20}(\theta) - \frac{\sqrt{3}}{2} p_Z Z T_{22}(\theta) \cos 2\phi \right],
$$

(5.11)

where $\sigma, \sigma_0$ are the polarized and unpolarized cross sections, respectively, $\xi$ represents the configuration $(S, \theta_p, \theta_d, \phi_{12})$. The parameters $i T_{11}$ and $p_Z$ are the vector-analyzing power and the vector beam polarization, respectively. The observables $T_{20}$ and $T_{22}$ are the tensor-analyzing powers, $p_Z Z$ is the tensor polarization of the beam, and $\phi$ is the azimuthal...
scattering angle of the deuteron. According to Eq. 5.11, for a deuteron beam with a pure vector polarization, $\frac{\sigma}{\sigma_0}$, should show a $\cos \phi$ distribution. When a pure tensor-polarized deuteron beam is used, the ratio $\frac{\sigma}{\sigma_0}$ should show a $\cos 2\phi$ distribution.

By exploiting the asymmetry distribution for each $S$-bin, the vector-analyzing power, $iT_{11}$ and the tensor-analyzing powers, $T_{20}$ and $T_{22}$, were obtained for every kinematical configuration, $(\theta_p, \theta_d, \phi_{12}, S)$. Figure 5.26 shows the ratio $\frac{\sigma}{\sigma_0}$ for a pure vector-polarized deuteron beam (top panel) and a pure tensor-polarized deuteron beam (bottom panel) for $(\theta_p = 28^\circ, \theta_d = 30^\circ, \phi_{12} = 180^\circ, S = 210$ MeV). The curves in the top and bottom panels are the results of a fit based on Eq. 2.34 through the obtained asymmetry distribution for a beam with a pure vector tensor polarization, respectively. The amplitude of the $\cos \phi$ modulation in the top panel equals $\sqrt{3}p_ZiT_{11}$ and the amplitude of the $\cos 2\phi$ modulation in the lower panel equals $-\frac{\sqrt{3}}{2}p_ZZT_{22}$. The offset from 1 in the lower panel equals $-\frac{1}{\sqrt{8}}p_ZZT_{20}$. The polarization values have been measured independently using BINA and verified by the measurements of the LSP, Sec. 5.3, to be $p_Z = -0.601 \pm 0.029$ and $p_{ZZ} = -1.517 \pm 0.032$.

The quality of the fits have been checked by comparing the distribution of the obtained $\chi^2$s with the expected $\chi^2$ distributions. The left (right) panel of Fig. 5.27 represents the reduced $\chi^2$ distributions of the fits for a beam of deuterons with a pure-vector (pure tensor) polarization. The observed $\chi^2$ distributions follow accurately the expected-$\chi^2$ distributions which are shown as the solid curves.
Figure 5.26: The ratio of the spin-dependent cross section to the unpolarized one for a pure vector-polarized deuteron beam (top panel) and a pure tensor-polarized deuteron beam (bottom panel) for \( \theta_p = 28^\circ, \theta_d = 30^\circ, \phi_{12} = 180^\circ, S = 210 \text{ MeV} \).
Figure 5.27: The left (right) panel shows the observed reduced $\chi^2$ distribution of the fits (open circles) for a beam of deuteron with a pure-vector (pure-tensor) polarization. The label “counts” refer to the number of configurations for the corresponding bin. The curves are the predicted reduced $\chi^2$ distributions.