3. Study of 3NF effects in $\vec{d} + p$ elastic scattering

A measurement of the differential cross sections in three-nucleon systems is one of the tools to study the general nature of the 3NF. A more detailed information can be obtained by measuring other observables such as analyzing powers. For instance, the spin-dependent part of the 3NF can be studied extensively by measuring the vector- and tensor-analyzing powers using polarized proton and deuteron beams. Precision measurements of the vector-analyzing power of elastic proton-deuteron scattering have been performed with polarized proton beams at various beam energies ranging from 90 to 250 MeV [9, 11, 18, 19]. Data on vector- and tensor-analyzing powers in $\vec{d} + p$ scattering are, however, scarce. Vector- and tensor-analyzing powers at several energies between 75-187 MeV have been obtained in the past [20, 21]. Most of these data do not have sufficient precision and, therefore, not enough sensitivity to study details of the 3NF. The only precision data set over a large angular range was obtained using a polarized deuteron beam with energies of 140, 200, and 270 MeV [12, 22]. For a systematic study of the 3NF, a larger and more precise data-base is, therefore, mandatory.

This chapter describes a precision measurement of vector- and tensor-analyzing powers in $\vec{d} + p$ elastic scattering. The experiment was conducted at the RIKEN accelerator research facility using a polarized deuteron beam with energies of 130 and 180 MeV.

Aside from providing information on the nature of 3NF, these measurements were part of a calibration for experiments performed at KVI [27, 28, 58, 59, 60] which made use of polarized deuteron beams. At KVI, the IBP setup (see chapter 4) is used to measure on-line the polarization of proton and deuteron beams. The proton beam polarization is measured via $p - p$ elastic scattering for which the analyzing powers are very well known. However, the polarization of a deuteron beam is measured via $d - p$ elastic scattering. The analyzing powers of this reaction have not been measured for all energies and the discrepancy between predictions of different theoretical models is not negligible. Therefore, we performed these measurements at two energies which correspond to energies that are used for experiments at KVI.

The following section will give a description of the experimental facilities at RIKEN and the techniques used to measure the spin observables. Results of the measurements will be compared and interpreted using modern Faddeev calculations as described in Chap. 2.

3.1 Experimental procedure and data analysis

Figure 3.1 shows a schematic top view of the RIKEN accelerator facility. The experiment was composed of two setups. In the first setup, the polarization asymmetries of the deuteron beam were determined by measuring the $^{12}\text{C}(\vec{d}, \alpha)^{10}\text{Be}(2^+)$ reaction with a theoretically known analyzing power at $0^\circ$ using the SMART spectrograph. In the second setup, polarization asymmetries in the elastic $\vec{d} + p$ scattering were measured simultaneously with the SMART measurements using the in-beam polarimeter in the D-room. The
Chapter 3: Study of 3NF effects in $\vec{d} + p$ elastic scattering

Figure 3.1: A schematic top view of the layout of the RIKEN accelerator research facility. The present experiment was performed using the in-beam polarimeter in the D-room (shown in the middle box in the picture) and the SMART spectrograph in the E4 hall.
vector- and tensor-analyzing powers in $d+p$ elastic scattering were subsequently obtained by combining results from the first and second experiment. A detailed description of the experimental method can be found in Refs. [32, 61]. In this section, we only provide a brief summary of the procedure.

The vector- and tensor-polarized deuteron beams were provided by the atomic beam polarized ion source. In this experiment, the polarization states of the deuteron beam were switched between off-mode $(p_Z, p_{ZZ}) = (0,0)$, up-mode $(p_Z, p_{ZZ}) = (1/3,+1)$, and down-mode $(p_Z, p_{ZZ}) = (1/3,-1)$. The values between parenthesis correspond to the maximum theoretical values of the vector $(p_Z)$ and tensor $(p_{ZZ})$ polarizations. The three different polarization states were switched every 5 s by changing the RF transition fields of the polarized ion source. The experimental polarization values were typically 60-80% of the maximum possible theoretical values. The beam intensity used during the experiment was typically 30 nA.

For the unambiguous determination of the beam polarization, we have exploited the relation between beam polarization and the $^{12}\text{C}(d,\alpha)^{10}\text{B}(2^+)$ reaction cross section at $0^\circ$ [62, 63, 64]. For symmetry reasons, this reaction has a maximum analyzing power at $\theta_{\text{c.m.}} = 0^\circ$:

$$T_{20}(0^\circ) = 1/\sqrt{2}$$
$$iT_{11}(0^\circ) = T_{22}(0^\circ) = T_{21}(0^\circ) = 0. \quad (3.1)$$

In such a case, Eq. 2.56 can be simplified as:

$$\frac{\sigma}{\sigma_0} = 1 + \frac{p_{ZZ}}{4}(3\cos^2\beta - 1). \quad (3.2)$$

Equation 3.2 allows us to determine the tensor polarization of the beam by measuring the ratio between the polarized and unpolarized cross sections at $0^\circ$. As a pre-requisite, the angle $\beta$ should be known during the experiment. The angle $\beta$ of the beam polarization can be manipulated at the ion source. By exploiting the $\sigma/\sigma_0$ in Eq. 3.2, detector-related parameters such as solid angle and efficiencies cancel out to a very large extent, since the same detector is used for both polarization states.

### 3.1.1 Measurement of $^{12}\text{C}(d,\alpha)^{10}\text{B}(2^+)$ reaction with SMART

A measurement of the beam polarization of the tensor-polarized deuteron beam was performed exploiting the SMART spectrograph. The SMART magnetic spectrograph [65] consists of a beam swinger and a cascade magnetic analyzer with two focal planes. It has three quadrupoles and two dipole magnets in a QQDQD configuration. The scattered $\alpha$ particles were momentum analyzed by the magnetic spectrograph and detected by a Multi-Wire Drift Chamber (MWDC) and three plastic scintillators placed at the second focal plane. A schematic top view of the SMART spectrograph is given in Fig. 3.2. In the present experiment, the reaction $^{12}\text{C}(d,\alpha)^{10}\text{B}(2^+)$ was studied with the SMART spectrograph by scattering a polarized-deuteron beam at an incident energy of 130 and 180 MeV from a $^{12}\text{C}$ target with a thickness of 20 mg/cm$^2$.

To study the polarization value, we measured the number of scattered $\alpha$ particles in the scattering plane with a polarized and an unpolarized beam. A hodoscope of two scintillator
plates allows to identify the $\alpha$ particles from the background signal as demonstrated in Fig. 3.3. In this graph, lighter elements like $^3$He, deuterons, and protons can be observed at lower channel numbers.

Before extracting the cross-section values, we improved the quality of the $\alpha$ peak by choosing the correct drift-time (DT) for the MWDC. The MWDC, which was used to determine the trajectory of particles, is made of an array of anode wires which are sandwiched between cathode plates and the space between is filled with counting gas. The interaction of charged particles with the electro-negative counting gas creates electrons. The number of electrons, created by ionization, increases by an avalanche process in the electric field of the anode wire. These electrons are finally collected by the wires. By taking into account the correct DT of the electron to the nearest wires, one can get the trajectory of the particle and, therefore, the position of the central wire can be calculated.

A DT is converted to a drift distance by using a polynomial function. The coefficients of this polynomial are determined empirically by iterations. For the first-order, we transform the boundaries of the MWDC-TDC to the maximum and minimum of drift distances ($10$ and $0$ mm, respectively). Figure 3.4 shows the TDC histogram for MWDC hits and the minimum and maximum TDC values are shown by the lines. Figure 3.5 shows the drift-time versus drift-distance in the left panel and versus the difference between the calculated hit position and the measured position in the right panel. For the second-order iteration, we used the left-hand panel as the starting point, and obtained a function form by fitting a polynomial to this distribution. Figure 3.6 shows the same spectra as in Fig. 3.5 after a few iterations. Note that the correlation between the distance and the DT of the $\alpha$ events have been improved significantly. The most optimum estimate of the DT inside the MWDC improves the measured energy resolution of the excited states of $^{10}$B. This procedure has been performed for both MWDCs (MWDC1 and MWDC2) and for three
3.1. Experimental procedure and data analysis

Figure 3.3: The left panel shows the uncalibrated energy deposit of scattered particles in two scintillators at the end of the SMART spectrometer. By using the deposited energy in the hodoscope (the polygon gate), α particles can be selected from background particles. The right panel depicts the projection of the same scatter plot on the energy axis of one of the scintillators. A clear α peak can be recognized around channel 800. In the lower channels, other particles such as protons and deuterons can be identified.

Figure 3.4: The TDC histogram for the X-plane of MWDC1 hits is shown. The minimum and maximum of the TDCs are shown by the lines.

different planes (X, Y, and U).

After correcting for the MWDC-DT, the excitation-energy spectrum of $^{10}$B can be
reconstructed by momentum analysis of the scattered $\alpha$ particles. Figure 3.7 shows the excitation spectrum of $^{10}$B. The solid line corresponds to a fit with a sum of several Gaussian functions representing the different states. With the achieved energy resolution of 200 KeV, the $2^+$ excited state of interest has little overlap with the neighboring states. These events are used for the extraction of the cross sections, $\sigma^\dagger$, $\sigma^\dagger$, and $\sigma^{off}$, corresponding to a measurement with a beam polarization of $(p_Z,p_{ZZ}) = (1/3,+1)$, $(1/3,-1)$, and $(0,0)$, respectively. With these cross sections, one can calculate the polarization of the deuteron beam using Eq. 3.2.

In the present experiment, the asymmetries, $(\sigma^\dagger - \sigma^{off})/\sigma^{off}$, and $(\sigma^\dagger - \sigma^{off})/\sigma^{off}$, of

Figure 3.5: The left panel shows the drift distance versus the drift time for the Y-plane of the MWDC after first iteration. Generally a third-rank polynomial is enough to transform the drift-time to a distance. The right panel shows the drift-time versus the difference between the calculated hit position and the measured wire in the center of the cluster hit after the first iteration.

Figure 3.6: The same as Fig. 3.5 but after multiple iterations.
3.1. Experimental procedure and data analysis

3.1.1 The (d, α) reaction

The (d, α) reaction have been measured using the SMART-spectrograph. Note that we used $\sigma^{off}$ instead of $\sigma_0$. In an ideal case, $\sigma^{off}$ corresponds to the cross section for a theoretically unpolarized beam. In our data analysis, however, a small non-zero polarization in the $(pz, pzz) = (0, 0)$ mode was observed and was taken into account. The asymmetries for the two polarization modes are plotted in Fig. 3.8 for center-of-mass angles close to 0°, which corresponds to a small data sample of 60 minutes of data taking.

To obtain a precise asymmetry at 0°, a second-order polynomial fit through the observed angular distribution was made, as shown by the solid lines. Fluctuations in asymmetry during the experiment were monitored by the above-mentioned fitting procedure for every hour of data taking. The variation in measured asymmetry as a function of time is accounted for in the final analysis. Figure 3.9 shows these fluctuations for both polarization states as a function of run number.

3.1.2 The D-room polarimeter measurements

The D-room setup at RIKEN was used to measure asymmetries in the elastic $d+p$ reaction using Eq. 2.56. Combined with a simultaneous measurement of the asymmetry using the SMART spectrometer, vector- and tensor-analyzing powers in elastic $d+p$ scattering were obtained.

The D-room polarimeter consists of 4×7 plastic scintillators placed at the right, left, up, and down of a solid CH$_2$ target. Figure 3.10 illustrates schematically the coincidence setup for the left and right detectors in the horizontal plane. The vertical plane is not
Chapter 3: Study of 3NF effects in $\vec{d} + p$ elastic scattering

Figure 3.8: Asymmetries of the $^{12}$C$(d,\alpha)^{11}$B$(2^+)$ reaction as a function of the scattering angle in the center-of-mass frame. The two data sets were obtained from two polarization states of $(p_Z, p_{ZZ}) = (1/3, +1)$ and $(p_Z, p_{ZZ}) = (1/3, -1)$ normalized to the off-polarization state, $(p_Z, p_{ZZ}) = (0, 0)$. The asymmetry at $\theta_{c.m.} = 0^\circ$ is determined by an extrapolation of asymmetries measured up to $4.5^\circ$ via a second-order polynomial fit. The amount of data shown in this figure corresponds to about 60 minutes of data taking.

The elastic $\vec{d} + p$ reaction can be identified by a left-right or up-down coincidence requirement in the D-room polarimeter. For this purpose, four deuteron detectors were placed at a polar scattering angle of $25^\circ$ covering a large part of the deuteron phase space. These detectors were required to be in coincidence with one of the smaller proton detectors placed on the other side of the beam at polar scattering angles between $30^\circ$ and $55^\circ$ in the lab frame. The positions of the proton and deuteron detectors in the laboratory frame were chosen such that (see Fig. 3.11) they cover center-of-mass angular ranges of $\theta_{c.m.} = 70^\circ - 120^\circ$ at $E_d = 130$ MeV and $\theta_{c.m.} = 76^\circ - 120^\circ$ at $E_d = 180$ MeV.

Figure 3.12 shows the response, corresponding to the deposited energy in one of the proton detectors in coincidence with the opposite deuteron detector. This proton detector was placed at an angle of $30^\circ$, and it had a thickness of 10 mm. All impinging protons punch through the detector and deposit an energy of about 15 MeV. The small tail on the left side of the spectrum stems predominantly from the break-up reaction plus a contribution from hadronic interactions with the scintillator material. Furthermore, note that the pile-up background is negligible, which can be observed from the lack of events on the right side of the main peak. For the asymmetry measurements in $\vec{d} + p$ scattering, events were selected within the gate shown in Fig. 3.12. The vector- and tensor-analyzing powers can be obtained by making use of the $\phi$ dependence according to Eq. 2.56.
3.1. Experimental procedure and data analysis

Figure 3.9: The asymmetry of the $^{12}$C(d,α)$^{11}$B(2+) reaction at 0° as a function of run number (time). For more information, we refer to Fig. 3.8. Only small fluctuations were observed, which demonstrates the stability of the deuteron beam polarization during the experiment.

3.1.3 The $\chi^2$-fitting of the asymmetry measurements

The analyzing powers have been obtained by a global $\chi^2$-minimization fit of all data from SMART and the D-room polarimeter using Eq. 2.56. The free parameters in this fit were the analyzing powers: $iT_{11}, T_{20}, T_{22}, T_{21}$, the tensor polarizations $P_{ZZ}^{L}, P_{ZZ}^{T}, P_{ZZ}^{eff}$, and intensities for an unpolarized beam, $\sigma_0$. Note that as a consequence of the operation mode of the atomic polarized-beam source, the vector polarization is 1/3 of the obtained tensor polarization, independent on the efficiencies of the transition units. The combined $\chi^2$ fitting procedure gave a redundancy of three, which was used to minimize and estimate systematic uncertainties. Details of the $\chi^2$ fitting procedure are presented in App. B.

The fitting procedure combines the asymmetry measurement from the SMART setup with the measured asymmetries from the D-room polarimeter. The data were monitored by dividing them into small pieces in time (runs). The $\chi^2$-fitting procedure was repeated for every data set taken during a run from both SMART and D-room setups. Figures 3.13 and 3.14 show $iT_{11}$ analyzing power at $E_{\text{lab}} = 130$ MeV and $E_{\text{lab}} = 180$ MeV in the course of time for different $\theta_{\text{c.m.}}$, respectively. To check the stability of the data during the entire experiment, another $\chi^2$-fit through the data as a function of time was performed. Only a small point-to-point error was added quadratically to the statistical errors to obtain a reduced $\chi^2$ of one, which demonstrates the good stability of the experiment. The PTP errors in Figs. 3.13 and 3.14 are represented by $\lambda > 1$, where $\lambda$ is used to give the added errors in % following the relation $(\frac{\Delta iT_{11}}{iT_{11}} \cdot \sqrt{\chi^2 - 1})$. For most of the cases, this point-to-point (PTP) error was less than 1%.
Figure 3.10: A sketch of the experimental setup used to measure the elastic deuteron-proton scattering process. Six small proton detectors are placed in coincidence with one deuteron detector placed on the other side of the beam. The coincidence setup in light gray and in dark gray correspond to an azimuthal plane of $\phi = 0^\circ$ (right) and $\phi = 180^\circ$ (left), respectively. The definition of the angles are as in the Madison convention, see Chap. 2. The coincidence planes at $\phi = 90^\circ$ and $270^\circ$ are not shown here.

Figure 3.11: Elastic $d+p$ kinematics in the center-of-mass and lab frames. In the present experiment, we covered the range included in the box.
3.2 Results and discussion

With the geometry shown in Fig. 3.10, the vector- and tensor-analyzing powers in elastic $\vec{d} + p$ scattering were measured for $\theta_{c.m.} = 70^\circ - 120^\circ$ at $E_{lab}^d = 130$ MeV and $\theta_{c.m.} = 77^\circ - 120^\circ$ at $E_{lab}^d = 180$ MeV. Results for $E_{lab}^d = 130$ MeV are shown in Fig. 3.15 and listed in Table 3.1. Similarly, results for $E_{lab}^d = 180$ MeV can be found in Fig. 3.16 and in Table 3.2. The error bars in Figs. 3.15 and 3.16 indicate only statistical uncertainties together with a small PTP uncertainty.

The dominant systematic uncertainty stems from the knowledge of the polar, $\beta$, and azimuthal, $\alpha$, angles of the polarization direction of the incoming beam particles with respect to the beam direction. These angles were determined in a separate measurement which was conducted immediately after the ($\vec{d}, \alpha$) and $\vec{d} + p$ measurements. In this measurement, the polarization axis precessed in the swinger dipole magnet of the SMART spectrograph which was rotated by $90^\circ$ in a vertical plane. The precession angle is measured before and after the spin precession by using the D-room polarimeter and the swinger polarimeter at the end of SMART swinger. For the beam energy of 130 MeV, the values of $\beta = 82.0^\circ \pm 0.5^\circ$ and $\alpha = 2.0^\circ \pm 0.5^\circ$ were obtained, whereas $\beta = 99.4^\circ \pm 0.5^\circ$ and $\alpha = 2.0^\circ \pm 0.5^\circ$ were obtained for a deuteron beam energy of 180 MeV. Since the sensitivity to the $T_{21}$ analyzing power in Eq. 3.2 is proportional to $\cos \beta \sin \beta$, the uncertainty in $T_{21}$ increases as $\beta$ approaches $90^\circ$. The large systematic errors in $T_{21}$ are primarily associated with the value of $\beta$ in these experiments. In addition, variations in the beam polarization angles ($\beta, \alpha$) during the experiment have been monitored by dividing the data into several bins in time, and were found to be small. Yet, these non-statistical fluctuations were taken

![Figure 3.12:](image)

*Figure 3.12: The response of one of the proton detectors placed at 30° and for a beam energy of 180 MeV. A clear signal stemming from the elastic deuteron-proton reaction can be observed with a small background. The events selected for the asymmetry measurement are indicated by the gate.*
Figure 3.13: The vector-analyzing power, \(iT_{11}\), at \(E_{lab} = 130\) MeV for different \(\theta_{c.m.}\) was monitored as a function of time (represented by Run No.). The final value of the vector-analyzing power for each angle is the average of the data which is determined via a \(\chi^2\) fit. A very small point-to-point error was added quadratically to the statistical errors (in the panels, \(\lambda > 1\)) for every point to come to a \(\chi^2 \sim 1\). For a definition of \(\lambda\) see the text.
3.2. Results and discussion

Figure 3.14: Same as Fig. 3.13 for data taken at $E_{lab} = 180$. 
into account in our $\chi^2$-fitting procedure. The total systematic error is the quadratic sum of these partial systematic errors which are given in Tables 3.1 and 3.2 with superscript $sys.$ and are plotted as gray bands on top of the figures.
Figure 3.15: Vector- and tensor-analyzing powers of the elastic $^3d + p$ scattering at $E_{lab}^d = 130$ MeV as a function of $\theta_{c.m.}$. Error bars are statistical plus a small point-to-point uncertainty added in quadrature. In each panel, filled circles are data from the present experiment and open triangles are data from Ref. [20] at $E_{lab}^d = 131$ MeV. The dark gray bands at the top of the panels represent the systematical uncertainty (2\sigma) for every data point. The other dark gray bands correspond to calculations including only two-nucleon potentials. The light gray bands represent calculations including an additional Tucson-Melbourne TM' three-nucleon force. The solid lines correspond to results of a Faddeev calculation using the AV18 two-nucleon potential combined with the Urbana-Illinois X (UIX) three-nucleon potential. The dotted line represents the results of a coupled-channel calculations (CDB+\Delta). The dashed line represents the results of CDB+\Delta calculation including the Coulomb force. The comparison between data from Refs. [20] and these data shows clearly that the precision of the new measurements has been improved significantly.
Figure 3.16: Vector- and tensor-analyzing powers in the elastic $\bar{d} + p$ scattering at an incident deuteron beam energy of $E_{\text{lab}}^d = 180$ MeV. The open triangles are data from Ref. [20] and the open squares are data from Ref. [21]. For a description of the bands and lines, we refer to Fig. 3.15.
3.2. Results and discussion

Table 3.1: The analyzing powers for elastic $\vec{d} + p$ scattering at $E^{d}_{\text{lab}} = 130$ MeV for different scattering angles in the center-of-mass frame. Statistical errors are quoted with the superscript $^{\text{st}}$: and systematical errors with the superscript $^{\text{sys}}$: Statistical errors are the output of a $\chi^2$-fitting procedure plus an additional point-to-point uncertainty added quadratically. The uncertainty in $\theta_{c.m.}$ is $\pm 0.5^\circ$. Note that all the values and errors of the analyzing powers have been multiplied by a factor 1000.

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Table 3.2: Same as Table 3.1 except for $E^{d}_{\text{lab}} = 180$ MeV.

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<td>12</td>
</tr>
<tr>
<td>119</td>
<td>$-280$</td>
<td>3</td>
<td>11</td>
<td>$-188$</td>
<td>2</td>
<td>8</td>
<td>$-342$</td>
<td>4</td>
<td>14</td>
<td>$-161$</td>
<td>4</td>
<td>11</td>
</tr>
</tbody>
</table>
3.3 Comparison between data and theory

The measured vector- and tensor-analyzing powers are shown in Figs. 3.15 and 3.16 by filled circles and compared to rigorous Faddeev calculations, represented by bands and lines. The dark gray bands correspond to calculations including only two-nucleon potentials, namely Argonne V18 (AV18) [38], Charge-Dependent Bonn (CDB) [40], Nijmegen I (NIJM I), and Nijmegen II (NIJM II) [4]. The width of the bands indicates the variation in predictions for the three-body systems when using different two-nucleon potentials. The light gray bands represent calculations including an additional TM’ three-nucleon force. The solid lines correspond to the results of a Faddeev calculation using the AV18 two-nucleon potential combined with the UIX three-nucleon potential [15]. The dotted lines present result from a calculation using the coupled-channels potential CDB+ [17, 42]. Also measurements from Ref. [20, 21] at energies close to our energy are included (open triangles and squares). The comparison shows that the precision of the new data is significantly higher.

A comparison between theory and experiment at $E_d = 130$ MeV shows that the Faddeev calculations based on a pure two-nucleon potential give a reasonable agreement with the measured polarization observables. At this energy, calculations with the inclusion of the well-established TM’ three-nucleon force fail to describe the data, in particular for $T_{22}$. Calculations using the UIX three-nucleon potential show, with the exception of $T_{20}$, significant discrepancies with the data as well. On the other hand, calculations using the coupled-channels potential, CDB+$\Delta$, demonstrate that the polarization observables in the three-nucleon system can be described reasonably well by incorporating consistently an intermediate $\Delta$ resonance which seems to have a small effect for all observables except for $T_{21}$. Note that the discrepancies for $T_{21}$ can be partly ascribed to the large systematic uncertainties in this polarization observable.

At $E_d = 180$ MeV the behavior of the Faddeev calculations with respect to the data changes drastically. The Faddeev calculations, incorporating two-nucleon forces only, show large deviations from the data for all observables. The inclusion of the TM’ three-nucleon potential remedies these deficiencies significantly for $iT_{11}$ and $T_{20}$. However, the predictions for the tensor-analyzing powers, $T_{22}$ and $T_{21}$, fail to describe the magnitude and the shape of the measured angular distributions. Furthermore, the model including the $\Delta$ resonance fails to describe a large part of these data as well, even though the same model gave a good description at 130 MeV.

From Figs. 3.15 and 3.16, we observe that the discrepancies between data and theory depend on the incident beam energy. As a further check on this, the beam-energy dependence of our data has been compared with the presently available world data-base at intermediate energies. Results are shown in Fig. 3.17. All data points correspond to a fixed angle of $\theta_{\text{c.m.}} = 100 \pm 0.5^\circ$ in the center-of-mass. Our data (filled circles) are consistent with the data from Ref. [20] (open triangles). In addition, the precision measurements of Sekiguchi et al. [12] at $E_{\text{lab}}^d = 140$ and 200 MeV are plotted as open diamonds. Results of the Faddeev calculations for the CDB potential without 3NF and with TM’ and $\Delta$ are drawn as dashed lines, dash-dotted and solid lines, respectively.

The large deviations between our data and the rigorous predictions from Faddeev calculations based on modern two-nucleon potentials show that the observables presented in this work are sensitive to 3NF effects. The role of the $\Delta$-resonance as a degree of
freedom for 3NF has proven to be the dominant ingredient to describe well the vector-analyzing powers in $^3\text{He} + d$ elastic scattering at intermediate energies from 108 MeV to 190 MeV/nucleon [11]. The present work, however, presents large discrepancies between data and a self-consistent coupled-channel model including a dynamic $\Delta$ resonance at an
incident energy of 90 MeV/nucleon for the vector- and tensor-analyzing powers of the deuteron. For these observables and energies, the role of the \( \Delta \) as mediator of a 3NF is predicted to be small, whereas the data show that effects beyond the two-nucleon potential are present. A description of 3NF effects using the phenomenological two-pion exchange approach such as the TM' 3NF, which is added to a 2NF, cannot remedy the observed discrepancies either. In addition to the models presented in this thesis, other approaches are becoming available in the literature. One of these, namely chiral-perturbation theory, is based on the symmetries of Quantum Chromodynamics. Within this approach, nuclear forces are generated systematically \([51, 66]\). Unfortunately, the present state of this calculation does not allow a comparison with the data at intermediate energies such as those mentioned above. Once higher orders are included in the calculations, one can make a sensible comparison with the present data.