Chapter 6

Conclusions and Outlook

With the advent of nuclear physics, one of the most fundamental questions up to date in physics was raised, namely, what is the interaction between nucleons and how can the properties of nuclei be explained from the basic nucleon-nucleon interaction.

Recently, several so-called high-quality two-nucleon potentials, Nijmegen-I, Nijmegen-II [Sto94], CD-Bonn [Mac96] and Argonne-V18 [Wir95], were developed. Results from calculations using these potentials describe two-nucleon scattering observables with rather high precision. All of these potentials have in common, that they contain about \( \approx 40 \) parameters, which were fitted to the world nucleon-nucleon scattering data. The potentials are based largely on phenomenology, with an exception for the long-range one-pion-exchange potential.

A question of interest is, whether calculations for three-nucleon systems using these modern two-nucleon potentials, will also give meaningful results or whether higher-order terms, so-called three-nucleon forces, have to be included into the calculations. Calculations for three-nucleon systems can be done exactly with the use of Faddeev equations. The existence of three-nucleon forces is also predicted by meson theory and quantum field theory. Deviations of the results of these calculations from experimental data at energies \( \lesssim 30 \) MeV for the vector analysing power \( A_y \) of elastic proton-deuteron scattering showed, that the use of two-nucleon potentials solely is insufficient to describe three-nucleon scattering observables. However, at lower energies, the inclusion of 3NFs did not solve the discrepancies, leading to the well-known \( A_y \) puzzle.

The necessity for the inclusion of 3NFs was also observed in the differential cross section of the reaction \(^{2}\text{H}(\vec{p}, dp)\) [Shi82]. Theoretical investigation showed that three-nucleon force effects should indeed be seen in the minimum of \( d\sigma/d\Omega \) at energies \( \gtrsim 65 \) MeV/nucleon. It would also be of interest to observe, whether the vector analysing power of elastic proton-deuteron scattering would be sensitive to 3NFs at intermediate energies. The latter one would give an indication about the spin-dependence and the non-central part of 3NFs.

A major drawback in the investigation of three-nucleon force effects at these intermediate energies was the lack of sufficiently precise experimental data. Where data were available, they either had large uncertainties or covered only a limited range of centre-of-mass angles, sometimes excluding the regions of specific interest. In a few cases, the measurements done at different laboratories for \( d\sigma/d\Omega \) were not in agreement with each other. Recently, data with high precision were measured at 135 MeV for the differential cross section [Sak00] and at 150 and 190 MeV...
for the vector analysing power [Bie00, Cad01]. However, also these data for the analysing power covered only a fraction of the centre-of-mass angles.

For a systematic investigation of the influence of three-nucleon forces, consistent measurements as a function of bombarding energy and centre-of-mass scattering angle are necessary. One of the most easily accessible three-nucleon systems is the proton-deuteron system. For this system, the differential cross section can be measured at energies above 60 MeV, where the effects of 3NFs are expected to show up in the minimum. In addition, analysing powers should be measured to investigate the spin-dependence of three-nucleon forces.

The purpose of this work was to systematically investigate both observables, the differential cross section and the vector analysing power, of the reaction $^2H(\vec{p}, dp)$ as a function of incident proton-beam energy and centre-of-mass scattering angle. Measurements of both observables were, therefore, done at incident-beam energies of 108, 120, 135, 150, 170 and 190 MeV, covering an angular range of $30^\circ \leq \theta_{cm} \leq 170^\circ$ at each energy.

As a feasibility test and to prepare future experiments at KVI, also measurements of the differential cross section and the vector and tensor analysing powers of the reaction $H(\vec{d}, dp)$ were done at 130 MeV incident deuteron-beam energy.

### The $^2H(\vec{p}, dp)$ Reaction

The measurements for the reaction $^2H(\vec{p}, dp)$ were performed at KVI using the combination of the Big-Bite Spectrometer (BBS) and the EuroSuperNova (ESN) focal-plane detection system. During the measurements of the analysing power, measurements of the polarisation degree of the incoming beam were done in parallel for each data point, using the KVI in-beam polarimeter (IBP).

As a target, deuterated polyethylene targets were used. For the measurement of the analysing power, those targets consisted of a C$_2$D$_4$ matrix. However, for the measurement of the differential cross section, the thickness of the target has to be determined as accurately as possible. Determining the target thickness directly via mechanical measurements or indirectly via its weight and its surface area does not take the uniformity of the surface of the target properly into account and can lead to false results. Furthermore, changes of the target thickness during the measurements will not be noticed. Therefore, for the measurements of the differential cross section, mixed C$_2$D$_4$-C$_2$H$_4$ targets were used with a mixing ratio of 9 : 1, which can be determined with high accuracy. Since the differential cross section for elastic proton-proton scattering can be calculated very precisely, a normalisation factor for the target thickness can be obtained via this observable. The normalisation factor obtained during the measurements included also the normalisation for the opening angle of the BBS, and does, therefore, not lead to the determination of the absolute target thickness, which is also not necessary.

During the experiments, problems were encountered when measuring the outgoing particles of the reaction $^2H(\vec{p}, dp)$ in coincidence. This problem was mainly a deviation in the differential cross section between measurements done with a singles-trigger condition and measurements done with a coincidence trigger. The reason for these deviations is probably the high background radiation which is due to the Faraday cup inside the scattering chamber, which leads to extremely high count rates in the coincidence scintillator. This seems to be confirmed by measurements
done at angles $\theta_{\text{lab}} \leq 14^\circ$, where the Faraday cup was removed from the scattering chamber. At these angles, the results of measurements done with coincidence- and singles-trigger conditions agree in general with each other within the statistical uncertainties. To be able to make coincidence measurements using the BBS/ESN detection system for the determination of absolute cross sections, a solution should be found to either shield the coincidence scintillator from the radiation or to place either the coincidence scintillator or the Faraday cup outside the scattering chamber.

In principle, measurements done with the singles-trigger conditions can be dealt with using an appropriate analysis procedure. However, due to the polyethylene matrix of the target, background from the reactions $^{12}\text{C}(p, p')^{12}\text{C}$ and $^{12}\text{C}(p, d)^{11}\text{C}$ will also be recorded. Background due to the first type is present especially at very forward angles, that due to the second type at large backward angles. Using a proper fitting procedure, the background can be subtracted. However, the background subtraction introduces further, but small uncertainties. Also, event-taking with the singles-trigger condition leads to larger dead-times. In this work, these dead-times have all been properly accounted for.

The data measured in this work, along with results from theoretical calculations, are shown in figures 5.4-5.12 and given in tables G.1-G.8. The statistical uncertainties are plotted in these figures at each data point. For the analysing power, the statistical uncertainties are, in general, $\lesssim 0.02$, for the differential cross section $\lesssim 1\%$. The systematic uncertainties for the analysing power are mainly due to the uncertainty in the polarisation. In general, they are $\lesssim 3\%$, with an exception for the second measurement at 120 MeV and part of the measurements at 190 MeV. However, the good agreement of the results for the analysing power from two different, independent measurements at 120 and 150 MeV shows that the systematic uncertainty is probably overestimated. For the differential cross section, the systematic uncertainty is, in general, $\lesssim 7\%$. This uncertainty is mainly due to the point-to-point uncertainty obtained from the fit through the data. A further uncertainty is due to the normalisation factor obtained from elastic proton-proton scattering. The contribution of the different uncertainties to the final results is summarised in table 4.2 on page 82.

Two-nucleon (NN) and two-nucleon+three-nucleon (NN+3N) calculations were performed for each energy by the Bochum-Cracow group [Glö02]. The two-nucleon calculations were done using the presently available high-quality potentials Nijmegen-I, Nijmegen-II, CD-Bonn and Argonne-V18. As an additional three-nucleon force, the modified Tuscon-Melbourne force TM$'$ [Coo79,Fri99,Coo00] was used, which is the most sophisticated three-nucleon-force model up to date. This model is based on three-nucleon two-pion-exchange with an explicit intermediate $\Delta$ excitation and it obeys chiral symmetry. Further interactions are included as point-like short-range interactions. Calculations for explicit $\rho-\pi$ and $\rho-\rho$ exchange within the framework of this model exist [Coo93,Coo95], but have so far not been included into the calculations [Wit01]. Another three-nucleon force, which is based on phenomenology, is the Urbana-IX three-nucleon potential [Car83,Pud95]. The Urbana-IX three-nucleon force was constructed along with the Argonne-V18 potential as input for quantum Monte-Carlo calculations for many-nucleon systems. At 108 MeV, also calculations from $\chi$PT were performed [Epe02a].

Further calculations were performed by the Hanover-group [Del02,Nem98,Haj83]. These are calculations based on two-pion exchange with an explicit intermediate $\Delta$ excitation as an
phenomenology than on theoretical principles. Also, the procedure of using a phenomenological two-nucleon potential and adding a three-nucleon force is, as already remarked, an ad-hoc approach. The basis of two-nucleon interactions should move from the level of phenomenological models to a sophisticated theory. For instance, calculations for correlated $2\pi$ exchanges exist [Ren99] but are not included in modern high-quality two-nucleon calculations, yet. A stand-alone theory, based on fundamental principles, is $\chi$PT. Present calculations from $\chi$PT describe two- and three-nucleon observables reasonably well at lower energies. However, it is not clear yet whether models based on $\chi$PT will also work for all energies used in this work.

In addition to the observables measured in this work, the measurement of more sophisticated observables, like spin-transfer and spin-correlation coefficients should give further insight into 3NFs. As the example of $d\sigma/d\Omega$ and $A_y$ shows, theoretical models may give rather good predictions for one observable, but may fail completely in the description of other observables. Further experiments to measure these observables are planned at KVI.

**The $H(d, dp)$ Reaction**

The feasibility test to measure the differential cross section and the vector and tensor analysing powers $iT_{11}, T_{20}$ and $T_{22}$ of the reaction $H(d, dp)$ were performed using the Small-Angle Large-Acceptance Detector (SALAD) at KVI. A major drawback during these measurements was that, at the time the measurements were performed, the degree of polarisation of the incident-beam could only be measured via scattering reactions using the IBP in the high-energy beam-line. However, the analysing powers necessary for the determination of the polarisation were to be measured simultaneously with SALAD. For future experiments, a Lamb-shift polarimeter in the low-energy beam-line will be available and this ambiguity will be remedied.

Another drawback, which is due to the kinematics of elastic deuteron-proton scattering, is the angular resolution of the MWPC with respect to the scattering angle $\theta$ in a laboratory angular region around $30^\circ$. The laboratory angular region with $29^\circ \lesssim \theta_{\text{deut,lab}} \lesssim 30^\circ$ corresponds to a centre-of-mass angular region of $105^\circ \lesssim \theta_{\text{cm}} \lesssim 135^\circ$. Ideally, the resolution of the MWPC for the polar angle is $\approx 1^\circ$ for the setup of SALAD used in this work. Even with this resolution and relying only on the deuteron detection, it is not possible to resolve the part of the centre-of-mass angular range, which is most promising with respect to the observation of three-nucleon-force effects in $d\sigma/d\Omega$ and vector and tensor analysing powers. This drawback may be remedied partially with the detection of the corresponding outgoing proton, which gives a better angular resolution. In this case, the proton has to be cleanly identified as a proton emerging from the reaction $H(d, dp)$, which is only possible, if the corresponding outgoing deuterons are also detected in coincidence.

For a clear distinction between protons and deuterons, the use of a $\Delta E-E$ hodoscope is essential. However, the use of a $\Delta E$ detector introduces a high energy threshold for the detection of the deuterons. Unfortunately, this threshold cuts out the deuterons coming from the low-energy solution which are scattered to angles $\theta_{\text{lab}} \lesssim 30^\circ$, where a clear coincidence detection of protons and deuterons is necessary. To optimise the use of the $\Delta E-E$ hodoscope, a thorough energy calibration of both detectors was necessary as well. To reduce the background and the dead-time, the beam current was kept at a low value of $\approx 50$ pA.
effective three-nucleon force. In contrast to the Tuscon-Melbourne force, they also include $\pi$-$\rho$ and $\rho$-$\rho$ exchange but no short-range interaction.

From the results shown in the figures, it can be seen that the predictions of the calculations using two-nucleon forces only describe the data reasonably well over a large angular region and for a large number of energies. The inclusion of three-nucleon forces improves the predictions further. With the high-precision data obtained in this work for several bombarding energies, covering a large centre-of-mass angular range, a systematic study of the discrepancies between different theoretical predictions and the data and the influence of three-nucleon forces is now feasible.

Calculations for the vector analysing power of the reaction $^2\text{H}(\vec{p}, d\vec{p})$ show deviations from our data at around $\theta_{\text{cm}} \approx 130^\circ$ and at large backward angles, as can be observed in figures 5.4 - 5.7 and 5.12. These deviations are smaller for calculations which include three-nucleon forces, but also here, deficiencies remain. Furthermore, the deviations in the angular range around $130^\circ \lesssim \theta_{\text{cm}} \lesssim 150^\circ$ increase with increasing bombarding energy. The predictions of the Hanover group seem to be closer to our data. In fact, up to 135 MeV, calculations from Nijmegen-II+$\Delta$ and CD-Bonn+$\Delta$ describe our data well within the experimental uncertainties, even though there is, a priori, no reason why one calculation should perform better than the other one.

Also in the differential cross section, deviations of the theoretical calculations from our data can be observed around $\theta_{\text{cm}} \approx 130^\circ$, as can be seen in figures 5.8-5.11 and 5.12. The minimum of the differential cross section occurs in this angular range, where three-nucleon force effects are expected to show up [Wit98]. Moreover, the calculations without three-nucleon forces fail completely to describe the differential cross section over a large angular range around the minimum. Also calculations which include three-nucleon forces show deviations from our data in this angular range. However, in contrast to the analysing power, the predictions obtained from different three-nucleon forces do not deviate from each other outside the theoretical uncertainty produced by employing different nucleon-nucleon potentials.

The deviations of the theoretical calculations from our data occur for both observables, the analysing power and the differential cross section, in a similar angular range. Furthermore, for both observables, the deviations increase with increasing incident-beam energy. Since the differences between the theoretical predictions are large for the analysing power but hardly significant in the case of the differential cross section, the differences between these calculations seem to be mainly due to the treatment of the spin-dependent part of the 3NFs.

The fact that for both observables the deviations of the theoretical calculations from our data are largest around $\theta_{\text{cm}} \approx 130^\circ$, i.e., a region where large momentum-transfers are involved, could give an indication that higher-order effects, such as $\rho$-$\pi$ or $\rho$-$\rho$ exchange or short-range interactions, are missing in the calculations. It might also be an indication that relativistic corrections are not properly included in the theoretical models. In fact, the Lippmann-Schwinger equations, which are based on the Schrödinger equation, are non-relativistic equations. Relativistic effects, such as spin-orbit coupling, can be included in these calculations, but the underlying theory is not covariant. Whether a covariant theory is necessary at the energies used in this work is still a subject of discussion.

The theoretical framework used to describe few-nucleon systems is, so far, based more on
The results obtained from the feasibility test show that it is possible to measure the differential cross section over an angular range between $30^\circ$ and $100^\circ$. In this region, deuterons emerging from the reaction $\text{H}(\vec{d}, dp)$ reach the detector as single events due to the acceptance of SALAD and the high energy solution of equations (4.29) and (4.30) has to be applied. If the energy and $\Delta E$ detectors are properly calibrated, the selection of the deuterons is trivial. In this region, also the analysing powers can be measured. However, since the tensor analysing power in this angular region is close to zero, a background-free event selection is essential, since the determination of the analysing power of the reaction of interest depends strongly on the analysing power of the background. For the detection of outgoing protons and deuterons in coincidence this can be achieved, e.g., by using a low beam current, as mentioned above.

In future experiments, using the modified setup of SALAD, cleaner event selection will be possible due to the coincidence detection of low-energy protons at larger angles. Furthermore, improvement in the data-acquisition system will hopefully lead to larger event rates and a further reduction of the dead-time.