Quasi-free elastic deuteron-proton scattering in the three-body break-up reaction of deuteron-deuteron scattering

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Abstract. This paper discusses some of the recent results obtained in a deuteron-deuteron scattering experiment using a polarized beam of deuterons with an incident energy of 130 MeV. A $4\pi$ detection system allowed to measure cross sections and spin observables for various final-state configurations. Here, we discuss the quasi-free elastic deuteron-proton scattering process in deuteron-deuteron scattering which has been observed by analyzing kinematical configurations for which the target neutron acts as a spectator particle. This part of the data can be compared directly to three-nucleon calculations and with existing data for the elastic deuteron-proton scattering process. The results for the polarization observables $i T_{11}$ and $T_{22}$ agree well with elastic $dp$ scattering data published so-far and measured concurrently using a proton target. Surprisingly, the tensor observable $T_{20}$ shows significant discrepancies with data taken using a proton target.

Although much has been learned about the interaction between two nucleons, it is clear that this knowledge is insufficient to describe the interaction between more than two nucleons. Already for the simplest three-nucleon system, the triton, an exact solution of the three-nucleon Faddeev equations employing 2NFs clearly underestimates the experimental binding energy [1], showing that 2NFs are not sufficient to describe the three-nucleon system accurately. In a three-nucleon system, the interaction between two of the nucleons may be influenced by the presence of the third nucleon. This extra effect comes from a force which is beyond the two-nucleon interaction and will be referred to as three-nucleon force (3NF). A well-known example of such a force is the Fujita-Miyazawa force [2] in which all three nucleons interact via a $2\pi$-exchange mechanism with an intermediate $\Delta$ excitation of one of the nucleons.
A comparison between experimental data obtained in nucleon-deuteron scattering and the predictions of rigorous theoretical calculations shows some significant deficiencies, in particular, in the case of spin observables [3–31]. This implies that the behavior of the systems with more than two nucleons are not completely understood yet. Therefore, theoretical calculations for these systems need improvements. Important here is the guidance by new experimental data. In particular, data that have a large sensitivity to the effects of 3NF are advantageous.

One might expect that 3NF effects increase in the four-nucleon system by the argument that the number of three-nucleon combinations with respect to the number of two-nucleon combinations gets larger with increasing number of nucleons. We, however, note that the saturation of 3NF effects sets in very quickly for large nuclei. This simple counting rule is supported by a comparison between predictions and data for the binding energies of light nuclei [32] from predictions of a Green’s function Monte Carlo calculation based on the Argonne V18 [33] NN interaction (AV18) and the Illinois-2 (IL2) 3NF [34,35]. While a calculation which only includes the AV18 NN potential deviates significantly from the experimental results, a calculation which includes as well a 3NF compares much better to the data, especially for the first few light nuclei. Note that the effect of the 3NF on the binding energy for the triton is ∼0.5 MeV, whereas the effect increases significantly for the four-nucleon system, $^4$He, to ∼4 MeV. For heavier nuclei, even adding the 3NF as modeled in the present calculations, is not enough to resolve the discrepancy between the theoretical predictions and the measurements. One might argue that the discrepancies for the binding energies of the heavier nuclei stem from four-nucleon force (4NF) effects. These higher-order many-body potentials are, however, predicted by $\chi$PT approaches [36, 37] to be small compared to 3NF effects. Therefore, the large discrepancies cannot be explained by a missing 4NF or even higher-order nuclear-force effects.

We performed two scattering experiments at KVI using the Big Instrument for Nuclear-polarization Analysis (BINA) experimental setup [38]. In the first experiment, a polarized beam of deuterons with a kinetic energy of 65 MeV/nucleon was impinged on a liquid deuterium target. The elastic channel, the neutron transfer channel, and break-up channels leading to three- and four-body final states were uniquely identified using the information on the energies of the outgoing particles, their scattering angles, and their time-of-flight (TOF). The three-body break-up reaction in $\vec{d}d$ scattering process, $\vec{d} + d \rightarrow p + n + d$, at intermediate energies has been measured in a background-free experiment [39,40]. This reaction is extremely rich in phase space even more than the $\vec{p} + d$ break-up reaction, since all the final-state particles are non-identical. The measured differential cross sections, vector- and tensor-analyzing powers for a large number of kinematical configurations of the three-body break-up reaction are reported in Ref. [39].

The second reaction was $^1$H($\vec{d}, dp$) with a deuteron-beam energy of 65 MeV/nucleon in which a solid CH$_2$ was used as the target. We made use of this reaction to check the systematic uncertainties and also to measure the polarization of the beam of deuterons. The differential cross sections, vector-, and tensor-analyzing powers were measured. The differential cross section for this reaction at 65 MeV/nucleon is well known and can, therefore, be exploited to verify independently the read-out and analysis procedure, the applied detector inefficiencies, and the beam-current measurement. The measurement of the polarization observables allows us to check several aspects of the experiment and the analysis procedure, excluding the absolute normalization, by comparing our results with data from the literature. The data for this reaction are found to be in excellent agreement with the existing database, which proves that BINA and our analysis procedure are well suited to measure the elastic channel with high precision. Furthermore, we can use this reaction to obtain the polarization of the deuteron beam which was used for the first deuteron-deuteron scattering experiment at 65 MeV/nucleon. Also a part of the phase space in the $\vec{dp}$ elastic reaction in which both particles are scattered to forward angles, can be compared with the results of the three-body reaction in the deuteron-deuteron scattering process.
Table 1. The selected configurations in the three-body break-up reaction for which the neutron energy, $E_n < 0.3$ MeV. These configurations were identified as the quasi-elastic dp reactions. The corresponding center-of-mass angle, $\theta_{c.m.}$, is indicated as well.

| $\theta_d$ [deg] | $\theta_p$ [deg] | $\phi_{12}$ [deg] | $S$ [MeV] | $\theta_{c.m.}$ [deg] |
|------------------|------------------|-------------------|-----------|------------------------|
| 28 ± 1           | 20 ± 1           | 180 ± 5           | 230 ± 10  | 139 ± 1                |
| 29 ± 1           | 22 ± 1           | 180 ± 5           | 220 ± 10  | 135 ± 1                |
| 29 ± 1           | 24 ± 1           | 180 ± 5           | 220 ± 10  | 130 ± 1                |
| 30 ± 1           | 26 ± 1           | 180 ± 5           | 220 ± 10  | 127 ± 1                |
| 30 ± 1           | 28 ± 1           | 180 ± 5           | 210 ± 10  | 123 ± 1                |

The polarized beam of deuterons for both $\vec{d}p$ and $\vec{d}d$ experiments was produced by the polarized ion source (POLIS) [41, 42] at KVI and was accelerated by AGOR (Accélérateur Groningen ORsay). The three-body break-up reaction in the $\vec{d}d$ scattering process has an interesting aspect in the part of the phase-space in which the energy of the neutron is very small. Figure 1 represents the cross sections obtained for all analyzed configurations as a function of the energy of the neutron, $E_n$. The cross sections are presented in an arbitrary unit. Note that the cross section is at its maximum when the energy of the neutron is very small. This region is interesting since it corresponds to the quasi-free elastic deuteron-proton scattering process with the neutron acting as a spectator particle. This part of the data can be compared directly to various calculations and the existing data of the elastic deuteron-proton scattering process. For such a comparison, we limited the analysis to those configurations at which the momentum of the neutron does not exceed 23 MeV/c ($E_n < 0.3$ MeV), corresponding to configurations with the largest cross sections. After making this selection, we were left over with a few configurations which are presented in Tab. 1. The $S$ values of these configurations correspond to $E_p + E_d = 127.7$ MeV, which must be the case had it been scattering of a deuterons from a...
proton target. Figure 2 depicts the ratio between the normalized spin-dependent cross section and the cross section for the unpolarized beam as a function of the azimuthal angle $\phi$ for a pure vector-polarized deuteron beam (top panel) and a pure tensor-polarized deuteron beam (bottom panel) for one of the five configurations, namely ($\theta_p = 28^\circ$, $\theta_d = 30^\circ$, $\phi_{12} = 180^\circ$, $S = 210$ MeV). The data are fitted to obtain the vector- and tensor-analyzing powers. The results of the fit are shown as solid lines. Note that the fit describes the data very well. The results for the analyzing powers of these configurations are shown in Fig. 3 by filled squares and compared with $dp$ elastic-scattering data taken in this work (filled circles) and with the data from Ref. [43] (open circles). The horizontal dark gray bands at the top of the panels represent the systematic uncertainty ($2\sigma$) for every data point. The dark gray bands correspond to calculations including only two-nucleon potentials for $dp$ elastic scattering. The light gray bands represent calculations including an additional Tucson-Melbourne TM’ three-body force [44]. The solid lines correspond to results of a Faddeev calculation using the AV18 two-nucleon potential [33] combined with the Urbana-Illinois X (UIX) three-body potential [45]. The dotted lines represent the results of a coupled-channel calculation (CDB+$\Delta$). The dashed lines represent the results of a CDB+$\Delta$ calculation including the Coulomb force [46]. The angular bin size in the present measurement is $2^\circ$. The results of the $iT_{11}$ and $T_{22}$ for the quasi-free elastic scattering data agree very well with the previous $dp$ elastic-scattering data and also with the $dp$ elastic-scattering data presented in this work. However, there are small discrepancies at large scattering angles for $T_{20}$ which could be attributed to the role of the spectator neutron.

In this paper we presented some of the recent results obtained in a deuteron-deuteron

Figure 3. See the text.
scattering experiment using a polarized beam of deuterons with an incident energy of 130 MeV. The three-body break-up reaction in \( \vec{d}d \) scattering process, \( \vec{d} + d \rightarrow p + n + d \), at intermediate energies has been measured. The break-up reaction in deuteron-deuteron scattering has a very rich kinematics. As a consequence, part of its phase space can be compared directly to results of the previously studied elastic deuteron-proton scattering reaction, while other parts of its phase space explore regions which has not been studied before. This feature provides an excellent basis for a systematic study that is mandatory to obtain insight in 3NF effects.

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