

## Three-body break-up in deuteron-deuteron scattering at 65 MeV/nucleon

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**Abstract.** We successfully identified several multibody final states in deuteron-deuteron scattering at 65 MeV/nucleon at KVI using a unique and advanced detection system called BINA. This facility enabled us to perform cross sections and polarization measurements with an improved statistical and systematic precision. The analysis procedure and a part of the results of the three-body break-up channel in the deuteron-deuteron scattering at 65 MeV/nucleon are presented.

The physics phenomena of nuclei are for a large part understood by considering the interaction between their building blocks, the nucleons. In 1935 Yukawa described the nucleon-nucleon (NN) force by the exchange of massive mesons [1] in analogy to the electromagnetic interaction which can be represented by the exchange of a massless photon. Several phenomenological nucleon-nucleon potentials have been derived based on Yukawa's theory and are able to reproduce the whole bulk of data points in neutron-proton and proton-proton scattering with extremely high precision. These so-called high-quality NN potentials are used in Faddeev equations [2,3] to give an exact solution of the scattering problem of the three-nucleon system. Already, for the simplest three-nucleon system, the triton, an exact solution of the three-nucleon Faddeev equations employing two-nucleon forces (2NFs) underestimates the experimental binding energy [4], showing that 2NFs are not sufficient to describe the three-nucleon system accurately. The existence of an additional force, the three-nucleon (3N) interaction, was predicted by Primakov [5] and confirmed by a comparison between precision data and state-of-the-art calculations. In general, adding 3NF effects to the NN potentials gives a better agreement between the cross section data of the proton-deuteron scattering and corresponding calculations [6–17], whereas a similar comparison for the spin observables yields various discrepancies [7–9,18–22]. This demon-

strated that spin-dependent parts of the 3NFs are poorly understood and that more studies in this field are needed.

The 3NF effects are in general small in the three-nucleon system. A complementary approach is to examine heavier systems for which the 3NF effects are significantly enhanced in magnitude. For this, it was proposed to study the four-nucleon system since the experimental database in the four-nucleon system is presently poor in comparison with that of the three-nucleon system. Most of the available data have been measured at very low energies, in particular below the three-body break-up threshold of 2.2 MeV. Also, theoretical developments are evolving rapidly at low energies [23–26], but lag behind at higher energies. The experimental database at intermediate energies is very limited [27–29]. This situation calls for extensive four-nucleon studies at intermediate energies. The goal of our work was to perform a comprehensive measurement of the cross sections and spin observables in several  $d + d$  scattering processes at 65 MeV/nucleon, namely the elastic and three-body break-up channels. With these data, we have significantly enriched the four-nucleon scattering database. The extensive database of spin and cross section observables in various deuteron-deuteron scattering processes together with precise, ab-initio calculations may reveal some details of 3NF effects.

Deuteron-deuteron scattering below the pion-production threshold leads to 5 possible final states with a pure hadronic signature, namely:

1. Elastic channel:  $\mathbf{d} + d \longrightarrow d + d$  ;

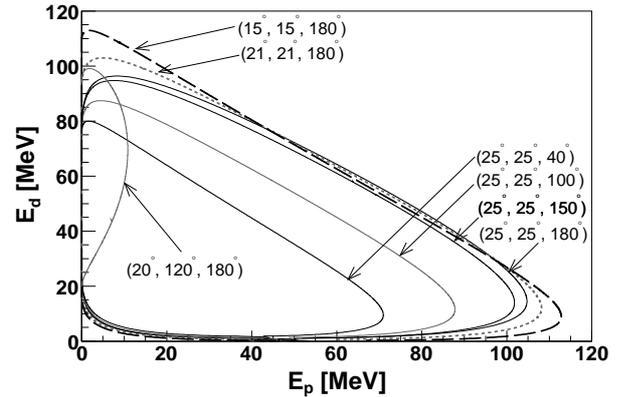
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2. Neutron-transfer channel:  $\mathbf{d} + \mathbf{d} \rightarrow p + t$  ;
3. Proton-transfer channel:  $\mathbf{d} + \mathbf{d} \rightarrow n + {}^3\text{He}$  ;
4. Three-body final-state break-up:  $\mathbf{d} + \mathbf{d} \rightarrow p + n + \mathbf{d}$  ;
5. Four-body final-state break-up:  $\mathbf{d} + \mathbf{d} \rightarrow p + n + p + n$ .

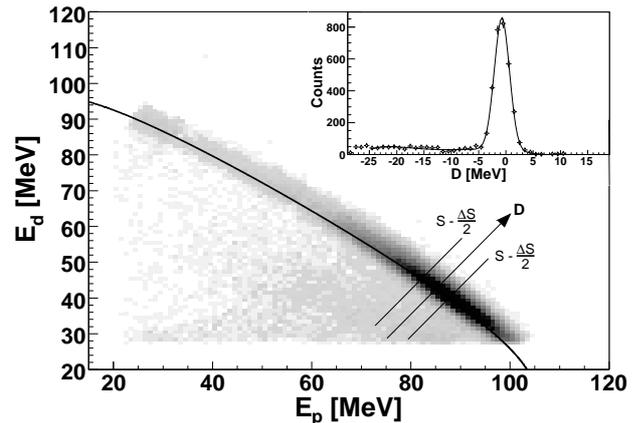
In this work, the three-body final-state break-up in deuteron-deuteron scattering is further referred to as the three-body break-up. The study and identification of these final states requires an experimental setup with specific features, namely, a large phase space coverage, a good energy and angular resolution, and the ability of particle identification (PID). The experiment presented in this paper was carried out at KVI using the Big Instrument for Nuclear-polarization Analysis, BINA, which has many of these requirements [30]. A polarized beam of deuterons with a kinetic energy of 65 MeV/nucleon impinged on a liquid deuterium target [31]. The elastic, neutron-transfer and three- and four-body break-up channels were identified using the energy, scattering angles and time-of-flight (TOF) information. In this paper only the three-body break-up channel is discussed.

For the analysis of the three-body break-up data we measured the kinetic energies, and the polar and azimuthal angles of the two coincident, charged particles. Using the 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 relation between their energies presented by the kinematical curve which is called the  $S$ -curve. The angles  $\theta_p$  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 energies of the proton,  $E_p$ , and deuteron,  $E_d$ , were described as a function of two new variables,  $D$  and  $S$ . The variable  $S$  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. 1. Each  $S$ -curve is labeled by three numbers. For example, the label  $(20^\circ, 30^\circ, 180^\circ)$  shows a kinematical relation of energies of a deuteron that scatters to  $20^\circ$  and a proton that scatters to  $30^\circ$ , and the azimuthal opening angle,  $\phi_{12}$ , between them equal to  $180^\circ$ .

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 ( $\theta_p, \theta_d, \phi_{12}$ ). The number of break-up events in an interval  $S - \frac{\Delta S}{2}$ , and  $S + \frac{\Delta S}{2}$  was obtained by projecting the events on a line perpendicular to the  $S$ -curve ( $D$ -axis). The value of  $\Delta S$  was  $\pm 5$  MeV for the forward wall data. Figure 2 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. 2. This spectrum consists of mainly break-



**Fig. 1.** The energy correlation between protons and deuterons in coincidence for the three-body break-up reaction in  $\mathbf{d} + \mathbf{d}$  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 their relative azimuthal angle.



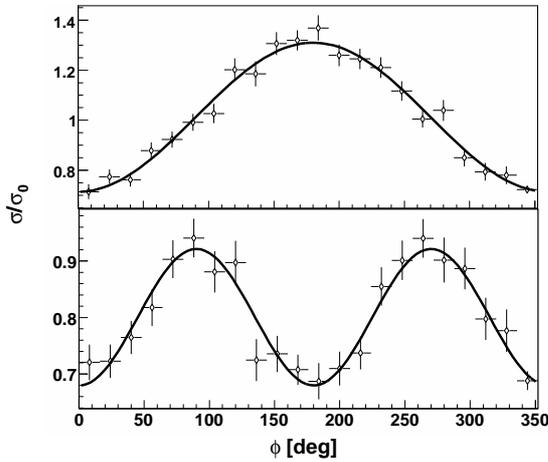
**Fig. 2.** The correlation between the energies of the deuteron and the proton originating from three-body break-up channel in one selected configuration. The projection of the events from one  $S$ -bin on  $D$ -axis is shown in the inset.

up events with a negligible amount of accidental background. Particles from most of the break-up events deposit all their energy in the scintillator, which gives rise to a peak around zero in the variable  $D$ . In a fraction of the break-up events one or (rarely) both particles 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 the inset of Fig. 2). 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.

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 general expression for the cross section of any reaction induced by a polarized spin-1 projectile is [32,33]:

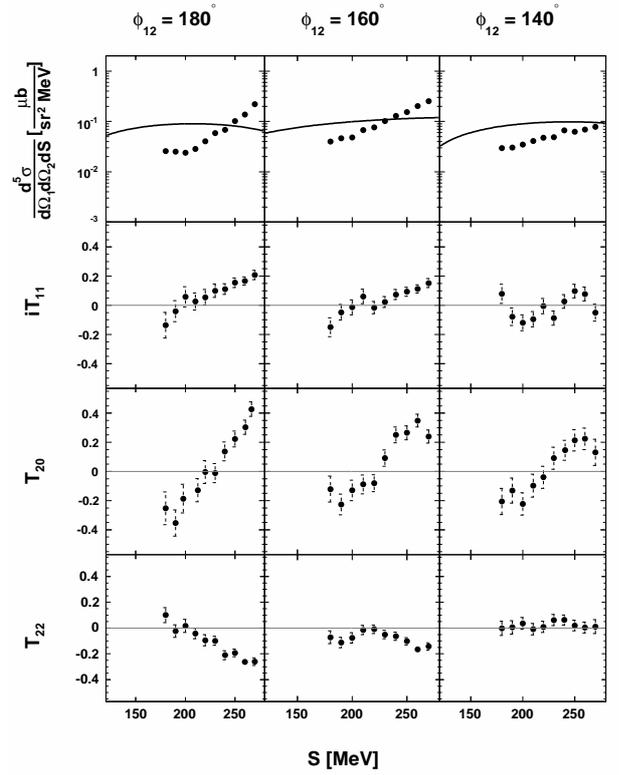
$$\begin{aligned} \sigma(\xi, \phi) = \sigma_0(\xi) & \left[ 1 + \sqrt{3} p_Z \text{Re}(iT_{11}(\xi)) \cos \phi \right. \\ & - \frac{1}{\sqrt{8}} p_{ZZ} \text{Re}(T_{20}(\xi)) \\ & \left. - \frac{\sqrt{3}}{2} p_{ZZ} \text{Re}(T_{22}(\xi)) \cos 2\phi \right]. \quad (1) \end{aligned}$$

where  $\sigma$  and  $\sigma_0$  are the polarized and unpolarized cross sections, respectively, and  $\xi$  represents the configuration  $(\theta_p, \theta_d, \phi_{12}, S)$ . Note that Eq. 1 does not contain terms with  $\text{Im}(iT_{11})$ ,  $\text{Re}(T_{21})$ ,  $\text{Im}(T_{20})$  and  $\text{Im}(T_{22})$ . These contributions vanish because we took explicitly  $\beta = 90^\circ$  and  $\phi_{12} = |\phi_1 - \phi_2|$ . The angle  $\beta$  is the angle between the polarization axis and the momentum of the incoming beam. In this work, the variables  $\text{Re}(iT_{11})$ ,  $\text{Re}(T_{20})$  and  $\text{Re}(T_{22})$  will be referred to as  $iT_{11}$ ,  $T_{20}$  and  $T_{22}$ , respectively. The quantities  $iT_{11}$  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,  $p_{ZZ}$  is the tensor polarization of the beam, and  $\phi$  is the azimuthal scattering angle of the deuteron.



**Fig. 3.** 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  $(\theta_p = 28^\circ, \theta_d = 30^\circ, \phi_{12} = 180^\circ, S = 210 \text{ MeV})$ .

According to Eq. 1, for a deuteron beam with a pure vector polarization, the ratio  $\frac{\sigma}{\sigma_0}$  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. These asymmetries are exploited to extract the vector-analyzing power,  $iT_{11}$  and the tensor-analyzing powers,  $T_{20}$  and  $T_{22}$ , for every kinematical configuration,  $(\theta_p, \theta_d, \phi_{12}, S)$ .



**Fig. 4.** The cross sections, vector-, and tensor-analyzing powers at  $(\theta_d, \theta_p) = (15^\circ, 15^\circ)$  as a function of  $S$  for different azimuthal opening angles. The solid curves in the top panels correspond to phase-space distributions. They have arbitrary normalization with respect to the data. The gray lines in other panels show the zero level of the analyzing powers. Only statistical uncertainties are indicated.

Figure 3 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  $(\theta_p = 28^\circ, \theta_d = 30^\circ, \phi_{12} = 180^\circ, S = 210 \text{ MeV})$ . The curves in the top and bottom panels are the results of a fit based on Eq. 1 through the obtained asymmetry distribution for a beam with a pure vector and tensor polarization, respectively. The amplitude of the  $\cos \phi$  modulation in the top panel equals to  $\sqrt{3} p_Z iT_{11}$  and that of the  $\cos 2\phi$  modulation in the lower panel equals to  $-\frac{\sqrt{3}}{2} p_{ZZ} T_{22}$ . The offset from 1 in the lower panel is  $-\frac{1}{\sqrt{8}} p_{ZZ} T_{20}$ . The polarization values have been measured independently using BINA and verified by measurements using a Lamb-Shift polarimeter [34], and were found to be  $p_Z = -0.601 \pm 0.029$  and  $p_{ZZ} = -1.517 \pm 0.032$ .

The differential cross section and vector- and tensor-analyzing powers for a few kinematical configurations of the three-body break-up reaction were extracted. The differential cross sections were compared with a phase-space distribution obtained from a Monte Carlo simulation based on the GEANT3 framework. This comparison demonstrates that there are large variations in the dynamical part of the  $t$ -matrix as a function of  $S$  for different configurations.

Figure 4 represents the cross sections, vector-, and tensor-analyzing powers at  $(\theta_d, \theta_p) = (15^\circ, 15^\circ)$  as a function of  $S$  for different azimuthal opening angles. The solid curves in the top panels correspond to the phase-space distributions. They have arbitrary normalization with respect to the data. The gray lines in other panels show the zero level of the analyzing powers. Only statistical uncertainties are indicated. The total systematic uncertainty for the cross sections and analyzing power are estimated to be  $\sim 7\%$  and  $\sim 4.5\%$ , respectively.

The three-body break-up reaction in deuteron-deuteron scattering has been clearly identified using the scattering angles, the energies and the TOF measurements of the final state proton and deuteron. In this work, we analyzed a part of the data in which the protons and deuterons were scattered into the forward wall of BINA. The performed four-body scattering experiments at KVI will provide a new database for the elastic and transfer channels at 65 MeV/nucleon and 90 MeV/nucleon and also for the three-body break-up reaction at 65 MeV/nucleon. It is hoped that these more precise, new data for the deuteron-deuteron scattering can be used to check the upcoming theoretical calculations for the four-body systems.

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