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# Studies of Deuteron–Proton Collisions at 100 MeV

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**Abstract** Differential cross section for the $^{1}H(d, pp)n$ reaction is sensitive to various dynamical ingredients and allows for thorough tests of theoretical potentials describing the interaction in the three nucleon systems. The analysis of the experimental data collected for the breakup reaction at the beam energy of 100 MeV has been performed and the first cross section results for selected configurations are presented in this paper. They are in good agreement with calculations based on the realistic potentials. Studies at this relatively low energy will also be important for examining awaited calculations within the Chiral Effective Field Theory.

## 1 Introduction

The deuteron breakup reaction: $p + d \rightarrow p + p + n$ is characterized by a rich kinematics of the final state. Particular kinematic configurations of the outgoing nucleons show various sensitivity to specific components of the reaction dynamics. Therefore the breakup reaction is a perfect tool for testing nuclear interaction models. With increasing energy of interaction, the dynamical effects of few-nucleons, like three nucleon force (3NF) [1,2] and the relativistic component [3], start playing an important role and must be included in theoretical calculations. In case of the *dp* breakup reaction, the Coulomb force has also a very significant influence on the cross section and also should be included in theory.

The 3NF models, like Tucson Melbourn (TM99) [1] or Urbana IX (UIX) [2] are combined with realistic NN potentials (CD Bonn [4], AV18 [5], Nijm I and Nijm II [6]) to calculate the 3N system observables [7]. The 3NF appears naturally in Chiral Effective Field Theory ($\chi$EFT) at the next-to-next-to-leading order($N^2LO$). In case of Coupled Channel (CC) framework the 3N interactions are modelled by explicit treatment of a single $\Delta$-isobar degree of freedom.

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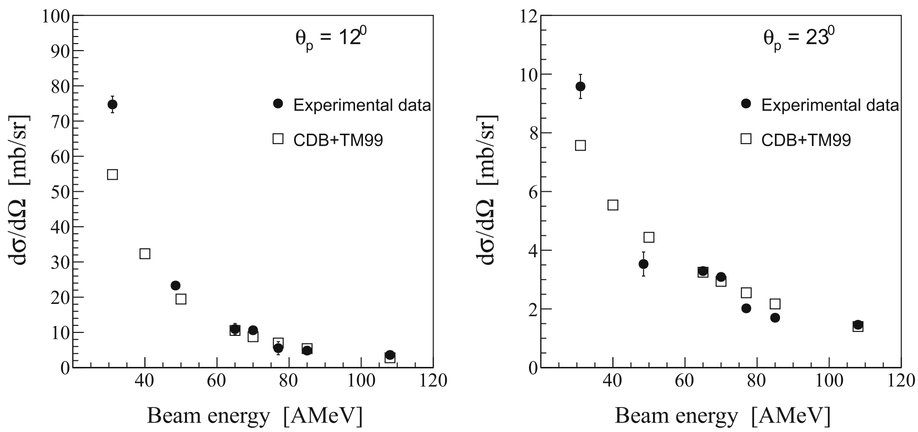


**Fig. 1** Elastic scattering cross section for two selected proton angles $\theta = 12°$ and $\theta = 23°$ for given beam energy. The full points correspond to experimental data [15–21] while the open squares to theoretical calculations for CD Bonn+TM99 [22]

Over the last few years a big effort for including all dynamical components in theoretical calculations has been made. Currently calculations combining the 3NF and the long-range Coulomb interaction are available [8, 9] as well as relativistic calculations [10, 11]. Also in case of Chiral Effective Field Theory the new, improved version is currently being developed [12].

## 2 Experiment

Experimental studies of the proton-deuteron reactions with deuteron beams of energy 100 MeV were performed at KVI in Groningen, using the BINA detector [13, 14] consisted of two parts: forward Wall and backward Ball. The first one was built of a three-plane MWPC and a scintilator hodoscopes: 12 horizontal detectors ($\Delta E$) and 10 vertical stopping detectors ($E$), arranged perpendicularly to one another. It covered laboratory polar angles between 12° and 35° with the full range of azimuthal angles up to 30°. Ball was built of almost 150 scintilators and covered laboratory polar angles up to 165° and the full range of azimuthal angles. In the case of this particular experiment the $\Delta E$ detector was removed in order to reduce the energy threshold for registered particles.

## 3 Data Analysis and Results

During the experiment, the elastic scattering and the breakup data have been collected. All registered particles in event, i.e. proton pairs from the breakup process and proton deuteron pairs from the elastic scattering channel were identified using the Time-Of-Flight technique. After identification, the data analysis was concentrated on the proton-proton ($p - p$) coincidences with the aim to determine the differential cross section for the breakup reaction.
In order to obtain differential cross section, the luminosity should be determined on the basis of the number of the elastically-scattered protons at a given polar angle and the known cross section for elastic scattering at the studied energy. In Fig. 1 it is visible that in general the experimental cross sections for elastic scattering in the region of beam energy of 50 MeV/nucleon are in a good agreement with a given theoretical predictions.

This fact motivated normalization of the experimental number of elastic-scattered protons to theoretical calculations with the CD Bonn potential and TM99 3NF (CDB+TM99) [22]. Values of the luminosity obtained for a set of the proton scattering polar angles are shown in Fig. 2 (left panel). The luminosity, calculated as a weighted average (black solid line), was established to be $(15.49 \pm 0.19^{stat} \pm 1.15^{syst}) \times 10^6 \text{mb}^{-1}$. Using this value for the whole range of tested proton angles (from 22° to 35°) the experimental elastic scattering cross sections were determined. Figure 2, right pannel, presents the measured and calculated [23] cross sections. The accordance of the shapes of these distributions is a confirmation of the agreement of the luminosity results for the whole range of studied proton angles. The geometry of a coincident proton-proton pair is characterized by their polar angles $\theta_1$ and $\theta_2$ and the relative azimuthal angle $\varphi_{12}$ defined as $\varphi_{12} = |\varphi_1 - \varphi_2|$. For such a geometry a momentum and energy conservation introduce coincidence between energies of two protons, $E_2$

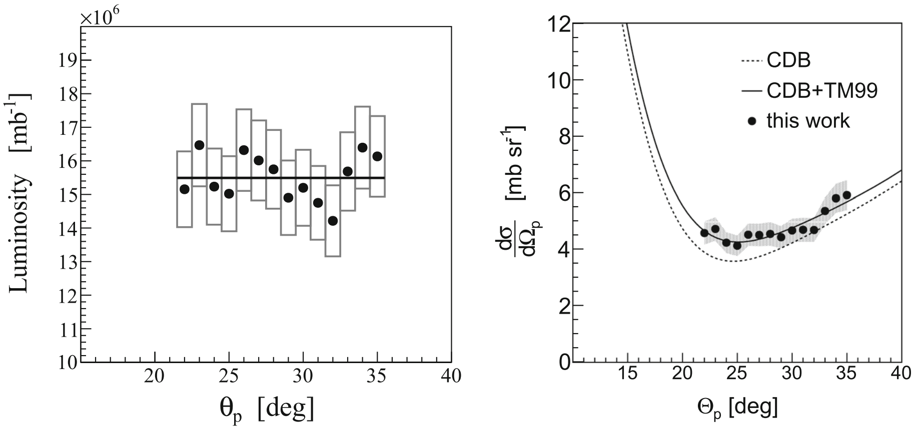


**Fig. 2** *Left panel:* The luminosity values obtained for a set of proton scattering polar angles and their weighted average (horizontal line). The rectangles represent systematic uncertainties, statistical uncertainties are smaller than the data points. *Right panel:* The distibutions of the measured (full points) and theoretically calculated [23] (lines) cross sections for elastic scattering. Grey area around points represents systematic uncertainties

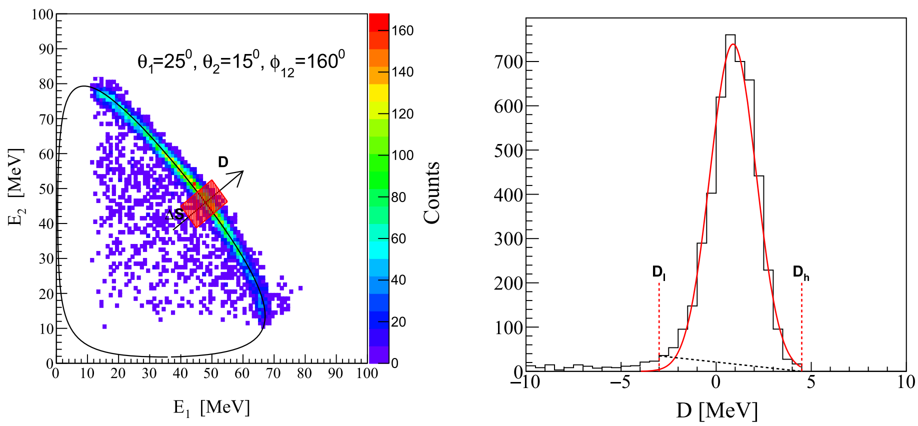


**Fig. 3** *Left panel:* The coincidence spectrum of energies of two protons registered at $\theta_1 = 25° \pm 1°$, $\theta_2 = 20° \pm 1°$, $\varphi_{12} = 160° \pm 10°$. The solid line shows a three-body kinematical curve. $\Delta S$ bin and $D$ variable are presented in a schematic way. *Right panel:* The sample $D$ distribution of events belonging to one $\Delta S$ bin with Gaussian distribution fitted in the range $\pm 3\sigma$ from the fitted peak position (from $D_l$ to $D_h$)

vs $E_1$. Example of such correlation obtained for data points together with kinematical curve was plotted in Fig. 3 (left panel).

The energies $E_1$, $E_2$ were transformed into new variables, $D$ and $S$, defined in $E_2$-$E_1$ plane as a distance of each ($E_1$, $E_2$) point from the kinematical curve and arc-length along kinematics with the starting point at the minimal $E_2$, respectively. In the analysis, the angular integration limits for kinematic spectra were chosen as follows $\Delta\theta_1 = \Delta\theta_2 = 2°$ and $\Delta\varphi_{12} = 20°$. For each slice of $\Delta S = 4$ MeV, the events placed inside the bin were projected onto the $D$ axis (see Fig. 3, right panel). The breakup events are grouped in a peak with a very low background, which is approximated as a linear function (black dashed line in Fig. 3, right panel). To calculate the cross section in a function of $S$, the Gauss function was fitted to the $D$ distributions and the background was cut out. A part of the background below the peak and the tail of the distribution due to protons undergoing hadronic interactions, and this loss was corrected on the basis of Monte Carlo simulations. In order to treat all kinematic configurations consistently, the integration limits in $D$ variable were chosen at the values $D_l$ and $D_h$ (see Fig. 3, right panel) that correspond to $-3\sigma$ and $+3\sigma$ from the maximum of the fitted peak. An examples of the preliminary cross section obtained for the chosen kinematic configurations are presented in Fig. 4.

In these figures, the theoretical calculations are represented as lines and bands. Black solid line shows theoretical calculations with CD Bonn potential only [24]. The remaining solid lines represent the calculations within the coupled-channel approach [24] with the CD Bonn + $\Delta$ potential without (red line) and with (green

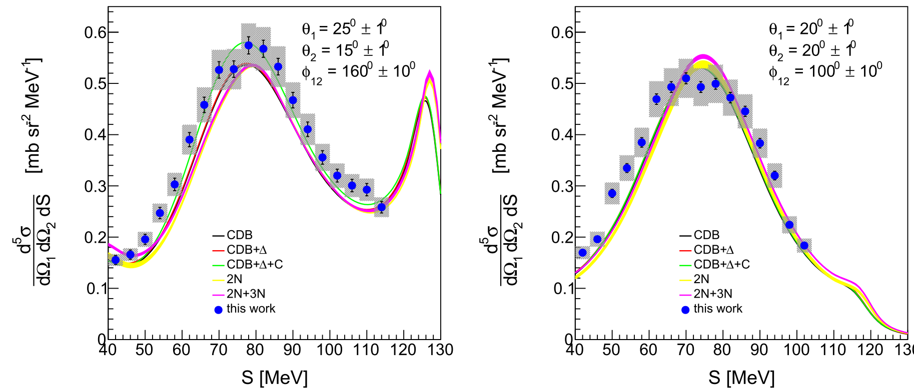


**Fig. 4** Examples of the preliminary differential cross section of breakup reaction obtained for chosen kinematic configurations as a function of the $S$ value, blue points. The error bars present statistical uncertainties only. The grey rectangles show systematic uncertainties. The lines and bands represent theoretical calculations (see text)

line) the Coulomb force included (CDB + Δ + C). The bands represent calculations based on realistic NN potentials [23]: the yellow shows pure NN calculations done for the CD Bonn, AV18, Nijm I and Nijm II potentials, the magenta one corresponds to NN calculations with TM99 3NF included. These preliminary results show that obtained experimental breakup cross sections appear in line with the theoretical calculations.

## 4 Summary and Outlook

In this paper the procedure of normalization of the deuteron breakup cross section and the general scheme of breakup events analysis are described. Agreement of the luminosity results for the whole range of studied proton angles is confirmed by the accordance of the shapes of measured and calculated elastic scattering cross section distributions.

Currently, the analysis is focused on determination of the differential cross sections for the deuteron breakup process for a large set (around 100) of kinematic configurations. This step is required for a deep comparative analysis of experimental data to the state-of-the-art theoretical calculations, including upcoming ones in the framework of the Chiral Perturbation Theory.



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