CROSS SECTION OF TRANSFER REACTIONS IN $d+d$ COLLISIONS AT THE DEUTERON BEAM ENERGY OF 160 MeV*

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In this paper, we report on the ^{2}H(d,^{3}He)n differential cross section, which was measured at the energy of 160 MeV. The data were collected at the KVI Groningen with the use of the BINA detector. The crucial steps of the data analysis are outlined. The results are presented in comparison to the existing world data set.

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1. Introduction

Interaction between nucleons in the few-nucleon systems is one of the basic subjects of precise experimental studies in nuclear physics. In the intermediate-energy range, below the pion production threshold, the dominant contribution to the nuclear potential comes from the nucleon–nucleon interaction, however subtle effects of three-nucleon force (3NF) can also be observed. It is commonly expected that in four-nucleon (4N) systems, the 3NF effects are even more enhanced in magnitude than in three-nucleon systems.

Recently, several theoretical calculations for the elastic scattering and the transfer reactions in d–d systems have been performed and developed even above the d–d breakup threshold [1, 2]. There also exist calculations for p–^{3}H and n–^{3}He systems [3, 4]. For significantly higher energies, above the three-body breakup and near the quasi-free scattering (QFS) region, the cross sections were calculated based on the Single Scattering Approximation (SSA) [4].

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The data analyzed in this work were collected in 2011 at the KVI Groningen with the use of the BINA detector, which was described in detail in *e.g.* Ref. [6]. One of the possible reaction channels in deuteron–deuteron collisions at 160 MeV is the proton transfer reaction ^{2}H(d,^{3}He)n. This reaction has been theoretically described up to 30 MeV of the deuteron beam energy, using the exact four-body formalism [1, 2]. From the experimental side, there exists only one set of systematic measurements of the cross-section data for the transfer reactions [5] which can be used to test the modern calculations. The main motivation of the present work was providing independent experimental data.

2. Steps of the data analysis

2.1. Particle identification

The particle identification (PID) was performed using the ΔE–E method, from a combination of the total ^{3}He energy deposited in a thick E detector with the energy loss in a thin ΔE detector. ΔE and E detectors were parts of the Wall detector, which is the forward part of the BINA setup [6].

2.2. Energy at the reaction point

The energy deposited by the ^{3}He ions in the E stopping detector was obtained based on the calibration performed with the use of the elastically scattered protons from the d–p reaction [7] and utilizing the Bethe–Bloch law. In the next step, dedicated Monte-Carlo simulations, accounting for the exact geometry of the detector, were used in order to relate the energy measured in the thick scintillator with that reconstructed at the reaction point (see Fig. 1). As a by-product of this analysis, the effect of saturation of the scintillation light produced by ^{3}He ions as compared to protons and deuterons has been determined. Finally, the exactness of the calibration was tested by checking how well the reconstructed energy of the ^{3}He ions reproduces the kinematical relation between the energy and the polar angle (see Fig. 2).

2.3. Detector efficiency

The main contribution to the detector inefficiency comes from malfunctioning wires of the Multiwire Proportional Chamber (MWPC), used for the angle reconstruction. Using the hit wire information, specific for trajectories identified as ^{3}He events, a map of MWPC efficiency as a function of position has been obtained and subsequently used to correct the collected number of ^{3}He events. The efficiency of the scintillator detectors was assumed to be close to unity (above the threshold) and was neglected in this analysis.

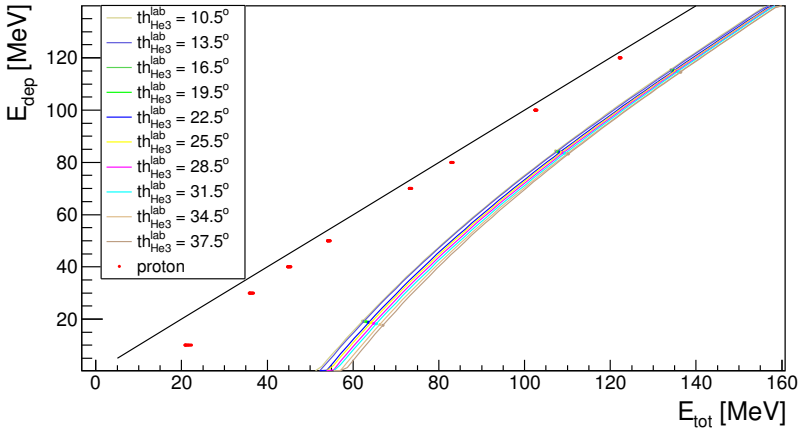


Fig. 1. Relation between the energy deposited and the energy at the reaction point for ^{3}He ions (solid curves) and protons (points) for the investigated angular range. The diagonal line shows the deviation from the linear response. This relation depends on the polar angle, which is known as the straggling effect and can be seen in the plot.

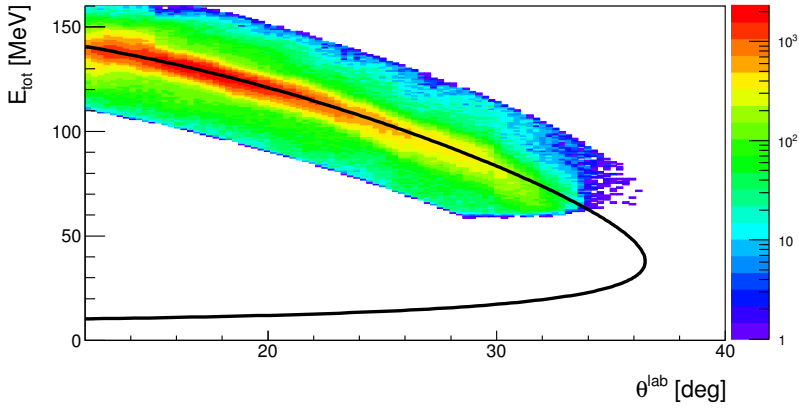


Fig. 2. Distribution of the reconstructed energy *versus* the polar angle for ^{3}He ions. A clear agreement with the ^{2}H(d,^{3}He)n theoretical kinematics (black line) can be seen.

2.4. Background subtraction

After the efficiency correction, the background was estimated from the energy spectra for all available angular bins $\Delta\theta$ ($\theta \in [16°; 30°]$, $\Delta\theta = 1°$). After the background subtraction, a Gaussian function was fitted to each spectrum and events in the range of $\pm 3\sigma$ were accepted. A sample energy spectrum collected at $\theta = 18°$ is presented in Fig. 3.

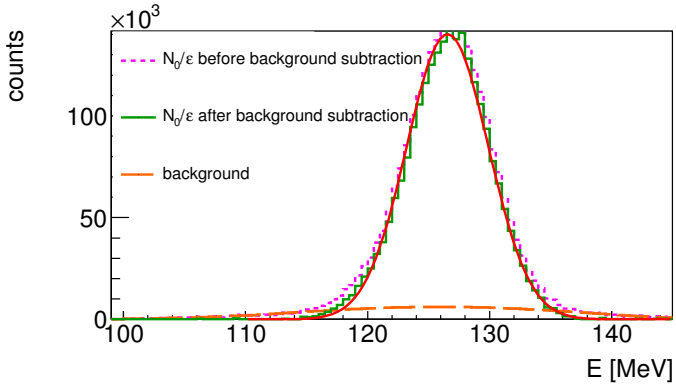


Fig. 3. A sample energy spectrum of ^{3}He at the polar angle $\theta = 18°$.

2.5. Cross section

The cross section of the proton transfer reaction $^2\mathrm{H}(d,^3\mathrm{He})n$ was calculated as follows:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{^3\mathrm{He}}}\left(\Omega_{^3\mathrm{He}}\right) = \frac{1}{k}\,\frac{N\left(\Omega_{^3\mathrm{He}}\right)}{\Delta\Omega_{^3\mathrm{He}}}\,\frac{1}{\varepsilon\left(\Omega_{^3\mathrm{He}}\right)}\,,$$

where k is a scaling factor related to the luminosity integrated over the measurement time, N is the number of the accepted events, $\Omega_{^3\mathrm{He}}$ is the solid angle of detected ^{3}He ions and ε is the efficiency of ^{3}He detection.

3. Results

The cross section for the $^2\mathrm{H}(d,^3\mathrm{He})n$ proton-transfer reaction in the angular range of $\theta \in [16°; 30°]$ was determined. The results are presented in Fig. 4 as a function of the four-momentum transfer $\Delta t = q^2 = 2pp_{\mathrm{beam}}(\cos\theta - 1)$, where: p and p_{beam} are the momenta of ^{3}He and deuterium beam in the centre-of-mass (CM) system, respectively, and θ is the polar scattering angle of ^{3}He in the CM system.

The results in Fig. 4 are presented together with the existing world data set. The possible sources of systematic uncertainty, shown in Fig. 4, arise from the PID method, normalization, angle reconstruction and background subtraction.

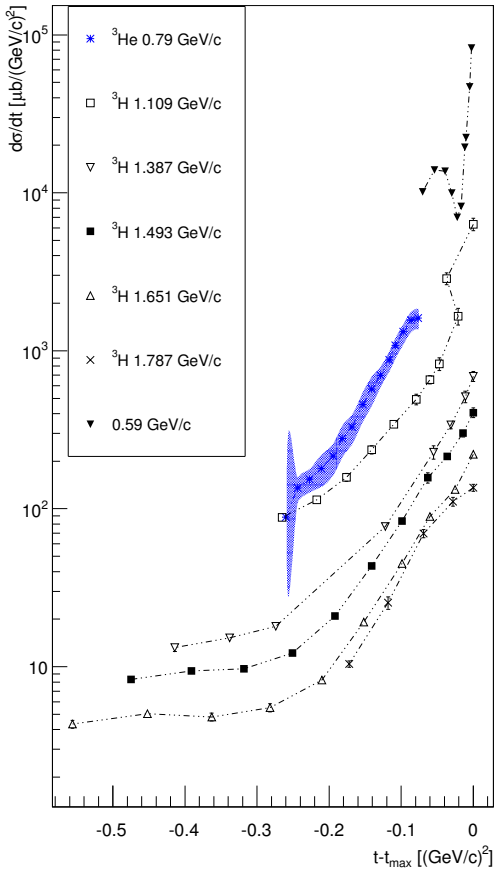


Fig. 4. Cross section of the proton-transfer reaction ^{2}H(d,^{3}He)n as a function of four-momentum transfer. Black points — available world data [5]. Stars (blue) — data from the present analysis. Shaded (blue) area — experimental systematic error.

4. Conclusions

The obtained cross-section data enrich the available world data by a set of points measured for a new energy. In general, the absolute value obtained in the new measurement fits well within the trend observed in the former experiments, with a slightly larger slope for lower momenta. Further analysis of the other channels of d–d scattering at 160 MeV is in progress. We also hope that the theoretical calculations at 160 MeV will be soon developed.

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