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The Reaction $d+d \to p+t$ and Elastic Deuteron-Deuteron Scattering at 51.5 MeV

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The elastic deuteron-deuteron scattering and the reactions $d(d,p)t$ and $d(d,{}^3\mathrm{He})n$ have been investigated at an incident deuteron energy of 51.5 MeV. Time-of-flight technique was used for the particle identification. The observed angular distributions for the (d,p) and (d,n) reaction are identical within the accuracy of the experimental data. The experimental results for the reaction $d(d,p)t$ are compared with a theoretical prediction based on the application of a generalized separable potential model to the four nucleon systems. Information on the single deuteron break-up reaction $d+d \to d+p+n$ and on the double deuteron break-up reaction $d+d \to p+p+n+n$ is contained in the observed continuous proton and deuteron spectra. The double break-up seems to be contribute only with a rather small amount to the whole break-up cross section.

Introduction

Reactions between two deuterons are of particular interest because of their relevance to the general study of few nucleon problems. The reactions involve four nucleons in total and if one considers only exit channels with two strongly interacting reaction products not more than 3 such channels are open: the elastic deuteron-deuteron scattering and the reactions $d(d,p)t$ and $d(d,n)^3\mathrm{He}$. The last two reactions are one nucleon transfer reactions of particular simplicity. The two lightest mirror nuclei $^3\mathrm{H}$ and $^3\mathrm{He}$ are produced in the presence of only one additional nucleon. A comparison of these two reactions is an experimental check for charge symmetry of the nuclear forces. To be complete, a theoretical description of nuclear reaction mechanisms has to be based on calculations which solve the many body problem using only the knowledge of the nucleon-nucleon forces.

Recently such many body calculations[1] have been carried out for the reaction $d+d \to p+t$. From a comparison of these calculations with the experimental data an increasing understanding is to be expected in the field of few nucleon reactions.

Fig. 1 a shows the simple graph for the reaction $d+d \to p+t$. The one nucleon transfer graph of Fig. 1a contributes in first order but in a

1 Alt, E. O., Grassberger, P., Sandhas, W.: Phys. Rev. (in press) and report 2-48 University of Bonn, Oct. 1968.

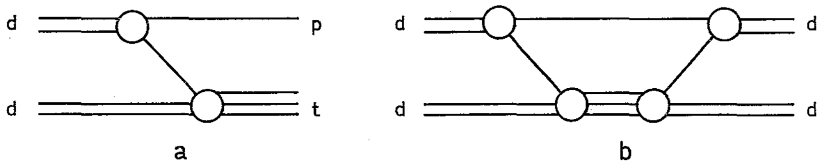

Fig. 1. a) One nucleon transfer graph for the reaction $d+d\to p+t$. b) The simplest graph for elastic deuteron scattering if one accounts only for nuclear forces. The graph contains already two vertices

realistic theory rearrangement into the elastic channel has to be taken into account.

The elastic d—d scattering involves an even more complicated basic graph than the reactions discussed above. The simplest graph contains two particle transfers as is to be seen in Fig. 1b (interaction limited to nuclear forces).

Additionally two break-up reactions are involved in the reactions between two deuterons. The one deuteron break-up produces the three body system $d+p+n$ and the two deuteron break-up produces four free nucleons. The exact theoretical treatment is even more complex but experimental results might be discussed in terms of simplified models[2].

Up to 25 MeV the $d(d, p)t$ and the $d(d, n)^3$He reaction have been studied thoroughly (see for instance[3]). At higher energies only very few investigations were carried out. Results obtained with a bubble chamber were reported between 50 und 69 MeV[4]. Recently an Orsay group investigated the same reactions in detail at an incident deuteron energy of 83 MeV[5]. We have investigated the elastic scattering, the reactions $d+d\to p+t$ and $d+d\to {}^3\text{He}+n$, and the break-up reactions at an incident deuteron energy of 51.5 MeV. The experimental data will be discussed in this paper. Preliminary results have been presented at the "Frühjahrstagung 1967 der Deutschen Physikalischen Gesellschaft"[6].

Experimental Procedure

The focussed beam of 51.5 MeV deuterons from the Karlsruhe isochronous cyclotron was used to bombard a deuterium gas target. The scattering chamber and the details of the experimental set-up are de-

2 Brückmann, H., Kluge, W., Schänzler, L.: Z. Physik **217**, 350 (1968).
3 Oers, W.T.H. van, Brockman, K.W.: Nucl. Phys. **48**, 625 (1963); **74**, 73 (1965). — Oers, W.T.H. van, Arnold, H., Brockman, K.W.: Nucl. Phys. **46**, 611 (1963).
4 Lys, J.E.A., Lyons, L.: Nucl. Phys. **74**, 261 (1965).
5 Roy, M., Bachelier, D., Bernas, M., Boyard, J.L., Brissaud, I., Détraz, C., Radvanyi, P., Sowinski, M.: Phys. Letters **29** B, 95 (1969).
6 Brückmann, H., Haase, E.L., Kluge, W., Schänzler, L., Schmidt, F.K.: Verhandl. DPG (IV) **2**, 356 (1967).

scribed elsewhere[2]. The gas target chamber was held at a constant pressure of 1 atm and at a constant temperature of 34 °C. The reaction products were detected by a NaI(Tl) scintillation counter situated outside the scattering chamber. The particles had to pass a Havar foil of 5.3 mg/cm^2 covering the gas target. In addition, a total of 5 mg/cm^2 of mylar foils and 6.8 mg/cm^2 of aluminium foils covering the scattering chamber and the detector assembly contributed to the energy loss of the detected particles. A distance of 1.23 m between target and detector allowed the particle identification to be made by time-of-flight technique[7]. This rather large distance was also convenient to achieve a very small angular resolution of $\Delta\Omega = 0.25°$.

The beam current was measured with a Faraday cup and a current integrator was used to obtain the total charge. The relative intensities were monitored additionally by means of a separate detector mounted at a fixed angle. For background corrections, measurements were made without deuterium gas in the target chamber.

Fig. 2 shows a typical map display of the reaction products. The data were accumulated with a two-dimensional multichannel analyser. The energy E of the detected particles is plotted versus their time-of-flight τ in an array of 128×32 channels. The special features of the time-of-flight system have been reported previously[7]. The reaction products are identified according to their masses. The left hand branch in Fig. 2 corresponds to protons and the right hand branch is due to deuterons. The mass 3 is represented in this example only by two isolated peaks originating from tritons and ^{3}He.

Because of the different Q-values of the reactions and the different energy losses in the thin foils ^{3}He-particles and tritons are very well separated. The quality of the mass separation is shown in the example of Fig. 3. This figure shows the distribution of events for a constant particle energy. The three peaks arising from protons, deuterons and tritons are separated very well. The hatched area in Fig. 3 indicates a small amount of time correlated background. This effect is generated by fast neutrons which produce charged particles in the NaI(Tl) scintillation crystal and in the mounting material.

Two dimensional spectra as shown in the example of Fig. 2 were taken for scattering angles between 8° and 50° in the laboratory system. A restriction to a maximum angle of 50° was allowed because the identity of two particles cause angular distributions which are symmetrical around 90° in the center-of-mass system. From the map displays energy spectra for protons, deuterons, tritons and ^{3}He were evaluated. Fig. 4 shows a typical proton energy spectrum. The isolated peak at high energy results

7 Brückmann, H., Haase, E.L., Kluge, W., Schänzler, L.: Nucl. Instr. Methods **67**, 29 (1969).

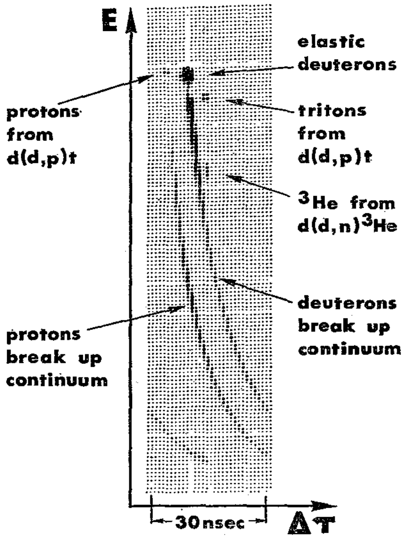

Fig. 2. Map display of the reaction products for a laboratory angle of 15°. Protons, deuterons and mass-three particles populate different branches in the energy versus time plot[7]

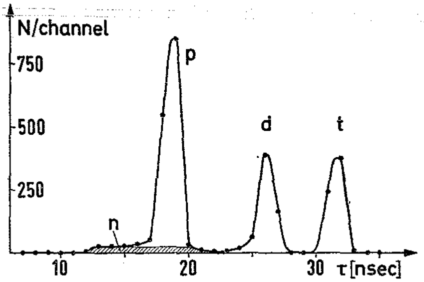

Fig. 3. Typical example for the quality of the achieved mass identification. The distribution of events is shown versus time of flight for an arbitrary energy

from the $d(d,p)t$ reaction. At lower energy a continuous spectrum is observed. The gap between the maximum energy of the continuum and the energy of the peak is due to the binding energy of the neutron in the triton. The central part of the continuum is mainly contributed by a quasifree deuteron-nucleon scattering. The width of this central part is determined by the internal momentum distribution in the deuteron. The small bump on the high energy side of the continuum results from final state interactions (FSI) in the three nucleon system $n+d$.

Fig. 5 shows a deuteron spectrum taken at the same reaction angle of 10°. The narrow peak is due to elastic $d-d$ scattering. The continuous deuteron spectrum has a completely different shape from the proton

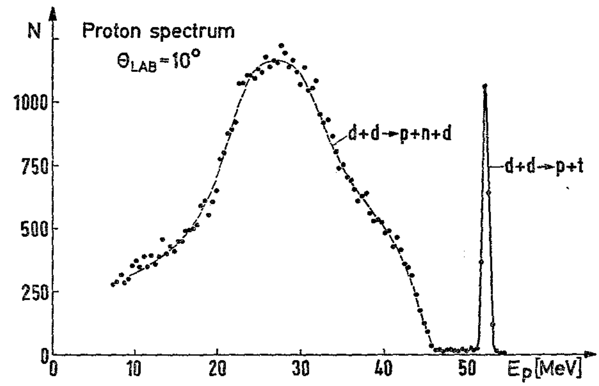

Fig. 4. A typical energy spectrum of protons observed at a reaction angle of 10° in the laboratory system

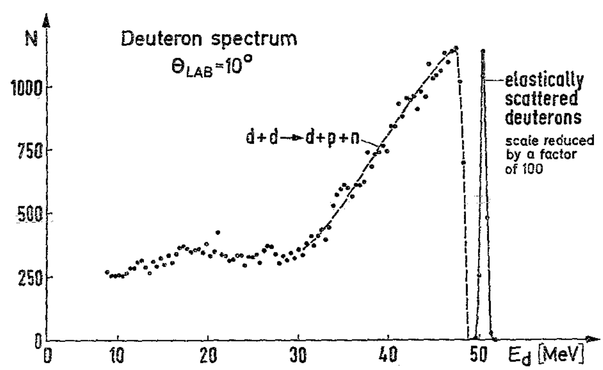

Fig. 5. Deuteron energy spectrum at $\theta_{lab}=10°$. The scale of the elastic peak is reduced by a factor of 100

spectrum. Contributions of various final state interactions determine the shape of the continuum. The $n-p$ final state interaction produces the high energy part of the continuum which rises very rapidly at an energy just below the elastic peak. In addition the $d-n$ and $d-p$ FSI contributes to the spectrum in the whole energy range.

Results and Discussion

Fig. 6 summarizes the experimental results for elastic deuteron-deuteron scattering and the reactions $d(d,p)t$ and $d(d,n)^3$He. The angular distribution of the elastically scattered deuterons shows a broad forward peak and a slight enhancement around the angle of symmetry (90° CM). The general shape is comparable with proton-proton scattering but nuclear forces and the large size of the deuteron broaden the forward peak considerably.

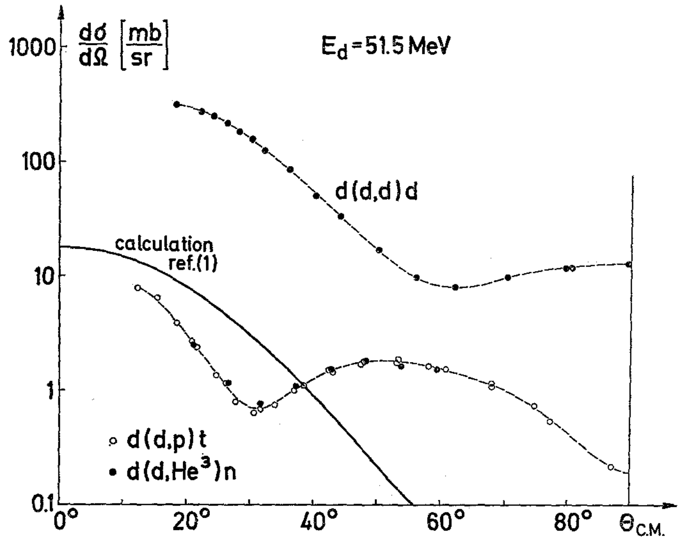

Fig. 6. Angular distribution for elastic deuteron scattering and the reactions $d+d \to p+t$ (solid dots) and $d+d \to n+{}^3\text{He}$ (circles). The solid curve is taken from Ref.[1] and represents the result of a many body calculation

The two reactions $d+d \to p+t$ and $d+d \to {}^3\text{He}+n$ are expected to yield the same angular distribution if charge symmetry of nuclear forces is exactly valid and Coulomb distortion effects are to be neglected. The circles in Fig. 6 refer to the angular distribution of the reaction $d(d,p)t$ and the solid dots represent measurements of the reactions $d(d,n)\,{}^3\text{He}$. For the evaluation of the angular distribution of the (d,p) reaction both the "stripped" protons and the "recoil" tritons have been measured. This double information is a check of the consistency of the measurements. The statistical errors are smaller than the size of the circles and dots in Fig. 6. The error of the absolute scale of the differential cross section is estimated to be smaller than 5%. A comparison between the two mirror reactions $d(d,p)t$ and $d(d,n)\,{}^3\text{He}$ (circles and points) shows that they produce two identical angular distributions as is to be expected from general considerations on symmetry as discussed above. Similar results were obtained at an energy of 25.3 MeV[3] and at 83 MeV deuteron energy[5].

The solid curve in Fig. 6 represents the result of a theoretical calculation published by Alt, Grassberger and Sandhas[1]. These authors apply a generalized separable potential model[8] to the four nucleon

8 Yamaguchi, Y.: Phys. Rev. **95**, 1628 (1954). — Yamaguchi, Y., Yamaguchi, Y.: Phys. Rev. **95**, 1635 (1954).

system. The significance of such a theoretical description is that it attempts to calculate a nuclear reaction without adjusting any free parameters and with only inserting the nucleon-nucleon forces. As reported by Sandhas and his coworkers solutions of the scattering equations have been found. The numerical calculations include only a few separable terms and a K-Matrix Born approximation. If one gives consideration to the basic character of this approach the comparison of the calculation with the experimental data shows an amazing agreement at forward angles. The second maximum at larger angles is not expected to be explained by this calculation. One probably has to include the higher order approximations to the K-matrix formalism[1]. It should be pointed out that a theoretical interpretation of the elastic $d-d$ scattering on the basis of this treatment needs far more sophisticated calculations. As is already seen from Fig. 1b the first approximation contains already a two step exchange term.

Finally there is the information contained in the observed continuous spectra. As already mentioned the continua are produced by deuteron break up mechanisms. Reactions with 3 or 4 particles in the exit channel can be investigated with advantage by means of kinematically complete experiments where at least two reaction products are detected in coincidence. Such kinematically complete experiments are discussed elsewhere (see e.g.[2,9]) but these particular topics are not within the scope of the experiments presented in this report. Nevertheless one might draw some conclusions from the continuous spectra which were observed in the course of this experiment. By summing up the whole continous part of the deuteron spectrum one gets the differential cross section for the one deuteron break up reaction $d+d \to d+p+n$. The result is shown in Fig. 7 (solid curve) and refers to laboratory angles between 8° and 50°. The differential cross section decreases with increasing angle θ_{lab} and shows a slight bump between 15° and 20°. This bump might be due to the production mechanism for the singlet $n-p$ scattering state. It can be seen from the deuteron spectra (see for example Fig. 5) that the $n-p$ final state interaction (FSI) accounts for a considerable part of the events which are registered in the continuum. A separate investigation of $n-p$ FSI in the reaction $p+d \to p+p+n$ demonstrates how strongly the cross section is able to vary with angle in a deuteron break up reaction[9].

The dashed curve in Fig. 7 shows the angular distribution for protons which was also evaluated by summing up the whole continuous part of the spectra. In contrast to the deuteron continua events from single as well as double deuteron break-up are contained in the proton spectra. Protons are produced by the $d+d \to d+p+n$ and the $d+d \to p+p+n+n$

9 Brückmann, H., Gehrke, W., Kluge, W., Matthäy, H., Schänzler, L., Wick, K.: To be published.

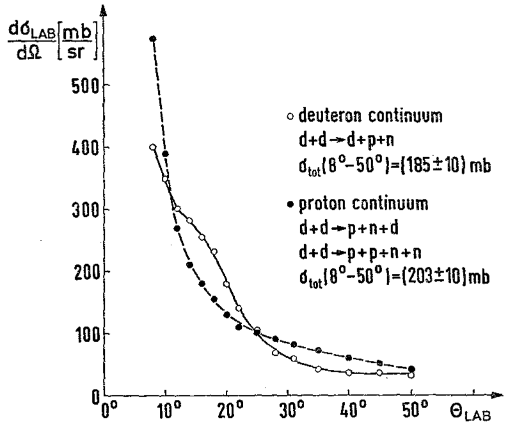

Fig. 7. Angular distributions for break-up reactions. The solid curve was obtained by summing up the whole continuous deuteron spectra and represents the break-up of one deuteron. The dashed curve was evaluated in the same way from the continuous proton spectra and contains one and two deuteron break-up processes

reaction. From other investigations (for literature see Ref. [2]) one would predict a pronounced forward peak in the differential cross section of break-up protons. One of the strongly contributing reaction mechanisms is the spectator process (see Fig. 4). When a neutron or a proton from the projectile-deuteron acts as a spectator one will always observe a proton in a rather small forward angle. This produces a forward peak in the angular distribution if the single deuteron break-up reaction dominates.

A measure for the double deuteron break-up is the difference between the integral over the proton differential cross section $d\sigma/d\Omega$ and the integral over the deuteron differential cross section. The integration was carried out between 8° and 50° and yields for the protons $\sigma=(203\pm 10)$ mb and for the deuterons $\sigma=(185\pm 10)$ mb. The comparison of the two results indicates a rather small contribution of the double deuteron break-up.

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