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The Break-up Reaction $p+d \rightarrow p+p+n$

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The three-particle reaction $p+d \rightarrow p+p+n$ has been investigated at a deuteron bombarding energy of 52.0 MeV. Single counter experiments as well as coincidence measurements have been carried out. The laboratory angular distribution of the break-up reaction and the total break-up cross-section have been determined by means of the single counter experiments. The angular distribution for final-state interacting neutron-proton pairs was obtained by means of coincidence measurements. The coincidence experiments provide a strong evidence for very different shapes of the angular distributions for neutron-proton singlet and triplet final-state interaction.

1. Introduction

Several groups have investigated the deuteron break-up reaction $p+d \rightarrow p+p+n$ in "single counter experiments" where only one of the three particles in the final state is detected. From such kinematically incomplete experiments the differential cross-section and the total disintegration cross-section were obtained[1–5]. The mechanisms of the three-particle reaction was also studied by kinematically complete experiments where two particles in the final state are detected in coincidence[6–16]. Evidence has been found for the contribution of neutron-

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proton[9,10,12-14,16] and proton-proton final-state interaction [FSI][1-5,13] as well as for proton-proton quasielastic scattering [6-8,11,14,15] in both types of experiments.

The theory of the three-body problem may be regarded as solved in principle from the point of view of a formal scattering theory[17]. The numerical calculations however require very large computer capacities even if approximations are used. Therefore most of the data have been analysed by simple models like the Watson-Migdal model for final state interaction[18] and the spectator model for quasielastic scattering[6,19]. The singlet scattering length for neutron-proton and proton-proton scattering has been extracted by means of the Watson-Migdal model from the three-particle cross-section measured at different incident energies and at several particular pairs of angles. Reasonable agreement has been found between the values extracted from the three-particle reaction and the values known from free neutron-proton and proton-proton scattering[10,12,13,16].

We have studied the reaction $p+d \to p+p+n$ induced by 52.0 MeV deuterons by means of single counter experiments as well as coincidence experiments. The kinematically incomplete experiments have been carried out with the aim to determine the laboratory angular distribution of the break-up reaction and the total break-up cross-section. The kinematically complete experiments have been performed with the purpose to establish the angular distribution for the production of *n-p*-subsystems with final state interaction. The neutron-proton pairs might

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interact in the singlet or the triplet state. The dependence of the three-particle cross-section on the relative energy E_{np} of the neutron and proton differs for the two spin states[13b,c] and the angular distributions observed at different relative energies E_{np} are therefore expected to reflect the contribution of the two spin states.

2. Experimental Procedure

The measurements were performed using the external beam of 52.0 MeV deuterons available at the Karlsruhe sector-focused cyclotron. The scattering chamber and the details of the experimental set-up have been described elsewhere[12]. The single counter spectra were taken with a hydrogen gas target. For the coincidence spectra a polyethylene target was used. The reaction products were detected in NaI(Tl) scintillation counters which were positioned outside the scattering chamber. The large distances between the target and the detectors (1.26 m for single counter experiments, 0.92 and 1.28 m for coincidence experiments) assured a very good angular resolution ($\Delta\theta = \pm 0.2°$ and $\pm 0.4°$ for the single counter and the coincidence experiments respectively) and allowed the particle identification to be performed by time-of-flight technique[20].

In the coincidence experiments two time-of-flight circuits as discussed in details in Ref.[20] have been used and the fast coincidence was achieved with the two "selected RF-signals". Each coincidence event was characterised by two energy signals and two time-of-flight signals which were fed via a four-parameter data acquisition system to a CDC 3100 computer (for details see Ref.[21]). The data were recorded on magnetic tape. The particle identification and the subtraction of random coincidences were made by computer analysis.

The charge collected in the Faraday cup was measured with a current integrator. The relative intensities were additionally monitored by means of a separate detector mounted at a fixed angle.

3. Results and Discussion of Single Counter Experiments

As an example the left hand side of Fig. 1 shows a map display of the two-dimensional spectrum observed at a laboratory angle of 12.5°. The energy E of the detected particles is shown versus their time of flight $\Delta\tau$ in an array of 128×32 channels. In the map display the left hand branch corresponds to protons (mass 1). The elastically scattered

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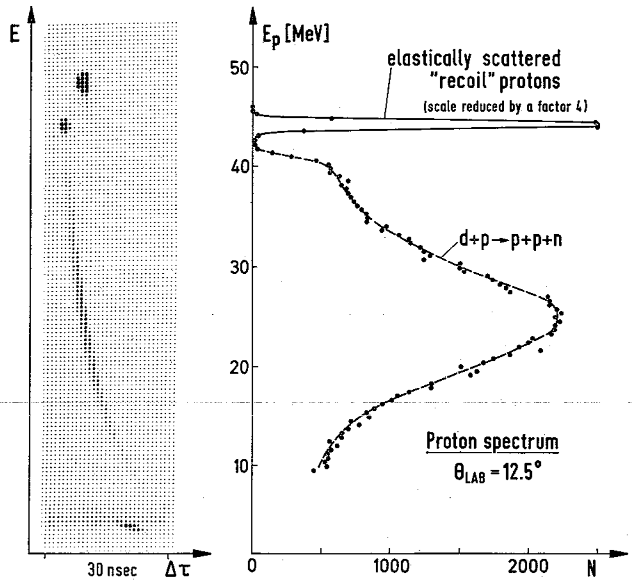

Fig. 1. Example for the measurements of single counter spectra. The data was taken at a laboratory angle of 12.5°. On the left hand side a energy versus time-of-flight plot of all the reaction products is shown. The protons and the deuterons are identified from this map display. The corresponding proton spectrum is presented on the right hand side

"recoil" protons produce the single peak while the broad proton continuum arises from the break-up reaction $p+d \to p+p+n$. The deuteron branch (mass 2) is represented only by the isolated peak of the elastically scattered deuterons. The angular distribution for the elastic proton-deuteron scattering at 52 MeV deuteron energy was already published in Ref.[12b].

The measurements of the proton spectra were carried out at laboratory angles between 7.5° and 49.5°. Typical proton spectra are shown on the right hand side of Fig. 1 and in 2. At forward angles (e.g. $\theta_{\text{lab}}=$ 7.5°) the most characteristic feature of the break-up spectrum is the maximum at a proton energy $E_p=25$ MeV. This maximum is mainly caused by the "spectator protons" arising in reactions where a quasifree neutron-proton scattering occurs. Because the spectator protons were bound in the projectile deuterons, their energies are determined by the laboratory deuteron energy and by the internal momentum distribution in the deuteron. As can be seen from Fig. 2 the contribution of the quasi-elastic scattering decreases rapidly with increasing angles. The enhancement of the spectrum at the high energy end of the continuum is due

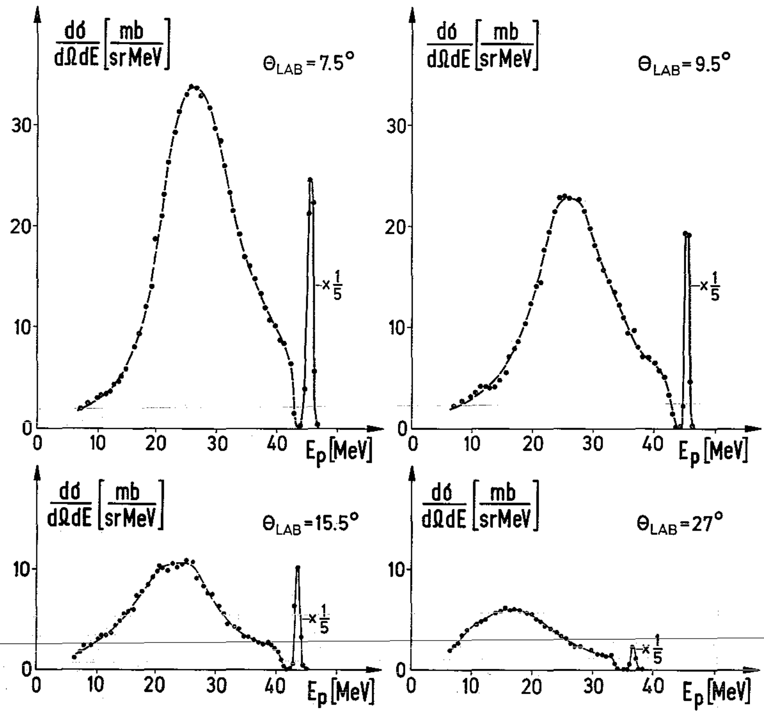

Fig. 2. Typical single counter proton spectra observed at four different laboratory angles

to the neutron-proton FSI. Additionally the quasielastic proton-proton scattering and proton-proton FSI contribute to the reaction cross-section. An unambigious separation of the different reaction mechanisms can hardly be obtained by carrying out only single counter experiments.

The laboratory differential cross-section of the break-up reaction was obtained by summing up the break-up spectra. Because of a background at low energies only those protons with an energy of more than 5 MeV were taken into account. The curve *a* in Fig. 3 shows the differential cross-section.

The curve *b* was calculated using the simple Serber spectator model[22] for the deuteron break-up reaction. Although this model is not able to predict the absolute values of the cross-section the agreement between the shape of the measured and the calculated angular distributions supports the assumption that mainly the quasifree scattering contributes to the reaction cross-section. A lower limit for the total cross-section σ_t was

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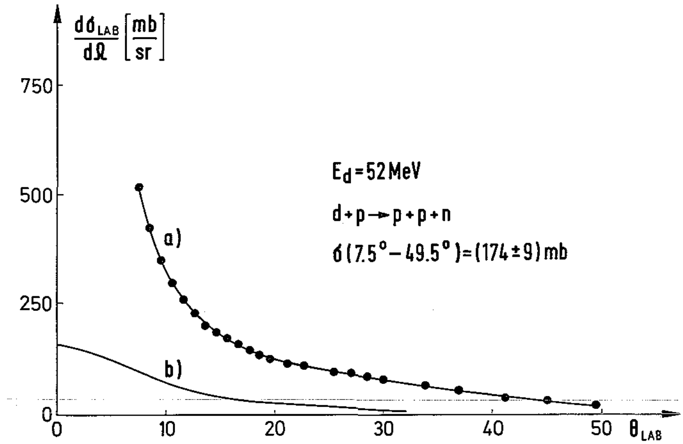

Fig. 3. The laboratory angular distribution of the break-up reaction $p+d\to p+p+n$. Curve *a* represents the experimental results obtained by summing up the continuous proton spectra. Curve *b* was calculated by means of the Serber model[22]

obtained by integration of the differential break-up cross-section between 7.5° and 49.5°. The upper limit of σ_t was evaluated by extrapolation of the differential cross-section to small angles and a $\sigma_t = 174^{+40}_{-\ 9}$ mb was obtained. Van Oers and Brockman[23] calculated the scattering phases of nucleon-deuteron scattering and determined the energy dependence

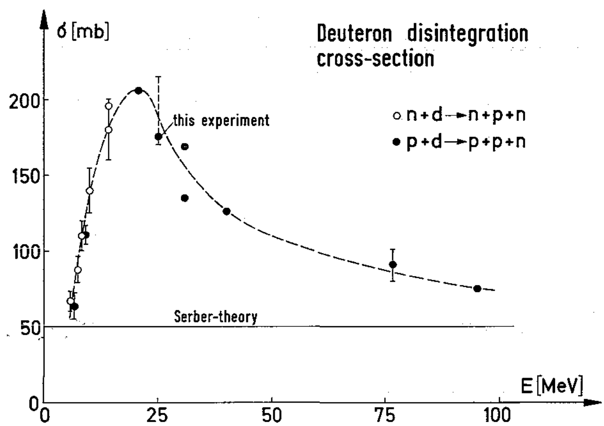

Fig. 4. The total nucleon-deuteron disintegration cross-section as a function of the nucleon laboratory energy. The dashed line is based on a phase-shift analysis[23]

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of σ_t. In Fig. 4 the calculated cross-section (dashed curve) and the experimental values at different incident nucleon energies which are compiled in Ref.[23] are shown. The cross-section obtained in our experiment is included in the diagramm of Fig. 4 (incident deuterons of 52 MeV energy are equivalent to incident protons of 26 MeV energy). Our result agrees quite well with the phase-shift analysis of Ref.[23]. The full line in Fig. 4 represents the energy independent cross-section predicted by the Serber theory[22]. As is already pointed out in Ref.[22] this theory provides a reasonable approximation to the experimental values only at high energies.

4. Results and Discussion of Coincidence Experiments

In the kinematically complete experiments two protons have been detected in coincidence. The aim of this investigation was the measurement of the angular distribution of the neutron-proton final state interaction. Hence in all experiments the angles were chosen to observe neutron-proton pairs with relative energy down to zero[12]. As an example of the experimental data a map display of the E_3-E_4 plane is shown on the left hand side of Fig. 5. E_3 and E_4 are the energies of the two protons which were detected at the angles $\theta_3=42.0°$ and $\theta_4=25.3°$. Only the region allowed by the kinematics of the reaction is populated by coincidence events. The neutron-proton FSI enhances the number of events registered at the maximum energy E_3 (corresponding to $E_{np}=0$)[10,12,14,16]. The projection of the experimental data on the E_4-axis is shown on the right hand side of Fig. 5. Such coincidence measurements have been

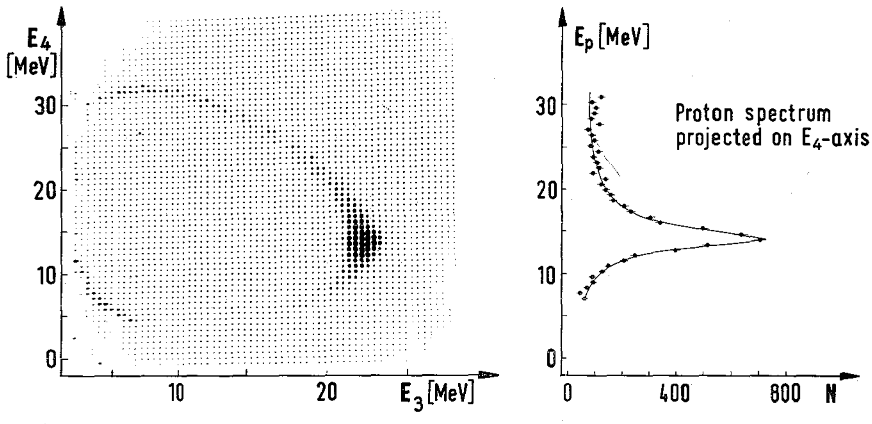

Fig. 5. Example for the measurements of coincidence spectra. Two protons with energies E_3 and E_4 were detected in coincidence at the angles $\theta_3=42.0°$ and $\theta_4=25.3°$. A map display of the experimental data is shown on the left hand side. A projection of the data on the E_4-axis is plotted on the right hand side

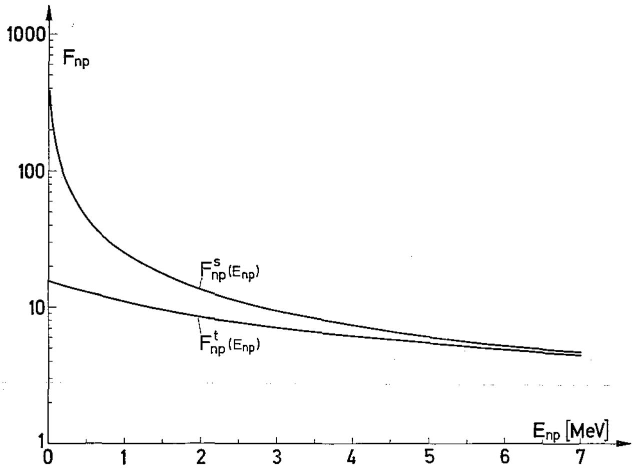

Fig. 6. The two enhancement factors F^s_{np} and F^t_{np} for neutron-proton singlet and triplet final state interaction are shown in a logarithmic scale (arbitrary units) versus the relative energy E_{np}

performed at fourteen different pairs of angles. The investigated region of angles covered center-of-mass angles $\theta^{d*}_{\text{c.m.}}$ between 55° and 152° for the production of the $n-p$ subsystem.

In the Watson-model of final state interaction[18] the three-particle reaction is treated as a two-step process. Accordingly the matrix element can be factorised. The factor which accounts for the production probability of a neutron-proton subsystem depends only on the angle $\theta^{d*}_{\text{c.m.}}$. The enhancement factor F_{np} which accounts for the final state interaction in the neutron-proton subsystem depends only on the relative energy E_{np}. Two enhancement factors F^s_{np} and F^t_{np} have to be considered [13b] for the interaction of the neutron-proton pair in the singlet and the triplet state. The energy dependence of these two enhancement factors is different as can be seen from Fig. 6. As a consequence of the rapid decrease of F^s_{np} the contribution of neutron-proton singlet FSI is restricted to a region of very low energy E_{np}. With increasing energy the enhancement factor for $n-p$ triplet FSI gains in importance relative to F^s_{np}.

Fig. 7 shows the differential cross-section of the three-particle reaction $d+p\rightarrow p+p+n$ at $E_{np}=0$ as a function of the angle $\theta^{d*}_{\text{c.m.}}$. The characteristic feature of this angular distribution is the deep minimum at $\theta^{d*}_{\text{c.m.}}=130°$. The applicability of the Watson model was confirmed at the pair of angles $\theta_3=40°$ and $\theta_4=26°$ (corresponding to $\theta^{d*}_{\text{c.m.}}=95.8°$). At these particular pairs of angles it was shown[12b] that at $E_{np}=0$ almost only the $n-p$ singlet FSI contributes while at $E_{np}=2$ MeV the contribu-

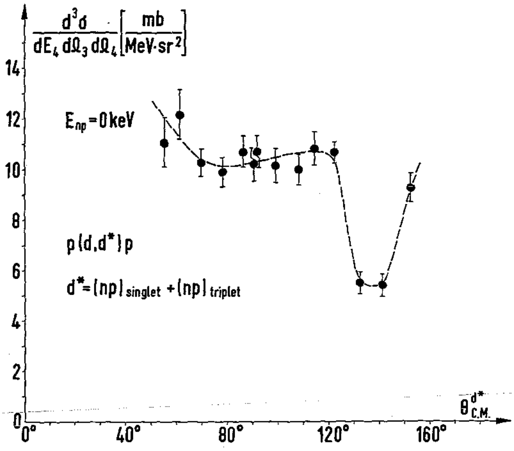

Fig. 7. The differential three-particle cross-section for the reaction $p+d \to p+p+n$ at $E_{np}=0$ keV as a function of the angle $\theta^{d^*}_{c.m.}$ at which the $n-p$ subsystem is produced in the center-of-mass system

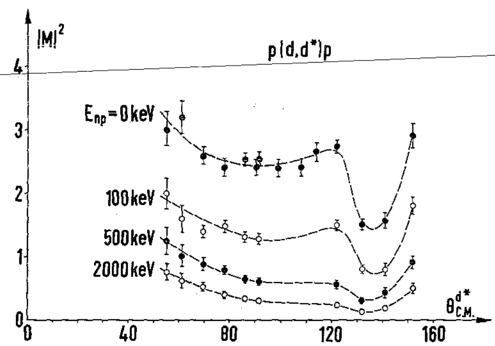

Fig. 8. The matrixelement $|M|^2$ of the three-particle reaction $p+d \to p+p+n$ at different relative energies E_{np} as a function of the production angle $\theta^{d^*}_{c.m.}$. Different shapes of the angular distributions for $n-p$ singlet and triplet final state interaction are revealed

tion of $n-p$ triplet FSI is predominant. Therefore the angular distribution of Fig. 7 is assumed to be mainly due to $n-p$ singlet FSI. At $E_{np}=2$ MeV one expects to observe an angular distribution of dominating $n-p$ triplet FSI. Fig. 8 shows the variation of the angular distributions with the relative energy E_{np}. The square of the matrix element $|M|^2$ given by the ratio of the cross-section and the phase space factor is plotted versus the production angle $\theta^{d^*}_{c.m.}$. By comparison of the angular distributions of Fig. 8 two main features are exhibited. First a rapid decrease of $|M|^2$ is observed with increasing relative energy E_{np}. This justifies the assumption of a dom inating contribution of the $n-p$ singlet FSI to the three-particle cross-section. Second the shapes of the angular distributions observed at $E_{np}=0$ and at $E_{np}=2$ MeV are quite different. It can be concluded that the cross-section for neutron-proton singlet and triplet FSI depend differently on the production angle $\theta^{d^*}_{c.m.}$. Comparing the angular distribution of $|M|^2$ at $E_{np}=2$ MeV with the elastic deuteron-proton scattering[12] one observes a remarkable similarity of the two distributions. A quantitative relation between the cross-section of the elastic deuteron-proton scattering and the neutron-proton triplet FSI has been derived and will be discussed elsewhere[24].

The results obtained in the experiments discussed above provide a strong evidence for very different shapes of the angular distributions for neutron-proton singlet and triplet FSI. The discussion stimulated further investigations on the three-particle reaction $p+d \to p+p+n$. In a more sophisticated analysis of kinematically complete experiments the reliability of the Watson model can be checked and the contributions from singlet and triplet FSI can be separated. Preliminary results of such an analysis have been reported at the Birmingham Conference on the three-body problem[13c] and a separate paper will cover this topic.

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