KERNFORSCHUNGSZENTRUM

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Institut für Experimentelle Kernphysik

Experimental Investigation of the n-p and p-p Final State Interaction in the Three Body Reaction p+d→ p+p+n with 52 MeV Deuterons

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Abstract

The reaction d+p →p+p+n has been studied in kinematically complete experiments at a deuteron bombarding energy of 52 MeV. Two of the outgoing nucleons (two protons or the neutron and one of the protons) were detected in coincidence. The reaction was investigated at different sets of angles where a n-p respectively a p-p final state interaction is expected to be the dominating reaction mechanism.

The n-p final state interaction data were analysed assuming incoherent contributions of an n-p singlet and an n-p triplet final state interaction. Three independent parameters, the singlet scattering length a_s and the two intensities for singlet and triplet scattering were determined by a least square fit to the experimental data. The results for different center of mass angles of the third particle show the dominating singlet final state interaction in the investigated kinematical region. A surprisingly fair agreement is obtained by comparing the data with calculations based on Watson's theory.

The p-p final state interaction data were analysed assuming only an interaction of two protons in an S state. These data are also compared with calculations based on the Watson model using the effective range approximation. The singlet p-p scattering length extracted from this analysis is $a_{pp} = -(7.5 \pm 0.5)$ f. The fair agreement between this value and the known scattering length of the free p-p scattering shows that the production of S-state proton pairs seems to be the predominant feature of the investigated reaction p+d →p+p+n.

In the last few years the progress in experimental and theoretical investigations of the unbound three nucleon system stimulated still increasing interest in this field. Experimentally the use of on-line computer techniques facilitates the performance of kinematically complete experiments. The reactions p+d→p+p+n and n+d→p+n+n have been investigated in complete experiments by several authors (for references see for example ref. 1-7).

In the field of formal theory the exact treatment of three body systems is regarded as a principally solved problem. Nevertheless numerical calculations afford so extremely large computer facilities that only a few authors have presented numerical results which can be directly compared with experimental results (for theoretical treatment see for instance ref. 8-14)

Experimental investigations of the reaction p+d→p+p+n were carried out at the Karlsruhe isochronous cyclotron. Hydrogen targets were bombarded with deuterons of 52.3 MeV. Two of the outgoing nucleons (two protons or the neutron and one of the protons) were detected in coincidence to perform a kinematically complete experiment. Particle identification and measurement of the neutron energy were carried out by the use of time-of-flight technique. Fig. 1 shows the experimental set-up schematically. Each coincidence event is characterised by both the energies and the times of flight of two outgoing nucleons. These four independent parameters are registered in a CDC 3100 computer using a new four dimensional data acquisition system developed at Karlsruhe. The knowledge of energy and time of flight allows also the particle identification to be made by computer analysis of the experimental data (15).

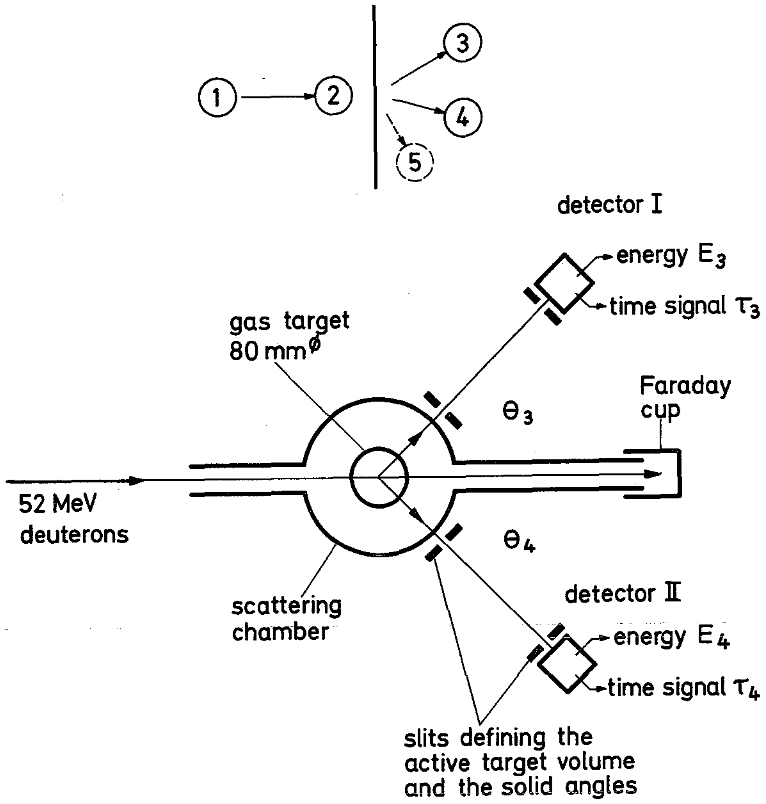

Fig. 1 Schematic representation of the experimental set-up. Each coincidence event produces four independent analogue signals, an energy and a time-of-flight signal from each detector. The signals are digitalized and are transfered on-line to the data acquisition system DATA.

The main points of interest in this simple reaction concentrate on:

1) the test for charge independence of the n-p and p-p interaction and an examination of methods for extraction of two nucleon scattering data from three body reactions. These questions are of fundamental interest for similar experiments which have the aim to determine the n-n scattering length;

2) the extraction of proton-proton scattering parameters from data taken for p-p systems with very low relative energies;

3) the comparison of n-p and p-p final state interaction at identical kinematical conditions;

4) the test of the simplified theoretical description of a final state interaction which was given by Watson (8);

5) the angular distribution for the production of nucleon-nucleon systems in their singulet and triplet states;

6) the search for interference effects between different reaction mechanisms.

Fig. 2 shows as an example a map display of coincident proton pairs.

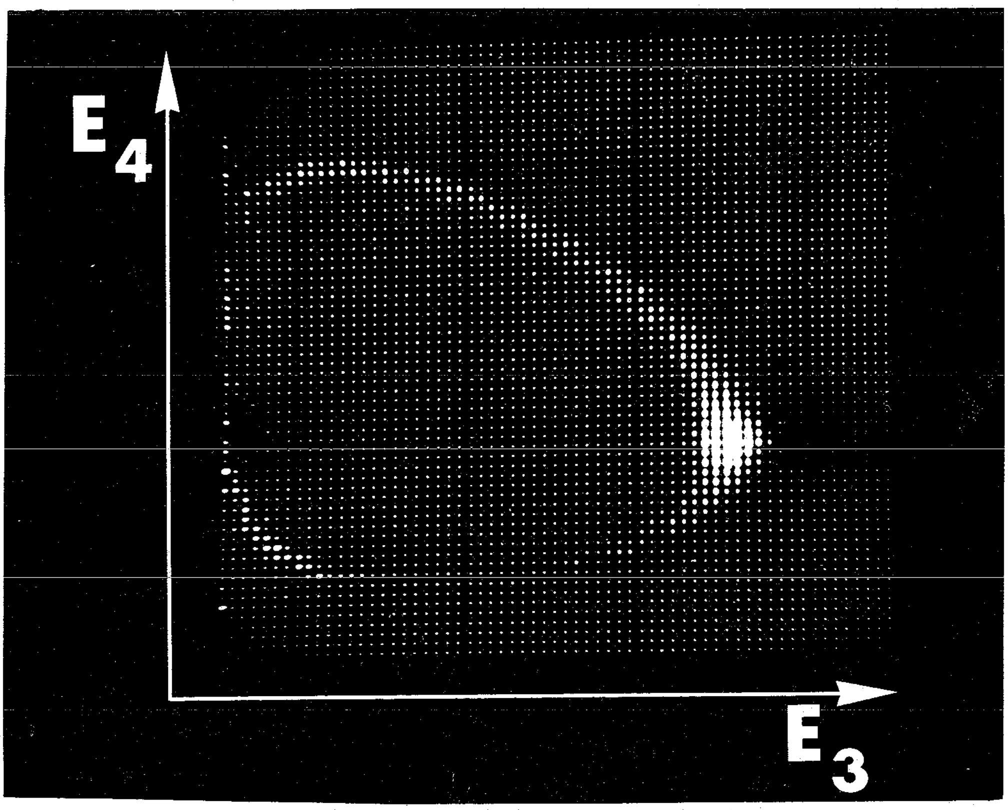

Fig. 2 Example for the measurement of n-p final state interaction in the reaction p+d →p+p+n. Two protons (θ_3 = 42,0°, θ_4 = 25,3°) were detected in coincidence. The results are shown in a map display of the energy versus E_3 .

The registered events are located on a closed kinematical curve. The relative energy in the neutron-proton system reaches down to zero at the point where the proton energy E_3 has its maximum value. It is clearly to be seen that the coincidence events accumulate in the region of low relative energy in the n-p system.

In fig. 3 a second example is shown where the two angles of the proton detectors were chosen to be symmetrical ($\theta_3 = \theta_4 = 27.7^o$).

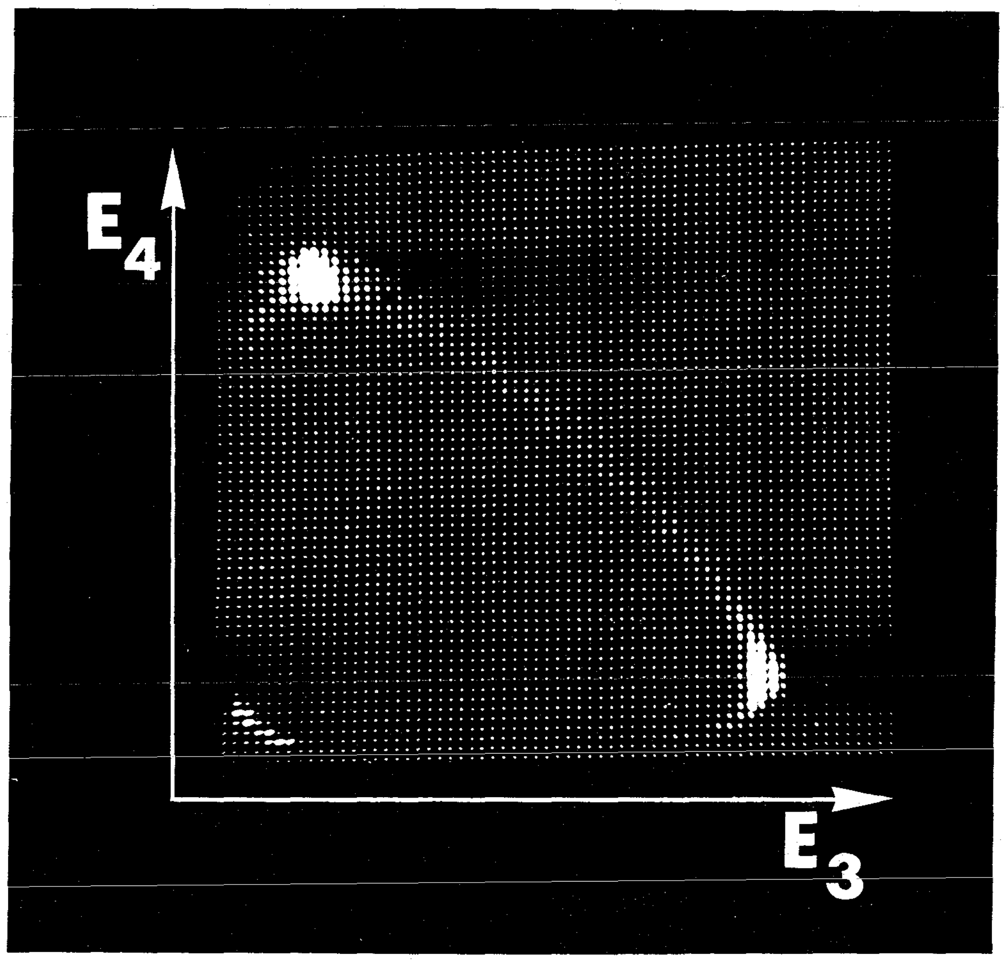

Fig. 3 Map display for the two coincident protons from the reaction p+d→p+p+n. The detector geometry was chosen to be symmetrical ($\theta_3 = \theta_4 = 27,7^o$). The notation is the same as in fig. 2.

In this special case two final state peaks are observed. To evaluate the physical information the projection of the experimental data onto one energy axis was used. Representative for such a onedimensional plot is fig. 4

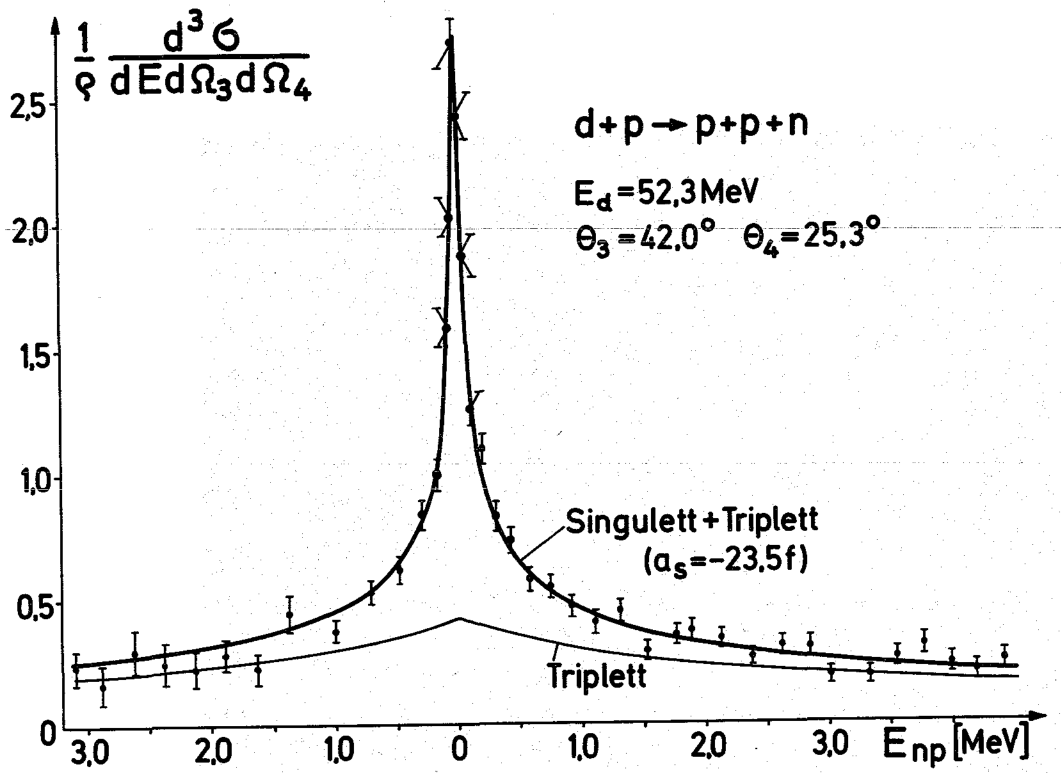

Fig. 4 The three particle differential cross section versus the relative energy E_{np} of the neutron-proton pair. The n-p final state interaction produces the sharp peak at E_{np} = 0. In the analysis singlet and triplet interaction were taken into account. The curves show the result obtained by a least square fit.

In this figure the three particle differential cross section divided by the phase space factor ρ is plotted versus the relative energy E_{np} in the n-p system. The data were analysed assuming incoherent contributions of n-p singlet and triplet final state interaction. Calculations were carried out using the Goldberger-Watson theory of final state interaction (8). For the triplet scattering length and the two effective range parameters the values known from free n-p scattering (18) were used. Three independent parameters are determined by a least square fit to the experimental data: the singlet scattering length a_s and the two intensities for singlet and triplet scattering. In this experiment the n-p scattering length has been determined to be $a_s=-(23.5\pm0.5)$f. This value extracted from the three body reaction is in fair agreement with the value known from the free n-p scattering: $a_s=-(23.68\pm0.03)$f. (18)

Experimental data as shown in fig. 2 - 4 were taken at ten different pairs of angles. In fig. 5 the angular dependence of the ratio A_{Tripl}/A_{Sing} is shown.

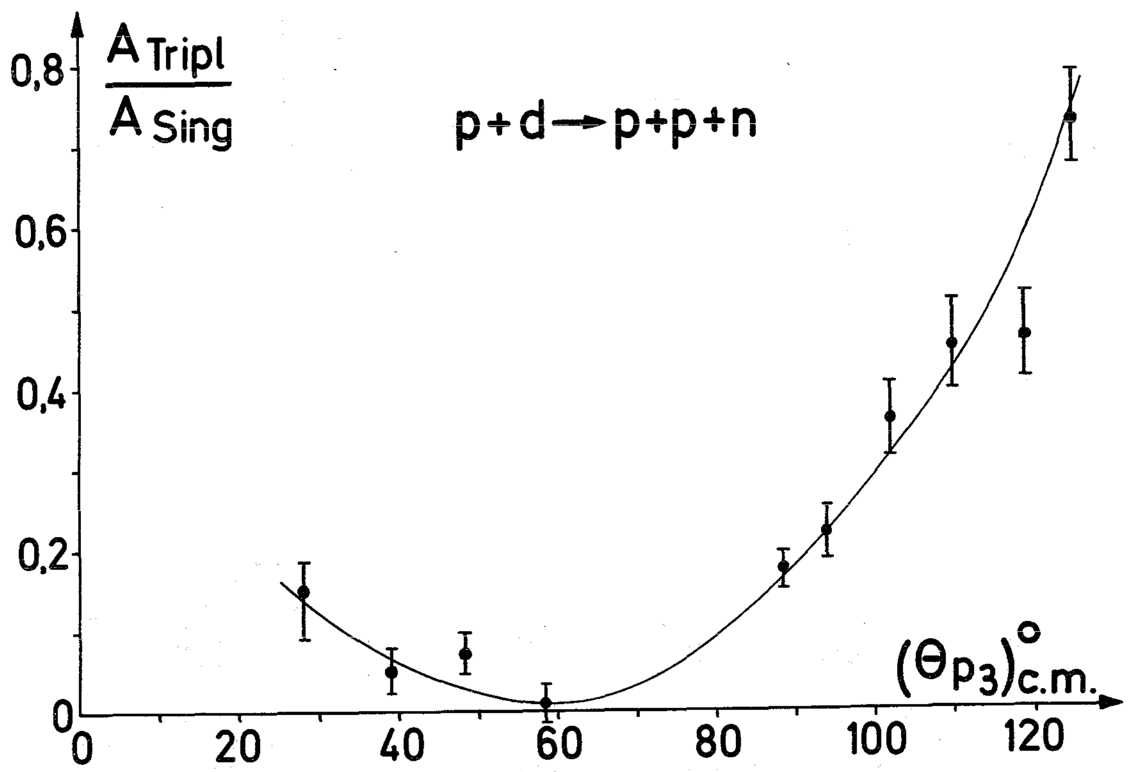

Fig. 5 Contribution of n-p singlet and triplet final state interaction for different production angles of the n-p pair. The ratio of the cross sections A_{Tripl}/A_{Sing} was taken at relative energy $E_{np} = 0$ and is plotted versus the c.m. angle of the third particle.

This quantity is the ratio of the triplet and singlet cross section at the relative energy $E_{np}=0$ and it is equal to the ratio of the triplet and singlet scattering intensities. The lowest triplet contribution was found in the case of symmetric detector geometry (the example illustrated in fig.3). In the analysis of the data the cross section at low relative energy in the n-p system is described only by the Watson term of final state interaction between these two nucleons. Contributions from other reaction mechanisms are disregarded in the special kinematic region under investigation. To check the validity of these approximations the scattering length a_s was evaluated as a function of the production angle for the n-p system. The results are shown in fig. 6.

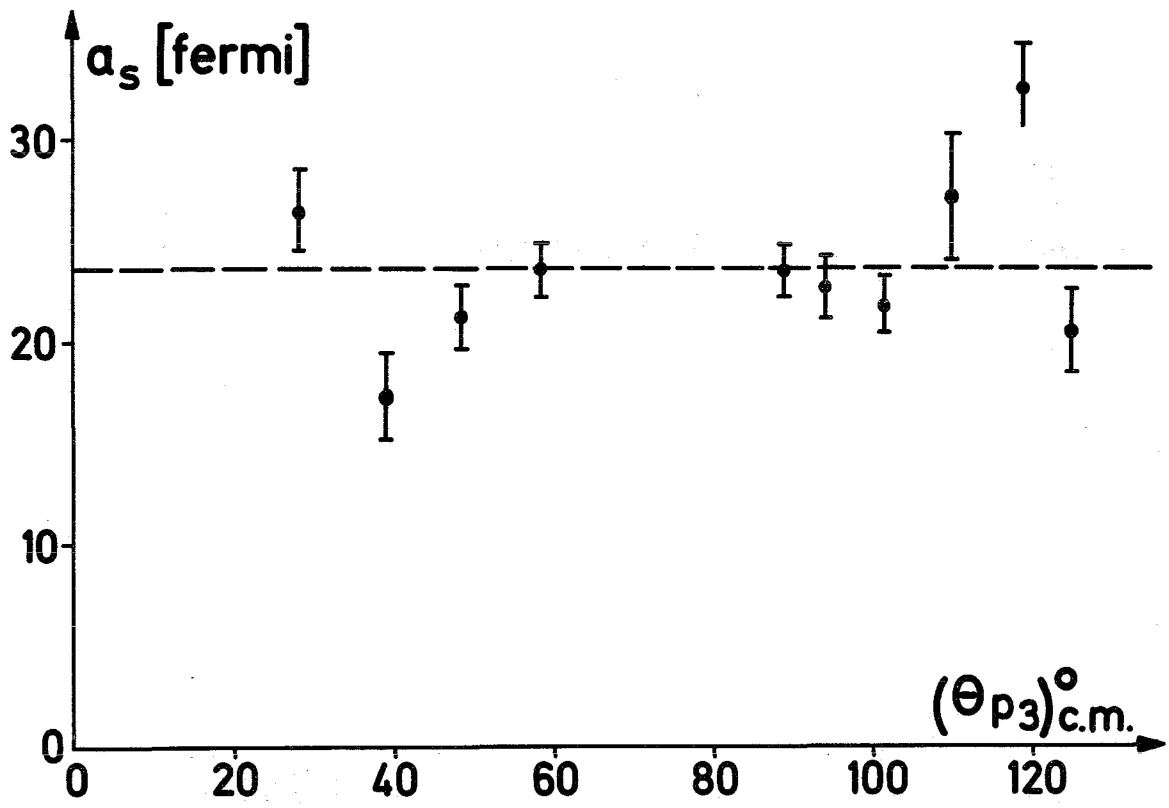

Fig. 6 The extracted singlet scattering length a_s versus the angle θ_{p3} of the third particle. The dashed line represents the value $a_s=-23{,}68$ f known from the free n-p scattering.

The dashed line corresponds to the scattering length obtained from the free n-p scattering. The plots in fig. 5 and fig. 6 show that the singlet final state interaction dominates in the investigated region and a surprisingly fair description is obtained by the Watson theory.

A second approach to get further information on a three particle reaction might be based on the evaluation of the angular distribution. For the reaction $p(d,d^x)p$ such an angular distribution was obtained by integration of the c.m. cross section over a limited interval of the relative energy E_{np} and the solid angle Ω_{np} in the n-p system (16). The results were compared with the calculations of Amado et al. for elastic n-d scattering (10). The details will be discussed in a separate paper.

So far the effects of the nuclear force had to be taken into account. The Coulomb interaction has to be included if a p-p final state interaction is observed in the same reaction $p+d \rightarrow p+p+n$. Evidence for final state interaction of a pair of protons was reported to be present in another reaction namely $^3He(p,pd)p$ (17).

By only changing the particle identification we were able to observe neutron-proton coincidences for the same kinematical conditions. Fig. 7 shows a map display (energy of the proton E_p versus time of flight of the neutron τ_n) of the experimental data. The angle for the neutron detector was chosen to be $\theta_3=48.3^o$.

This fixes the proton angle to $\theta_4=22.4^o$ if one wants the relative energy between the two protons to become zero along the kinematical curve. The angular resolutions of the detectors were $\Delta\theta_3=\pm1.8^o$ and $\Delta\theta_4=\pm0.5^o$ respectively.

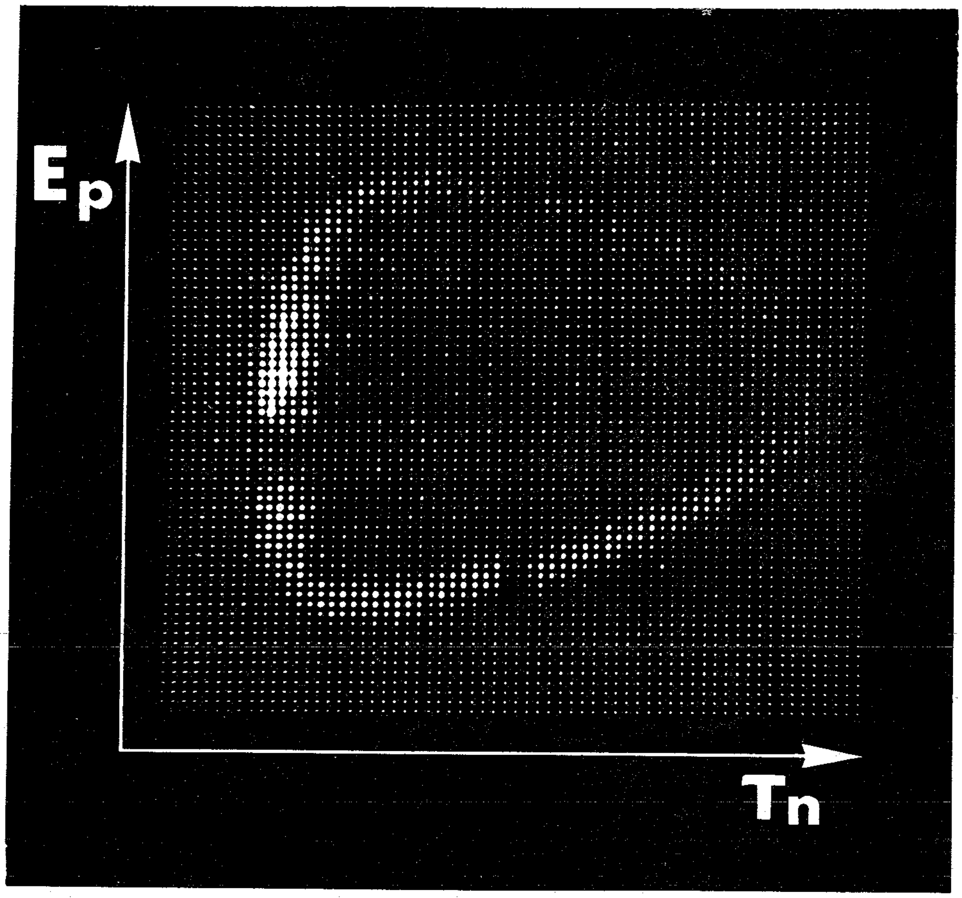

Fig. 7 Example of a map display of the experimental data taken with the aim to observe the p-p final state interaction. For this purpose neutrons (θ_n=48,3°) and protons (θ_p=22,4°) were detected in coincidence. The coincidence events are shown in the plane of the proton energy E_p versus the neutron time-of-flight τ_n.

The true n-p coincidences are located on the kinematically allowed curve E_p=f(τ_n). A pronounced minimum appears at the point where the relative energy between the two protons is zero. The characteristic feature in the measured energy dependence of the cross section is a very low value at zero relative energy in the p-p system.

The experimental data for p-p and p-n final state interaction are shown in fig. 8 for comparison.

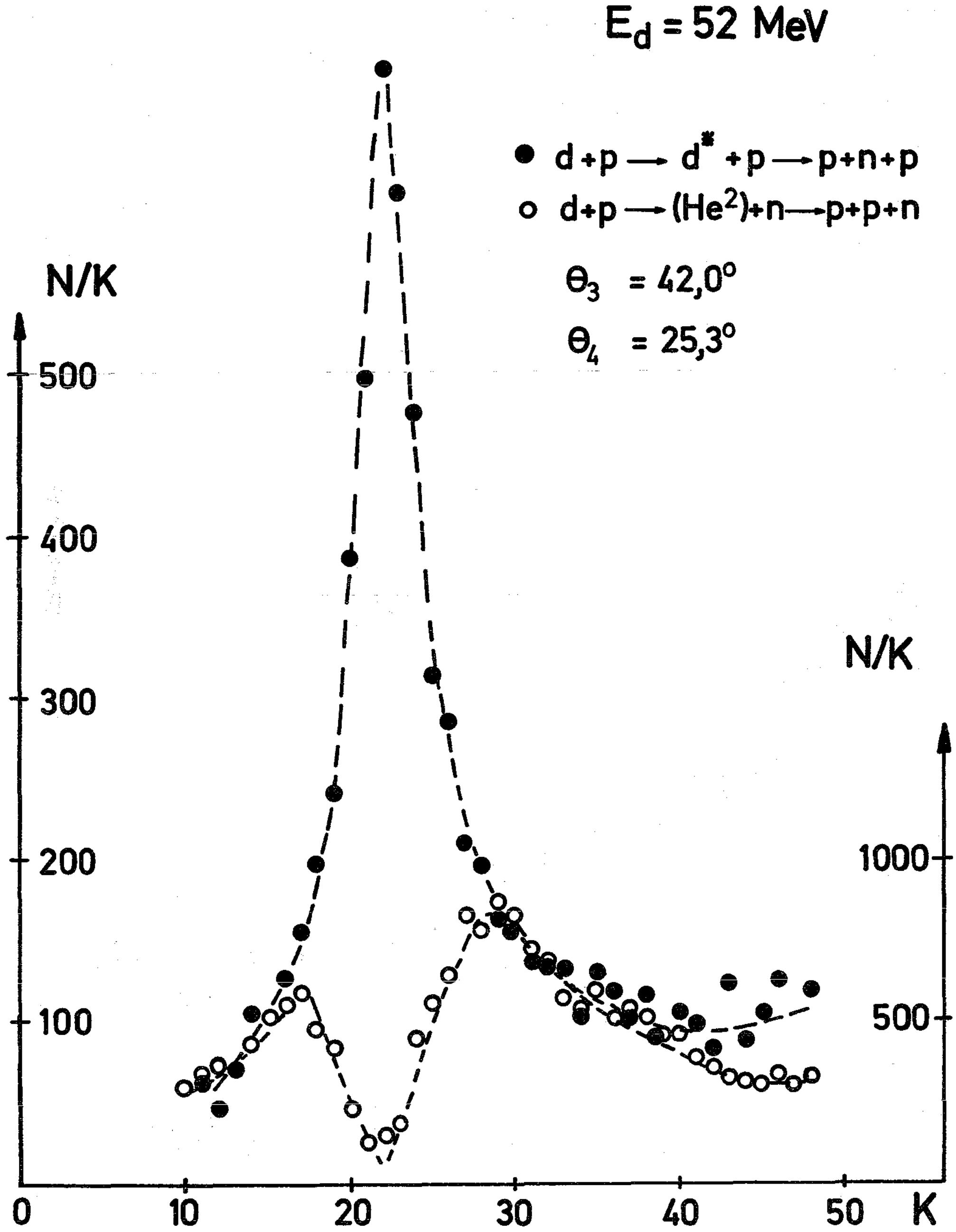

Fig. 8 Comparison of the p-n final state interaction (solid dots, left side ordinate) and the p-p final state interaction (circles, right side ordinate) at identical kinematical conditions.

The results show marked differences in the energy dependence of the cross sections. Contrary to the narrow peak of n-p final state interaction the proton-proton final state interaction shows a pronounced minimum at the relative energy E_{pp}=0 keV. The difference between the shape of the two spectra arises from interference between Coulomb and nuclear forces in the case of p-p final state interaction. Fig. 9 shows the experimental data for p-p final state interaction divided by the phase factor as a function of the energy E_{pp} of the two protons in their c.m. system.

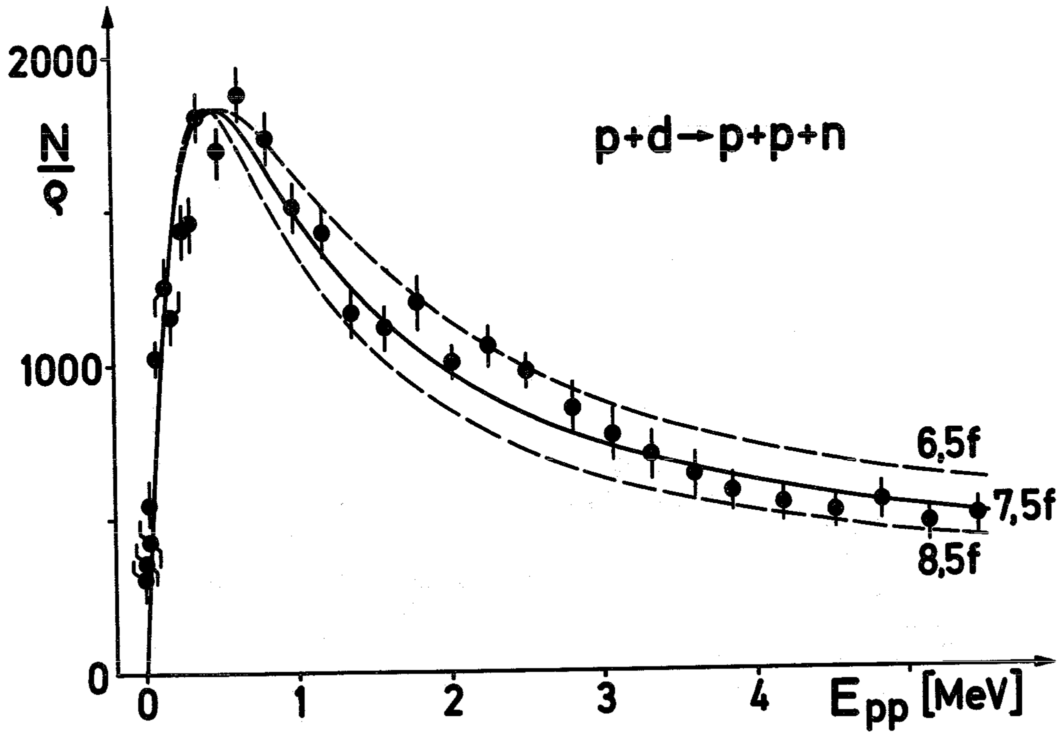

Fig. 9 The number of observed coincidence events divided by the phase space factor ρ is plotted versus the relative energy E_{pp} in the p-p system. Curves calculated with a modified Migdal-Watson theory and using effective range approximation are shown for different p-p scattering lengths.

The data are compared with calculations based on the Watson-Migdal model using the effective range approximation. The calculated enhancement factor is

$$F_{pp} = \frac{\left(\frac{1}{r_o} - \frac{1}{a} + \frac{1}{2}r_o k^2 + \frac{1}{R}\left(\ln\frac{r_o}{R} + 2\gamma - 1\right)\right)^2}{C^2(\eta)k^2 + \frac{1}{C^2(\eta)}\left(-\frac{1}{a} + \frac{1}{2}r_o k^2 - \frac{h(\eta)}{R}\right)^2}$$

r_o is the effective range and a the scattering length for p-p scattering. $k=(M\,E_{pp}/\hbar^2)^{1/2}$ with M the proton mass. The value of R is given by $R = \hbar^2/Me^2$, $C^2(\eta) = 2\pi\eta/(e^{2\pi\eta}-1)$ with $\eta=(2kR)^{-1}$.
$h(\eta)$ is a function as evaluated by Jackson and Blatt (14).
γ=Euler's constant.

According to Phillips (13) at low energies the k-dependence of the transition matrix element is given by the S-wave function ψ_{2p} of the two protons

$$\psi_{2p} = e^{-i\delta_o}(F_o \cos\delta_o + G_o \sin\delta_o)/kr$$

δ_o is the S-phase shift of p-p scattering. F_o and G_o are the regular and irregular Coulomb wave functions which are used in the following expansion:

$$F_o = C(\eta)\cdot kr$$

$$G_o = \frac{1}{C(\eta)}\left(1 + \frac{r}{R}\left(\ln\frac{r}{R} + h(\eta) + 2\gamma - 1\right)\right)$$

Using the effective range formula for p-p scattering and inserting $r=r_o$ one finds the enhancement factor F_{pp} mentioned above.

The scattering length extracted from the experimental data shown in fig. 8 was influenced appreciably by taking into account the higher order terms of the Coulomb wave function G_o. The analysis results in a p-p scattering length $a_{pp} = -(7.5\pm0.5)$ f which is to be compared with the value $a_{pp} = -(7.69\pm0.01)$ f obtained by the free p-p scattering.

The very remarkable results are based on the assumption of the production of a p-p system in a pure S-state. It should be mentioned that in the case of free p-p scattering higher angular momenta have to be taken into account because of the long range of the Coulomb force. The production of S-state proton pairs seems to be the predominant feature of the investigated three particle reaction $p+d \rightarrow p+p+n$.

A measurement of the angular distribution of the two protons in their c.m. system would yield the angular momentum contributions. The consequence of a pure S-state would be an isotropic angular distribution. For this purpose additional coincidence measurements were carried out at suitable pairs of angles. Fig. 10 shows the corresponding map displays of the experimental data. The detailed discussion will be covered in a separate paper.

Finally the investigation of the four nucleon reaction $d+d \rightarrow d+p+n$ is expected to bring more insight into the three-nucleon problem. In this peculiar reaction excited states of three nucleon systems might be explored by d-p or d-n final state interaction.

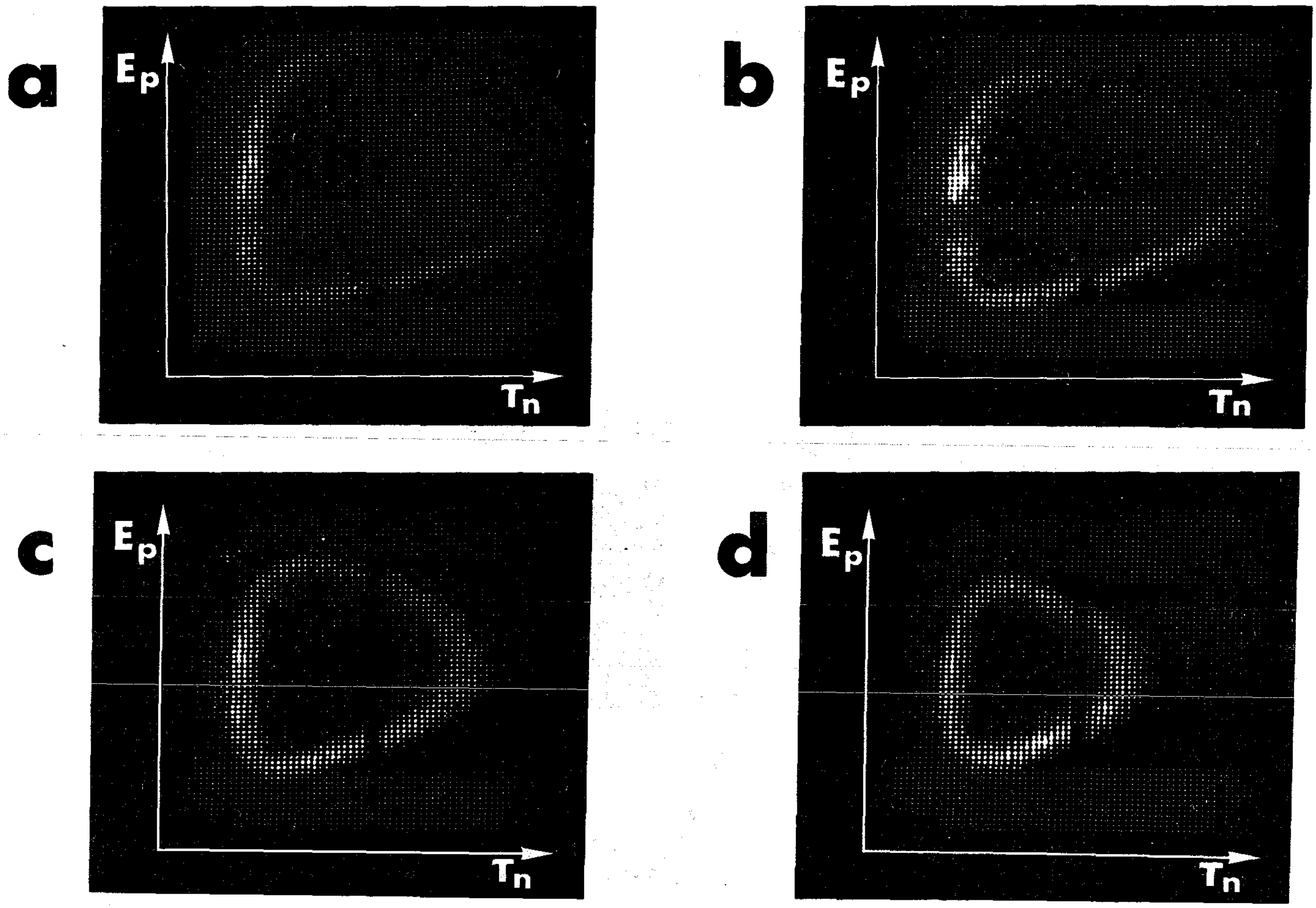

Fig. 10 Measurements of neutron-proton coincidences at different pairs of angles in the reaction p+d→p+p+n. The neutrons were detected at a fixed angle of θ_n=48,3°. The proton angles were 19,5° (map display a), 22,4° (b), 25,5° (c) and 28,3° (d). Notation same as in fig. 7.

Fig. 11 shows a map display for p-d coincidences and the projection of the coincidence events onto the E_d axis. The main peak of the spectrum is caused by quasielastic p-d scattering while the smaller peak is probably due to a p-d resonance corresponding to an excited state in ^3He with an energy of 14 MeV.

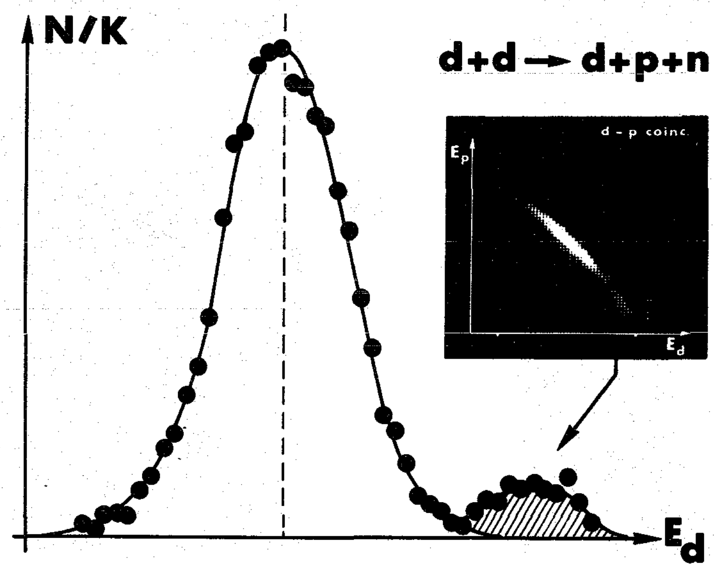

Fig. 11 Example for the observation of proton-deuteron coincidences in the reaction d+d→d+p+n (proton angle $\theta_p=40^o$ and deuteron angle $\theta_d=26^o$). The main peak is due to quasielastic p-d scattering. The hatched area shows clearly the contribution of an additional interaction. Interpretation as a p-d final state interaction leads to an exited state in ^3He at 14 MeV.

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