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Investigation of Proton Proton Scattering by Observation of p-p Final State Interaction in the Reaction $d+p \rightarrow n+p+p$

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Investigation of proton-proton scattering by observation of p-p final state interaction in the reaction d + p → n + p + p

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Abstract

The three nucleon reaction p+d$\rightarrow$p+p+n has been investigated at a deuteron bombarding energy of 52.3 MeV. A kinematically complete experiment was carried out with the aim to observe the proton-proton final-state interaction. Contrary to the narrow peak of neutron-proton final-state interaction the proton-proton final-state interaction shows a pronounced minimum at the zero relative energy. For the proton-proton scattering length a value of $a_{pp}=(-7.5 \pm 0.5)$fm is obtained. The Watson-Migdal model and the effective range approximation were used for the analysis and animproved enhancement factor was calculated.

Up to now a great part of our knowledge of nuclear forces, their charge symmetry and their charge independence has been deduced from experimental investigations of free nucleon-nucleon scattering. In the low energy region the energy dependence of nucleon-nucleon scattering is mainly determined by two fundamental parameters the scattering length and the effective range. For n-p scattering the experimental data being necessary to determine these parameters are available down to zero energy, whereas free p-p scattering experiments are so difficult at low energies that data are only available for energies above 300 keV. In contrast to this situation p-p forces can be studied in three body reactions at relative energies down to zero by investigating the p-p final state interaction [FSI].

Exactly valid theoretical descriptions of three body systems were given for instance by Faddeev [1], Amado et.al. [2], and Sandhas et.al. [3]. Nevertheless more effort has to be concentrated on numerical calculations which can be directly compared with experimental results.

Simplified models like Watson's approximation [4] are presently in use to extract nucleon-nucleon scattering parameters from the observation of FSI. The reliability of this approximation was carefully checked in the case of neutron-proton FSI. Quite satisfactory results were obtained for the n-p scattering length [5, 6]. Encouraged by these results the simplest three body reaction which allows the investigation of a p-p final state interaction was studied.
This is the reaction $p+d \rightarrow p+p+n$.

In order to obtain the full information of a three body reaction two of the outgoing three particles have to be detected in coincidence. In the reaction $p+d \rightarrow p+p+n$ protons have to be detected in coincidence with neutrons to observe p-p FSI down to zero relative energy. So far such coincidence measurements have not been reported. Up to now the p-p FSI was investigated by kinematically complete experiments only in the reactions $^3He(p, pd)p$ and $^3He(^3He, pp)^4He$ [see for instance 7, 8].

These reactions involve more than three nucleons and the interpretations must account for a larger number of reaction mechanisms.

In kinematical regions where the final state interaction between two protons dominates the reaction $p+d \to p+p+n$ can be taken as a two step process. The graph is shown in fig. 1. In the first step a p-p-system is created with low internal energy. The angular momentum distribution in this system is only determined by the primary break-up reaction and therefore it is expected to be quite different from the initial distribution in a free p-p-system at low energies. The second step takes the p-p FSI into account.

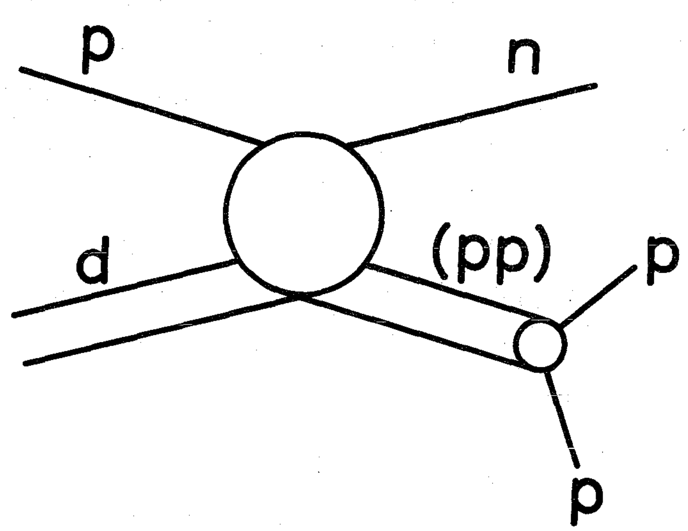

Fig. 1 Graph of the reaction $p+d \to p+p+n$. Only the two step mechanism leading to the p-p final state interaction has been drawn.

A polyethylene target was bombarded with 52.3 MeV deuterons from the Karlsruhe isochronous cyclotron. One of the two protons and the neutron were detected in coincidence. The proton was registered in a NaJ scintillation detector, for the detection of the neutron a plastic scintillator was used. The experimental set-up was the same as for the investigation of the n-p FSI, details are described in [6]. Each coincidence event was characterized by both the energies and the times of flight of the two particles. These four independent parameters were transferred to a CDC 3100 computer using a new four dimensional data acquisition system developed at Karlsruhe [9]. The knowledge of energies and times of flight for each coincidence event allows the particle identification to be made by computer analysis.

The angle for the neutron detector was chosen to be $\theta_3 = 42^o$. This fixes the proton angle to $\theta_4 = 25.3^o$ if one wants the relative energy between the two protons to become zero along the kinematically allowed curve. The angular resolutions of the detectors were $\Delta\theta_3 = \pm 1.8^o$ and $\Delta\theta_4 = \pm 0.5^o$ respectively. Fig. 2 shows a map display of the experimental data in an array of 64 × 64 channels (energy of the proton E_p versus time of flight of the neutron τ_n). The true n-p coincidences are located on the closed curve $E_p = f(\tau_n)$ given by the kinematics of the reaction. A pronounced minimum appears at the point where the relative energy between the two protons is zero. The distribution of events on the kinematical curve of fig. 2 was projected onto the E_p-axis. The result is shown in fig. 3 in comparison with data for n-p FSI.

The p-p FSI and the n-p FSI respectively have been observed at identical kinematical conditions by only changing the particle identification. The observer might regard this change in the particle identification as aquivalent to "switching on" the Coulomb force.

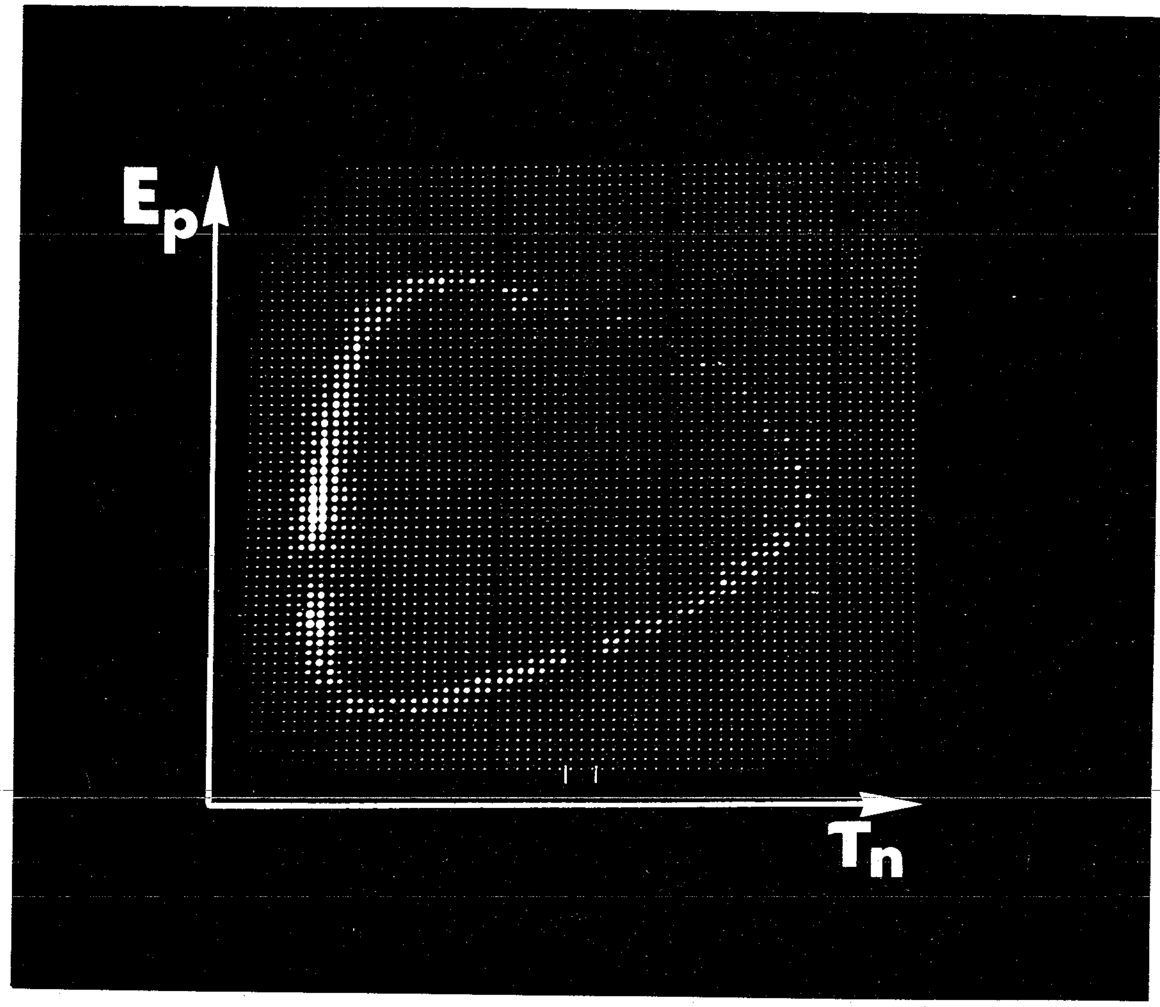

Fig. 2 Map display of the experimental data of the reaction p+d →p+p+n. Neutrons were detected in coincidence with protons. The angles were $\theta_n = 42.0^o$ and $\theta_p = 25.3^o$. E_p is the proton energy and τ_n is the neutron time-of-flight (the gap in the center of the τ_n-axis is caused by the use of two time-of-flight circuits).

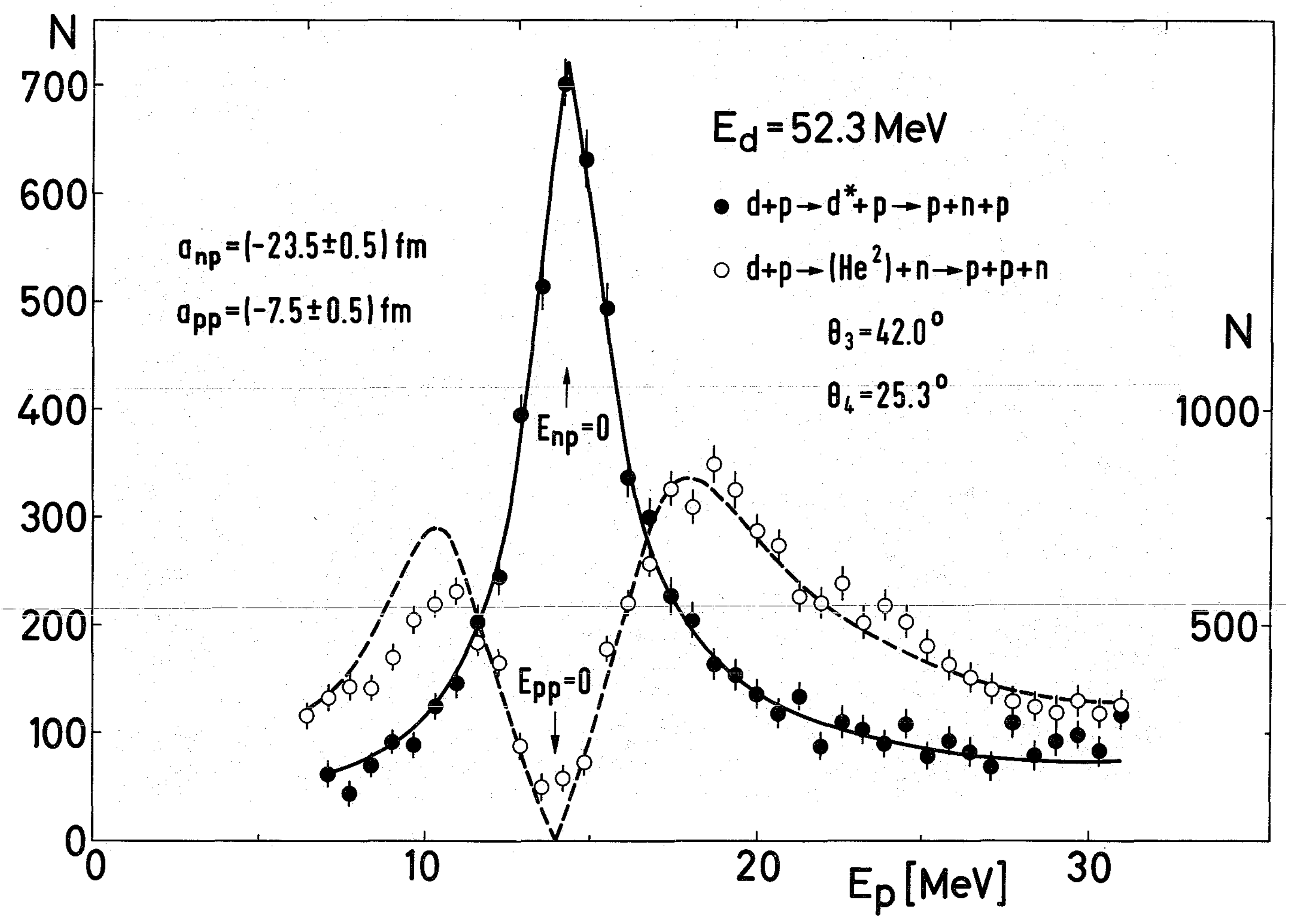

Fig. 3 Comparison of the p-n FSI data (solid dots, left side ordinate) and the p-p FSI data (circles, right side ordinate) at identical kinematical conditions. A least square fit with equation (1) results in a_{pp} = -(7,5 ± 0,5)f. a_{np} was determined from these data to be -(23,5 ± 0,5)f [6b].

The results show marked differences in the energy dependence of the cross-sections. Contrary to the narrow peak of n-p FSI the proton-proton FSI shows a pronounced minimum at the relative energy E_{pp} = 0 keV. Responsible for the shape-difference of the two spectra is the addition of the Coulomb forces and the interference with the nuclear forces. Fig. 4 shows the p-p FSI data of fig. 3 as a function of the energy E_{pp} of the two protons in their C.M. system. The data have been divided by the phase space factor. Calculations based on the Watson-Migdal model and the effective range approximation are used to analyse the data [4].

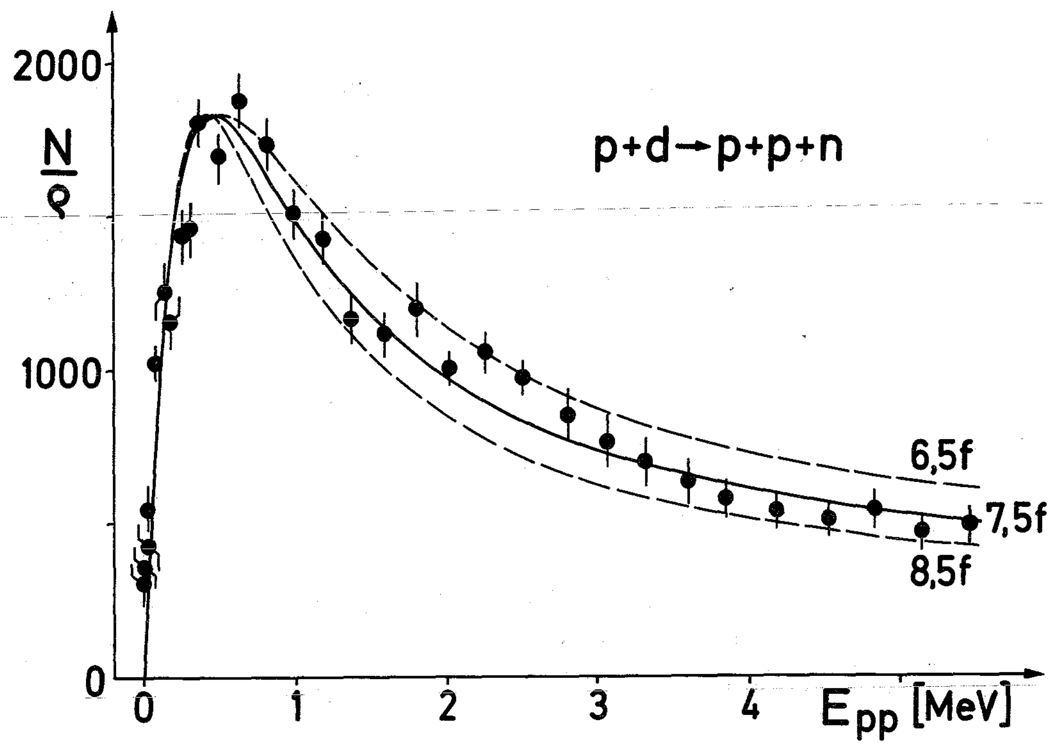

Fig. 4 The number of observed coincidence events divided by the phase space factor ϱ is plotted versus the relative energy E_{pp} in the p-p system. Curves calculated with equation (1) are shown for different p-p scattering lengths.

The calculated enhancement factor is

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

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 [10]

γ is Euler's constant.

According to Phillips [11] the k-dependence of the transition matrix element is given at low energies 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:

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

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

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. 4 was influenced appreciably by taking into account the higher order terms of the Coulomb function G_o. The analysis results in a p-p scattering length of $a_{pp} = -(7.5 \pm 0.5)$ f which is to compared with the value $a_{pp} = -(7.69 \pm 0.01)$ f obtained by the free p-p scattering [12]. The dotted curve in fig. 3 shows the result of the calculation based on the enhancement factor of equation (1) with $a_{pp} = -7.5$ f and including the phase space factor ρ. In contrast to free p-p scattering the production of S-state proton pairs seems to be at the chosen kinematical condition the predominant feature of the investigated three particle reaction.

The predominant production of S-state proton pairs might be confirmed by an experiment which shows directly the contribution of higher angular momenta. Measurements of the angular distribution of the two protons in their center of mass system were carried out. If only a pure S-state contributes an isotropic angular distribution would be expected. The analysis of this data has not yet been finished.

The comparison of the experimental p-p FSI data with the calculated curve of fig. 3 shows a slight discrepancy at low proton energies. Two higher order effects might cause a divergence from the predictions given by the Watson-Migdal model.

Firstly a constant matrixelement was used in the first step of the reaction. This assumption is allowed only as long as the emission angle of the p-p compound stays constant. A detailed discussion however shows a slight variation of this angle along the used part of the kinematically allowed curve. In other experiments a variation of the differential cross section has been found for the first step of the reaction [13].

Secondly the spectator effects might interfere with the two step reaction mechanism. From fig. 2 can be seen that this influence will mainly occur at low proton energies.

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