KERNFORSCHUNGSZENTRUM

KARLSRUHE

Juni 1967 KFK 608

Institut für Experimentelle Kernphysik

Experimental Investigations of the Reactions H(d, 2p)n and D(d, dp)n with 50 MeV Deuterons

H. Brückmann, W. Kluge, L. Schänzler

GESELLSCHAFT FÜR KERNFORSCHUNG M. B. H.

KARLSRUHE

GESELLSCHAFT FÜR KERNFORSCHUNG M.B.H.
KARLSRUHE

KERNFORSCHUNGSZENTRUM KARLSRUHE

July 1967 KFK 608

Institut für Experimentelle Kernphysik

Experimental investigations of the reactions p(d,pp)n and d(d,dp)n with 50 MeV deuterons

H. Brückmann, W. Kluge, L. Schänzler

Gesellschaft für Kernforschung m.b.H. Karlsruhe

Paper presented at the Symposium on Light Nuclei, Few-Body-Problems and Nuclear Forces, Brela, Yugoslavia, June 26 - July 5, 1967

Abstract

A collimated beam of 51.5 MeV deuterons from the Karlsruhe isochronous cyclotron was used to investigate the three particle reactions $p + d \rightarrow n + p + p$ and $d + d \rightarrow d + p + n$. The two emitted protons or the proton and the deuteron, respectively, were detected in coincidence with two scintillation counters.

The experimental data for the reaction p(d,pp)n exhibit a pronounced peak due to final state interaction between the outgoing neutron and one proton (the proton angles were chosen to be $\Theta_{lab} = 40^{\circ}$ and $\Theta_{lab} = 25^{\circ}$ accordingly). The analysis shows that this final state interaction is dominated by the virtual singulet state of the deuteron. The extracted n-p scattering length is $|a_s| = (19 \pm 2.5)$f.

In the investigation of the reaction d(d,dp)n the angles were chosen so as to observe predominantly the process where the neutron in the target deuteron acts as a 'spectator' particle. The analysis in terms of the Chew-Low extrapolation procedure yields a straight line intersecting the E_n-axis at $-(0.95 \pm 0.15)$ MeV (E_n, energy of the spectator neutron). The extrapolated d-p cross section is (14 ± 5) mb/sr. The value obtained from an independent measurement of elastic deuteron-proton scattering is (32 ± 3) mb/sr.

The experimental investigation of two of the simplest three particle reactions namely the reactions $p + d \rightarrow n + p + p$ and $d + d \rightarrow d + p + n$ is of great interest from two different points of view:

a) The general understanding of reactions with three particles in the exit channel requires more detailed experimental data on these reactions.

b) The corresponding reaction $n + d \rightarrow n + n + p$ involving two outgoing neutrons is one of the main tools to provide information about the neutron-neutron force. However the needed connection between a two particle interaction and the results which con be obtained from a three particle reaction can only be checked experimentally in those cases, where the two particle interaction is known from an independent experiment. The mentioned reactions $p + d \rightarrow n + p + p$ and $d + d \rightarrow d + p + n$ are well suited to this basic task.

The experimental results published hitherto for these reactions provide evidence of three different reaction models to be taken into account [1 - 8]:

1) The three nucleons populate the available phase space statistically.
2) The process can be treated as a quasifree scattering between two particles; one nucleon acts only as a 'spectator'.
3) A final state interaction between two nucleons characterises the reaction.

The experimental conditions for our investigations were selected in such a way that we observed predominantly a neutron - proton final state interaction in the reaction $p + d \rightarrow n + p + p$. In the second reaction $d + d \rightarrow d + p + n$ the parameters were chosen to study predominantly a quasifree deuteron-proton scattering.

A collimated beam of 51.5 MeV deuterons from the Karlsruhe isochronous cyclotron was used to bombard a gas target filled with hydrogen or deuterium. The two emitted protons or the proton and the deuteron were detected in coincidence with two scintillation counters. The angles with respect to the beam axis were Θ_3 and Θ_4 (Fig. 1).

The momentum $\vec{P}_3$ and $\vec{P}_4$ of the outgoing particles was coplanar with the momentum $\vec{P}_1$ of the projectile deuteron. The energies of two particles (E_3 and E_4) are registered, and each event is thus kinematically completely defined. The energy and the direction of the third particle (the neutron) as well as the relative energies between two outgoing particles are calculated.
Large distances between the target and the detector (L_3 = 70 cm, L_4 = 92 cm) allowed a particle identification by using time-of-flight technique [9]. These large distances were also convenient to achieve the necessary small resolution of $\Delta\Theta_4 = \pm 0.5^{\circ}$ and $\Delta\Theta_3 = \pm 0.75^{\circ}$. The coincident events were registered in a two dimensional 4096 channel analyser.

Final state interaction in the reaction $p + d \rightarrow n + p + p$

The requirement for a study of the neutron-proton final state interaction is that one wants E_{45} (the relative energy between one proton and the neutron) to become zero along the kinematically allowed curve $E_4 = f(E_3)$. For our experiment this condition fixed Θ_4 to 25° after Θ_3 had been chosen to be 40° in the laboratory system. The point, where E_{45} is zero corresponds to the maximum allowed value of E_3.

Fig. 2 shows on the left a map display of the experimental data with E_3 as abscissa and E_4 as ordinate in an array of 32 x 128 channels. Most of the registered events populate the kinematically allowed curve $E_4 = f(E_3)$. A distinct peak appears in the region where E_3 reaches its maximum allowed value. This peak is assigned to a final state interaction between one outgoing proton and the neutron. The right hand side of Fig. 1 shows the projection onto the E_4 axis. For comparison the full line represents the normalized phase space.

The aim of the following interpretation of the experimental results is to achieve more insight into the n-p final state interaction. The analysis of these data should directly show the S-matrix pole of the deuteron singulet state. One should also be able to compare three particle results with values obtained from the corresponding two particle reaction, namely the free n-p scattering.

The cross section for the 3 particle reaction may be written as

$$\frac{d^3\sigma}{d\Omega_3 \, d\Omega_4 \, dE_4} = \varrho\,(\Theta_3, \Theta_4, E_4) \cdot \sum_{SI} |M_{SI}|^2 \cdot g_{SI} \quad (1)$$

where I is the channel spin and S the total spin of the two particles experiencing the final state interaction, and g_{SI} and $\varrho\,(\Theta_3, \Theta_4, E_4)$ are the statistical factors due to spin and space respectively.

The contribution of the virtual singulet deuteron state to be final state interaction can now be described by writing $|M_{0\frac{1}{2}}|^2$ as

$$|M_{0\frac{1}{2}}|^2 = \left| A + \frac{B}{k + i\varkappa_s} \right|^2 \quad (2)$$

Here, k is the internal momentum within the n-p system and $-i\varkappa_s$ characterizes the position of the pole of the S-matrix (see, for instance, Watson [10]).

In order to check the pole character of the matrix element it is convenient to plot the quantity $\frac{1}{(N/PSF)-1}$ versus the relative energy E_{np}. N is the number of counts per dE_4 interval. The phase space factor PSF is proportional to $\varrho(\Theta_3, \Theta_4, E_4)$ and is normalized to the experimental data.

Fig. 3 shows such a plot for our experimental data. Within the statistical errors the plotted points are represented fairly well by a straight line intersecting the abscissa at $E_o = -\frac{\hbar^2 \cdot \varkappa^2}{2m}$. The value obtained for E_o is $E_o = -(120 \pm 30)$ KeV. This would correspond to a scattering length of $|a_s| = (19 \pm 2.5)$f. This value, obtained from the investigation of the n-p final state interaction, may be compared with the scattering length known from the n-p singulet cross section which is $a_s = -(23.73 \pm 0.007)$f.

The following conclusions can be drawn from our experiment:

1) The final state interaction as observed in our experiment is dominated by the virtual singulet state of the deuteron.

2) The extracted scattering length a_s appears to be smaller than the value known from the n-p cross section. If this result will be confirmed by an experiment with improved statistics it might be explained by an influence of the triplet bound state or by an interference effect. Only a part of this interference between the A and B term of equation (2) has the same E dependence as the pure B term.

<u>Quasielastic scattering in the reaction $d + d \rightarrow d + p + n$</u>

A quasielastic scattering process where one particle acts only as a 'spectator' particle can be observed in the laboratory system in two different ways. Either the 'spectator' is part of the projectile nucleus ('projectile spectator') or it is part of the target nucleus ('target spectator'). The difference arises only because two detectors have to be used at fixed positions in the laboratory. This can be outlined in a discussion of two examples. The neutron in a deuteron is assumed to act as a spectator particle in both examples.

In the reaction $d + p \rightarrow n + p + p$ the neutron acts as a projectile spectator, if this reaction is induced by accelerated deuteron. The spectator neutron will carry away about half the primary energy and the two coincident protons will be found in the lab.system under angles where $(\Theta_3 + \Theta_4)$ is near 90^o. For such combinations of angles the kinematically allowed curve contracts to a very small circle and finally becomes a point. The spectator peak is always located in the corner of low E_3 and E_4 values. This situation is not favourable to the study of the quasielastic scattering process. Fig. 4 shows an experimental result for this example. Deuterons with an energy of 51.5 MeV were used to bombard a hydrogen target. The angles of the two proton counters have been $\Theta_3 = 40^o$ and $\Theta_4 = 40^o$.

On the other hand a 'target spectator' neutron is considered. There the neutron is left over with only its internal momentum distribution from the deuteron and almost the total energy is available for the two particles to be detected in coincidence. The spectator peak will be located in the neighbourhood of the line $E_3 + E_4 = E_1 - E_B$, (E_B is the binding energy of the deuteron). This configuration should be preferred of one wants to investigate mainly effects of quasielastic scattering. Fig. 5 shows our experimental result for the reaction $d + d \rightarrow d + p + n$. A broad 'target spectator' peak is clearly visible. The angles were chosen so that the neutron energy E_5 reaches down to zero along the kinematically allowed curve ($\Theta_3 = 40^o$, $\Theta_4 = 25^o$)
A projection of the data onto the E_4 axis is shown on the right of Fig. 5. The dashed curve represents the normalized phase space.

For analysis the Chew-Low theory [11,5] was used. Within the assumption of this theory the three particle cross section for a pure spectator mechanism can be written as

$$\frac{d^3\sigma}{d\Omega_3\, d\Omega_4\, dE_4} = C \cdot \varrho\,(E_4) \cdot |< p_1, -p_5 | V | p_3, p_4 >|^2 \cdot \frac{1}{(E_5 + E_B/2)^2} \qquad (3)$$

where the phase space factor is labelled $\varrho\,(E_4)$ and C is a constant containing the masses, the initial momentum, and the normalization factor of the deuteron wave function. The matrix element

$$|f|^2 = |< p_1, -p_5 | V | p_3, p_4 >|^2$$

represents a multiple of the free elastic deuteron-proton scattering only at the position of the pole where E_5 is $E_5 = P_5^2/2\,m_5 = -\,E_B/2$ (indices according to Fig.1). It should be noticed that a measurement of the three particle cross section at the pole can never be realized experimentally, because the spectator energy E_5 would have to be negative at this point. The fourth factor in this expression results from the internal momentum distribution within the deuteron. Here E_B denotes the binding energy of the deuteron.

In the comparison of our experimental result with the theoretical predictions two aspects were regarded. In a first step only a test for the pole character was carried out. For this purpose it is convenient to plot the quantity $\sqrt{\frac{PSF}{N}}$ versus the spectator energy E_n. Here N denotes the number of events registered per channel and PSF is the normalized phase space factor. A pure pole character as predicted in formula (3) would result in a straight line intersecting the E_n axis at -1.1 MeV.

Fig. 6 shows our data plotted for the test of the pole character. Within statistics the points are located on a line crossing the axis at $-(0.95 \pm 0.15)$ MeV. It can be concluded, that the shape of the three particle cross section is dominated by the pole term which is caused by the internal momentum distribution in the deuteron.

The second aspect in the interpretation aims at extracting the elastic deuteron-proton cross section from the measured three particle cross section. As was outlined before, an extrapolation procedure has to be used to evaluate the matrix element $|f|^2$ at the unphysical point, where E_n is equal to $-E_B/2$. For this analysis we assumed that the pole term of equation (3) is exactly valid and we are able then to plot the quantity $|f|^2$ as a function of E_n. The dashed curve in Fig. 5 proportional to the phase space factor was assumed to be a background which can be subtracted. The obtained plot $|f|^2$ in units of mb/sr versus E_n is shown in Fig. 7. The points denote numbers from the lower half and the crosses numbers from the upper half of the experimental curve N versus E_4. Only a few points are labeled with the statistical errors. As can be seen, most of the plotted values can be represented by a straight line. Only the points at high neutron energy E_n which are marked with crosses do not fit this line. The reason for this discrepancy might be a final state interaction between the deuteron and the proton which increases the counting rate at these high values of E_4. (Additional events in the same energy region were observed clearly in a separate experiment, where other angles were used). For the extrapolation into the unphysical region the straight line is used and this yields a value of (14 ± 1) mb/sr for the free elastic proton-deuteron cross section.
The error contains only the statistical uncertainty.
The absolute accuracy is estimated to be $\pm$ 5 mb/sr.

By using this matrix element $|f|^2$ as a linear function of E_n this interpretation describes the shape of the spectator peak as shown for comparison in the lower part of Fig. 7. Significant deviations are only seen in the region of high E_4 values where another mechanism contributes to the cross section.

To compare the d-p cross section extracted from the three particle reaction with a value obtained from free deuteron-proton scattering the d-p differential cross section was measured separately. The result is shown in Fig. 8. From this measurement a value of (32 ± 3) mb/sr is obtained for the angles used in the coincidence experiment. The comparison shows that these results differ by a factor of about two. For an explanation of this difference more experimental data are needed and the extrapolation procedure has to be examined in detail.

In the course of a further study of simple three particle reactions we plan to repeat the experiments described. The aim is to obtain much better statistics and to check all quantities which have an influence on the absolute calibration of the three particle cross section. The investigation of the neutron-neutron interaction in reactions like $n + d \rightarrow n + n + p$ will follow after experience has been gathered with reactions involving only the n-p interaction.

References

1) W.D. Simpson, J.D. Bronson, W.R. Jackson, G.C. Philips, Rev. Mod. Phys. 37, 523, (1965)

2) P.F. Donovan, Rev. Mod. Phys. 37, 501, (1965)

3) I. Šlaus, J.W. Verba, J.R. Richardson, R.F. Carlson, L.S. August, Phys. Lett. 23, 358, (1966)

4) R.J. Griffiths, K.M. Knight, Nucl. Phys. 54, 56, (1964)

5) A.F. Kuckes, R. Wilson, P.F. Cooper, Ann. Phys. 15, 193, (1961)

6) R.F. Carlson, Rev. Mod. Phys. 37, 531, (1965)

7) W.D. Simpson, Ph.D. Thesis, Rice University Houston, Texas 1965

8) H. Brückmann, W. Kluge, L. Schänzler, Phys. Lett. 24B, 649, (1967)

9) H. Brückmann, Habilitationsschrift Technische Hochschule Karlsruhe 1966

   H. Brückmann, E.L. Haase, W. Kluge, L. Schänzler (to be published)

10) K.M. Watson, Phys. Rev. 88, 1163, (1952)

11) G.F. Chew, F.E. Low, Phys. Rev. 113, 1640, (1959)

Captions of figures

Fig. 1:

Schematic drawing of the experimental arrangement. Coincidences between the two detector output signals are registered.

Fig. 2:

Experimental data for the reaction p + d → n + p + p. A map display for the two protons (with energies E_3 and E_4) registered in coincidence is shown on the left. The data projected onto the E_4 axis and the normalized phase space factor are shown on the right.

Fig. 3:

Analysis of the pole character of the final state interaction peak. The straight line intersects the abszissa at $E_{np} = -(120 \pm 30)$ KeV.

Fig. 4:

Experimental data for the reaction p + d → n + p + p. Map display of events where two reaction products were registered in coincidence (with energies E_3 and E_4). The proton-proton coincidences are populating a small circle. On this circle a projectile spectator peak can be seen. The angles were $\Theta_3 = 40^\circ$ and $\Theta_4 = 40^\circ$.

Fig. 5:

Data for the reaction d + d → d + p + n. The map display shows proton-deuteron coincidences. Here E_4 denotes the deuteron energy and E_3 the proton energy. The data projected onto the E_4 axis and the normalized phase space factor are shown on the right.

Fig. 6:

Chew-Low plot for the data shown in Fig. 5. The straight line fit intersects the E_n-axis at $E_n = -(0.95 \pm 0.15)$ MeV.

Fig. 7:

The upper part shows the matrix element $|f|^2$ plotted versus the neutron spectator energy E_n. A straight line extrapolation to $E_n = -1.1$ MeV yields (14 ± 1) mb/sr for the differential cross section in elastic deuteron-proton scattering. In the lower part the shape of the spectator peak resulting from this fit is compared with the experimental data shown in Fig. 5.

Fig. 8:

Differential cross section for elastic deuteron-proton scattering.

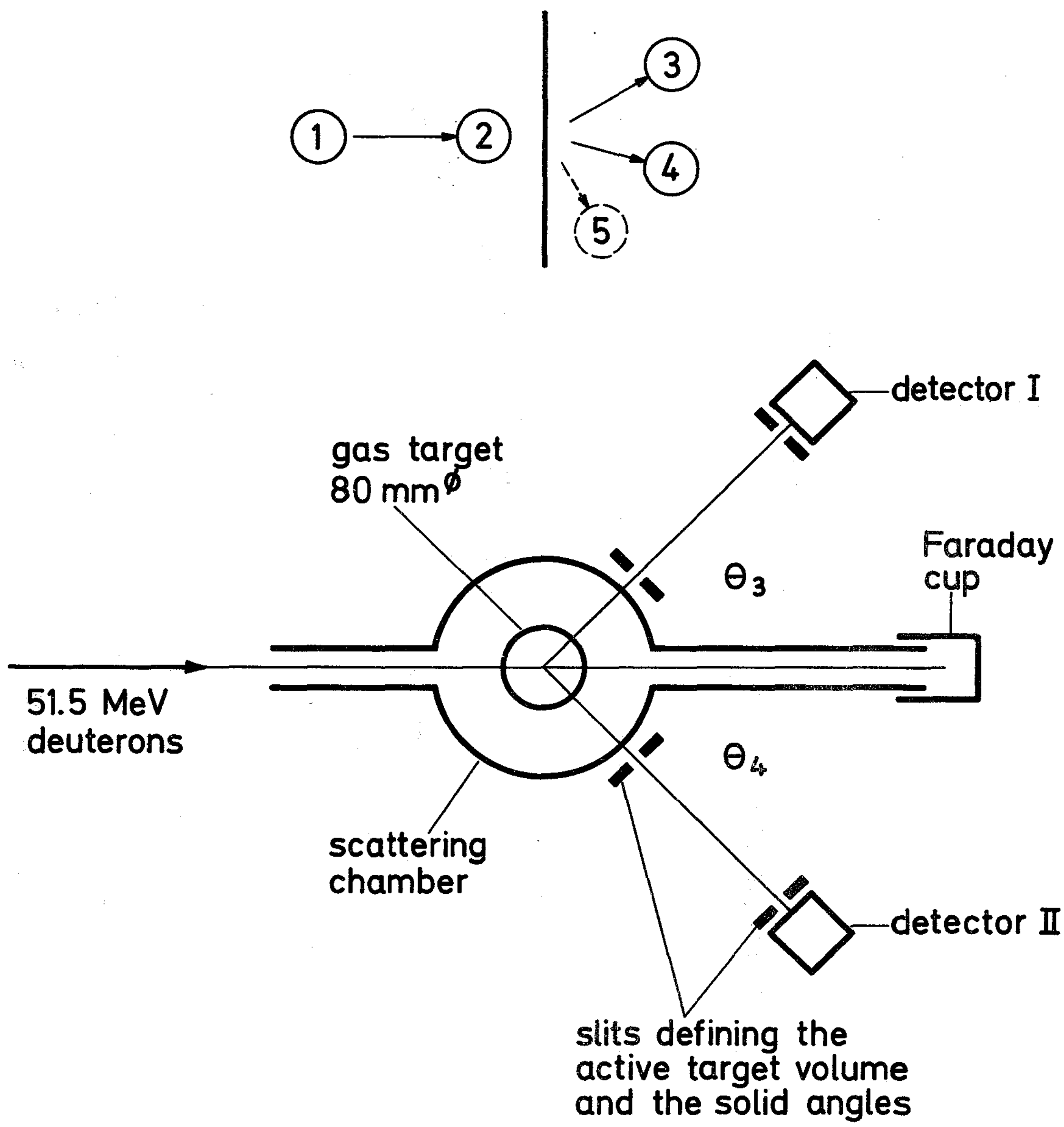

1
2
3
4
5
detector I
gas target
80 mm$^{\phi}$
Faraday
cup
Θ_3
51.5 MeV
deuterons
Θ_4
scattering
chamber
detector II
slits defining the
active target volume
and the solid angles

Fig. 1

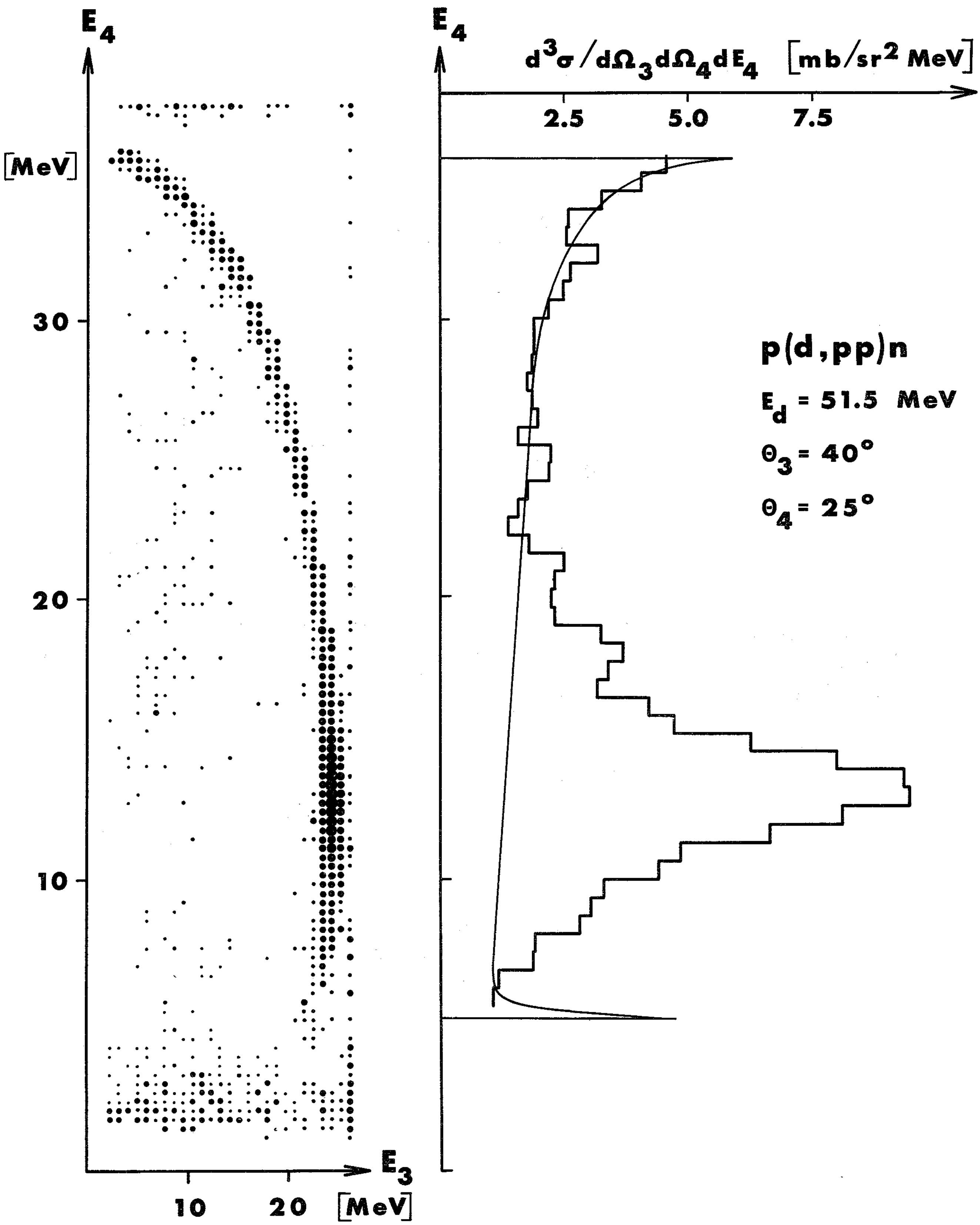
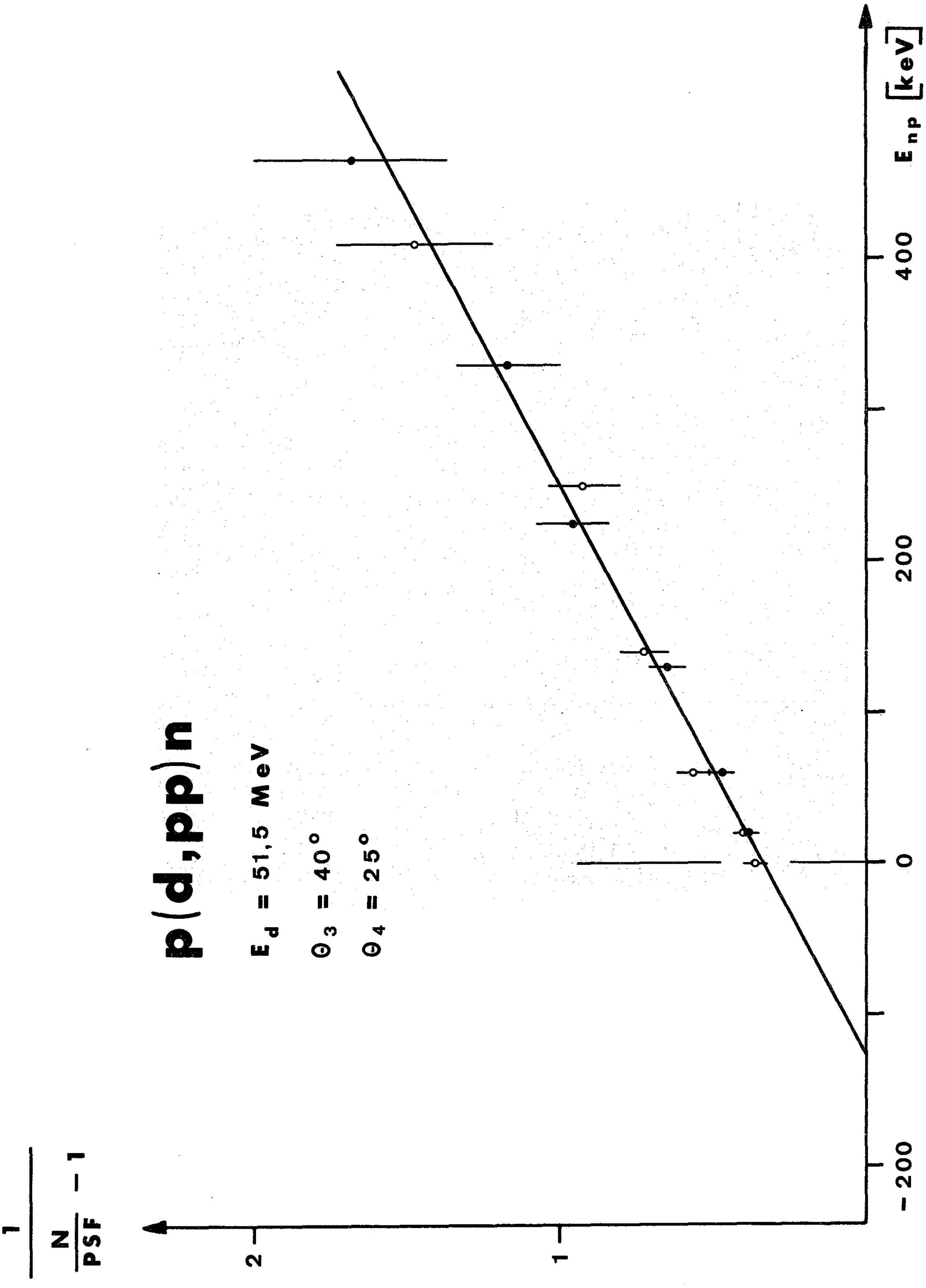

E4
[MeV]
30
20
10
E3
10
20
[MeV]
E4
d3σ/dΩ3dΩ4dE4 [mb/sr2 MeV]
2.5
5.0
7.5
p(d,pp)n
Ed = 51.5 MeV
Θ3 = 40°
Θ4 = 25°

Fig. 2



p(d,pp)n
E_d = 51,5 MeV
Θ_3 = 40°
Θ_4 = 25°
E_{np} [keV]
−200
0
200
400
$\frac{1}{\frac{N}{PSF}} - 1$
1
2

Fig. 3

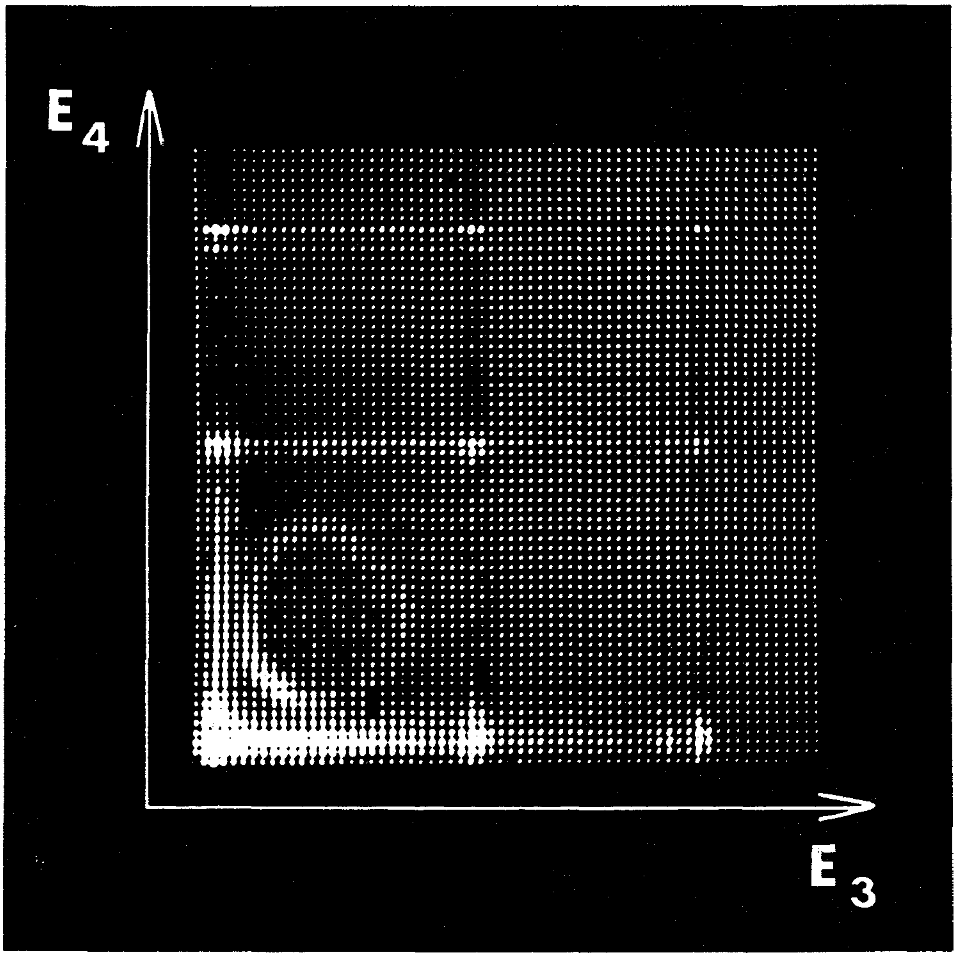
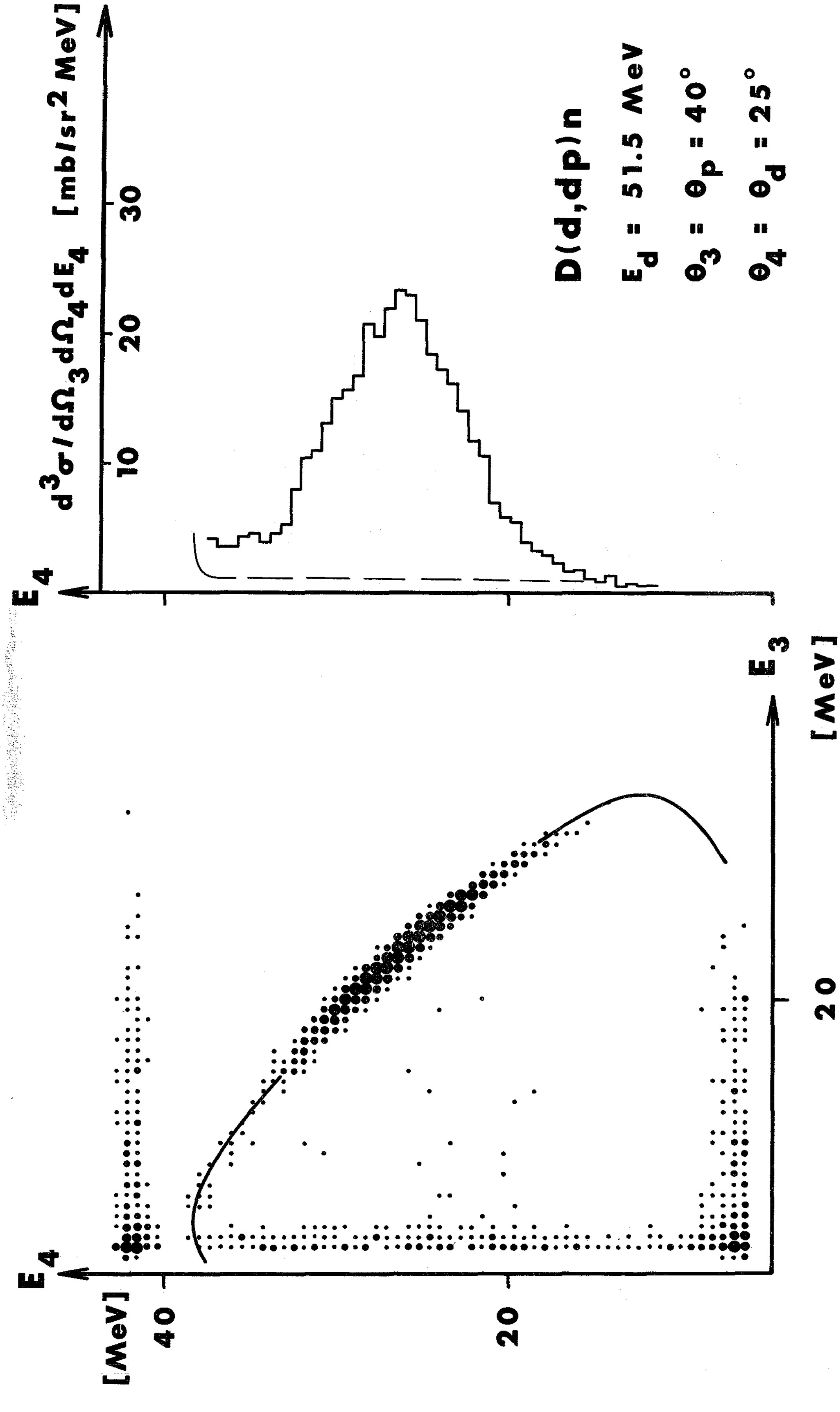


Fig. 4



D(d,dp)n
E_d = 51.5 MeV
θ_3 = θ_p = 40°
θ_4 = θ_d = 25°
d³σ/dΩ_3dΩ_4dE_4 [mb/sr² MeV]
10
20
30
E_4
E_4
[MeV]
40
20
20
E_3
[MeV]

Fig. 5

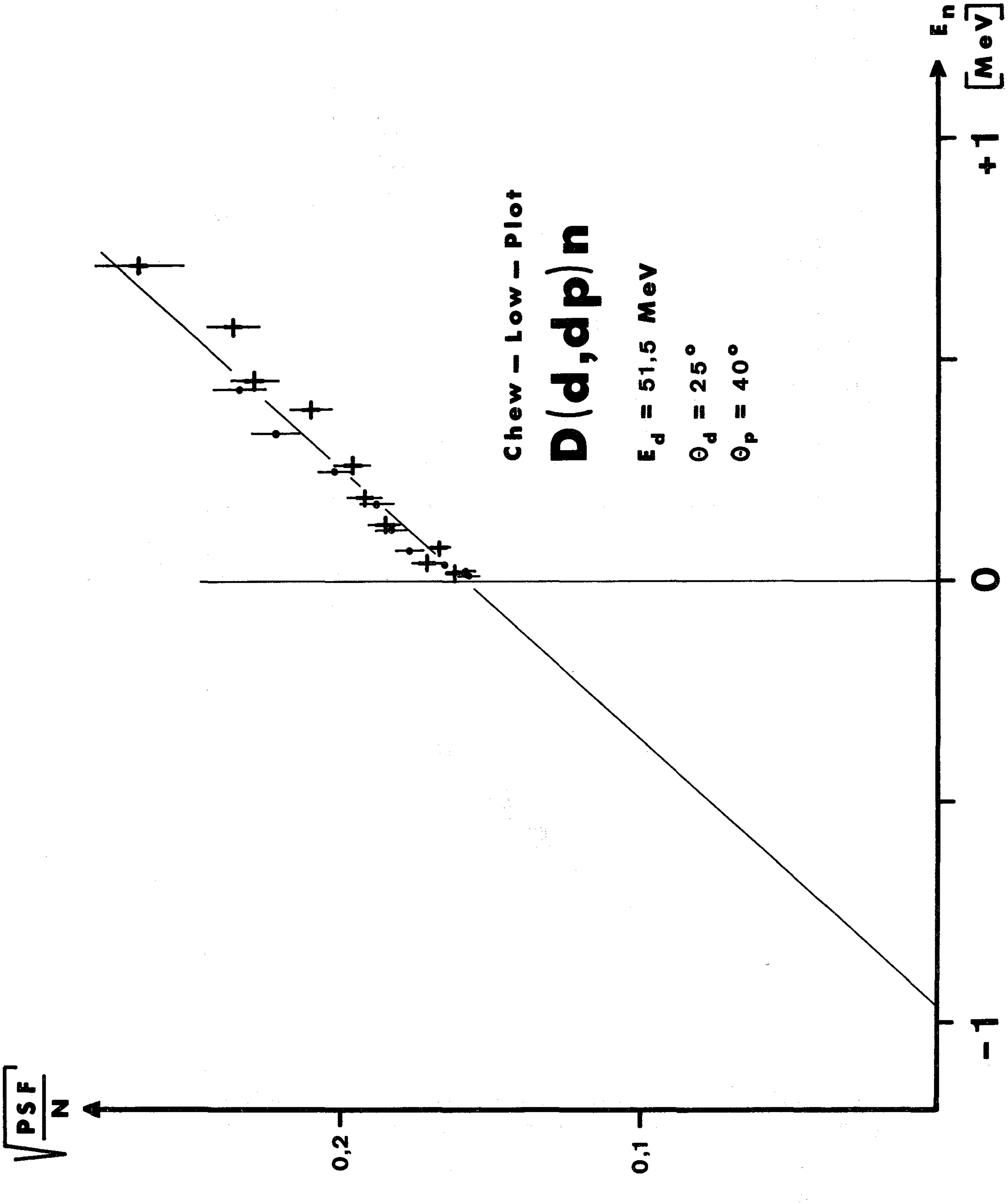
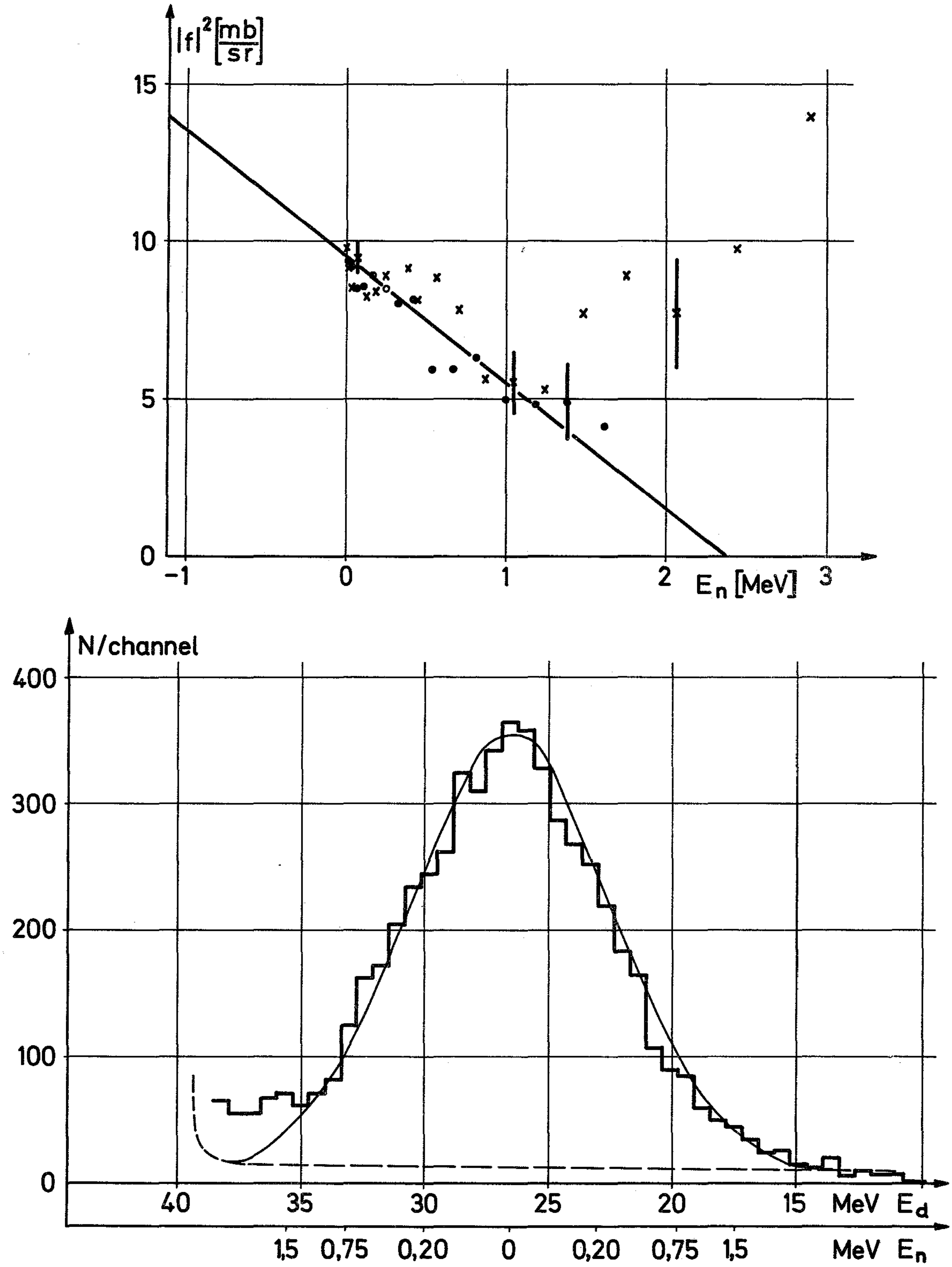
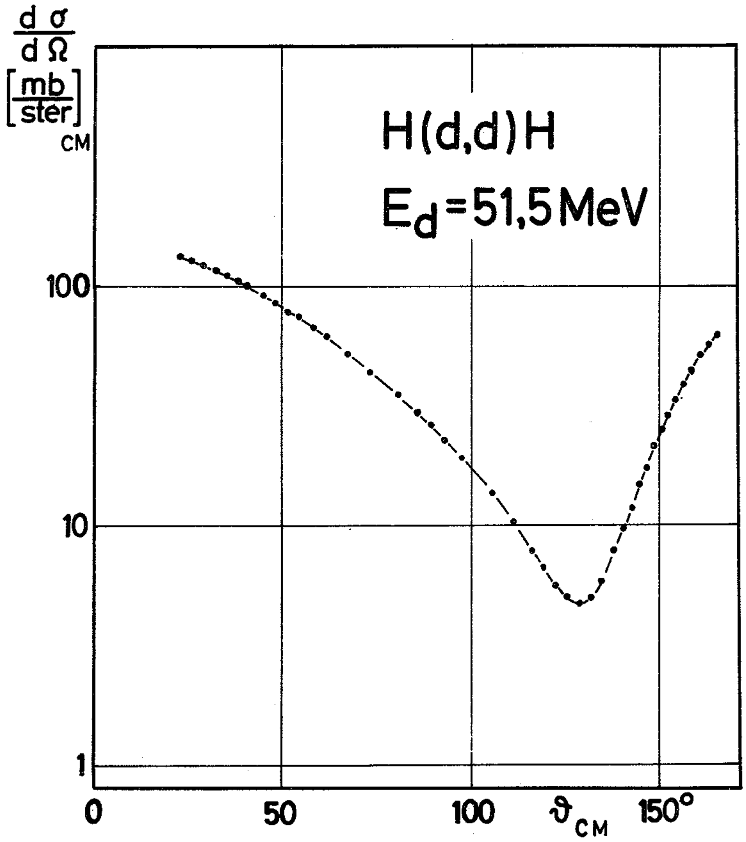

Chew – Low – Plot
D(d,dp)n
E_d = 51,5 MeV
Θ_d = 25°
Θ_p = 40°
E_n [MeV]
+1
0
−1
$\sqrt{\frac{PSF}{N}}$
0,2
0,1

Fig. 6



|f|²[mb/sr]
15
10
5
0
−1
0
1
2
3
E_n [MeV]
N/channel
400
300
200
100
0
40
35
30
25
20
15
MeV E_d
1,5
0,75
0,20
0
0,20
0,75
1,5
MeV E_n

Fig. 7



$\frac{d\sigma}{d\Omega}$
$\left[\frac{mb}{ster}\right]_{CM}$
H(d,d)H
E_d=51,5 MeV
100
10
1
0
50
100
ϑ_{CM}
150°

Fig. 8