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THE ^{19}F(p, α)^{16}O, ^{12}C(p, α)^{9}B and ^{7}Li(p, α)^{4}He REACTIONS NEAR 45 MeV

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Abstract: Ground state group (p, α) angular distributions have been obtained at energies between 30.5 MeV and 45 MeV. It appears that an energy range free from significant resonance effects has been found for the (p, α) reaction. The main process for the ^{19}F(p, α)^{16}O and the ^{12}C(p, α)^{9}B reactions is direct triton pickup, however, the backward angle region is quite different for the two angular distributions and the ^{12}C(p, α)^{9}B reaction probably contains significant heavy particle stripping.

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NUCLEAR REACTIONS ^{19}F(p, α), ^{12}C(p, α), ^{7}Li(p, α), $E = 30.5$–45.1 MeV; measured $\sigma(E; \theta)$. Natural targets.

1. Introduction

The (p, α) reaction mechanism is by no means as clearly understood as the (p, d) reaction or its inverse. Because of its historic value as a spectroscopic tool, deuteron stripping and pickup have been investigated in some detail and the dominant process is well established as a direct single nucleon transfer reaction. The contributions from resonant intermediate states are known to be quite small at energies above say 10 MeV, and the exchange effects have been shown to be negligible unless there is some selection rule which favours them relative to the nonexchange direct pickup process.

None of these conclusions can yet be applied with certainty to the (p, α) reaction. There is considerable variety in the shapes of the angular distributions which have so far been observed, frequently including a strong backward peaking [1]). At the lowest energies the resonances are easily identifiable in terms of compound levels, but there is a range of energies above this where it is not clear whether broad resonances are generating the observed angular distributions or whether an exchange direct process is responsible. In this energy range, which lies roughly between 5 MeV and 30 MeV, the strong backward peaking has been ascribed to (a) interference between two or more compound levels [3]), (b) an overlap of the focus which is produced by the distorted ingoing and outgoing waves [4]) and therefore is a characteristic of the pickup process iself, and (c) an interference between the pickup and the exchange interactions, both being one step direct interactions [5]). Such complications prevent an accurate assessment of the (p, α) reaction in terms of what is believed to be the main process, the direct pickup of three nucleons in the target by the incoming proton [6]).

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All the other contributions to the reaction would be expected to decrease relative to the direct pickup as the energy is raised. There may therefore exist an energy range above about 30 MeV where it is possible to make a detailed quantitative fit using DWBA theory. The present experiments constitute a search for such a region. A theoretical analysis of the present experimental data is being made and will be reported in a separate paper.

We have investigated three reactions where the nuclear structure properties are reasonably well known and where the transferred triton has a unique l value. The $^{19}F(p, \alpha)^{16}O$ angular distribution was measured at a proton beam energy of 44.5 MeV and showed no quantitative indication of any process other than pickup. On the other hand the $^{12}C(p, \alpha)^{9}B$ angular distribution, when measured at the same energy, showed significantly more backward peaking than would be expected from triton pickup, so the backward angle measurements were repeated over a range of energies down to 30.5 MeV in order to try to establish the cause.

The $^{7}Li(p, \alpha)^{4}He$ angular distribution was also investigated at two energies. Forward backward symmetry is required in this angular distribution because of the identity of the two particles in the final state. It does not seem to be possible, without first attempting a detailed theoretical fit, to interpret the results for the $^{7}Li(p, \alpha)^{4}He$ reaction.

2. Experimental procedure

The University of Manitoba cyclotron was used to provide a beam of 44.5 MeV protons. Lower energies were obtained during the early part of the measurements by placing beryllium foils in the beam at an intermediate focus upstream from the scattering chamber. This simple method sufficed down to an energy of 38.5 MeV. The variable energy facility of the cyclotron, whereby the negative ion beam is extracted at different radii by moving the stripping foil [7]), was installed during the course of the experiments and the measurements were extended to lower energies using the direct beam from the cyclotron.

The alpha particles were detected by means of a 1 mm silicon counter which was mounted on a rotating platform in a precision 36 cm scattering chamber. This counter thickness is just sufficient to stop 50 MeV alphas and at forward angles it was possible to separate the ground state group by pulse height analysis with very little background. At larger reaction angles a 150 μm thick transmission counter was placed in front of the 1 mm stopping counter. In the case of the $^{12}C(p, \alpha)^{9}B$ reaction at backward angles the range of the alpha particles became too short to give a reasonable energy loss in the back counter and the transmission counter was changed to one 30 μm thick. The output of the two counters were used to drive a particle identification circuit [8]), which was adjusted to accept only doubly charged particles for energy analysis. The ^{3}He groups in all three reactions were sufficiently low in energy to be easily separated out in the summed energy spectrum. The background using this counter telescope was found to be negligible at all angles.

The angular resolution in all the measurements, as determined by the solid angle of the counter system and the emittance of the beam at the target was 1° at all angles measured.

2.1. THE $^{19}F(p, \alpha)^{16}O$ REACTION

Thin targets containing fluorine were made by cutting layers of tetrafluoroethylene (CF_2) from a block of material with a microtome. These targets were used in a variety of thicknesses, depending on the angle being investigated. They were all within the range 10 μm to 50 μm. It was found that the tetrafluoroethylene gradually decreased in thickness during each run and that the useful life of a target corresponded to about 500 $\mu C \cdot cm^{-2}$ of the beam, independent of the rate of bombardment. This is in rough agreement with the observations of Holmgren and Fulmer [1]). To obtain the angular variation of the differential cross section the count at each angle was compared to the alpha particle count in a 600 μm thick monitor detector which was set at a fixed angle of about 20° to the beam direction. The absolute value of the differential cross section was determined in several short runs, each using a fresh 50 μm thick target which was carefully measured before being placed in the scattering chamber. At forward angles statistical accuracy could be obtained in a short enough time to reduce the target losses to a few percent. The absolute differential cross sections obtained in this way had an estimated error of ± 7 % of which ± 3 % was in the measurements of the target thickness.

2.2. THE $^{12}C(p, \alpha)^{9}B$ REACTION

Polyethylene (CH_2) targets 10μm thick were used throughout as carbon targets. This material showed no sign of deterioration during each run and the absolute differential cross section was obtained from the detector count and charge passing through the target at each angle measured.

2.3. THE $^{7}Li(p, \alpha)^{4}He$ REACTION

Uniform layers of metallic lithium were prepared by pressing pellets of the material between steel plates while they were immersed in dried kerosene. The thickness of the targets was determined by machining out an area of the steel plates to the required depth and then applying sufficient pressure to force out all the surplus lithium. The targets were measured with a micrometer while still immersed. They were then mounted in the scattering chamber which was promptly evacuated while the lithium was still covered with a layer of kerosene. Because there was no difficulty in separating the ground state alpha group quite thick lithium targets were used. They were mostly 125 μm thick. An absolute error of ± 20 % was assigned to the differential cross section results because of the estimated inaccuracies in the measurement of the target thickness.

3. Results and discussion

The angular distribution of the reaction $^{19}F(p, \alpha)^{16}O$ at 44.5 MeV is shown in fig. 1 and in table 1. There is evidently a well developed diffraction pattern of the type expected from the triton pickup process. The ground state spins of ^{19}F and ^{16}O limit the angular momentum transfer to a single value $l_t = 0$. A plane wave fit which has been smoothed to take into account the experimental angular resolution is also shown

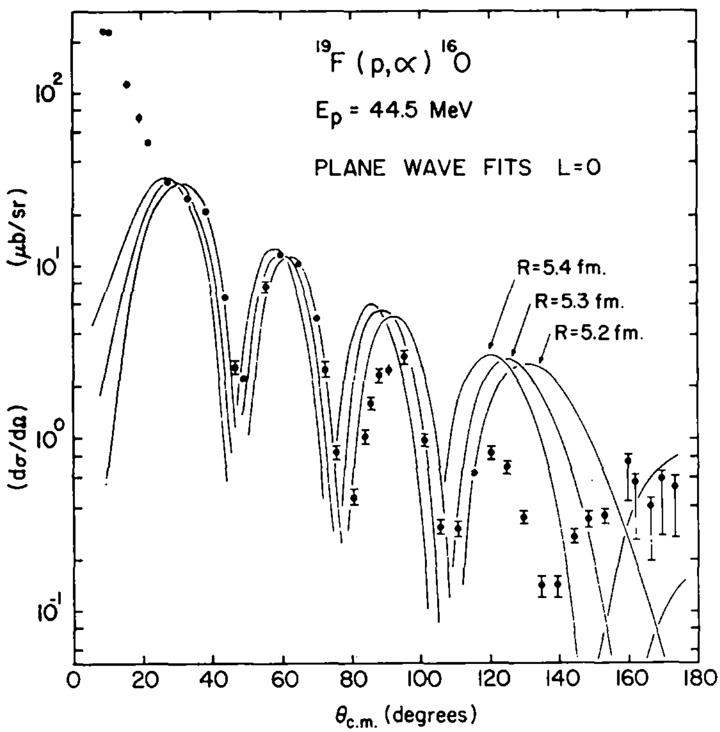

Fig. 1. The differential cross section of the reaction $^{19}F(p, \alpha)^{16}O$ at 44.5 MeV. The curves are plane wave fits with cut-off radii of 5.2 fm, 5.3 fm and 5.4 fm. When the 5.2 fm curve is matched to the experimental peak near 60° the reduced width for the reaction is 0.017.

for a range of cutoff radii, and it appears that a reasonable fit for such a crude theory can be obtained with a cutoff radius of about 5.3 fm. The reduced width when the second maximum near 60° is fitted is then 0.017.

In an attempt to confirm that the main diffraction pattern was a characteristic of triton pickup, the angular distribution in the region of the second maximum was remeasured over a range of bombarding energies. These are shown in fig. 2. Here the differential cross section is plotted as a function of the momentum transfer Q. In the plane wave theory the energy enters the angular distribution only through the factor QR, so that the maximum in the plane wave theory would always come at the angle which corresponds to the same value of Q. In the distorted wave theory there is no unique momentum transfer of the triton cluster for each reaction angle and the observed shift in the peak position at the lower energies may be due to the change in the mean momentum transferred away from its plane wave value. Presumably the distortion effects increase as the energy is lowered.

TABLE 1

$^{19}F(p, \alpha)^{16}O$

$E_p = 44.5$ MeV					
$\theta^{\circ}_{c.m.}$	$d\sigma/d\Omega$ (μb/sr)	Error $\pm$(μb/sr)	$\theta^{\circ}_{c.m.}$	$d\sigma/d\Omega$ (μb/sr)	Error $\pm$(μb/sr)
8.9	231	10	91.2	2.5	0.1
11.1	227	6	96.2	2.9	0.2
16.6	113	5	101.2	0.98	0.09
19.4	73	5	106.1	0.31	0.03
22.1	52	3	111.0	0.30	0.02
27.6	31	1	115.8	0.64	0.04
33.1	25	1	120.6	0.83	0.06
38.5	21.3	0.7	125.3	0.69	0.04
44.0	6.6	0.3	130.1	0.35	0.03
46.7	2.6	0.2	134.7	0.14	0.02
49.4	2.2	0.1	139.4	0.14	0.02
54.7	7.6	0.4	144.0	0.27	0.02
60.1	11.9	0.5	148.5	0.34	0.03
65.4	10.3	0.5	153.1	0.46	0.03
70.6	5.0	0.2	157.6	0.74	$^{+0.07}_{-0.30}$
73.2	2.5	0.2	162.1	0.56	$^{+0.06}_{-0.30}$
75.8	0.84	0.06	166.6	0.41	$^{+0.03}_{-0.20}$
81.0	0.47	0.05	170.2	0.58	$^{+0.06}_{-0.30}$
83.5	1.03	0.06	173.4	0.53	$^{+0.07}_{-0.26}$
86.1	1.60	0.1			
88.6	2.3	0.2			

The experimental results at 44.5 MeV, for the reaction $^{12}C(p, \alpha)^{9}B$ are shown in fig. 3 and in table 2. The ground state spin of ^{9}B is very probably $\frac{3}{2}^{-}$. This is the shell model prediction and also the spin of the mirror nucleus ^{9}Be. Assuming this value for the ^{9}B spin, the $^{12}C(p, \alpha)^{9}B$ triton pickup interaction will be a unique $l_t = 1$ process. The plane wave predictions corresponding to a cut-off radius of 4.0 fm is also shown in fig. 3. Here again the positions of the maxima are in quite good agreement and if the curves are normalized to the points in the region of the maximum near to 70° then the reduced width for the reaction is about 0.04.

There is clearly some backward peaking in the angular distribution. The measurements were repeated at 41.6 MeV and 38.6 MeV and a similar angular distribution with backward peaking was obtained. At intermediate angles, the maxima seem to move in a systematic way towards larger angles as the energy is decreased. The pickup theory would predict such behaviour and, as there should be no interference with backward peaking direct interactions, it seems to indicate that the pickup process dominates right out to about 140° or 150°. Measurements of the interesting region beyond this were continued down in energy to 30.5 MeV. The observed changes in the angular

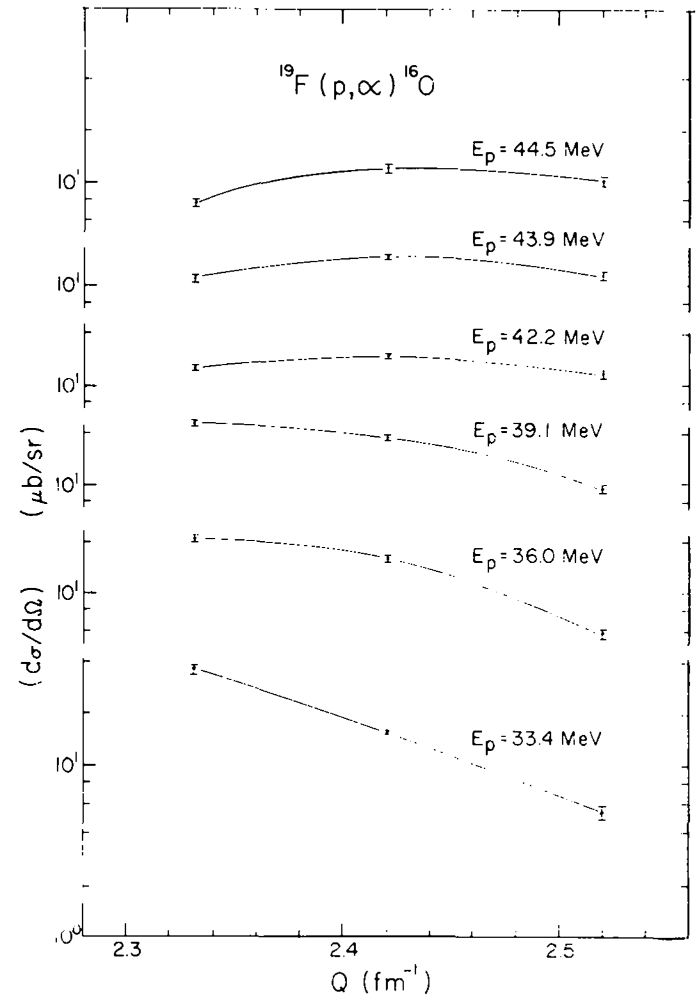

Fig. 2. The variation of the peak in the differential cross section near 60° with energy. The differential cross section is plotted as a function of the momentum transfer $Q = K_\alpha - \frac{16}{19}K_p$ fm^{-1}.

distribution as the energy is varied are shown in fig. 4. The backward peaking seems to persist over the entire energy range and only at the lowest energies measured does a substantial change of shape occur.

Interference involving compound resonances is very unlikely to be the cause of backward peaking over such a wide energy range, though Gruhn and Wall have explained a backward rise in alpha elastic scattering by assuming a resonating partial wave [10]). Of the other proposed mechanisms, the focus effect of Kromminga and McCarthy [4]) seems an unlikely explanation. Calculations by Eisberg, McCarthy and Spurrier [9]) indicate that the focus is near the nuclear surface for 40 MeV protons in

TABLE 2

$^{12}C(p, \alpha)^{9}B$

E_p = 44.5 MeV		
$\theta^{\circ}_{c.m.}$	$d\sigma/d\Omega$ (μb/sr)	Error $\pm$(μb/sr)
24.3	548	10
30.3	402	9
36.3	265	8
42.2	159	6
48.0	92	4
53.8	56	3
59.6	65	3
65.3	71	3
70.8	78	3
76.4	68	3
81.8	62	3
87.1	40	2
92.4	25	1.2
97.5	17.8	1.3
102.5	12.3	1.0
107.5	13.6	1.2
112.4	12.7	1.0
117.1	13.7	0.9
121.7	15.2	0.7
126.3	16.3	0.9
130.8	14.2	0.9
133.0	11.5	0.7
135.2	6.8	0.6
139.5	7.1	0.5
143.8	7.8	0.6
148.0	10.5	1.0
152.1	13.1	1.4
156.2	15.8	1.2
160.2	26.6	1.4
164.2	28.0	2.5
168.2	37.6	1.3
170.6	42	3
173.2	39	3

E_p = 41.6 MeV		
$\theta^{\circ}_{c.m.}$	$d\sigma/d\Omega$ (μb/sr)	Error $\pm$(μb/sr)
76.4	93	4
81.2	84	5
97.6	33	2
107.6	23	2
117.2	23	2
126.4	29	2
135.3	17	2
143.9	8.5	1.4
152.2	14.1	1.3
160.3	41	3
168.2	68	4
172.2	90	7

E_p = 38.5 MeV		
$\theta^{\circ}_{c.m.}$	$d\sigma/d\Omega$ (μb/sr)	Error $\pm$(μb/sr)
18.3	1140	30
24.3	980	40
36.3	540	20
48.2	240	14
59.7	186	11
71.0	198	7
82.0	126	6
92.5	63	4
102.7	49	4
112.5	45	4
121.9	63	4
131.0	75	5
139.7	45	4
148.1	38	4
156.3	39	5
164.3	93	11
172.2	210	15

lead and a little inside for 18 MeV alpha particles in the same nucleus. The present measurements involve higher energy particles and smaller radii and since the focus moves further out as the energy increases, the backward peaking from this cause should be much reduced at these energies.

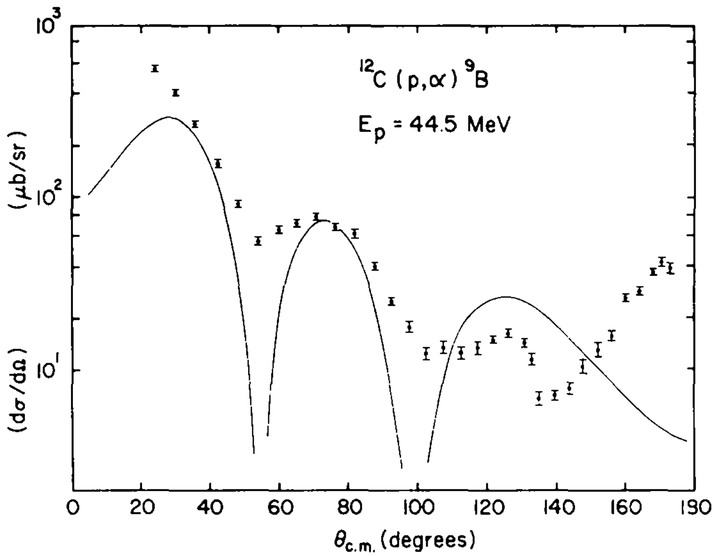

Fig. 3. The differential cross section of the reaction $^{12}C(p, \alpha)^{9}B$ at 44.5 MeV. The curve is a plane wave fit with a cutoff radius of 1.0 fm. When this is matched to the experimental peak near 70° the reduced width for the reaction is 0.04.

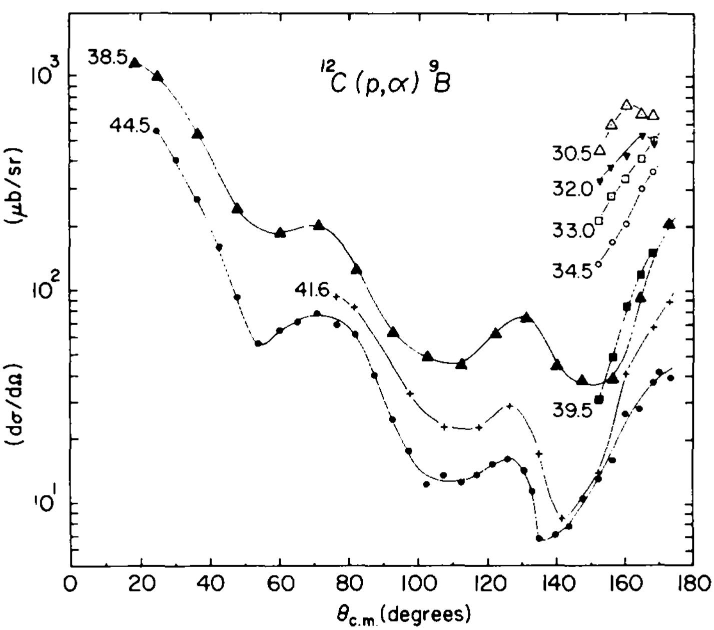

Fig. 4. The differential cross section of the reaction $^{12}C(p, \alpha)^{9}B$ at beam energies of 44.5, 41.6, 39.5, 38.5, 34.5, 33.0, 32.0 and 30.5 MeV.

The angular distribution of the $^7Li(p, \alpha)^4He$ reaction at 45 MeV and 41 MeV is shown in fig. 5 and table 3. In view of the symmetry about 90° no attempt was made at extreme forward angle measurements since the equivalent information is contained in the backward angle data.

TABLE 3
$^7Li(p, \alpha)^4He$

E_p = 45.2 MeV			E_p = 41.3 MeV		
$\theta^\circ_{c.m.}$	$d\sigma/d\Omega$ (μb/sr)	Error ±(μb/sr)	$\theta^\circ_{c.m.}$	$d\sigma/d\Omega$ (μb/sr)	Error ±(μb/sr)
19.8	105	5	23.0	98	4
26.3	67	4	26.2	94	3
32.8	64	3	29.5	86	2
39.2	58	2	32.7	83	3
42.3	60.0	2.5	36.0	81	4
45.6	61	2	39.1	86	2
48.6	58.5	2.5	42.3	86	3
51.9	58	2	45.4	85	2
58.1	47.5	1.4	48.7	78	5
64.2	39.3	1.0	51.7	88	2
70.2	29.2	0.7	54.1	83	2.5
76.1	26.5	0.8	57.8	79	1.5
81.8	23.7	0.8	60.9	80	3
87.5	22.8	0.9	64.0	62	1.5
93.0	22.4	0.6	67.0	56.5	2.5
98.3	26.7	0.8	69.9	47.6	1.4
103.5	29.7	1.2	72.9	44.5	1.7
108.6	34.0	2.5	75.8	36.3	1.2
151.8	69	4	81.6	28.5	1.5
155.5	82	5	87.2	28.0	1.3
157.3	93	15	90.0	28.0	1.2
159.2	90	3	92.7	30.5	1.7
160.9	96	8	98.0	33.8	1.9
162.7	104	4	103.3	39	3
164.4	135	35	108.3	46	4
166.2	160	80	147.8	81	3
167.9	170	150	151.6	79	5
169.7	190	80	153.5	87	5
			155.4	100	3
			157.2	110	6
			159.0	102	6
			162.6	108	8
			166.2	145	6
			169.7	129	13

It appears that there are no sudden changes in the shape of the angular distribution at the two energies. In this reaction the exchange and the nonexchange processes have equal status, so that the heavy particle process can be taken into account by reflecting the pickup reaction amplitude about the 90° direction and adding the amplitudes together coherently. On the other hand it will probably be necessary to use a proper finite range theory. The zero range DWBA would take one alpha particle as the composite particle consisting of a point triton coupled to a proton with no interaction range between them, whereas the other would be treated as the core and be described by an optical potential well of finite size. This difference in the treatment of two identical particles is clearly without physical justification.

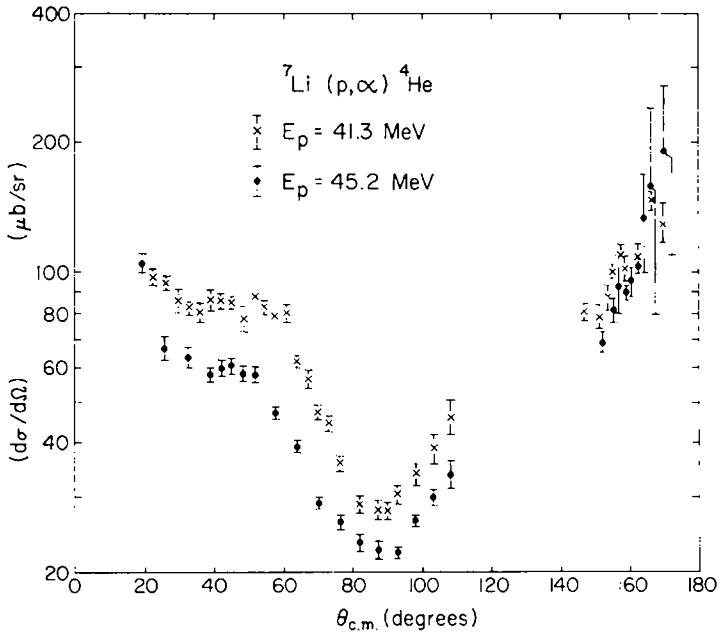

Fig. 5. The differential cross section of the reaction ^{7}Li(p, α)^{4}He at energies of 45.2 MeV and 41.3 MeV.

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