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ABSTRACT. A broad range magnetic spectrograph has been used to analyse the deuterons emitted from targets of ^{10}B, ^{11}B, ^{14}N and ^{27}Al bombarded with 5·2 Mev singly ionized ^{3}He particles. The angular distributions of a number of the deuteron groups have been measured and an attempt has been made to fit them with the predictions of stripping theory. The absolute differential cross sections have been compared with those of the corresponding (d, n) reactions and the published differential cross sections for some (d, t) and (p, d) reactions have been similarly compared.

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* Now at the University of Manchester, where this work was performed.

§ 1. INTRODUCTION

It has been suggested that (^{3}He, d) reactions at sufficiently high bombarding energies should proceed by a stripping mechanism similar to that which has been well established for (d, p) and (d, n) reactions (Newns 1952, Butler and Salpeter 1952). Since there was little available experimental evidence on these reactions, it was considered worth-while to measure angular distributions and absolute cross sections for a number of (^{3}He, d) reactions where the corresponding (d, n) reactions had already been investigated and where the properties of most of the initial states were known.

The following reactions: ^{10}B(He,d)^{11}C, ^{11}B(^{3}He,d)^{12}C, ^{14}N(^{3}He,d)^{15}O and ^{27}Al(^{3}He,d)^{28}Si were therefore studied at 5.2 Mev bombarding energy using the Manchester University Van de Graaff accelerator and a broad range magnetic spectrograph (Barros et al. 1959). An attempt has been made to interpret the results in terms of the stripping theories of Bhatia (Bhatia et al. 1952) and Butler (1951) modified for application to (^{3}He, d) or (t, d) reactions (Newns 1952, Butler and Salpeter 1952, Butler and Hittmair 1957) and comparisons have been made with the published results for the corresponding deuteron stripping reactions.

§ 2. EXPERIMENTAL DETAILS

After analysis by a 90° deflecting magnet, beams of approximately 0.4μA singly ionized ^{3}He particles were used to bombard a target spot (0.020in.×0.040in.) on a target at a distance of 24 feet. The ^{3}He gas used in the ion source was mixed with ^{4}He at approximately 30% concentration. The mixture was purified by charcoal at liquid air temperature and was used at a rate of about 3 cm^3 at N.P.T. per hour. Subsequent recovery with at least 95% efficiency was achieved. The triton contamination in the beam was found to be very small and certainly less than 0.01%.

Targets of natural boron and of adenine which had been prepared on VYNS foils, in some cases reinforced with a thin layer of evaporated gold, proved unable to withstand reasonable bombardment. Consequently, targets of natural boron and of adenine on aluminium foil were used. Although the attainable energy resolution was thus greatly reduced it was still sufficiently good for our main purpose of studying angular distributions of reactions leading to well established nuclear levels.

The target thicknesses were measured with an alpha-particle thickness gauge (Ramavataram and Porat 1959). The natural boron target was found to be 30μg cm^{-2} thick and the adenine target which contained 52% nitrogen had an effective thickness of 25μg cm^{-2} of ^{14}N. The aluminium backing was about 170μg cm^{-2} in each case.

The target plane lay along the -45° + 135° direction with respect to the beam with the backing facing the beam. The total beam bombardment was measured by current integration from a Faraday cup and, in addition, protons from the target were counted with a monitor at -135°.

The deuteron groups present on the photographic plates were identified by the variation of their energy with angle with respect to the ^{3}He beam. This identification was greatly facilitated by plotting a graph of the energies of the groups against the angle of observation and drawing loci connecting the points corresponding to particular groups. The shape of these loci gave an immediate indication of the probable target nuclei responsible, because the slopes of the curves depended mainly on the mass of the target nucleus, and a comparison could then be made between the loci and the theoretical curves for the various probable target masses and Q-values.

In the case of the boron target the beam energy could be estimated from the energy of a group of singly ionized elastically scattered ^{3}He which was present on the plates. A comparison between the energies of the corresponding groups from ^{27}Al showed that the beam energy for the adenine target was 20 ± 10 Kev higher than for the boron target.

The solid angle of the spectrograph was calculated from the geometry of the instrument and has been checked previously by observation of Rutherford scattering.

§ 3. RESULTS

Typical spectra from each of the targets are shown in figures 1 and 2.

The ^{28}Si (d_2) group on the spectrum from the boron target contains a small contribution from the contaminant group ^{15}O (d_o) which is observed at other angles but which overlaps with this group at 40°.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$^{10}B(^3He, d_o)^{11}C$	3.174±0.015	3.206[a]	0	0	1	6.5[f]	4.3[h], 5.8[j]	2.9(19°)	3.3
$^{10}B(^3He, d_1)^{11}C$	-	-	1.990±0.005	1.99 ±0.02	1	6.2[f]	4.3[h], 5.8[j]	0.4(19°)	-
$^{11}B(^3He, d_2)^{12}C$	2.780±0.015	2.808[a]	-	7.656±0.007[c]	1	4.5[f]	4.4[h]	0.1(29°)	-
$^{11}B(^3He, d_3)^{12}C$	-	-	9.629±0.010[m]	9.63 ±0.014	2	6.0[f]	4.4[h]	0.5(29°)	0.7
$^{14}N(^3He, d_o)^{15}O$	1.802±0.015	1.806[a]	0	0	1	5.0[f]	4.7[k]	2.5(18°)	2.4
$^{27}Al(^3He, d_2)^{28}Si$	1.432±0.015	1.478[b]	-	4.617±0.010[d]	-	-	-	0.15(33°)	-
$^{27}Al(^3He, d_3)^{28}Si$	-	-	4.979±0.015[m]	5.0	-	-	-	0.02(44°)	-
$^{27}Al(^3He, d_4)^{28}Si$	-	-	6.272±0.015[m]	6.2	0	4.5[g]	6.4[l]	0.7(9°)	1.4
$^{27}Al(^3He, d_5)^{28}Si$	-	-	6.880±0.015[m]	6.9	3	4.5[g]	-	0.2(66°)	-
$^{27}Al(^3He, d_6)^{28}Si$	-	-	7.392±0.015[m]	7.3	-	-	-	0.05(67°)	-
$^{27}Al(^3He, d_7)^{28}Si$	-	-	7.807±0.015[m]		3	4.5[g]	-	0.13(67°)	-
$^{27}Al(^3He, d_8)^{28}Si$	-	-	7.948±0.015[m]		-	-	-	-	-

(1) Reaction, (2) measured Q-value (Mev), (3) previous Q-value (Mev), (4) measured excitation (Mev), (5) previous excitation [e] (Mev), (6) l-value, (7) radius (10^{-13} cm), (8) radius used in (d, n) analyses (10^{-13} cm), (9) differential cross section at the centre-of-mass angle shown (mbn sterad^{-1}), (10) $|A_o|^2 N_i^2 (10^{12}$ cm$^{-1})$.

a Calculated from mass excesses and excitations listed by Ajzenberg-Selove and Lauritsen (1959)

b Calculated from mass excesses given by Endt and Braams (1957) and excitation given by Endt and Paris (1957)

c The value given by Ajzenberg-Selove and Lauritsen (1959)

d The value found by Endt and Paris (1957)

e Ajzenberg-Selove and Lauritsen (1959) and Endt and Braams (1957)

f Using Butler theory

g Using the Born approximation theory

h Maslin et al. (1956)

j Cerineo (1956)

k Evans et al. (1953)

l Calvert et al. (1955)

m Calculated from the measured Q-value difference from the lowest observed state and the excitation of this state given in (5).

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The observed levels for which the angular distributions were measured are presented in the table, and a number of the angular distributions are shown in figures 3, 4 and 5.

The levels of ^{11}C, ^{12}C and ^{15}O correspond well with known states of these nuclei, though these have not been previously studied in (^{3}He, d) reactions. The Q-value for the reaction ^{14}N(^{3}He, d_o)^{15}O agrees well with the value calculated from the masses using the recently revised mass of ^{15}O (Ajzenberg-Selove and Lauritsen 1959) but the Q-value for the ^{10}B(^{3}He, d_o)^{11}C reaction is somewhat lower than the calculated value.

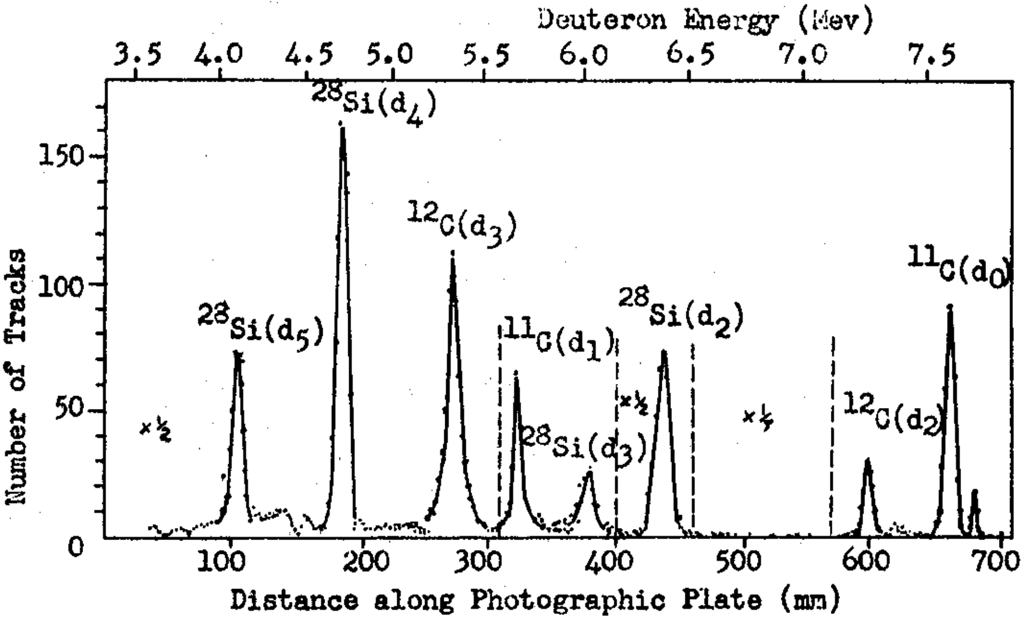

Figure 1. **The 40° deuteron spectrum from the boron target bombarded with 5.22 Mev ^{3}He. The small groups of slightly higher energy than some of the larger groups are assumed to arise from the presence of a small quantity of boron on the beam side of the aluminium backing.**

The energies of some of the levels of ^{28}Si, particularly those of higher excitation, differ from earlier data, but this is not surprising since, in this region of excitation, the only alternative reaction which has been used to produce these states is ^{27}Al(d, n)^{28}Si which gives poor resolution.

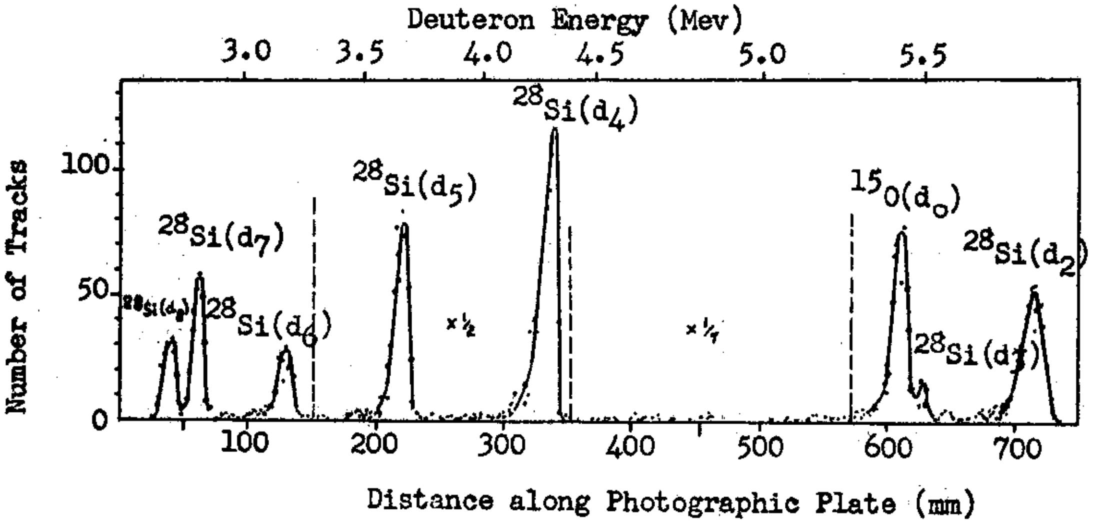

Figure 2. The 80° deuteron spectrum from the adenine target bombarded with 5.24 Mev ^{3}He.

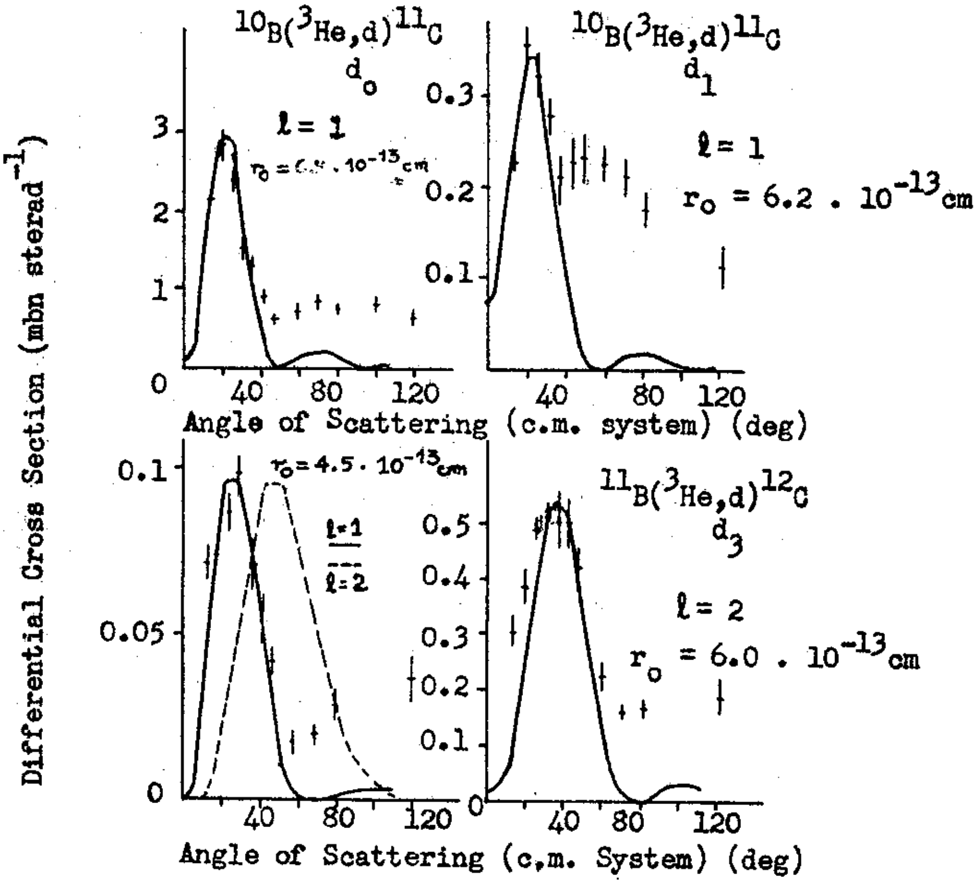

Figure 3. Angular distributions of deuteron groups from the reactions ^{10}B(^{3}He, d)^{11}C and ^{11}B(^{3}He, d)^{12}C at 5.1 Mev bombarding energy. The d$_3$ group has been erroneously labelled $\ell = 1$ in the figure instead of $\ell = 2$.

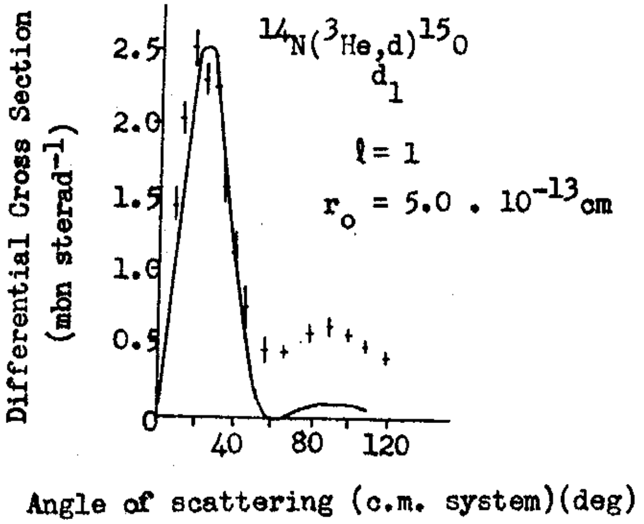

Figure 4. Angular distribution of the deuteron group from the reaction $^{14}N(^3He, d_o)^{15}O$ at 5.1 Mev bombarding energy.

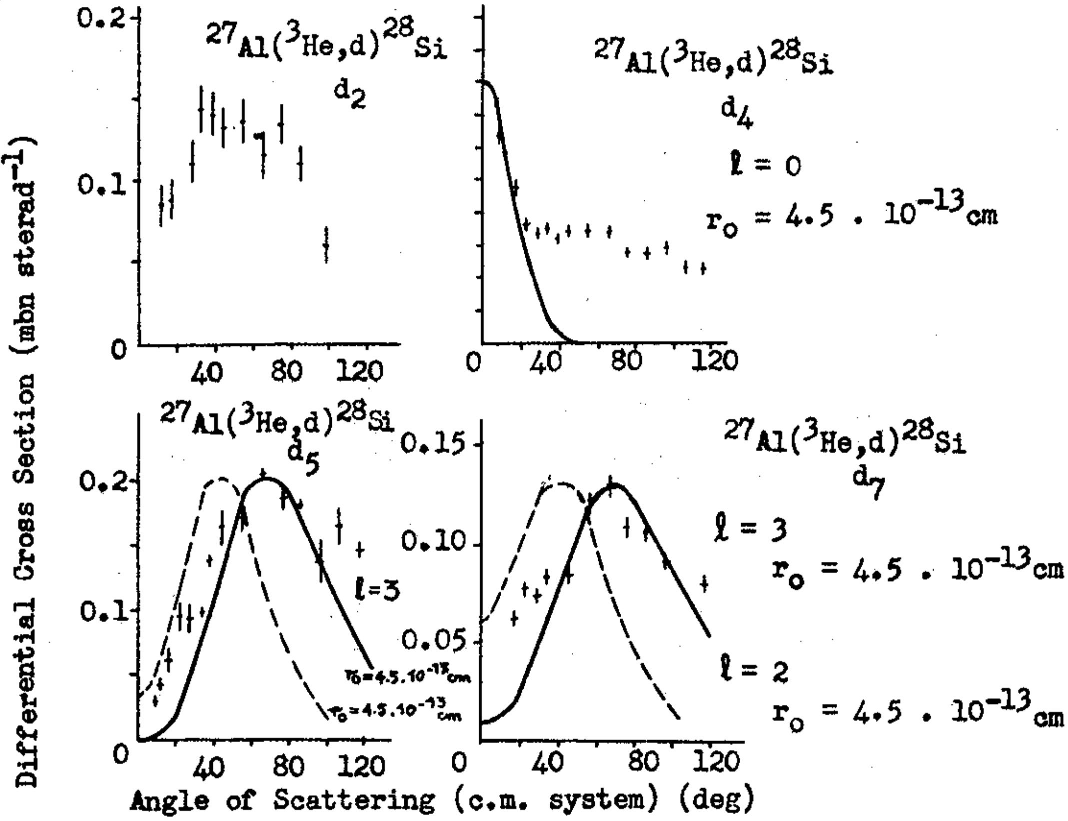

Figure 5. Angular distributions of deuteron groups from the reaction $^{27}Al(^3He, d)^{28}Si$ at 5.2 Mev bombarding energy.

§ 4. DISCUSSION

4.1 Theory

The theory of (^{3}He, d) and (t, d) reactions has been examined by Butler (Butler and Salpeter 1952, Butler and Hittmair 1957) and by Newns (1952). The expressions they give for the differential cross sections are similar to those for the (d, n) and (d, p) reactions (Bhatia et al. 1952, Butler 1951). In both cases the angular distribution of the outgoing particle depends on the orbital angular momentum transferred to the nucleus by the captured nucleon and on the effective radius at which the capture takes place. The angular distribution is modified by the presence of a form factor which is the probability of the captured nucleon in the bombarding particle (in this case ^{3}He) having the appropriate internal momentum ($\hbar\vec{K}$) necessary to conserve linear momentum in the reaction. The variation of this factor is the main difference between the two types of stripping process. For the (d,n) and (d,p) reactions, it is just the square of the Fourier transform of the internal deuteron wave function, normalized to unity. However, for the (^{3}He,d) reaction not only must the captured proton have the correct momentum but also the ^{3}He particle must be comprised of a deuteron in its ground state plus an odd proton, so that the reaction can take place by a simple stripping mechanism. The form factor can thus be written $|A_0|^2\left\{\phi(\vec{K})\right\}^2$ where $|A_0|^2$ is the probability of finding the ^{3}He nucleus in the required state and $\phi(\vec{K})$ is the Fourier transform of the wave function for the odd proton (again normalized to unity) when the ^{3}He nucleus is in this state. For large separations r between the odd proton and the centre of mass of the deuteron the wave function for the odd proton can be approximated by

$$\frac{N_i}{\sqrt{(4\pi)}} \; \frac{e^{-\lambda r}}{r}$$

where N_i is a normalization constant and λ is the wave number corresponding to the binding energy of the odd proton in the ^{3}He particle. This leads to a form factor

$$|A_0|^2 \; \frac{N_i^2}{2\pi^2} \; \frac{1}{(\lambda^2 + K^2)^2}$$

which would be valid only for small values of K (Butler and Hittmair 1957). Alternatively the form factor can be obtained directly from the wave functions for the mass-3 particle and the deuteron (Newns 1952, French and Fujii 1957) and will depend on the choice of these wave functions, although not very sensitively.

The nuclear properties enter the expressions for the differential cross section for both mass-3 stripping and deuteron stripping primarily through the presence of a reduced width (in the case of Butler's theory) or a capture probability (in the Born approximation theory of Bhatia et al. (1952)). These are proportional to the probability of finding the captured nucleon at the surface of the final nucleus with the orbital angular momentum with which it has been captured, when the final nucleus is in the state of target nucleus in its ground state plus the captured nucleon. For the various stripping reactions between the same initial and final nuclear states one would expect these factors to be almost the same, differing because of variations in the interaction radius (Butler and Salpeter 1952, Butler and Hittmair 1957).

The derivation of the expressions for the differential cross sections involves a number of major assumptions. These are that (i) the stripping occurs at a definite radius; (ii) the outgoing particle comes from the bombarding particle and not the nucleus, that is, exchange effects and compound nucleus formation are neglected; (iii) the outgoing particle does not interact with the initial or final nucleus; (iv) the bombarding particle does not undergo elastic or inelastic scattering by the target nucleus and (v) Coulomb effects can be neglected. Generally for deuteron stripping at moderately high energies these assumptions are reasonable, because the deuteron is loosely bound. However, for the (^{3}He, d) reaction, for example, they are questionable because the ^{3}He nucleus is more strongly bound than the deuteron and because its double charge makes Coulomb effects more serious. This will be expecially true at the energies used in the present experiment.

Only in those cases where the (^{3}He, d) and (d, n) reactions between the same nuclear states proceed predominantly by a stripping mechanism can one expect the cross sections to be related, and then the relationship will only be straightforward if in both cases the above assumptions are justified. The angular distributions of the outgoing particles should indicate whether stripping is important and if so the ratio of the absolute cross sections will give a measure of the extent to which the above assumptions are valid. In view of the high excitation of the compound system in the reactions we have studied (between 20 and 26 Mev), it is unlikely that such angular distributions could result from a small number of overlapping levels in a compound nucleus. Also, if a compound nucleus is formed by absorption of the incident ^{3}He particle it is relatively improbable that it will decay by deuteron emission since several more favourable channels are always open.

4.2. Angular Distributions

A number of the angular distributions strongly indicate a stripping mechanism. In such cases they could apparently be equally well fitted by the Born approximation theory or the Butler theory and with a variety of form factors providing the interaction radius parameter was suitably adjusted.

Reasonably good fits were obtained, for example, with the angular distributions of the ^{10}B(^{3}He, d_0)^{11}C, ^{11}B(^{3}He,d_3)^{12}C and ^{14}N(^{3}He,d_0)^{15}O groups. Those from ^{27}Al(^{3}He,d)^{28}Si could not be fitted quite as well, probably because the angular distributions were distorted by the Coulomb potential. This is borne out by the fact that the best fitting radius is small compared with that of the corresponding (d,n) reaction, as might be expected if large Coulomb effects were present. The theoretical curves shown in figures 3, 4 and 5 were calculated using the form factor given above, i.e.

$$|A_0|^2 \frac{N_1^2}{2\pi^2} \frac{1}{(\lambda^2 + K^2)^2}$$

and the choice between Born approximation and Butler theories was governed by corresponding (d, n) work and is indicated in the table.

Specific points concerning some of the angular distributions are dealt with below.

$^{10}B(^3He, d_0)^{11}C$.

A good fit was obtained using the ℓ-value which had been used to explain the $^{10}B(d, n_0)^{11}C$ angular distributions at 9 Mev (Maslin et al. 1956) and at 7.5 Mev (Cerineo 1956).

$^{10}B(^3He, d_1)^{11}C$.

The situation here is not simple. Previously, good $\ell = 1$ stripping distributions have been reported from the (d,n) reaction leading to this state of ^{11}C(Maslin et al. 1956, Cerineo 1956). However, since the spin and parity of the ^{10}B ground state is 3^+ and the first excited state of ^{11}C should have spin and parity of $\frac{1}{2}^-$, as does the corresponding level in the mirror nucleus ^{11}B (Ajzenberg-Selove and Lauritsen 1959), the usual stripping selection rules for angular momentum conservation cannot hold if $\ell = 1$. The deuteron stripping results have been explained on the grounds that the outgoing particle suffers a spin reversal brought about either by a spin-flip mechanism (Wilkinson 1957) or by a nucleon exchange process (Evans and French 1958). It is not surprising, then, that the simple stripping theory cannot be well applied to the reaction $^{10}B(^3He, d_1)^{11}C$. It is relevant that the (d,p) reaction leading to the mirror of this level in ^{11}B also appears to have only a small component in its angular distribution which is amenable to an $\ell = 1$ fit (Zeidman and Fowler 1958, Evans and Parkinson 1954).

$^{11}B(^{3}He, d_2)^{12}C$.

The angular distribution of the corresponding (d,n) reaction has not been observed at bombarding energies where stripping might predominate. This is probably because of the low intensity of the group and the poor neutron energy resolution (Maslin et al. 1956). The peak cross section in our work is about one fifth of that of the d_3 group. An $\ell = 1$ fit gives quite good agreement with the observed angular distribution. This is the value to be expected from the spin and parity assignment of 0^+ for this astrophysically significant level (Cook et al. 1957, Salpeter 1957). It is perhaps of interest that this result rules out the possibility of a spin and parity of 4^+.

$^{11}B(^{3}He, d_3)^{12}C$.

Quite good agreement is achieved with an $\ell = 2$ fit, and this ℓ -value agrees with the value used for the corresponding (d,n) angular distribution (Maslin et al. 1956).

$^{14}N(^{3}He, d_0)^{15}O$.

A good fit is obtained using an $\ell = 1$, agreeing with the value used for the $^{14}N(d, n_0)^{15}O$ angular distribution at 7.7 Mev (Evans et al. 1953).

$^{27}Al(^{3}He, d_4)^{28}Si$.

The value $\ell = 0$ may be considered well established from the (d,n) reaction at 9 Mev (Calvert et al. 1955) and 6 Mev (Rubin 1957). This is the only group from $^{27}Al(^{3}He, d)^{28}Si$ for which we have observed a peak in the 0° direction. Only partial agreement with the theoretical curve is obtained, however, but the Coulomb effect is almost certainly a distorting factor.

^{27}Al(^{3}He, d_5 and d_7)^{28}Si.

Again the fits are not good but $\ell = 3$ is best in both cases, suggesting that both these states have negative parity.

4.3. Absolute Cross Sections

The peak values of the absolute cross sections are given in the table and these may well be in error by ± 25% mainly because of the uncertainty in target thickness.

The (^{3}He, d) cross sections have been compared with the corresponding (d, n) cross sections in four instances: ^{10}B(^{3}He,d_0)^{11}C ^{11}B(^{3}He, d_3)^{12}C, ^{14}N(^{3}He, d_0)^{15}O and ^{27}Al(^{3}He, d_4)^{28}Si. This was done by fitting the (^{3}He, d) angular distributions with the same theory, Butler or Born approximation, as had been used for the (d, n) work with the form factor

$$|A_0|^2 \ \frac{N_1^2}{2\pi^2} \ \frac{1}{(\lambda^2 + K^2)^2}$$

mentioned above. The only unknown quantities in the expressions are $|A_0|^2 N_i^2$ and the reduced width or proton capture probability, depending on which theory had been used. Assuming that these latter factors are the same as for the corresponding (d, n) reactions, the factor $|A_0|^2 N_i^2$ could be estimated in each case at the peak of the angular distribution after a theoretical fit had been found. Reduced widths have been reported for the ^{10}B(d, n_0)^{11}C and ^{11}B(d, n_3)^{12}C reactions (Maslin et al. 1956) and also the proton capture probability for ^{27}Al(d,n_4)^{28}Si (Calvert et al. 1955). Although no reduced width was available for $^{14}N(d, n_0)^{15}O$, it could be estimated because a reduced width has been reported for $^{14}N(d, p_0)^{15}N$ (Warburton and McGruer 1957) and the ratio of reduced widths for these two reactions has been determined (Calvert et al. 1956). It was necessary that the reduced widths or capture probabilities should all have been calculated using the same deuteron form factor so that the values of $|A_0|^2 N_i^2$ could be compared correctly. This necessitated an adjustment in the published values of the reduced widths or capture probabilities obtained from the ^{27}Al, ^{10}B and $^{11}B(d, n)$ reactions because in these cases a different form factor from that given by Butler (1951) had been used.

The values of $|A_0|^2 N_i^2$ obtained are shown in the table.

The variations in this factor, which indicate variations in the validity of the stripping assumptions, are larger than the probable errors which arise from uncertainty in the reduced widths (possibly ± 50%). The smallness of this factor for $^{27}Al(^3He, d_4)^{28}Si$ is not surprising since a large Coulomb effect would be expected to reduce the observed cross section in this case. The value of $|A_0|^2 N_i^2$ in the case of $^{11}B(^3He, d_3)^{12}C$ is only one-fifth of that for $^{10}B(^3He, d_0)^{11}C$ where one might have expected similar values. It is possible that the $^{11}B(d, n_3)^{12}C$ reaction may not proceed by a simple stripping mechanism. This is supported by the fact that the angular distributions of the n_0 and n_1 groups from this reaction at 10 Mev bombarding energy have been explained by a mixture of simple stripping and heavy particle stripping (Zeidman and Fowler 1958). However, it is unlikely that a factor of five can be explained in this way.

It is of interest to compare those values of $|A_0|^2 N_1^2$ with values obtained from other experiments. At present, there are no (^{3}He, d) results available, although a number of reactions of the type (d, ^{3}He) and (d,t) have been studied. The (d,t) experiments are particularly suitable because the Coulomb effects will generally be smaller than in the ^{3}He experiments and because they can be compared with the corresponding (p,d) or (d,p) reactions between the same nuclear levels. The values of $|A_0|^2 N_1^2$ obtained from such comparisons will, of course, refer to the triton but will not be expected to differ greatly from the ^{3}He particle because the internal wave functions for the triton and ^{3}He are similar.

Comparisons have been made for the following (d,t) reactions:

^{7}Li(d,t)^{6}Li.

This reaction has been studied at 14.4 Mev (Levine et al. 1955) and angular distributions of triton groups leaving ^{6}Li in its ground state and first excited state have been reported. The corresponding (p,d) reactions have been studied at 17.5 Mev (Reynolds and Standing 1956) and reduced widths have been determined using Butler theory.

We have fitted the angular distributions of tritons with Butler theory and the form factor

$$|A_0|^2 \ \frac{N_1^2}{2\pi^2} \ \frac{1}{(\lambda^2 + K^2)^2}$$

where λ^2 is related to the binding energy of the odd neutron in the triton. Good fits have been obtained using $\ell = 1$ and radii of 6.0×10^{-13}cm and 6.5×10^{-13}cm for the t_0 and t_1 group angular distributions respectively. Insertion of the appropriate reduced widths gives values of $16.7 \times 10^{12}\mathrm{cm}^{-1}$[†] and $16.4 \times 10^{12}\mathrm{cm}^{-1}$ for $|A_0|^2 N_i^2$ for the reactions leading to the ground state and first excited state of ^{6}Li respectively, these being evaluated for the peaks of the angular distributions.

^{13}C(d,t)^{12}C.

The angular distribution of the ground state triton group has been studied at 3.3 Mev and 2.2 Mev by Holmgren et al. (1954) and the (d,p) reaction between the same nuclear states has been investigated at 8 Mev (Rotblat 1951). We have fitted the angular distribution for the (d,p) reaction with Butler theory (Butler

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[†] These results differ from those of Werner (1956) and El Nadi and Abou Hadid (1958) who obtain values of $|A_0|^2 C_T^2$ of 1.8, 1.08, and 0.27 for the reactions ^{13}C(d,t)^{12}C, ^{7}Li(d,t)^{6}Li ground state and ^{19}F(d,t)^{18}F respectively. The quantity C_T^2 is apparently intended to be the same as Butler's N_i^2 used above but no units are given in either of these papers and the results are presumably intended to be expressed in units of 10^{13} cm^{-1}. Although they use the same experimental results as we do their method of calculation differs only slightly from ours and we have been unable to explain the discrepancy between their results for the ^{13}C(d,t)^{12}C and ^{7}Li(d,t)^{6}Li reactions and our own.

and Hittmair 1957) using $l = 1$, $r_0 = 5.3 \times 10^{-13}$cm and have obtained a value of about 1.0×10^{-19} erg cm for the reduced width of the captured neutron.

We have fitted the triton angular distribution at 3.3 Mev quite well with Butler theory and using the same form factor as in the ^{7}Li(d,t)^{6}Li calculation with $l = 1$, $r_0 = 5.8 \times 10^{-13}$cm but we can only achieve a poor fit with the angular distribution at 2.2 Mev. Inserting the reduced width, the factor $|A_0|^2 N_i^2$ was evaluated for the peaks of the angular distributions and was found to be about 8.8×10^{12}cm^{-1} at 3.3 Mev† and 5.8×10^{12}cm^{-1} at 2.2 Mev, the latter value being relatively more uncertain because of the poor fit with theory at this energy.

^{19}F(d,t)^{18}F.

El Bedewi and Hussein (1957) have obtained the ground state triton angular distribution at 8.9 Mev and we have obtained a good fit with this using Butler theory and the usual form factor with $l = 0$, $r_0 = 6.0 \times 10^{-13}$cm. The reduced width for the corresponding (p,d) reaction has been found at 18.9 Mev by Reynolds and Standing (1956) and using this we obtain a value of 3.2×10^{12}cm^{-1} for $|A_0|^2 N_i^2$ evaluated at 10° †.

Since in all the (^{3}He,d) and (d,t) reactions studied, with the exception of the ^{13}C(d,t)^{12}C reactions, the deuteron energy is farther above the Coulomb barrier than the mass-3 particle energy, it seemed of interest to investigate the effect of the Coulomb interaction between the nucleus and the mass-3 particle on $|A_0|^2 N_i^2$.

This is shown in figure 6 where the values of $|A_0|^2 N_i^2$ are plotted against the ratio of the energy of the mass-3 particle in the centre-of-mass system to the approximate Coulomb barrier height. The inclusion of points corresponding to the $^{13}C(d,t)^{12}C$ reaction is questionable because in this case the Coulomb potential probably has a greater effect on the deuteron than on the triton. However, the general trend of the points suggests that the Coulomb effect on the mass-3 particle is an important factor in determining the magnitudes of stripping cross sections using mass-3 particles, even at energies well above the Coulomb barrier.

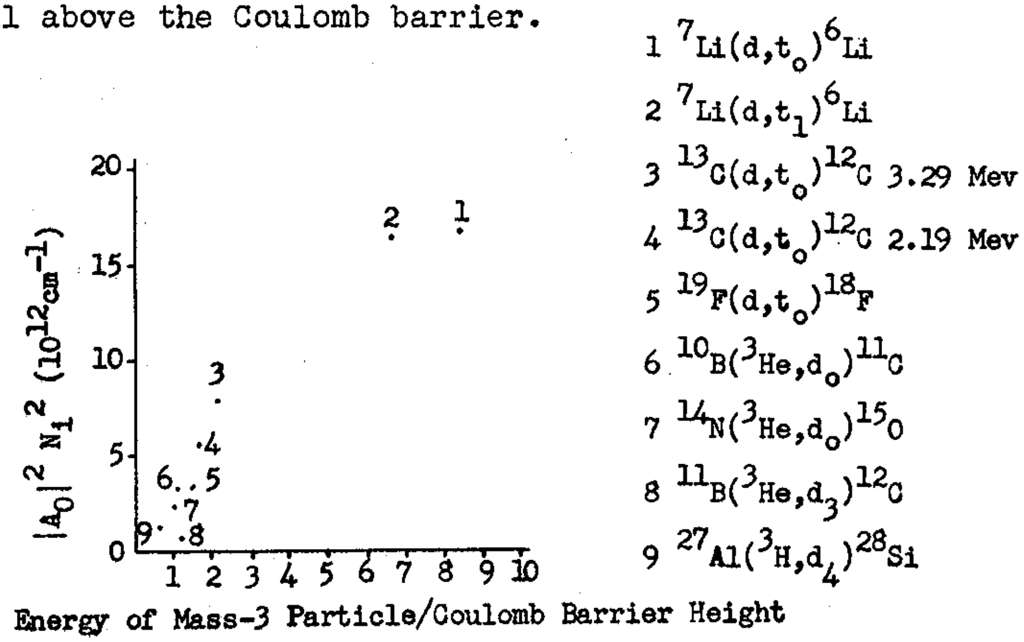

Figure 6. The variation of $|A_0|^2 N_i^2$ with the Coulomb effect on the mass-3 particle. † See footnote on previous page.

§ 5. CONCLUSIONS

The angular distributions of the (^3He, d) we have studied could be explained by an extension of the simple deuteron stripping theory provided the bombarding energy was above the

Coulomb barrier and the corresponding deuteron reaction showed good stripping. The absolute cross sections appear to be reduced below the value expected from simple theory, the reduction being largely due to the Coulomb effect on the mass-3 particle.

Thus the (^{3}He, d) reaction which can be studied at high resolution, may be used to derive useful information about nuclear levels in cases where the level structure is too complex to allow for investigation by the (d,n) reaction.

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REFERENCES

AJZENBERG-SELOVE, F., and LAURITSEN, T., 1959, Nucl.Phys., 11, 1.

BARROS, F. de S., FORSYTH, P.D., JAFFE, A.A., and TAYLOR, I.J., 1959, Proc.Phys.Soc., 73, 793.

BHATIA, A.B., HUANG, K., HYBY, R., and NEWNS, H. C., 1952, Phil. Mag., 43, 485.

BUTLER, S.T., 1951, Proc.Roy.Soc. A, 208, 559.

BUTLER, S.T., and HITTMAIR, O.H., 1957, Nuclear Stripping Reactions (London: Pitman).

BUTLER, S.T., and SALPETER, E.E., 1952, Phys.Rev., 88, 133.

CALVERT, J.M., JAFFE, A.A., LITHERLAND, A.E., and MASLIN, E.E., 1955, Proc.Phys.Soc. A, 68, 1008.

CALVERT, J.M., JAFFE, A.A. and MASLIN, E.E., 1956, Phys. Rev. 101, 501.

CERINEO, M., 1956, Nucl. Phys., 2, 113.

COOK, C.W., FOWLER, W.A., LAURITSEN, C.C., and LAURITSEN, T., 1957, Phys. Rev., 107, 508.

EL BEDEWI, F.A., and HUSSEIN, I., 1957, Proc.Phys.Soc. A, 70, 233.

EL NADI, M., and ABOU HADID, L., 1958, Nucl. Phys., 8, 51.

ENDT, P.M., and BRAAMS, C.M., 1957, Rev.Mod.Phys., 29, 683.

ENDT, P.M., and PARIS, C.H., 1957, Phys.Rev. 106, 764.

EVANS, N.T.S., and FRENCH, A.P., 1958, Phys.Rev. 109, 1272.

EVANS, N.T.S., and PARKINSON, W.C., 1954, Proc.Phys.Soc. A, 67, 684.

EVANS, W.H., GREEN, T.S., and MIDDLETON, R., 1953, Proc.Phys.Soc. A, 66, 108.

FRENCH, J.B., and FUJII, A., 1957, Phys. Rev. 105, 652.

HOLMGREN, H.D., BLAIR, J.M., SIMMONS, B.E., STRATTON, T.F., and STUART, R.V., 1954, Phys.Rev., 95, 1544.

LEVINE, S.H., BENDER, R.S., and McGRUER, J.N., 1955, Phys.Rev. 97, 1249.

MASLIN, E.E., CALVERT, J.M., and JAFFE, A.A., 1956, Proc.Phys.Soc. A, 69, 754.

NEWNS, H.C., 1952, Proc.Phys.Soc. A, 65, 916.

RAMAVATARAM, K., and PORAT, D.I., 1959, Nucl.Instrum., 4, 239.

REYNOLDS, J.B., and STANDING, K.G., 1956, Phys.Rev. 101, 158.

ROTBLAT, J., 1951, Nature, Lond., 167, 1027.

RUBIN, A.G., 1957, Phys.Rev., 108, 62.

SALPETER, E.E., 1957, Phys.Rev. 107, 516.

WARBURTON, E.K., and McGRUER, J.N., 1957, Phys.Rev., 105, 639.

WERNER, A., 1956, Nucl.Phys., 1, 9.

WILKINSON, D.H., 1957, Phys.Rev., 105, 666.

ZEIDMAN, B., and FOWLER, J.M., 1958, Phys. Rev., 112, 2020.

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