Angular Distributions of Deuterons from (p,d) Reactions in Light Nuclei. II. Lithium, Beryllium, Boron, Fluorine, and Aluminum*

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Angular distributions of deuteron groups resulting from the bombardment of various elements with ~18-Mev protons have been observed. Angular distributions for reactions leading to the following final nuclei were studied: Li^6, Li^{6*} (2.2 Mev), Be^8, B^9, B^{9*} (2.4 Mev), B^{10}, F^{18}, Al^{26}. The observed data are fitted to theoretical (Butler) curves and in all cases, except F^{18} and Al^{26}, l_n (the angular momentum carried away by the picked up neutron) is found to be unity. For F^{18} and Al^{26}, l_n is found to be 0 and 2 respectively. Absolute cross-section measurements for some of the reactions are given and are compared with theory.

A. INTRODUCTION

The present paper is a continuation of the preceding one.[1] Presented here are the results of measurements of deuteron angular distributions resulting from proton bombardment of the following elements: Li^7, Be^9, B^{10}, B^{11}, F^{19}, and Al^{26}. Since the general experimental method has been discussed in detail in I, we will proceed directly to a summary of results, mentioning only those procedural details which were peculiar to individual targets.

The errors shown by the flags on the experimental angular distribution curves are compounded of two parts. These are (1) the standard deviation of the total number of deuteron counts taken at the particular angle and (2) an estimated uncertainty in subtracting the proton background from the deuteron spectrum. Item (2) varied with the angle of observation and the element being studied.

Shown with the experimental angular distributions are theoretical ones calculated from the theory of Butler.[2] Values of Butler's parameters l_n and r_0 were chosen to give the best fit to the experimental data while making r_0 as nearly as possible equal to $1.7+1.2A^{\frac{1}{3}}$ (in units of 10^{-13} cm; these units for r_0 will be used throughout the paper) where A is the mass number of the target nucleus. Except in the case of lithium, the theoretical curves were normalized to the experimental points by the method of least squares using only data for angles less than 40°.

To give an indication of the background and associated problems in each reaction, Fig. 1 (see also Fig. 7) shows some typical spectra. Also shown in each case are estimated backgrounds determined, as described in I, Sec. B, by interposing sufficient absorber in the deuteron path to move the deuteron group to a different position in the spectrum. The strong background in the spectrum of deuterons leaving Li^{6*} in the first excited state was attributed to deuterons, tritons, and alphas from the breakup of Li^{6*} and Be^8. This background prevented a study of the Li^6 second excited state.

B. RESULTS AND DISCUSSION OF INDIVIDUAL REACTIONS

$Li^7(p,d)Li^6$

Results

A foil of lithium having a thickness of 1.3 mg/cm² was used as a target. The foil was rolled to this thickness

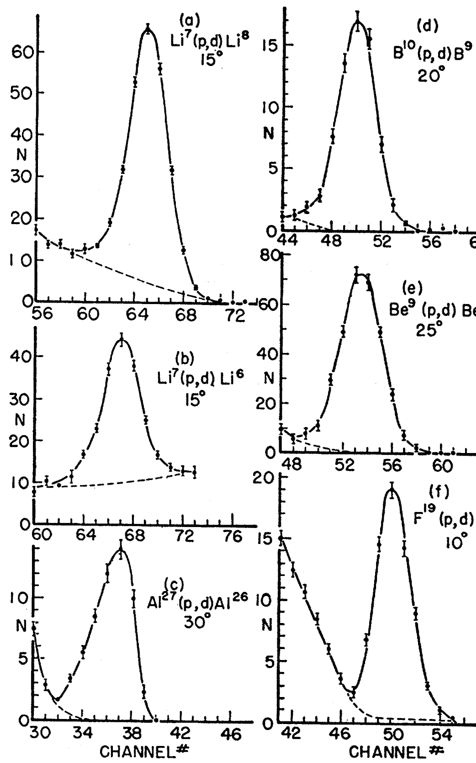

FIG. 1. Typical deuteron spectra for several elements. N is the number of counts per channel for a given number of incident protons. The relative heights of the various spectra are not meaningful in this figure. Estimated backgrounds are indicated by dashed lines. [*Note.*—Li^8 in (a) should read Li^6. Li^6 in (b) should read Li^{6*}.]

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[1] K. G. Standing, preceding paper [Phys. Rev. **101**, 152 (1955)], hereafter referred to as I.

[2] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).

under Nujol and was washed in n-decane immediately before being placed in the evacuated scattering chamber.

The levels studied in Li^6 were the ground state and the first excited state[3] (2.2 Mev). Figures 2 and 3 show the angular distributions. In both cases a theoretical fit was obtained for $r_0=5.5$ and l_n equal to unity. Assuming the Li^7 ground state to have $J=\frac{3}{2}$ (odd) this gives even parity and $J=0$, 1, 2, or 3 for both Li^6 states. The absolute cross section for the reaction leading to the Li^6 ground state was found to be (in the center-of-mass system) 17 ± 4 mb/sterad at the maximum of the angular distribution. The ratio of the ground-state differential cross section at the maximum to the excited state differential cross section at the maximum (both in the c.m. system) was found to be 2.0 ± 0.2.

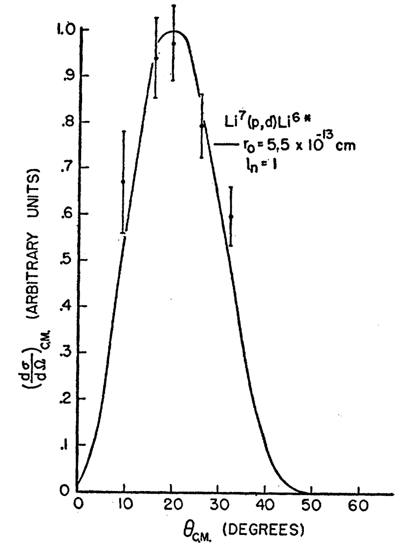


FIG. 3. Angular distribution of deuterons from the reaction $Li^7(p,d)Li^{6*}$ (2.2-Mev state). $E_p(\mathrm{lab})=17.5$ Mev.

Discussion

The results given above for spins and parities are consistent with previous observations.[3]

Reduced widths[4] as calculated from Butler's theory and the observed absolute cross sections are $\theta_g^2=0.05$ for the reaction leaving Li^6 in the ground state and $\theta_e^2=0.035$ for the first exicted state.

As discussed in I (Sec. A and Sec. D.2), the experimental reduced widths for stripping (or pickup) reactions, determined from the Butler theory, do not agree with the theoretical reduced widths calculated from the nuclear shell model. There is some indication that this disagreement is due to the neglect in Butler's theory of Coulomb and nuclear scattering effects. The calculations of Tobocman and Kalos[5] show that corrections due to the inclusion of such effects, for the reaction $F^{19}(d,p)F^{20}$, can increase the observed reduced widths by a factor of 2 to 6.

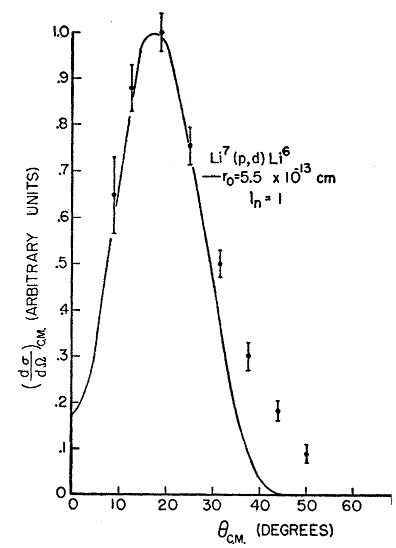


FIG. 2. Angular distribution of deuterons from the reaction $Li^7(p,d)Li^6$ (ground state). E_p (lab)$=17.5$ Mev.

Table I compares experimental reduced widths for several stripping and pick-up reactions in lithium with the shell model theoretical predictions. The experiments represented are the present one and that of Levine, Bender and McGruer[6] who studied the reactions $Li^6(d,p)Li^7$ and $Li^7(d,p)Li^8$. The experimental θ^2 were calculated using Butler's theory and the observed cross sections. The theoretical θ^2 were calculated in $L-S$ and $j-j$ coupling limits using Lane's[7] theoretical expression for θ^2/θ_0^2, where θ_0^2 is the single particle reduced width (reduced width for a single nucleon in a potential well). The calculations of Lane[7,8] for θ_0^2 for the $1p$ shell give values ranging from 0.2 to 0.5 (our units) depending on the binding energy of the stripped or pick-up particle to the parent nucleus. For the qualitative considerations of Table I we have taken θ_0^2 to be constant and equal to 0.3.

One sees from Table I that inclusion of corrections for Coulomb and nuclear scattering in the stripping theory would bring the experimental reduced widths for lithium into qualitative agreement with theory (at least in the $L-S$ coupling limit; intermediate coupling calculations, see below, indicate that in lithium one is quite close to $L-S$ coupling). This assumes the Tobocman-Kalos corrections to be the same for lithium as for fluorine. The assumed $L-S$ coupling configurations in Table I are those suggested by Inglis.[9]

While the approximate nature of Butler's theory limits the usefulness of the absolute stripping cross sections, Lane[7] has pointed out [in connection with the

[3] The reference used throughout this paper (except for Al^{26}) as to positions, spins, and parities of nuclear energy levels is F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[4] See I, Sec. A, for notation and references regarding reduced widths. Note that the definition of θ^2 used in this paper and in I is $\theta^2=2Mr_0\gamma^2/3\hbar^2$, where γ^2 is the usual reduced width.

[5] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).

[6] Levine, Bender, and McGruer, Phys. Rev. **97**, 1249 (1955).

[7] A. M. Lane, Proc. Phys. Soc. (London) **A66**, 977 (1953).

[8] A. M. Lane, Atomic Energy Research Establishment (Harwell) Report T/R 1298 (unpublished).

[9] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).

TABLE I. Experimental and theoretical reduced widths for stripping reactions in lithium.[a]

Reaction	Assumed initial spin	Assumed final spin	Assumed transition in $L-S$ coupling	Theoretical θ^2/θ_0^2 $L-S$ coupling	Theoretical θ^2/θ_0^2 $j-j$ coupling	Experimental θ^2	$\frac{\theta^2(\text{theor.})}{\theta^2(\text{exp.})}$ $L-S$ coupling	$\frac{\theta^2(\text{theor.})}{\theta^2(\text{exp.})}$ $j-j$ coupling
$Li^7(p,d)Li^6(0)$	$\frac{3}{2}$	1	$^{22}P-^{13}S$	0.83	0.45	0.05	5	3
$Li^7(p,d)Li^{6*}(2.19)$	$\frac{3}{2}$	3	$^{22}P-^{13}D$	0.47	1.05	0.035	4	9
$Li^6(d,p)Li^7(0)$	1	$\frac{3}{2}$	$^{13}S-^{22}P$	0.83	0.45	0.05	5	3
$Li^6(d,p)Li^{7*}(0.98)$	1	$\frac{1}{2}$	$^{13}S-^{22}P$	0.83	1.5	0.075	3	6
$Li^7(d,p)Li^8(0)$	$\frac{3}{2}$	2	$^{22}P-^{33}P$	1.1	2.4	0.045	7	16
$Li^7(d,p)Li^{8*}(0.97)$	$\frac{3}{2}$	1	$^{22}P-^{33}P$	0.4	0.27	0.024	5	3

[a] Data on pick-up reactions are from this paper. Cross sections for stripping reactions were taken from reference 6. θ_0^2 was taken to be 0.3 for all reactions.

reaction $C^{12}(d,p)C^{13}$] that the ratio, θ_g^2/θ_e^2, of reduced widths for neutron emission from a ground state and from an excited state of the same nucleus as measured by stripping agrees with θ_g^2/θ_e^2 as measured by resonance scattering. This indicates the possibility (also observed by Lane) that the corrections to the Butler theory are nearly the same for stripping reactions leading to different states of the same final nucleus and may therefore cancel out when ratios are taken. In view of this it seems of interest to compare the observed θ_g^2/θ_e^2 for the lithium reactions with the theoretical ratios.

Table II shows observed θ_g^2/θ_e^2 for this experiment as well as for the stripping experiments of Holt and Marsham[10] who give data from which θ_g^2/θ_e^2 can be determined for the reactions $Li^6(d,p)$ leaving Li^7 in the ground state and the 0.49-Mev state. Also shown are the ratios calculated from the data of Levine *et al.*[6] for the reactions $Li^6(d,p)Li^7$ (ground and 0.49-Mev states) (with different deuteron energy than that used by Holt and Marsham) and $Li^7(d,p)Li^8$ (ground and 0.97-Mev states). In addition Table II gives theoretical values of θ_g^2/θ_e^2 calculated from Lane's theory[7,8] in the limits of $L-S$ and $j-j$ coupling. The single-particle reduced widths, θ_0^2, are assumed to be the same for ground and first excited states and the assumed $L-S$ transitions are those suggested by Inglis.[9] In the case of reactions involving Li^6 and Li^7 the spins of all participating states are quite well known and the calculations are unambiguous. It will be noticed that in each case the observed ratio θ_g^2/θ_e^2 is bracketed by the calculated ratios for the two coupling extremes. Ajzenberg and Lauritsen[3] list the spin of the Li^8 ground state as 2 (not certain) and the spin of the first excited state as $\leqslant 3$. Two values of θ_g^2/θ_e^2 were calculated, assuming an excited state spin of 1 (^{33}P state in $L-S$ coupling) and also a spin of 3 (^{33}D $L-S$ state). In both cases, the observed ratio is bracketed by the theoretical ones.

The above results are in agreement with detailed intermediate coupling calculations for lithium which have been done by Auerbach and French[11] and Lane[12] The results of Auerbach and French may be summarized as follows: For the ratio of differential cross sections for the reactions $Li^7(p,d)$ leading to the ground and first excited states of Li^6 (as determined by the present experiment) agreement with theory is found using an intermediate coupling parameter ζ (=Inglis'[9] a/K) such that $1.4 \leqslant \zeta \leqslant 2.1$. For Holt and Marsham's result for the ratio of the $Li^6(d,p)Li^7$ and $Li^6(d,p)Li^{7*}$ cross sections, agreement with theory is found by taking $2.3 \leqslant \zeta \leqslant 3.5$. Lane finds agreement of theory with 12 experimental data in lithium by taking $2 \leqslant \zeta \leqslant 4$.

The agreement (within experimental error) between the observed values of θ_g^2/θ_e^2 for the same $Li^6(d,p)Li^7$ reactions for two quite different deuteron energies (see Table I) is to be noticed. It indicates, among other things, that the assumption of cancellation of Butler theory corrections for such ratios is not a bad one.

It may be noted here that the $Li^7(p,d)Li^6$ (ground state) cross section as determined by the present

TABLE II. Comparison of observed and calculated values of θ_g^2/θ_e^2 for stripping and pick-up reactions in lithium.[a]

Reaction	Initial spin	Final spin g	Final spin e	Observed θ_g^2/θ_e^2	Transition in $L-S$ limit to g	Transition in $L-S$ limit to e	Calculated θ_g^2/θ_e^2 $L-S$ limit	Calculated θ_g^2/θ_e^2 $j-j$ limit	Reference
$Li^7(p,d)Li^6$	$\frac{3}{2}$	1	3	1.4	$^{22}P-^{13}S$	$^{22}P-^{13}D$	1.77	0.42	b
$Li^6(d,p)Li^7$	1	$\frac{3}{2}$	$\frac{1}{2}$	0.69	$^{13}S-^{22}P$	$^{13}S-^{22}P$	1.0	0.3	c
$Li^6(d,p)Li^7$	1	$\frac{3}{2}$	$\frac{1}{2}$	0.66	$^{13}S-^{22}P$	$^{13}S-^{22}P$	1.0	0.3	d
$Li^7(d,p)Li^8$	$\frac{3}{2}$	2	1	1.83	$^{22}P-^{33}P$	$^{22}P-^{33}P$	1.66	9.0	d
$Li^7(d,p)Li^8$	$\frac{3}{2}$	2	3	4.4	$^{22}P-^{33}P$	$^{22}P-^{33}D$	2.8	9.0	d

[a] g refers to ground state of the final nucleus and e refers to the excited state. In each case the excited state involved was that indicated by Ajzenberg and Lauritsen (reference 3) as being the first excited state.
[b] This paper, $E_p=17.5$ Mev.
[c] J. R. Holt and T. N. Marsham, reference 10, $E_d=8$ Mev.
[d] Levine, Bender, and McGruer, reference 6, $E_d=14.4$ Mev.

[10] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 1032 (1953).
[11] T. Auerbach and J. B. French, Phys. Rev. **98**, 1276 (1955).
[12] A. M. Lane, Proc. Phys. Soc. (London) **A68**, 189 (1955).

experiment agrees with the $Li^6(d,p)Li^7$ (ground state) cross section as determined by Levine *et al.* Since the reaction energy is nearly the same in each case, application of detailed balancing predicts a ratio $\sigma(d,p)/\sigma(p,d)=1.31$. Experimentally, the ratio is (at the peak of the angular distributions) $17/12.8=1.33$, in considerably better agreement than is warranted by the experimental uncertainties.

$Be^9(p,d)Be^8$

Results

The Be^9 target consisted of a 4.9 mg/cm² beryllium foil. Deuteron groups were observed corresponding to Be^8 being left in the ground state and the 2.90-Mev state. The latter state is so broad as to make it impractical to study by our method. No data on it are presented here. The angular distribution of deuterons leaving Be^8 in the ground state is shown in Fig. 4. Also shown in Fig. 4 are possible theoretical curves for this reaction. While the curve for $l_n=1$ gives a somewhat better fit than the one for $l_n=2$ it is not entirely clear (on the basis of the data alone) that the latter is not the correct one. In most cases, where two theoretical curves fit the experimental stripping data, r_0 as determined by one of them will have a more reasonable value than that determined by the other and a choice can be made on basis. Holt and Marsham[10] and others have used the empirical rule that the correct r_0 is that which is closest to $1.7+1.2A^{\frac{1}{3}}$. According to this the curve for $r_0=3(l_n=1)$ in Fig. 4 would be the correct one. However, an

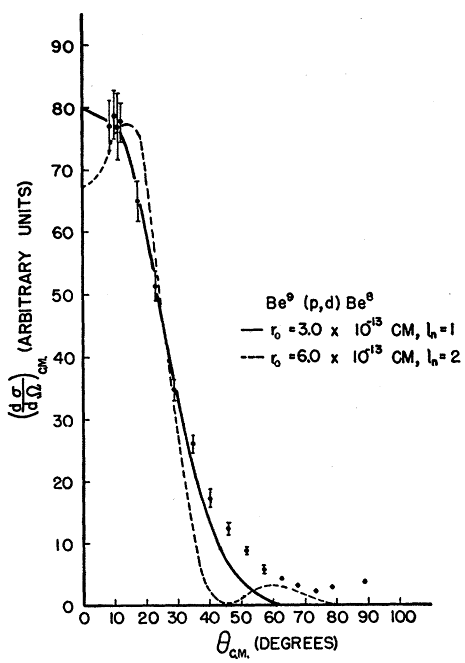
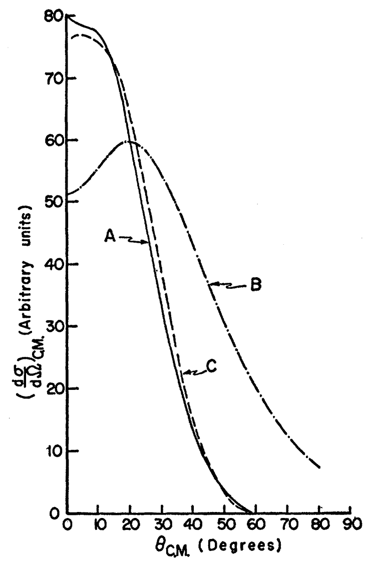


FIG. 4. Angular distribution of deuterons from the reaction $Be^9(p,d)Be^8$ (ground state). Two possible theoretical curves are shown. E_p(lab)$=16.5$ Mev.

FIG. 5. Theoretical angular distributions for $Be^9(p,d)Be^8$. All curves are for $l_n=1$. Curve A is for $r_0=3$ and E_p(lab) $=16.5$ Mev. Curve B is for $r_0=3$ and E_p(lab) $=4.8$ Mev, while curve C is for $r_0=6$ and E_p(lab)$=4.8$ Mev. The experimental angular distributions are the same, within experimental error, for proton energies of 4.8 and 16.5 Mev and are quite well represented by curve A. Butler's theory predicts quite different distributions (A and B) for given r_0 and different E_p; however, agreement between theory and experiment can be obtained by letting r_0 vary with E_p. This is illustrated by the similarity of curves C and A.



equally good (perhaps better) criterion would seem to be that r_0 be chosen as nearly as possible equal to the average of r_0 for stripping reactions in neighboring elements of about the same A. In the vicinity of Be the average r_0 is 4.88 (see Fig. 13); thus a choice of $r_0=6$ $(l_n=2)$ would be indicated.

Fortunately, the spin-parity assignments of Be^8 and Be^9 are already quite well established[3] as being 0 (even) and $\frac{3}{2}$ (odd) respectively, and we therefore take the $l_n=1$, $r_0=3$ curve in Fig. 4 as being the correct one. If there were grave doubt as to the correct theoretical curve, a choice could probably be made in this case by obtaining more and better experimental data for angles $<10°$, thus determining whether the observed cross section continues to increase $(l_n=1)$ or decreases $(l_n=2)$ as θ becomes small. A fit of the data with any l_n other than the two considered above was ruled out by the extreme values of r_0 required.

The absolute cross section in the c.m. system for $Be^9(p,d)Be^8$ at $\theta=23°$ was found to be 11 ± 2 mb/sterad.

Discussion

Our observed angular distribution for $Be^9(p,d)Be^8$ agrees in shape, within experimental error, with that obtained by Cohen *et al.*[13] using 22-Mev protons and with that obtained by Harvey[14] using 5- to 8-Mev protons. That is, the angular distribution appears to be independent of energy over a range of from 5 to 22 Mev. Such a result cannot be explained by Butler's theory if one assumes r_0 to be the same for all proton energies. Figure 5 illustrates this fact. Curves A and B are both theoretical curves for $l_n=1$. Curve A is for E_p

[13] Cohen, Newman, Handley, and Timmick, Phys. Rev. **90**, 323 (1953).

[14] As quoted by Cohen *et al.* (reference 13); see their Fig. 1. See also J. A. Harvey, Massachusetts Institute of Technology Progress Report NP-3434, October 1, 1950 (unpublished).

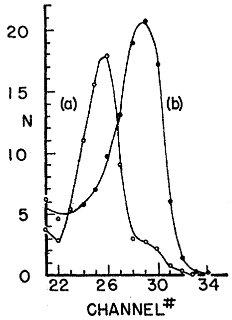


FIG. 6. Deuteron spectra taken under identical conditions except that for (a) a natural boron foil was used (main peak is due to deuterons from $B^{11}(p,d)B^{10}$) and for (b) enriched (97%) B^{10} foil was used [main peak due to deuterons from $B^{10}(p,d)B^{9*}$ (2.4-Mev state)].

$=16.5$ Mev (lab system), $r_0=3$, and was found, in Fig. 4, to fit the data of the present experiment (and hence of all 3 experiments) quite well. Curve B is for $E_p=5$ Mev, $r_0=3$, and one sees that it agrees poorly with curve A (and hence with the experimental data) as would be expected. We find, however, that choice of a higher value of r_0 for the low-energy data brings theory and experiment into agreement. Curve C of Fig. 5 is for $l_n=1$, $r_0=6.0$ and $E_p=5$ Mev. One sees that this choice of r_0 gives as good agreement of theory and experiment for $E_p=5$ Mev as does the choice $r_0=3.0$ for $E_p=16.5$ Mev. Similarly, for the 22-Mev data a good fit of theory to experiment was obtained for $r_0=2.5$, although, in this case, $r_0=3.0$ gave fair agreement. Such large variations in r_0 are not usually found necessary to fit data at different energies. For example, Holt and Marsham[10] using $E_d=8$ Mev were able to fit their $Li^6(d,p)$ data with $r_0=4.9$ while Levine *et al.*[6] using $E_d=14.4$ Mev were able to fit data for the same reaction with $r_0=5.4$.

It will be noted, however, that for the reaction $Li^7(d,p)Li^8$, the 8-Mev data[10] required $r_0=5.3$ while the 14.4-Mev data[6] required $r_0=4.2$. This is the same trend observed above for $Be^9(p,d)$. It is possible that this behavior may be attributed to the fact that in both reactions the binding energy of a neutron to the parent nucleus is low, combined with evidence[15,16] that the Butler theory loses validity for very low binding energies of the stripped (or pickup) particle.

Using the observed differential cross section and Butler's theory one obtains an experimental reduced width for this reaction of $\theta^2=0.024$. The theoretical predictions[7] for this case are $\theta^2/\theta_0^2=0.67$ in the $L-S$ coupling limit and $\theta^2/\theta_0^2=0.5$ in the $j-j$ coupling limit. If one assumes (see discussion of lithium above) $\theta_0^2=0.3$, the theoretical θ^2 are 0.2 and 0.15 respectively. Again assuming the factor by which one miltuplies the observed θ^2 to account for corrections to the Butler theory to be the same here as for $F^{19}(d,p)F^{20}$ (Tobocman and Kalos[5]), one finds qualitative agreement of theoretical and experimental reduced widths.[17]

$B^{10}(p,d)B^9$

Results

B^{10} and B^{11} targets were prepared[18] by suspending finely powdered boron in a solution of polystyrene in benzene. The mixture was poured out on water and allowed to evaporate, leaving polystyrene film with boron imbedded in it. The very high threshold for the (p,d) reaction in C^{12} and O^{16} renders these elements unobjectionable in target backing materials as far as undesired deuteron groups are concerned. Their presence does contribute to the proton background, making it desirable to reduce the ratio of polystyrene to boron in the target film. The B^{10} used was isotopically enriched and contained $\sim$97% B^{10}.

Identification of the deuteron group leaving B^9 in the ground state was unambiguous since this group was well separated from any others. However, the Q's for the reactions $B^{10}(p,d)B^{9*}$ (2.4 Mev) and $B^{11}(p,d)B^{10}$ (ground state) are nearly the same so that the two resulting deuteron groups overlapped somewhat. Figure 6 illustrates the identification of these groups. Curves (a) and (b) were taken under identical conditions except that for (b) the 97% B^{10} foil was used and for (a) a natural boron foil ($\sim$80% B^{11}) was used. The measured energy difference between the peaks checked with that to be expected from the known Q-difference for the two reactions. As a further check the excitation energy of the B^9 excited state was calculated from the measured energies of the two B^9 deuteron groups and was found to be 2.40 ± 0.15 Mev in agreement with previous measurements.[3] Figure 7 illustrates the procedure used in separating the contributions of the $B^{10}(p,d)B^{9*}$ and $B^{11}(p,d)B^{10}$ reactions to the deuteron spectra. Curve (a)

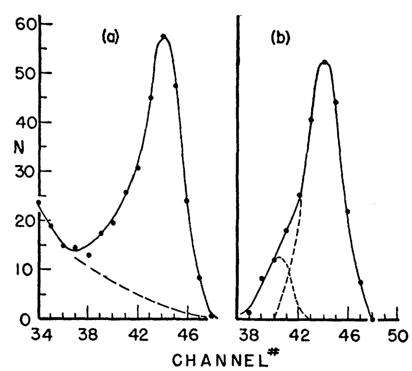


FIG. 7. Subtraction of the $B^{11}(p,d)B^{10}$ deuterons from the B^{10}-$(p,d)B^{9*}$ spectrum. (a) Total spectrum, background shown dashed. (b) Spectrum with background subtracted showing decomposition into components due to $B^{10}(p,d)B^{9*}$ (right) and $B^{11}(p,d)B^{10}$ (left).

[15] Bhatia, Huang, Huby, and Newns, Phil. Mag. 43, 485 (1952).

[16] R. Huby, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, London, 1953), Chap. 7.

[17] The recently published work of J. E. Bowcock, Proc. Phys. Soc. (London) A68, 512 (1955) may open the way to more easily obtainable quantitative results for the stripping absolute reduced widths. Bowcock gives a procedure for reduced width determination by comparison with Butler theory in such a way that corrections due to proton-nucleus interaction are taken into account (presumably in such a manner that the calculations are much less laborious than are the corresponding ones in the Tobocman-Kalos theory which requires rather extensive computer programing).

[18] This method was suggested by Dr. Fay Ajzenberg.

shows the raw results of a run at $\theta = 25°$ as well as a background run. Curve (b) shows the spectrum with background subtracted and also shows the decomposition of the spectrum into the $B^{11}(p,d)$ peak and the $B^{10}(p,d)$ peak. The decomposition was effected by observing that the B^{11} peak contributes little to channels 42–46. The B^{10} peak was accordingly obtained by reflecting the spectral curve for channels greater than 43 in channel 43 to give a symmetrized spectrum. The B^{11} spectrum shown in Fig. 7(b) was obtained by subtracting the symmetrized B^{10} spectrum from the total. The two peaks so obtained each resemble, both in width and in shape, the peaks normally observed for a single deuteron group. A similar procedure to the above was used to subtract the unwanted B^{10} deuterons from the B^{11} deuterons when a natural boron target was used to measure the $B^{11}(p,d)B^{10}$ (ground state) angular distribution. In both cases the undesired group was appreciably smaller than the desired group.

Figures 8 and 9 show the angular distributions obtained for deuterons leaving B^9 in the ground and 2.4-Mev states respectively. Best fits to theory for both states are given by $l_n = 1$ and $r_0 = 4.5$. Accepting the rather well established assignment[3] of $J = 3$ (even) for the B^{10} ground state, one obtains negative parity and $\frac{1}{2} < J \leqslant 9/2$ for the two B^9 states. The ratio in the c.m. system of the $B^{10}(p,d)B^9$ ground-state differential cross section to the excited state differential cross section, both taken at 24°, was found to be $\sigma/\sigma' = 1.65 \pm 0.15$.

Discussion

No previous information exists on the spins and parities of levels in B^9. The B^9 ground state would be

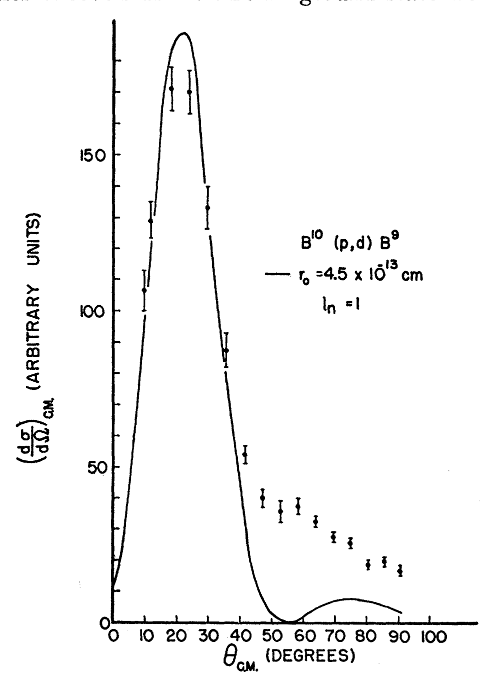


FIG. 8. Angular distribution of deuterons from the reaction $B^{10}(p,d)B^9$ (ground state). E_p(lab) = 18.9 Mev.

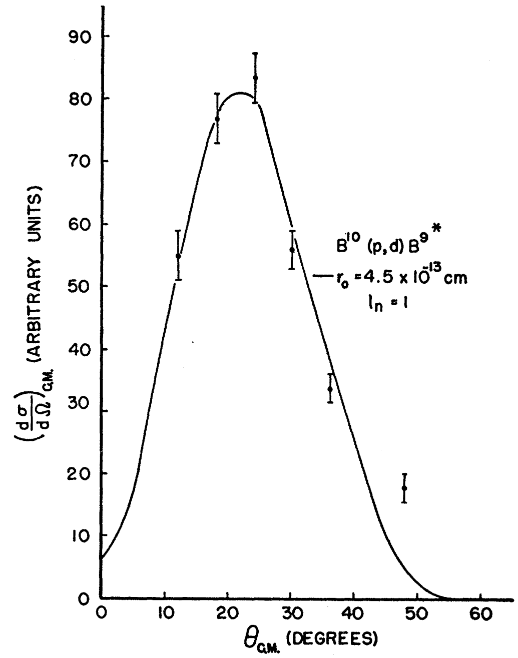


FIG. 9. Angular distribution of deuterons from the reaction $B^{10}(p,d)B^{9*}$ (2.4-Mev state). E_p(lab) = 18.9 Mev.

expected to have the same properties as its mirror state in Be^9 which is known to have $J = \frac{3}{2}$ and odd parity.[3] Of interest here are the results of Ribe and Seagrave[19] who observed the "mirror" reaction $B^{10}(n,d)Be^9$. They studied the two analogous levels in Be^9 with the same results as reported above for $B^{10}(p,d)B^9$, i.e., $l_n = 1$ for the deuteron groups leaving the final nucleus in both the ground and first excited states. They also found the best fit of their data to theory to be given by $r_0 = 4.5$.

French, Halbert and Pandya[20] have carried out intermediate coupling calculations for pick-up reactions on B^{10}. They find good agreement of theory with our value of σ/σ' (quoted above) for $B^{10}(p,d)B^9$, as well as the corresponding σ/σ' for $B^{10}(n,d)Be^9$ (as measured by Ribe and Seagrave), by using an intermediate coupling parameter $\zeta = 1.4$ for the mass 9 nuclide and $\zeta = 3.8$ for B^{10}. These values of ζ are the ones which were also found to give agreement between theory and experiment for several other data, such as the $Be^9 - B^9$ energy level scheme and the Be^9 magnetic dipole moment and electric quadrupole moment.

$B^{11}(p,d)B^{10}$

Target preparation and identification of the deuteron group leaving B^{10} in the ground state are discussed under $B^{10}(p,d)B^9$. The angular distribution is shown in Fig. 10. The assignment $l_n = 1$ is in agreement with $J = 3$ (even) for the B^{10} ground state and $J = \frac{3}{2}$ (odd) for the B^{11} ground state.[3]

[19] F. L. Ribe and J. D. Seagrave, Phys. Rev. 94, 934 (1954).
[20] French, Halbert, and Pandya, Phys. Rev. 99, 1387 (1955).

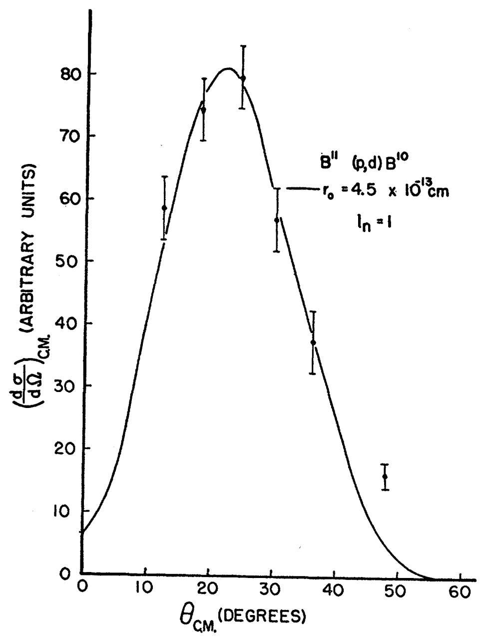


FIG. 10. Angular distribution of deuterons from the reaction $B^{11}(p,d)B^{10}$. E_p(lab) = 18.9 Mev.

$F^{19}(p,d)F^{18}$

Results

Teflon (CF_4) foil 11.9 mg/cm² thick was used as the F^{19} target. Only the deuteron group leaving F^{18} in the ground state was studied. The measured Q was -8.12 ± 0.2 Mev as compared to a value of -8.18 given by Ajzenberg and Lauritsen.[3] Since the first excited state of F^{18} is 1.08 Mev above the ground state, the identification of the deuteron group is quite certain.

Figure 11 shows the observed angular distribution. Parameters necessary to give a fit with theory were $r_0 = 5.0$ and $l_n = 0$. If one assumes the F^{19} ground state to have $J = \frac{1}{2}$ (even), the F^{18} ground state has either $J = 0$ (even) or $J = 1$ (even).

The differential cross section in the c.m. system at 11° was found to be 8.5±1.5 mb/sterad.

Discussion

The assignment $J = 1$ (even) for F^{18} appears to be a reasonable one since odd-odd nuclei seldom seem to have $J = 0$ and since $J = 1$ (even) is consistent with the β decay of F^{18}. The experimental reduced width for this reaction was found to be 0.009.

Nuclear levels in this region are known[21] to be linear combinations of single particle orbitals of the form (for mass 18) $(1d)^{2-x}(2s)^x$, where x can be 0, 1 or 2. The presence of quite large percentages of $(1d)^2$, $(1d)(2s)$ and $(2s)^2$ configurations in F^{18} as well as large percentages of $(1d)^2(2s)$, $(1d)(2s)^2$, and $(2s)^3$ configurations in F^{19} makes the $l_n = 0$ angular distribution possible. The reduced width for the $l_n = 2$ distribution is no doubt also large but it is suppressed by the kinematical features of the Butler theory which emphasize the lower values of l_n.

$Al^{27}(p,d)Al^{26}$

The target consisted of a 2.93-mg/cm² Al foil. One deuteron group was observed. It is probable that it consisted of deuterons leaving Al^{26} in any or all of the three lowest states shown in Fig. 2 of the paper by Kavanagh, Mills, and Sherr.[22] Our resolution was not sufficiently good to separate deuteron groups corresponding to any two of these states. Using the mass defects of Al^{27} and Mg^{26} given by Endt and Kluyver[23] and the data of Kavanagh *et al.*, one calculates -10.82 Mev for the Q of the $Al^{27}(p,d)$ reaction leading to the β decaying state of Al^{26}. The measured Q for this reaction was -10.8 Mev.

Figure 12 shows the angular distribution. A fit with theory was obtained for $r_0 = 5.0$ and $l_n = 2$. This is consistent with one or more of the states in Al^{26} having the same parity as Al^{27} and any integral spin less than 6. The observed differential cross section in the c.m. system at 32° was 1.9±0.4 mb/sterad.

C. THE PARAMETER r_0

Figure 13 compares the values of r_0 found necessary to give best agreement between experiment and theory

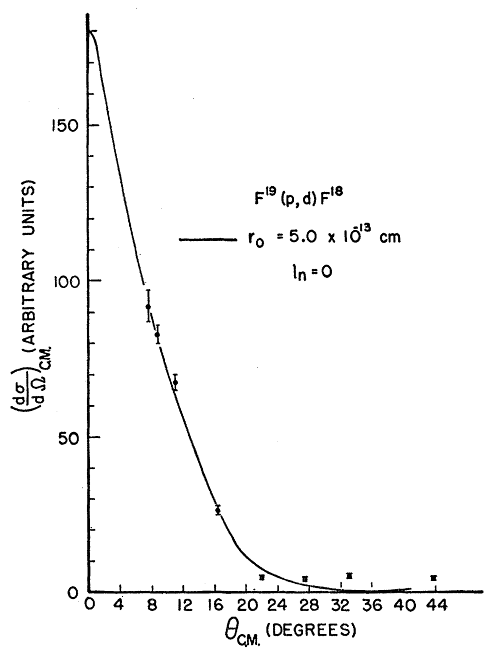


FIG. 11. Angular distribution of deuterons from the reaction $F^{19}(p,d)F^{18}$. E_p(lab) = 18.9 Mev.

[21] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955); M. Redlich, Phys. Rev. **98**, 199 (1955) and to be published.

[22] Kavanagh, Mills, and Sherr, Phys. Rev. **97**, 248 (1955).

[23] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

in the present experiment and in several stripping experiments. The points obtained from this experiment are in general agreement with the others. In all cases except $Be^9(p,d)$ (discussed in Sec. B) determinations of l_n by either of the following two methods agreed with one another and were unambiguous: (1) l_n and r_0 should be chosen to fit the data and to make r_0 as nearly as possible equal to $1.7+1.2A^{\frac{1}{3}}$ (Holt and Marsham[9]). (2) The parameters should be chosen to fit the data and make r_0 as nearly as possible equal to $a+bA$, where $a=4.37$ and $b=0.042$ are chosen by least squares fitting a straight line to the data of Fig. 13. From an empirical point of view procedure (2) would seem to be the preferable one of the two despite the fact that for the data of this experiment it apparently gives the wrong answer for the (peculiar) reaction $Be^9(p,d)Be^8$ (see Sec. B).

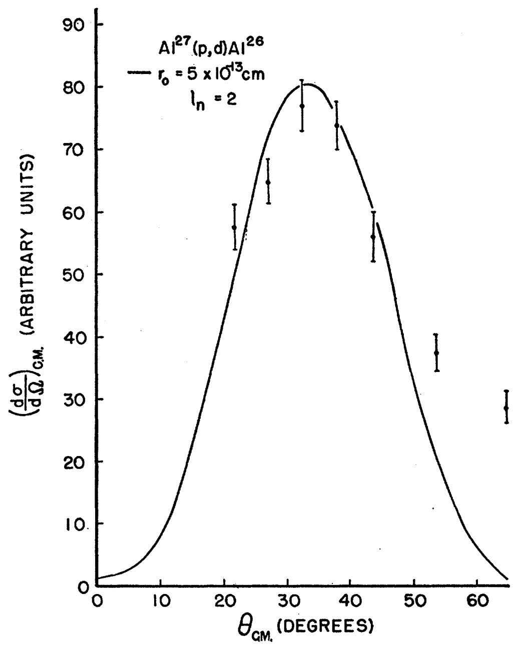


FIG. 12. Angular distribution of deuterons from the reaction $Al^{27}(p,d)Al^{26}$. E_p(lab)=18.9 Mev.

The agreement of the values of r_0 determined for the reactions $B^{10}(n,d)$ and $B^{10}(p,d)$ have already been mentioned (in Sec. B), as well as the variation with energy of r_0 for the reactions $Li^7(d,p)Li^8$ and $Be^9(p,d)Be^8$. There seems also to be some indication of r_0 being energy-dependent in the reaction[6,10] $Li^6(d,p)Li^7$. Here the binding energy of a neutron in Li^7 is quite high and r_0 appears to decrease with decreasing deuteron energy

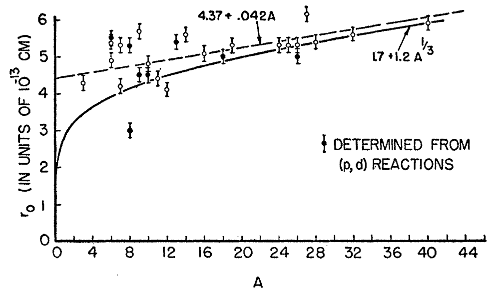


FIG. 13. Values of r_0 as determined from stripping and pick-up reactions. Solid circles represent values from pick-up reactions. r_0 is plotted as a function of the A of the target nucleus for stripping reactions and the A of the final nucleus for pick-up reactions. The upper point at $A=8$ (determined from the data of Harvey[14]) should be at $r_0=6.0$ rather than 5.3.

[as opposed to the situation in $Li^7(d,p)$ and $Be^9(p,d)$]. The value of r_0 as determined by Holt and Marsham for the reaction $Be^9(d,p)Be^{10}$ is 5.7 while the value from the present experiment for $B^{10}(p,d)B^9$ is 4.5. This difference is presumably due to the fact that the state in the $A=10$ nucleus is $T=1$ in one case and $T=0$ in the other. It is difficult to explain so large a difference in radii by the difference in nuclear states since in most cases the same r_0 fits theory to data for excited states as well as the ground state of the final nucleus. The alternative explanation of the difference is that there are considerably different corrections to the Butler theory for the two reactions. Tobocman and Kalos[5] find that in the more precise calculation for $F^{19}(d,p)F^{20}$, consideration of Coulomb effects changes r_0 appreciably. However, in that instance the nuclear scattering corrections compensate to give about the same r_0 for the Tobocman Kalos theory as for the Butler theory. In other cases such compensation may not occur.

Holt and Marsham[10] (see their Fig. 12) have sought to relate the variation of r_0 with A in the lighter elements to variations in nuclear structure. They find an indication of such a relation in the similarity of the curve of r_0 *vs* A and that of the nuclear radius (from fast neutron scattering) *vs* A. While some of the fluctuations are surely related to variations in nuclear structure, it would seem difficult to separate them from those due to inadequacies of the Butler theory.

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