PHYSICAL REVIEW VOLUME 121, NUMBER 3 FEBRUARY 1, 1961

Deuteron Stripping and Pickup Reactions in Oxygen-16†

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(Received August 15, 1960)

The reactions $O^{16}(d,p)O^{17}$ and $O^{16}(d,t)O^{15}$ were studied by bombarding thin nickel oxide foils with 15-Mev deuterons from the University of Pittsburgh cyclotron. The reaction particles were magnetically analyzed and detected either by nuclear emulsions or by a CsI(Tl) scintillator. Angular distributions and absolute cross sections were obtained for the first six states of O^{17} and for the ground state of O^{15}. Reduced widths having values $\Theta^2=0.045$, 0.16, 0.0024, 0.0024, 0.0071, 0.047, and 0.012, respectively, were extracted from a comparison of the data with the predictions of Butler stripping theory. The most notable results of the (d,p) experiment indicate that: (1) the $\frac{7}{2}^-$ state at 3.846 Mev does not appear to be a good $1f_{7/2}$ single-particle state, (2) the $2p_{3/2}$ single-particle component seems to be fragmented over more than two states, and (3) the $\frac{1}{2}^-$ state at 3.058 Mev contains a $2p_{1/2}$ single-particle component. The results of the (d,t) experiment suggest a dependence of the $1p$ single-particle reduced width on Q value.

I. INTRODUCTION

THE study of deuteron induced stripping and pickup reactions in O^{16} is of considerable interest[1] because they involve transitions from the doubly magic nucleus O^{16} to single-particle and single-hole states coupled to that nucleus. The (d,p) reaction has been extensively studied[2] at various deuteron energies by several investigators, but the (d,t) reaction has not been previously reported.

Butler stripping theory[3] provides a convenient means for reducing stripping data to a usable form and was used in the analysis of the experimental data. The results are summarized in Table I.

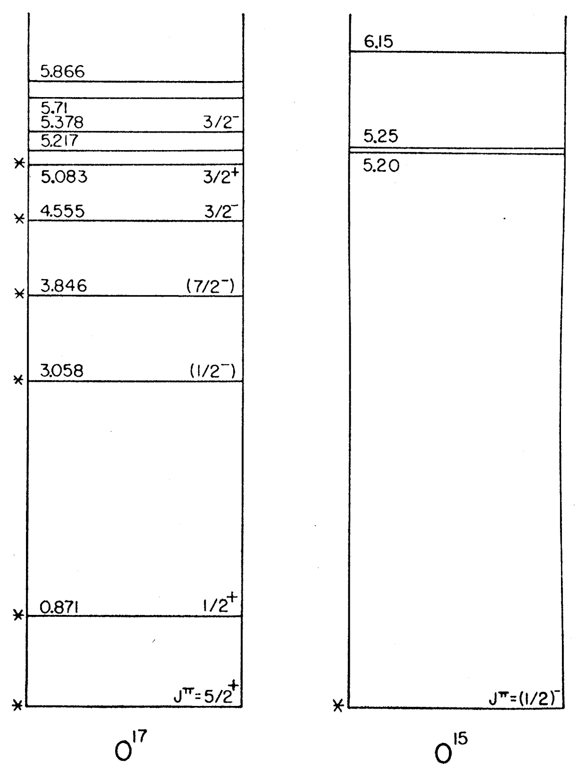

FIG. 1. Energy levels of O^{17} and O^{15}. Asterisks denote levels studied in this work.

II. EXPERIMENTAL PROCEDURE

The apparatus used has been previously described.[4,5] The collimated beam of 15-Mev deuterons incident upon the target had an energy spread of ±20 kev and a total angular spread of about 1.8°. Typical beam currents were 0.3–0.7 μa. Nickel oxide foils having a thickness ≈0.3 mg/cm² O^{16} were prepared by heating thin nickel foils in an oxygen atmosphere by the method described by Holmgren, *et al.*[6]

TABLE I. Summary of reduced widths.

Final state (Mev)	Q (Mev)	J^π	l_n	r_0	Peak cross section (mb/sr)	Relative Θ^2	Absolute Θ^2
				$O^{16}(d,p)O^{17}$			
0	1.919	$\frac{5}{2}^+$	2	6.18	34.00	1	0.045
0.871	1.048	$\frac{1}{2}^+$	0	4.67	95.04	3.6	0.16
3.058	−1.139	$\frac{1}{2}^-$	1	5.40	1.581	0.053	0.0024
3.846	−1.927	$\frac{7}{2}^-$	3	6.00	2.370	0.053	0.0024
			3	6.87		0.047	0.0021
4.555	−2.636	$\frac{3}{2}^-$	1	4.40	8.527	0.16	0.0071
5.083	−3.164	$\frac{3}{2}^+$	2	5.09	50.00	1.04	0.047
				$O^{16}(d,t)O^{15}$			
0	−9.395	$\frac{1}{2}^-$	1	4.75	0.842	···	0.012

† This work was assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
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1 M. H. Macfarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).

2 F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

3 S. T. Butler and O. H. Hittmair, *Nuclear Stripping Reactions* (John Wiley & Sons, Inc., New York, 1957).

4 R. S. Bender, E. M. Reilley, A. J. Allen, R. Ely, J. S. Arthur, and H. J. Hausman, Rev. Sci. Instr. **23**, 542 (1952).

5 E. W. Hamburger, Ph.D. thesis, University of Pittsburgh, 1959 (unpublished).

6 H. D. Holmgren, J. M. Blair, K. F. Famularo, T. F. Stratton, and R. V. Stuart, Rev. Sci. Instr. **25**, 1026 (1954).

The uncertainties indicated in the angular distribution plots shown are combinations of all uncertainties including the statistical uncertainties. The major uncertainty in the data points for $\Theta_{c.m.}<10°$ arose from the uncertainty introduced by the use of beam monitoring techniques other than the conventional Faraday cup method, resulting in estimated low angle uncertainties of 10% for the scintillator data and 20% for the emulsion data.

The absolute cross sections of the levels were determined by obtaining their cross sections relative to that of the $O^{16}(d,p)O^{17}$ ground state (g.s.) whose peak absolute cross section has been previously determined[5] to be 34 millibarns per steradian. This value is uncertain to ±25% and hence all absolute cross sections and reduced widths quoted herein have that uncertainty.

III. $O^{16}(d,p)O^{17}$

A. Experimental Results

The energy level diagram of O^{17} is shown in Fig. 1. The asterisks denote the levels that were studied via the stripping reaction. The experimental angular distributions for these states are shown in Figs. 2–7 together with their Butler stripping theory comparisons. The reduced widths extracted from these comparisons are listed in Table I as are the peak absolute cross sections determined for these transitions. The two curves fitted to the 3.846-Mev state data represent the two "fits" which yielded the largest and the smallest reduced widths for that state.

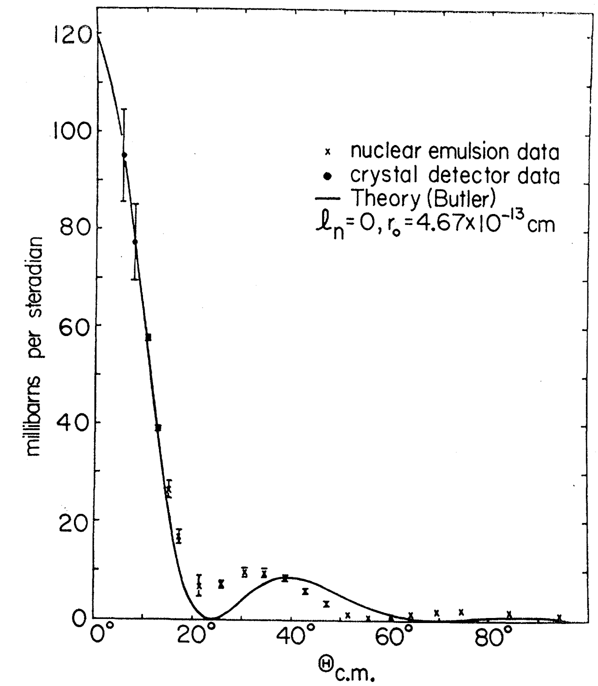

FIG. 3. Angular distribution of the $O^{16}(d,p)O^{17}$ 0.871-Mev level.

B. Discussion

This reaction provides an ideal means for studying single-particle reduced widths because it involves transitions from a doubly magic nucleus to configu-

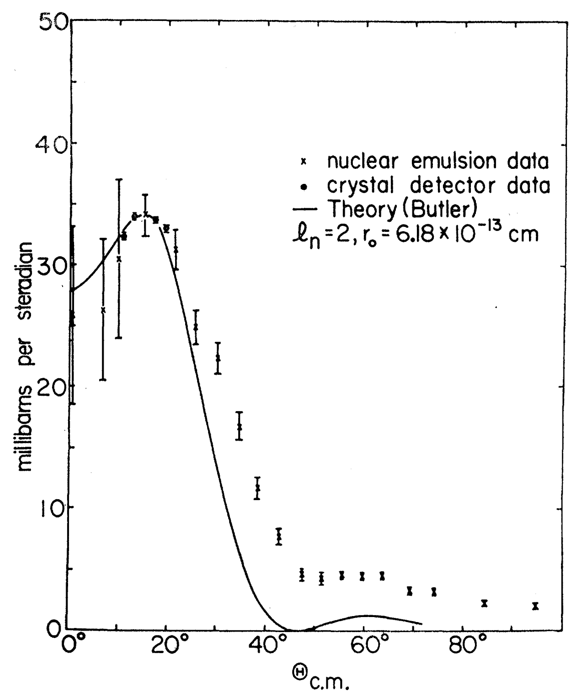

FIG. 2. Angular distribution of the $O^{16}(d,p)O^{17}$ ground state.

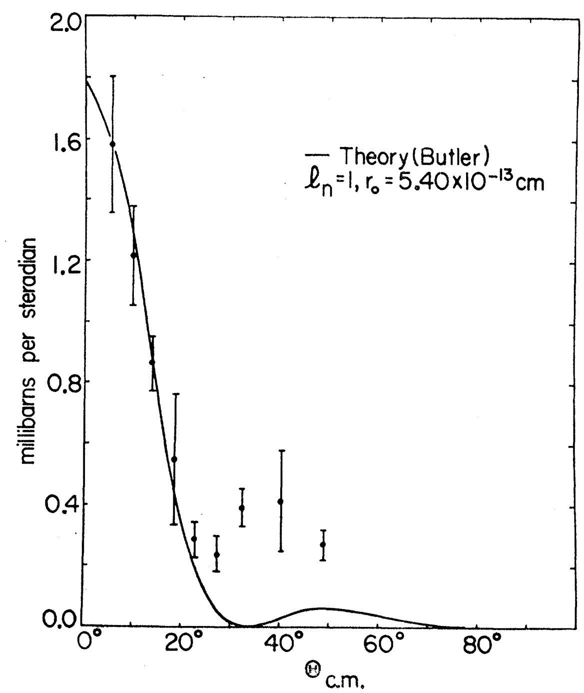

FIG. 4. Angular distribution of the $O^{16}(d,p)O^{17}$ 3.058-Mev level.

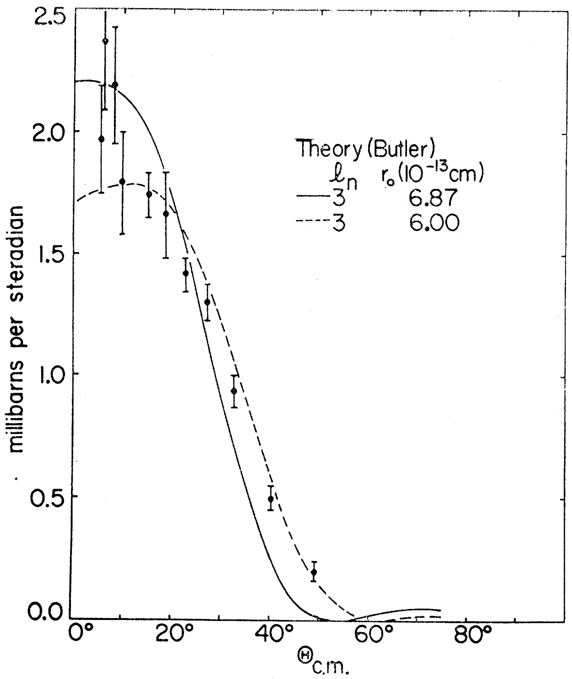

FIG. 5. Angular distribution of the $O^{16}(d,p)O^{17}$ 3.846-Mev level.

rations in which one neutron of the appropriate angular momentum is coupled to that core. The low-lying ($E_{exc}<5.1$ Mev) states of O^{17} have been the subject of many investigations[2] and are reasonably well understood.[1]

1. Positive Parity States

Since the $1p$ shell closes at O^{16}, the low-lying positive parity states of O^{17} will consist of single neutrons from the ds shell coupled to the O^{16} core. As shown in Fig. 1, the spin and parity of the ground, 0.871-, and 5.083-Mev states of O^{17} are $J^\pi=\frac{5}{2}^+$, $\frac{1}{2}^+$, and $\frac{3}{2}^+$, respectively. The angular momentum transfers for these states, as determined in this work, are consistent with the interpretation that $1d_{5/2}$ $2s_{1/2}$, and $1d_{3/2}$ neutrons, respectively, are coupled to the O^{16} core. In addition, the large cross sections observed for these transitions are consistent with the assumption that these are relatively pure single-particle states. The state at 5.083 Mev is considered to be the spin-orbit doublet companion to the ground state, as evidenced by the fact that $\Theta^2(d_{3/2})\approx\Theta^2(d_{5/2})$. The single-particle reduced widths for these positive parity states, as determined from the present experiment, are in agreement with the values currently used in analyses of stripping reactions.[1]

2. Negative Parity States

The states at 3.058, 3.846, and 4.555 Mev have $J^\pi=\frac{1}{2}^-$, $\frac{7}{2}^-$, and $\frac{3}{2}^-$, respectively. The probable configurations for the $\frac{7}{2}^-$ and $\frac{3}{2}^-$ states are $1f_{7/2}$ and $2p_{3/2}$ neutrons, respectively, coupled to the O^{16} core. However, the small reduced widths ($\Theta^2=0.0024$ and 0.0071, respectively) suggest that these may not be pure single-particle states. This could perhaps be explained by the interaction of these states with other $\frac{7}{2}^-$ and $\frac{3}{2}^-$ states of O^{17} thus "spreading" the single-particle components over several states.

The next $\frac{3}{2}^-$ state, being only 823 kev above the 4.555-Mev state, is close enough to allow considerable mixing. However, available data at this laboratory indicate that this state at 5.378 Mev is very weakly excited and its reduced width is certainly no larger than $\Theta^2=0.001$. Noting that single-particle reduced widths in the $2p$ shell typically have values $\Theta_0^2(2p)\approx0.025$,[1] it is seen that even the sum of the reduced widths for the 4.555- and 5.378-Mev states is a factor of 3 smaller than $\Theta_0^2(2p)$. These results suggest that the $2p_{3/2}$ single-particle component is fragmented over more than two states and that, in fact, another state above $E_{exc}=5.70$ Mev contains the major portion of the $2p_{3/2}$ single-particle component.

The value obtained in the present experiment for the ratio $\Theta_{3.846}^2/\Theta_{g.s.}^2=0.053$ is only one quarter as large as the value found for the same ratio by Green and Middleton[7] using 9-Mev deuterons. Using the Green and Middleton value for this ratio and noting that the next $\frac{7}{2}^-$ state of O^{17} lies 1.851 Mev higher, Macfarlane and French[1] concluded that the 3.846-Mev state is a good $1f_{7/2}$ single-particle state since a very large interaction would be required to "spread" the

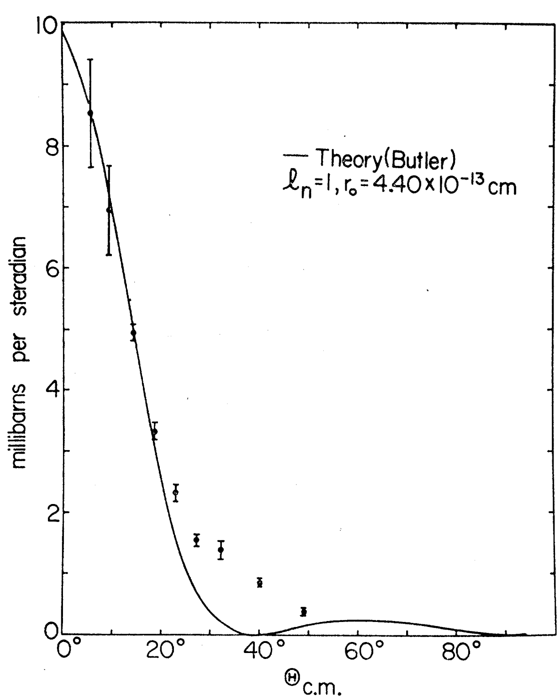

FIG. 6. Angular distribution of the $O^{16}(d,p)O^{17}$ 4.555-Mev level.

[7] T. S. Green and R. Middleton, Proc. Phys. Soc. (London) **A69**, 28 (1956).

$l=3$ components over so large a region. However, fragmentary data available at this laboratory indicate that the unresolved doublet at 5.71 Mev (part of which is the $\frac{7}{2}^-$ state at 5.697 Mev) shows relatively strong stripping structure having a cross section of 11.3 millibarns per steradian at $\Theta_{\text{c.m.}}=14.1°$. This information, although not conclusive, together with the small reduced width obtained for the 3.846-Mev state suggests that it may contain a smaller fragment of the $1f_{7/2}$ single-particle component than is concluded by Macfarlane and French.[1]

The $\frac{1}{2}^-$ state at 3.058 Mev exhibits stripping, although weakly. Theoretical considerations[1] indicate that this state is probably formed by an excitation of the O^{16} core rather than by a $2p_{1/2}$ neutron coupled to O^{16}. However, the stripping structure observed indicates the presence of a $2p_{1/2}$ single-particle component in the configuration of this state.

IV. $O^{16}(d,t)O^{15}$

A. Experimental Results

The O^{15} energy level diagram is shown in Fig. 1. Since this pickup reaction is very endothermic ($Q=-9.395$ Mev),[8] it was possible to study only the transition to the ground state in O^{15}.[9] The angular distribution for this reaction is shown in Fig. 8 and has been fitted with a Butler curve with $l_n=1$ and $r_0=4.75\times10^{-13}$ cm. From this comparison one obtains $\Lambda\Theta^2=2.38$, where Λ is the factor proportional to the normalization constant for the asymptotic triton wave function and Θ^2 is the single-particle reduced width Θ_0^2 times the spectroscopic factor or relative reduced width S.[1]

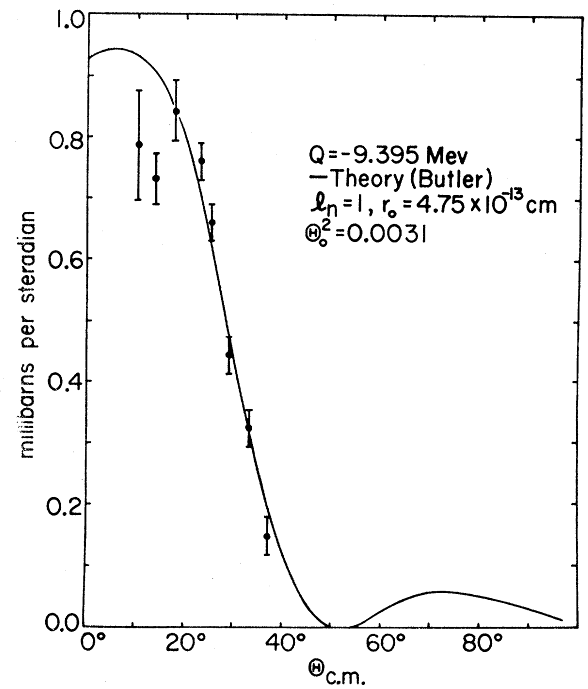

FIG. 8. Angular distribution of the $O^{16}(d,t)O^{15}$ ground state.

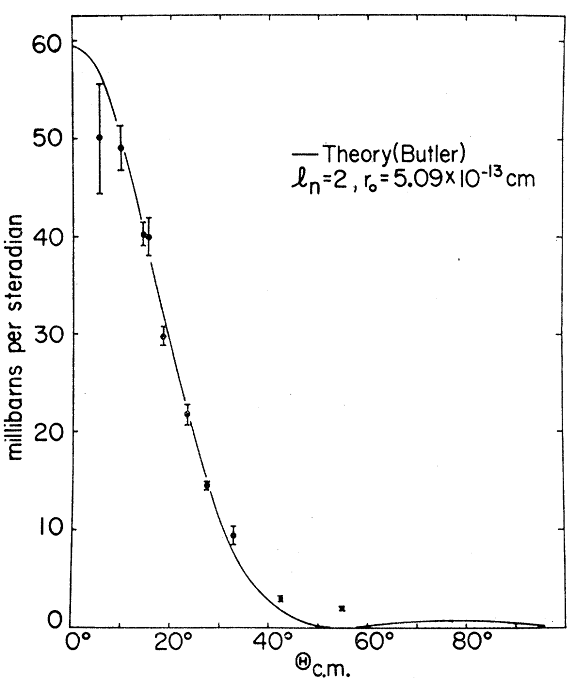

FIG. 7. Angular distribution of the $O^{16}(d,p)O^{17}$ 5.083-Mev level.

B. Discussion

At the present time very little is known about the dependence of single-particle reduced widths on incident energy and Q whereas there is considerable information available[1] concerning their dependence on other parameters (e.g., n, l, J, r_0, and A). Because of its high negative Q, the $O^{16}(d,t)O^{15}$ reaction can yield information concerning the Q dependence.

This reaction presumably involves a transition from the closed $1p$ shell to a $1p_{1/2}$ hole state of O^{15}. Since single-particle reduced widths in the $1p$ shell typically have values $\Theta_0^2(1p)=0.04$–0.06, one should expect to observe a large cross section for this transition because the relative reduced width has the value $S=4$ and in pickup reactions there are no statistical factors which cancel the effects of a large reduced width. The peak cross section (0.842 millibarn per steradian), however, is not large and consequently when the reasonable value of $\Lambda=195$[1] is used, a single-particle reduced width of $\Theta_0^2=0.0031$ is obtained.

Recent studies by Macfarlane and French[1] indicate that values of $1d$ and $2s$ single-particle reduced widths

[8] V. J. Ashby and H. J. Catron, University of California Radiation Laboratory Report UCRL-5419, 1959 (unpublished).
[9] This work has been previously reported. See E. L. Keller, Bull. Am. Phys. Soc. 5, 246 (1960).

for nuclei having $12<A<32$ decrease significantly when the binding energy of the transferred nucleon in the heavier nucleus increases from 3 Mev to 9 Mev. Such an effect, if present in $1p$ single-particle reduced widths, might explain the small value of $\Theta_0^2=0.0031$ since the binding energy of the transferred neutron in O^{16} is 15.652 Mev.

ACKNOWLEDGMENTS

The author wishes to thank J. N. McGruer for his interest and guidance in this work and A. J. Allen for his support. He wishes to acknowledge helpful discussions with J. B. French, M. H. Macfarlane, E. U. Baranger, J. R. Cameron, J. C. Armstrong, A. G. Blair, and E. W. Hamburger.

PHYSICAL REVIEW VOLUME 121, NUMBER 3 FEBRUARY 1, 1961

Lithium-Induced Reaction Yields Below 4 Mev*

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Thick-target yields of the following reactions were measured by counting the beta active products: $Li^7(Li^6,2n)C^{11}$, $Be^9(Li^6,2n)N^{13}$, $C^{12}(Li^6,n)F^{17}$, $C^{12}(Li^7,n)F^{18}$, $N^{14}(Li^6, He^5)O^{15}$, $N^{14}(Li^6,d)F^{18}$, $N^{14}(Li^7,t)F^{18}$, $O^{16}(Li^6,n)Na^{21}$, $O^{16}(Li^6,He^4)F^{18}$, $F^{19}(Li^6,Li^5)F^{20}$, $Na^{23}(Li^6,Li^5)Na^{24}$. The reactions $F^{19}(Li^6,2p)Ne^{23}$ and $Na^{23}(Li^7,Li^6)Na^{24}$ had too small a yield to permit accurate measurement. All of the yield curves show a very rapid but smooth increase of yield with energy. Some general rules are given for estimating the yield to be expected for any positive "Q" lithium beam reaction in the energy range under consideration.

IN a previous work[1] yields are reported for a number of nuclear reactions with lithium beams under 2.0 Mev. In one recent paper, the excitation curve for $Be^9(Li^7,Li^8)Be^8$ has been extended up to 3.9 Mev.[2] In the present work the beam energy is in the range of 1.2 to 3.7 Mev. Although all possible reactions are not covered by this survey, there is enough variety so that one may make reasonable estimates of the yields to be expected from other reactions. From the thick-target yield curves presented here, one can read directly the expected thin-target yield if the target thickness is expressed in terms of the energy loss by the beam. By making use of stopping-power information, one could calculate actual nuclear cross sections for these reactions.

EXPERIMENTAL

The production and analysis of lithium ion beams by the Minnesota Van de Graaff machine has been described previously.[2] The thick targets to be bombarded were mounted at the bottom of a Faraday cup. After the bombardment they were removed and counted under a low background, end window counter. The number of counts were recorded by a printer which was activated by a clock so that it would print every 1, 5, 10, 20, or 60 minutes. The shorter-lived activities were timed with a stopwatch and the number of counts recorded by hand.

A variety of methods were used for making targets. The carbon and beryllium targets were cut from the elements. The nitrogen targets were made by heating titanium in an atmosphere of anhydrous ammonia, the oxygen targets by heating titanium in oxygen. The other targets were made by melting salts onto thin steel backings, LiF for lithium, NaF for fluorine, and NaCl for sodium. In each case, because of decrease in reaction yield as the atomic number is increased, the

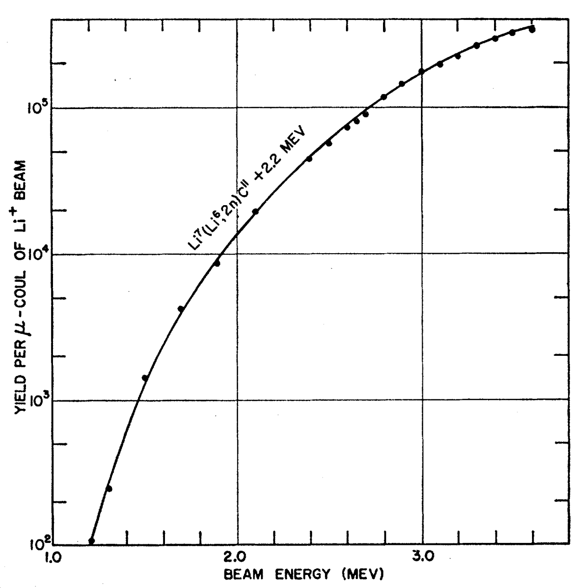

FIG. 1. Thick-target yields of C^{11} from a Li^6 beam on enriched LiF targets.

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* This work was supported in part by the joint program of the U. S. Atomic Energy Commission and the Office of Naval Research.
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[1] E. Norbeck, Jr., and C. S. Littlejohn, Phys. Rev. **108**, 754 (1957).
[2] E. Norbeck, J. M. Blair, L. Pinsonneault, and R. J. Gerbracht, Phys. Rev. **116**, 1560 (1959).