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Energy Dependence of the $B^{10}(Li^6,\alpha)C^{12}$ and $Be^9(Li^6,p)C^{14}$ Reaction Cross Sections*

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The cross sections of the reactions $B^{10}(Li^6,\alpha_0)C^{12}$ and $B^{10}(Li^6,\alpha_1)C^{12*}$ have been measured at 0° for Li^6 energies of 3.20 to 13.60 MeV. The $Be^9(Li^6,p_0)C^{14}$ and $Be^9(Li^9,p_1)C^{14*}$ cross sections at 0° were measured for Li^6 energies ranging from 3.84 to 6.40 MeV. The analysis of the yield curves in terms of Ericson fluctuation theory gave values of the average level width, Γ, of 1.40 MeV for O^{16} at 36-MeV excitation and approximately 0.40 MeV for N^{15} at 28-MeV excitation. From the same data it was found that there is a considerable contribution of direct reaction mechanism as well as compound nucleus to both reactions.

I. INTRODUCTION

LITHIUM-INDUCED nuclear reactions have several advantages in studies of nuclear structure and spectroscopy. The high mass excesses of Li^6 and Li^7 make it possible to study many nuclei at high excitations and to study neutron-rich nuclei which are not produced easily by other means. However, the nature of the reaction mechanism in these nuclear reactions is still rather uncertain. Information on this matter would make these reactions much more useful for nuclear-structure studies.

Investigations of the Li^6+C^{12} nuclear reaction have shown both compound nucleus and direct reaction effects.[1–5] Dzubay[5] has observed pronounced fluctuations in the cross section for production of certain particle groups in this reaction. His analysis on the basis of Ericson fluctuation theory[6] indicated a strong statistical compound-nucleus contribution to the reaction, although a direct reaction contribution of up to 60% was possible. The compound nucleus F^{18} was found to have an average level width, or coherence energy, of 220 keV at an excitation of 17 MeV. This is in agreement with estimates for this excitation and mass [see Eq. (1) and related discussion in Sec. IV].

The present work was undertaken in order to look for fluctuations in the yield of lithium-induced nuclear reactions. The reactions studied are shown in Table I. Observations were made at 0° in the expectation that fluctuations would be relatively large at this angle.[7] The Li^6+Be^9 yield curves were measured for Li^6 energies ranging from 3.84 to 6.40 MeV in both 40- and 80-keV steps. The range of excitation in the compound nucleus N^{15} was from 26.74 to 29.17 MeV. The Li^6 energy range for Li^6+B^{10} was 3.20 to 13.60 MeV which covers excitation energies in the compound nucleus O^{16} of 32.88 to 39.38 MeV. The energy was varied in 100-keV steps except for Li^6 energies of 6.4 to 9.6 MeV, where the low intensity (0.007 μA) of the doubly charged beam necessitated 200-keV steps.

Previous investigations of the Li^6+Be^9 reaction include (Li^6,α) angular distributions[8] in the Li^6 energy range of 2.0 to 4.0 MeV, a search for $Be^9(Li^6,\gamma)N^{15}$ at 3.3 MeV, and a search for discrete Li^7 particle groups for Li^6 energies between 3.0 and 3.75 MeV.[9] Leigh[10] was able to make a good plane-wave Born-approximation fit to the (Li^6,α_0) angular distribution and a qualitative fit to the (Li^6,α_1) distribution indicating that near 3.25 MeV the direct reaction mechanism seems to predominate. Carlson and Throop,[11] in looking for capture γ rays in Li^6+Be^9, indicate that at 3.3-MeV bombarding energy no compound-nucleus γ rays were observed to the extent of their experimental sensitivity. However, the limit which was set was inconclusive.

The angular distributions measured for the Li^6+B^{10} reaction by Morrison *et al.*[12] in the Li^6 energy range of 3.5 to 4.5 MeV indicated predominance of the direct reaction mechanism. Near 5 MeV, McGrath,[13] in his work on Li^6 and Li^7 bombardment of B^{10} and B^{11}, saw strong forward peaking in the (Li^6,d), (Li^7,t), and (Li^6,α) angular distributions which can be an indication of

TABLE I. Reactions observed in the present experiment.

$Be^9(Li^6,p_0)C^{14}$,	$Q=15.12$	$E_{Li^6}=3.84$–6.40 MeV
$Be^9(Li^6,p_1)C^{14*}$,	$Q=9.03$	$E_{exc}(N^{15})=27.64$–29.17 MeV
$B^{10}(Li^6,\alpha_0)C^{12}$,	$Q=23.71$	$E_{Li^6}=3.20$–13.60 MeV
$B^{10}(Li^6,\alpha_1)C^{12*}$,	$Q=19.28$	$E_{exc}(O^{16})=32.88$–39.38 MeV

* Research supported in part by National Science Foundation.
[1] Russell K. Hobbie and Fred F. Forbes, Phys. Rev. **126**, 2137 (1962).
[2] J. M. Blair and R. K. Hobbie, Phys. Rev. **128**, 2282 (1962).
[3] D. W. Heikkinen, Phys. Rev. **141**, 1007 (1966).
[4] T. Honda and H. Horie (to be published).
[5] T. G. Dzubay (to be published).
[6] Torleif Ericson, Ann. Phys. (N. Y.) **23**, 390 (1963).
[7] J. O. Newton, Phys. Letters **17**, 132 (1965).
[8] Russell K. Hobbie, C. W. Lewis, and J. M. Blair, Phys. Rev. **124**, 1506 (1961); J. J. Leigh and J. M. Blair, *ibid.* **121**, 246 (1961).
[9] Baldev Sahai, Phys. Rev. **142**, 612 (1966).
[10] J. J. Leigh, Phys. Rev. **123**, 2145 (1961).
[11] R. R. Carlson and M. Throop, Phys. Rev. **136**, B630 (1964).
[12] G. C. Morrison, N. H. Gale, M. Hussain, and G. Murray, in *Proceedings of the Third Conference on Reactions Between Complex Nuclei*, edited by A. Ghiorso, R. M. Diamond, and H. E. Conzett (University of California Press, Berkeley, California, 1963), p. 168; G. C. Morrison, in *Direct Interactions and Nuclear Reaction Mechanisms*, edited by E. Clementel and C. Villi (Gordon and Breach Science Publishers, Inc., New York, 1963), p. 878.
[13] Robert J. McGrath, Phys. Rev. **145**, 802 (1966).

the presence of a direct reaction mechanism. The main characteristic of these data, however, was the proportionality of the integrated cross sections to $2J+1$ (J is the known spin of the residual nucleus) for a large percentage of the angular distributions which were measured. MacDonald[14] has shown that the statistical-compound-nucleus theory predicts that total cross sections will be proportional to $2J+1$ if certain conditions are satsified: (a) An appreciable number of orbital angular momenta contribute to the reaction, and (b) the exit channel energy is much larger than the Coulomb-barrier energy. From the shapes of some of the angular distributions and the deviations from $2J+1$, McGrath concluded that direct reaction mechanisms may be important for some of the lower Q reactions he observed. However, it was not possible to measure quantitatively the proportions of compound nucleus and direct reaction mechanisms with these data. Zafiratos[15] has measured the angular distribution of the inverse reaction $C^{12}(\alpha,Li^6)B^{10}$ at an alpha energy of 42 MeV, which corresponds to a Li^6 energy of 12.45 MeV. The forward peaking of the angular distribution encouraged him to try a distorted-wave Born-approximation fit which turned out to be only qualitative. He concluded that his poor fit may have been the result of the simplicity of the interaction chosen for the calculation. Carlson and Throop's[11] search for $B^{10}(Li^6,\gamma)0^{16}$ at 3.8 MeV set the same inconclusive upper limit for this reaction as in the $Be^9(Li^6,\gamma)N^{15}$ search.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The lithium-ion beams were produced by the University of Iowa Van de Graaff accelerator.[16] It was possible to reach a maximum terminal voltage of 6.4 MeV during the period in which the data were collected. By passing singly ionized lithium ions[17] through a thin carbon foil[18] after being accelerated through 41.6% of the terminal voltage, the charge state of the ion was increased to two or three, producing an ion energy of 1.58 or 2.16 times the terminal voltage. The ion beams were momentum-analyzed by a 90° magnet which allowed a beam energy spread of about 0.3%. The energy calibration of this magnet was known to $\pm 0.2\%$.

In order to ensure reliable beam-current integration, a short insulated section of beam pipe through which the beam passed after collimation was biased at -300 V with respect to both the collimation section and the Faraday-cup–target combination. The target backing material was thick enough to stop the beam and any knock-on electrons.

[14] N. MacDonald, Nucl. Phys. **33**, 110 (1962).

[15] Chris D. Zafiratos, Phys. Rev. **136**, B1279 (1964).

[16] Manufactured by High Voltage Engineering Corporation, Burlington, Massachusetts. Model CN(5.5 MeV).

[17] Dale W. Heikkinen [Ph.D. dissertation, University of Iowa, 1965 (unpublished)] describes the lithium-ion source.

[18] Kenneth G. Kibler [Ph.D. dissertation, University of Iowa, 1965 (unpublished)] describes the beam stripping cell.

The beryllium targets were made by evaporating beryllium metal shavings onto clean copper, which was 0.002 in. thick. Targets of 40 or 100 keV thickness to a 5-MeV Li^6 ion were used for 40- or 80-keV steps, respectively, in the Li^6+Be^9 yield curve. The boron targets were made by evaporating 86% pure B^{10} onto backings of 9 mg/cm^2 of aluminum or 6 mg/cm^2 of nickel. The energy loss of a 5-MeV Li^6 ion ranged from 30 to 75 keV in the aluminum-backed targets; the energy loss in the nickel-backed target was 80 keV.

The target thickness of the Be^9 was determined by measuring the increase in width of the $Be^9(p,\gamma)$ resonance at 1.09 MeV and the B^{10} thickness measured by noting the apparent shift of the $Al^{27}(p,\gamma)$ resonance at 992 keV when the HH^+ beam lost energy in the B^{10} layer before striking the aluminum backing.

Several target problems could have caused nonreproducible yields: (1) uneven deposition caused by evaporation in a poor vacuum or by the configuration of the electron gun used in evaporating the boron; (2) changes in target thickness due to heating by the beam; and (3) carbon buildup on the target. Several runs with different targets and, in the Li^6+B^{10} case, with a different target backing material (nickel) gave relative yields which were equal within statistical deviations, indicating that target nonuniformities were not troublesome.

In order to check for contaminant reactions resulting from the aluminum target backing used for the B^{10} targets, the back of the target was bombarded, with the result that the yield in the same energy range as α_1 and α_0 was less than 2.5% of the normal yield. When the nickel-backed target was tested, the spurious yield was less than 0.1%.

In all runs, the detector was a lithium-drifted silicon detector[19] with a depletion depth of 2 mm. In the measurements of the $Be^9(Li^6,p)$ yield curves, reaction products passed through the 0.002 in. of copper backing, 0.010 in. of aluminum separating the vacuum system from air, 1 in. of air, and then into the detector situated in an atmosphere of dry air. A layer of aluminum foil (approximately 1.7 mg/cm^2) prevented light from hitting the detector's surface. The solid angle for these runs was 0.067 sr. The angle subtended by the circular detector aperture was ± 8.4 deg. In the B^{10} data runs, the detector was mounted inside the vacuum system with a solid angle of 0.083 sr. The detector subtended an angle of ± 9.3 deg at the target. The beam spot was about 0.10 in. in diameter.

The detector pulses were fed into a charge-integrating preamplifier[20] with an internal bias supply and then sent to a linear amplifier[21] before analysis in an analog-to-

[19] Technical Measurement Corporation, North Haven, Connecticut. Detector model W-80-2A.

[20] Tennelec Instrument Company, Oak Ridge, Tennessee. Model TC-100B.

[21] Sturrup, Inc., Middletown, Connecticut. Linear Amplifier Model 101. Discriminator Model 501.

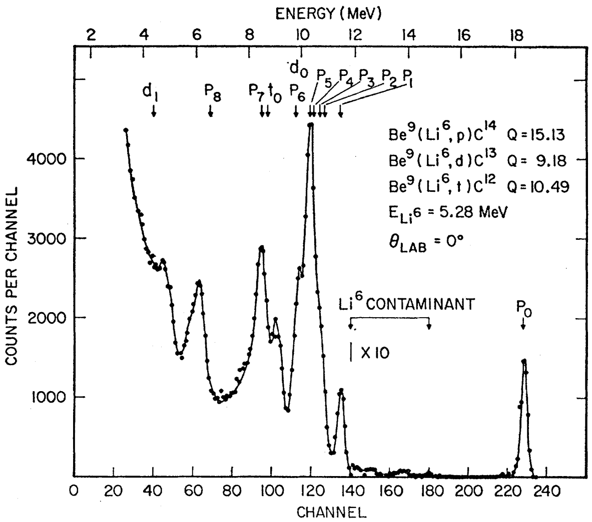

FIG. 1. A typical charged-particle spectrum resulting from Li^6+Be^9 taken at 0° detector angle and $E_{Li^6}=5.28$ MeV. The abscissa is marked by channel number and by energy loss of the particles in the detector. The ordinate gives the number of counts per channel. The position of the possible protons, deuterons, and tritons are indicated on the graph according to the 1962 compilation by T. Lauritsen and F. Ajzenberg-Selove, NRC 61-5, 6; the subscript refers to the excited level of the appropriate residual nucleus. Only the yield curves for p_0 and p_1 were measured.

digital converter.[22] A discriminator[21] was used to gate the converter so that pulses from unwanted particle groups would not necessitate dead-time corrections. The spectrum was stored in a computer[23] and the desired peaks were summed at the end of each run. Within the summing program, there was a subtraction routine which could be used for subtracting continua resulting from the reactions caused by lithium bombarding lithium deposited in the target backing. At energies greater than 10 MeV, the background under the α group from $B^{10}(Li^6,\alpha_1)C^{12*}$ required subtractions of no more than 15%. The proton group resulting from $Be^9(Li^6,p_1)C^{14*}$ was superimposed upon a background of protons caused by the reaction $Li^6(Li^6,p)$. In a separate experiment[18] none of the proton groups from $Li^6(Li^6,p)$ was significantly larger than the two groups seen between the 6.09-MeV level group and the ground-state group. Contributions from this source of contaminant were less than 5%. The Li^6+Be^9 particle spectrum is shown in Fig. 1; the $Li+B^{10}$ spectrum is shown in Fig. 2.

III. RESULTS

The results of this experiment are contained in the four yield curves shown in Figs. 3–6. Yields were obtained by summing under the appropriate peaks in the energy spectrum for each beam energy, making any necessary background subtractions, and correcting the Li^6+Be^9 data for dead-time losses in the pulse-

[22] Nuclear Data, Inc., Madison, Wisconsin.
[23] Control Data Corporation, St. Paul, Minnesota. Model 160A.

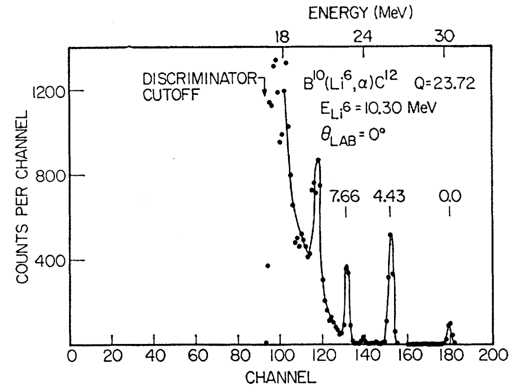

FIG. 2. A typical α spectrum from the reaction $B^{10}(Li^6,\alpha)C^{12}$ taken at 0° detector angle and $E_{Li^6}=10.30$ MeV. The abscissa is marked by channel number and by energy loss of the particles in the detector. The ordinate gives the number of counts per channel. The groups are identified by the associated energy level in the residual nucleus C^{12}. Only the yield curves for α_0, the group leaving C^{12} in its ground state, and α_1, corresponding to the 4.43-MeV level of C^{12}, were measured.

height analyzer. The laboratory cross section was calculated using the expression $d\sigma/d\omega=Y/NI\Delta\Omega$, where Y is the corrected yield, N is the number of target particles per square centimeter, I is the number of ions which have bombarded the target, and $\Delta\Omega$ is the measured solid angle. This was converted to center-of-mass cross section and plotted in the figures as a function of the energy of the Li^6 ions at the center of the target.

In addition to the above thin-target measurements of the cross section, a thick-target measurement of the $B^{10}(Li^6,\alpha_0)$ cross section was made. This was done by measuring the yield of ground-state alphas (α_0) from a boron target which was infinitely thick to Li^6 ions but thin to α particles. This was done for Li^6 energies of 4.80 and 5.94 MeV. The difference in the yields is given by the expression

$$Y(5.94\text{ MeV})-Y(4.80\text{ MeV})=I\int_{4.80}^{5.94}\frac{\Delta\Omega[d\sigma(E)/d\omega]}{\epsilon(E)}dE$$

$$=\frac{d\sigma(4.8)}{d\omega}I\Delta\Omega\int_{4.80}^{5.94}\frac{1}{\epsilon(E)}\frac{d\sigma(E)/d\omega}{d\sigma(4.8)/d\omega}dE,$$

where ϵ is the stopping cross section per atom. This approach obviated the dependence on the target thickness measurement and the associated problem of target contamination during the boron evaporation. The possibility of contamination was small during the thick-target preparation since it involved only the deposition of a slurry of boron powder of known composition which was thick enough to stop the Li^6 ions. The stopping cross section for lithium was calculated using an approximation for the proton stopping cross section found in Whaling's article[24] combined with information on

[24] W. Whaling, in *Handbuch der Physik* (Springer-Verlag, Berlin, 1958), Vol. XXXIV, p. 193.

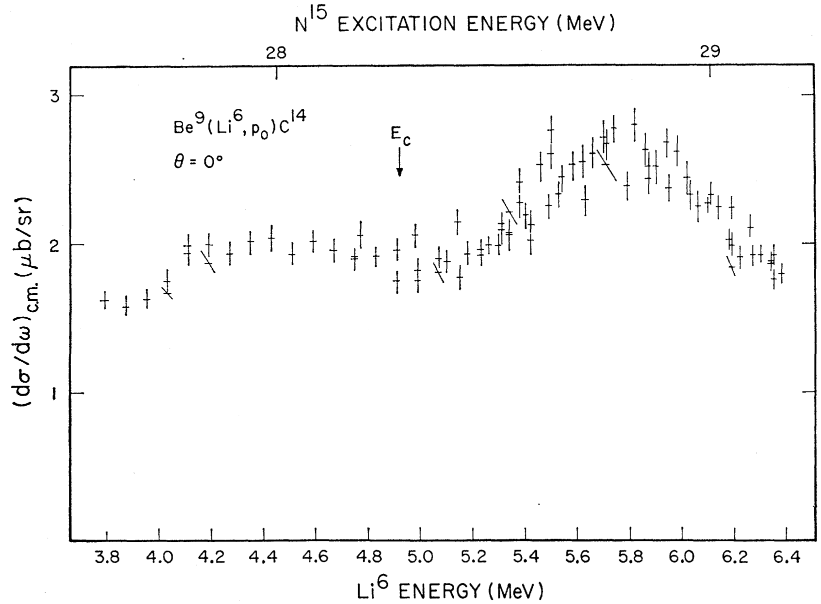

FIG. 3. Yield curve for $Be^9(Li^6,p_0)C^{14}$. $E_{Li^6}=3.84-6.40$ MeV. The center-of-mass differential cross section is plotted versus the Li^6 energy at the center of the target. The excitation energy in the compound nucleus is shown along the upper edge of the figure. E_c indicates the Coulomb barrier. The error bars represent statistical erorrs only.

the average charge of the lithium ions taken from an article by Allison *et al.*[25] By using the relative yield of the thin-target measurements, the integral was evaluated numerically. The result was a differential cross section of 40.1 μb/sr at 4.8 MeV after conversion to the center of mass. The thin target method gave a center-of-mass cross section of 45.0 μb/sr at this same laboratory energy. The disagreement of these values with McGrath's[13] measurement in this laboratory is probably due to an error in target-thickness measurement in the earlier work.

Because of the difficulty of separating the deuterons and tritons from the lower-energy proton groups (see Fig. 1) in the Li^6+Be^9 reaction, only the p_0 (Fig. 3) and p_1(Fig. 4) groups have been analyzed and plotted. The proton yields for both 40- and 80-keV steps have been plotted together using only the measured target thicknesses and beam currents for the normalization. The Li^6+B^{10} data from both the aluminum-backed target and the nickel-backed target were plotted together using the same normalization for α_0 (Fig. 5) and α_1(Fig. 6) to indicate the reproducibility of the

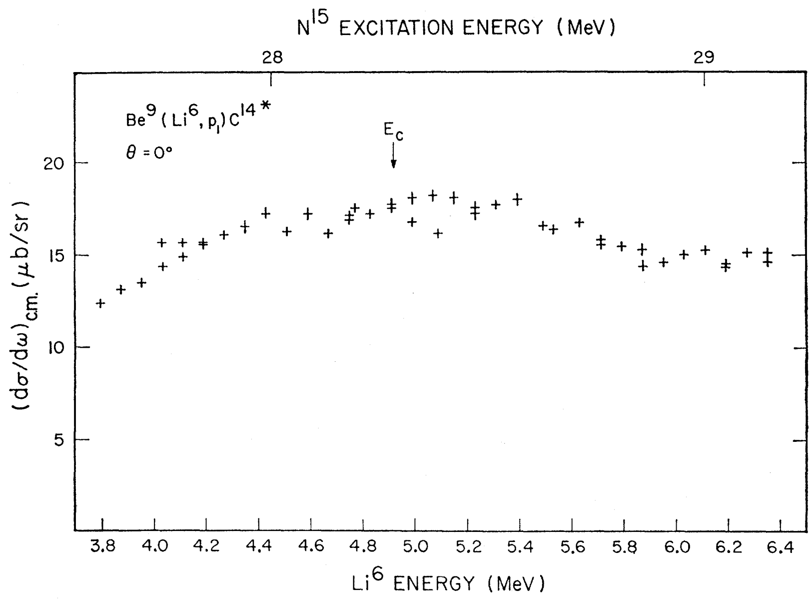

FIG. 4. Yield curve for $Be^9(Li^6,p_1)C^{14*}$. $E_{Li^6}=3.84=6.40$ MeV. See caption for Fig. 3.

[25] S. K. Allison, D. Auton, and R. A. Morrison, Phys. Rev. **138**, A688 (1965).

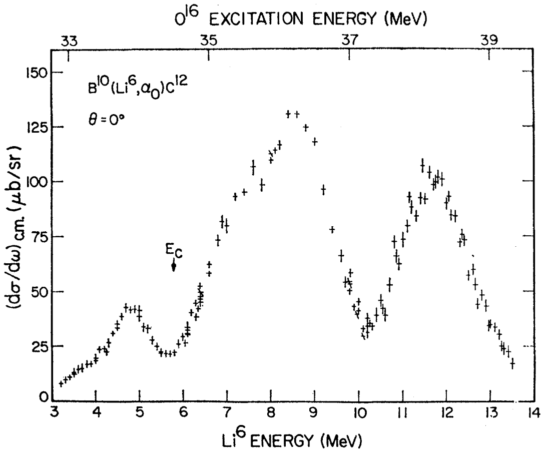

FIG. 5. Yield curve for $B^{10}(Li^6,\alpha_0)C^{12}$. $E_{Li^6}=3.20$–13.60 MeV. See caption for Fig. 3.

relative cross section. The Coulomb-barrier energies, E_c (4.92 MeV for Li^6+Be^9, 5.81 MeV for Li^6+B^{10}) are indicated on the graphs.

The errors in the absolute cross sections are as follows: target-thickness measurements (15%), statistics (5%), integrator calibration (3%), and solid angle [5% for $B^{10}(Li^6,\alpha)$ data; 10% for $Be^9(Li^6,p)$ data]. In addition, there were subtraction errors (2%) for the higher-energy Li^6+B^{10} data as well as target nonuniformities of about 18% which also could have affected the relative cross section to that extent. However, in several runs, the observed variation in the relative cross section was only $\pm 4\%$. The major source of error in the thick-target–cross-section measurement is caused by the 15% uncertainty in the lithium stopping cross section. Thus, for both reactions, the uncertainty in the absolute cross section is $\pm 20\%$.

IV. DISCUSSION

In order to analyze these data in terms of Ericson fluctuation theory, it is necessary that there be overlapping levels in the energy range of the compound nucleus under investigation. Ericson[6] mentions only that the condition $\Gamma \gg D$ (D is the spacing of states in the region of study) must be satisfied and suggests that 3–5 MeV above the threshold for neutron emission should be adequate. In both of the reactions studied here, the excitation in the compound system is more than 17 MeV above the threshold for neutron emission. Moldauer[26] has shown that $\Gamma/D_{J\pi}$ should be much greater than unity for all effective spins and parities (J,π) if one is to expect Ericson's derivation to be meaningful. However, an analysis of synthesized yield curves by Dallimore and Hall[27] leads them to conclude that $\Gamma/D \geq 2$ may be satisfactory for a fluctuation analysis.

[26] P. A. Moldauer, Phys. Letters **8**, 70 (1964).
[27] P. J. Dallimore and I. Hall, Nucl. Phys. **88**, 193 (1966).

Estimates of the level spacing D in N^{15} and O^{16} have been made by using an expression given by Lang.[28] Estimates of the average level width Γ have been made by using Ericson's[29] estimate of the mean lifetime for neutron emission:

$$\tau_n = \frac{200}{E-B_n} A^{1/3} \exp\left[\frac{B_n}{(10E/A)^{1/2}}\right] \times 10^{-23}\,\text{sec}\,, \quad (1)$$

where B_n is the neutron binding energy, E is the excitation energy, and A is the atomic mass number. If one assumes that $\Gamma \sim 2\Gamma_n = 2\hbar/\tau_n$ in the presence of other exit channels besides neutrons, then for N^{15}, $\Gamma \approx 400$ keV at 28 MeV; for O^{16}, $\Gamma \approx 200$ keV at 36 MeV. The resulting values of Γ/D_J for N^{15} and O^{16} are given in Table II.

In a fluctuation analysis of measurements in O^{16} at 21 MeV, Temmer[30] found $\Gamma = 230$ keV. Extrapolating this value to 36 MeV in O^{16} gives a value of 2.5 MeV. However, Eisenberg *et al.*[31] have given an estimate of four 2^+, $T=0$ states per MeV in this excitation region of O^{16}. This estimate of D is about ten times the value given by Lang's expression. Combining the extrapolated value of Γ and the estimate of D results in nearly the same value of Γ/D as given in Table II.

Assuming that the condition $\Gamma/D \gg 1$ is satisfied, at least under the criterion of Dallimore and Hall,[27] one may proceed with the analysis outlined by Ericson[6,29,32] and Brink *et al.*[33] Ericson has shown that, for spinless particles and a compound nucleus in the region of over-

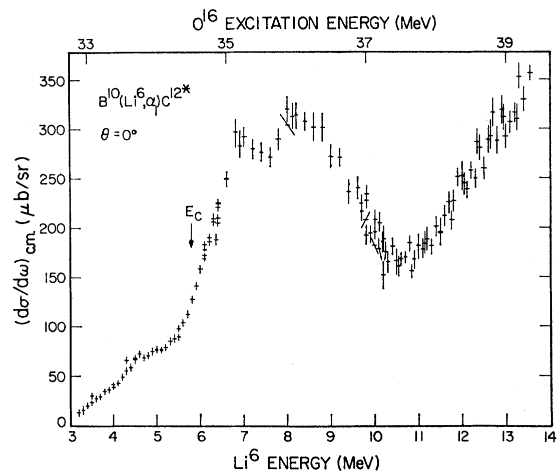

FIG. 6. Yield curve for $B^{10}(Li^6,\alpha_1)C^{12*}$. $E_{Li^6}=3.20$–13.60 MeV. See caption for Fig. 3.

[28] D. W. Lang, Nucl. Phys. **26**, 434 (1961).
[29] Torleif Ericson, Advan. Phys. **9**, 425 (1960).
[30] G. M. Temmer, Phys. Rev. Letters **12**, 330 (1964).
[31] J. M. Eisenberg, M. B. Spicer, and M. E. Rose, Nucl. Phys. **71**, 273 (1965).
[32] T. Ericson, Phys. Letters **4**, 258 (1963).
[33] D. M. Brink, R. O. Stephen, and N. W. Tanner, Nucl. Phys. **54**, 577 (1964); D. M. Brink and R. O. Stephen, Phys. Letters **8**, 324 (1964); **5**, 77 (1963).

TABLE II. Values of Γ/D for N^{15} at 28 MeV and O^{16} at 36 MeV.

	Γ/D_0	Γ/D_1	Γ/D_2	Γ/D_3	Γ/D_4
N^{15}	2.3	5.5	5	3	1
O^{16}	7.6	16.8	9.2	3.6	0.7

lapping levels, the relative fluctuations in the differential cross section will be unity. To study these fluctuations systematically, one evaluates the autocorrelation function

$$R(\epsilon)=\frac{\langle\sigma(E+\epsilon)\sigma(E)\rangle-\langle\sigma(E)\rangle^2}{\langle\sigma(E)\rangle^2}.$$

One can show[34] that the autocorrelation function has the form

$$R(\epsilon)=\frac{(1-y_D{}^2)}{1+(\epsilon/\Gamma)^2},$$

where $y_D=\sigma_D/\sigma_{\text{tot}}$, the fraction of direct interaction in the total cross section. If, in addition, particle spins are included in this formulation, Ericson shows that the fluctuations are damped by a factor $1/N$, where

$$N=\tfrac{1}{2}(2I+1)(2i+1)(2I'+1)(2i'+1)$$

and I, i, I', i' are the spins in the entrance and exit channels. In case the value of N given by the expression is not an integer, the proper value to use is the next larger integer. Newton[7] shows that at 0° or 180° only the smaller pair of factors arising from the entrance- or exit-channel spin-damping factors need be considered in calculating N. Thus, detecting alphas leading to the ground state of C^{12} or protons leading to the ground state of C^{14} at 0° as in this experiment leads to $N=1$ or the maximum possible cross-section fluctuations provided there is no appreciable direct interaction contribution. As shown by Brink *et al.*,[33] N increases to near the maximum value given above if the detector angle is greater than $(kR)^{-1}$, where R is the nuclear radius and k the center-of-mass wave number. This angle is approximately 15° for the two reactions considered so the angle subtended by the detector is assumed to cause little damping of fluctuations.

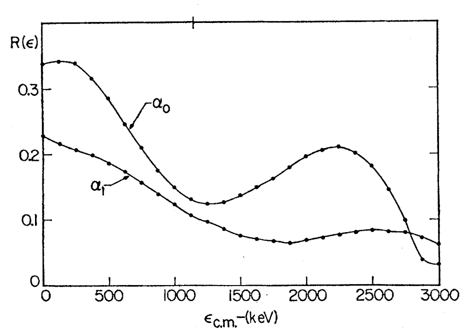

FIG. 7. The autocorrelation function $R(\epsilon)=(\langle\sigma(E+\epsilon)\sigma(E)\rangle-\langle\sigma(E)\rangle^2)/\langle\sigma(E)\rangle^2$ has been calculated for the yield curves of α_0 and α_1 and plotted for the center-of-mass energy ϵ in keV.

[34] See Appendix II of Ref. 6.

Another test of whether the data meet Ericson's criteria, besides $\Gamma/D\gg1$, is the lack of correlation between different final states, α and α'. There is some assurance that the fluctuations are random if the cross-correlation coefficient,[27]

$$C_{\alpha\alpha'}=\frac{\langle\sigma_\alpha(E)\sigma_{\alpha'}(E)\rangle}{\langle\sigma_\alpha(E)\rangle\langle\sigma_{\alpha'}(E)\rangle}-1,$$

is near zero. The α_0 and α_1 groups satisfy this condition within the deviation allowed, $\Delta C=[\pi/2nN_{\alpha_0}N_{\alpha_1}]^{1/2}$, where n is the sample size defined below and N_{α_0} and N_{α_1} are damping factors.

The errors involved with a limited amount of data due to a finite energy range ΔE place a severe restriction on the use of these data. Gibbs[35] has discussed this problem in detail and some of his results are quoted below in applying his corrections to the present data.

Gibbs shows that the number of independent points measured in a yield curve of span ΔE is given by $n=(\Delta E/\pi\Gamma)+1$. The main concern here is to find the effect of small n on Γ as well as the effect on $R(0)$ in order to determine y_D. In addition, Gibbs[35] gives estimates of the size of the errors to be attached to the corrected quantities. For the sample sizes encountered in this experiment, the errors range up to 80%. The results of this analysis (see Fig. 7) are listed by reaction in Table III.

Though the O^{16} yield-curve data have been analyzed in terms of Ericson fluctuation theory using Gibbs's[35] corrections for the small sample size of 2.5, the N^{15} sample size is even smaller. One can estimate Γ in this case by counting peaks in the p_0 yield curve and using the expression quoted by Dallimore and Hall,[27] $\Gamma=0.55/m$, where m is the number of peaks per unit energy interval. This gives a Γ of approximately 400 keV. From this, one can see that the sample size is much too small (>2) to analyze in the same manner as the $B^{10}(Li^6,\alpha)$ data. The low cross section of the $Be^9(Li^6,p)$ reactions (less than 20 μb/sr) precluded a larger energy range of data collection.

The direct reaction contribution to the cross section is considered slowly varying with energy.[6,36] Thus, the structure in the $Be^9(Li^6,p_0)$ yield curve at 5.8 MeV gives some evidence for a compound-nucleus contribution to this reaction. It is, of course, only very weak evidence.

The results of the analysis of the $B^{10}(Li^6,\alpha)$ yield curves are in agreement with the conclusions reached in previous experiments[12,13,15] that the direct reaction mechanism plays an important part in the 3.5- to 5.0-MeV lithium energy range as well as at 12.5 MeV.

[35] W. R. Gibbs, Phys. Rev. **139**, B1185 (1965); Los Alamos Scientific Laboratory Report No. LA-3266 (unpublished).

[36] N. Austern, in *Selected Topics in Nuclear Theory* (International Atomic Energy Agency, Vienna, 1963), Vol. 39, p. 17.

TABLE III. Results of analysis. The cross correlation coefficient and its estimated error were evaluated using expressions found in Dallimore and Hall.[a] The theoretical $R(0)$ and the errors in $R(0)$, y_D, and Γ come from Gibbs's analysis.[b] Symbols are defined in text.

Reaction	Cross correlation coefficient	N	$[N(0°)]^{-1}$	$R(0)$ theor. $y_D=0$ $n=2.5$	$R(0)$ expt.	y_D	Γ (MeV) autocorrelation analysis	Γ (MeV) peak counting	Γ (MeV) uncorrected auto-correlation width
$B^{12}(Li^6,\alpha_0)C^{12}$	0.17±0.45	11	1	0.43±0.33	0.34	0–65%	1.38±0.37	1.2	0.90
$B^{10}Li^6,\alpha_1)C^{12*}$		53	0.33	0.18±0.18	0.23	0–90%	1.37±0.38	1.2	1.06
$Be^9(Li^6,p_0)C^{14}$		12	1					0.40	
$Be^9(Li^6,p_1)C^{14*}$		36	0.33						

[a] Reference 27.
[b] Reference 35.

However, McGarth's analysis[13] showed also that the compound-nucleus mechanism may be playing an equally important part in the reaction. The present results reinforce this conclusion.

Extrapolation of Temmer's measurement[30] of Γ at 21 MeV in O^{16} to 36 MeV gives an expected value of Γ differing only by a factor of 2 from the result presented in Table III. In light of the approximation nature of the expression used to extrapolate Γ, the use of an Ericson fluctuation analysis gives consistent results.

Another possible explanation of the structure in the α_0 yield curve is the existence of individual nuclear states at 0^{16} excitation energies of 33.9, 36.2, and 38.2 MeV. The corresponding widths would be 0.49, 1.53, and 0.89 MeV (c.m.). The α_1 yield curve has peaks corresponding to O^{16} excitations of 35.2 and 36.1 MeV. This explanation would require one to disbelieve the above quoted estimates of level density. If such levels existed, they would appear in other channels as well, so investigation of other reactions should show their presence at the same excitations.

Investigations of elastic and inelastic scattering of α on C^{12} for α energies of 34 to 43 MeV will give information on any natural parity states for an O^{16} excitation range of 32.9 to 39.4 MeV. Mikumo[37] has measured angular distributions for $C^{12}(\alpha,\alpha_0)C^{12}$ and $C^{12}(\alpha,\alpha_1)C^{12*}$ at eight α energies between 27.0 and 35.5 MeV. He could not explain the large variations in the angular distributions as a function of energy on a simple direct interaction theory. The integrated cross section as a function of energy for the inelastic scattering shows peaks at alpha energies of 31.5 and 35.5 MeV corresponding to O^{16} excitations of 30.8 and 33.8 MeV. This structure is not evidence for compound nucleus resonances since investigations[38] of other channels, such as $C^{12}(\alpha,p)N^{15}$, do not support such a view.

The reaction $O^{16}(\gamma,n)O^{15}$ has been used to investigate O^{16} in the excitation range from 15 to 65 MeV.[39] The region around 35 MeV was investigated with a resolution of 250 keV, and although there is structure present in the region, it is not at the same excitation energy as the peaks in the $B^{10}(Li^6,\alpha)$ yield curves.

V. CONCLUSION

The yield curves for the reactions $B^{10}(Li^6,\alpha_0)C^{12}$, $B^{10}(Li^6,\alpha_1)C^{12*}$, $Be^9(Li^6,p_0)C^{14}$, and $Be^9(Li^6,p_1)C^{14*}$ have been treated in terms of the Ericson fluctuation theory. The results indicate that both compound-nucleus and direct-reaction modes contribute to the Li^6+B^{10} reactions while the evidence for the compound-nucleus mode was much weaker in the Li^6+Be^9 data. The average width in O^{16} near an excitation of 36 MeV was found to be approximately 1.4 MeV. The number of peaks in the p_0 yield curve indicates a level width of about 400 keV near an excitation of 28 MeV in N^{15}. The low sample size of the data does not preclude some other explanation for the fluctuations in the yield curve, but the sizable Γ/D values in the compound nucleus weighs against these peaks representing individual nuclear states.

Note added in proof. Measurements of the relative yield at 90° for $B^{10}(Li^6,\alpha_0)$ and $B^{10}(Li^6,\alpha_1)$ between 9.7 and 13.0 MeV exhibit none of the structure seen in the 0° yield curves. These results strengthen the conclusion that the Li^6+B^{10} structure is explained by Ericson fluctuation theory and not by isolated states in the O^{16} compound nucleus.

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