not vary too much between $b=k_F=1.36$ F^{-1} and $b=\infty$. For the parameters of v_l as in Eq. (1), $U_l(k_F)=-88.3$ MeV, while $U_l(\infty)=-70$ MeV.

We wish to emphasize clearly that it is by no means our original idea to incorporate bubble diagrams into single-particle energies. We have, however, shown that the bubble graphs so accounted for give most of the contribution to higher-order clusters. It should also be remembered that we do not imply Eq. (10) to be the entire $U(b)$, but only the part required to cancel long-range effects.

Finally, it is clear that to the extent that they matter, the contribution of v_l to five-body clusters and so on will also be dominated by bubble graphs, which will automatically be cancelled by the above choice of $U_1(b)$.

In conclusion, we note that since the $U_1(b)$ so chosen is large and negative, if it were the *only* contribution to the particle potential energies, it is likely to lower the energies of the particle states near k_F to values below the hole energies. This would result in zero- and negative-energy demoninators, and the reference-spectrum method will not work. However, it seems possible[11] that there may be a contribution to $U(b)$ due to tensor forces that will be positive for $b\sim k_F$ and will lift the particle energies above the hole energies. One can also try to increase $U(b)$ near k_F by including more complicated inserts than just the "bubble."

ACKNOWLEDGMENTS

The author is indebted to Professor H. A. Bethe for donating some of his valuable time for discussions. Deep gratitude also goes to Dr. M. Kirson for the use of his excellent thesis which helped clarify many ideas, and to Dr. Ben Day for a useful discussion. The author is indebted to the hospitality of the members of the Laboratory of Nuclear Studies, Cornell University, where part of this work was done.

[11] T. Dahlblom and H. A. Bethe (private communication).

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Differential and Total Cross Sections of Reaction Products from Li^7+Li^6 between 3.78 and 5.95 MeV*

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Reactions initiated by Li^7+Li^6 have been studied at six bombarding energies between 3.78 and 5.95 MeV. A *dE/dx-E* system was used for particle detection and identification, and an on-line computer was utilized for pulse-height analysis, storage, and data analysis. Differential and total cross sections were obtained for protons leading to the 0.0, 0.95, 1.67, 2.62–2.72, and 3.39-MeV levels of B^{12}; deuterons leading to the 0.0, 2.14, 4.46, 5.03, 6.76–6.81, and 7.30-MeV levels of B^{11}; tritons leading to the 0.0 and 0.717-MeV B^{10} levels; and alphas leading to the Be^9 ground state. The dominant reaction process appears to be the transfer of an α particle, as evidenced by the angular distributions and total cross sections for B^{10} and B^{11} levels. In all cases, the total cross sections are generally smoothly increasing over the observed energy range with no evidence for structure. The proton cross sections have the lowest magnitude of the particles observed here, and a compound-nucleus process seems most likely for those groups.

I. INTRODUCTION

It is now well known that the cluster structure of Li ions as $(\alpha+d)$ or $(\alpha+t)$ often plays a dominant role in Li-induced reactions. An extensive study of the Li^6+Li^6 reaction over a considerable range of bombarding energies demonstrated that residual nuclei which may be formed via the transfer of an α particle are observed with great strength, particularly if a level may be formed by an $l_\alpha=0$ transfer.[1] Other work on the Li^6+Li^6 reaction at Chicago,[2] and the Argonne results from $B^{10}(d,Li^6)Li^6$,[3] substantiate the importance of the α-transfer process.

Less experimental information is available on a similar cluster configuration for Li^7 as $(\alpha+t)$. The Chicago results at 2.1 MeV for Li^7+Li^6 and Li^7+Li^7 do give strong indication of the importance of an $(\alpha+t)$ structure for Li^7, however.[2] The α separation energy is 2.47 MeV in Li^7 compared with 1.47 MeV in Li^6, so the α transfer may occur less strongly from Li^7 than from Li^6, but should still be an important mode of interaction.

* Research supported in part by the National Science Foundation.
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[1] K. G. Kibler, Phys. Rev. **152**, 932 (1966).
[2] M. N. Huberman, M. Kamegai, and G. C. Morrison, Phys. Rev. **129**, 791 (1963). G. C. Morrison and M. N. Huberman, in *Reactions Between Complex Nuclei*, edited by A. Zucker, F. T. Howard, and E. C. Halbert (John Wiley & Sons, Inc., New York, 1960).
[3] D. S. Gemmell, J. R. Erskine, and J. P. Schiffer, Phys. Rev **134**, B110 (1964).

Compound-nucleus (CN) effects are far from negligible in Li-induced reactions, so this CN process may usually be expected to complicate any straightforward interpretation of results in terms of a simple direct reaction (DR) model. The work of Heikkinen on Li^6+C^{12},[4] and particularly the results of McGrath on Li+B,[5] indicated strong contributions from the compound nucleus process. In Li^6+Li^6 and Li^7+Li^6 one reaches a high-excitation energy (about 28 MeV) in the compound nucleus, because of the large mass excesses in the incident channel. Simple calculations of level widths and level densities then indicate that the application of statistical arguments may be fruitful (cf. Refs. 1, 4, and 5). In such cases one may expect a $(2J+1)$ dependence of the cross reactions, where J is the spin of the residual level. Considerable success along these lines was achieved by McGrath,[5] and some limited applicability was indicated in the previous Li^6+Li^6 work.[1]

In the absence of such a $(2J+1)$ dependence of the cross sections (which indicates the presence of compound-nucleus effects if the levels studied are known to be of dissimilar configuration), the determination of the importance of the CN mode is quite difficult. One may see fluctuations in the shape and magnitude of differential and total cross sections as a function of incident energy, but the absence of such effects further complicates the indications for a possible compound nucleus process. Indeed, even if one is certainly in a region of the compound nucleus where statistical arguments are appropriate, the presence of non-negligible spins (J) of target, projectile, etc., may severely damp any fluctuations which may be present.

Consider the many difficulties inherent in attempting to assign reaction mechanisms, the present paper is primarily a report of the differential and total cross sections for the following reactions:

$$\begin{aligned} Li^7+Li^6 &\to B^{12}+p+8.34\text{ MeV}, \\ &\to B^{11}+d+7.20\text{ MeV}, \\ &\to B^{10}+t+2.00\text{ MeV}, \\ &\to Be^9+\alpha+15.22\text{ MeV}. \end{aligned}$$

The $Li^7(Li^6)$ energies at which the above reactions were observed were 3.78(3.25), 4.34(3.72), 4.88(4.18), 5.20(4.45), 5.53(4.74), and 5.95(5.10)MeV. These energies correspond to 1.75, 2.0, 2.25, 2.4, 2.55, and 2.75 MeV in the c.m. system. Results for the following residual levels are reported: B^{12}-0.0, 0.95, 1.67, 2.62-2.72 (unresolved), and 3.39 MeV; B^{11}-0.0, 2.14, 4.46, 5.03, 6.76-6.81 (unresolved), and 7.30 MeV; B^{10}-0.0, 0.72, 1.74 MeV; Be^9-0.0 MeV.

Because of the nature of the data collection system, all charged particles from these reactions are observed simultaneously. With this abundance of observed final-state particles, one can hardly hope to avoid the problem of competing reaction modes in discussing the results. There are, however, certain important features to be searched for in the results.

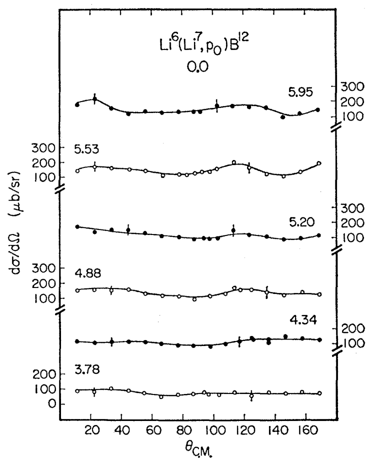

FIG. 1. Differential cross sections in μb/sr of protons from the ground state of B^{12}. Zero levels are often suppressed. Open and closed data points refer to ordinates on the left and right, respectively. Error bars represent statistical deviations and analysis errors.

The prominence of the α-transfer process should be reflected in the present (Li^7,t) results compared to the previous (Li^6,d) work. This Li^7+Li^6 reaction was studied over an energy range comparable to that used in the Li^6+Li^6 experiment. The Li^7 energies were chosen to match the Li^6 c.m. energies in Ref. 1, which provides some connection between the experiments for comparison purposes, though not necessarily a very meaningful one. The Coulomb barriers are nearly the same in both experiments (2.4 MeV in the c.m. system), and the Q values are similar [2.00 MeV for $Li^6(Li^7,t_0)B^{10}$ and 2.99 MeV for $Li^6(Li^6,d_0)B^{10}$].

In the present Li^7+Li^6 experiment, one has the opportunity to observe the transfer of α particles both to the target and to the projectile by interchanging beam and target. The results obtained for the $\alpha+Be^9$ and $p+B^{12}$ final states are presented here primarily for the sake of completeness, since the spirit of this report is intended to be a compilation of differential and total cross sections from the Li^7+Li^6 reactions.

II. EXPERIMENTAL PROCEDURE

The Li beams used in this experiment were produced by the 5.5-MeV Van de Graaff of the University of Iowa. The absolute energy calibration and long-term stability of the accelerator have been discussed previously.[6]

The target chamber used in this experiment has been described elsewhere[7] in some detail. Apertures at the chamber entrance define the beam spot to be 0.080 in. in diameter at the target. A small surface-barrier detector mounted at 90° (lab) was used as a monitor to normalize the data between various angles.

[4] D. W. Heikkinen, Phys. Rev. **141**, 1007 (1966).
[5] R. L. McGrath, Phys. Rev. **145**, 803 (1966).
[6] D. W. Heikkinen, Ph.D. dissertation, University of Iowa, SUI 65-24, 1965 (unpublished).
[7] R. R. Carlson, R. L. McGrath, and E. Norbeck, Phys. Rev. **136**, B1687 (1964).

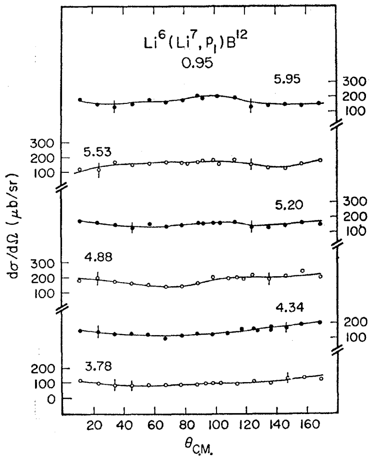

FIG. 2. Differential cross sections in μb/sr of protons from the 0.95-MeV level of B^{12}. See caption for Fig. 1.

The particle detection and identification system consists of a lithium-drifted silicon detector (E detector) mounted inside a gas proportional counter (ΔE detector). A Control Data 160-A computer was used for two parameter analysis of the E and ΔE pulses in a manner previously described.[1] The data analysis was also performed on this computer, and the method is outlined in detail in Ref. 1.

For the angular distribution measurements, the targets were made by evaporating Li^6F or Li^7F onto 1.7-mg/cm² Al backings. For normalization of the data between different energies, the Li^6 F was evaporated onto self-supporting carbon backings, and these targets were then bombarded using standard change collection techniques. For the absolute normalization, these Li^6 targets were then bombarded with a Li^6 beam, and using the measured cross sections from previous Li^6+Li^6 work,[1] the Li^7+Li^6 results were normalized to this. Targets had a thickness such that a 5.0-MeV lithium beam lost about 100 keV in the lithium fluoride. The total cross sections were obtained with a sinθ-weighted integration of the differential cross sections using a trapezoidal rule.

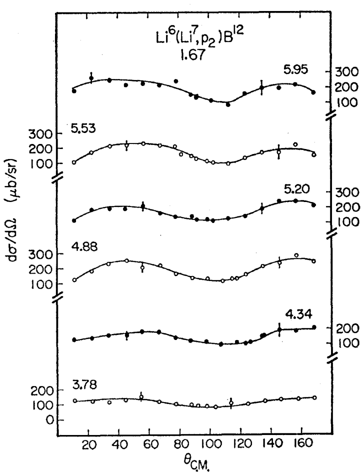

FIG. 3. Differential cross sections in μb/sr of protons from the 1.67-MeV level of B^{12}. See caption for Fig. 1.

Relative errors assigned to the differential cross sections total 10–15% in general, which includes primarily the repeatability of normalization runs and statistics. Errors in the total cross sections are considered to be about 25%, which is primarily due to the error assignment in the previous Li^6+Li^6 cross-section measurements.

In all cases, the differential cross sections were measured with both beam-target combinations, namely Li^6 target–Li^7 projectile, and Li^7 target–Li^6 projectile. This allowed observation of particles at angles greater than are physically accessible due to the target chamber construction (139° lab), and also permitted observation of particle groups from low-Q reactions over a wider angular range than would be possible with a fixed beam-target choice. All results are plotted as if a Li^7 beam and a Li^6 target were used and the bombarding energies refer to a Li^7 beam. For the data collected with a Li^7 target and Li^6 beam, the machine energy was, of course, lowered so that the c.m. energy was the same, and the data were plotted at angles corresponding to $180°-\theta$, where θ is the c.m. angle.

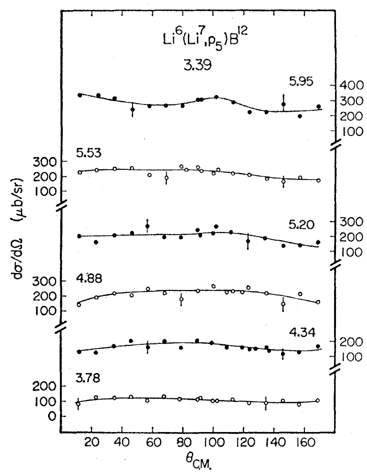

FIG. 5. Differential cross sections in μb/sr of protons from the 3.39-MeV level of B^{12}. See caption for Fig. 1.

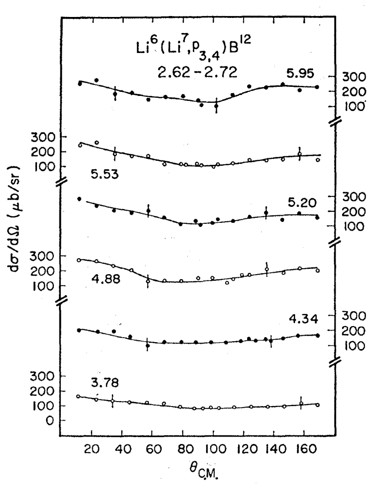

FIG. 4. Differential cross sections in μb/sr of protons from the 2.62 and 2.72-MeV levels of B^{12}. See caption for Fig. 1.

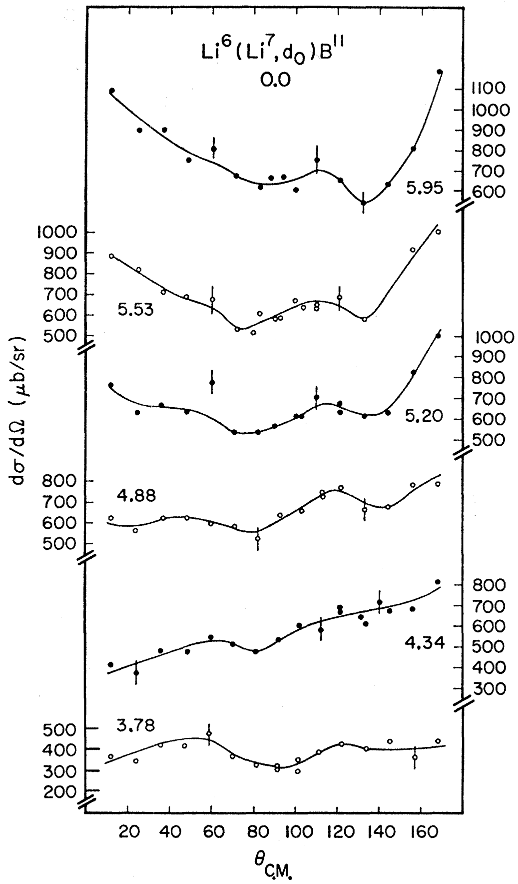

FIG. 6. Differential cross sections in μb/sr of deuterons from the ground state of B^{11}. See caption for Fig. 1.

III. RESULTS

The differential cross sections measured in this experiment are shown in Figs. 1–14. In each figure the results for a given residual level are plotted for each of the bombarding energies at which the reaction was observed. Although the results were obtained in each case by interchanging target and projectile for back-angle data as mentioned in the previous section, all results are plotted in the frame in which Li^6 is the target and Li^7 is the projectile.

Zero levels are in general suppressed in the figures, and the open and closed data points refer to the left and right ordinates, respectively. The solid curves have been drawn as a visual aid in connecting the data points, and no other significance for these curves is intended. One should note the incomplete data over the middle portion of the angular range for $d_{4,5}$ and d_6. This is due to the low Q to these levels which therefore could not be observed at all energies. Also no data are presented for α_0 at 4.34 and 4.88 MeV at forward angles because of an unfortunate gain setting of the analyzer.

The proton results are shown in Figs. 1–5. The most noticeable characteristic of all the proton results is the near isotropy of the angular distributions both as a function of bombarding energy and as a function of the particular residual level in B^{12}. The only fairly obvious exception to this is p_2; the angular distribution for this group has a minimum at 110° which persists throughout the energy range. Small variations in shape may be seen in the differential cross sections for the other proton groups, but these variations are seldom outside of experimenal statistics.

The differential cross sections for deuterons from levels in B^{11} are shown in Figs. 6–11. Both d_0 and d_3 (Figs. 6 and 9) show forward and backward peaking, particularly as the incident energy increases. At the higher energies, both of these groups have a noticeable peak at 110°–120°. Figures 7 and 8 indicate some similarity in the results for d_1 and d_2. Both show consistent backward peaks as the energy increases, with little or no evidence for a forward peak, except at the lower energies. Both d_1 and d_2 also have a maximum at most energies around 60–80°. Figures 10 and 11 show the results for $d_{4,5}$ and d_6. Both these groups are generally peaked forward and backward, and their differential cross sections generally show the greatest peak-to-valley ratio of any of the deuteron groups (as much as 5 to 1).

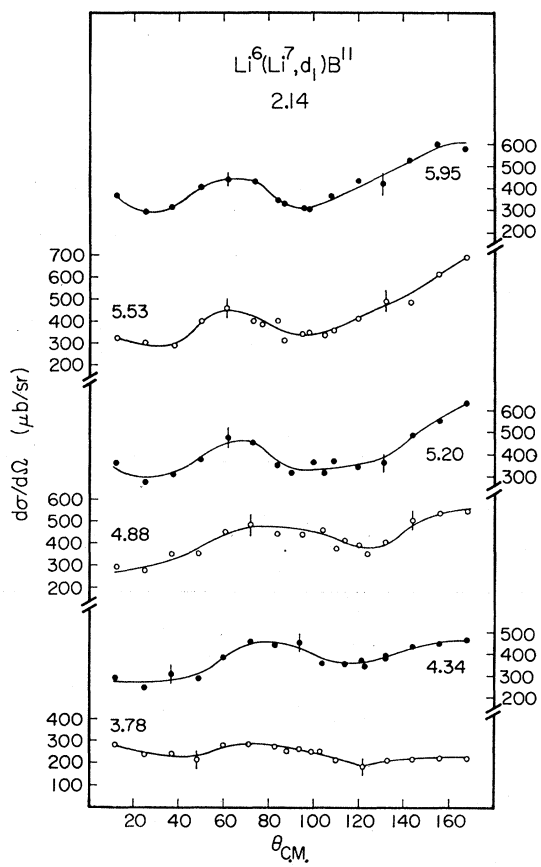

FIG. 7. Differential cross sections in μb/sr of deuterons from the 2.14-MeV level of B^{11}. See caption for Fig. 1.

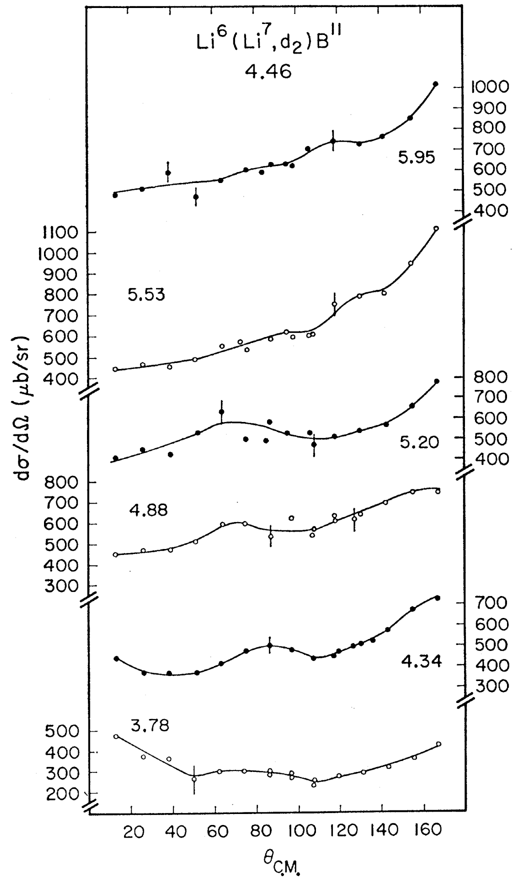

FIG. 8. Differential cross sections in μb/sr of deuterons from the 4.46-MeV level of B^{11}. See caption for Fig. 1.

The triton results appear in Figs. 12 and 13. The t_0 angular distribution is rather isotropic at 3.78 MeV, but develops a maximum at 110–120° and a minimum at about 140° as the bombarding energy increases. The t_1 results, however, are quite different. A strong forward peak appears at all energies with a secondary maximum near 90°.

Figure 14 contains the α_0 results. These curves exhibit a greater amount of variation as a function of angle than any of the other particle groups. Maxima are generally observed near 40°, 100°, and 180° with pronounced minima at 60° and 120° (and 0° at the higher energies).

TABLE I. Total cross sections in mb as a function of energy.

Bombarding energy (MeV) / Observed particle	3.78	4.34	4.88	5.20	5.53	5.95
p_0	1.0	1.4	1.7	1.5	1.9	1.9
p_1	1.3	1.8	2.2	2.0	2.0	2.2
p_2	1.4	1.8	2.3	2.1	2.1	2.4
$p_{3,4}$	1.3	1.7	2.1	2.0	1.9	2.3
p_5	1.4	2.1	2.8	2.5	2.8	3.5
d_0	4.9	7.1	8.2	8.0	8.4	9.2
d_1	3.1	4.8	5.3	5.0	5.2	5.1
d_2	3.9	5.8	7.3	6.9	7.9	8.2
d_3	4.4	7.0	8.2	7.4	8.0	7.5
$d_{4,5}$	6.8	9.4	10.7	9.8	11.4	12.2
d_6	···	24.4	30.6	27.3	25.7	28.8
t_0	3.1	4.2	5.2	5.1	5.4	5.7
t_1	7.8	12.0	12.2	11.1	11.7	11.7
α_0	2.2	3.0	3.3	3.3	3.0	3.6

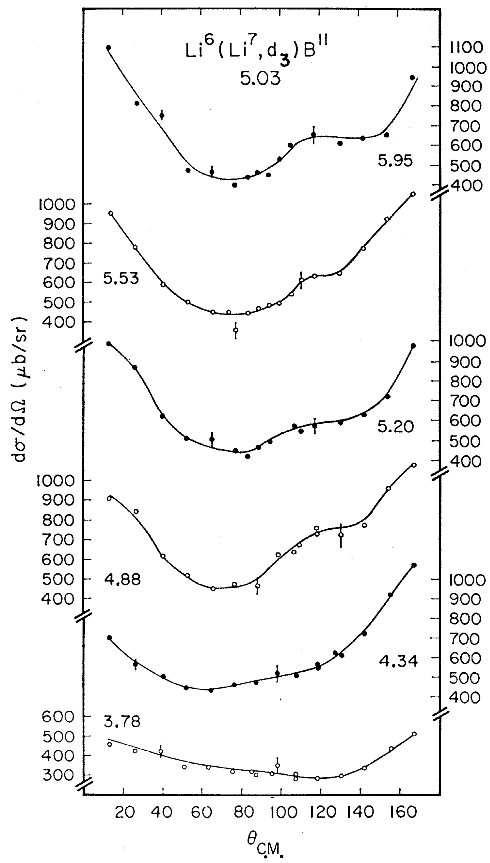

FIG. 9. Differential cross sections in μb/sr of deuterons from the 5.03-MeV level of B^{11}. See caption for Fig. 1.

The integrated total cross sections for all groups appear in Tables I and II. Table I summarizes the cross-section behavior for all groups as a function of energy, while Table II gives the energy-averaged total cross sections. The values given at some energies for $d_{4,5}$, d_6, and α_0 should be regarded with some caution on account of the previously mentioned incompleteness of the data. For the unobserved angles for $d_{4,5}$ and d_6, the differential cross section was assumed to be of the shape indicated by dotted curves in Figs. 10 and 11. For α_0 at 4.34 and 4.88 MeV, the cross section at unobserved angles was taken as the average over observed angles.

From Table I we see a general increase of all cross sections as the bombarding energy is raised. Small variations from a smooth behavior are evident, but these variations are well within the 25% error assignment. The average values of Table II allow a rapid comparison of cross-section magnitudes between the various types of particles. The d and t values are the largest as one might expect if α transfer is quite important, followed in magnitude by the α and p values.

IV. DISCUSSION

As mentioned previously, the proton angular distributions (Figs. 1–5) exhibit little structure, and in fact are relatively isotropic in most cases. If we want to visualize this process as a direct one, we must consider the transfer of either 6 nucleons from Li^7 or 5 nucleons from Li^6. The proton-separation energies of Li^6 and Li^7 would render such transfers unlikely. Little is known

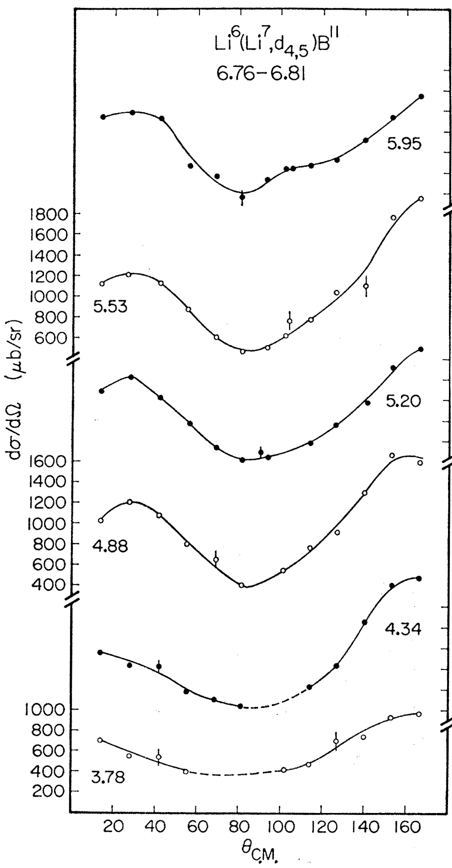

FIG. 10. Differential cross sections in μb/sr of deuterons from the 6.76 and 6.81-MeV levels of B^{11}. See caption for Fig. 1.

about the configuration of the B^{12} levels. Talmi and Unna[8] suggest that the ground state and the 0.95-MeV level may be mainly $p_{3/2}{}^7p_{1/2}$ in analogy with the corresponding $T=1$ levels in C^{12}, but there is no reason to suppose that a favored mode of formation may occur via Li^6+(6 nucleons) or Li^7+(5 nucleons).

One is thus led to believe the $p+B^{12}$ final state is a product of a CN process. The excitation reached in the C^{13} compound nucleus is around 28 MeV. At a similar excitation in C^{12} (see Ref. 1), it was likely that $\Gamma/D>1$ (Γ is level width and D is level spacing), which indicated

TABLE II. Energy-averaged total cross sections.

Observed particle	Residual nucleus and level		J^π residual level	σ (mb)
p_0	B^{12}	0.0	1^+	1.6
p_1		0.95	$(2^+,3^+)$	1.9
p_2		1.67	$1^-,2^-$	2.0
$p_{3,4}$		2.62,2.72	...	1.9
p_5		3.39	$\leq 3^-$	2.5
d_0	B^{11}	0.0	$\frac{3}{2}^-$	7.6
d_1		2.14	$\frac{1}{2}^-$	4.8
d_2		4.46	$\frac{5}{2}^-$	6.7
d_3		5.03	$(\frac{1}{2},\frac{3}{2})^-$	7.1
$d_{4,5}$		6.76,6.81	$\frac{7}{2}^-,(\frac{1}{2},\frac{3}{2})^+$	10.0
d_6		7.30	$(\frac{3}{2},\frac{5}{2})^+$	27.4
t_0	B^{10}	0.0	3^+	4.8
t_1		0.72	1^+	11.1
t_2		1.74	$0^+(T=1)$	0.2-1.0
α_0	Be^9	0.0	$\frac{3}{2}^-$	3.1

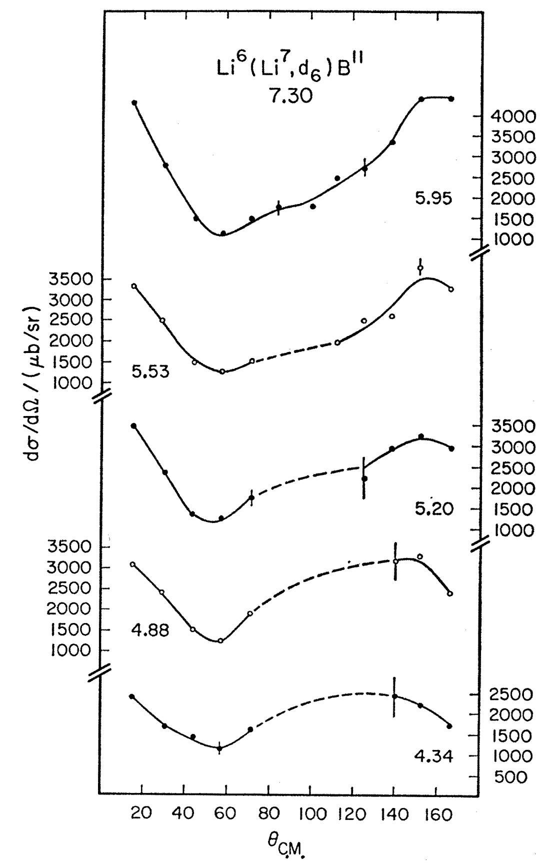

FIG. 11. Differential cross sections in μb/sr of deuterons from the 7.30-MeV level of B^{11}. See caption for Fig. 1.

[8] I. Talmi and I. Unna, in *Annual Review of Nuclear Science*, edited by E. Segrè, G. Friedlander, and W. E. Meyerhof (Annual Reviews Inc., Palo Alto, California, 1960), Vol. 10, p. 353.

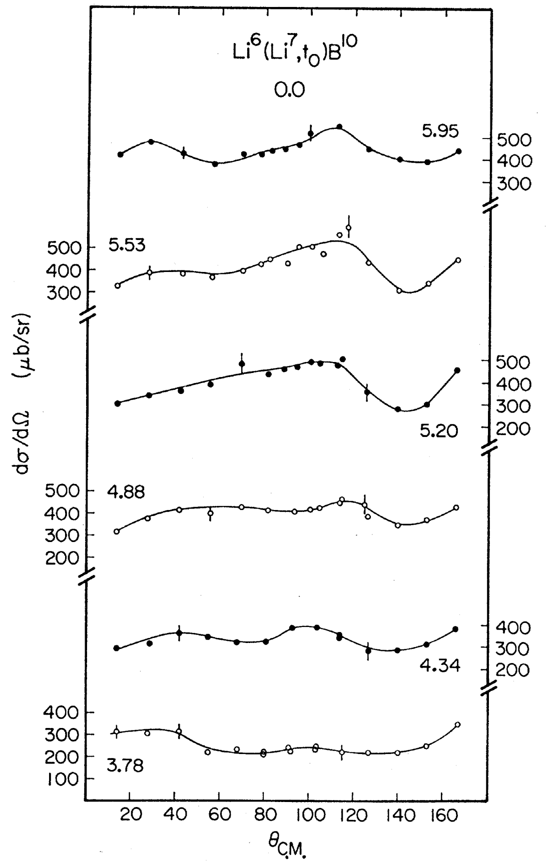

FIG. 12. Differential cross sections in μb/sr of tritons from the ground state of B^{10}. See caption for Fig. 1.

the possible applicability of statistical arguments. If a similar situation exists in C^{13}, then the total cross sections for formation of B^{12} levels might be proportional to $(2J+1)$, where J is the spin of a particular level in B^{12}. There is however, no indication of such dependence in the tabulated cross sections (Tables I and II).

If the reaction were proceeding through such a statistical region of the compound nucleus, we might expect to see variation in the differential cross sections as a function of energy even if all the requirements for a $(2J+1)$-dependence were not fulfilled. No such variations are evident, however. We might point out that such variations depend on the number N of independently-fluctuating cross sections and on the fraction of the average cross section arising from DR contributions.[9] This number N is given, at angles not near 0° or 180° by

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

where i, I, i', and I' are the spins in initial and final channels of the relevant particles. For one of the most favorable cases, namely a transition to the 1^+ B^{12} ground state, N equals 36. If such a large N is used in the equation for the probability distribution of the differential cross section given by Newton,[9] the chances for seeing large variations about the average cross section are not good. In addition, the experimental energy spread from the target thickness is comparable to the expected value of Γ which would tend to smooth out the remaining variations.

Comparing the present proton results with those obtained at Chicago,[2] we find that the cross sections have increased by roughly a factor of 3 between 2.1- and 3.78-MeV incident energy. The shapes of the angular distributions are generally more isotropic here than at 2.1 MeV.

The deuteron results are shown in Figs. 6–11. The situation here is somewhat unusual. If we consistently discuss the reaction in terms of a Li^7 projectile and a Li^6 target, then all mention of α transfer must refer to transfer from the target to the projectile. This process is likely to be quite important however, due to the low separation energy of $Li^6 \rightarrow \alpha+d$ (1.47 MeV). The most noticeable feature of the deuteron angular distributions is the general forward and backward peaking.

Viewed quite simply, one might expect the following results which indeed appear in the figures. We consider the Li^6 as a loosely bound $(\alpha+d)$ structure which is easily separated by the strong Coulomb fields inherent

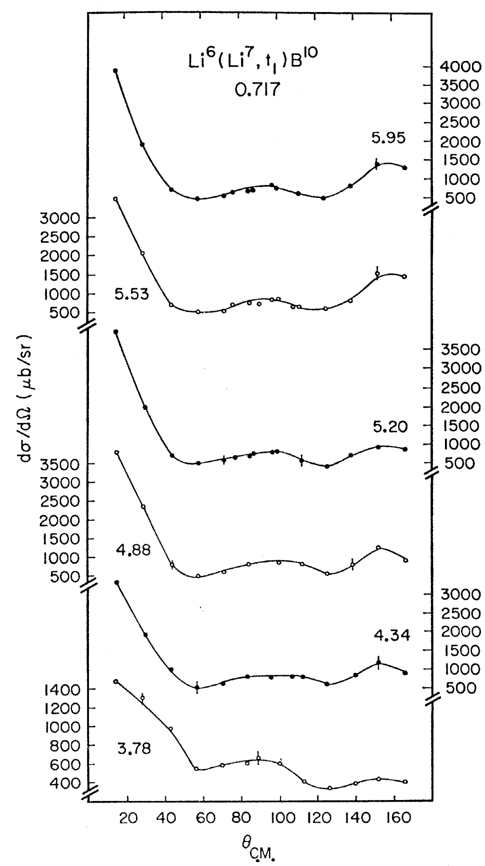

FIG. 13. Differential cross sections in μb/sr of tritons from the 0.72-MeV level of B^{10}. See caption for Fig. 1.

[9] J. O. Newton, Phys. Letters 17, 132 (1965).

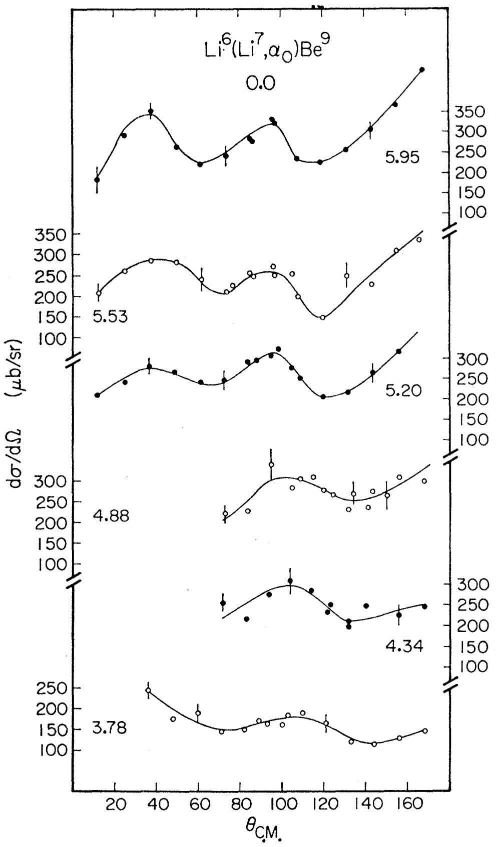

FIG. 14. Differential cross sections in μb/sr of alphas from the ground state of Be^9. See caption for Fig. 1.

in encounters between complex nuclei. For large impact parameters, the Li^7 projectile simply "picks up" the α from Li^6 and continues as B^{11} in the forward direction, giving rise to a strong deuteron yield then in the backward direction. For close encounters, i.e., small impact parameters, the Li^7 projectile "knocks out" the deuteron from Li^6, and the deuteron proceeds forward giving rise to a peaking at 0°. Qualitatively then, this simple picture can adequately account for the gross features in the observed angular distributions.

If indeed this α-transfer process is important, the observed differential cross sections should be affected strongly by the angular momentum of the transferred α particle. In such a case, we expect to see similarities in the differential cross sections between states which may be formed by α particles with the same l value. Consider the B^{11} ground state, definitely of spin and parity $\frac{3}{2}^-$, and the 5.03-MeV state, of $(\frac{1}{2},\frac{3}{2})^-$. We could possibly form both these states via Li$^7+\alpha$,with $l_\alpha=0$. Comparing the results for these states in Figs. 6 and 9, we see that both are characterized by strong forward and backward peaking at higher energies, and both exhibit a secondary maximum near 120°.

Continuing along these same lines, both the 2.14-MeV state and the 4.46-MeV state require at least $l_\alpha=2$ for their formation. In Figs. 7 and 8 we notice both states are characterized by backward peaking in general, with a secondary maximum around 60°–80° in some cases. We notice also that the total cross sections for these states (Table II) are somewhat less than those for the ground state and 5.03-MeV level, perhaps indicating formation which is indeed more difficult if larger l values must be transferred.

The two other deuteron groups observed, corresponding to the 6.76-6.81-MeV doublet with spin and parity $\frac{7}{2}^-$, $(\frac{1}{2},\frac{3}{2})^+$ and the 7.30-MeV state with $(\frac{3}{2},\frac{5}{2})^+$ are shown in Figs. 10 and 11. Both these groups have positive parity associated with them and thus require $l_\alpha=1$ transfer, among other possibilities, for their formation. We see both states characterized by strong fore-and-aft peaking with little or no structure in the central portion of the angular range.

The structure of these B^{11} levels is quite complicated, as mentioned in a comprehensive paper by Olness *et al.*[10] The ground, 4.46-MeV, and 6.76-MeV states are fairly strongly excited in (d,p) work,[11] thus indicating a single-particle character for those levels. Talmi and Unna report that the ground state, 5.03-MeV, and 6.81-MeV levels are mainly of a $p_{3/2}{}^7$ and $p_{3/2}{}^5p_{1/2}{}^2$ nature, while the 2.14-, 4.46-, 6.76-, and 7.30-MeV levels are admixtures of $p_{3/2}{}^6p_{1/2}$, $p_{3/2}{}^5p_{1/2}{}^2$, and $p_{3/2}{}^4p_{1/2}{}^3$ configurations.[8] This generally complicated nature of the B^{11} levels and their large cross sections in the present experiment indicate that the determining factor in their formation is probably the ease of separation of Li^6 into $(\alpha+d)$. Indeed the similarities mentioned above between the angular distributions for levels which may be formed by α transfer with equal l values emphasizes the importance of this α-transfer process.

The cross sections for formation of the first four odd-parity levels are all similar in magnitude, with a slight suppression of the 2.14- and 4.46-MeV levels which require larger transferred l for their formation. The $d_{4,5}$ and d_6 yields are larger however, particularly the d_6 group from the 7.30-MeV level. Larger yields to these states were noted in the Li^6(Li^6,p)B^{11} reaction (1) and, similarly larger cross sections were observed for analog levels in the Li^6(Li^6,n)C^{11} reaction.[12] Perhaps large admixtures of $p_{3/2}{}^5p_{1/2}{}^2$ and $p_{3/2}{}^4p_{1/2}{}^3$ configurations in these levels make their formation via 4 or 5-nucleon transfer considerably easier than similar formation for other B^{11} levels.

The triton results appear in Figs. 12 and 13. The ground state triton group exhibits considerable isotropy at low energies, becoming more anisotropic as the incident energy is raised. The t_1 results are uniformly forward peaked at all energies. In the (Li^7,t) reaction,

[10] J. N. Olness, E. K. Warburton, D. E. Alburger, and J. A. Becker, Phys. Rev. **139**, B512 (1965).

[11] O. M. Bilaniuk and J. C. Hensel, Phys. Rev. **120**, 211 (1960); S. Hinds and R Middleton, Nucl. Phys. **38**, 114 (1962).

[12] R. M. Bahnsen, Ph.D. dissertation, University of Iowa, SUI 66-23, 1966 (unpublished).

we expect the results to be strongly governed by the α-transfer process from the Li^7, and in fact the results may be similar to those for (Li^6,d) reported in Ref. 1. If we consider the transferred l values which influence formation of these states, we find $l_\alpha=0$ possible for the 1^+ B^{10} state at 0.717 MeV, but at least $l_\alpha=2$ is necessary for ground state formation. Indeed the strong forward peaking of t_1 at all energies lends considerable support to this suggestion, while the $l_\alpha=2$ necessary for ground-state production may be capable of causing the observed anisotropy at intermediate angles.

The t_1 total cross section is typically three times greater than that for t_0, reflecting the relative ease of formation via $l_\alpha=0$, where no centrifugal barrier is present. The cross sections for formation of both these states are reduced by roughly a factor of 2 from the cross sections in the $Li^6(Li^6,d)B^{10}$ results.[1] This may just indicate the slightly more difficult α-transfer formation due to the higher binding of the α in Li^7.

No differential cross sections are presented for B^{10} levels above 0.72 MeV, since groups from higher states could seldom be observed at most angles because of the prohibitively low Q values. Rough limits have been set on formation of the 0^+, $T=1$ level at 1.74 MeV, and these values are shown in Table II. This t_2 group was noticeable in the triton spectra when energetically possible, but its separation from background was quite difficult. The situation for producing this $T=1$ level is interesting when compared to its formation in the Li^6+Li^6 reaction, as Morrison has previously noted.[2] In the Li^6+Li^6 reaction, isospin considerations forbid formation of this level, but no such restrictions are imposed in the present Li^7+Li^6 work. If we do consider formation via the transfer of an α particle, however, then spin-parity restrictions in both reactions inhibit the formation of this 0^+ state by a $Li^6(1^+)$ plus$+\alpha$ particle process. The low yield to this state then provides further evidence of the importance of the α-transfer process in the Li^7+Li^6 reaction.

The results for α_0 from the Be^9 ground state are shown in Fig. 14. The shape of the differential cross section changes as a function of energy with regard to the growing prominence of the backward peak with increasing energy. In this $Li^6(Li^7,\alpha)Be^9$ reaction, the reaction may occur by either the Li^6 or the Li^7 losing an α, in which case the d or t is captured by the other nucleus. If Li^7 absorbs the deuteron, we can have $l_d=0$, but $l_t=1$ is required for triton capture by Li^6. Morrison's results at 2.1 MeV were suggestive of $l=1$ capture, since the only peak evident was near 60° in the c.m. system of Li^7 projectile, Li^6 target. This is similar to the results here, but the $l=0$ process (deuteron capture by Li^7) apparently grows more prominent as the energy is raised as evidenced by the backward peak at the higher energies. The differential cross section in general shows considerable variation with angle, perhaps due to the competition between deuteron and triton capture.

If we briefly consider the total cross sections from the Li^7+Li^6 reactions as functions of bombarding energy, the results are quite similar to those from the Li^6+Li^6 reactions in Ref. 1. Comparing Li^7+Li^6 between 3.78 and 5.95 MeV to Li^6+Li^6 between 4.0 and 5.5 MeV the increase in cross sections with energy is generally similar, being roughly a factor of 1.5–2.0. The Coulomb barrier is nearly equal in both cases (2.4 MeV in the c.m. system) so the variation of cross sections near the barrier is not rapid. The most rapid change in magnitude of the cross sections occurs between the Chicago energy (2.1 MeV) and about 4 MeV, namely in the region of half the barrier height upward to a value somewhat below the barrier height. Such behavior is expected if the l values and penetrabilities are important.

Although direct-type processes are apparently the most important ones in Li^7+Li^6 (except possibly for the $p+B^{12}$ final state), one cannot ignore possible competition from a CN mode. The finite size of the reacting ions and the classical distance of closest approach at these energies render compound nucleus formation possible in most cases.

V. CONCLUSIONS

We have provided further evidence for the importance of the reacting cluster picture in Li-Li encounters. In the present case we have the possibility of transferring an α particle both from the target and from the projectile. The large magnitude of the cross sections from the observed deuteron and triton groups support this transfer picture. The differential cross sections for levels in B^{10} and B^{11} appear in most cases to be influenced to a large extent by the l value of the transferred alpha. In the Be^9 case, where we might have formation by either d or t transfer, the magnitude of the cross section is reduced below the B^{10} and B^{11} values, which perhaps indicates that the transfer of a more tightly bound α is favored. The proton cross sections are lower than those for all other groups, even though the Q value for these reactions is higher than that for emission of deuterons and tritons. Though a compound nucleus process is most likely for the case of proton emission, its competition in the other reactions is not unlikely.