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Cross Sections for Li^7+Li^7 from 2 MeV to 6 MeV*

R. R. CARLSON AND H. W. WYBORNY

Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52240

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Differential cross sections for 16 charged-particle groups resulting from the Li^7+Li^7 nuclear reaction were measured as a function of angle and energy. Measurements were generally made every 10° from 0° to 90° in the laboratory and every 0.75 MeV from 2.10- to 5.75-MeV bombarding energy. This bombarding energy range reaches from well below to well above the classical Coulomb barrier. The general shapes of the angular distributions do not change over the energy range below the barrier, but there are marked changes in some cases for energies above the barrier. A barrier-penetration energy dependence of the total cross sections is found at low energies, but marked deviations from this dependence occur as the barrier is surmounted. The absolute values of the cross sections were measured, and the sum of the total cross sections is decidedly less than the calculated cross section for barrier penetration.

I. INTRODUCTION

THE differential cross sections for nuclear reactions resulting from Li^7 bombardment of Li^7 were measured as a function of angle and energy in order to obtain information about the reaction mechanism in lithium-induced reactions. As the lightest of the "heavy" ions, lithium should be a useful tool for probing nuclear structure. Its high mass excess, or loose binding, makes it similar to the deuteron in this respect. In order to make use of this tool, however, a good understanding of the reaction mechanism is necessary.

The reactions which were studied in the present work were

$$Li^7+Li^7 \to B^{13}+p+5.964 \text{ MeV}$$
$$\to B^{12}+d+3.308 \text{ MeV}$$
$$\to B^{11}+t+6.197 \text{ MeV}$$
$$\to Be^{10}+\alpha+14.783 \text{ MeV}.$$

Absolute differential and total cross sections were measured for a total of 16 particle groups at six incident laboratory energies from 2.10 to 5.75 MeV. Table I lists the particle groups observed, the corresponding residual states,[1] and the designations of the groups.

These reactions have been studied by Huberman *et al.*[2] at Chicago at 2.10-MeV bombarding energy. The $Li^7(Li^7, \alpha)Be^{10}$ reaction was also studied by Dzubay and Blair[3] at Minnesota for incident energies from 2.45 to 3.90 MeV. Downward extrapolation in energy of the absolute value of the cross section as measured by the Minnesota group gives a value in serious disagreement with the Chicago result. One objective of the present work was to clear up this disagreement. It was for this reason that the bombarding energy range was extended down to 2.10 MeV.

The upper end of the bombarding energy range in the present work was set so as to include the region of the classical Coulomb barrier. This corresponds to a bombarding energy of 4.5 MeV. The angular distributions obtained by the Chicago group were interpreted in terms of a direct reaction mechanism. This is not unreasonable in view of the loose binding of Li^7. However, work on other lithium-induced nuclear reactions on lithium,[4,5] boron,[6,7] carbon,[8,9] and oxygen[10] for bombarding energies at or near the Coulomb barrier indicate a substantial, if not predominant, compound

* Research supported in part by the National Science Foundation.

[1] T. Lauritsen and F. Ajzenberg-Selove, National Research Council Report Nos. NRC-61-5 and NRC-61-6 (unpublished); and report, 1966, (unpublished).

[2] M. N. Huberman, M. Kasegai, and G. C. Morrison, Phys. Rev. **129**, 791 (1963).
[3] T. G. Dzubay and J. M. Blair, Phys. Rev. **134**, B586 (1964).
[4] K. G. Kibler, Phys. Rev. **152**, 932 (1966).
[5] K. G. Kibler, Phys. Rev. **155**, 1110 (1967).
[6] R. L. McGrath, Phys. Rev. **145**, 802 (1966).
[7] W. A. Seale, Phys. Rev. **160**, 809 (1967).
[8] D. W. Heikkinen, Phys. Rev. **141**, 1007 (1966).
[9] T. G. Dzubay, Phys. Rev. **158**, 977 (1967).
[10] M. W. Greene, Phys. Rev. **176**, 1204 (1968).

TABLE I. Particle designations.

Type	Corresponding residual level (MeV)	Designation
Proton	B^{13} 0.00	p_0
	3.48, 3.53	p_{12}
	3.68, 3.71	p_{34}
	4.13	p_5
	4.82	p_6
	5.01	p_7
Deuteron	B^{12} 0.00	d_0
	0.95	d_1
	1.67	d_2
	2.62, 2.72	d_{34}
Triton	B^{11} 0.00	t_0
	2.13	t_1
	4.45	t_2
	5.03	t_3
α particle	Be^{10} 0.00	α_0
	3.37	α_1
	5.96, 6.18, 6.26	α_{234}

nucleus contribution to the reaction mechanism. By studying the angular distributions and cross sections for the Li^7+Li^7 reactions as a function of energy, through the barrier region, it is hoped that a clearer understanding of the reaction mechanism and its variation with bombarding energy can be obtained.

II. APPARATUS AND METHOD

Lithium ions were accelerated by the University of Iowa HVEC Van de Graaff. This machine has been operated with up to 6.7 MV on the terminal. With the singly-ionized lithium ions used in the present experiment, it was therefore no problem to obtain energies above the Coulomb barrier. The beam energy was determined by a 90° bending magnet and controlled in the standard manner. Beam energy was known to an accuracy of $\pm0.2\%$ from previous calibration of the bending magnet. Beam energy spread was about 0.3%.

Targets were made by evaporating enriched Li^7F onto aluminum backings of 1.7 mg/cm² thickness. It is assumed that the targets had Li^7 and F present in a one-to-one ratio. Targets were approximately 50 μg/cm² thick, resulting in a 150-keV energy loss for a 5-MeV Li^7 beam passing through the target at 45° to the normal. The energy loss was calculated from Whaling's tables[11] and Northcliffe's[12] compilation. These targets were used in angular distribution measurements and in yield curve measurements. In order to measure the absolute cross section, a target which was infinitely thick to the lithium beam was used. This target was also made by evaporation. It is necessary that this target be sufficiently thick to integrate over all beam energies for which there is significant yield, but not so thick as to unnecessarily degrade the energy of the outgoing reaction products. The target was known to be sufficiently thick from the manner in which the yield increased when the bombarding energy was increased.

The target chambers which were used have been described in previous publications. An 8-inch diameter scattering chamber[6,13] with a 2-mm-thick solid-state detector (E detector) inside a proportional counter (ΔE detector) was used to measure the angular distributions of the charged particles resulting from the reactions. The E detector subtended an angle of $\pm1.7°$. Signals from the detectors were amplified by conventional electronics and fed to two analog-to-digital converters. The outputs of these units were read by a 16384-word, general-purpose computer, which was programmed[13] to form a $60(\Delta E)$ by $256(E)$ channel matrix. Proton, deuteron, and triton groups were identified from the energy loss-rate curve upon which they fell. Alpha-particle groups have such a large energy loss-rate that they could be identified on-line. The counts arising from alpha particles were stored, therefore, in a single parameter pulse-height distribution rather than the two parameter one used for charge-one particles. The alpha-particle groups under study were not confused with other groups of particles of charge two or higher because these groups all have low Q values. Both the two-parameter and one-parameter data could be displayed live as the measurements were underway.

The two-parameter data were reduced to one-parameter data by off-line use of the same computer used to take the original data. The resulting pulse-height distributions for protons, deuterons, and tritons-as well as alphas, which were obtained on-line, were displayed by the computer. Areas under the peaks, corresponding to states of the residual nucleus, were then summed and printed out. In this way, the yields of all measured groups were obtained under the same conditions. A monitor counter at 90° was used to normalize the measurements at different angles.

Measurements were made at 2.10-, 2.75-, 3.50-, 4.25-, 5.00-, and 5.75-MeV bombarding energy, and in 10° steps from 0° (lab) to 90° (lab), inclusive, in most cases. Measurements were not carried beyond 90° (lab) since the identity of the beam and target particles insured symmetry about 90° (center of mass). Once reduced to yields, the data were normalized and transformed to the center-of-mass system by a com-

[11] W. Whaling, in *Handbuch der Physik*, edited by S. Flügge, (Springer-Verlag, Berlin, 1958), Vol. XXIV, p. 193.
[12] L. C. Northcliffe, Ann. Rev. Nucl. Sci. **13**, 67 (1963).
[13] R. R. Carlson, R. L. McGrath, and E. Norbeck, Phys. Rev. **136**, B1687 (1964).

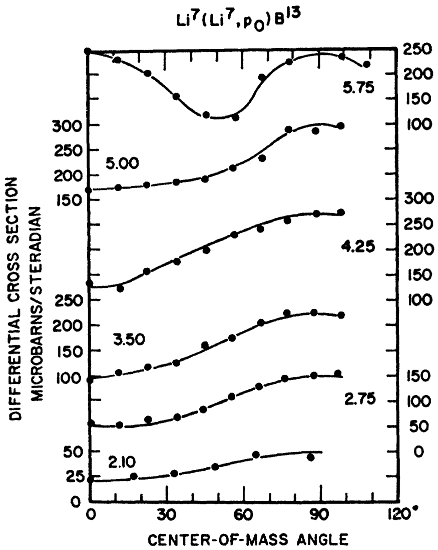

FIG. 1. Center-of-mass differential cross sections for the Li^7+Li^7 reaction indicated at the figure top. Bombarding energies are indicated on the curves near the cross-section scale to be associated with that energy. All cross sections were measured with Li^7F targets which were about 150-keV thick to 5.0-MeV Li^7 ions. Curves are drawn to guide the eye.

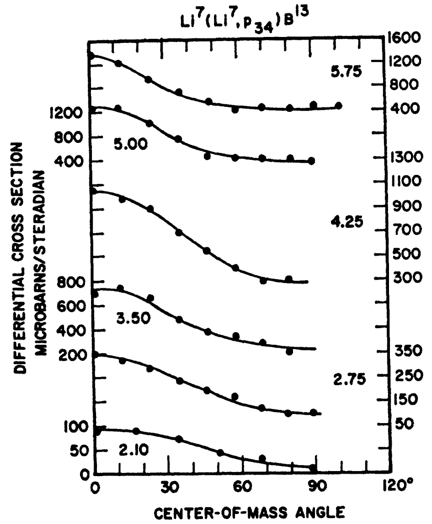

FIG. 3. See caption on Fig. 1

puter program. The program also gave the angle-integrated yield.

In order to put these angular distributions on an absolute basis, measurements were performed in another target chamber. This chamber has also been described elsewhere.[7] Essentially, it is a Faraday cup with the target inside the cup and the detector behind the cup at 0° to the beam. The back side of the cup, on which the target was deposited, was made thick enough to stop the full-energy lithium beam. The thickness was 5.1 mg/cm^2 of Al. However, the backing plus the target was still thin enough to allow alpha particles from the reaction to penetrate without appreciable broadening of the ground and first excited state groups. Targets of the same thickness as those used in the angular distribution work were used here. An 800-μ, solid-state detector was used to detect the alpha particles. The detector subtended a full angle of 8.3° at the beam spot. Pulse-height distributions were taken at a number of energies including the energies at which the angular distributions were measured.

The number of counts under the first excited-state alpha group was used to tie the various angular distributions together on a relative basis. The first excited-state group, rather than the ground-state group, was used for this purpose because of its larger yield.

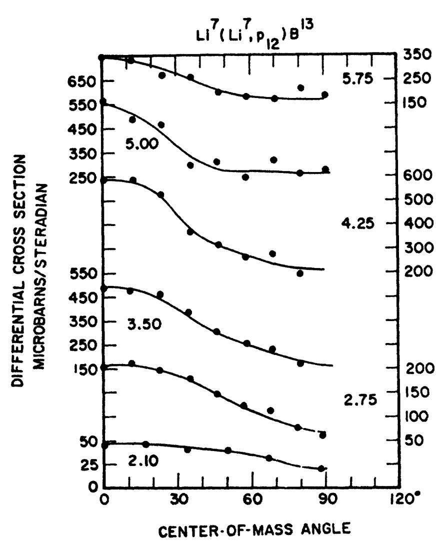

FIG. 2. See caption on Fig. 1.

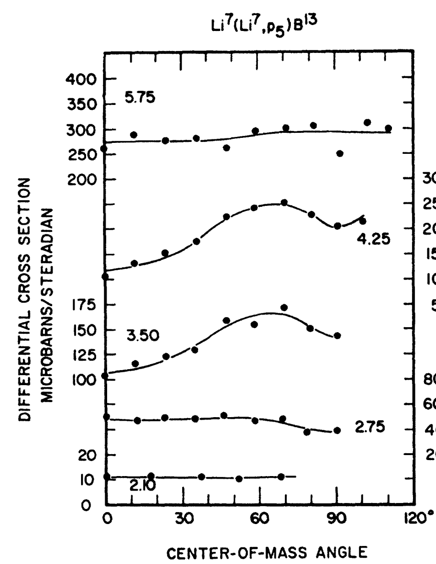

FIG. 4. See caption on Fig. 1.

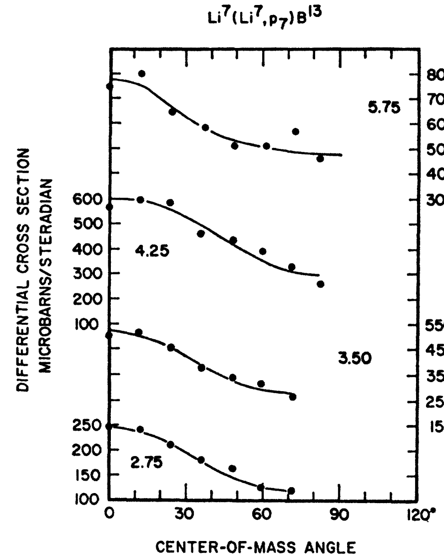

FIG. 5. See caption on Fig. 1.

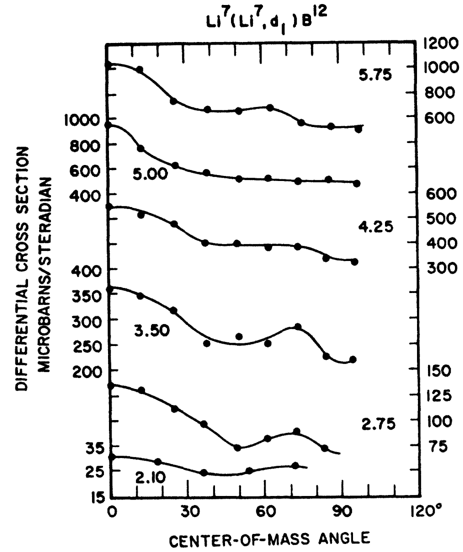

FIG. 7. See caption on Fig. 1.

As a final step, the target chamber used for the 0° yield curve was also used to obtain the absolute value of the $Li^7(Li^7, \alpha_1)Be^{10}$ cross section. The infinitely thick target was placed in the Faraday cup. Peaks in the pulse-height distributions obtained with this target were, of course, broad and asymmetric because of contributions to the yield from energy degraded lithium ions, but this caused no difficulty in obtaining the number of counts because the peaks were still separated. The yield was measured at several energies between 2.10 and 3.50 MeV.

The absolute cross section was obtained from the measured yield of the infinitely thick target, the measured relative yield of the thin target as a function of energy and the energy loss rate of Li^7 ions as a function of energy. The latter was constructed by interpolation between published values for energy loss-rates[11,12] and by use of the average charge state of the lithium ions as given by Teplova *et al.*[14] Having the absolute value of one group at one energy and angle, all of the other relative values can be placed on an absolute basis.[15] The absolute cross sections are estimated to be

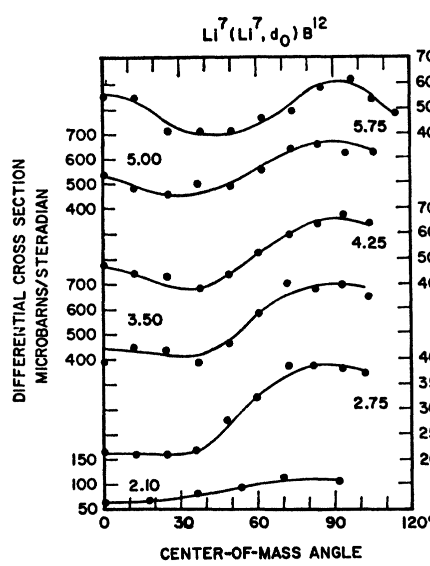

FIG. 6. See caption on Fig. 1.

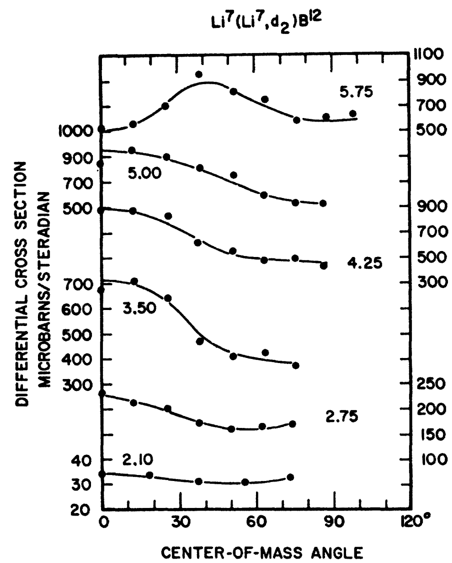

FIG. 8. See caption on Fig. 1.

[14] I. A. A. Teplova, I. S. Smitrev, V. S. Nikolaev, and L. N. Fateeva, Zh. Eksperim. i Teor. Fiz. **32**, 974 (1957) [English transl.: Soviet Phys.—JETP **5**, 797 (1957)].

[15] An earlier unpublished account of these cross-section measurements [University of Iowa Report No. 68-22 (unpublished)] gives values which are all too large by 20%.

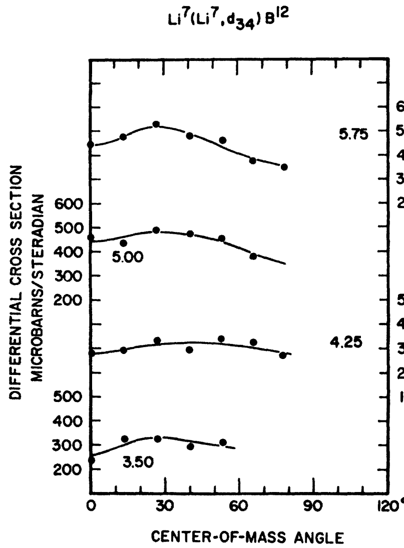

FIG. 9. See caption on Fig. 1.

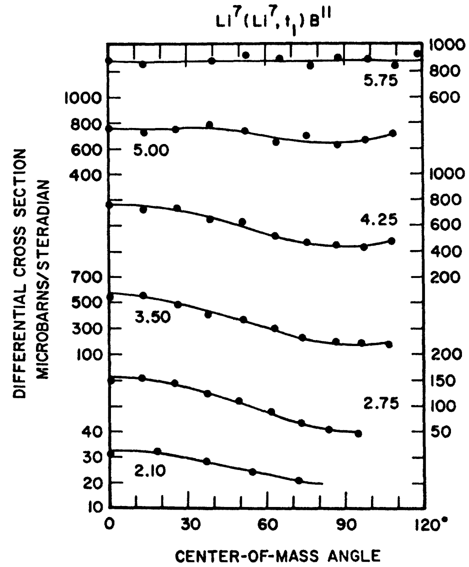

FIG. 11. See caption on Fig. 1.

good to ±20%. The relative accuracy of the various cross sections is better than that of the absolute values. Except in a few cases where groups of particles of different types overlapped, the relative accuracy is about equal to the point size in the figures.

III. RESULTS AND DISCUSSION

Figures 1 through 16 give the measured differential cross sections for 16 groups of particles, three of which are unresolved doublets and one of which is an unresolved triplet. In almost all cases, the character of the angular distribution does not change over the bombarding energy range from the lowest energy up to the region of the classical Coulomb barrier, which is 4.5 MeV in the laboratory. The cross sections increase with energy, of course, and any anisotropies become more pronounced, but the nature of the anisotropies generally remain the same. Forward peaking, if it exists, becomes more pronounced as the energy increases, but does not change into peaking at other angles until the barrier energy is exceeded. Peaking at other angles behaves similarly.

In the majority of cases, the general shape of the angular distribution is unchanged as the bombarding energy is increased to values definitely over the barrier. However, there are a number of cases for which decided

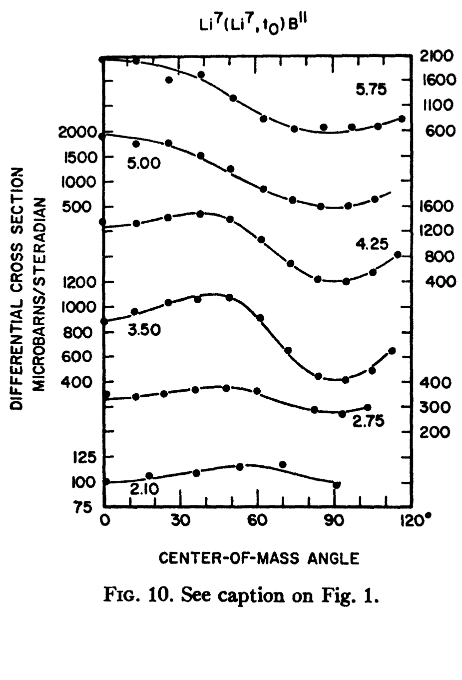

FIG. 10. See caption on Fig. 1.

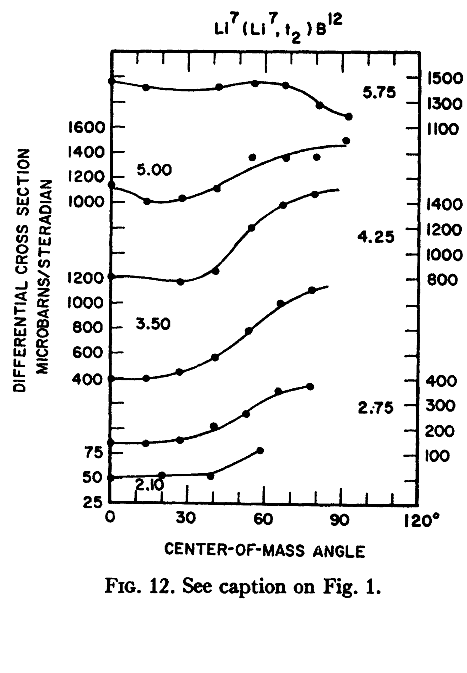

FIG. 12. See caption on Fig. 1.

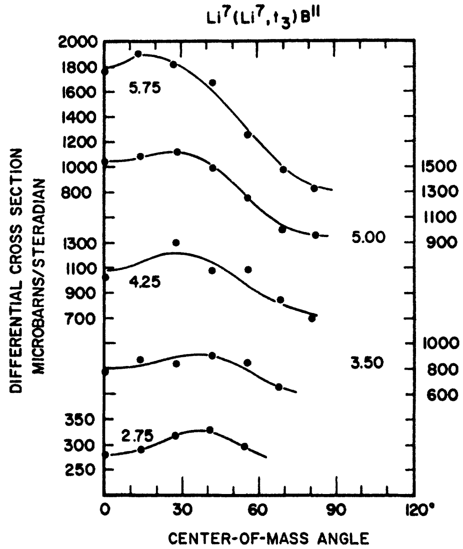

FIG. 13. See caption on Fig. 1.

changes in shape occur at the barrier. The p_0 group rather suddenly changes from a 90° peaking to a 0° and 90° peaking. The p_5, d_0, d_2, t_0, t_2, and α_1 groups all show noticeable changes in shape at the barrier. The existence of these shape changes is an indication that the Coulomb forces cannot be neglected when fitting the angular distributions, as has been done in the past.[16] The persistence of angular distribution shapes over wide ranges of bombarding energy is an indication that some sort of direct mechanism makes a significant contribution to the cross section in the energy range under consideration. On the other hand, one cannot rule out a significant contribution from a compound nucleus mechanism, as shown by the magnitude of the total cross sections.

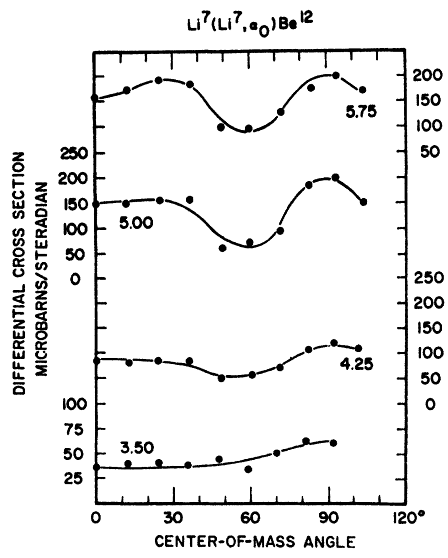

FIG. 14. See caption on Fig. 1.

[16] G. C. Morrison and M. N. Huberman, in *Proceedings of the Second Conference on Reactions Between Complex Nuclei, 1960*, edited by A. Zucker, E. C. Halbert, and F. T. Howard (John Wiley & Sons, Inc., New York, 1960), p. 246.

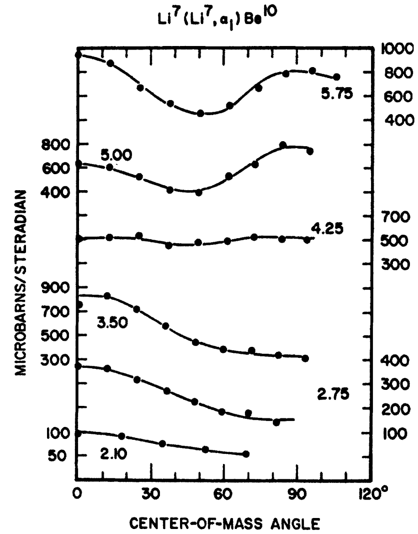

FIG. 15. See caption on Fig. 1.

Figure 17 shows the total cross sections of the α groups as functions of bombarding energy, corrected to the middle of the target, as given by the present work and by Dzubay and Blair.[3] The total cross sections were obtained by integrating the differential cross sections over 180°, taking advantage of the identity of projectile and target to obtain the differential cross section for the backward angles. In cases where data cover an angular range which is less than 90° in the center of mass, the

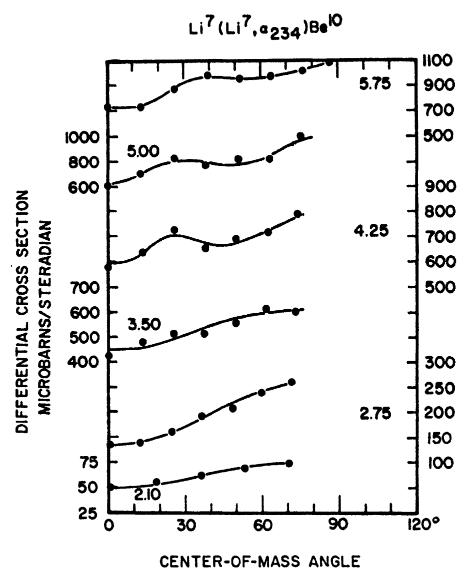

FIG. 16. See caption on Fig. 1.

integration was carried out by taking the differential cross section in the unmeasured range to be equal to the average of the cross section in the measured range. The agreement is reasonable. Both the α_1 and α_{234} groups, in the present work and in that of Dzubay and Blair, have cross sections which are about a factor of 3 less than the values of Huberman *et al.*[2] Confidence in the values obtained here and by Dzubay and Blair should be increased by the fact that quite different methods of obtaining the absolute cross sections were used in the two measurements. Dzubay and Blair[3] based their measurements on a comparison of reaction cross sections with Rutherford scattering. On the other hand, the method used in the present work is actually very similar to that used by Huberman *et al.*[2]

In addition to the above two alpha groups, the cross sections obtained here for 11 of the charge-one particle groups can be directly compared with the values obtained by Huberman *et al.*[2] With two exceptions, all groups have cross sections which are smaller than the values given by Huberman *et al.*[2] by essentially the same factor as in the case of the alpha-particle groups. One exception is the p_5 group which has a quite small yield and the other is the t_1 group whose yield is somewhat less than the other groups, but not nearly as much less as found by Huberman *et al.*[2] It should be noted here that the shapes of the angular distributions measured by Huberman *et al.*[2] are in quite good agreement with those measured here.

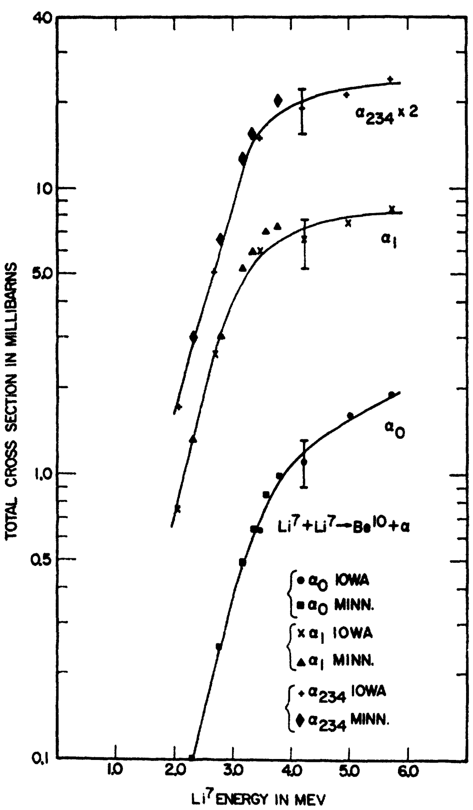

FIG. 17. Angle-integrated total cross sections of various α-particle groups in the Li^7+Li^7 reaction. Differential cross sections were integrated over 180° making use of the identity of target and projectile. Data labeled "Minn" are taken from Ref. 3.

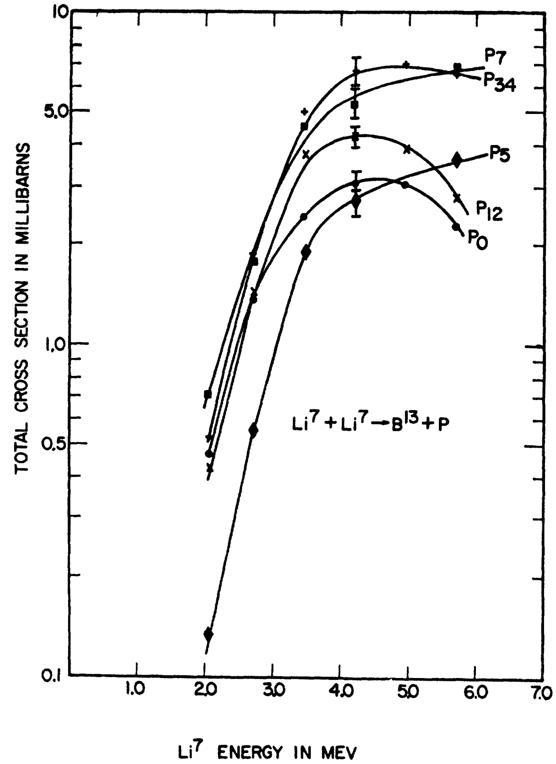

FIG. 18. Angle-integrated total cross sections of various proton groups in the Li^7+Li^7 reaction. Differential cross sections were integrated over 180° making use of the identity of target and projectile.

Figures 18 to 20 show total cross sections of the charge-one particle groups plotted against bombarding energy. Below the Coulomb barrier, the yield of all groups essentially follow a barrier penetration dependence on bombarding energy. However, there is a difference in the energy dependence of the t_0 triton group corresponding to the formation of a spin-$\frac{3}{2}^-$ state in B^{11} as contrasted with that of the t_1 and t_2 groups corresponding to the formation of spin-$\frac{1}{2}^-$ and -$\frac{5}{2}^-$ states in B^{11}. The energy dependence in the former case is not as steep as in the latter, which is consistent with the presence of a higher barrier in the latter case where $l=2$ alpha particles would have to be transferred in a direct process. The t_0 group, on such a picture, can be formed by the capture of an $l=0$ alpha particle by Li^7 with spin-$\frac{3}{2}^-$.

The sum of the total cross sections measured here may be compared with values previously calculated for the total absorption cross section. Huberman *et al.*[2] calculated a value of 16 mb at 2.1 MeV on the basis of simple barrier penetration as compared with a measured

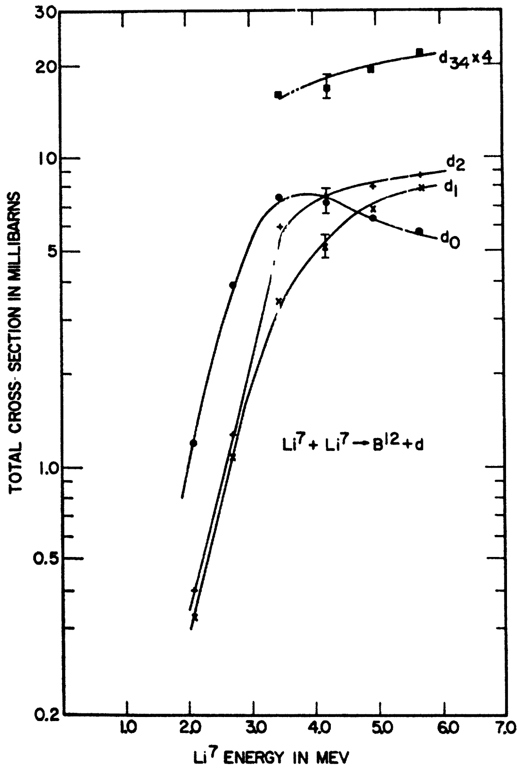

FIG. 19. Angle-integrated total cross sections of various deuteron groups in the Li^7+Li^7 reactions. Differential cross sections were integrated over 180° making use of the identity of target and projectile.

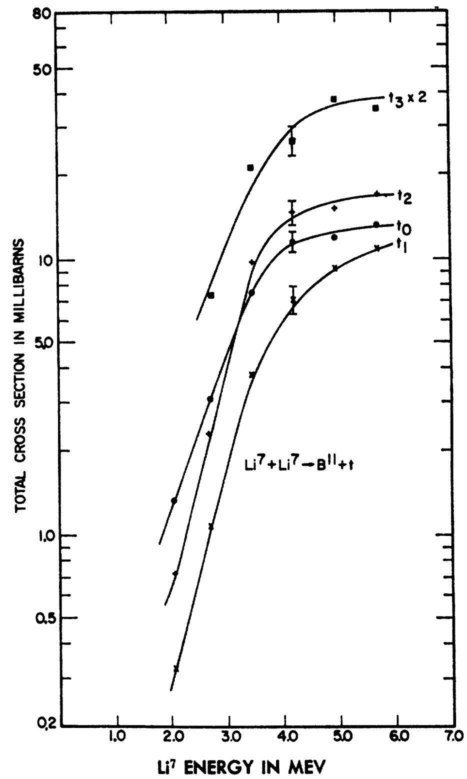

FIG. 20. Angle-integrated total cross sections of various triton groups in the Li^7+Li^7 reactions. Differential cross sections were integrated over 180° making use of the identity of target and projectile.

value of 33 mb for 15 exit channels. The total cross section measured here for the same exit channels is 10 mb which is less than the calculated value, as it should be in view of the unmeasured neutron channels. The calculation, of course, is very sensitively dependent on the assumed nuclear radius so one should not make too much of these comparisons.

Another value of the absorption cross section has been obtained by measurements on the elastic scattering of Li^7 on Li^7 by Pinsonneault and Blair.[17] Using a continuum theory analysis of their data to give them the nuclear radius, they obtain the value of the total reaction, or absorption, cross section for laboratory energies from 3.0 to 7.0 MeV. In the present work, the sum of the measured cross sections for 5.7 MeV taken from Figs. 17 to 20 is 130 mb; the analysis of Pinsonneault and Blair gives 750 mb. The fraction of the reaction cross section accounted for by the charged particles measured here is quite reasonable in view of the large Q value (18.62 MeV) of the $C^{13}+n$ exit channel.

In conclusion, the measured cross sections show that the Li^7+Li^7 reactions in the present energy range probably occur by means of a mixture of compound nucleus and direct reaction mechanisms. Furthermore, the Coulomb field has a marked effect on the cross section and cannot be ignored in the fitting of the angular distributions. More exact statements about the reaction mechanism will await the detailed fitting of these data.

[17] L. L. Pinsonneault and J. M. Blair, Phys. Rev. **141**, 961 (1966).