Reactions $Li^7(\alpha,n)B^{10}$, $Li^7(\alpha,\alpha')Li^{7*}$, and $B^{10}(n,\alpha)Li^7$ †

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The nuclear reactions $Li^7(\alpha,n)B^{10}$ and $Li^7(\alpha,\alpha')Li^{7*}$ have been studied for monoenergetic α particles from a Van de Graaff accelerator. The threshold in the (α,n) reaction was measured to be 4.379 Mev which gives a Q value of -2.788 Mev. Resonances in the yield of 0.477-Mev γ radiation were observed at α-particle energies of 1.91, 2.49, 3.06, 3.6, 4.39, 4.6, and 5.0 Mev. The inverse reaction $B^{10}(n,\alpha)Li^7$ was also studied by using monoenergetic neutrons with energies between 0.020 and 4.80 Mev. Resonances were observed at neutron energies of 0.53, 1.86, 2.8, and 4.1 Mev. Excited states in B^{11} from these experiments are indicated at 9.88, 10.25, 10.62, 10.97, 11.46, 11.6, 11.9, 13.2, 14.0, and 15.2 Mev.

INTRODUCTION

EXPERIMENTS on the yield of neutrons and γ radiation from the α-particle bombardment of Be^9, B^{10}, B^{11}, C^{13}, and O^{18} have been previously reported.[1] With the good resolution available with a Van de Graaff accelerator, many sharp resonances are observed; these resonances give information about states in the compound nucleus. The present experiment was undertaken with the purpose of observing the yield of neutrons from the reaction:

$$_3Li^7+{}_2He^4\rightarrow({}_5B^{11})\rightarrow{}_5B^{10}+{}_0n^1-2.797 \text{ Mev.} \quad (1)$$

The only other competing reaction for α particles with energies less than 6 Mev is $Li^7(\alpha,\alpha')Li^{7*}$ which produces Li^{7*} excited to the well-known state at 0.477 Mev. The 0.477-Mev γ radiation from the inelastic scattering of α particles on Li^7 has been observed by Heydenburg and Temmer,[2] and by Li and Sherr[3] for α-particle energies from 1.2 to 3.5 Mev. One purpose of the present experiment was to extend these measurements to higher energies. Another objective was to measure the cross section of the reaction $B^{10}(n,\alpha)Li^7$ which is the inverse of reaction (1). With thermal neutrons the $B^{10}(n,\alpha)$ reaction proceeds in about 94% of the disintegrations to Li^{7*} and only about 6% of the time to Li^7 in the ground state. At higher neutron energies this ratio changes but the reaction going to the excited state is always important.[4] Thus the total cross section for the (n,α) reaction in B^{10} cannot be calculated by the method of detailed balance from the (α,n) cross section.

EXPERIMENTAL PROCEDURES

The neutrons of the $Li^7(\alpha,n)$ reaction were detected with the modified long counter[1] at 0° and 90°. The cross section was obtained from a comparison of the yields of the $Li^7(p,n)$ and the $Li^7(\alpha,n)$ reactions from the same target carried out at bombarding energies such that the neutrons from each of the reactions had the same energy of 0.57 Mev.

The 0.477-Mev γ radiation was observed with a 1-inch by 1-inch NaI crystal mounted on a DuMont 6292 photomultiplier tube in conjunction with a 20-channel pulse-height analyzer. Cross sections were estimated from target thickness and γ-ray efficiency of the crystal and agreed within our rather large experimental uncertainty with the cross section obtained by Li and Sherr.[3] Their absolute measurements were considered to be more accurate and were used to normalize our data at 2.5 Mev.

For detection of the $B^{10}(n,\alpha)Li^7$, Li^{7*} reaction a commercial BF_3 counter was used (active volume $\sim$2.2 cm diameter, 11 cm long, filled with $B^{10}F_3$ at a pressure of 40 cm of Hg). A cylindrical coat of $\sim$0.5 mm of B^{10} (covering 2.5 cm more than the active volume) was used to reduce the background of thermal neutrons from the room. The target which serves as a source of neutrons from the (p,n) reactions in Li^7 or H^3 was 3.6 meters from the closest moderator of neutrons. The front of the BF_3 counter was placed 3 cm from the neutron source. The pulses were monitored with a 20-channel pulse-height analyzer and care was taken that no B^{10} or F^{19} recoils were counted. The largest background from room neutrons was produced at a neutron energy of 2 Mev and was measured to be less than 10%. The background effect was obtained by moving the counter from its usual position close to the target to a position 85 cm from the target but at the same distance from the analyzing magnet. For neutron energies above 2 Mev, pulse-height information was good enough so that disintegrations by low-energy neutrons could be eliminated. Some low-energy neutrons came from the room but the most important source was from the Zr layer in the Zr-T target. Although the yield of neutrons from Zr was small, these produced a relatively large number of disintegrations because of the large cross section of the $B^{10}(n,\alpha)$ reaction at low energies.

Neutrons in the energy range 20–240 kev were obtained from the $Li^7(p,n)$ reaction at 120° to the di-

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[1] Bonner, Kraus, Marion, and Schiffer, Phys. Rev. **102**, 1348 (1956).

[2] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **94**, 1252 (1954).

[3] C. W. Li and R. Sherr, Phys. Rev. **96**, 389 (1954).

[4] Bichsel, Hälg, Huber, and Stebler, Helv. Phys. Acta **25**, 119 (1952).

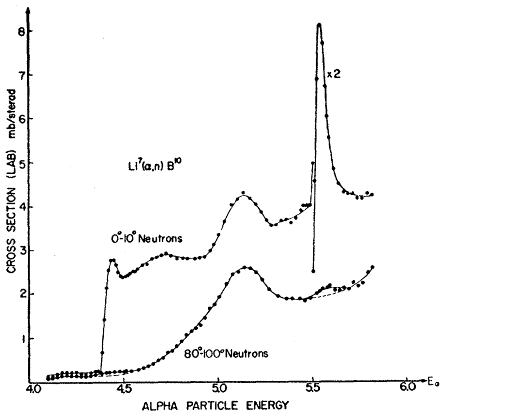

FIG. 1. The reaction $Li^7(\alpha,n)B^{10}$ at 0° and 90°. The cross sections above 5.5 Mev in the case of the 0° data are to be multiplied by 2.

rection of the beam. Neutrons with energies from 80–600 kev were obtained from the same reaction at 0°. Neutrons with energies from 0.3 to 4.8 Mev were obtained from the $T^3(p,n)$ reaction at 0° to the bombarding beam. An absolute cross-section measurement, which involved knowing the amount of B^{10} in the gas of the counter, was considered to be less accurate than using the (n,α) cross section at thermal energies and calculating the cross section at 20 kev assuming a $1/v$ law.

$Li^7(\alpha,n)B^{10}$

Figure 1 gives the excitation curve for the $Li^7(\alpha,n)$ reaction. Neutrons observed at 0° to 10° with respect to the α beam have two neutron thresholds: at 4.379 Mev for the (α,n) reaction leaving B^{10} in the ground state and at 5.51 Mev when B^{10} is left in the excited state at 0.720 Mev.

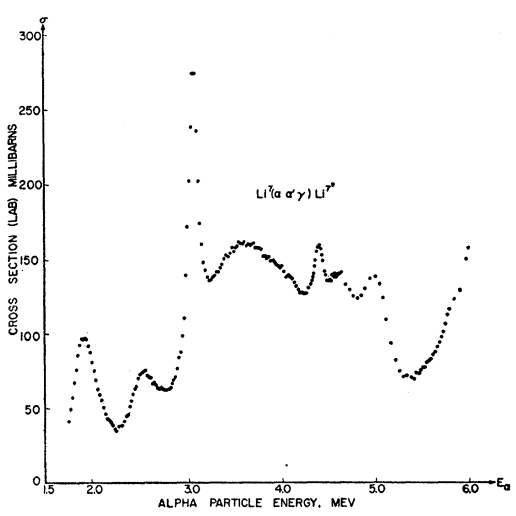

FIG. 2. The total cross sections of the reaction $Li^7(\alpha,\alpha'\gamma)Li^{7*}$ as deduced from observations at 0°. The cross sections deduced from observations at 90° are the same within an accuracy of 20%.

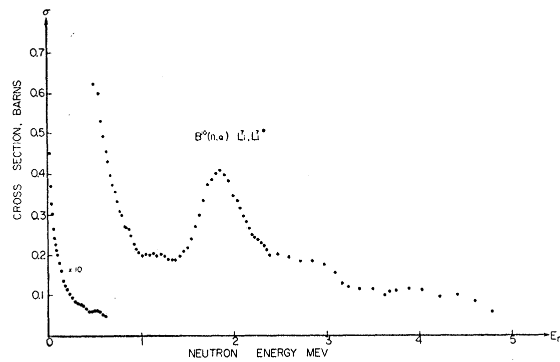

FIG. 3. $B^{10}(n,\alpha)Li^7$, Li^{7*} cross section. The cross section below 0.7 Mev is to be multiplied by 10.

Neutrons observed at 90° show a yield starting at the proper energy computed from the cone opening. Two small bumps at 4.4 and 5.6 Mev, indicated by the dashed lines, are presumably produced by neutrons scattered from the 0° counter and the target holder. Two resonances are found: a broad and rather weak resonance at 4.7 Mev, which is not evident in the 90° data, and a resonance at 5.15±0.08 Mev with a width of 0.22 Mev in the laboratory system. The two resonances correspond to levels in B^{11} at 11.68±0.10 and 11.95±0.08 Mev.

An accurate measurement of the energy of the $Li^7(\alpha,n)$ threshold was made with doubly charged α particles, since the energy of the singly charged particles at threshold could not be determined very accurately because the iron in the magnetic analyzer was approaching saturation for such particles. The doubly charged beam was obtained by the use of a gas stripper which is placed above the magnetic analyzer. The observed threshold is at 4.379±0.006 Mev which gives a Q value of -2.788 ± 0.004 Mev. This Q value is to be compared to a calculated value of -2.793 ±0.009 Mev from masses given by Wapstra[5] and

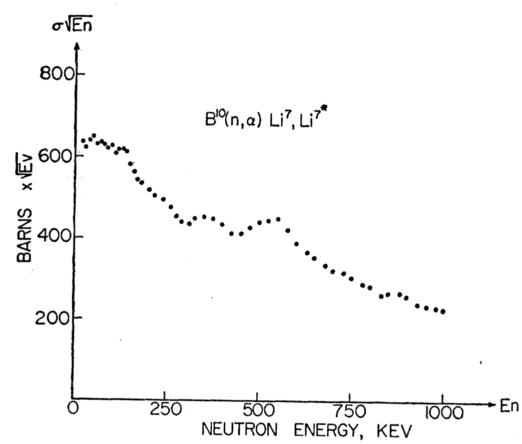

FIG. 4. Inverse velocity law for $B^{10}(n,\alpha)$ at low neutron energies.

[5] A. H. Wapstra, Physica 21, 367 (1955).

TABLE I. Resonances in the reaction $Li^7(\alpha,\alpha')Li^{7*}$.

Energy of resonance (Mev)	Energy level in B^{11} (Mev)	Level width (c.m.) (Mev)
1.91±0.02	9.88	0.16
2.49±0.05	10.25	0.22
3.06±0.03	10.62	0.10
3.6 ±0.1	10.97	0.67
4.39±0.01	11.46	0.07
4.6 ±0.1	11.60	0.14
5.0 ±0.1	11.85	0.17

−2.792 Mev from the masses given by Ajzenberg and Lauritsen.[6]

$Li^7(\alpha,\alpha'\gamma)Li^{7*}$

The excitation curve for 0.477-Mev γ radiation is shown in Fig. 2. The resonances at α-particle energies of 1.91, 2.49, and 3.06 Mev have been reported by Heydenburg and Temmer[2]; the two lower resonances have also been observed by Li and Sherr.[3] At higher energies there is a very broad resonance at 3.6 Mev, a rather narrow resonance at 4.39 Mev, a broad resonance at 4.6 Mev, and a resonance at 5.0 Mev. The energies of the resonances are corrected for target thickness (which is 27 $\mu g/cm^2$, approximately 25 kev at 3 Mev). Levels in B^{11} then are computed by conversion of the α energy into the center-of-mass system and adding it to the difference in mass of B^{11} and Li^7+He^4. Table I gives a list with α energies, energy of the levels, and estimated width of levels in the center-of-mass system.

$B^{10}(n,\alpha)Li^7$, Li^{7*}

In this reaction the total cross section was measured, since it was not possible to separate the two groups of α particles by their pulse sizes. Figure 3 gives the experimental results. At low energies the cross section decreases rapidly as the neutron energy is increased. In order to test the $1/v$ law at low energies, a separate plot of the data below 1 Mev is shown in Fig. 4 where the cross section is multiplied by the velocity of the neutron. Below a neutron energy of 100 kev the curve remains flat, indicating a $1/v$ law for the reaction. Above an energy of 140 kev the data deviate sharply from the $1/v$ dependence. The data from 0 to 250 kev can be interpreted on the assumption that the levels in B^{11} at 11.46 ($\Gamma=70$ kev) and 11.60 Mev ($\Gamma=140$ kev), as determined by the $(\alpha,\alpha')\gamma$ data, are largely responsible for the neutron yield. These levels in B^{11} correspond to neutrons with energies of 0 kev and 140 kev. There is an indication of a resonance at 530 kev. Other resonances are shown in Fig. 3 at 1.86, 2.8, and 4.1 Mev. The corresponding energies in the center-of-mass system and in the B^{11} compound nucleus are given in Table II.

TABLE II. Resonances in the reaction $B^{10}(n,\alpha)Li^7$.

E_n (Mev)	$E_{c.m.}$ (Mev)	Level in B^{11} (Mev)	Level width (c.m.) (Mev)
0.53	0.48	11.94	0.10
1.86	1.69	13.15	0.45
2.8	2.5	14.0	0.3
4.1	3.7	15.2	0.5

The resonance at 1.86 Mev agrees in energy with the results of Petree, Johnson, and Miller.[7] The peak cross section which they obtained is 0.51 barn which is to be compared to our value of 0.41 barn. This is in reasonable agreement considering the estimated errors of ±25%. Indications of broad resonances in the total scattering cross section of B^{10} have been obtained at energies of 0.2, 0.45, 1.8, 2.75, and 4.3 Mev[8]; these seem to be in rough agreement with the resonances obtained in the (n,α) reaction.

DISCUSSION

All the reactions investigated lead to the same intermediate nucleus: B^{11}. The range of excitation covered by our measurement is between 9.8 and 15.8 Mev, and ten levels in B^{11} were observed in this interval. The only region covered by all three reactions is between 11.46 and 12 Mev.

The calculated energies of the excited states of B^{11} differ by considerable amounts as determined by the different reactions. However, these differences in the energy of the peaks of the resonances are not more than 30% of the level widths and are to be expected for wide overlapping levels where interference effects are important.

[6] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[7] Petree, Johnson, and Miller, Phys. Rev. **83**, 1148 (1951).

[8] Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951).