is not populated appreciably in the $F^{19}(p,\alpha)$ and $N^{15}(d,n)$ reactions at the bombarding energies used because of high angular-momentum barriers.

VI. SUMMARY AND CONCLUSIONS

A weak ground-state transition from the 2^- state at 8.87 Mev was observed with 0.07 ± 0.02 the intensity of the 2.73-Mev cascade transition to the 3^-, 6.14-Mev state.

A state was found at 10.98 ± 0.04 Mev which decays by γ emission predominantly to the 1^-, 7.12-Mev state. This decay mode, and the angular correlation of the 3.86- and 7.12-Mev γ rays suggest a 0^- spin and parity assignment for the 10.98-Mev state.

According to the calculations of Kameny,[12] identification (*b*) of the alpha-particle model of O^{16} predicts a 0^- state at 11.5 Mev which may be identified with the level observed at 10.98 Mev in the present work. However, this model also predicts a 1^+ state at about 9.4 Mev, which was not observed in the present experiments.

Both the 0^- state at 10.98 Mev and the relative intensity of the ground state transition from the 8.87-Mev state can be accounted for by the shell-model calculations of Elliot and Flowers.[13]

[12] S. L. Kameny, Phys. Rev. **103**, 358 (1956).

TABLE II. Upper limits for the intensities of possible transitions from the 10.98-Mev state of O^{16}.

Transition	Gamma-ray energy (Mev)	Relative intensity
10.98 → ground	10.98	<0.05
10.98 → 6.04	4.94	<0.01
10.98 → 6.14	4.84	<0.06
10.98 → 6.92	4.06	<0.2
10.98 → 7.12	3.86	1
10.98 → 8.87	2.11	<0.4

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[13] J. P. Elliot and B. H. Flowers (to be published).

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Excited States in Be^7 and Be^8†

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The neutron-threshold method has been used to observe the neutrons emitted in the deuteron bombardment of both Li^6 and Li^7. From the bombardment of Li^6, two broad thresholds were observed corresponding to levels in Be^7 at excitation energies of 6.5 Mev ($\Gamma=1.2$ Mev) and 7.2 Mev ($\Gamma=0.5$ Mev). Four thresholds were observed in the bombardment of Li^7, corresponding to excited-state energies in Be^8 of 16.07 Mev, 16.65 Mev, 17.60 Mev, and 18.19 Mev.

INTRODUCTION

THE neutron-threshold method of energy level measurement has been described in the literature.[1–4] Two moderated BF_3 counters are used in this procedure, one sensitive preferentially to low-energy neutrons (less than 300 kev) and the other sensitive to higher energy neutrons. Neutron thresholds are indicated by a rise in the ratio of the number of low-energy to high-energy neutrons. This in turn indicates an energy level in the residual nucleus.

We have applied the technique to the observation of the levels in Be^7 and Be^8 accessible through the reactions $Li^6(d,n)Be^7$ ($Q=3.375$ Mev) and $Li^7(d,n)Be^8$ ($Q=15.017$ Mev).

EXPERIMENTAL PROCEDURE

The details of the counter-ratio method have been described previously.[1–4] In the experiments discussed here, however, most of the levels in the resulting nuclei are relatively broad, which modifies the shape of the ratio curve. If the level in the residual nucleus is narrow, the ratio curve will rise sharply at threshold and then fall off slowly above threshold, as the neutron energy increases. However, if the level width is considerably more than target thickness, then the ratio curve will rise and fall with the level, its appearance being very similar to the familiar broad resonance

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[1] T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954).
[2] Marion, Brugger, and Bonner, Phys. Rev. **100**, 46 (1955).
[3] Brugger, Bonner, and Marion, Phys. Rev. **100**, 84 (1955).
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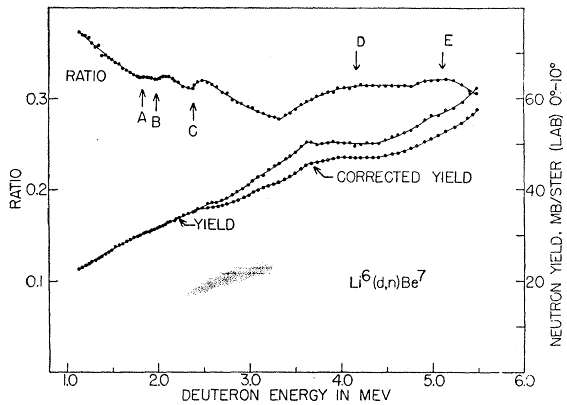

FIG. 1. $Li^6(d,n)Be^7$. Counter ratio and yield of neutrons in the forward direction. Thresholds are marked by labeled arrows.

shape. In this case, the level energy is computed from the peak value of the curve.

The precise measurement of the threshold energies is accomplished through magnetic analysis of the beam of the Rice Institute 6-Mev Van de Graaff accelerator. A proton and lithium resonance magnetometer measures the magnetic field, and the primary calibration standard is the $Li^7(p,n)Be^7$ threshold.[5] Due to saturation effects, a correction is applied to the calibration for higher energies. This correction is derived from several well-known thresholds.[2]

The neutron yields shown in the present work are determined with the modified long counter in position behind the slow counter, and are not corrected for the variation of counter sensitivity with neutron energy.

$Li^6(d,n)Be^7$, $Q=3.37$ Mev

The target used was a thin lithium film evaporated onto a tantalum blank in the vacuum system of the Van de Graaff accelerator. The lithium was obtained from the Isotopes Division of the Oak Ridge National Laboratory and contained 96% Li^6 and 4% Li^7.

The counter-ratio curve and yield of neutrons in the forward direction are shown in Fig. 1. The counter ratio below 1.8 Mev decreases with increasing energy of the deuterons; this is probably due to the fact that the average energy of neutrons from the three-body breakup ($Q=1.792$ Mev) is increasing. The thresholds at A and C correspond to the well-known ground and first state thresholds[2] of O^{16}, and are due to a slight oxygen contamination which always seems present from an evaporated lithium target. The relative strength of the threshold at C varied from target to target, hence the conclusion that it is due to oxygen contamination. The threshold at B corresponds in energy to a very strong threshold in N^{14} at 1.967 Mev[2] and is consequently assigned to a small amount of nitrogen contamination. At a deuteron energy of 3.3 Mev, the curve showing the counter ratio starts to rise and continues to do so for about one Mev, until it reaches a peak at D. This is attributed to a broad level in Be^7 at 6.5-Mev excitation. Another threshold at E is due to a broad level in Be^7 at 7.2-Mev excitation.

These last two excitation energies are accessible to other methods of observation. For example, Reynolds[6] has observed the α groups given off by the reaction $B^{10}(p,\alpha)Be^7$ at a bombarding energy of 18 Mev. He finds evidence for states in Be^7 at 0.49 ± 0.10 Mev, 4.72 ± 0.08 Mev, 6.27 ± 0.10 Mev, 7.21 ± 0.10 Mev, and 14.6 ± 0.3 Mev. The state at 7.21 Mev agrees within the experimental errors with the value of 7.2 observed in the present work. There is a considerable difference between his value of 6.27 Mev and ours of 6.5 ± 0.2 Mev, but the present experiment shows that this state is quite broad, which tends to make its exact position somewhat indefinite.

The reaction $Li^6(p,\alpha)He^3$ and the elastic scattering of protons by Li^6 both show resonances[7] which may be interpreted as due to a level in Be^7 at 7.16 Mev with a width $\Gamma=0.5$ Mev.

There is evidence for a state in Be^7 at about 4.6-Mev excitation, mirror to the 4.61-Mev Li^7 level. Both an α-particle group[6] from $B^{10}(p,\alpha)Be^7$ and a neutron group[8] from $Li^7(p,n)Be^7$ going to this state have been observed. More recently what is undoubtably the same level has been observed in the scattering of He^3 from He^4.[9] A preliminary analysis of the data gives resonance parameters indicating an excitation in Be^7 of 4.59 Mev. A threshold for this level should be observed in the $Li^6(d,n)Be^7$ reaction at a bombarding energy of 1.62 Mev; however, it is not observed. The state we are trying to see in Be^7 has a total angular momentum of $\frac{7}{2}$ and odd parity. Therefore, it is possible that the angular-momentum barrier for the outcoming neutrons is high enough so that they are not emitted in appreciable numbers until the slow-counter efficiency has fallen off. If the yield near threshold is mainly due to the formation of Be^8 in a low angular-momentum state, say 2 or less, then the neutrons must carry off one or more units of angular momentum. It is very likely

TABLE I. Neutron thresholds in the reaction $Li^6(d,n)Be^7$.

	Threshold energy (Mev)	Q-value (Mev)	Excitation in Be^7 (Mev)	Center-of-mass width (Mev)
A	1.83	O^{16} contamination		
B	1.97	N^{14} contamination		
C	2.40	O^{16} contamination		
D	4.2	-3.2	6.5	1.2
E	5.1	-3.8	7.2	0.5

[5] A. H. Wapstra, Physica **21**, 367 (1955). Energy threshold: 1882.5±0.9 kev.

[6] J. B. Reynolds, Phys. Rev. **98**, 1288 (1955).

[7] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955); S. Bashkin and H. T. Richards, Phys. Rev. **84**, 1124 (1951).

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that a threshold involving neutrons with orbital angular momentum of one or more units would not be observed.

Table I lists the thresholds, calculated Q-values, energies of excited states in Be^7, and the observed level widths.

The cross section for neutron production from the $Li^6(d,n)$ reaction was obtained by comparing the yield of neutrons from the $Li^7(p,n)Be^7$ at 2.35 Mev with that from $Li^6(d,n)Be^7$ at a deuteron energy of 1.5 Mev. The cross section is probably good to an accuracy about 50% since the two comparison neutron energies differ widely.

Since the $Li^6(d,n)Be^7$ cross section was measured at an energy below the $O^{16}(d,n)F^{17}$ threshold, it was possible to estimate the oxygen contribution to the yield from the magnitude of the two oxygen thresholds. The neutron yield, with the oxygen contribution subtracted, is given in Fig. 1 with the label "corrected yield." There is a small (about 4% at 2-Mev bombarding energy) contribution to the yield from the Li^7 present.

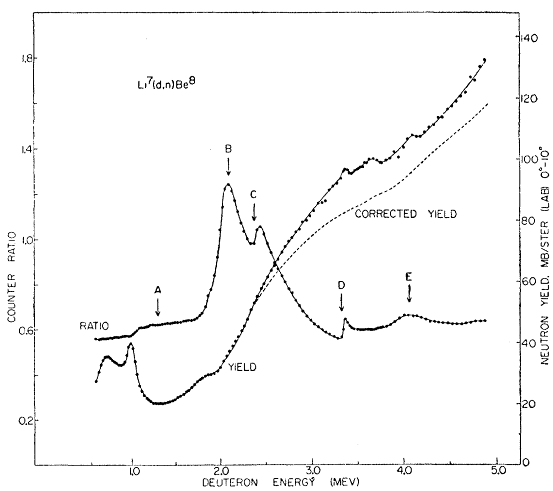

FIG. 2. $Li^7(d,n)Be^8$. Counter ratio and yield of neutrons in the forward direction. Thresholds are marked by labeled arrows.

$Li^7(d,n)Be^8$, $Q = 15.017$ Mev

This reaction has been studied previously,[1] however, it was decided to repeat the experiment to take advantage of somewhat improved techniques. The ratio curve and yield of neutrons in the forward direction are shown in Fig. 2. The target used was evaporated in place in the vacuum system of the Van de Graaff, using normal-abundance lithium, containing 92.5% Li^7 and 7.2% Li^6. The target was about 35 kev thick to 1.8-Mev deuterons. The energy scale of Fig. 2 had been corrected for target thickness (i.e., the scale now corresponds to the energy at the middle of the target).

The counter ratio indicates broad resonances at A, B, and E and sharp resonances at C and D. In order to determine where threshold A had its maximum value, a Breit-Wigner curve was drawn at B, using the measured parameters ($E_{res} = 2.10$ Mev, $\Gamma = 250$ kev). This Breit-Wigner curve was then subtracted from the ratio curve. The resulting peak was at 1.35 Mev, and the measured width at half-height was 0.4 Mev.

The threshold at 2.40 Mev corresponds to the first excited state threshold of oxygen, and is attributed to oxygen contamination. The threshold at D (3.32 Mev) is attributed to an excited state in Be^8. This is the only level observed with a width less than target thickness (20 kev at this energy). The Q-value obtained agrees fairly well with the known level[10] in Be^8 at 17.63 Mev, measured by the reaction on $Li^7(p,\gamma)Be^8$.

The thresholds are listed in Table II with the excitation energies in Be^8 and the center-of-mass widths of the levels.

TABLE II. Neutron thresholds in the reaction $Li^7(d,n)Be^8$.

	Threshold energy (Mev)	Q-value (Mev)	Excitation in Be^8 (Mev)	Center-of-mass width (Mev)
A	1.35	−1.05	16.07	0.31
B	2.10	−1.64	16.65	0.19
C	2.40		O^{16} contamination	
D	3.32	−2.58	17.60	<0.02
E	4.08	−3.17	18.19	0.23

The cross section for neutron production was obtained by comparison to the $Li^7(p,n)Be^7$ cross section. The (d,n) counting rate at a deuteron energy of 1.4 Mev was compared to the (p,n) counting rate at a proton energy of 4.1 Mev in the same target. Because of the differing comparison neutron energies, the cross section is probably good to an accuracy of about 50%.

It was possible to subtract out the estimated oxygen yield, and when this was carried out the result was the smooth, dashed curve marked "corrected yield" in Fig. 2. The two resonances in the yield at 0.7 Mev and 1.0 Mev have been observed by other workers.[11] The work of Baggett and Bame[11] shows a steeper rise in the yield above 1.8 Mev than the present work. However, the targets used by them were Li_2SO_4 and a part of their yield is due to the oxygen contribution. There is an indication of another resonance at about 1.8 Mev.

[10] T. W. Bonner and J. E. Evans, Phys. Rev. **73**, 666 (1948).
[11] Bennett, Bonner, Richards, and Watt, Phys. Rev. **71**, 11 (1947); L. M. Baggett and S. J. Bame, Phys. Rev. **85**, 434 (1952).