high, at least for Ni^{60}. It seems, therefore, that in calculations for the Ni(d,t) reactions the correct asymptotic behaviour of the neutron form factor is important, and CB calculations give results less consistent than the standard (separation energy) methods.

ACKNOWLEDGMENTS

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α Particles from the Triton Bombardment of Li^7, C^{12}, and O^{16}†

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A Li^7 oxide layer deposited on a carbon foil has been bombarded by 13-MeV tritons from the Aldermaston tandem. The spectra of α particles emitted at 24 angles relative to the incident beam (5° to 175°) have been determined with the Aldermaston multigap spectrograph, using nuclear plates as detectors. The first excited state of He^6 is found to have an excitation energy of 1.797±0.025 MeV and a width of 113±20 keV. No other excited states of He^6 below an excitation energy of 12 MeV have been observed, for $\theta=5°$ to 35°. Angular distributions of α particles have been determined to the following states: $E_x=0$ and 1.80 MeV in He^6; $E_x=0$, 5.28+5.31, and 6.33 MeV in N^{15}; $E_x=0$, 2.14, 4.46, and 5.03 MeV in B^{11}. The angular distributions show strong direct-interaction features.

INTRODUCTION

THE only exoergic reaction leading to He^6 is the $Li^7(t,\alpha)He^6$ reaction with a Q value of 9.833 MeV.[1] It is therefore not surprising that most of the known information on the structure of He^6 has been derived from work with this reaction. K. W. Allen *et al.*[2–4] have observed two excited states of He^6 with $E_x=1.71\pm0.01$ MeV ($\Gamma\lesssim100$ keV) and 3.4±0.2 MeV ($\Gamma<300$ keV). These experiments used low-energy tritons ($E_t<1$ MeV), and a proportional-counter technique. The α-particle group attributed to the 3.4-MeV state[4] was observed at $\theta=131°$ at $E_t=0.24$ MeV, and at $\theta=90°$ at $E_t=0.71$ and 0.90 MeV. Evidence has also been reported[5] for one or more states at $E_x=9.3\pm0.7$ MeV and possibly for a state at $E_x=6\pm0.9$ MeV. The summed proton spectrum from the $Li^7(p,2p)He^6$ reaction suggests[1] an excited state of He^6 with $E_x\sim15$ MeV and $J=1^-$ or 2^-. It appears fair to say that only the existence of an excited state with $E_x\sim1.7$ MeV has been established with any certainty.

While there is no question of the existence of the 1.7-MeV state, its parameters and decay modes are only poorly established. Its angular momentum and parity are probably[6,7] 2^+, but there has been conflicting evidence on its width and on its decay modes. There have been reports that the 1.7-MeV state decays by γ emission.[8,9] On the other hand the absence of He^{6*} recoils,[3] and the fact that the state is broad,[10] suggest that the decay is by particle emission via one or both of the

† The exposure of the plates was carried out at the Atomic Weapons Research Establishment, Aldermaston, England. The remainder of this work was supported by the National Science Foundation.

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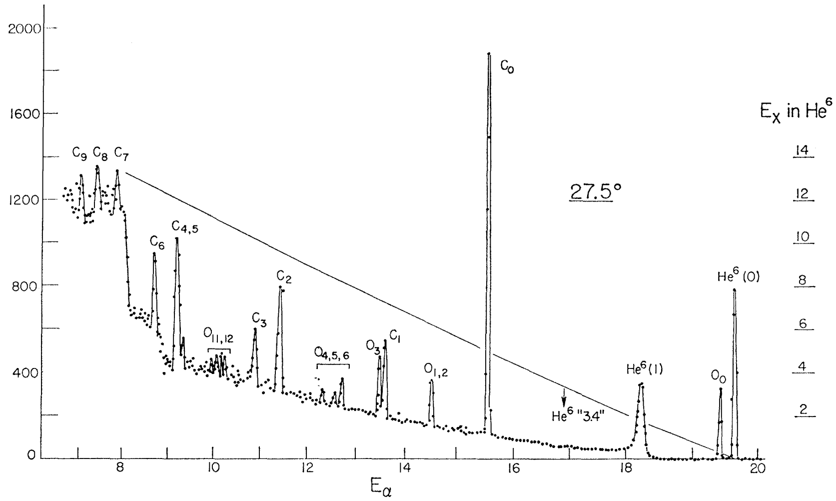

FIG. 1. Spectrum of α particles from $Li^7(t,\alpha)He^6$, $C^{12}(t,\alpha)B^{11}$, and $O^{16}(t,\alpha)N^{15}$ at $E_t=12.97$ MeV ($\theta=27.5°$). The left-hand ordinate gives the number of α tracks recorded in a 200-μ-wide "bin" of the photographic plate detector; the right-hand ordinate gives the excitation energy (in MeV) in He^6 corresponding to α-particle energies referred to the diagonal line. $He^6(0)$ and $He^6(1)$ are α groups corresponding to the ground state of He^6 and to the excited state at $E_x=1.80$ MeV. The location of the previously postulated state at 3.4 MeV (see text) is indicated as He^6 "3.4." The groups labeled C_x ($x=0$ to 9) and O_x ($x=0$ to 7 and 11 to 12) correspond to states in B^{11} and N^{15}.

modes

$$He^{6*} \rightarrow He^4+2n,\ Q\sim 0.8 \text{ MeV};$$

or[11]

$$He^{6*} \rightarrow He^5+n,\ Q\sim -0.2 \text{ MeV}.$$

In fact, the branching ratio Γ_γ/Γ_n has been recently determined[12] to be less than 4×10^{-4}.

We decided to study the $Li^7(t,\alpha)He^6$ reaction for three reasons: (1) to determine accurately the excitation energy and the width of the first excited state of He^6; (2) to try to observe higher excited states; (3) to study the (t,α) reaction mechanism.

One is often able to predict the location of excited states by looking at the structure of the isobars. For instance, all states in He^6 should be reproduced in the mirror nucleus Be^6, and in the $T=1$ level structure of Li^6. Unfortunately, only the ground state[1] and possibly[13] an excited state at $E_x=1.5\pm 0.2$ MeV have been reported in Be^6. In Li^6, states with probable $T=1$ which had been reported by Allen *et al.*[4] at $E_x=6.63\pm 0.08$ and 8.37 ± 0.08 MeV have not been observed by other workers.[1] The two known $T=1$ states in Li^6 at $E_x=3.56$ and 5.35 MeV are the analog states of the ground and first excited states of He^6. Thus no clues can be derived concerning higher states of He^6 from the known energy levels of Li^6 and Be^6.

There has been very little experimental evidence on (t,α) angular distributions, particularly for triton energies ($\gtrsim 8$ MeV) where analysis in terms of direct-interaction theories might be reasonable. Only one such study[14] has been published, that of the $C^{12}(t,\alpha)B^{11}$ reaction at $E_t=10.1$ MeV. We decided to try to obtain additional data on (t,α) angular distributions.

EXPERIMENTAL PROCEDURES AND RESULTS

1. Experimental Setup

A thin target of isotopically pure ($\sim 99\%$) Li^7, evaporated on a carbon backing, was transferred under vacuum to the target chamber of the Aldermaston multigap spectrograph. There it was bombarded by 13-MeV tritons accelerated in the tandem Van de Graaff. The outgoing α particles were detected by 25-μ-thick K-minus-one Ilford emulsions located at 24 angles relative to the incident beam, in the range $\theta=5°$ to 175°. The magnetic-field setting (11.509 kG) was selected so as just to deflect the group corresponding to the ground state of He^6 onto the plate detector, at the forward angles. The exposure of the plates was of 700 μC (i.e., 4.4×10^{15} tritons). Unfortunately, as we will show, the Li^7 target oxidized despite the care taken during its transfer to the spectrograph, and its thickness can be estimated only very roughly. The thickness of the carbon backing was $\sim 15\ \mu g/cm^2$. The target was positioned at 45° to the incident beam.

2. Spectrum of α Particles

Figure 1 shows a typical α-particle spectrum, at $\theta=27.5°$. Spectra were obtained at 24 angles. The groups labeled $He^6(0)$ and (1) correspond to the ground and first excited states. The groups labeled C and O correspond, respectively, to states in B^{11} [from $C^{12}(t,\alpha)B^{11}$] and N^{15} [from $O^{16}(t,\alpha)N^{15}$]. The subscript denotes which state is reached in B^{11} and N^{15}. All the α groups observed at this and at every other angle can be accounted for in terms of the two states in He^6, and in terms of known states in B^{11} and in N^{15}. The continuous background of α particles is consistent with the Q values for the breakup $Li^7+t \rightarrow 2\alpha+2n[Q=8.864]$ and $Li^7+t \rightarrow He^5$

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[11] An endoergic decay would not usually be possible but the width of the ground state of He^5 is ~ 0.5 MeV.

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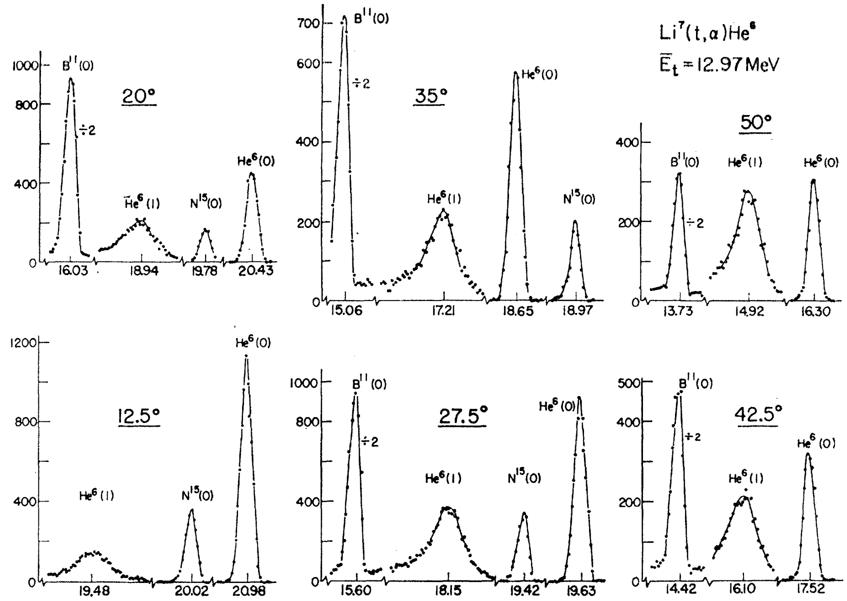

FIG. 2. The broad He^6 state at $E_x = 1.80$ MeV ($He^6(1)$) is shown in comparison with nearby sharp states, at six angles. The groups labeled $He^6(0)$, $B^{11}(0)$ and $N^{15}(0)$ correspond to the ground states of these three nuclei. The ordinate gives the number of α tracks in 0.2-mm bins; the abscissa is the α-particle energy in MeV.

$+\alpha+n[Q=7.907]$. The location of the He^{6*} group makes it impossible to find the maximum energy of the breakup α particles, and the shape of the distribution near these two Q values. The large rise in the continuum background at $E_\alpha \sim 8$ MeV corresponds to the triton binding energy $[E_b = 12.299$ MeV$]$ and therefore to the onset of $Li^7+t \rightarrow t+t+\alpha[Q=-2.466$ MeV$]$.

The mean triton energy in the Li^7 oxide target was calculated relativistically from the α-particle energies of the $He^6(0)$ and $N^{15}(0)$ groups, whose Q values are known to ± 4 keV and ± 1 keV, respectively. Results of calculations at eleven angles give a weighted average $\bar{E}_t = 12.972 \pm 0.010$ MeV in the Li^7 oxide. A similar calculation with the $B^{11}(0)$ groups (from the carbon backing) gives $\bar{E}_t = 12.948 \pm 0.010$ MeV.

3. The First Excited State of He^6

The α-particle groups to the first excited state of He^6 were studied carefully at eleven angles ($\theta = 5°$ to $87.5°$). Figure 2 shows six of the spectra for $He^6(1)$ compared with neighboring groups to the sharp ground states of He^6, B^{11}, and N^{15}. The intrinsic width of the first excited state is clearly apparent. It is determined to be

$$\Gamma_{\text{c.m.}} = 113 \pm 20 \text{ keV}.$$

[The rms deviation of the values obtained for Γ at eleven angles is 11 keV.]

The excitation energy of the excited state was calculated from the α-particle energies corresponding to the midpoints of the $He^6(0)$ and $He^6(1)$ groups and $\bar{E}_t = 12.972$ MeV. We find

$$E_x = 1.797 \pm 0.025 \text{ MeV}.$$

[The rms deviation of the eleven values of Q is 17 keV.] This excitation energy is appreciably different from the value $E_x = 1.71 \pm 0.01$ MeV given by Allen *et al.*[2–4].

4. Other Excited States of He^6

A search was made for the α groups corresponding to the reported[4] state at 3.4 MeV. No such groups were observed at any of eleven angles between 5° and 100° (see, i.e., Fig. 1): The upper limit to the intensity of the "3.4-MeV" group is 7% of the intensity of the "1.8-MeV" group [$He^6(1)$], if a width $\lesssim 100$ keV is assumed for the 3.4-MeV "state." If a width of ~ 300 keV is assumed, the upper limit to the intensities of the groups is 20%.

No "sharp" groups ($\lesssim 100$ keV) are observed corresponding to states in He^6 with $E_x \lesssim 12$ MeV (5–35°) to $E_x \lesssim 4$ MeV (100°). Above an excitation of 12 MeV, the $Li^7(t,\alpha)2H^3$ background is so high that even sharp states could have been missed. The continuum background is very smooth and does not indicate the presence of groups of α particles of appreciable intensities corresponding to broad states in He^6.

Figure 3 shows the isobaric diagram for the $A=6$ triad. The usual[15] isobaric correction has been made to the He^6-Li^6 and Be^6-Li^6 mass differences. In calculating the Coulomb-energy difference, the crude assumption of uniform distribution of charge has been made.

5. (t,α) Angular Distributions

The angular distributions were calculated from the intensity of the α groups at the various angles, after

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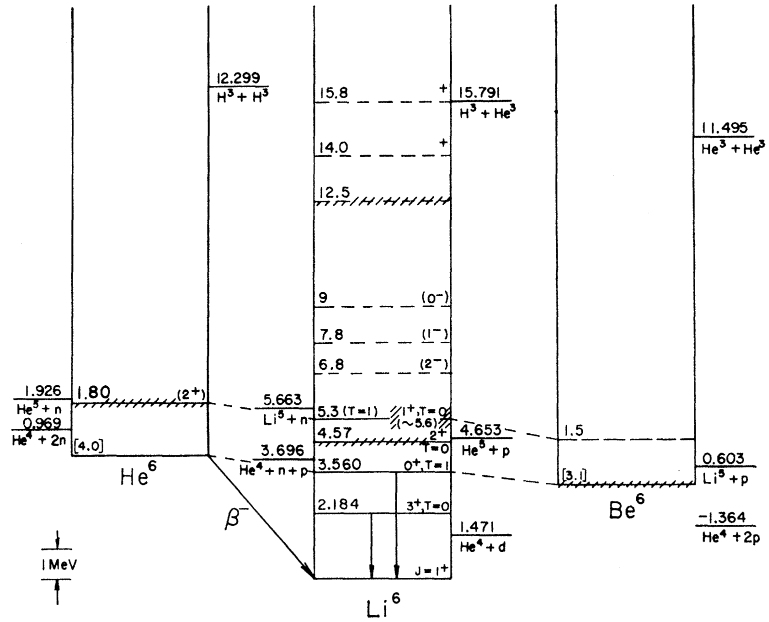

FIG. 3. The mass-6 isobaric triad. Corrections have been made for Coulomb energy differences and the *n-p* mass difference. See text for further details.

correction for solid angle and other geometric factors, and after conversion into the center-of-mass system.

Figure 4 shows the angular distributions of the α particles to the ground and 1.8-MeV states of He^6. The ordinate gives the relative differential cross section in the center-of-mass system. One would expect both curves to correspond to an $l=1$ transfer, assuming $J^\pi=0^+$ and 2^+ for the He^6 states.

Figures 5 and 6 show the angular distributions to the ground state of B^{11} and to the states at 2.14, 4.46, and 5.03 MeV.[16] These states have, respectively, $J^\pi=\frac{3}{2}^-, \frac{1}{2}^-, \frac{5}{2}^-$, and $\frac{3}{2}^-$. The distributions to the $J=\frac{1}{2}$ and $\frac{3}{2}$ states involve an $l=1$ transfer, while the distribution to the $\frac{5}{2}^-$ state at 4.46 MeV involves $l=3$. The angular distributions to these states obtained at $E_t=10.1$ MeV by Pullen *et al.*[14] also show the relatively large cross section of the reaction to the ground state of B^{11}. At $E_t=10.1$ MeV, the $B^{11}(0)$ and (1) groups are peaked forward and back.[14] Back-peaking could not have been observed under the conditions of this experiment.

Figure 7 shows the angular distributions to the ground state of $N^{15}(J^\pi=\frac{1}{2}^-;\ l=1)$, to the unresolved

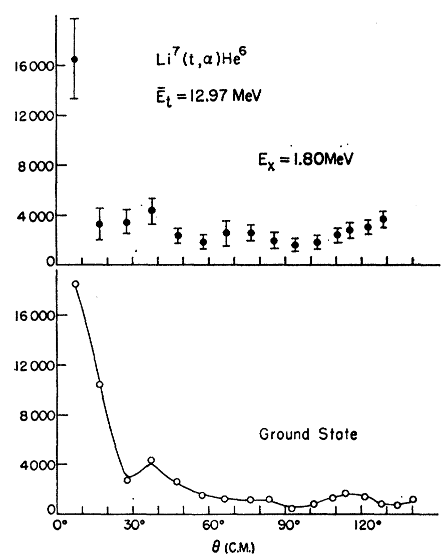

FIG. 4. Angular distribution of α particles in the center-of-mass system at $E_t=12.97$ MeV. The two distributions shown are to the ground state of He^6 and to the excited state at 1.80 MeV. When statistical errors are not shown they are contained within the data points. The ordinate gives the relative intensity of the group. The lines through the data points simply serve to connect these points.

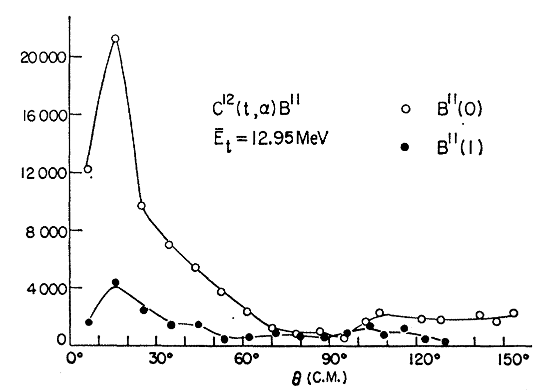

FIG. 5. Angular distributions of the α particles to the ground state of B^{11} (open circles) and to the state at 2.14 MeV (dots). See also caption of Fig. 4, and Ref. 16.

[16] In Figs. 5 and 6, a relative intensity of 1000 corresponds to $d\sigma/d\Omega \sim 1.2$ mb/sr ($\pm 50\%$). Similar calculations for Figs. 4 and 7 cannot be made because of the large uncertainty in the thickness of the Li^7 oxide layer.

(5.28+5.31)-MeV states ($J^\pi = \frac{5}{2}^+, \frac{1}{2}^+$; $l=2$, 0) and to the 6.33-MeV state ($J^\pi = \frac{3}{2}^-$; $l=1$). The relatively low cross section of the distribution to the unresolved 5.3-MeV states may perhaps be explained in terms of the small reduced width[17] of the 5.31-MeV state, coupled with $l=2$ transfer for the 5.28-MeV state.

An attempt was made[18] to fit these curves using a least-squares program with Legendre polynomials up to order 8. This was unsuccessful. Although it is obvious that by including Legendre polynomials up to sufficiently high order a good fit could be obtained, we felt that such an analysis would not be useful in the present state of theoretical understanding of (t,α) reactions.

Pullen *et al.*[14] had made an attempt to fit their $C^{12}(t,\alpha)B^{11}$ distributions with Born approximation pick-up theory. While the qualitative agreement in the location of the most prominent maximum was fairly good, the detailed structure of the curves could not be reproduced. Further, Pullen *et al.* point out that the large backward peaks they observe show that a simple proton pick-up mechanism does not hold. At this time, the needed parameters (i.e., well depths, etc.) for more sophisticated calculations are not available.

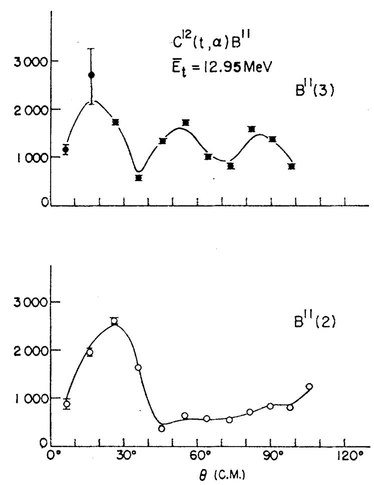

FIG. 6. Angular distributions of the α particles to the states of B^{11} at 4.46 MeV (open circles) and 5.03 MeV (dots). See also caption of Fig. 4, and Ref. 16.

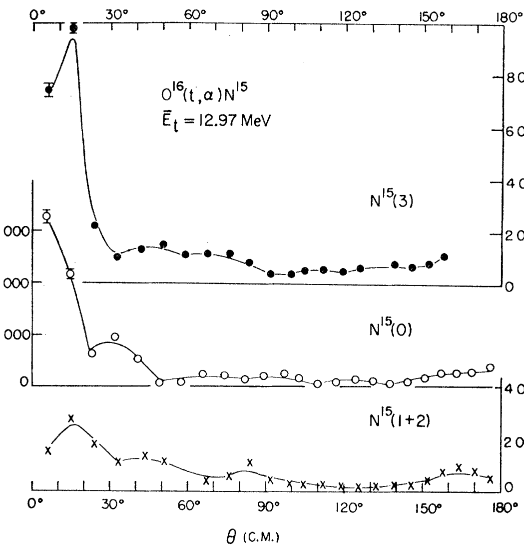

FIG. 7. Angular distributions of the α particles to the ground state of N^{15} (open circles) and to the states at 5.28 and 5.31 MeV (unresolved) (crosses), and 6.33 MeV (dots). See also caption of Fig. 4.

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[18] The least-squares program was made available by Dr. Lloyd F. Chase and Dr. W. W. True. Dr. John Olness of Brookhaven National Laboratory very kindly ran these calculations on the BNL computer. We are very grateful to Dr. Olness, Dr. Chase, and Dr. True for their help.