Disintegration of Li^6 and Li^7 by 0.24-Mev Tritons

K. W. ALLEN,* E. ALMQVIST, J. T. DEWAN,† AND T. P. PEPPER,‡
Chalk River Laboratory, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada
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The energy distributions of charged particles emitted in the bombardment of Li^6 and Li^7 by 0.24-Mev tritons have been obtained by magnetic analysis and by measuring pulse heights in a proportional counter. Q values for the reactions $Li^6(t,d)Li^7$, $Li^6(t,p)Li^8$, and $Li^7(t,\alpha)He^6$ were found to be 0.986 ± 0.007 Mev, 0.790 ± 0.011 Mev and 9.79 ± 0.03 Mev, respectively. The latter, when combined with other accurately measured Q values, leads to a He^6-Li^6 mass difference of 3.55 ± 0.03 Mev, which is in agreement with the most recent β-ray measurements. Evidence is also presented for an excited state of He^6 at 1.71 ± 0.01 Mev above the ground state.

I. INTRODUCTION

THE reactions produced by the bombardment of light elements with tritium and He^3 in general have large Q values and sometimes lead to the formation of residual nuclei which cannot easily be produced in other ways. A systematic study of these reactions has been made possible by the technique[1] developed in this laboratory for handling and recovering small quantities of tritium and He^3 gases used in the ion source of a specially designed low-voltage accelerator,[2] The present paper deals with the energy distributions of the protons, deuterons and α-particles emitted when the lithium isotopes are bombarded with 0.24-Mev tritons. With a Li^6 target, the reactions $Li^6(t,d)Li^7$, $Li^6(t,p)Li^8$ and $Li^6(t,\alpha)He^5$ have been observed as well as a continuum of α-particles from the three-body disintegration $Li^6(t,n)2\alpha$ proceeding directly or via virtual α-emitting states of Be^8. With Li^7 as a target, two groups of α-particles from the reaction $Li^7(t,\alpha)He^6$ were observed leading to the ground state of He^6 and to a previously unreported excited state at 1.71 Mev. These groups were superimposed on an α-particle continuum from the various multibody disintegrations that are possible. Brief accounts of these experiments have already been published.[3]

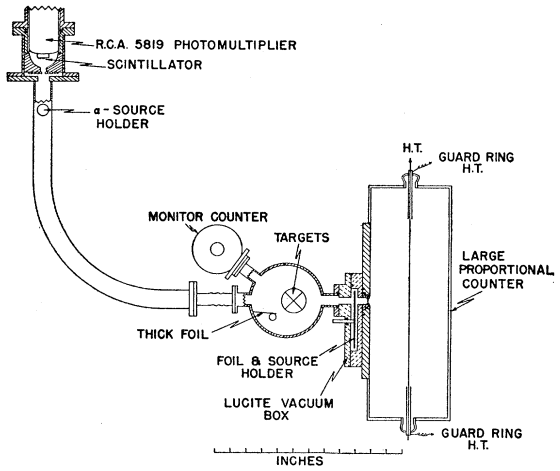

FIG. 1. Diagram showing arrangement of target chamber, magnetic analyzer and proportional counters.

II. EXPERIMENTAL TECHNIQUE

A. Accelerator and Gas Recovery

The low-voltage accelerator and gas recovery system have been described in detail elsewhere.[1,2] Hydrogen containing 15 percent tritium was fed into the rf ion source through a palladium leak at the rate of about 10 cc per hour. More than 96 percent of the gas leaving the ion source was recovered by a differential pumping system employing mercury diffusion pumps. The exhaust gas from the last pump, which was modified to operate against a backing pressure of 15 mm of mercury, was absorbed at room temperature in pyrophoric uranium contained in a stainless steel reservoir. By heating the reservoir to about 450°C, the hydrogen-tritium mixture was re-evolved in a pure state and used again in the ion source. A magnetic valve controlled from a vacuum gauge was provided to prevent air entering the pyrophoric uranium in the event of a leak developing in some part of the apparatus.

B. Target Assembly

The particle detectors used in this work consisted of a large proportional counter which recorded energy distributions of disintegration particles directly, and a ZnS(Ag) screen and photomultiplier which detected particles after their passage through a 90° analyzing magnet. In each case the sizes of the amplified pulses were displayed on a thirty-channel pulse-height analyzer.[4] The arrangement of the apparatus is shown diagrammatically in Fig. 1.

The vertical beam from the accelerator was deflected in a 90° magnet whose field was chosen to select the

* Now at the University of Liverpool, Liverpool, England.
† Now with Schlumberger Well Surveying Corporation, Houston, Texas.
‡ Now with Isotope Products Ltd., Oakville, Ontario, Canada.
[1] K. W. Allen and E. Almqvist, Rev. Sci. Instr. **24**, 70 (1953).
[2] Allen, Almqvist, Dewan, and Pepper, Can. J. Phys. **29**, 557 (1951).
[3] Pepper, Allen, Almqvist, and Dewan, Phys. Rev. **85**, 155 (1952); Dewan, Pepper, Allen, and Almqvist, Phys. Rev. **86**, 416 (1952).
[4] Moody, Howell, Battell, and Taplin, Rev. Sci. Instr. **22**, 551 (1951).

mass-3 component (T^+ and H_3^+ ions). This component of the beam, after collimation by $\frac{3}{16}$-in. diameter apertures 4 in. apart, was allowed to bombard one of four targets mounted on a water-cooled insulated assembly. The target assembly could be moved on vacuum seals so that any one of the four targets could be brought into the bombarding position facing either a magnetic analyzer or a large proportional counter. In the working position a target was inclined at 45° to both the ion beam and the particle detector. The collimation and entrance apertures were such that disintegration particles emitted at 90±2° to the beam were recorded. However, because of the low bombarding energy employed, this angular spread did not cause appreciable broadening of the particle energy distribution.

An additional small proportional counter was provided on one side of the target chamber to monitor the yield when the magnetic analyzer was in use.

C. The Magnetic Analyzer

Disintegration particles from the target were deflected through 90° in a homogeneous magnetic field on a radius of curvature of 20 cm. The field was variable up to a maximum of 15 000 gauss and the current through the coils was electronically stabilized. Relative values of the magnetic field were measured by the voltage developed across a coil rotating in the fringing field and driven by a synchronous motor. Absolute calibration was made by means of known particle groups. As normally set up, the resolution of the magnetic analyzer was about 2 percent in momentum (total width at half-height). The particles were detected by their scintillations in a ZnS(Ag) screen viewed by a 5819 photomultiplier. The ZnS screen was made by dusting the powder on to a piece of cellulose tape and shaking off the excess. The screen was mounted on the end of a short Lucite light pipe shaped at the other end to fit the surface of the photomultiplier. The photomultiplier was provided with mu metal and iron shields to reduce the effect of the stray field of the analyzing magnet on its operation. The pulses from the photomultiplier, after suitable amplification, were dispalyed on a thirty-channel pulse-height analyzer.[4]

D. The Proportional Counter

The large proportional counter used for measuring the energies of disintegration particles was constructed from an aluminum cylinder 5 in. in diameter and 15 in. long. It was provided with a mica window $\frac{1}{4}$ in. in diameter and 1 mg cm^{-2} thick. The mica window was plugged into the counter wall on an O-ring vacuum seal, so that windows could be changed easily in case of failure. The inner conductor was a tungsten wire 0.010 in. in diameter, supported at either end by copper to glass seals incorporating a guard ring construction.

TABLE I. α-particle energy calibration points obtained from radioactive sources and nuclear reactions.

Source	α-particle energy (Mev)	Reference
$D(t,\alpha)n$	3.43	a
U^{233}	4.823	b
Pu^{239}	5.150	c
Am^{241}	5.476	d
Cm^{242}	6.100	d
$Li^7(p,\alpha)He^4$	8.76	a

[a] Energies are those at 90° to 0.24-Mev beam. Q values were calculated from the masses (see reference 5).
[b] See reference 6.
[c] See reference 7.
[d] See reference 8.

The counter was filled to a pressure of 70 cm of mercury with a gas mixture consisting of welding argon with 1 percent carbon dioxide added. Particles entering through the mica window crossed the counter in a direction perpendicular to the wire in its central region. The counter was normally used with a gas amplification of five, obtained with the wire about 2400 volts positive with respect to the outer cylinder. The best resolution was obtained immediately after filling, when the total width at half-maximum was 1.5 percent of the mean pulse height for 8.75-Mev α-particles from the $Li^7(p\alpha)He^4$ reaction. The width deteriorated to ~2.5 percent in a few hours, and then stayed constant for long periods. Counter pulses were taken from the central wire through a 50-μμf ceramic condenser to a preamplifier mounted on the end of the counter. Thence, the pulses were led to a linear amplifier and pulse-height analyzer which were located near the control desk of the accelerator. Pulse heights were always referred to the output of a stable pulse generator which was connected to the input of the preamplifier via a 5-μμf condenser.

A wheel carrying aluminum absorbers and α-particle sources for calibration purposes was mounted *in vacuo* between the counter and the target. Table I lists the energy calibration points which were used.[5–8]

III. DISINTEGRATION OF Li^6

The possible exothermic reactions, with Q values calculated from the masses,[5] are:

$$Li^6+T=Li^7+D^2+0.988 \text{ Mev}, \quad (1)$$

$$Li^8+H^1+0.799 \text{ Mev}, \quad (2)$$

$$2He^4+n+16.100 \text{ Mev}, \quad (3)$$

$$He^5+He^4+15.2 \text{ Mev}, \quad (4)$$

$$Be^8+n+16.004 \text{ Mev}. \quad (5)$$

The low-energy deuterons and protons from reactions (1) and (2) were studied with the magnetic analyzer,

[5] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).
[6] T. E. Cranshaw and J. A. Harvey, Can. J. Research **A26**, 243 (1948).
[7] F. Asaro and I. Perlman, Phys. Rev. **88**, 828 (1952).
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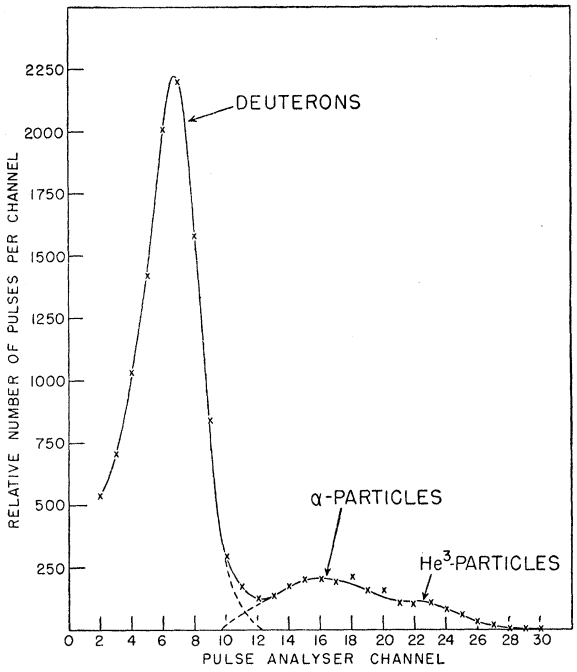

FIG. 2. The pulse-height distribution from a ZnS(Ag) screen produced by different particles with the same $H\rho$. The energies are: deuterons 0.866 Mev, α-particles 1.74 Mev, and He^3 particles 2.32 Mev.

and the α-particles from reaction (3), (4), and (5) with both the analyzer and the proportional counter. Thick targets of lithium fluoride were used in which the isotopic content of the lithium was 99.4 percent Li^6, 0.6 percent Li^7. The triton bombarding energy was 0.24 Mev.

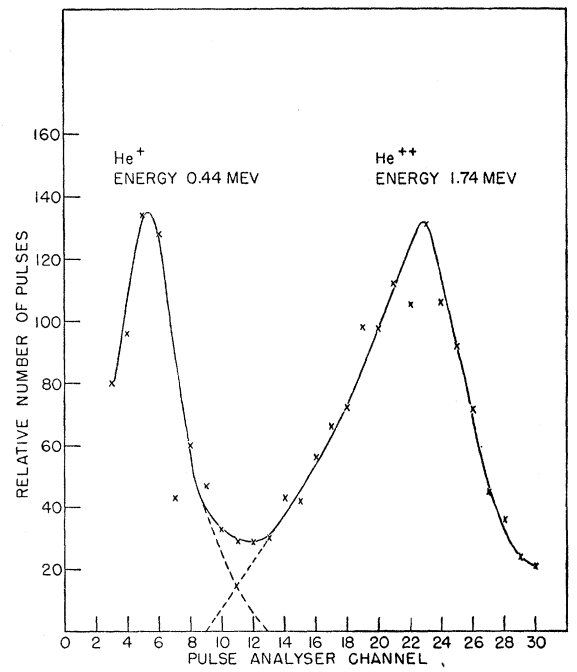

FIG. 3. Pulse-height distribution from ZnS(Ag) screen produced by singly and doubly charged α-particles with the same momentum-to-charge ratio.

A. The Reactions $Li^6(t,d)Li^7$ and $Li^6(t,p)Li^8$

A preliminary investigation with the magnetic analyzer revealed two strong deuteron groups from reaction (1) superimposed on a background of α-particles from reactions (3), (4), and (5). Disintegration particles from the reaction $Li^6(p,\alpha)He^3$, which was produced by 80-kev protons arising from the HHH^+ component of the ion beam, were also observed.

It so happened that, under the conditions of this experiment, the magnetic field required to bend the ground state deuterons on to the detector also selected doubly charged α-particles and He^3 particles from the $Li^6(p\alpha)He^3$ reaction. At the low bombarding energy of 80 kev and at 90° to the beam, these α-particles and He^3 particles had almost identical momenta and were not resolved by the magnet. Figure 2 shows a pulse-height analysis for a magnetic field close to the ground-state deuteron peak from reaction (1). The deuterons are quite well separated from the α-particles and He^3 particles, which are barely resolved. The calculated energy ratios for deuterons, doubly charged α-particles and He^3 particles with the same magnetic rigidity are 1:2:2.67; the estimated pulse-height ratios are 1:2.1:2.9. If only α-particles can reach the ZnS screen, then a pulse-height spectrum similar to that of Fig. 3 is observed. This curve was obtained by bombarding a Li^7 target with tritons, with the analyzing magnet setting the same as for Fig. 2. The two groups are singly and doubly charged α-particles, and the ratio of pulse heights is about 0.25, as it should be if the response of the ZnS screen is proportional to α-particle energy. These measurements suggest that the light output of ZnS(Ag) is proportional to the energy of heavy particles incident upon it, and independent of their nature, as is generally believed. Presumably this will only be true for short-range particles, for loss of light by scattering and absorption will be serious in the thicker layers of ZnS required to stop more energetic particles. Thus a ZnS screen forms a very convenient energy sensitive detector for use with a magnetic analyzer in the low-energy region, where a window is undesirable.

The momentum distributions of the deuterons and protons from the reactions $Li^6(t,d)Li^7$ and $Li^6(t,p)Li^8$ are shown in Fig. 4. The two intense groups are deuterons associated with the formation of Li^7 in the ground state and in the well-known 478-kev excited state. The weak proton group was readily detected when the ZnS screen was covered with aluminum foil just sufficiently thick to stop α-particles with the same momentum as the protons. The dashed curve represents the contribution from the reaction $Li^6(p,\alpha)He^3$, which was separated from the deuterons by analysis of the

pulse-height distribution from the detector as noted above.

B. Q Values and Discussion

It was found that the ground-state deuteron group coincided exactly in momentum with the α-particles and He^3 particles from the reaction $Li^6(p,\alpha)He^3$, within the accuracy of these measurements which was about 0.5 percent in momentum. As the Q value for the $Li^6(p,\alpha)He^3$ reaction has been measured accurately in several laboratories, it provided an excellent calibration for determining the Q value of the $Li^6(t,d)Li^7$ reaction. Taking a value of 4.023 ± 0.002 Mev for the former, which is a weighted mean of the best measurements,[5,9] the latter was found to be 0.986 ± 0.007 Mev. Allowance was made for an oil layer equivalent to 0.005 cm air on the target. The thickness of this oil layer was estimated very roughly by measuring the yield of α-particles from the $D(t,\alpha)n$ reaction when the target was turned to face the proportional counter on the other side of the target assembly. As the H.T. set had never had deuterium in it, it was assumed the source of deuterium was the natural isotopic content of hydrogenous vapors which condensed on the target. It is known that the deuterium contamination can be reduced very considerably by heating the target.[10] This estimate of the thickness of the oil layer was almost certainly too low as some of the oil must have been carbonized by the beam. The Q value is however fairly insensitive to the amount of oil on the target since both calibrating α-particles and deuterons go through it. A correction of +5 kev was made for thick target effect.

TABLE II. Comparison of measured Q values with those calculated from the masses.

Reaction	Calc. Q (Mev)	Meas. Q (Mev)
$Li^6(t,d)Li^7$	0.988	0.986 ± 0.007
$Li^6(t,p)Li^8$	0.799	0.790 ± 0.011

If the energy of the first excited state of Li^7 is assumed to be 0.478 ± 0.007 Mev,[11] the Q of the reaction $Li^6(t,d)Li^7$ becomes 0.508 ± 0.007 Mev. From this value, and the measured separation in momentum of the low energy deuterons and protons from the reaction $Li^6(t,p)Li^8$, the Q value of the latter reaction was found to be 0.790 ± 0.011 Mev. Corrections for an oil layer and thick target effect were included. Comparison of the measured Q values with those calculated from the masses is made in Table II. The difference between the two measured Q values, 0.196 Mev, may also be compared with the directly measured Q value of the reaction $Li^7(d,p)Li^8$; i.e., 0.191 ± 0.001.[12]

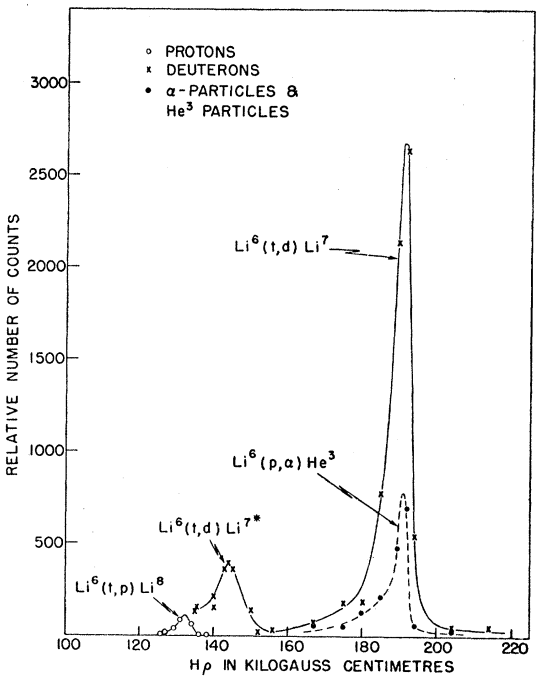

FIG. 4. Protons and deuterons from Li^6+T reactions observed at 90° to a 0.24-Mev triton beam. The dashed curve represents He^3 particles and α-particles produced by 80-kev protons on Li^6.

C. α-Particles from Li^6+T

The energy spectrum of α-particles from reactions (3), (4), and (5) obtained from magnetic deflection and proportional counter measurements is shown in Fig. 5. In the magnetic measurements, the intensity of doubly charged α-particles was obtained by integrating the area under the upper peak in the pulse analyzer curve (compare Fig. 3). The data were then corrected for charge exchange in the target[13] and plotted on a

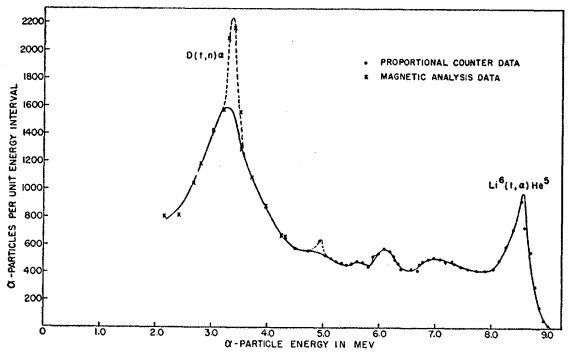

FIG. 5. The 90° α-particle energy distribution from Li^6+T reactions at a triton energy of 0.24 Mev.

[9] Collins, McKenzie, and Ramm, Proc. Roy. Soc. (London) **A216**, 242 (1953).
[10] Allen, Almqvist, Dewan, Pepper, and Sanders, Phys. Rev. **82**, 262 (1951).
[11] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).
[12] Williamson, Browne, Craig, and Donahue, Phys. Rev. **84**, 731 (1951).
[13] G. H. Briggs, Proc. Roy. Soc. (London) **A114**, 341 (1927).

number *versus* energy curve to correspond with the proportional counter measurements.

The peak at 8.5 Mev near the upper end of the energy spectrum is associated with the formation of He^5 in its unstable ground state. A similar peak is observed in the reaction $Li^7(d,\alpha)He^5$.[14] The remainder of the spectrum appears to be due to the superposition of broad overlapping groups of α-particles from the breakup of excited states of Be^8. No detailed comparison with known states of Be^8 can be made without additional information about the neutron groups from reaction (5).

The dashed portion of the curve in the region of 3.4 Mev represents α-particles from the $D(t,n)He^4$ reaction which are always observed when a cooled target is bombarded by low-energy tritons. Very low-intensity contamination groups at 4.9 and 5.9 Mev, arising from the bombardment of a trace of Li^7 in the target, also appeared.

IV. DISINTEGRATION OF Li^7

The energetically possible reactions are:

$$Li^7+T=He^6+He^4+9.79 \text{ Mev}, \quad (1)$$

$$=2He^4+2n+8.85 \text{ Mev}, \quad (2)$$

$$=Be^9+n+10.42 \text{ Mev}, \quad (3)$$

Reaction (2) may also represent the final products of two step processes via the unstable nuclei He^5 and Be^8 or through virtual excited states of He^6 and Be^9.

The bombardments were carried out at a triton energy of 0.24 Mev, using thick targets of LiF and Li_2SO_4 in which the isotopic content of the lithium was 99.91 percent Li^7 and 0.09 percent Li^6. The results are shown in Fig. 6, identical energy spectra being observed for each type of target. In addition to the α-particle continuum from reaction (2), there are prominent groups at 5.93 and 4.91 Mev and a double peak at $\sim$3.5 Mev.

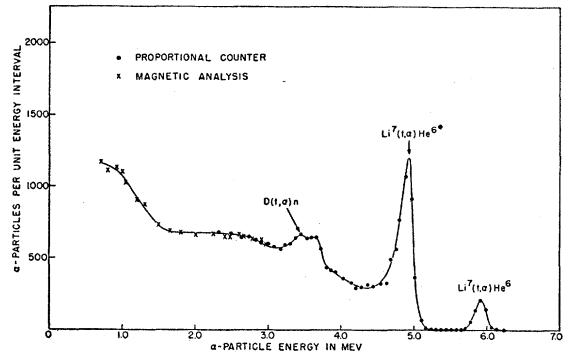

FIG. 6. The 90° α-particle energy distribution from the Li^7+T reactions at a triton energy of 0.24 Mev.

[14] Williams, Shepherd, and Haxby, Phys. Rev. **52**, 390 (1937).

Mass of He^6

The group at 5.93 Mev is associated with the formation of He^6 in its ground state. The energy of this group was determined accurately by allowing the α-particles to enter the counter simultaneously with α-particles from Cm^{242}. In this way any small shifts in counter calibration between runs were eliminated. Such small shifts in pulse height, dependent on over-all counting rate in the counter, are known to occur. An expanded portion of the pulse-height distribution (Fig. 7) shows the two groups clearly resolved. The separation of the peaks was found to be 0.165 ± 0.017 Mev. Asaro, Reynolds, and Perlman[8] have shown that the α-particle spectrum from Cm^{242} is complex, 73 percent of the α-particles being emitted with an energy of 6.110 ± 003 Mev and 27 percent with an energy of 6.064 ± 0.003 Mev; residual groups account for less than 0.1 percent of the total intensity.[15] Therefore, if a weighted mean of 6.100 ± 0.003 is taken for Cm^{242}, the energy of the ground-state α-particle group becomes 5.945 ± 0.017 Mev after corrections totalling $+0.010$ Mev are added for thick target effect and for an oil layer on the target. The Q value of the reaction $Li^7(t\alpha)He^6$ is then calculated to be 9.79 ± 0.03 Mev.

It may be shown that the energy equivalent of the mass difference He^6-Li^6 is $(Q_1+Q_2)-(Q_3+Q_4)$, where Q_1, Q_2, Q_3, and Q_4 are respectively the Q values of the reactions $Li^7(p,\alpha)\alpha$, $T(\beta)He^3$, $Li^6(p,\alpha)He^3$, and $Li^7(t,\alpha)$-He^6. The following values were assumed for the Q values: $Q_1=17.343\pm0.007$ Mev,[5,9] $Q_2=0.0186\pm0.0002$ Mev,[16] $Q_3=4.023\pm0.002$ Mev,[5,9] $Q_4=9.79\pm0.03$ Mev. Thus,

$$He^6-Li^6=3.55\pm0.03 \text{ Mev}.$$

If the mass of Li^6 is assumed to be 6.01703, the mass of He^6 is, therefore, 6.02084 ± 0.00003.

Excited States of He^6

The strong group of α-particles at 4.9 Mev (Fig. 6) is believed to be associated with the first excited state of He^6. The energy of the group was found by direct comparison with α-particles from Pu^{239} ($E=5.150$ Mev) which were allowed to enter the target simultaneously with those from the Li target. The mean energy derived from these runs was 4.91 ± 0.02 Mev. From the directly measured energy difference of 1.03 ± 0.01 Mev between this group and the ground state group, the energy of the first excited state was found to be 1.71 ± 0.01 Mev.

The double peak at $\sim$3.5 Mev is believed to be a superposition of the usual T+D α-particles at 3.43 Mev and the ground-state He^6 particles associated with the 5.945-Mev α-particles. There is no evidence for the existence of other excited states of He^6 from the 90° α-particle spectrum (Fig. 6). However, in the course of

[15] Asaro, Thompson, and Perlman, Phys. Rev. **92**, 694 (1953).
[16] Curran, Angus, and Cockcroft, Phil. Mag. **40**, 53 (1949). G. C. Hanna and B. Pontecorvo, Phys. Rev. **75**, 983 (1949).

some measurements of the angular distribution of the two prominent groups, a third group of α-particles was observed at backward angles. This group is believed to be associated with a second excited state of He^6 at 3.35 Mev. A fuller discussion of this state will appear in a forthcoming publication.

DISCUSSION

Before the present measurements were made, the best value for the He^6-Li^6 mass difference appeared to be that given by the end point of the β-ray spectrum, 3.215 ± 0.015 Mev.[17] However, this value was inconsistent with earlier measurements of the same quantity by absorption techniques,[18,19] and also with the observation that the neutron threshold for the production of He^6 radioactivity in the reaction $Be^9(n,\alpha)He^6$ was greater than 0.6 Mev.[20] This latter observation implies that the He^6-Li^6 mass difference must be greater than 3.44 Mev. There is no evidence for a γ ray associated with the β-particles.[19] This puzzling discrepancy is now clear since the end point of the β spectrum has been remeasured as 3.50 ± 0.05 Mev,[21] which is in agreement, within experimental error, with the value obtained here from reaction Q values.

The first excited state of He^6 is unstable against dissociation into an α-particle and two neutrons by 0.78 Mev, and it may be inferred that the dissociation does take place because no group of He^6 particles corresponding to the 4.9-Mev α-particles was observed. Indeed it would be surprising if the breakup did not take place. Although unstable against three body disintegrations, this excited state cannot break up into He^5 and a neutron and may be quite narrow. The observed width of the 4.9-Mev group was not noticeably greater than the experimental width for a particle of this energy, which suggests that the width of the excited state of He^6 is probably not greater than about 100 kev.

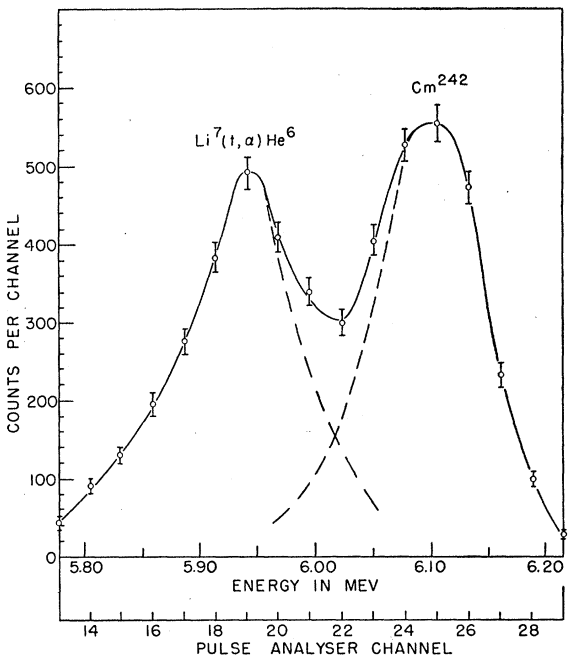

FIG. 7. The pulse-height distribution obtained when α-particles from the $Li^7(t,\alpha)He^6$ reaction and from Cm^{242} are admitted to the counter simultaneously through the same window. Observation at 90° to a 0.24-Mev triton beam.

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[17] V. Perez-Mendez and H. Brown, Phys. Rev. **77**, 404 (1950).
[18] T. Bjerge and K. J. Brostrom, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **16**, No. 8 (1938); H. S. Sommers, Jr., and R. Sherr, Phys. Rev. **69**, 21 (1946).
[19] W. J. Knox, Phys. Rev. **74**, 1192 (1948).
[20] Allen, Burcham, and Wilkinson, Proc. Roy. Soc. (London) **A192**, 114 (1947).
[21] Wu, Rustad, Perez-Mendez, and Lidofsky, Phys. Rev. **87**, 1140 (1952).