First Excited State of He^5†

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The reaction $Li^7(d,\alpha)He^5$ was studied with the use of coincidence circuitry and solid-state charged-particle detectors. Targets of natural and isotopic lithium were bombarded with 150–200 keV deuterons, and α particles emitted at laboratory angles of 90 and 82 deg were detected in coincidence. The (d,α) reaction proceeding to the ground state of He^5 was observed, its differential cross section at 90 deg was measured relative to that for $Li^6(d,\alpha)\alpha$, and a value of $2.4_{-1.0}^{+1.5}$ was assigned to the parameter A in the function $f(\theta)=1+A\sin^2\theta$ which describes the center-of-mass α-particle distribution resulting from the disintegration of He^5. The first excited state of He^5 was found to have an excitation energy of 2.6 ± 0.4 MeV and a width of 4.0 ± 1.0 MeV. The intensity of the excited state alpha group was greater than that of the ground-state group by a factor of about 1.5. There was no evidence for any other excited state up to at least 7 MeV. The ratio of the differential cross sections at 90 deg for $Li^6(d,p)Li^7$ and $Li^6(d,\alpha)\alpha$ was determined for several values of E_d and found to agree with reported cross-section data.

I. INTRODUCTION

THE shell model of the nucleus, with the assumption of spin-orbit forces, predicts that the He^5 and Li^5 nuclei should have their lowest two states in the $1P_{1/2}$ and $1P_{3/2}$ configurations. In 1950, Goldstein[1] showed that experimental data at that time could best be explained by an inverted P-doublet with a splitting of from 2–5 MeV. Later, Koester *et al.*[2] showed how the spin-orbit interaction for the mirror pair He^5 and Li^5 leads to an inverted doublet with an energy separation of 4 MeV (qualitative). Recently, Pearlstein *et al.*[3] have used a variational procedure to calculate the first three levels in He^5. Their analysis concludes that spin-orbit forces lead to a well-defined ground-state $P_{3/2}$ level and a broad $P_{1/2}$ level for the first excited state.

The ground state of He^5 has a width of about 0.55 MeV,[4] which corresponds to a mean life of 1.2×10^{-21} sec; the nucleus decays by neutron emission too rapidly to allow direct detection. However, this state has been well established as a resonance in the n-α scattering cross section,[5,6] and as peaks in the spectra from at least ten different reactions, the one most frequently investigated being $Li^7(d,\alpha)He^5$.[7–15] Moreover, the anisotropy of the particles emitted in the decay of the ground state has been observed by several people, and supports an assignment of $P_{3/2}$ to this state. (A $P_{1/2}$ assignment requires an isotropic distribution of the particles resulting from the disintegration of He^5.)[8,9,12]

There exists some confusion concerning the low-lying excited state of He^5 which completes the $1P$ doublet. N-α scattering data have been obtained which indicate a $P_{1/2}$ level about 5 MeV above the $P_{3/2}$ level,[5] or about 2.6 MeV above the $P_{3/2}$ level.[6] Leland and Agnew[16] found a weak neutron peak from the $H^3(t,n)He^5$ reaction which points to a state at about 2.5 MeV in He^5. Cüer and Jung,[11] investigating $Li^7(d,\alpha)He^5$, found a peak in single-particle spectra which they attributed to a 2.5-MeV state in He^5, and Riviere[12] found indications of a similar state when he used an α-α coincidence technique to study the same reaction. Frye[17] did not observe a peak in the deuteron spectrum from $Li^6(n,d)He^5$ which would correspond to a low-lying excited state in He^5, but he did consider a continuum in the lower part of the energy spectrum as attributable to such a state. However, Hannah *et al.*[18] used an n-α coincidence technique to study this reaction and found evidence for a 4.6-MeV state only, which was later dismissed as most likely due to a broad level in Be^8 from the $Li^7(d,n)Be^8$ reaction.[19] Also, Weber[13] using high magnetic resolution techniques, and Buechner *et al.*[10] investigated $Li^7(d,\alpha)He^5$ without noting significant evidence of any first excited state of He^5.

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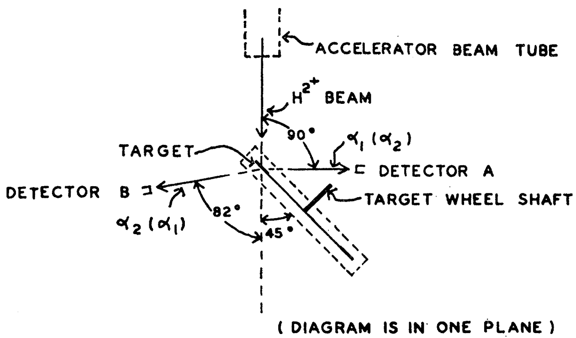

FIG. 1. Experimental arrangement showing position of beam, target, and detectors.

II. REACTIONS

When natural lithium is bombarded with deuterons of energy 200 keV or less, charged particles are emitted as the result of the following reactions which are significantly above threshold:

(1)	$Li^7(d,\alpha_1)He^5$	$Q=14.15$ MeV	
	$He^5 \to n+\alpha_2$	$Q=0.96$	(1)
(2)	$Li^7(d,n)Be^8$	$Q=15.03$	
	$Be^8 \to \alpha+\alpha$	$Q=0.094$	(2)
(3)	$Li^7(d,n\alpha)\alpha$	$Q=15.12$	(3)
(4)	$Li^6(d,\alpha)\alpha$	$Q=22.36$	(4)
(5)	$Li^6(d,p)Li^7$	$Q=5.02.$	(5)

The first step of reaction (1) should permit the identification of narrow states of He^5 via observation of the corresponding monoenergetic α_1-particle groups. However, there are several competing sources of α particles which might conceal the presence of an α_1 peak due to a weak or broad state of He^5. These include disintegration α-particle continua from the breakup of He^5 and Be^8 in reactions (1) and (2), respectively, as well as alphas from the direct three-body breakup of reaction (3). When Li^6 is present, reaction (4) produces an isolated α peak near 11 MeV, and reaction (5) leads to a proton peak superimposed on the α spectrum.

A coincidence technique is necessary to separate the α-particle groups of interest from the competing continua. There is a choice between α_1-n and α_1-α_2 coincidences. In either case a direction would be chosen for α_1 from the $Li^7(d,\alpha_1)He^5$ step, and energy and momentum conservation would specify the direction of the recoil He^5. When the He^5 breaks up into the α_2 and a neutron, both particles are restricted to forward cones in the laboratory system. The n cone (semiangle about 50 deg for the ground state) is much larger than the α_2 cone (semiangle about 11 deg), but an α_1 spectrum could be taken in coincidence with either disintegration particle traveling in a fixed direction with a known energy for a particular excitation energy of He^5.

In this experiment, α_1-α_2 coincidences rather than α_1-n coincidences were observed. The method adopted was advantageous in that both particles could be detected with solid-state counters of virtually 100% detection efficiency and good-energy resolution, in contrast to the much lower efficiency and/or inferior resolution of a comparable neutron counter. The detection of α_1-α_2 rather than α_1-n coincidences was also desirable from the standpoint of geometrical efficiency, since the disintegration α_2's were confined to a smaller cone than the neutrons, so that there were more α_2 particles than neutrons available per unit solid angle for coincidence detection.

A point that must be considered is that even in a coincidence experiment the two-step process $Li^7(d,n)Be^8$, $Be^8 \to \alpha+\alpha$ can be troublesome. The final products are the same here as in the $Li^7(d,\alpha)He^5$ process, so that certain values of Be^8 excitation energy can lead to α-α coincidences which may be misinterpreted as due to formation of He^5. However, there is an important difference between the two cases. The α_1 from the $Li^7(d,\alpha_1)He^5$ leads to a monoenergetic group (except for the level width) in the energy spectrum observed with a single counter. On the other hand, both α's from $Li^7(d,n)Be^8$ are emitted in the second step of a two-step process, with the result that even a very narrow state of Be^8 will produce a continuum of alpha energies in a singles spectrum.

III. EXPERIMENTAL

Since the incident deuteron energy is low and the $Li^7(d,\alpha_1)He^5$ reaction is highly exothermic, the α_1 and

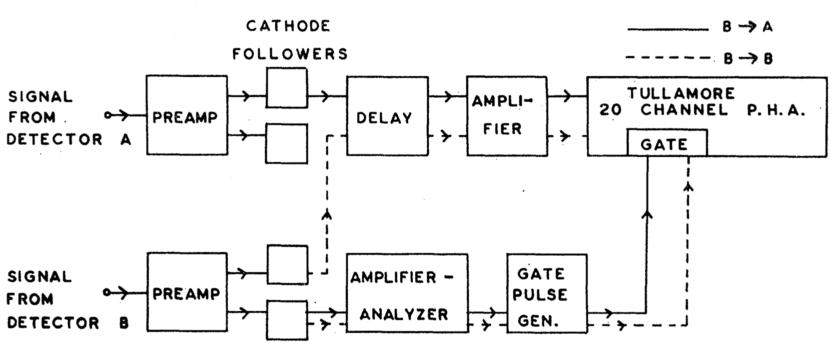

FIG. 2. Block diagram of electronics.

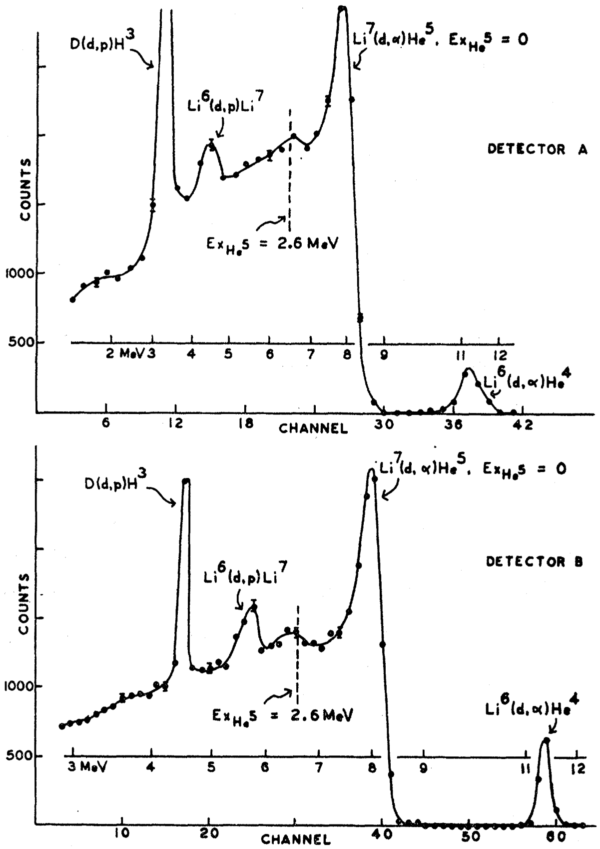

FIG. 3. Singles spectra obtained with 170-keV deuterons incident on the natural lithium target. The upper curve was secured with the 90° detector, and the lower curve with the 82° detector.

He^5 travel in nearly opposite directions in the laboratory system. Also, the (relatively narrow) disintegration α_2 cone is centered about the direction of motion of the He^5 nucleus. Thus, if α_1 and α_2 are to be detected in coincidence, one of the particles must travel through nearly the total thickness of the target and backing. This prevents any conventional means of cooling the reaction target. A very satisfactory solution was to use a 7-in.-diam rotating target wheel with 18 separate target sections which passed consecutively through the deuteron beam at the rate of 180 rpm. This system allowed continuous beams of 150 μA to be used with a beam spot of less than $\frac{1}{4}$-in. diam. (A stationary target would have punctured almost immediately with beams on the order of 10 μA.)

Two targets were used in the present experiment: One made from natural lithium (7.5% Li^6) was about 0.03 mg/cm² thick, and the other was pure Li^7 about 0.3 mg/cm² thick. Both targets were prepared by evaporating metallic lithium from a graphite-sleeved molybdenum crucible on to 0.075-mil nickel foils.

Figure 1 presents the experimental arrangement. The deuteron beam and detectors are in the same plane. The angle of 90° was chosen for experimental convenience, and the angle of 82° was then fixed as approximately the center of the cone of disintegration α_2 particles in coincidence with α_1's detected at 90°. Both detectors were RCA Victor silicon *p-n* junction alpha detectors with 10^3 Ω cm nominal resistivity. They were operated with a reverse bias of 70 V, which resulted in a depletion layer such that α particles between 0.5 and 12 MeV were detected linearly. Each detector has a surface area of 20 mm², and the energy resolution of the detectors with the associated electronics averaged less than 6% for α particles up to 12 MeV. The geometry for a beam spot of $\frac{1}{4}$-in. diam was 90 ± 2 deg for detector A and 82 ± 1.5 deg for detector B.

A block diagram of the electronics is shown in Fig. 2. The solid-line sequence refers to the condition when a window of the energy spectrum of detector B (82 deg) was used to gate the energy spectrum from detector A (90 deg). The dashed line sequence shows detector B gating itself, and thus allowing exact determination of the portion of the B spectrum that was selected by the amplifier-analyzer window settings. The single-particle (i.e., ungated) spectrum from either counter could be obtained by sending the pulses through the electronics in the upper portion of the diagram, without requiring coincidence pulses.

A number of singles spectra were taken with each detector at various deuteron energies between 150 and 200 keV. Two main sets of coincidence data were taken, one for each target, in which the spectrum from detector A was gated with successively higher energy windows of the detector B spectrum. In addition, several runs were taken in which the spectrum from A (or B) was gated with the entire spectrum from detector B (or A). The chance spectra were secured by changing the time delay in one branch of the electronics by an amount sufficient to ensure that no true coincidences could occur. Thus, a simple channel by channel subtraction yielded the true coincidence spectra from the total (true plus chance).

IV. RESULTS AND ANALYSIS

Figure 3 shows some singles spectra obtained with the natural lithium target with $E_d = 170$ keV. The upper curve was obtained with the 90° detector, and the lower curve with the other detector, at 82°. Three peaks are very prominent in both spectra: the proton peak from $D(d,p)H^3$, and the alpha peaks from formation of He^5 in the ground state and from $Li^6(d,\alpha)\alpha$. These peaks were used for energy calibration of the spectrometers. (The energy scale indicated here and elsewhere refers to α-particle energies at the time of production.) A proton peak from the unresolved doublet $Li^6(d,p)Li^7$, Li^{7*} ($E_x = 0.461$ MeV) is clearly evident, and there is also a possible α peak indicative of an excited state in He^5 at about 2.6 MeV. The isolation of the $Li^6(d,\alpha)\alpha$ peak and therefore its usefulness for relative cross-section measurements is well illustrated.

Figure 4 shows two singles spectra obtained with de-

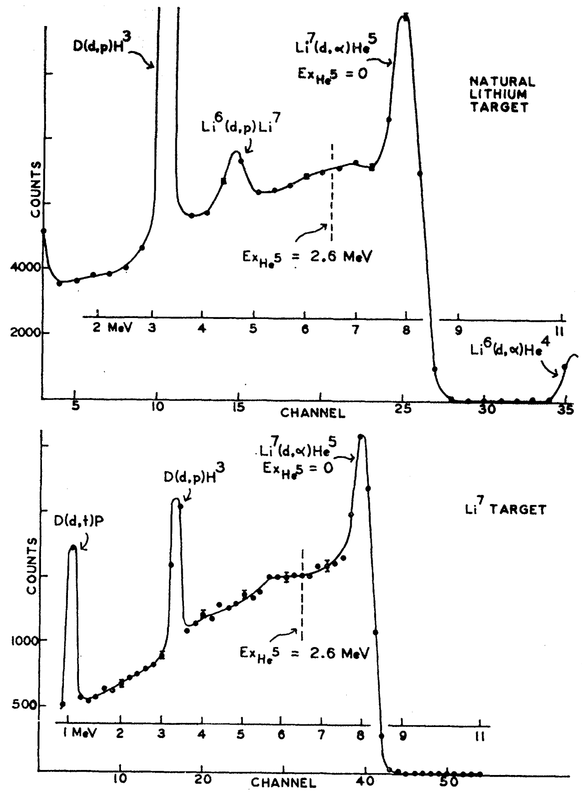

FIG. 4. Some singles spectra obtained with the 90° detector. The upper curve resulted from 170-keV deuterons incident on the natural lithium target, and the lower curve resulted from the Li^7 target with E_d=180 keV.

tector A. The upper curve was obtained with 170-keV deutrons incident on the natural lithium target. The lower curve resulted from 180-keV deuterons incident on the isotopic Li^7 target, and therefore neither the $Li^6(d,p)$ nor the $Li^6(d,\alpha)$ peak is present. These graphs have better statistics (hardly larger than the points for the top curve) than the previous ones, and there are still indications of inflexions in the spectra corresponding to a possible excited state of He^5 centered about E_x=2.6 MeV.

The coincidence data obtained with the Li^7 target are presented in Fig. 5. Each plot is the result of gating the spectrum of detector A (90°) with a portion of the energy spectrum of detector B. These data can be interpreted by referring to the calculated curves of Fig. 6 in which the possible laboratory alpha energies $E_{\alpha 1}$ and $E_{\alpha 2}$ (for the experimental geometry used) are shown plotted as functions of the excitation energy of the He^5 nucleus.

The solid curves of Fig. 6 refer to the situation when the α_1 (designated α_{1A}) from $Li^7(d,\alpha_1)He^5$ is detected at detector A at 90° in coincidence with α_2 (designated α_{2B}) at detector B at 82°. The dashed curves refer to the situation when the first α (designated α_{1B}) is detected at 82° in coincidence with $\alpha_2(\alpha_{2A})$ at 90°. The two different physical situations are illustrated schematically in the upper part of the figure. There are two α_{2A} and two α_{2B} curves because the disintegration α_2 particles can have two values of energy. The physical basis for this result is that for a given α_2 direction (with respect to the He^5 direction) in the laboratory system, there are two directions in the He^5 center-of-mass system which are consistent with the conservation laws. The curves of Fig. 6 show exactly what portion of the A spectrum should be in coincidence with a given window of the B spectrum (for a particular value of excitation energy). These values are of course smeared somewhat experimentally.

Run 1 (Fig. 5) has a gate consisting of the portion of the B spectrum between 5.0 and 5.7 MeV, corresponding to $E_{\alpha 2B}$ and $E_{\alpha 1B}$ between 5.0 and 5.7 MeV. The curves of Fig. 6 show that no coincidences due to the ground state (E_x=0) of He^5 are possible. However, the region of the A spectrum of run 1, Fig. 5, centered about 8.5 MeV, is seen to be in coincidence with this gate. Figure 6 shows that this peak must be attributed to α_{2A}-α_{1B} coincidences from the disintegration of an excited state of He^5 extending to possibly E_x=5 MeV. Continuation of this procedure led to the labeling of the peaks as shown in Fig. 5, and pointed to an excited state centered at about 2.6 MeV with a width of about 4 MeV.

The splitting of the peaks at the right-hand sides of runs 5 and 6 is statistically inconclusive, and it might be argued that what appears is merely one wide group. A

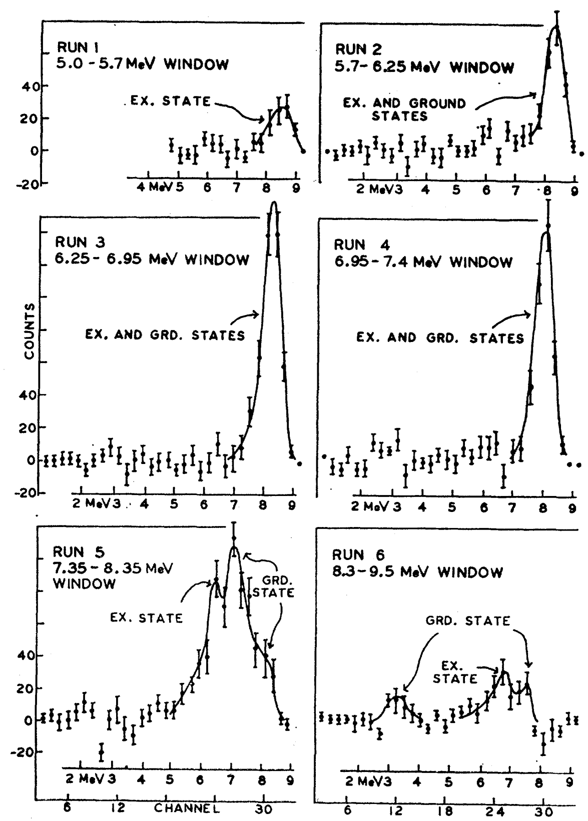

FIG. 5. Spectra taken at 90° gated by consecutive energy windows of the 82° detector over the range 5.0–9.5 MeV. 200-keV deuterons were incident on the Li^7 target.

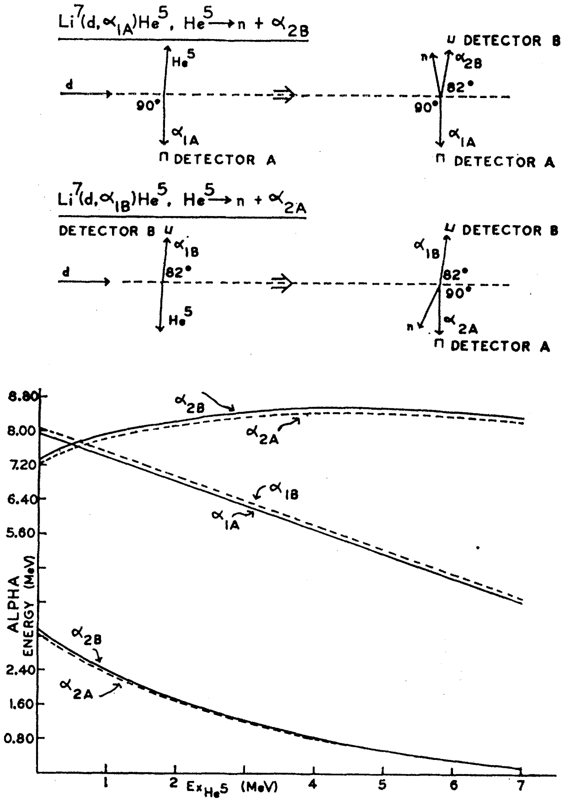

FIG. 6. Energetics of He^5 formation. The solid curves apply when α_1 is detected at 90° (detector A) in coincidence with α_2 at 82° (detector B). The dashed curves apply when α_1 is detected at 82° and the disintegration α_2 at 90°.

corresponding peak, completely unresolved, appears in each of the other spectra. The peak changes in intensity and shifts downward as the energy window is raised. In run 1 the peak is centered at about 8.5 MeV because only the excited state is contributing. By run 3 the peak is centered roughly halfway between 7.93 (the position of a peak indicative of the ground state) and 8.5 MeV because both states are contributing, and by run 6 the peak in question is gone altogether. In order to display this shifting of importance from the excited state to the ground state as the gate window is moved to higher positions of spectrum B, a different method was used to display the data. The number of counts appearing in each coincidence spectrum in the region of the 7.93–8.5 MeV peak was determined and plotted in Fig. 7 as a function of the window setting. The result shows with good statistics that there are two peaks present, indicative of two different states of He^5. (Runs 7 and 8 of Fig. 7 were obtained in the same fashion as Runs 1 to 6 of Fig. 5.)

Figures 8(a) and (b) illustrate the coincidence spectra obtained when the spectrum from detector B (A) was gated with the entire spectrum from detector A (B). The similarity of the two is clear, and several peaks can be identified easily. An analysis from this type of spectrum alone is ambiguous because of the uncertainty as to what part of the spectrum from one detector is in coincidence with a peak in the spectrum from the other detector. These spectra were obtained using the natural lithium target, so that some α-α coincidences from $Li^6(d,\alpha)\alpha$ were recorded.

In order to determine the relative strengths of the ground and excited states of He^5 and to obtain a better understanding of the data, additional analysis is required. This analysis commences with the determination of the shape of the α_2-particle distribution resulting from the breakup of He^5 in the ground state. This state is a $P_{3/2}$ configuration, which leads to a center-of-mass angular distribution of the form $f(\theta)=1+A\sin^2\theta$.[8,9,12] It may be shown from simple consideration of the velocity vector diagram describing the He^5 breakup that the function $f(\theta)$, when plotted as a function of $\cos\theta$, has the same shape as the laboratory energy distribution of α_2.[8] Thus, the shape of the laboratory energy distribu-

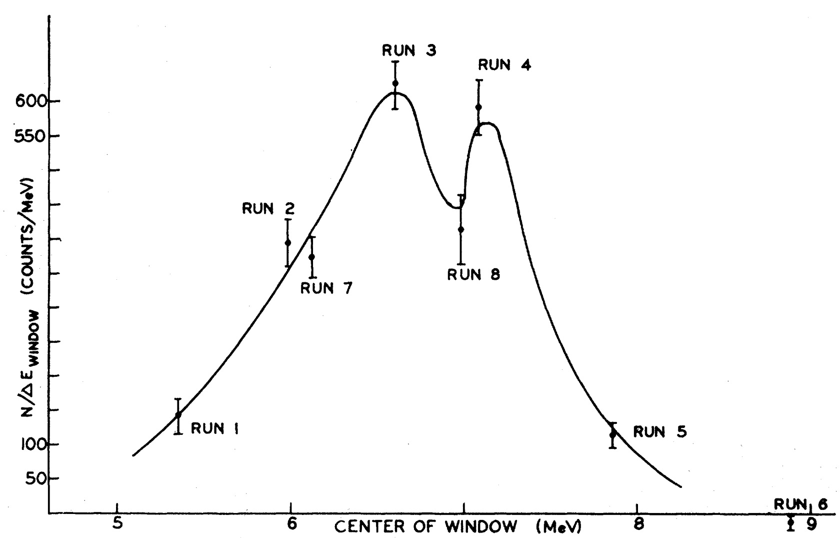

FIG. 7. Counts observed in high-energy portion of Fig. 5 coincidence spectra versus window setting.

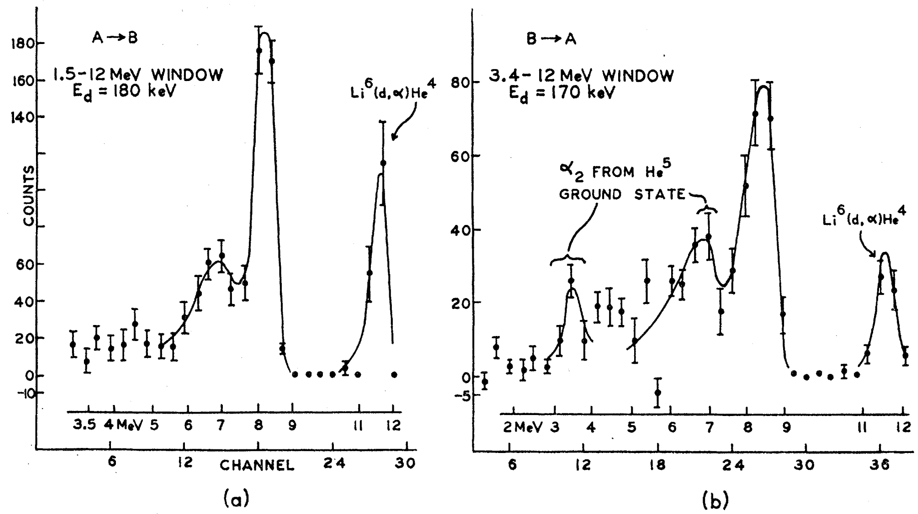

FIG. 8. Natural lithium coincidence spectra observed with maximum energy windows when (a) the 82° spectrum was displayed on the multichannel analyzer and (b) the 90° spectrum was displayed.

tion, which is a major component of a singles spectrum, will be known if the asymmetry parameter A can be determined. Figure 9(a) shows this shape dependence. The sharp energy cutoffs (which are smeared experimentally) at about 3.3 and 7.3 MeV are dictated by the energetics of the ground state $Li^7(d,\alpha_1)He^5$, $He^5 \rightarrow \alpha_2 + n$ process.

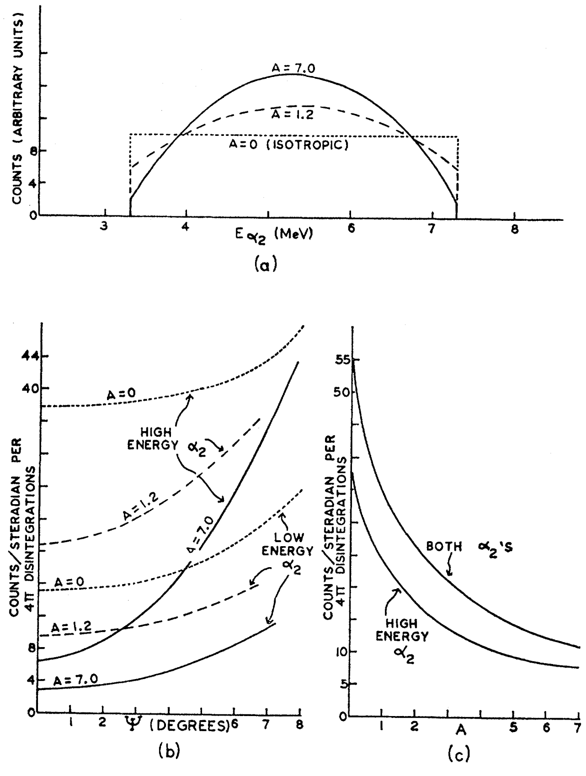

FIG. 9. (a) The dependence of the ground state α_2 energy distribution on the asymmetry parameter. (b) The coincidence detection efficiency for α_2 as a function of the laboratory angle Ψ between the He^5 and α_2 directions. (c) The coincidence detection efficiency for α_2 as a function of the asymmetry parameter.

When the He^5 breaks up, the disintegration α_2's are restricted to a forward cone in the laboratory system. The axis of this cone is the initial He^5 direction. The fraction of the α_2 particles detected in a coincidence experiment is dependent on three factors: the excitation of the He^5 (which determines the size of the disintegration cone), the laboratory angle Ψ between the He^5 direction and the direction of the detected α_2's and the value of the asymmetry parameter A. For the $P_{3/2}$ ground state, which has an A different from zero, the semiaxis of the α_2 cone is slightly greater than 11 deg, corresponding to a solid angle of 0.13 sr. The coincidence detection efficiency for ground state α_2's is illustrated in Figs. 9(b) and (c). Figure 9(b) shows the number of α_2's detected per steradian of detector for a total of 4π He^5 disintegrations, as a function of Ψ. Figure 9(c) shows the detection efficiency for the actual ground state Ψ (about 1.5 deg) as a function of the asymmetry parameter.

There is a direct correspondence between the singles spectra and the coincidence spectra. The number of ground state α_1's detected in a singles spectrum equals the number of He^5 nuclei traveling in a certain direction, a fraction of which are detected in a coincidence experiment by means of the disintegration α_2 particles. Since the angle Ψ is known, Fig. 9(c) may be used to yield the value of the parameter A once the ratio of the number of α_2's detected in a coincidence run to the number of α_1's detected in a singles spectrum is determined.

Similarly, the first excited state is a $P_{1/2}$ state and must lead to an isotropic distribution in this experiment, so the asymmetry parameter is known to be zero for this state.[8,12] Thus the detection efficiency as a function of He^5 excitation can be calculated.

The relative strengths of the two states may be determined from a knowledge of the detection efficiencies and the actual numbers of counts due to the individual states appearing in the coincidence spectra.

The starting point of the analysis consisted of making a reasonable estimate of the number of counts in the He^5

TABLE I. Asymmetry parameter for the ground state of He^5.

E_d (keV)	A	Reference
160	0.75 ± 0.05	Farley and White (Ref. 9)
170	$2.44^{+1.5}_{-1.0}$	Present experiment
900	7.0	Riviere (Ref. 12)
930	1.2 ± 0.1	French and Treacy (Ref. 8)

ground state α_1 peak appearing near 8 MeV in Fig. 4 (top curve). This number was then compared to the number of ground state α_2's appearing in the coincidence spectrum of Fig. 8(b). From the ratio of these numbers, numerical values were found for the detection efficiency and the asymmetry parameter (for the ground state). The coincidence data of Fig. 5 indicated how strongly the excited and ground states appeared, and hence the relative populations of the two He^5 states could be determined. The results were then used to reconstruct the singles and coincidence spectra, and an iterative procedure was followed to successively improve the input numbers and obtain a self-consistent interpretation of all of the spectra. (The shape ascribed to the ground state α_1 peak was based on the real level width of about 0.55 MeV[4] and on the experimental 3.5 MeV α peak from the $T(d,n)\alpha$ reaction which was used in preliminary tests. Paul and Kohler,[15] and Weber[13] have calculated this α_1-peak shape from an expression containing parameters empirically derived from p-α scattering analysis.[20] Their calculated shape agrees with the shape used here except for a low-energy tail in their shape which, if 100% authentic, would lead to 10 or 15% changes in the results of the present report. However, there is some uncertainty as to the complete validity of the parameters basic to the Paul and Kohler, and Weber calculation because these parameters include an assumption that the $P_{3/2}$-$P_{1/2}$ doublet is split by 5 MeV in both the mirror nuclei Li^5 and He^5. The uncertainty as to the correct shape to use for the α_1 distribution in question is the greatest source of error in our report.)

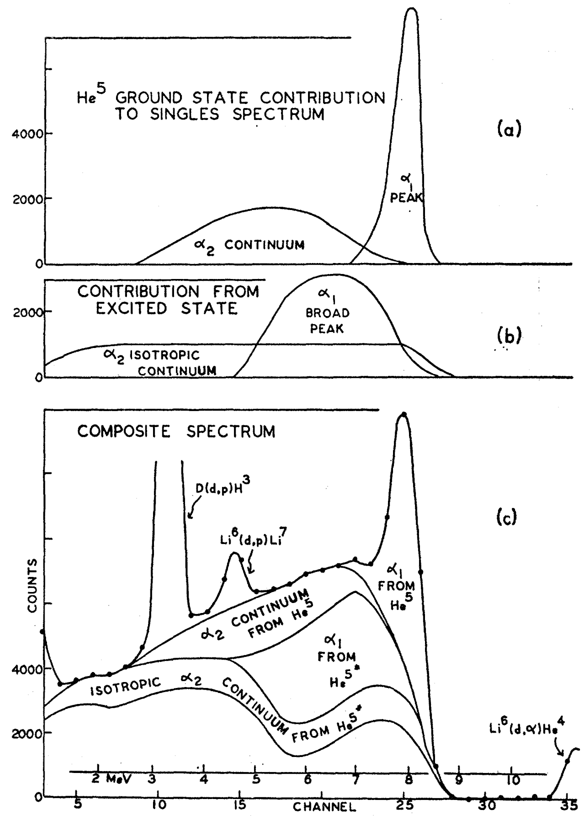

FIG. 10. Component analysis of the 90° detector singles spectrum of Fig. 4 (top curve). (a) and (b) show the separate contributions from the ground and excited states, respectively. (c) shows the experimental spectrum with the contributions indicated.

The results of the present analysis are presented in Tables I and II along with results from other workers. The value of A reported by us is within the range indicated by the previously reported values. The asym-

TABLE II. First excited state of He^5.

Reaction	E_x(MeV)	Γ(MeV)	Intensity relative to ground state	Reference
$Li^7(d,\alpha)He^5$	2.6 ± 0.4 (up to 7 MeV would have been observed)	4.0 ± 1.0	1.45 ± 0.50	present experiment
$Li^7(d,\alpha)He^5$	4.6[a]	≈3	<0.1 (assuming isotropy of ground state)	Hannah *et al.* (Refs. 14, 18)
$Li^7(d,\alpha)He^5$	≈2.6			Riviere (Ref. 12)
$Li^7(d,\alpha)He^5$	2.50 ± 0.2	1.5 ± 0.3	≈1	Cüer and Jung (Ref. 11)
$Li^7(d,\alpha)He^5$	≈2.5	broad		Jung and Cüer (Ref. 11)
$Li^7(d,\alpha)He^5$	?	≈1–2?		Weber (Ref. 13)
$Li^6(n,d)He^5$	inconclusive			Frye (Ref. 17)
$H^3(t,n)He^5$	≈2.6			Leland and Agnew (Ref. 16)
n-α scattering	≈5	<5		Adair (Ref. 5)
n-α scattering	≈2.6			Huber and Baldinger (Ref. 6)
n-α scattering	large	very broad		Seagrave and Austin *et al.* (Ref. 5)

[a] Hannah concluded later that this result was probably due to a broad excited state of Be^8 (Ref. 19).

[20] Robert K. Adair, Phys. Rev. 82, 750 (1951).

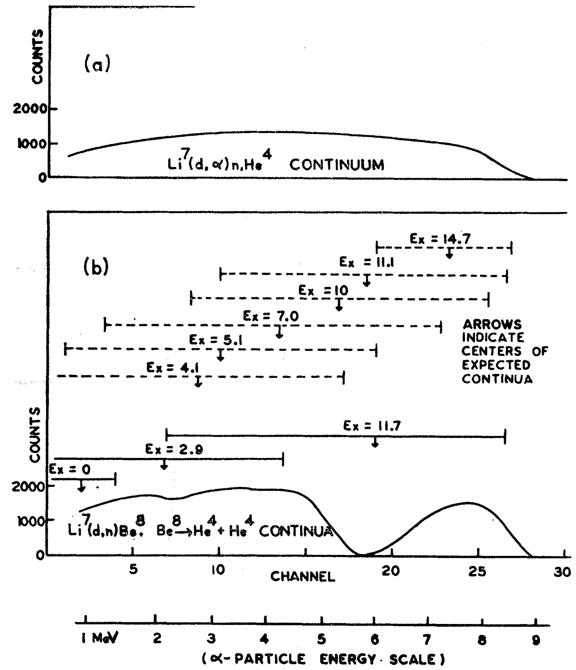

FIG. 11. Contributions to singles spectrum attributed to (a) $Li^7(d,n\alpha)\alpha$ and (b) $Li^7(d,n)Be^8$, $Be^8 \rightarrow \alpha + \alpha$.

metry parameter appears to be increasing with incident deuteron energy up to almost 1 MeV. Table II shows that the work of Cüer and Jung is in good agreement with our results.

Once the excitation energies, widths, asymmetry parameters, and relative intensities for the two He^5 states have been determined, one may construct the individual contributions to the singles spectra from the two α_1 peaks and the two α_2 continua. Figures 10(a) and (b) show the separate contributions from the ground and excited states, respectively, and Fig. 10(c) contains the actual experimental spectrum ($E_d = 170$ keV, 90° detector) with the contributions indicated. After these α groups have been subtracted there still remains a sizeable portion of the spectrum unaccounted for. This residue presumably must be attributed to alpha particles from the formation and subsequent decay of Be^8, and from the direct three-body breakup into two α's and a neutron. Such an interpretation indicates a differential cross section of 0.50 ± 0.13 mb/sr for these two processes together, which agrees within quoted errors with the reported values of[21] 0.54 ± 0.14 mb/sr and[22] 0.88 ± 0.44 mb/sr.

Figures 11(a) and (b) show an attempt to account for that portion of the alpha spectrum which is not associated with He^5 formation and decay. The residue of the spectrum of Fig. 10(c) is shown divided into contributions from the three-body breakup and from the $Li^7(d,n)Be^8$ reaction. The three-body distribution. [Fig. 11(a)] was derived from a calculation based on the assumption that the probability for a particular energy distribution is proportional to the corresponding volume in phase space.[23] The solid line brackets drawn in Fig. 11(b) represent the continua expected in a singles α spectrum from states of Be^8 that have been well established.[24] The dashed line brackets represent continua expected from states of Be^8 not well established, but reported from studies of the $Li^7(d,n)Be^8$ reaction.[25] The 11.7-MeV state in Be^8 is well established but has $J^\pi = 4^+$, and conservation of angular momentum forbids the formation of such a state in an experiment with low-energy incident (s-wave) deuterons. Accordingly, no substantial contribution from the decay of well-established levels of Be^8 would be expected at alpha energies near 6 MeV; this was the basis for the otherwise arbitrary relative weighting assigned to the $Li^7(d,\alpha n)He^4$ and $Li^7(d,n)Be^8$ reactions. The curves in Fig. 11(a) and (b) are presented only to show the plausibility of the statement that the portion of the singles spectrum of Fig. 10(c) which is not due to $Li^7(d,\alpha)He^5$, He^{5*} is contributed by α particles from $Li^7(d,n)Be^8$ and $Li^7(d,n\alpha)\alpha$.

The concidence spectra were analyzed as if they contained no contribution from states of Be^8, and there are several indications that this is a valid procedure. The reaction energetics dictate that only a fairly narrow (less than 1 MeV wide) state in Be^8 at about 14.5 MeV could lead to coincidences in the present experiment which might be misinterpreted as due to He^{5*} formation. Such a state would produce a relatively high intensity broad peak in the singles spectrum centered at 7.3 MeV, and Fig. 10(c) shows no such peak. Moreover, if a significant portion of the part of the singles spectrum attributed to He^{5*} formation were actually due to a 14.5-MeV state of Be^8, this state would be more predominant than either of the well-known ground or 2.9-MeV states of Be^8. This seems unlikely on the basis of experiments performed by Dietrich and Cranberg,[26] and by Riviere.[12] The first group searched for Be^8 states by observing the neutrons from $Li^7(d,n)Be^8$, but detected no states between $E_x =$ 2.9 and 16.64 MeV. Riviere studied the same reaction in such a manner than α-α coincidences would have been noticed for Be^8 excitation between 9.5 and 15.7 MeV. However, no groups indicative of Be^8 states were observed. (The incident deuteron energies for the experiments cited were 3.6–7.25 MeV and 900 keV, respectively, while that of the present experiment was 200 keV or less. The Q value for formation of a 14.5-MeV state in Be^8 is about 0.5 MeV.)

Similarly, the 2.5-MeV state in He^5 reported by Cüer and Jung[11] could, on the basis of energetics alone, be due

[21] N. Jarmie and J. D. Seagrave, Los Alamos Report 2014, 90, 1956 (unpublished).

[22] G. A. Sawyer and J. A. Phillips, Los Alamos Report 1578, 1953 (unpublished).

[23] O. C. Kolar, Phys. Rev. **122**, 139 (1961).

[24] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 44 (1959).

[25] F. Ajzenberg-Selov and T. Lauritsen, Nucl. Phys. **11**, 53 (1959).

[26] F. S. Dietrich and L. Cranberg, Bull Am. Phys. Soc. **5**, 493 (1960).

to a state in Be^8 of between 7- and 10-MeV excitation.[27] The fact that such a state of Be^8 could not lead to confusion in the present experiment, and that a 14.5-MeV state of Be^8 could not lead to confusion in the Cüer and Jung experiment, supports the unlikelihood that a state of Be^8 is responsible for the data interpreted here as evidence for the first excited state of He^5.

The analysis of the present experiment led to the determination of some relative cross sections. Figure 12 shows the differential cross section at 90° for $Li^7(d,\alpha)He^5$ (ground state). The numerical values are based on the previously measured cross section of the $Li^6(d,\alpha)\alpha$ reaction[28] which, in this experiment, was observed simultaneously with $Li^7(d,\alpha)$ in the natural lithium spectra. The curve, which is normalized to the data at 160 keV, was calculated from tables of Coulomb functions[29] and applies to the cross section for formation of the Be^9 compound nucleus. The Coulomb barrier for a deuteron incident on Li^7 is about 1 MeV. The only datum available for comparison is an approximate value (shown in brackets) obtained by Hannah at 120 keV.[14]

The natural lithium spectra also afforded measurements of the ratio of the cross section of the unresolved doublet $Li^6(d,p)Li^7$, Li^{7*} to the cross section of $Li^6(d,\alpha)\alpha$. The ratios obtained are presented in Table III and are compared with ratios based on reported cross section.[30] There is agreement well within reported errors.

TABLE III. $[\sigma(90°)Li^6(d,p)Li^7,Li^{7*}]/[\sigma(90°)Li^6(d,\alpha)\alpha]$.

E_d (keV)	Ratio of reported cross sections	Ratio from present experiment
160	2.2±0.6	1.9±0.5
170	2.1±0.6	1.8±0.4
200	2.0±0.6	2.3±0.6

[27] F. Ajzenberg-Selove and T. Lauritsen, Rev. Mod. Phys. **27**, 77 (1955).
[28] N. Jarmie and J. D. Seagrave, Los Alamos Report 2014, 99, 1956 (unpublished).
[29] A. Tubis, Los Alamos Report 2150, 1958 (unpublished).
[30] N. Jarmie and J. D. Seagrave, Los Alamos Report 2014, 95, 99, 1956 (unpublished).

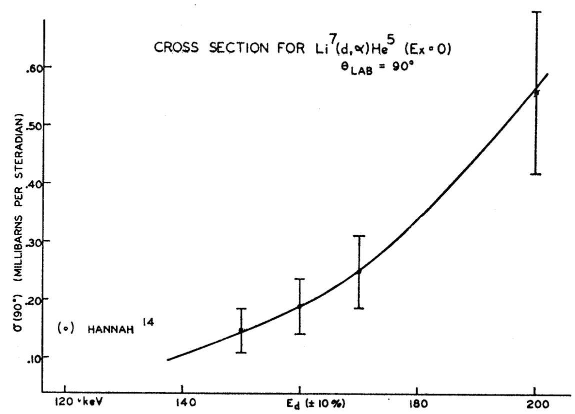

FIG. 12. Differential cross section for $Li^7(d,\alpha)He^5$ (ground state) at a laboratory angle of 90 deg. The curve, which is normalized to the data at 160 keV, is the theoretical cross section for formation of the Be^9 compound nucleus.

V. CONCLUSION

This experiment has shown that the first excited state of He^5 has an excitation and width as predicted by theory. The coincidence spectra show definitely that some state besides the He^5 ground state is present, and it is very unlikely that the main results of the experiment could be significantly affected by misidentification of alphas from Be^8. The analysis leading to the He^5 ground-state asymmetry parameter and the relative intensities of the He^5 α groups is very important, for it illustrates the nature of the singles spectra and explains how the excited state can be well populated but not immediately evident in the spectra. Without a detailed interpretation of the energy spectra, one might readily underestimate the intensity of the excited state alpha group, or even fail to recognize its presence. The lack of information in Table II concerning the relative intensity of the excited state is a reflection of the absence of such analysis in previous investigations.

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