(*a*) F_1. The values of F_1 in Table III are consistently lower than the experimental values, over the region of momentum transfer measured. Since the normalization is such that $F_1(0)=1$,[11] our wave functions are *too smooth*. With our present trial functions, this discrepancy is not significant.

(*b*) F_2. The values of F_2 given by ψ_1 are much too low; those given by ψ_2 are also much too low and have the wrong sign. Neither of these results is significant. The low magnitudes reflect the percentages of state 3 which we find; these are rather lower than the 4% required by Schiff to fit F_2. It is not clear whether a better trial function would increase the percentage of state 3; but, in any event, the discrepancies are of the general order of magnitude of the contributions expected from the D states. No significance can be attached to the sign of F_2 given by ψ_2. This wave function has the form $\psi_2=\alpha\psi_1+\beta\psi_{n+d}$, where ψ_{n+d} is constructed to represent loosely a neutron bound to a deuteron. The major contribution to state 3 in ψ_2 comes from ψ_{n+d}, and from the manner of construction of ψ_{n+d} its amplitude is *fixed* to be equal (and of opposite sign) to that of the state 1 part of ψ_{n+d}. Hence, the sign of F_2 has been essentially fixed in advance in this way.

[11] In Schiff's approximation. Actually $F_1(0)$ gives the probability of the principal S state.

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Be^9 States from the Reaction $Li^6(Li^7,\alpha)Be^9$†

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Li^6 and Li^7 ions accelerated to energies between 2.15 and 3.0 MeV were used to study the reaction $Li^6(Li^7,\alpha)Be^9$. Alpha particles were distinguished from other reaction products by a dE/dX-E system based upon a general-purpose digital computer. States were observed at 0.00, 1.75, 2.43, 3.04, and 11.9 MeV excitation in Be^9 in the presence of a very prominent continuum. The width of the 11.9±0.2-MeV state was measured at 500±100 keV. No other states up to an upper limit of 13.0-MeV excitation could be observed above the continuum. The yield of the 2.43-MeV state at 0° was found to have an energy dependence different from the ground and 3.04-MeV states. Angular distributions of the ground-state alpha particles obtained at Li^6 bombarding energies of 2.2 and 3.0 MeV were observed to be slightly energy-dependent.

INTRODUCTION

RECENT papers by Garin *et al.*[1,2] and Karadeny *et al.*[3] at Saclay, France, studying the alpha particles and neutrons from the reaction Li^6 on Li^7 at 1.8 MeV have concluded that the predominant reaction sequence contributing to the alpha-particle continuum is

$$Li^6+Li^7 \rightarrow \alpha_{I}+Be^{9*},$$
$$Be^{9*} \rightarrow \alpha_{II}+He^5,$$
$$He^5 \rightarrow \alpha_{III}+n.$$

It is postulated that α_I comes from a state in Be^9 having a Li^7+d character and an excitation of between 11 and 15 MeV. Garin *et al.*[1] have reported that they have been unable to observe this state directly due to the low energy of α_I, lack of particle identification, and the interference of the contamination reaction:

$$Li^6+p \rightarrow He^3+He^4+4.02\text{ MeV}.$$

In the present experiment the target and projectile have been interchanged to remove the contamination reaction products. A dE/dX and E detection system was employed to identify low-energy alpha particles.

In addition, energy spectra have been taken at 0° of alpha particles from the ground and first three excited states of Be^9 at Li^6 energies of 2.15, 2.6, and 3.0 MeV. Angular distributions of the ground state were obtained at 2.2 and 3.0 MeV.

EXPERIMENTAL

Lithium ions were accelerated by the State University of Iowa Van de Graaff. The momentum of the ions was determined by measuring the current applied to a bending magnet which deflected the beam through 25°. The beam was defined by a series of apertures which assured homogeneity of energy to 1%.

The relative angular distributions were measured with the target chamber shown in Fig. 1. The axis of the chamber is inclined at 20°30′ to the vertical, which allows rotation of the movable counter from 0° to 139°. A fixed monitor consisting of a solid-state detector is located at 90° to the beam path.

The particle identification system consisted of a

† Work supported in part by the National Science Foundation.
[1] A. Garin, C. Lemeille, L. Marquez, and N. Saunier, Phys. Letters 3, 299 (1963).
[2] A. Garin and L. Marquez, Colloque de Physique Nucleaire, Orsay, France, 1963 (unpublished).
[3] A. Karadeny and C. Lemeille, Colloque de Physique Nucleaire, Orsay, France, 1963 (unpublished).

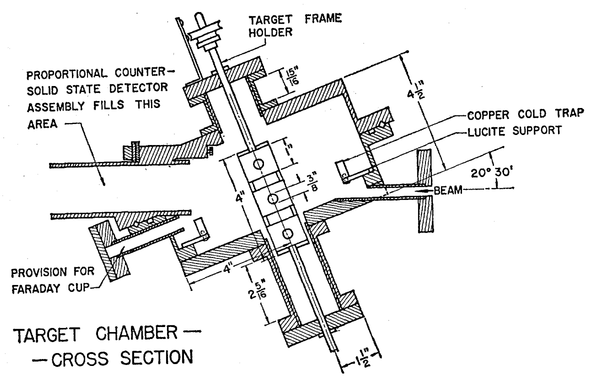


FIG. 1. Target chamber used for angular-distribution measurements.

cylindrical gas proportional counter which gave a pulse proportional to the energy loss (ΔE) of a charged particle traversing its length. The counter was filled with a 95% Ar−5% CO_2 mixture which could be varied in pressure from 2 to 14 cm Hg and was contained by a 0.0001-in. Mylar window. A solid-state detector subtending $\pm 3.5°$ and mounted inside the proportional counter was used to measure the energy (E) of the particles.

A schematic diagram of the system is shown in Fig. 2. Pulses from the E counter were used to gate the ΔE pulse so that an (E, ΔE) pair was recorded only when a particle arrived at the E counter. The pulses were each gated, amplified and analyzed in commercially available 256-channel pulse-height analyzers. The two pulse heights were stored in a Control Data Corporation 160-A computer until 64 events accumulated. The computer then recorded these pairs of 8 bit pulse heights on magnetic tape for permanent storage. These records were transferred to the tape units through a buffered channel so that no time was lost in the accumulation of data. A two-dimensional condensed 60×128 channel display of ΔE versus E was displayed during data accumulation.

Reduction of data was accomplished by calling a 60×128 channel matrix from magnetic tape into the computer memory. This matrix, consisting of either a condensed display of all the data or any block of the 256×256 channel data, was then displayed on an oscilloscope. A desired portion of the display was then marked by means of a light pen.

The light pen consisted of a photo diode (mounted in place of the ball-point in a ball-point pen) which was examined by the computer for a signal after points on the oscilloscope were displayed by the computer. If the pen was in a region of the display which was to be marked, the sign bit of the corresponding computer word was changed. The marked region was exhibited by sweeping the oscilloscope twice for every time the entire matrix was displayed. A marked region would be centered on an ionization curve for a particular type of particle. After the required region was marked it was then summed by means of the appropriate computer program to give an energy pulse-height distribution for a particular type of particle. The distribution was then punched on paper tape and typed out. Further details of the system have been discussed by Carlson and Norbeck.[4]

Targets were made from isotopically pure LiF evaporated on thin aluminum foils. The thickness of these targets was approximately 150-keV to 3-MeV Li ions. Foils of varying thicknesses were rotated in front of the proportional counter to stop elastically scattered beam.

The monitor detector was covered by a 2.2 mg/cm^2 foil and only pulses from particles with energy greater than 6 MeV were recorded.

In order to determine the high-energy alpha-particle spectrum more precisely, the counting rate was increased by using a single solid-state detector which subtended $\pm 5.5°$. This was mounted in a cylindrical chamber[4] at zero degrees in conjunction with a 100-keV thick target mounted on a 3.6 mg/cm^2 aluminum backing. The pulses were analyzed by means of a conventional 256-channel pulse-height analyzer.

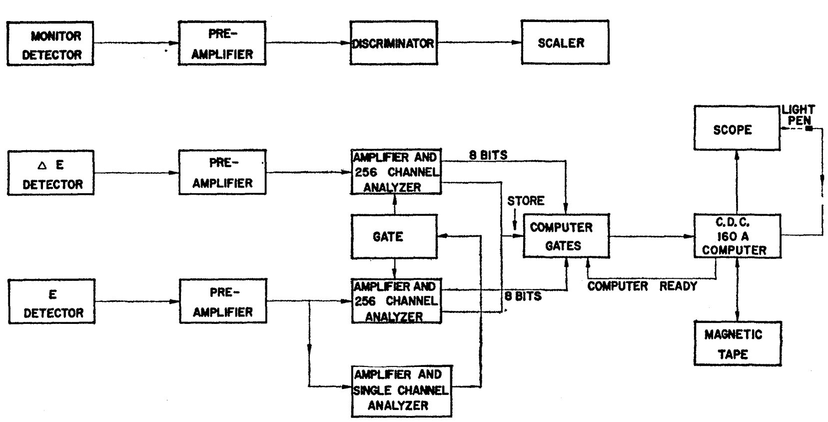


FIG. 2. Block diagram of electronics.

[4] R. R. Carlson and E. Norbeck, Phys. Rev. **131**, 1204 (1963).

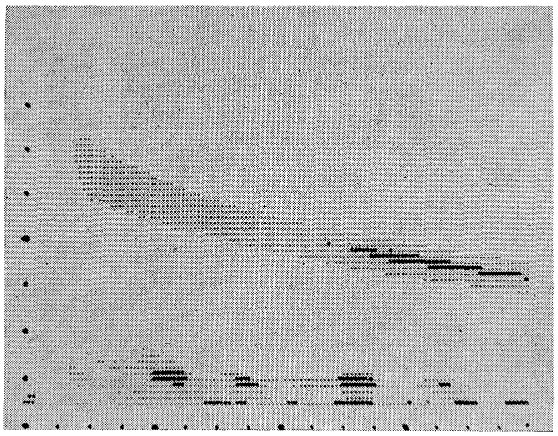


FIG. 3. Photograph of 60×128 channel oscilloscope display of E versus ΔE. High and low count contours are displayed by means of a double exposure.

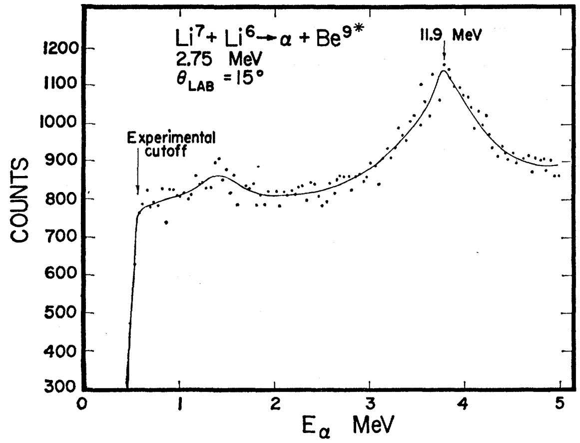


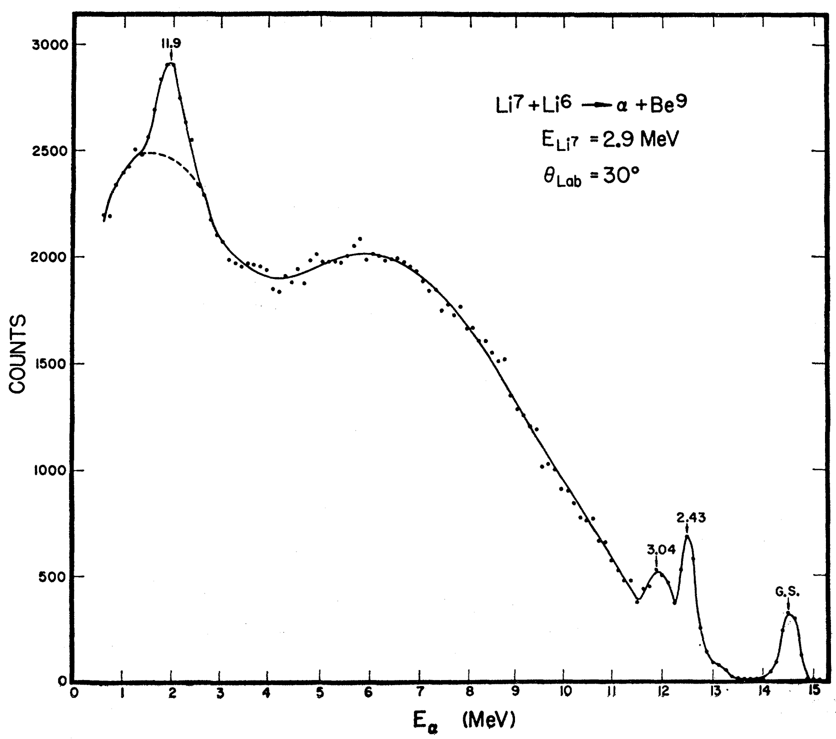
FIG. 4. Summed energy pulse-height distribution of alpha particles shown in Fig. 3. The E gain is highly expanded to show the region of the 11.9-MeV state in Be^9. The small peak just above cutoff may be due to unresolved He^3 from $Li^6(Li^7,He^3)Be^{10}$.

RESULTS

11.9-MeV State

Using the dE/dX and E system a peak in the alpha-particle continuum was observed which is believed to be due to a highly excited state in Be^9. Figure 3 shows a photograph of a condensed 60×128 channel oscilloscope display of ΔE versus E taken at $E_{Li^7}=2.75$ MeV and $\theta_{lab}=15°$, with a highly expanded E gain. Low and high contour levels are exhibited by means of a double exposure. Triton and deuteron peaks are seen in the lower ΔE channels. The summed alpha-particle pulse-height distribution is shown in Fig. 4. The excitation and width were determined from these data to be 11.9 ± 0.2 MeV and 500 ± 100 keV, respectively. Runs at 30° and 40° yielded results which are consistent with these values within experimental errors. At laboratory angles greater than 50° this group of alpha particles had too low an energy to be observable in the counter. Measurements at 15° (approximately 163° in the Li^7 on Li^6 barycentric system) from Li^6 bombardment of Li^7 at 2.35 and 2.90 MeV also yielded the same Q value and width for this peak. Thus, over a wide range of angles and bombarding energies the peak changed energy in a manner kinematically consistent with its interpretation as a state in Be^9.

FIG. 5. Complete alpha-particle energy pulse-height distribution showing states at 0.00-, 2.43-, 3.04-, and 11.9-MeV excitation in Be^9. The 1.8-MeV state cannot be seen here due to its very low yield.



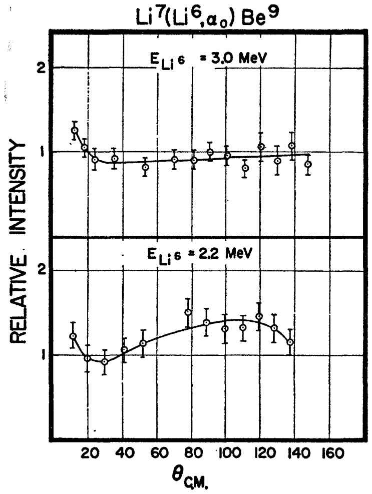


FIG. 6. Angular distribution of alpha particles from the ground state of Be^9 at 2.2- and 3.0-MeV Li^6 bombarding energy.

Figure 5 illustrates a complete alpha-particle spectrum taken at 30° at 2.90-MeV Li^7 bombarding energy. As can be seen, there are apparently no states other than the ground, second, and third excited, and the 11.9-MeV states that can be resolved above the prominent continuum. The states at 1.75 MeV (see Fig. 7) and 3.04 MeV have not been previously reported for this reaction.[1] It should also be noted that the yield of the 11.9-MeV state is small compared to that of the total continuum even though it is larger than that of any of the other Be^9 states. In this experiment, states with excitations as high as 13.0 MeV in Be^9 could have been observed. The best estimate by Garin *et al.*[2] for the excitation of the predicted states is 11.7 to 13.7 MeV.

The results of this experiment are in agreement with a recent study by Fisher and Whaling[5] of the states in B^9, the mirror nucleus of Be^9. Using the reaction $B^{10}(He^3,\alpha)B^9$, they found a state with an excitation of 11.62 MeV and a width of 700 keV. It seems likely that this is the mirror state of the 11.9-MeV state observed in this reaction. The $B^{10}(He^3,\alpha)B^9$ reaction also shows a strong continuum analogous to that seen in the present experiment.[6]

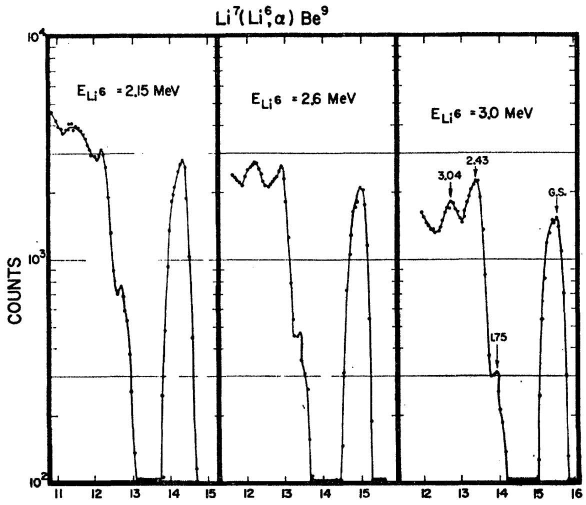


FIG. 7. Zero-degree energy spectra showing the 1.8-MeV state and the increase in the 2.43-MeV state relative to the ground state as the Li^6 bombarding energy is increased.

Low Excitation States

The angular distributions of the ground-state alpha particles are shown in Fig. 6. Comparison with the work of Huberman *et al.*[7] at a Li^6 bombarding energy of 1.8 MeV shows a consistent decrease of the peaking in the angular distribution as the bombarding energy is increased.

Zero-degree spectra (Fig. 7) at 2.15-, 2.6-, and 3.0-MeV Li^6 bombarding energies show a systematic increase in the 2.43-MeV state relative to the ground state. As most of the continuum appears to extrapolate to an energy near the $\alpha+\alpha+He^5$ continuum end point (see Fig. 5) which corresponds to an excitation in Be^9 of 2.62 MeV, the peak height gives a fairly good indication of the intensity of the 2.43-MeV state. The yield of the 2.43-MeV state at zero degrees increases by a factor of 1.4 relative to the ground state as the center-of-mass energy is raised from 1.1 to 1.6 MeV.

The presence of a small peak at 1.8-MeV excitation was observed. This is believed due to the reported state at 1.75 MeV. The interpretation of this state is still uncertain.[8,9]

CONCLUSIONS

A state at 11.9±0.2-MeV excitation with a width of 500±100 keV was observed. As the yield of this state relative to the continuum was small at several forward and one backward angle, it is believed to make only a small contribution to the total continuum of alpha particles. It is thus concluded that modes other than the $Be^9+\alpha$ are predominant. As these exit channel modes are numerous and may contribute to varying degrees, no attempt has been made to fit the continuum.

The angular distributions of the ground-state alpha particles from Be^9 were observed to change somewhat with energy. In addition, the 2.43-MeV state was found to increase relative to the ground state with increasing energy. These variations cannot be explained by Coulomb effects in the outgoing channel because of the high-Q value. Tunneling effects in the incoming channel could account for these variations since the ground and first excited states have different spins and parities, and different l values may become important as the energy is changed.

[5] T. R. Fisher and W. Whaling, Bull. Am. Phys. Soc. **8**, 600 (1963).

[6] L. G. Earwaker, J. G. Jenkins, and E. W. Titterton, Nucl. Phys. **46**, 540 (1963).

[7] M. N. Huberman, M. Kamegai, and G. C. Morrison, Phys. Rev. **129**, 791 (1963).

[8] F. C. Barker and P. B. Treacy, Nucl. Phys. **38**, 33 (1962).

[9] R. Spencer, G. C. Phillips, and T. E. Young, Nucl. Phys. **21**, 311 (1960).

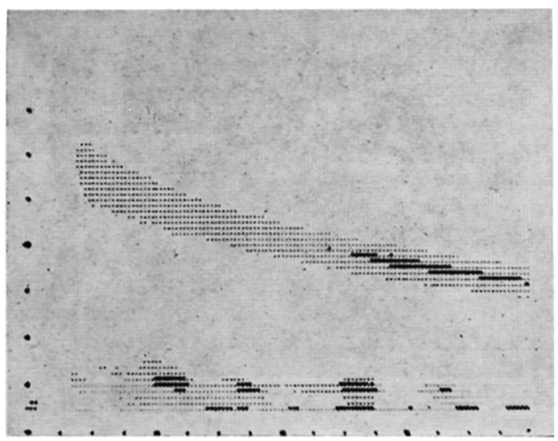


FIG. 3. Photograph of 60×128 channel oscilloscope display of E versus ΔE. High and low count contours are displayed by means of a double exposure.