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Search for Excited States of ^{6}He

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The excitation spectrum of ^{6}He has been examined through measurements of charged-particle energy spectra from four nuclear reactions. Triton energies up to 22 MeV were used to induce the ^{7}Li(t, α)^{6}He, ^{4}He(t,p)^{6}He, and ^{6}Li(t, ^{3}He)^{6}He reactions. Deuterons of 16- and 22-MeV energy were used to induce the ^{7}Li(d, ^{3}He)^{6}He reaction. All of the energy spectra show peaks from the ^{6}He ground and first excited (1.80-MeV) states, but no other structure attributable to states of ^{6}He was observed. Differential cross-section data for the ground and first excited states were obtained for three of the reactions. The (d, ^{3}He) cross-section data were compared with the results of distorted-wave Born-approximation calculations and with data collected from the ^{11}B(d, ^{3}He)^{10}Be reaction. These comparisons were consistent with an assignment of 2^+ for the ^{6}He 1.80-MeV state.

INTRODUCTION

The situation with respect to $T=1$ levels in $A=6$ nuclei has been in a state of controversy for an extended period of time. At present the ground and first excited states of ^{6}He and ^{6}Be as well as their analogs in ^{6}Li are well established. However, the reality of $T=1$ levels at higher excitation energy is uncertain, although the existence of many such levels has been reported on the basis of experiment and proposed on the basis of theory. While the results of some experimental searches for higher $T=1$ states have suggested their existence, other searches have had negative results. We shall review some of the previous experimental work on higher $T=1$ states, beginning with experiments which observe the spectrum of ^{6}He.

Early work[1] with the ^{7}Li(t,α)^{6}He reaction indicated the existence of a second excited state of ^{6}He at 3.4 MeV. Later results[2] from the same reaction indicated a state of 9.3 MeV and possibly a state around 6 MeV. An experiment[3] based on the ^{9}Be(n,α)^{6}He reaction suggested states at 3.29 and 6.05 MeV, although the detected particles were not identified and there may have been some confusion from the contribution of ^{6}He ions to the spectra. Subsequent work[4] with the (n,α) reaction was compatible with states at 3.4 and 6.0 MeV. A high-resolution experiment[5] based on the ^{7}Li(t , α)^{6}He reaction established the position and width of the first excited state, but no higher excited states were observed up to an excitation energy of 12 MeV. States at 13.4 and 15.3 MeV have been reported[6] from observations of the summed proton energy spectra from the ^{7}Li($p,2p$)^{6}He reaction.

In ^{6}Li both members of the lowest two $T=1$ triplets are well known (3.562 and 5.36 MeV). However, no other higher $T=1$ states have been definitely established.[7-9] In ^{6}Be there have been many states reported at excitation energies greater than 2 MeV. A series of ^{6}Li(p,n)^{6}Be experiments[10] from the Rutherford Laboratory first reported eight states above 2 MeV in ^{6}Be, later only two states, and finally one state at 3.47 MeV. Based on data from the ^{4}He(^{3}He,n)^{6}Be and ^{6}Li(p,n)^{6}Be reactions, a Livermore group[11] observed no levels of ^{6}Be between 2 and 5.5 MeV, whereas a Brookhaven experiment[12] using the ^{6}Li(^{3}He,t)^{6}Be reaction resulted in a statistically doubtful suggestion of a level at 3.0 MeV. A (^{3}He,t) experiment[13] which extended the observed range of excitation energy up to 12 MeV resulted in no evidence for states above 2 MeV, while a later (p,n) experiment[14] showed evidence for a state at 3.0 MeV. A Minnesota group[15] used the (^{3}He,t) reaction with counter telescope detection to observe a range of ^{6}Be excitation energy up to 11 MeV. In a separate experiment[16] a magnetic spectrometer was used to search the range 1.89 to 2.33 MeV with high resolution. Their final conclusion was that no states except the ground and first excited had been observed. Analysis of ^{3}He + ^{3}He elastic scattering data[17,18] gives evidence for a broad $l=3$ resonance above 15 MeV. Finally, a series of experiments[19,20] at Seattle searched for new states in ^{6}He, ^{6}Li, and ^{6}Be. No new $T=1$ levels were observed in the six different reactions used.

Theoretical predictions for $A=6$ nuclei fall into two general categories. First, we summarize the shell-model calculations[9,21-26] of normal parity states which use the α-particle core plus two nucleons as a basis. Relative to the ground state of ^{6}He, these predictions place the second excited level ($J^\pi=2^+$, $T=1$) at various positions as follows: 7.0 MeV,[22] 4.2 MeV,[23] greater than 3.7 MeV,[24] about 5.6 MeV,[25] about 5.4 MeV,[9] and at 6.8 MeV.[26] A particle-hole calculation[27] resulted in a lowest odd-parity state at about 10 MeV in ^{6}He.

The other method of predicting the position of $A=6$ levels is based on resonating group calculations. In ^{6}He, for example, levels with a predominate triton-plus-triton cluster structure are expected. The "bound" triton cluster levels predicted[28] to lie below the two-triton mass ($E_x=12.3$ MeV) are a ^1S level at 3.2 MeV, and a ^1D level at 6.2 MeV. Based on scattering data, predictions[29] of unbound resonances are also made: a ^3P level at 18.1 MeV, and a ^3F level at 25.6 MeV. It is suggested[29] that the state[6,7] reported at ~15 MeV with $J^\pi=1^-$ or 2^- may correspond to the $^3P_2$ or $^3P_1$ component of the predicted ^3P level.

The purpose of the present experiment was to search for states above the first excited state of ^{6}He. In addition, differential cross-section measurements were made of the ground and first excited states. Four nuclear reactions which produce ^{6}He as a residual nucleus were induced with particles of various energies including the highest available from the Los Alamos three-state tandem accelerator. This enables a search for new states throughout a large range of ^{6}He excitation energy. Two of the reactions, ^{7}Li$(t,\alpha)^6$He and ^{7}Li$(d,{}^3$He$)$-^{6}He, have previously been used[7] with lower energy beams of tritons and deuterons. The other two reactions, ^{4}He$(t,p)^6$He and ^{6}Li$(t,{}^3$He$)^6$He, have not been reported, although we recently learned of an initial ^{3}H$(\alpha,p)^6$He experiment[20] which made use of a tritiated titanium target and consequently has a higher background than the present (t,p) experiment in which a gas target was used. The (t,p) reaction should be useful in the search for higher $T=1$ states, since two-nucleon stripping reactions are expected to populate such states more effectively than reactions which transfer one nucleon.[20] In the search for triton-plus-triton cluster states, use of the ^{6}Li$(t,{}^3$He$)^6$He reaction is attractive in that the mechanism should be favorable to the formation of such configurations. This is based on evidence that the ground state of ^{6}Li has a substantial $t+{}^3$He component.[30]

APPARATUS AND PROCEDURE

The Los Alamos three-stage tandem accelerator was used to produce deuteron or triton beams of various energies up to 22 MeV. The accelerated particles passed through a magnetic analyzing system and a series of collimators before entering a 20-in. scattering chamber which had the target at its center. The ^{7}Li target material was enriched to 99.99% ^{7}Li, and the ^{6}Li was enriched to 95.63% ^{6}Li. These targets which had thicknesses in the range 270–400 μg/cm^2 were evaporated onto a substrate from which they were stripped. A thinner foil consisting of 135 μg/cm^2 of ^{7}Li on a 50-μg/cm^2 carbon backing was used for part of the experimental work. From the many sets of data taken with lithium targets it was found that they all contained impurities of ^{1}H, ^{12}C, and ^{16}O, but no evidence for nitrogen impurities was observed. The boron target consisted of a self-supporting foil 180 μg/cm^2 thick, enriched to 98.55% ^{11}B. When ^{4}He was used as a target, it was contained in a gas cell which had a 25-μm-thick Be entrance window and a 12-μm Be exit window.

For detection of the charged particles (^{1}H, ^{3}He, and ^{4}He ions) from the four reactions a ΔE-E-reject counter telescope was used. This system which contains a gas ΔE proportional detector and silicon E and R detectors has been described elsewhere.[31] Coincident ΔE and E pulses which had no accompanying R pulse were amplified and fed into separate analog-to-digital converters and then into an on-line SDS-930 computer. The computer permitted the ΔE-E pulse pairs to be recorded on magnetic tape and also allowed the collected data to be displayed in a 64×128 channel array. In addition, a parallel electronic system containing an analog particle identifier and a 400-channel pulse-height analyzer monitored the course of the experiment. Curve fitting techniques were used off-line to analyze the ΔE-E data. This procedure produced $E+\Delta E$ spectra for the various reaction particles.

EXPERIMENTAL RESULTS

A. ^{7}Li$(t,\alpha)^6$He Reaction ($Q_0=+9.83$ MeV)

Data were collected at triton energies of 16, 18, 20, and 22 MeV and at laboratory scattering angles of 10, 15, 20, and 30°. In addition, at $E_t=22$ MeV spectra were obtained at 10 angles between 8 and 90°. A carbon target was used to obtain α-particle spectra in order to establish the calibration of the energy scale. Portions of the ^{7}Li$(t,\alpha)^6$He data are shown in Figs. 1–4. Peaks corresponding to the ground and first excited state of ^{6}He are present in all spectra. The spectra also contain peaks from the carbon contaminant. The carbon contaminant situation is quantitatively illustrated by Fig. 3 in which the spectrum from a carbon target is normalized to the amount of carbon present on the ^{7}Li target. This shows that the ^{7}Li$(t,\alpha)^6$He spectrum is not appreciably affected by the carbon impurity for α-particle energies less than 18 MeV. A pair of arrows is associated with each spectrum of Figs. 1 and 2. These arrows are chosen to be at the centers of two peaks in the $E_t=22$ MeV, $\theta=10°$ spectrum corresponding to ^{6}He excitation energies of 14.8 and 16.7 MeV. The arrows associated with the remaining spectra in Figs. 1 and 2 correspond to these same two excitation energies.

Although the excitation energy of the peaks of Fig. 1 appear to be rather invariant to changes of scattering angle, the peaks of Fig. 2 move with respect to the arrows as the beam energy is changed. In this way we conclude that these peaks do not arise from states of ^{6}He but probably result from the breakup of the first excited state of ^{6}He into $\alpha + 2n$, or alternatively from the ^{7}Li(t,^{8}Be)$2n$ reaction with ^{8}Be in the 2.90-MeV state breaking up into $\alpha + \alpha$. This interpretation is consistent with the results of kinematic calculations applicable to these breakup modes.

In the α-particle spectrum taken at $\theta = 10°$ there is an instrumental cutoff at approximately 6 MeV. This occurs when α particles have less than enough energy to penetrate the ΔE detector and consequently do not produce a ΔE-E coincidence. The ^{6}He excitation energy at which this occurs is about 24 MeV. From the above discussion we conclude that throughout this range the ground and first excited states are the only structure which can be definitely attributed to ^{6}He. However, since the region around 14 MeV is obscured by breakup α particles, our observations may be compatible with the existence of previously reported states[6] at 13.4 and 15.3 MeV. Figure 4 shows the differential cross section for the ^{7}Li(t, α)^{6}He ground- and first-excited-state reactions. Both the 0^+ ground state and the first excited state, which has previously been assigned[7] a spin-parity of $(2)^+$, can be reached through an $l = 1$ pickup. The

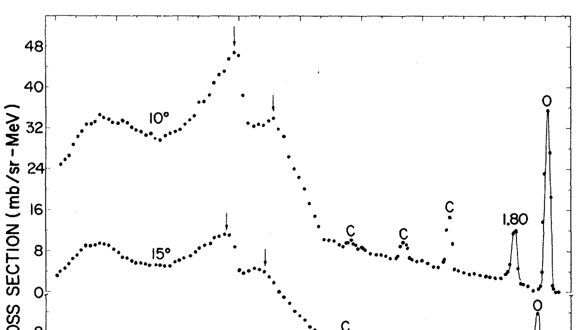

FIG. 1. α-particle energy spectra from the ^{7}Li(t, α)^{6}He reaction observed at four scattering angles and with a triton energy of 22 MeV. Peaks from the ground state (0) and the first excited state (1.80) of ^{6}He are present in all spectra. Peaks from the carbon impurity in the target are designated by the letter C. The significance of the arrows is discussed in the text.

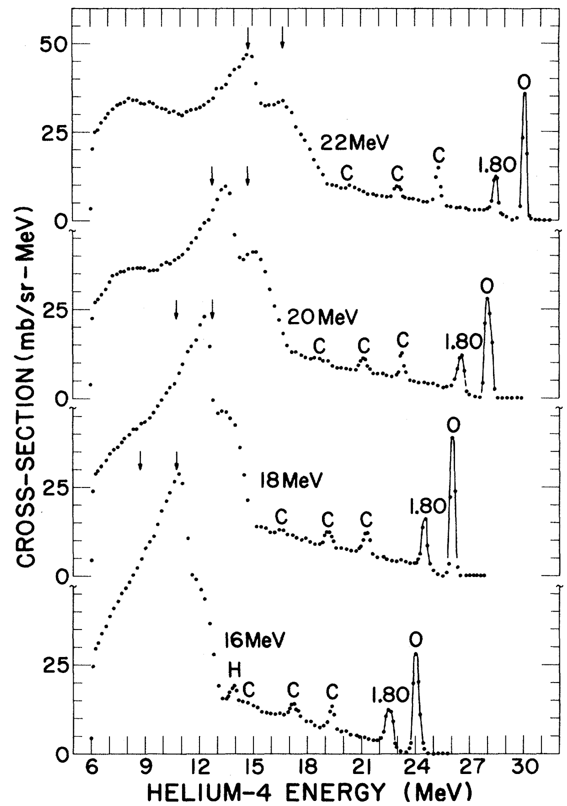

FIG. 2. α-particle energy spectra from the ^{7}Li(t, α)^{6}He reaction observed with four triton beam energies and a scattering angle of 10°. Peaks from the ground state (0) and the first excited state (1.80) of ^{6}He are present in all spectra. Peaks from the carbon impurity in the target are designated by the letter C. The significance of the arrows is discussed in the text.

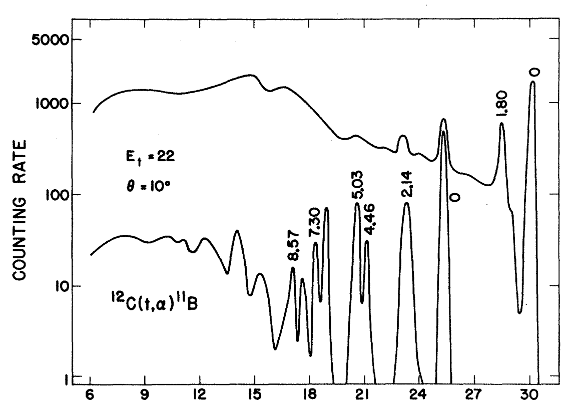

FIG. 3. Spectra showing the contribution of the carbon target impurity to the measured ^{7}Li(t, α)^{6}He spectra. Below an α-particle energy of 18 MeV the effect of the impurity is negligible.

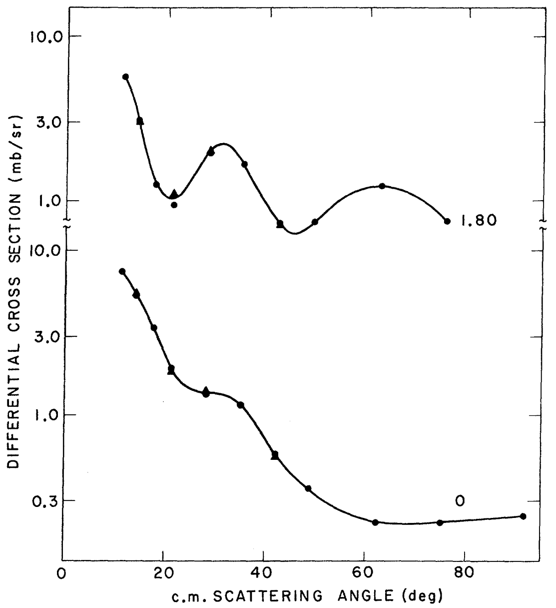

FIG. 4. Differential cross sections of the ground state (0) and first excited state (1.80) from the ^{7}Li$(t, \alpha)^6$He reaction. The circles are relative measurements and the triangles are the results of a separate data run used to obtain an absolute value of the cross section. As a guide to the eye a smooth curve has been drawn through the experimental points.

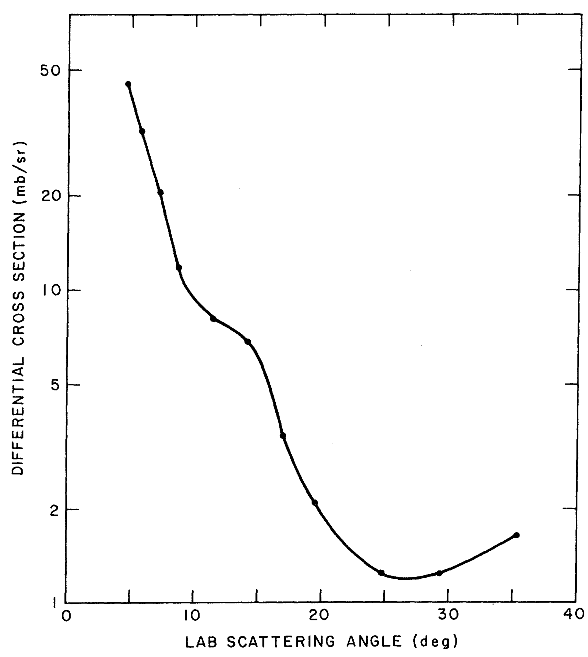

FIG. 5. The results of transforming the ground-state data of Fig. 4 to represent the lab cross section for the ^{4}He(^{7}Li, ^{6}He)^{4}He reaction induced by 51.2-MeV ^{7}Li ions. As a guide to the eye a smooth curve has been drawn through the experimental points.

similar shape of the two distributions of Fig. 4 is consistent with a 2^+ assignment of the 1.80-MeV state.

The ^{3}H(^{7}Li, ^{6}He)^{4}He reaction offers a method to produce a beam of ^{6}He ions. Such a beam would be very useful in reaching neutron-rich nuclei through the (^{6}He,p) or other reactions. The cross-section data of Fig. 4 correspond to the use of 51.2-MeV ^{7}Li ions bombarding a tritium target producing ^{6}He at forward scattering angles. For use in estimating the beam intensity of ^{6}He ions produced by this process we have transformed the cross-section data of Fig. 4. Figure 5 shows the lab differential cross section for the ^{3}H(^{7}Li, ^{6}He)^{4}He reaction induced by 51.2-MeV ^{7}Li ions. At small scattering angles, ^{6}He ions with a lab energy of 61 MeV would be produced.

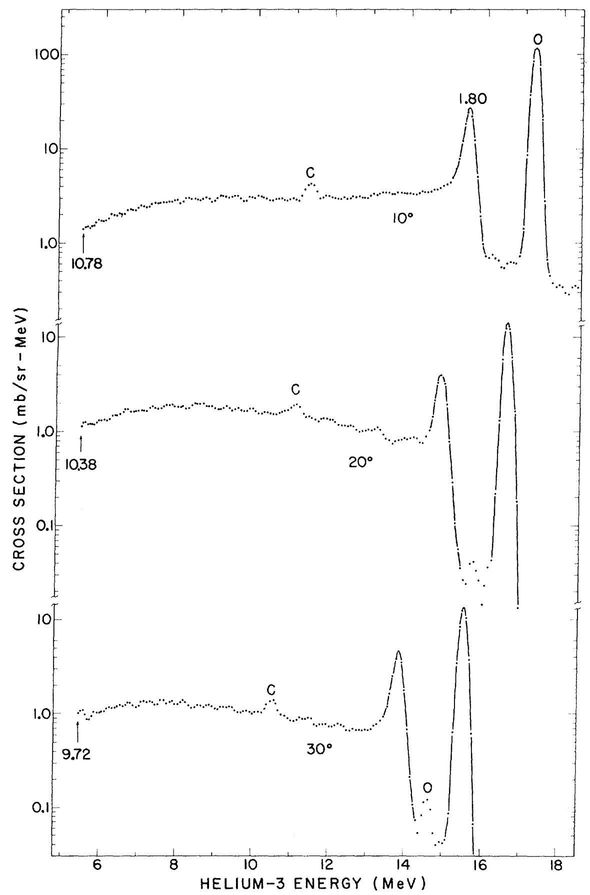

FIG. 6. ^{3}He energy spectra from the ^{7}Li(d, ^{3}He)^{6}He reaction observed at three scattering angles. Peaks arising from the carbon contaminant in the target are designated by the letter C, and in the 30° spectrum a peak from the oxygen impurity is designated by the letter O. The instrumental cutoffs at low ^{3}He energy are labeled with the corresponding ^{6}He excitation energies.

B. ^{7}Li(d, ^{3}He)^{6}He Reaction ($Q_0 = -4.49$ MeV)

The ^{7}Li(d,^{3}He)^{6}He, as well as the two reactions reported in Secs. C and D, have the advantage that there is no contribution to the observed spectra from the breakup of the residual nucleus ^{6}He until excitation energies greater than 20 MeV are reached. With a deuteron beam energy of 22 MeV, spectra from the ^{7}Li(d,^{3}He)^{6}He reaction were observed at 20 scattering angles between 8 and 70°. Figure 6 shows spectra at 10, 20, and 30°. The ^{6}He ground and first excited states are prominent in each spectrum. The small peaks labeled C and O arise from carbon and oxygen target impurities. No higher excited states of ^{6}He are observed in these spectra which cover a range of ^{6}He excitation energy up to 10.7 MeV. ^{3}He energy spectra from the ^{7}Li(d,^{3}He)^{6}He reaction were also measured at 11 angles between 16 and 60° with a deuteron beam energy of 16 MeV. These spectra also provided no evidence for new states of ^{6}He.

The ^{7}Li(d,^{3}He)^{6}He reaction permits both the 0^+ ground state and the previously assigned[7] $(2)^+$ first excited state to be produced through an $l=1$ process. Figure 7 shows the ground-state angular distribution compared with $l=0$, 1, 2, and 3 curves obtained with the distorted-wave Born-approximation (DWBA) code JULIE.[32] The optical-model parameters used for the ^{7}Li$+d$ input channel were based upon our use of the PEREY code[33] to fit ^{9}Be$+d$ elastic scattering data[34] taken at $E_d = 24$ MeV. The parameters used in the ^{3}He$+^6$He channel were estimated from parameters extract-

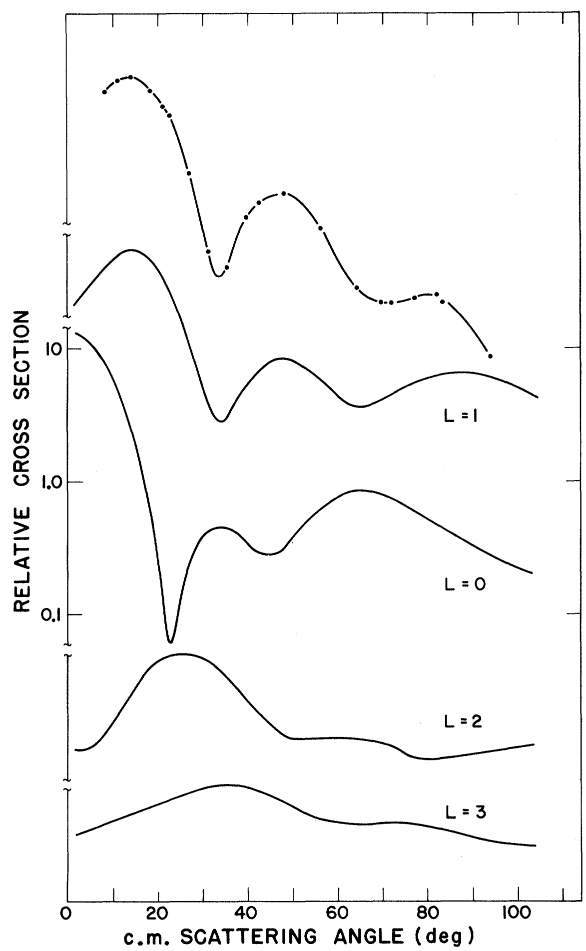

FIG. 7. Angular distribution for the ^{7}Li(d, ^{3}He)^{6}He ground-state reaction. The points are the results of measurements while the lower four curves are the results of DWBA calculations. As a guide to the eye a smooth curve has been drawn through the experimental points.

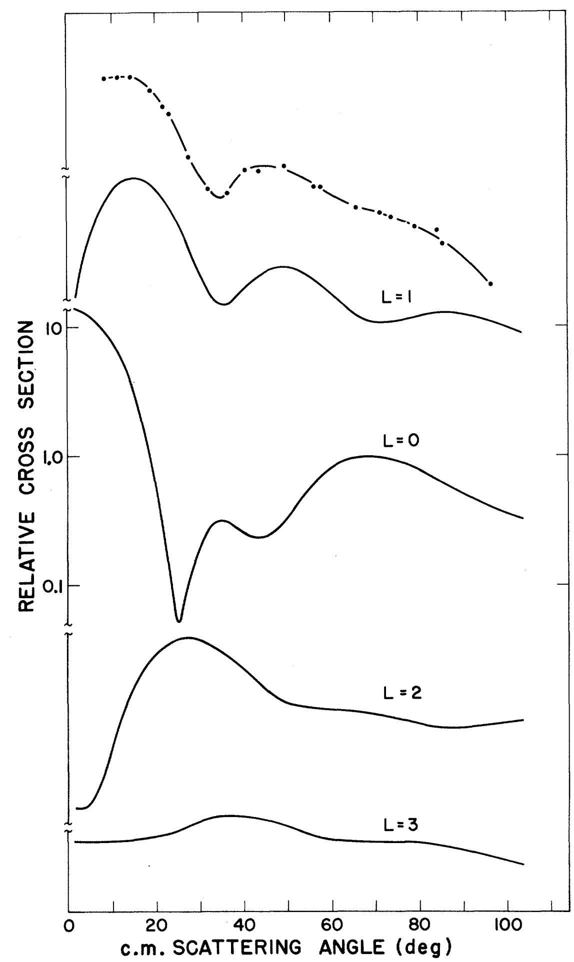

FIG. 8. Angular distribution for the ^{7}Li(d, ^{3}He)^{6}He first excited state. The points are the results of measurements while the lower four curves are the results of DWBA calculations. As a guide to the eye a smooth curve has been drawn through the experimental points.

ed from ^{3}He elastic scattering measurements[35] involving nuclei with $A \simeq 50$. These calculations are intended as qualitative guides only, and no attempt was made to obtain exact fits to the data. The experimental curve is clearly in best agreement with the $l=1$ DWBA curve. Likewise, Fig. 8 shows the angular-distribution data for the first excited state of ^{6}He. Here, also, the $l=1$ DWBA curve is similar to the data and is consistent with a 2^+ assignment. In order to obtain a direct experimental comparison to the ^{7}Li(d, ^{3}He)^{6}He angular distribution, data were obtained from the ^{11}B(d, ^{3}He)^{10}Be reaction at the same deuteron beam energy. The target in both reactions is known to be $\frac{3}{2}^-$ and the Q values are rather similar. The ground states of the final nuclei are both 0^+ and the first excited state of ^{10}Be is known to be 2^+. The data in Fig. 9 show that the differential cross sections all have a similar shape, which again is consistent with ^{6}He (1.80) having a 2^+ assignment.

C. ^{4}He(t, p)^{6}He Reaction ($Q_0 = -7.51$ MeV)

Data from the ^{4}He(t,p)^{6}He reaction have not previously been reported, probably because of the high triton energy required. In spite of the large c.m. effect and negative Q value a 22-MeV triton beam permits a study of ^{6}He excitation spectra up to about 5 MeV. Particularly attractive is the expectation that the reaction mechanism will be favorable[20] to the formation of many predicted excited states of ^{6}He.

A gas ^{4}He target was bombarded with 22-MeV tritons, and proton energy spectra were measured at 21 scattering angles in the range 8 to 55°. These measured spectra were all plotted on the same scale of excitation energy, assembled in a columnar array, and carefully examined for any structure which might indicate new states of ^{6}He. Although minor variations were present, no consistent structure was present at a constant excitation energy. Representative proton energy spectra are shown in Fig. 10. Figure 11 is the measured differential cross section for the ground and 1.80-MeV states. DWBA calculations for the ground state were made with the code CJULIE.[36] The shape of the $l=0$ curve resembled the measured

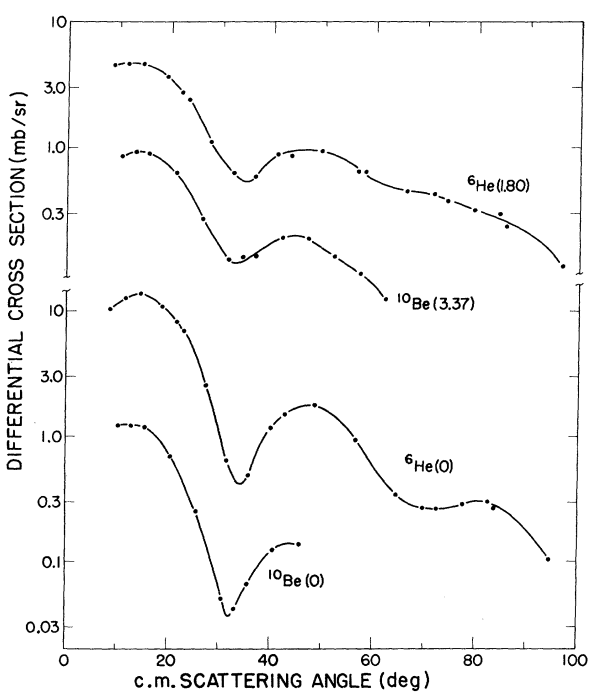

FIG. 9. Comparison of the measured differential cross sections for the ^{7}Li(d, ^{3}He)^{6}He and the ^{11}B(d, ^{3}He)^{10}Be reactions. As a guide to the eye a smooth curve has been drawn through the experimental points.

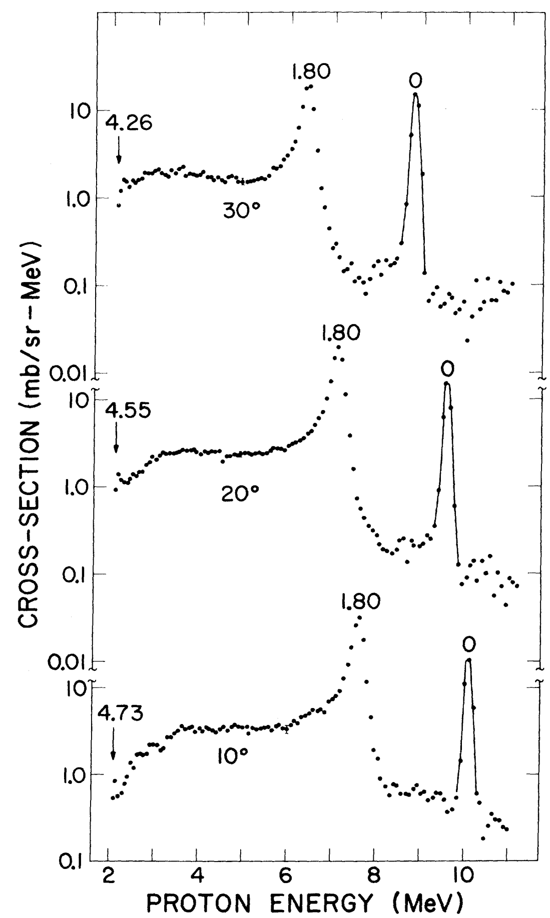

FIG. 10. Measured proton energy spectra from the ^{4}He(t,p)^{6}He reaction. The instrumental cutoffs at low proton energy are labeled with the corresponding ^{6}He excitation energies.

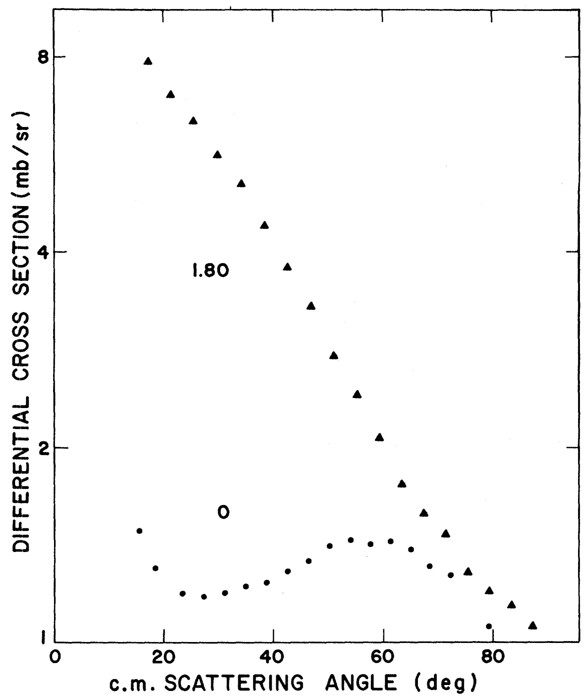

FIG. 11. Differential cross sections for the $^4He(t,p)^6He$ ground-state (0) and first excited state (1.80) reactions.

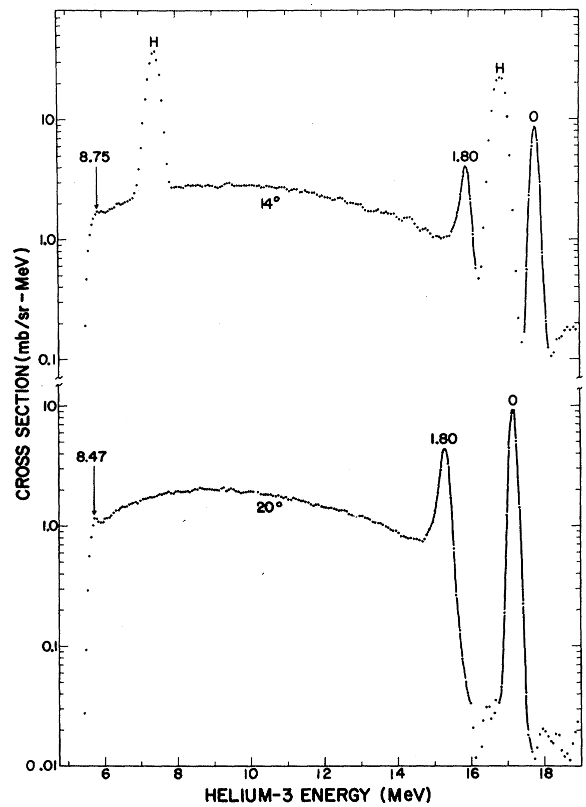

FIG. 12. ^3He energy spectra from the $^6Li(t,{}^3He)^6He$ reaction induced by 22-MeV tritons. The peaks in the 14° spectrum labeled with the letter H result from the $^1H(t,{}^3He)n$ reaction caused by the presence of a hydrogen impurity. The instrumental cutoffs at low ^3He energy are labeled with the corresponding ^6He excitation energies.

ground-state angular distribution. The 1.80-MeV state with $J^\pi = 2^+$ would require $l = 2$; however, the shape of the $l = 2$ DWBA curve (calculated with ground-state parameters) differed greatly from both the ground-state and the 1.80-MeV state data. Further efforts to fit the 1.80-MeV state were not made because of the difficulty of obtaining optical-model parameters and the uncertainty in using CJULIE for unbound states.

D. $^6Li(t,{}^3He)^6He$ Reaction ($Q_0 = -3.49$ MeV)

As discussed in the Introduction, the $^6Li(t,{}^3He)$-^6He reaction is particularly attractive to use in the search for the triton-plus-triton cluster states proposed by Thompson and Tang.[28] The lowest of these are predicted to be at 3.2 and 6.2 MeV above the ^6He ground state. With a 22-MeV triton beam this range can be adequately examined through the $(t,{}^3He)$ reaction. Figure 12 shows the data observed at lab angles of 14 and 20°. Also, spectra were measured at eight other angles between 6 and 35°. Except for the ground and first excited states, no structure due to ^6He was observed.

CONCLUSIONS

A search for ^6He states above the 1.80-MeV first excited state has been made with four nuclear reactions which lead to ^6He as a residual nucleus. These studies, in which 80 different spectra were observed, covered a range of excitation energies where new states have been proposed both from theory and experiment. A few of the measured spectra showed slight structure which taken by itself might be attributed to new excited states. However, the indications did not persist at other scattering angles, at other beam energies, or in other reactions, and therefore do not provide evidence for new states of ^6He. In contrast, peaks from the ground and first excited state were observed in all of the measured spectra which were gathered under widely different experimental conditions.

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