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August 1967

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A SEARCH FOR T = 3/2 STATES IN ^{5}Li, ^{5}He, AND ^{5}H*

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ABSTRACT

Three experiments to search for T=3/2 mass-five analogue states have been performed. Both triton energy spectra from the ^{7}Li(p,t)^{5}Li reaction and particle-particle coincidence data on the ^{7}Li(p,t)^{5}Li and ^{7}Li(p,^{3}He)^{5}He reactions failed to reveal well-defined ^{5}Li or ^{5}He states having expected T=3/2 properties. Tentative evidence is found from these measurements for broad T=1/2 states at 22-, 25-, and 34-MeV excitation energy. ^{8}B energy spectra from the ^{9}Be(α,^{8}B)^{5}H reaction also exhibited no peaks which might be associated with sharp states of ^{5}H. These results are qualitatively in agreement with several theoretical predictions that ^{5}H is unbound to particle emission by at least several MeV.

I. INTRODUCTION

The problem of the existence of the ^5H isotope has been the subject of numerous investigations.[1] A comprehensive review of the literature has been given by Baź, et al.[2] Most experimenters have attempted to observe β^- activity from the ^5H ground state, with almost unanimously negative results. Consequently, while the consensus seems to be that ^5H is unbound to particle emission, little information has been available concerning the properties of possible virtual states of ^5H. Data from one of the few experiments capable of observing such states, in which the $^7Li(\pi^-,d)^5H$ reaction was observed, exhibited no deuteron peaks corresponding to well-defined states of ^5H, but were labeled "inconclusive" by the authors[3] because of a large continuum background.

Alternatively, studies on the T=3/2 analogue states of ^5He and ^5Li can provide useful information on the mass and width of ^5H states. If ^5H is particle stable, then the lowest T=3/2 state of ^5He should occur below 19.5 MeV. However, three recent theoretical calculations indicate that the lowest T=3/2 state of ^5He lies considerably higher, at about 23 MeV,[4] 24 MeV,[5] or 26 MeV.[6] Noting Fig. 1, which illustrates the known mass-five energy levels, one sees that only T=1/2 states at 16.7 (16.65) MeV and 20 MeV have been observed in $^5He(^5Li)$ at high excitation. Nevertheless, since most of the reactions which have been used to search for states of ^5He or ^5Li were incapable of forming T=3/2 states, except through T=1/2 admixtures, it is perhaps not surprising that the analogue states have not been observed.

It has been demonstrated that the (p,t) and (p,^3He) reactions readily populate analogue states with $T = |T_z(\text{target})+1|$ in several light nuclei.[7]

An unsuccessful search for the mass-five T=3/2 states utilizing these reactions on a ^{7}Li target has already been reported by this laboratory.[8] As seen in Fig. 2, taken from Ref. 8, the spectra from the ^{7}Li(p,^{3}He)^{5}He reaction revealed only the well-known 16.7- and 20-MeV states of ^{5}He in the region of high excitation, while the ^{7}Li(p,t)^{5}Li spectra exhibited no peaks in this region other than from contaminants (see Ref. 8). The absence of transitions to the mirror states of ^{5}Li was attributed to the selection rule requiring S=0 for the spin of the transferred neutron pair, which forbids formation of the 16.65-MeV [$^4S_{3/2}$] and 20-MeV [$^4D_{3/2,5/2}$] ^{5}Li states by two neutron pickup from the ^{7}Li ground state [$^2P_{3/2}$]. Since the spin selection rule in the (p,^{3}He) reaction permits S=0 or 1, the 16.7- and 20-MeV ^{5}He states are formed via the S=1 component. The absence of transitions corresponding to the known T=1/2 states of ^{5}Li in the excitation region of interest would seem to make this reaction a sensitive probe for the lowest T=3/2 state, which should be a doublet in intrinsic spin. Unfortunately, large continuum backgrounds might have obscured transitions with small cross sections and/or to broad states.

We report in this paper on three further experiments on the properties of the mass-five T=3/2 states. First, we have obtained triton spectra from the ^{7}Li(p,t)^{5}Li reaction under conditions similar to those of the previous work, but with improved counting statistics. Second, data on coincidences between tritons, ^{3}He's, and alphas resulting from reactions of p + ^{7}Li have been collected in order to study the decay properties of intermediate ^{5}He and ^{5}Li states. Third, we have directly searched for ^{5}H states by observing ^{8}B energy spectra from the ^{9}Be(α,^{8}B)^{5}H reaction.

II. THE $^{7}Li(p,t)^{5}Li$ REACTION

Figure 3 shows a triton spectrum at 14.1^{o} obtained by bombarding an 800 $\mu g/cm^2$ self-supporting ^{7}Li target with 43.7-MeV protons from the Berkeley 88-inch cyclotron. Signals from a counter telescope consisting of an 140μ ΔE, 3200μ E, and 600μ E-reject semiconductor detectors were fed to a Goulding-Landis [9] particle identifier. The summed (ΔE + E) pulses were then passed on to a 4096-channel analyzer gated so as to store 1024-channel energy spectra corresponding to selected portions of the identifier spectrum. An anti-coincidence requirement utilizing signals from the E-reject counter eliminated particles traversing the E counter. The complete spectrum was accumulated for 940μc; the data in the inset were taken for 2200μc and summed over 4-channel intervals to improve the counting statistics. In obtaining these latter data, the beam intensity was increased and a relatively narrow window was set on the E amplifier output covering the excitation region of interest, thus maintaining a reasonable counting rate in the identifier.

Since the lowest mass-five T=3/2 state configuration is probably $(1s)^3(1p)^2$, an L=1 angular momentum transfer is required to form the ^{5}Li member. Angular distribution data in Ref. 8 indicated that 14^{o} was a good angle for observing such an L=1 transition. The complete spectrum in Fig. 3 contains no obvious reasonably narrow peaks other than that of the ^{5}Li ground state. Positions of possible ^{12}C and ^{16}O contaminant peaks are indicated on the spectrum. The large continuum is primarily associated with the multi-particle final states listed at the top of the figure. This absence of peaks is an indication that the T=3/2 state(s) must lie at fairly high excitation and be broad: for example, assuming a hypothetical state at 20 MeV with a width of 500 keV, then an easily discernible peak would have appeared in the complete spectrum provided the center of mass cross section was bigger than about 13 μb/sr. For comparison, (p,t) transitions to T=3/2 states under these experimental conditions possess peak cross sections between about 50 and 140 μb/sr.[10] In particular, the $^{19}F[1/2+,T=1/2](p,t)^{17}F[1/2-,T=3/2]$ transition, which requires an L=1 pickup of a neutron pair, closely resembles a $^{7}Li[3/2-,T=1/2](p,t)^{5}Li[1/2+,T=3/2]$ transition which also requires an L=1 pickup of two neutrons. The calculated structure factors[11] appear comparable and the cross section of the ^{19}F transition is about 60 μb/sr at 14° (lab).[12] If the analogue state lies at higher excitation, then of course the sensitivity for observing the state decreases due to the rising continuum background and because the width of such a state is likely to increase.

Two broad peaks corresponding to 22 ± 0.5 MeV and 25 ± 0.5 Mev excitation are apparent in the inset. The line in the figure represents a sum of the $t + \alpha + p$, $t + {}^{3}He + d$, and $t + d + d + p$ final state phase-space distributions. This set of final states, along with their relative amplitudes, was chosen to minimize the residual area under the two peaks, subject to the requirement that the height of the resultant phase-space envelope did not exceed the height of the complete spectrum at any energy. The cross sections for the peaks with this phase-space background subtracted were 14 and 41 μb/sr, respectively; the width of both peaks corresponded to approximately 1.5 MeV with respect to the ^{5}Li recoil system. It appears on the basis of the complete spectrum that ^{12}C contamination was negligible; however, from the known[12] $^{16}O(p,t)^{14}O$ cross sections it was estimated that at most 50% of the counts under the 22-MeV peak may have been due to the ^{14}O 6.60-MeV state. These cross sections should be considered as lower limits, provided that they can be associated with real ^{5}Li states; that is, we attribute no particular significance to the actual shape or magnitude of the phase-space distribution, so the actual cross sections may be larger than those given. It is well known that the observation of peaks at excitations higher than particle thresholds in the residual nucleus does not necessarily establish the existence of a corresponding state of this nucleus because the kinematics of possible multi-particle reactions are not fixed by a single-counter experiment. The resulting ambiguity in the interpretation of these peaks both with regard to their origin and their isospin was one of the reasons for performing the coincidence experiment, which is described below.

III. COINCIDENCE SPECTRA FROM THE p + ^{7}Li REACTION

If the momenta of two particles of a three-particle final state are determined, then the kinematics of the reaction constrain all such events to lie along a curved line in the two-dimensional energy plane of the detected particles.[13] Sequential reactions proceeding through well-defined two-particle intermediate states will be characterized by peaks lying along the curve. The kinematical behavior of these peaks, as the detector angles are varied, often provides sufficient information to decide unambiguously which two-particle states are involved.

Triton-triton, triton-^{3}He, triton-alpha, ^{3}He-^{3}He, and ^{3}He-alpha coincidences from reactions of p + ^{7}Li yield information concerning the three- and four-particle final states listed in Table I. Various sequential reactions leading to three-particle final states are given explicitly in the table; the much larger set of possible sequential reactions yielding four-particle final states is not shown. The three-particle reactions 1,2,4, and 7 are interesting with respect to intermediate mass-five states which decay by breakup into two particles. Similar four-particle sequential reactions also provide information on intermediate mass-five states which breakup into three particles; however, the momenta of all four particles are not determined by double coincidence data so that four-particle events are confined to a region of the energy plane bounded by a curve given by kinematics. With coincidence data substantial improvement over the single detector system triton results was anticipated: (1) The "signal to noise" ratio of peaks relative to the continuum should be enhanced with coincidence data since the laboratory cone angle of decay particles from ^5He or ^5Li states is usually smaller than 4π. (2) The decay properties of intermediate states, i.e., whether the state decays into two or three particles, are uniquely determined by the kinematics. The latter effect is particularly relevant to the search for the mass-five T=3/2 states. Reference to Figure 1 shows that in order to satisfy the isospin selection rules, pure T=3/2 states must decay by emission of three particles,[14] whereas T=1/2 states may decay by emission of either two or three particles (for the latter states penetrability and phase-space volume effects probably favor two-particle decay near the three-particle thresholds). For example, events from reaction (2) in Table I proceeding through the 20 MeV $\left[{}^4D_{3/2,5/2}\right]^5He$ intermediate state are expected to appear on a narrow segment along the three-particle curve in the triton-^3He coincidence array. On the other hand, a sharp ^5He T=3/2 state at 20 MeV decaying to t + n + p would manifest itself by events falling along a straight line perpendicular to the ^{3}He energy axis and lying in the four-particle region of the array. The kinematic limit of this region is separated by the 2.3-MeV deuteron binding energy from the three-particle curve. The distribution of events along this line with respect to triton energy depends on the dynamics of the decay; e.g., if the n-p final state interaction were dominant, then the line would degenerate to a point near the four-particle kinematic limit corresponding to the pseudo three-particle final state ^{3}He + t + d*. In any case a projection of these events onto the ^{3}He energy axis would yield a peak corresponding to the ^{5}He 20-MeV excitation energy.

The coincidence experiments were performed with a 49.6-MeV proton beam focused to 60 X 100 mils on a 500 μg/cm^2 ^{7}Li self-supporting target. One counter telescope (System 1) consisting of 81μ ΔE, 3050μ E, and 510μ E-reject semiconductor detectors subtended 0.6 msr; the second telescope (System 2) consisting of 32μ ΔE and 1000μ E detectors subtended 3.84 msr. Pulses from System 1 were fed to a particle identifier plus router system adjusted to provide signals corresponding to triton or ^{3}He particles. Pulses from System 2 were fed to a second particle identifier plus router system adjusted to pass triton, ^{3}He, or alpha routing signals if the E pulse was in fast coincidence (2τ=50ns) with the ΔE pulse from System 1. If an additional slow coincidence requirement on the routing signals from the two systems was satisfied, then the two (ΔE + E) total energy pulses from the telescopes and the appropriate two routing signals from both identifier-router systems were fed to an eight channel analogue buffer unit coupled to a 4096-channel analogue-to-digital converter.[15] The digital numbers were read by an on-line PDP-5 computer which stored the events on magnetic tape; in addition, six 32 X 32 two-dimensional energy arrays were stored in core to enable data monitoring on an oscilloscope display during the experiment.

Typical coincidence arrays are shown in Figures 4 (and 5) in which tritons were counted at 50° (40°) and ^{3}He's at -60° (-70°). The rather large acceptance angles, necessitated by the expected small cross sections, meant the overall energy resolutions of Systems 1 and 2 were only about 0.5 and 1.0 MeV, respectively. Since relatively few events were collected, the data on magnetic tape were sorted and condensed to 64 X 64 channel arrays. The three- and four-particle final states are cleanly separated in the figure. The kinematic curves for these final states are shown in the arrays. A few events resulting from alpha-particle leak-through into the ^{3}He region of the particle identifier spectrum appear in the upper right corner of the arrays, but the relatively small negative Q value of the t + α + p reaction makes the effect negligible. Projections of both the three- and four-particle events, proportional to $\frac{d^3\sigma}{dE_3^{\ell} d\Omega_3^{\ell} d\Omega_4^{\ell}}$, onto each energy axis are given in the figures. The numbers denote particles 3 and 4 in the symbolic reactions [1 + 2 $\rightarrow$ 3 + 4 + 5] or [1 + 2 $\rightarrow$ 3 + 4 + 5 + 6], and ℓ refers to laboratory coordinates. Excitations of the (4 + 5) or (4 + 5 + 6) recoil systems are also indicated along with E_3^{ℓ} in the figures. The phase-space volume in both figures is given by the dotted lines for comparison with the data. The triton phase-space distributions are normalized with respect to the ^{3}He distributions which in turn are normalized to the data at 8 MeV ^{3}He energy. The phase space is singular along the ^{3}He axis where the three-particle kinematic curve is perpendicular to this axis. However, the peak obtained by projecting this segment of the curve in either figure onto the triton axis implies that phase space is not solely responsible for the observed peak in the ^{3}He spectrum. These projections are discussed in more detail below.

Further coincidence arrays will not be shown;[16] qualitatively the remaining triton-^{3}He data are similar to those shown in Figures 4 and 5. Data were collected at two pairs of angles (50°,-60°) and (40°,-70°) so that triton-^{3}He projections at four angles were obtained. These are shown in Figure 6 where the three-particle spectra have been transformed from the laboratory coordinate system (finite geometry effects have not been included) to one at rest with respect to the recoil ^{5}He or ^{5}Li nuclei to facilitate comparison of the spectra at different angles. Peaks on the right side of the figure obviously are related to peaks on the left side since the spectra were obtained from the same three-particle curve in the original two-dimensional energy plane. A trivial exception occurs where the ^{5}He counterpart to the peak at 34 Mev in ^{5}Li disappears because, due to the tangent effect pointed out in the discussion of Figure 4, the ^{5}He Jacobian vanishes at this point.

It is clear from Figure 6 that the width of the observed peaks, together with the poor counting statistics, precludes their unambiguous association with states in one of the various two-particle systems on the basis of kinematic shifts alone. [In fact, the two pairs of angles were chosen to maximize the laboratory energy of the decay particles from intermediate mass-five states at around 22 MeV so that kinematic shifts were typically on the order of only several hundreds of keV.] However, the peak at 20 MeV in ^{5}He (and the associated peak at an apparent excitation of 27 MeV in ^{5}Li) is consistent with Ref. 8 where the 20 MeV ^{5}He state was found to have a relatively large cross section (at 40^{o} the center of mass cross section was 60 μb/sr) and a width of approximately 2.7 MeV. A width of 3 ± 0.6 MeV is obtained from the -40^{o} ^{5}He spectrum in these data. Figure 6 also presents peaks corresponding to a state at 21.5 MeV in ^{5}Li or at 25 MeV in ^{5}He, or perhaps to contributions from both such states. Any of these possibilities is consistent with the triton spectrum discussed previously where "peaks" tentatively associated with 22- and 25-MeV ^{5}Li states were found, provided mirror states of ^{5}He are also postulated. Unfortunately we are unable to make any additional conclusion from the present data except that it appears any new states at 22 or 25 MeV would more likely have T=1/2. In fact, from these coincidence data alone, it is conceivable that an intermediate ^{6}Li state at about 34.6 MeV with $\Gamma \lesssim 0.7$ MeV could account for both pairs of peaks discussed above. We regard this as unlikely both because the width seems narrow for such a highly excited state, and because the interpretation of both pairs of peaks as due to mass-five states is consistent with the single counter results discussed above and with Ref. 8.

The peak at about 34 MeV in the ^{5}Li spectra near the experimental cutoff is probably due to the mirror of the $(1s)^{-2}$ ^{5}He state previously observed in the $^{7}Li(\pi^{+},2p)^{5}He$ reaction, [17] although once again we cannot rule out an intermediate ^{6}Li state at about 30.8 MeV on the basis of our data alone.

As has already been stressed, a primary reason for performing the coincidence experiment was that T=3/2 intermediate mass-five states should decay into three particles if such decay is energetically allowed, so that these events lead to four-particle final states. Projections of all the four-particle data are shown in Figures 7 and 8. Figure 7, containing the triton-

^{3}He data, is the analogue to Figure 6 where the three-particle spectra are shown. As in Figure 6, the four-particle spectra have been transformed to the recoil ^{5}He or ^{5}Li coordinate systems. The four-particle two-dimensional energy spectra in Figs. 4 and 5, which are proportional to $\frac{d^4\sigma}{dE_3^{\ell}\ dE_4^{\ell}\ d\Omega_3^{\ell}\ d\Omega_4^{\ell}}$, are first transformed to the appropriate recoil system and then integrated over particle 4 energy (the notation is the same as defined earlier). The relative heights of the resulting spectra given in the figures should not be directly compared, since the particle 4 integration interval depends both on the low energy cutoff of the particle 4 counter (which is different for the two counter-telescopes), and on the kinematics associated with the counter angles. In contrast to Figures 6 and 7 where two spectra in the same row are obtained from the same two-dimensional energy spectrum, the spectra on the left side of Figure 8 are obtained from the ^{3}He-^{3}He coincidence data while the spectra on the right side are derived from the triton-triton data. Hence, the first and fourth spectrum in each column represent the two projections of the (40°, -70°) data while the 2nd and 3rd spectrum in each column are obtained from the (50°,-60°) data.

In general the four-particle spectra in both figures simply rise with increasing excitation energy and possess no well-defined peak structure which might be associated with the sought analogue states. The ^{5}He spectra in Figure 7 are exceptions, exhibiting a broad peak extending from about 22 MeV to 25 MeV, but there is no hint of this structure in the ^{5}Li spectra in the same figure. This asymmetry still persists (although it is less pronounced) when the ^{5}He projected spectra are obtained by integrating over those triton energies corresponding to the ^{3}He energies which have been integrated to give the ^{5}Li spectra on the right side of Figure 7; therefore the bump in the ^{5}He spectra is not solely due to integrating over the many low energy triton events which are apparent in the ^{5}Li projections. This bump is not understood and one might consider it to arise from the same states at 22 and/or 25 MeV as were earlier observed in the three-particle data; however, we do not feel that we can associate it or the ^{5}Li states at these energies with the desired T=3/2 states <u>since comparable structure is not observed in any of the ^{5}Li four-particle spectra</u>. It has been demonstrated [7] several times that the ratio of (p,t) to (p,^{3}He) cross sections to analogue states is primarily dependent only on isospin-coupling coefficients and phase-space factors which for the present case give a ratio of unity.

Calculated four-particle phase-space distributions have been fitted by eye to the spectra in Figures 7 and 8 for comparison. Except for the bump in the ^{5}He spectra mentioned above, the fits approximate rather well the shapes of the spectra extending from the experimental cutoffs up to about 27-MeV excitation energy in both ^{5}He and ^{5}Li. Unfortunately the data do not extend down to the three-particle decay thresholds given in Figure 1, so that decays from hypothetical states below about 20 MeV in ^{5}He and about 20.5 MeV in ^{5}Li could not have been detected in the triton-^{3}He data. The ^{3}He-^{3}He data in Figure 8 cut off at about 21.5 MeV in ^{5}He whereas the triton-triton data extend down to about 19.0 MeV in ^{5}Li. Therefore these triton-triton data permit examination for three-particle decay of states lying at lower excitation in mass-five than any of the other data. We could not have observed a ^{5}Li state with an open T=3/2 decay mode lying between the t + p + p threshold at 17.85 MeV and 19 MeV; however, such a state would probably be narrow enough to be discernible in the triton singles data discussed above.

Since we find no indication of mass-five T=3/2 states in the four-particle data, it is of interest to estimate singles cross section upper limits for formation of such states. The arbitrary units corresponding to the +40° ^{5}Li spectrum in Figure 8 are equivalent to 0.10±0.03 μb/MeV.sr^2 so that the absolute cross section at 20 MeV ^{5}Li excitation is 0.28±0.09 μb/MeV.sr^2. To obtain the singles cross section, it is assumed a T=3/2 state at this excitation could decay into t + p + p with no dependence either on the angle of emission or on the energy of the decay triton with respect to the ^{5}Li rest system . The former assumption will be valid provided the hypothetical state has a spin of 1/2 as expected for the lowest T=3/2 state; the latter assumption is necessitated by the experimental cutoff which permits observation of roughly 75% of the total triton decay energy spectrum allowed by kinematics. Correcting for the unobserved portion of the decay energy spectrum, multiplying by 4π, and dividing by the square of the Clebsch-Gordan isospin coupling coefficient for the t + p + p component of a T=3/2 state, then the absolute singles cross section related to the coincidence data is estimated to be 14.3±4.8 μb/MeV.sr. Therefore if such a T=3/2 state exists at 20-MeV excitation with a width less than 1 MeV, it should be apparent in the data if the ^{7}Li(p,t)^{5}Li cross section is larger than about 5 μb/sr at this angle.

To conclude this section, no evidence is found for ^{5}He or ^{5}Li states which decay via T=3/2 modes, implying that the analogue states are very broad. It is, of course, possible that these states could have sufficiently mixed isospin that decay by T=1/2 modes is favored.

IV. THE $^9Be(\alpha,{}^8B)^5H$ REACTION

Observation of ^8B ions from reactions of alpha-particles on ^9Be targets permits direct examination of the ^5H system. An 129-MeV alpha-particle beam was used to bombard a self-supporting 650 μg/cm^2 ^9Be target and, in addition, a 250 μg/cm^2 ^{12}C target for calibration purposes. Two four-counter telescopes were used: one positioned both at 10° and 14.1° consisted of a 61μ ΔE2 counter, a 32μ ΔE1 counter, a 300μ E counter, and a 500μ E-reject counter; the other, at 11.2°, consisted of a 37μ ΔE2 counter, a 23μ ΔE1 counter, a 300μ E counter, and a 500μ E-reject counter. Signals from these detectors were fed to two triple-counter particle identifiers which have been previously described.[18] An identifier spectrum collected at 10° is shown in Figure 9. ^8B energy spectra were collected by gating a pulse height analyzer with appropriate routing signals from the identifiers. These data were obtained while establishing the feasibility of using these identifiers for particles of Z = 4, 5, and 6, and a description of the general experimental setup has been published elsewhere.[19]

A $^{12}C(\alpha,{}^8B)^8Li$ energy spectrum is shown in Figure 10 where the data from both telescopes have been added together after the necessary kinematic adjustments. The energy resolutions of both systems were comparable, being about 440 keV FWHM for the ^8Li ground state peak. Most of the known[1] states of ^8Li are apparent in the spectrum; however, the states lying above the 2.26-MeV state are quite broad and are not resolved (in this part of the spectrum the data have been summed over four channels and divided by four in order to improve the counting statistics). The shape of the continuum, beginning at the ^7Li + n threshold, is fit by the three-particle phase-space distribution shown in the figure. The average center of mass cross sections at the three angles are 0.54 μb/sr and 0.88 μb/sr for the ^{8}Li ground state and 2.26-MeV state, respectively.

Figure 11 presents the ^{8}B spectra from the $\alpha + {}^{9}Be$ reaction. The energy calibration was taken from the ^{8}Li data discussed above. No sharp states are evident in the data from either telescope. Instead, the spectra rise rather smoothly above the threshold for ^{5}H particle stability (relative to decay into t + n + n). We have attempted to fit the spectra with arbitrary combinations of three- and four-particle phase-space distributions but with little success. Both spectra exhibit a residual "peak" extending from near the threshold to about 20 MeV excitation in ^{5}H peaking in both cases at 11.6-MeV excitation above threshold. This peak can certainly not be associated with a single state of ^{5}H. Whether it results from several broad states and/or angular momentum or other effects not considered in the phase-space calculations is not clear. It is possible to set an upper limit on the cross section of a well-defined state of ^{5}H. If the state is narrower than about 1 MeV and lies lower than 1.5 MeV above the threshold it would have been obvious in the data if it possessed an average cross section at the two angles larger than 22 nb/sr or, in other words, larger than 1/25 the cross section for the $^{12}C(\alpha, {}^{8}B){}^{8}Li$ g.s. reaction. If ^{5}H is just bound, then it would be apparent in the data if the average cross section were about 1/88 that of ^{8}Li g.s. reaction.

V. CONCLUSIONS

The triton spectra first discussed contained very small broad peaks corresponding to possible 22- and 25-MeV states of ^{5}Li. The three-particle coincidence data are consistent with the existence of mass-five states at these energies but are not unambiguous, making the evidence for these states tentative. On the other hand, we find no evidence for mass-five states having the expected T=3/2 decay properties. In the vicinity of 20-MeV excitation in ^{5}Li (the region of interest with respect to the particle stability of ^{5}H) cross section upper limits for well-defined T=3/2 states have been estimated which are substantially smaller than (p,t), (p,^{3}He) cross sections for formation of T=3/2 states in other nuclei. Further, the $^{9}Be(\alpha,{}^{8}B){}^{5}H$ data exhibit no peaks which can be associated with sharp ^{5}H states. Therefore we conclude from these data that the lowest mass-five T=3/2 states exist at relatively high excitation above the relevant three-particle decay thresholds and, hence, are quite broad. These results are qualitatively consistent with the theoretical predictions [4, 5, 6] that ^{5}H is unbound by at least several MeV.

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FOOTNOTES AND REFERENCES

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14. Possible sequential decay of T=3/2 states involving mass-four T=1 states + nucleon effectively yield three particles since the lowest T=1 states are themselves particle unstable. [See, for example, J. Cerny, C. Détraz, and R. H. Pehl, Phys Rev. Letters 15, 300 (1965)].

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16. The triton-alpha data are dominated by a broad peak corresponding to either a 29-MeV ^{7}Li(Γ~4 MeV), a 32-MeV ^{4}He(Γ~6 MeV), or a 20-MeV ^{5}Li(Γ~10 MeV) state; the last possibility can be rejected on the basis of known level data. The ^{3}He-alpha arrays also exhibit a broad peak corresponding to either a 29-MeV ^{7}Be(Γ~3 MeV), a 34-MeV ^{4}He(Γ~8 MeV), or a 15.5-MeV ^{5}He(Γ~10 MeV) state. Again, the last possibility can be ruled out. The existence of ^{4}He states at about 30 MeV is known (see Ref. 17); unfortunately little information is available on mass-seven states at the appropriate excitations. Since

these data are inconclusive and are not relevant to the mass-five states, they are ignored in the remaining discussion.

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FIGURE CAPTIONS

Fig. 1. Energy level diagrams for ^{5}He and ^{5}Li including particle-decay thresholds, taken from Ref. 1.

Fig. 2. The energy spectra of the $^{7}Li(p,t)^{5}Li$ and $^{7}Li(p,^{3}He)^{5}He$ reactions at 14° taken from Ref. 8.

Fig. 3. The energy spectrum of the $^{7}Li(p,t)^{5}Li$ reaction at 14.1°. The complete spectrum was accumulated for 940 μC, while the data in the inset were collected for 2200 μC. The positions of possible contaminant peaks are indicated as are the multi-particle breakup thresholds. The solid line in the inset is a composite phase-space distribution which is discussed in the text.

Fig. 4. A triton (50°), ^{3}He (-60°) coincidence spectrum. The solid lines in the two-dimensional array are the three- and four-particle final state kinematic curves. Projections of the data onto both energy axes are shown; the phase-space distributions are given by the dashed lines for comparison. If ^{5}H is bound, the excitation of the lowest T=3/2 state of either ^{5}He or ^{5}Li is less than ~19.5 MeV which is indicated by the arrow in the four-particle spectra.

Fig. 5. A triton (40°), ^{3}He(-70°) coincidence spectrum. See caption of Fig. 4.

Fig. 6. Projections of the triton-^{3}He three-particle final state coincidence data taken at (40°,-70°) and (50°,-60°). The spectra on the left are obtained by projection onto the ^{3}He energy axis, and transformation to the ^{5}He recoil system; similarly, the spectra on the right are obtained by projection onto the triton axis and transformation to the ^{5}Li recoil system.

Fig. 7. Projections of the triton-^{3}He four-particle final state coincidence data. The spectra on the left are obtained by transformation of the

coincidence data into the ^{5}He recoil system and projection onto the ^{3}He axis and those on the right by transformation of the data into the ^{5}Li recoil system and projection onto the triton axis as described in the text. The solid lines are phase-space fits to the spectra.

Fig. 8. Projections of the ^{3}He-^{3}He four-particle final state coincidence data are shown on the left and projections of the triton-triton four-particle final state data are shown on the right after transformation to the ^{5}He and ^{5}Li recoil systems, respectively. The solid lines are phase-space fits to the spectra.

Fig. 9. Triple-counter particle identifier spectrum resulting from the 129-MeV α-particle bombardment of ^{12}C showing the separation of Be, B and C isotopes taken from Ref. 19.

Fig. 10. A composite $^{12}C(\alpha, {}^{8}B){}^{8}Li$ energy spectrum of data taken at 10°, 11.2°, and 14.1° (lab). The dashed line is a phase-space fit to the $^{8}B + {}^{7}Li + n$ continuum and the positions of most previously established ^{8}Li levels are marked.

Fig. 11. The $^{9}Be(\alpha, {}^{8}B){}^{5}H$ energy spectra at 10° and 11.7° (lab). The spectra are fitted with four-particle ($^{8}B + t + n + n$) phase-space distributions in the upper half of the figure and with a sum (solid line) of three-particle ($^{8}B + t + 2n$) and four-particle ($^{8}B + t + n + n$) phase-space distributions (dashed lines) in the lower half of the figure. In both cases, the spectra exhibit an "excess" above the phase-space curves which peak at ~11.6 MeV excitation above the t + n + n

threshold, but contain no evidence for well-defined states of ^{5}H.

Table I. Multi-particle reactions of $p + {}^{7}Li$

	3-particle final state	4-particle final state
$p + {}^{7}Li \rightarrow$	$t + {}^{5}Li^{*} \rightarrow t + {}^{3}He + d$ (1)	$t + {}^{3}He + n + p$
	${}^{3}He + {}^{5}He^{*} \rightarrow {}^{3}He + t + d$ (2)	
	$d + {}^{6}Li^{*} \rightarrow d + t + {}^{3}He$ (3)	
	$t + {}^{5}Li^{*} \rightarrow t + \alpha + p$ (4)	$t + {}^{3}He + n + p$
	$\alpha + {}^{4}He^{*} \rightarrow \alpha + t + p$ (5)	$t + t + p + p$
	$p + {}^{7}Li^{*} \rightarrow p + t + \alpha$ (6)	${}^{3}He + {}^{3}He + n + n$
	${}^{3}He + {}^{5}He^{*} \rightarrow {}^{3}He + \alpha + n$ (7)	
	$\alpha + {}^{4}He^{*} \rightarrow \alpha + {}^{3}He + n$ (8)	
	$n + {}^{7}Be^{*} \rightarrow n + {}^{3}He + \alpha$ (9)	

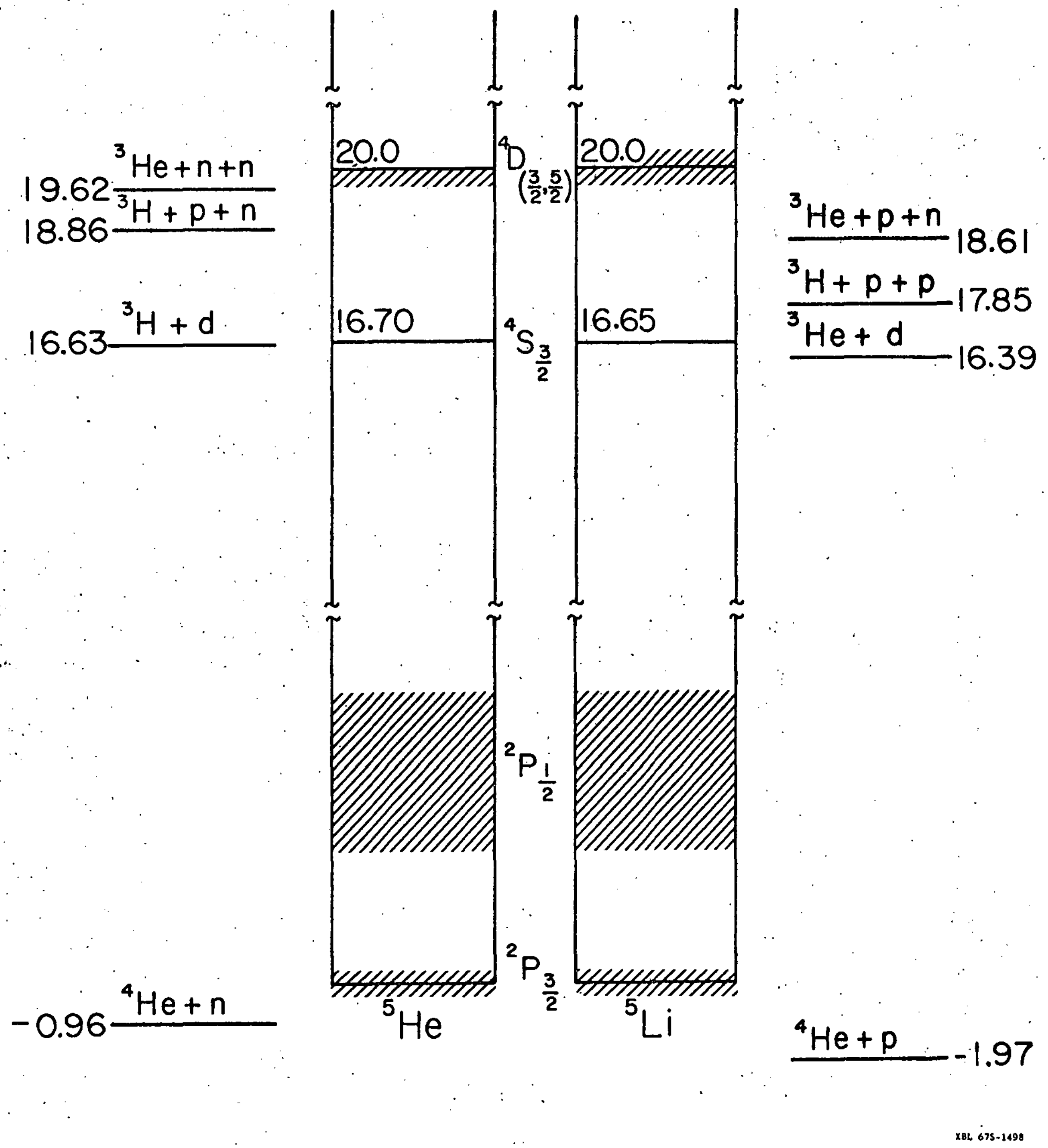
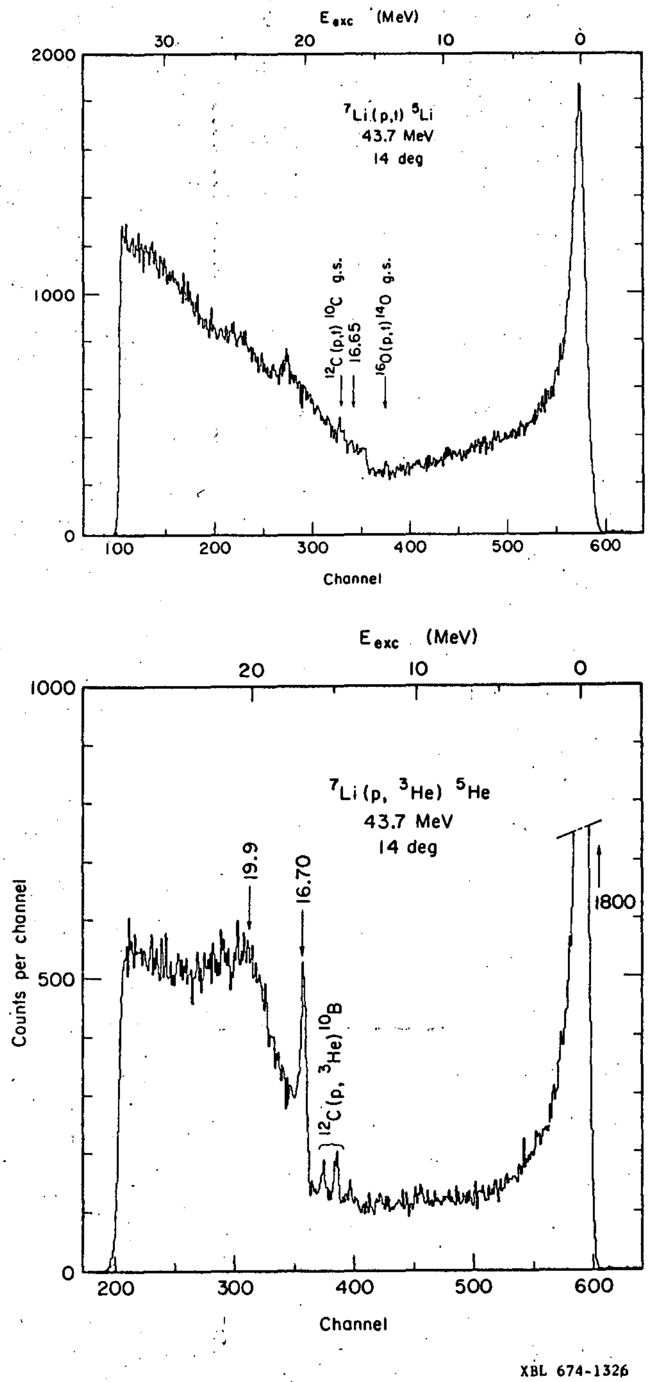
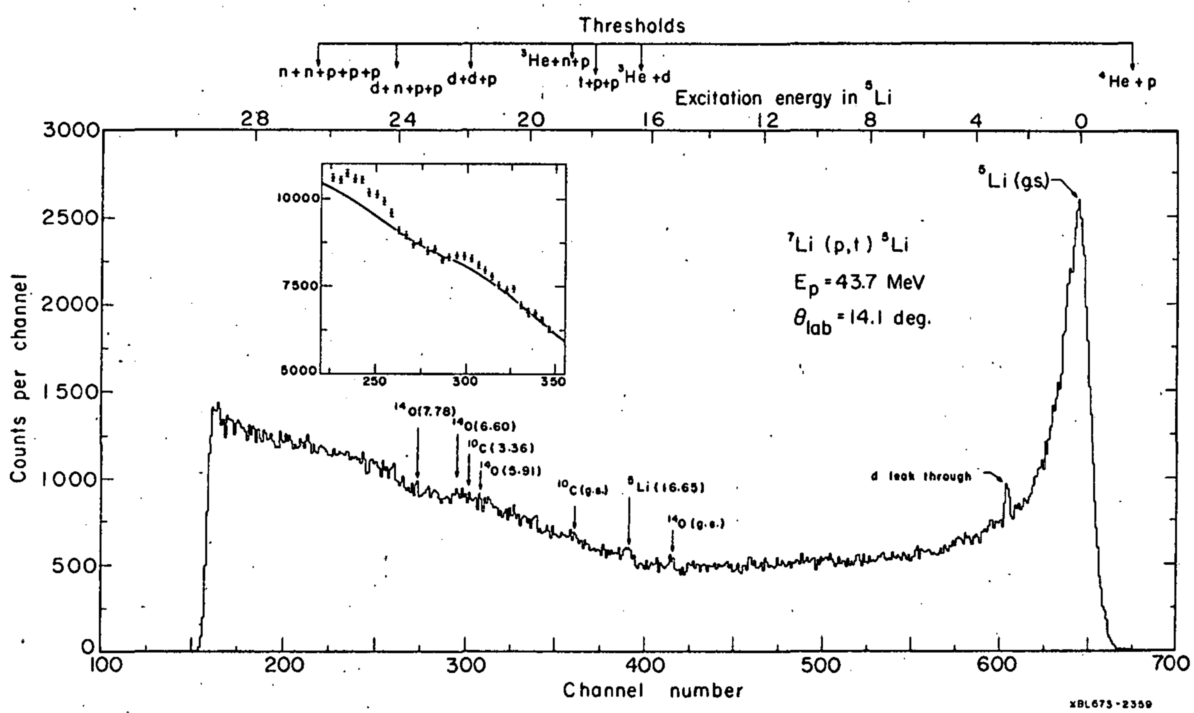

19.62
³He+n+n
³H+p+n
18.86
16.63
³H+d
-0.96
⁴He+n
20.0
16.70
⁵He
⁴D(3/2, 5/2)
⁴S3/2
²P1/2
²P3/2
20.0
16.65
⁵Li
³He+p+n
18.61
³H+p+p
17.85
³He+d
16.39
⁴He+p
-1.97
XBL 675-1498

Fig. 1



E exc (MeV)
30
20
10
0
2000
1000
0
^{7}Li(p,t) ^{5}Li
43.7 MeV
14 deg
^{12}C(p,t) ^{10}C g.s.
16.65
^{16}O(p,t) ^{14}O g.s.
100
200
300
400
500
600
Channel
E exc (MeV)
20
10
0
1000
500
0
^{7}Li(p, ^{3}He) ^{5}He
43.7 MeV
14 deg
19.9
16.70
1800
^{12}C(p, ^{3}He) ^{10}B
Counts per channel
200
300
400
500
600
Channel
XBL 674-1326

FIG. 2



Thresholds
n+n+p+p+p
d+n+p+p
d+d+p
^{3}He+n+p
t+p+p
^{3}He +d
^{4}He + p
Excitation energy in ^{5}Li
28
24
20
16
12
8
4
0
3000
2500
2000
1500
1000
500
0
Counts per channel
10000
7500
5000
250
300
350
^{5}Li (gs)
^{7}Li (p,t) ^{5}Li
E_p = 43.7 MeV
θ_{lab} = 14.1 deg.
^{14}O(7.78)
^{14}O(6.60)
^{10}C(3.36)
^{14}O(5.91)
^{10}C(g.s.)
^{5}Li(16.65)
^{14}O(g.s.)
d leak through
100
200
300
400
500
600
700
Channel number
XBL673-2359

Fig. 3

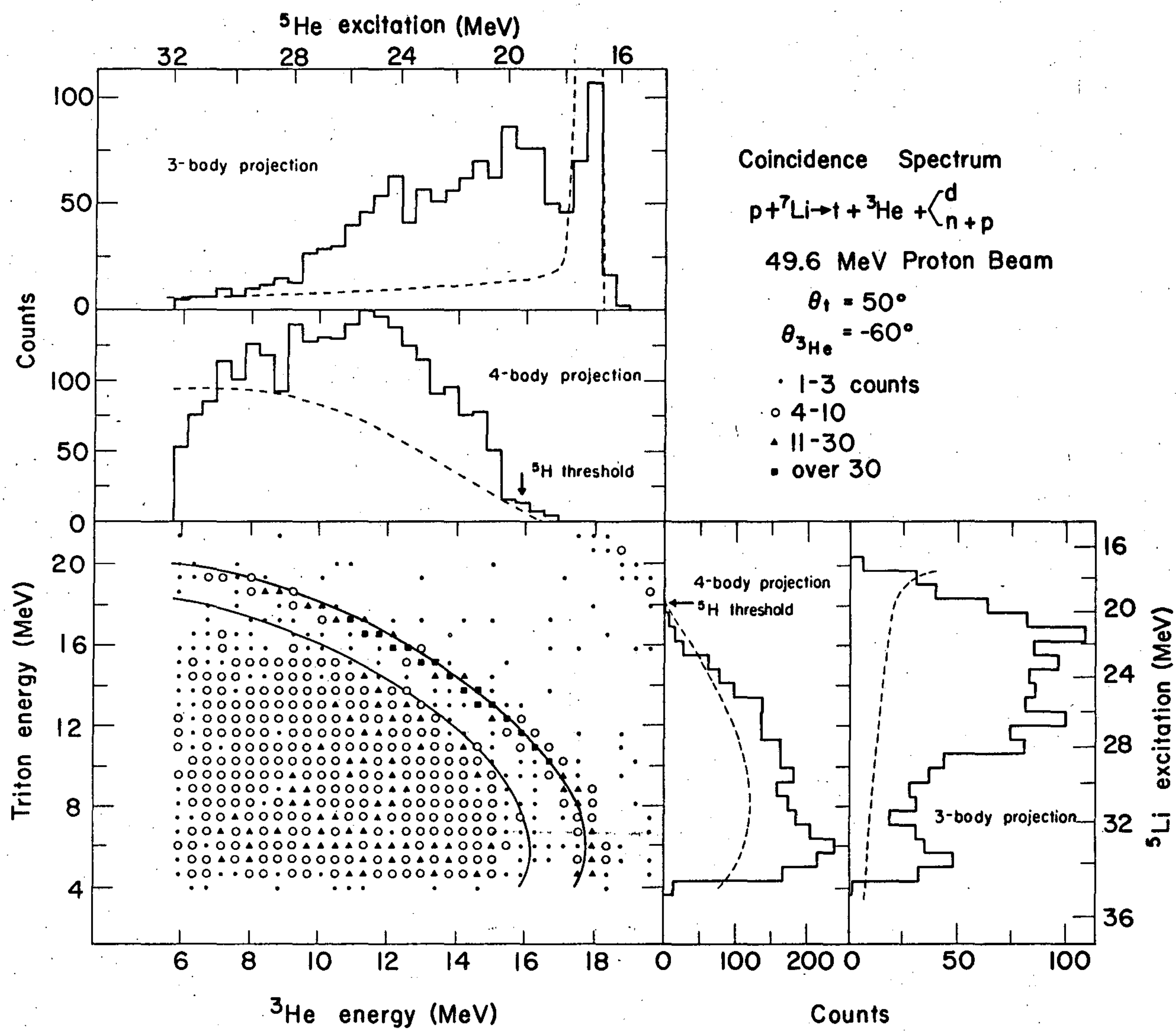


Fig. 4

XBL673-2364

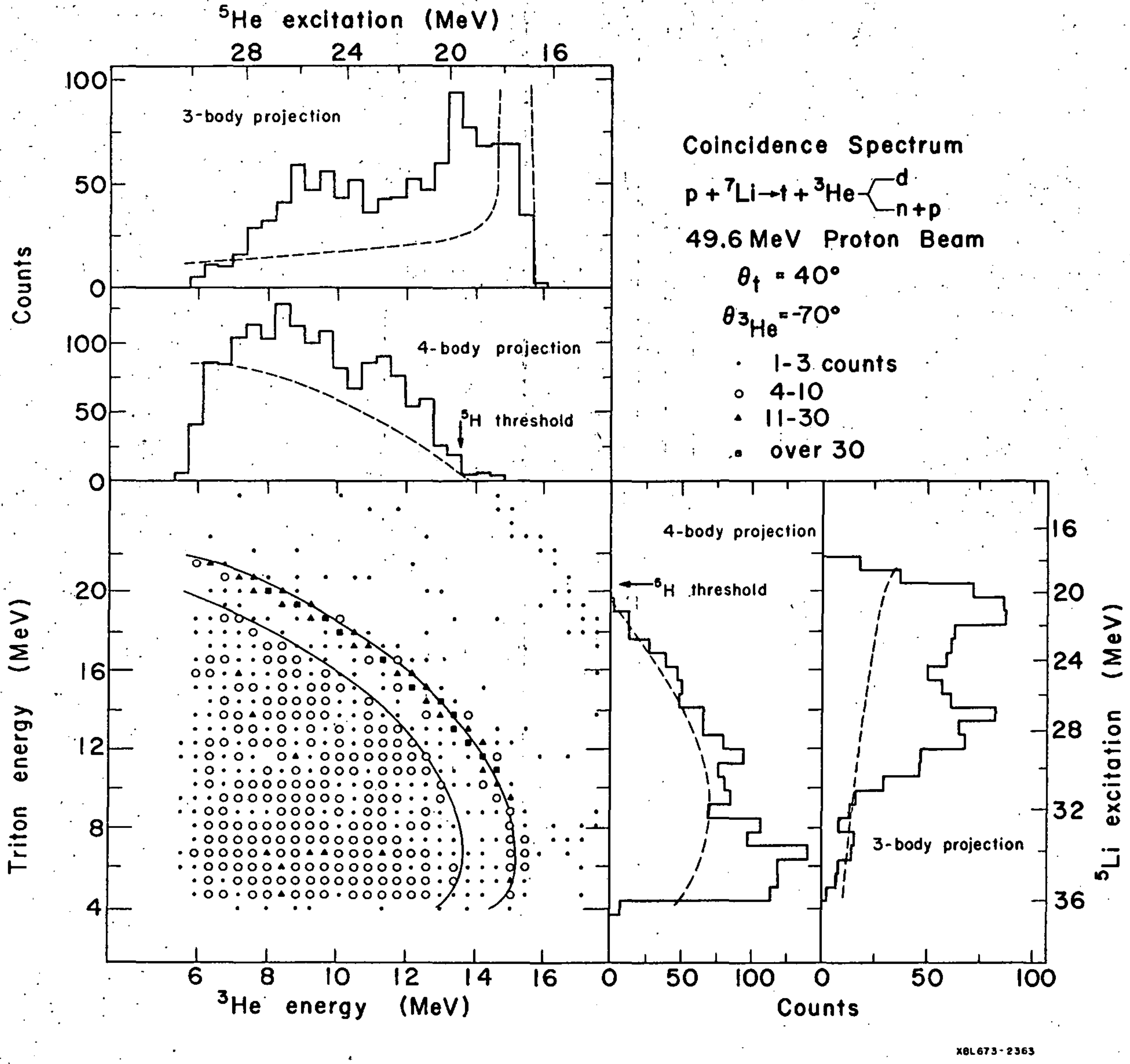

^{5}He excitation (MeV)
3-body projection
4-body projection
^{5}H threshold
Counts
Coincidence Spectrum
p + ^{7}Li → t + ^{3}He → d / n+p
49.6 MeV Proton Beam
θ_t = 40°
$\theta_{^3He}$ = -70°
· 1-3 counts
○ 4-10
▲ 11-30
■ over 30
Triton energy (MeV)
^{3}He energy (MeV)
4-body projection
^{5}H threshold
3-body projection
Counts
^{5}Li excitation (MeV)
XBL673-2363

Fig. 5

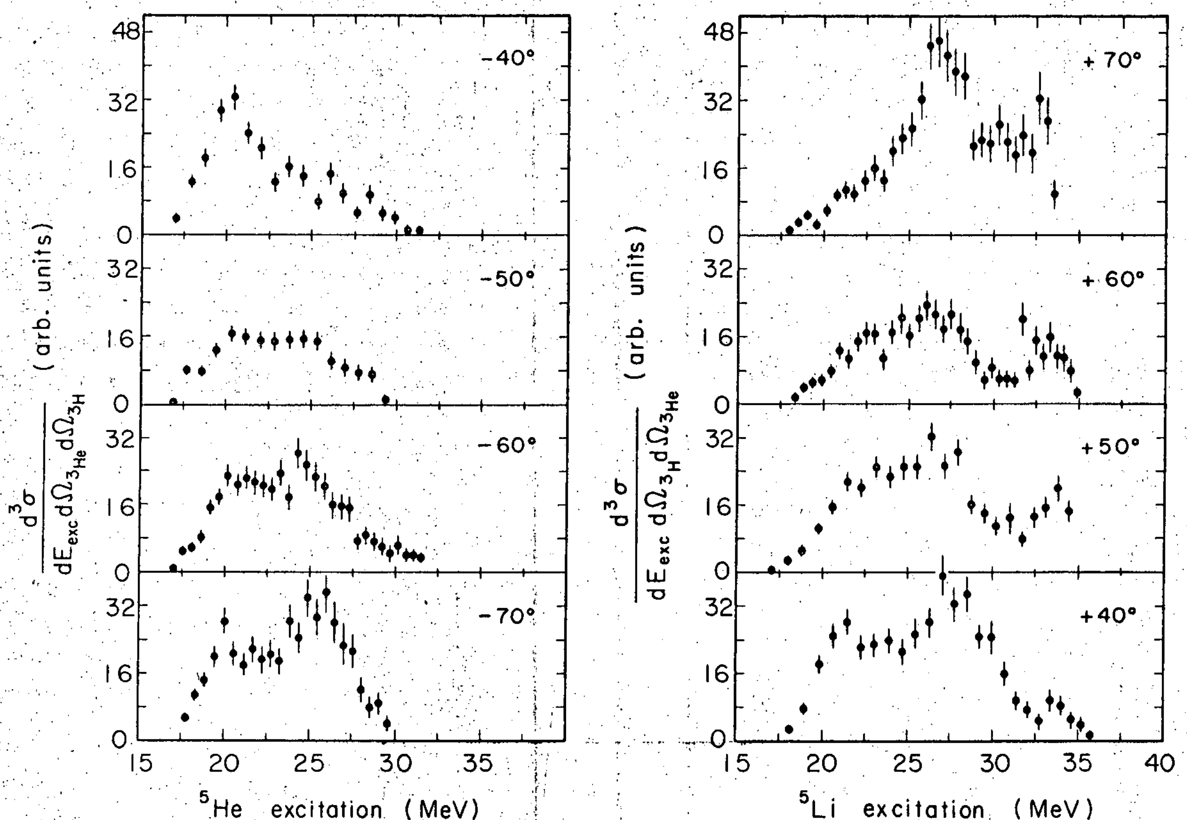
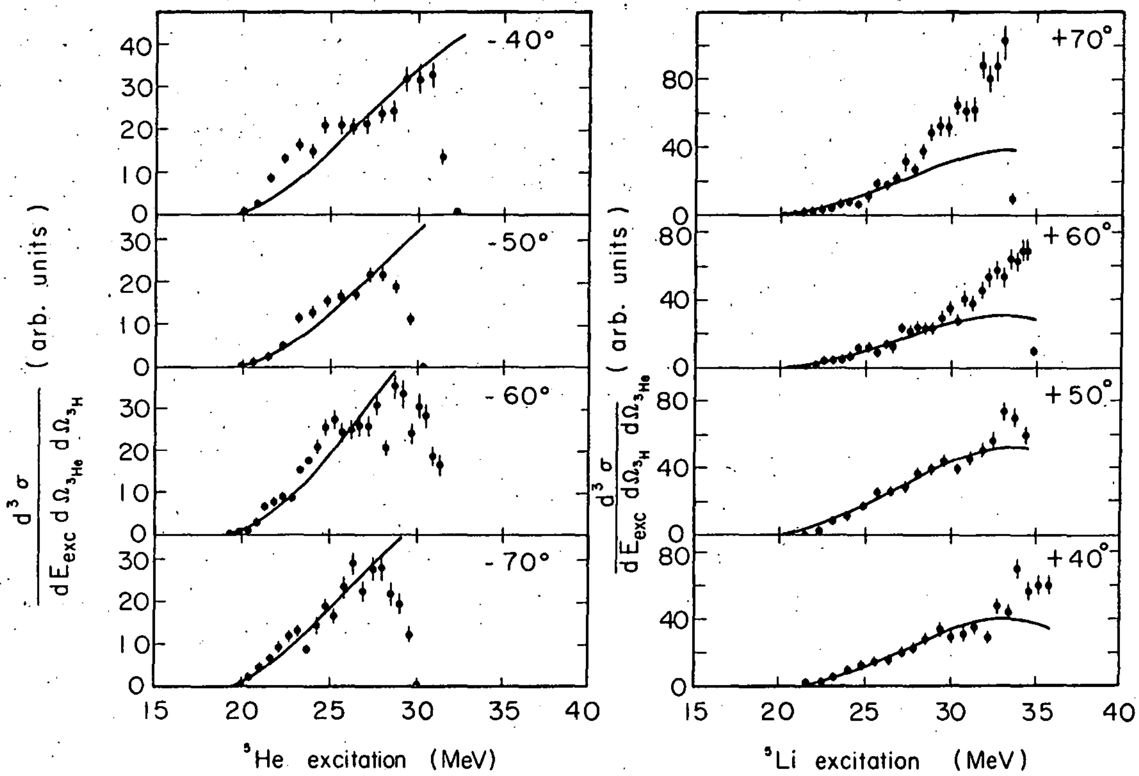

48
32
16
0
-40°
-50°
-60°
-70°
15
20
25
30
35
^{5}He excitation (MeV)
$\frac{d^3\sigma}{dE_{exc}\, d\Omega_{3He}\, d\Omega_{3H}}$ (arb. units)
+70°
+60°
+50°
+40°
40
^{5}Li excitation (MeV)
$\frac{d^3\sigma}{dE_{exc}\, d\Omega_{3H}\, d\Omega_{3He}}$ (arb. units)
XBL675-3146

Fig. 6



-40°
-50°
-60°
-70°
+70°
+60°
+50°
+40°
40
30
20
10
0
80
15
20
25
30
35
40
$\frac{d^3\sigma}{dE_{exc}\, d\Omega_{^3He}\, d\Omega_{^3H}}$ (arb. units)
^{5}He excitation (MeV)
^{5}Li excitation (MeV)
XBL675-3116

Fig. 7

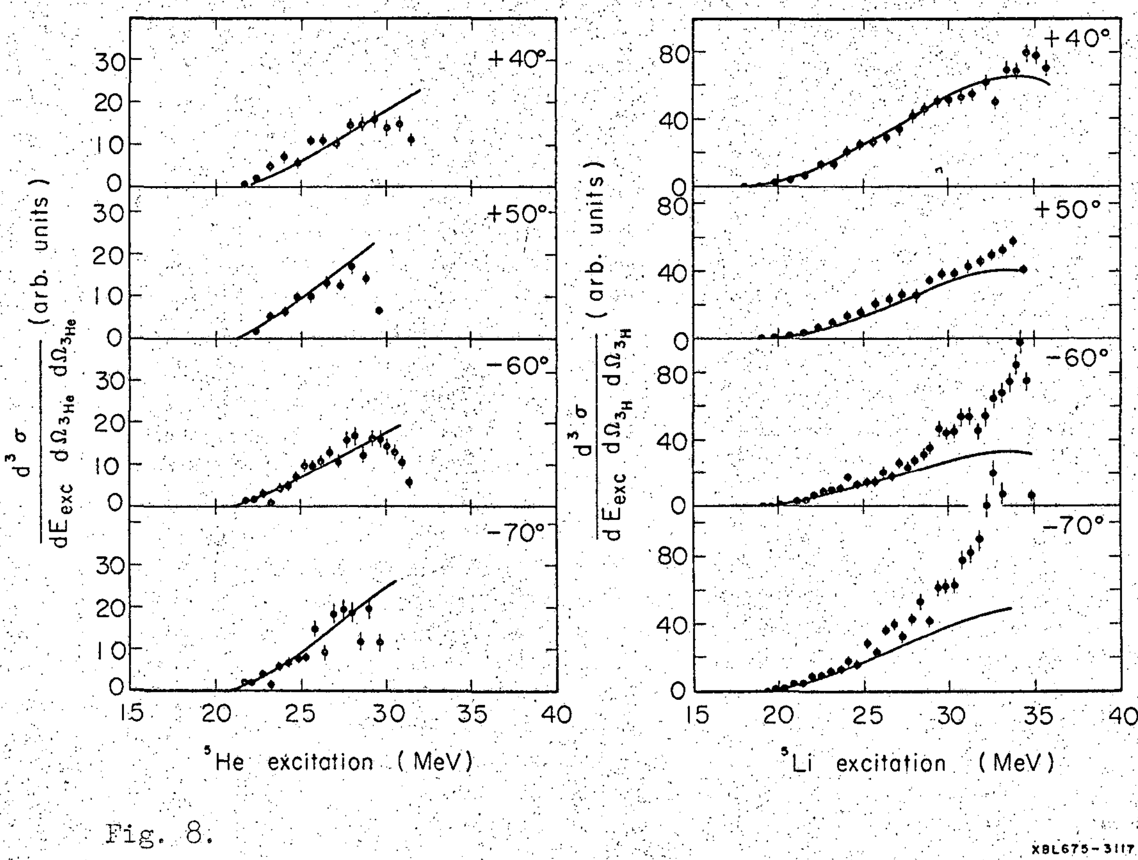
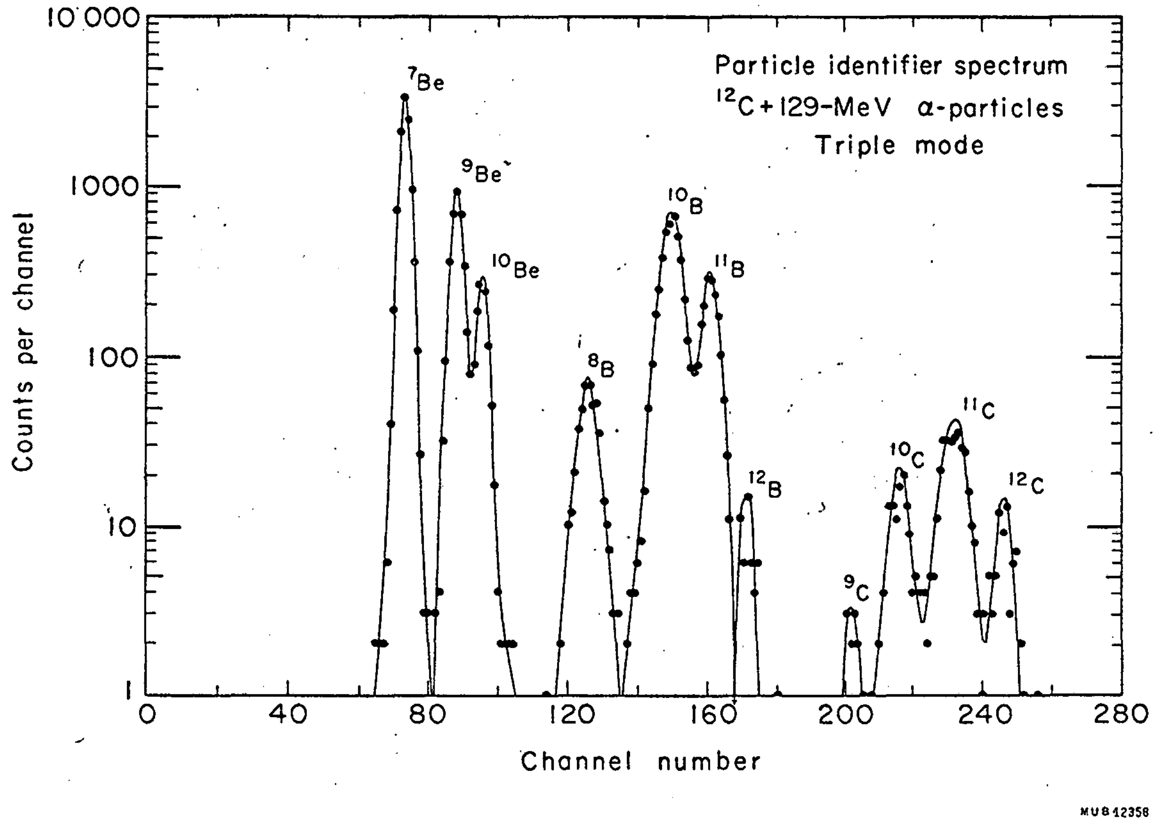

+40°
+50°
-60°
-70°
30
20
10
0
80
40
0
15
20
25
30
35
40
$\frac{d^3\sigma}{dE_{exc}\ d\Omega_{^3He}\ d\Omega_{^3He}}$ (arb. units)
$\frac{d^3\sigma}{dE_{exc}\ d\Omega_{^3H}\ d\Omega_{^3H}}$ (arb. units)
^{5}He excitation (MeV)
^{5}Li excitation (MeV)
XBL675-3117

Fig. 8.



10 000
1000
100
10
1
Counts per channel
Particle identifier spectrum
^{12}C + 129-MeV α-particles
Triple mode
^{7}Be
^{9}Be
^{10}Be
^{8}B
^{10}B
^{11}B
^{12}B
^{9}C
^{10}C
^{11}C
^{12}C
0
40
80
120
160
200
240
280
Channel number
MUB 12358

Fig. 9

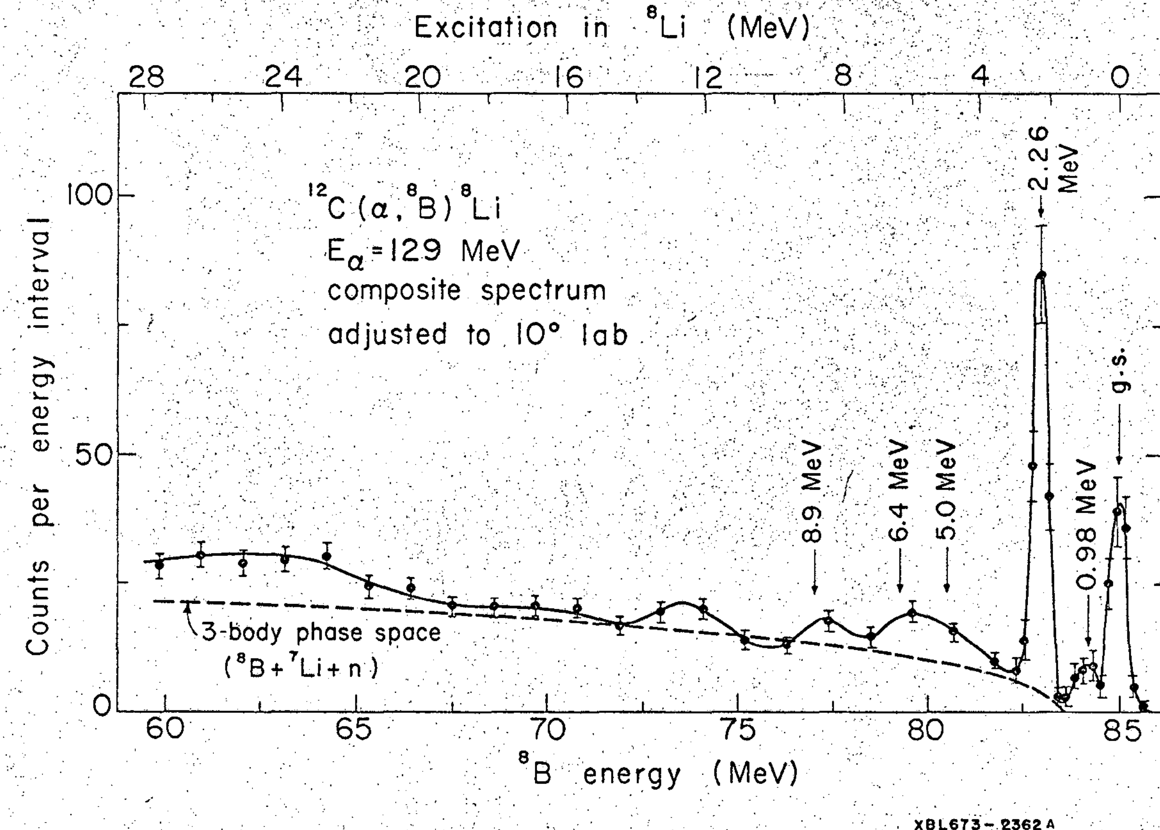
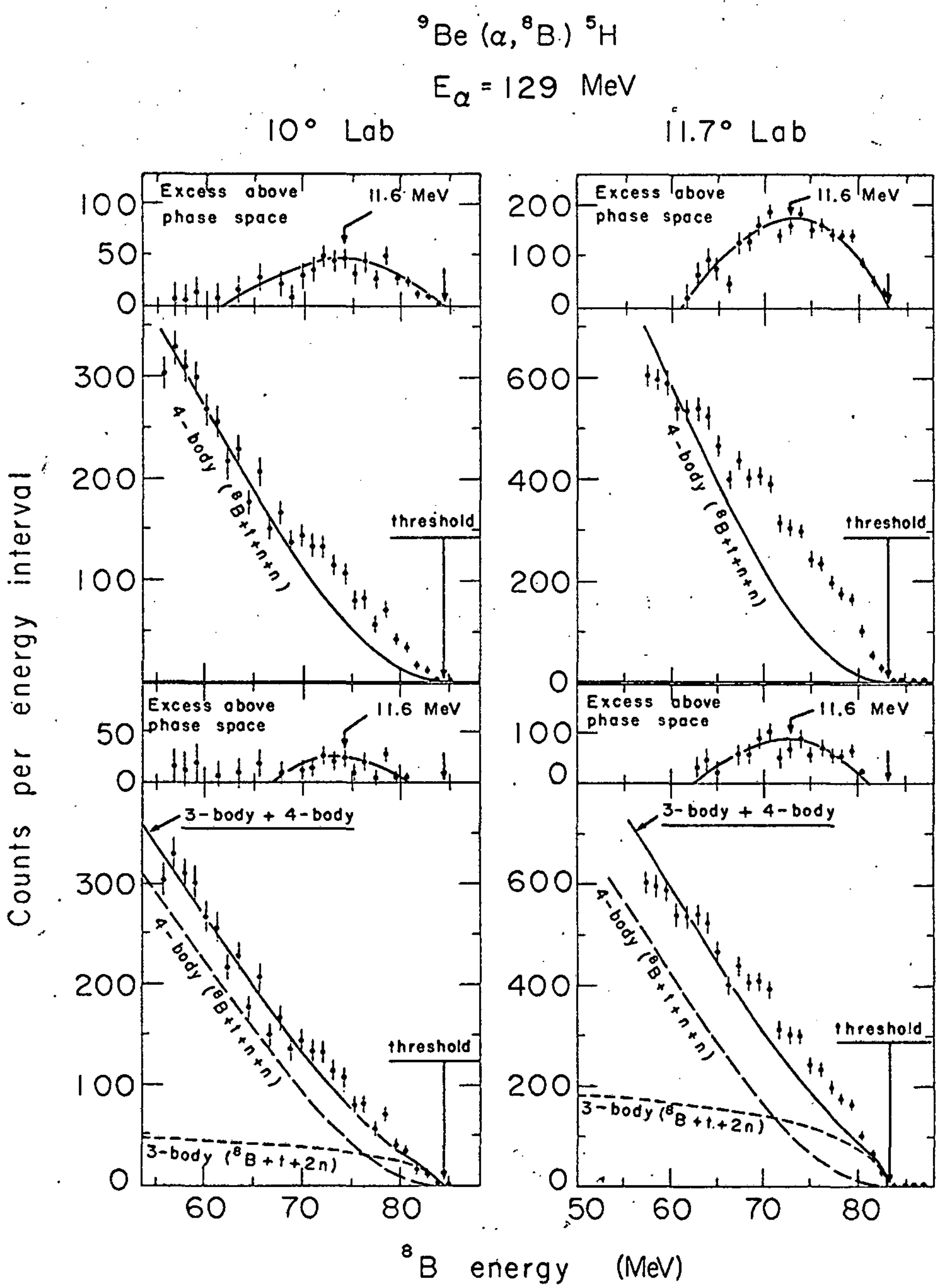

Excitation in ^{8}Li (MeV)
28
24
20
16
12
8
4
0
^{12}C (α, ^{8}B) ^{8}Li
E_α=129 MeV
composite spectrum
adjusted to 10° lab
2.26 MeV
g.s.
8.9 MeV
6.4 MeV
5.0 MeV
0.98 MeV
3-body phase space
(^{8}B + ^{7}Li + n)
Counts per energy interval
100
50
0
60
65
70
75
80
85
^{8}B energy (MeV)
XBL673-2362 A

Fig. 10



$^9Be(\alpha,^8B)^5H$
E_α = 129 MeV
10° Lab
11.7° Lab
Excess above phase space
11.6 MeV
4-body ($^8B+t+n+n$)
threshold
3-body + 4-body
3-body ($^8B+t+2n$)
Counts per energy interval
^8B energy (MeV)
XBL673-2358A

Fig. 11

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