The $Li^6(He^3, paa)$Reaction

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The bombardment of Li^6 with He^3 can lead to a three-body final state consisting of one proton and two alpha particles. At low bombarding energies this reaction may proceed by sequential processes through intermediate states of either Li^5 or Be^8. The terms state and sequential process are used here for simplicity even though they may refer to a modulation of the final-state wave function in phase space by resonance in the two-body final state interactions. These sequential processes may be represented by the following equations.

$$\begin{array}{l} \rightarrow p+Be^8 \\ \qquad\quad \rightarrow \alpha_1+\alpha_2 \\ Li^6+He^3 \\ \rightarrow \alpha_1+Li^5 \\ \qquad\quad \rightarrow p+\alpha_2. \end{array}$$

The energetically possible intermediate states of Be^8, which are known to break up predominantly by α decay, are the ground state, the 2^+ first excited state, the 4^+ broad second excited state, and the 16.62- and 16.92-MeV states. The energetically possible intermediate states of Li^5, which break up into a proton and an alpha particle are the $\frac{3}{2}^-$ ground state and the $\frac{1}{2}^-$ first excited state.

Studies of the spectra of the Li^6 $(He^3, p)2\alpha$ reaction by Erskine and Browne[1] have shown the existence of a large continuum in the proton spectrum. The origin of this continuum can be determined by measuring the energies, E_A and E_B, of two of the three particles emitted in the final system at angles θ_A and θ_B. Conservation of energy and momentum restrict all such events to a kinematic curve $E_B(E_A)$ in the two-dimensional energy spectrum, (E_A, E_B) at fixed θ_A and θ_B. Reactions which proceed by sequential processes through discrete states of the intermediate system will appear as points on this curve, segments of the curve in the case of broad states.[2]

The kinematic calculations for this reaction proceeding through the various intermediate states to the three-body final state have been carried out for 2.7-MeV incident He^3. One angle was held fixed at $+60°$ while the other angle was varied from $-150°$ to $+150°$. The results of such calculations are displayed on a two-dimensional plot of E_B versus E_A (Figs. 1 and 3) for two pairs of angles.

For reactions proceeding through intermediate states of small excitation energy, the particles resulting from the breakup of the intermediate state will be limited in angle to a cone about the recoil direction of the intermediate state. The kinematics allow two possible values for the energy of each emitted particle for every angle within this cone. (See Fig. 1 of Ref. 2). Therefore a given intermediate state may occur at two points on the kinematic curve. Also a given intermediate state is not necessarily observable at all angles. If the two particles detected are two alpha particles, there can be an additional two points on the kinematic curve for a given state, one point corresponding to the initial alpha particle being observed at θ_A, the other point corresponding to the initial alpha particle being observed at θ_B.[2]

Figure 1 illustrates the results of the calculations for $\theta_A=+60°$ and $\theta_B=-100°$. Kinematic curve A corresponds to detecting α particles at $+60°$ and protons at $-100°$. Curve B corresponds to detecting protons at $+60°$ and α particles at $-100°$. Curve C corresponds to detecting α particles at both $+60°$ and $-100°$. The locations of the various intermediate states and their widths (Γ) along the kinematic curves are indicated by the solid lines. In regions of overlapping states, the solid lines have been displaced slightly off the kinematic curve for clarity. This figure illustrates how complex a three-body breakup reaction can be for even such a simple system as $p\alpha\alpha$.

Figure 2 represents the experimentally observed two-dimensional energy spectrum for a thick solid state detector (9-MeV proton energy) at 60° and a thin solid-state detector (4-MeV proton energy) at 100°. This picture was obtained by applying the signals from the two solid state detectors to the x and y axes of an x–y oscilloscope and intensifying the trace whenever a coincidence occurred between the two counters. The α–α kinematic curve is clearly seen and peaks in the yield along this curve are observed corresponding to the $\frac{3}{2}$-ground state of Li^5 and the 16.62 to 16.92-MeV states (unresolved) of Be.[8] The p–α kinematic curves are seen for low proton energy only (due to the detector thicknesses), but no structure is observable along them. All pulses resulting from particles which pass through the depletion layer of the detector were removed electronically by rejecting pulses which had an appreciable slow-rise-time component. The intense

* Supported in part by the U. S. Atomic Energy Commission.
[1] J. R. Erskine and C. P. Browne, Phys. Rev. **123,** 958 (1961).
[2] C. Moazed, J. E. Etter, H. D. Holmgren, and M. A. Waggoner, Rev. Mod. Phys. **37,** 354 (1965).

peaks within the α–α kinematic curve correspond to the reaction Li^7 (He^3, α_0) Li^6 arising from the Li^7 contaminant in the isotopically enriched Li^6 target. The peak at the top of the picture corresponds to the C^{13} (He^3, α_0) C^{12} reaction arising from the carbon backing of the target.

The coincidence yield is strongly peaked in angle around $-100°$ and is predominately α–α coincidences resulting from the reaction proceeding through the $\frac{3}{2}^-$ ground state of Li^5 and the 16.62 to 16.92-MeV (unresolved) states of Be^8. However, the three-body kinematics limit the observation of these states of Be^8 to $-84° \geq \theta_B \geq -110°$ when $\theta_A = +60°$.

Quantitative information was obtained by projecting the kinematic curve onto both the x and y axes. A diagonal window condition requiring that $E_1 < E_A + E_B < E_2$, in addition to the coincidence requirement, can be imposed in order to remove most of the accidental coincidences from the projections. Windows

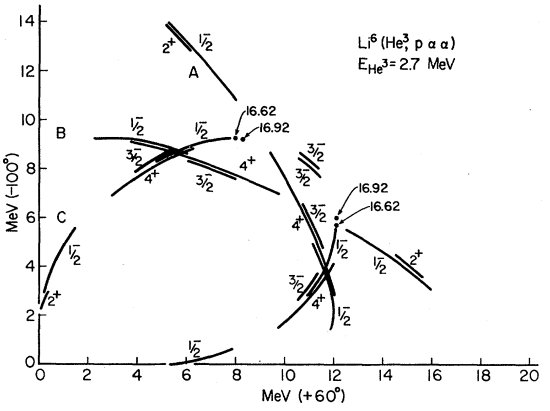


FIG. 1. The calculated two-dimensional energy spectrum for $\theta_A = +60°$ and $\theta_B = -100°$. The locations of various intermediate states of Be^8 and Li^5 are indicated.

can also be placed on the projected spectra in order to select regions of interest. Even with such restrictions, regions of the $(+60°, -100°)$ kinematic curve corresponding to particular intermediate states cannot be isolated for study because the p–α and α–α kinematic curves overlap. At other angles these kinematic curves do not overlap and it is possible to isolate particular intermediate states.

Figure 3 shows the kinematic calculations for $\theta_A = +60°$ and $\theta_B = -70°$. Curve A corresponds to detecting α particles at $+60°$ and protons at $-70°$. Curve B corresponds to detecting protons at $+60°$ and α particles at $-70°$. Curve C corresponds to detecting α particles at both $+60°$ and $-70°$. The labeling of the various intermediate states is the same as in Fig. 1. Figure 4 represents the experimental two-dimensional energy spectrum for thin solid-state detectors at both $+60°$ and $-70°$. The $\frac{1}{2}^-$ first excited state of Li^5

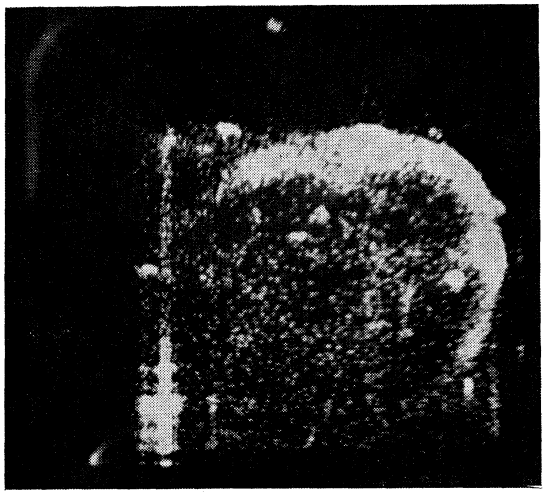


FIG. 2. The two-dimensional energy spectrum for the $Li^6(He^3, p\alpha\alpha)$ reaction at $\theta_A = +60°$ and $\theta_B = -100°$ for a bombarding energy of 2.7 MeV.

is evident in the α–α kinematic curve. The α–p kinematic curves are cut off at low proton energies, since thin detectors were used at both angles. The $\frac{1}{2}^-$ state in the α–α kinematic curve could be isolated in the projected spectra by using a diagonal window to eliminate the low energy accidentals and a differential window on the projections to eliminate the high-energy alphas from the p–α kinematic curves. The projected spectra must be transformed back to the kinematic curve in order to extract the energy and width of the state. The feasibility of obtaining such information has been demonstrated and detailed measurements are in progress.

The two-dimensional spectra obtained at a number of combinations of the angles θ_A and θ_B clearly show that at low bombarding energies the final-state two-body interactions between the three final-state particles

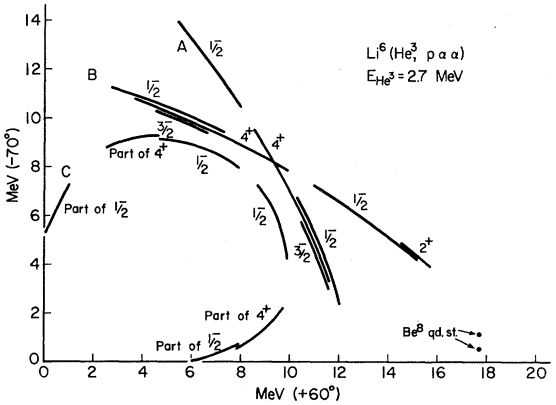
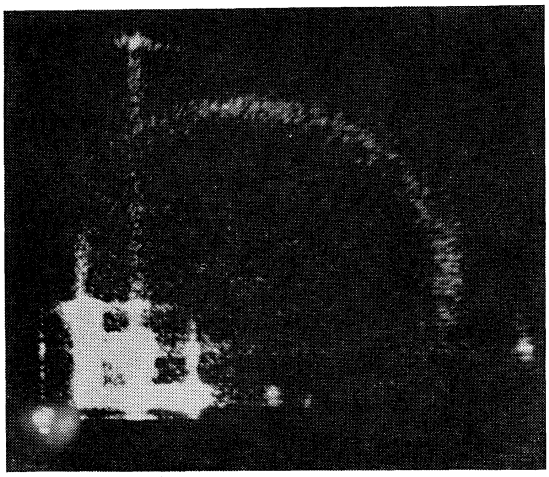


FIG. 3. The calculated two-dimensional energy spectrum for $\theta_A = +60°$ and $\theta_B = -70°$. The locations of various intermediate states of Be^8 and Li^5 are indicated.



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of the Li^6 (He^3, $p\alpha\alpha$) reaction strongly modulate the phase-space distribution of states.

Discussion for the 3 Preceding Papers

HENLEY: Thank you for this remarkable feat of presenting three papers so quickly.

PHILLIPS: What is the percentage of sequential decay in your experiments versus the percentage of simultaneous three-body or four-body decay? Could you give is an estimate of this?

HOLMGREN: The contribution from nonsequential processes is very small. Our best guess is that it is only a few percent; but it is difficult to give an accurate estimate since the correlations have not been studied out of the reaction plane. In addition, it is somewhat difficult to separate the contributions from the broad 4+ state of Be^8 from the nonsequential decay.

PHILLIPS: In all experiments this is our experience. The only thing we can say is that it is probably less than 5%.

NORBECK: Our experience with the Li^6 reaction which produces three alphas, is that probably over 50% of the reaction goes by mechanisms which are not sequential.

PHILLIPS: It seems to me, that before we can be quantitative on these percentages, we have to have a theory that starts with known final state interactions, with scattering phase shifts, or something of this sort. We must take the best theory we have, try to explain our data, and see how well we can succeed. And from the failure to explain the data, with the sequential model, then we can split limits. But right now no one knows.

KRAMER: I would like to add that it is necessary to measure the complete population of the plot, and therefore you need to change your angle in order to make comments on the percentage. One should be careful, in obtaining a percentage of sequential decay from one fixed angle.

WAGGONER: I agree completely that one can't do it on the basis of one fixed angle. In presenting the results on the three reactions I showed data at only one pair of angles for each reaction. But we have obtained two-dimensional energy spectra at *many* pairs of angles for each reaction and we see the same effect in each case. We see practically none of the quasifree type of process; in each case the effect of the two-body interactions among the components of final state is very strong.

DONOVAN: These experiments are even more sensitive than you might at first think to picking up any nonsequential processes. In general, direct processes tend to be co-planar with the beam axis, whereas the sequential processes can go out of the plane very easily.

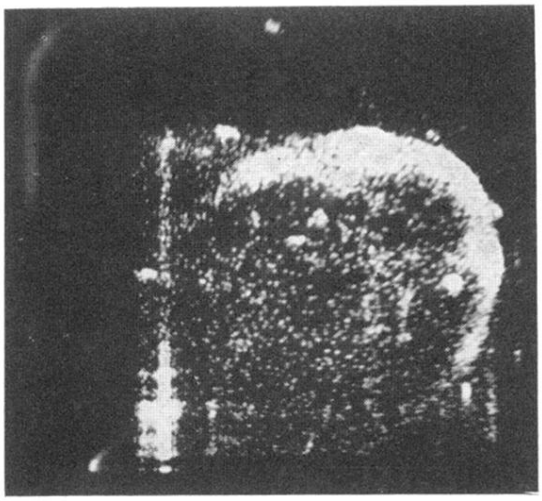
So now, since one is measuring in the plane in these experiments, you are looking really in the most sensitive way for nonsequential events. So when you see mostly sequential events in the plane, then the total process is very probably even much more sequential.

KAMKE: I would like to ask for a simple proof of the statement Mr. Donovan just made.

DONOVAN: Most of the cross section in the peripheral process comes where there is a low-momentum transfer to one of the constituent particles from one of the particles in the target or in the beam. In that case, in order to conserve momentum, the other two have to be co-planar. That's the simple, physical argument.

ZUPANČIČ: I somehow don't like the dogmatic war between the sequential people and the nonsequential people! Of course, if you are willing to call processes where broad states overlap sequential as well, you are free to do so. One can always in quantum mechanics expand any wave function in terms of any other complete set of wave functions. So in this sense you can always say everything is sequential. But I think, perhaps, you should reserve this term for processes where narrow, isolated states are involved. And it is clear that you certainly have another limit where you have very high energies and very weakly bound particles which, in principle, you can also describe in terms of intermediate states; but it is just not useful to do so.

WAGGONER: I agree strongly with that point. That is why I said I thought the question should be worded very carefully. We should be asking not whether the process is sequential or nonsequential but rather what is the extent to which the two-body interactions among the components of the final state effect the phase-space distribution in the final state.



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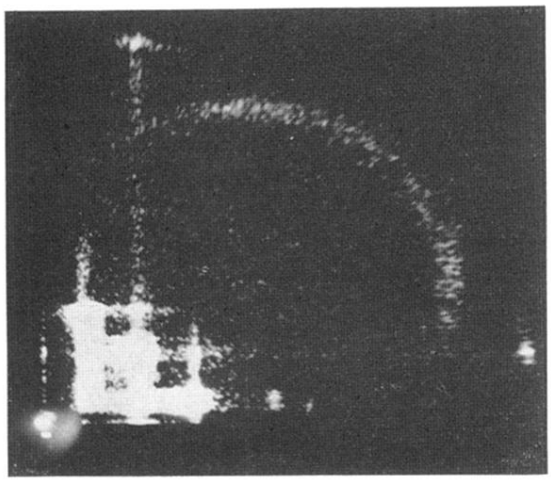

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