

INVESTIGATION OF THE MECHANISMS OF ${}^6\text{Li}$ -INDUCED REACTIONS

FAR ABOVE THE COULOMB BARRIER

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Our charged-particle singles¹⁾ and particle γ -ray coincidence measurements²⁾ have indicated that fragment transfer accounts for only about 10 to 13% of the production of fast α particles and deuterons. In an effort to ascertain other reaction mechanisms which will account for the rest of the cross section, we have extended our measurements to particle-particle coincidences. These measurements were performed in the IUCF 163-cm scattering chamber with two (200 μm and ΔE and 5000 μm E) silicon surface-barrier detector telescopes. Angular correlations were measured for the 75-MeV ${}^6\text{Li}$ bombardment of ${}^{197}\text{Au}$ by locating one telescope at 25° (lab) and moving the second over a variety of angles varying from 120° (95° back of the fixed detector) to -90° (on the opposite side of the beam from the fixed

telescope). In Figure 1 is shown the α -d correlation pattern which exhibits a pronounced double peaking on either side of the gating detector angle (25°). The black dots correspond to α -d coincidences for which the α particle was detected at 25° and the deuterons at various other angles (α -gated correlation). The open circles correspond to a d- α coincidences with the deuteron detector fixed at 25° (d-gated correlation). Both correlations were taken simultaneously and sorted later in the off-line analysis. Coincidences within approximately 13° of the gating detector are dominated by events from the sequential breakup of the ${}^6\text{Li}$ through its 2.18-MeV 3^+ first excited state. This type of breakup has several distinguishing characteristics, three of which are indicated in Figures 2 and 3. The gating spectrum in the inset of Figure 2 shows the typical double-peaking in the α -particle and deuteron spectra characteristic of the kinematics of the binary dissociation of a nucleus with a definite positive Q value (0.71 MeV in this case). The figure also illustrates that the high-energy α -particle group is correlated with the low-energy deuteron group and vice versa. In Figure 3 we see the coincidence particle spectra as a function of the angular separation (θ_{12}) of the two telescopes. It is clear that the energy separation of the α -particle peaks and also of the deuteron peaks decreases as θ_{12} increases. Furthermore this dual peaking characteristic survives only until θ_{12} equals approximately 13° , beyond which sequential breakup α +d coincidences are absent. This is consistent with kinematic limits on the expected size of the sequential breakup cone for dissociation from the 2.18-MeV 3^+ state in ${}^6\text{Li}$. There are also numerous coincidences beyond this sequential cone, and we

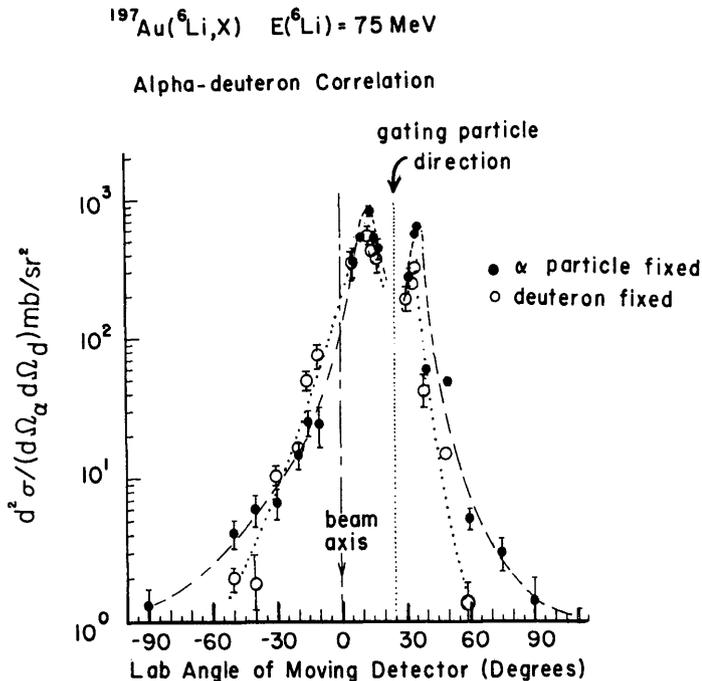
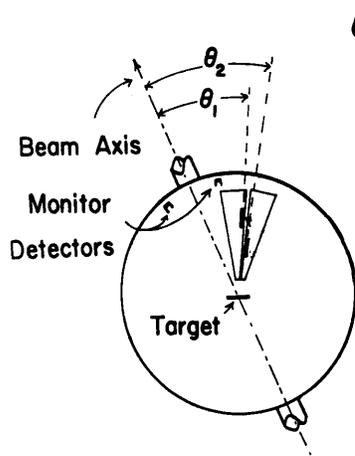


Figure 1. α -d correlation pattern from the 75-MeV ${}^6\text{Li}$ bombardment of ${}^{197}\text{Au}$. The black dots represent the deuteron intensity correlated with α particles detected at 25° ; the open circles represent the α particle intensity correlated with deuterons at 25° . The gating particle direction and the beam axis (0°) are indicated for clarity.

$^{197}\text{Au}({}^6\text{Li}, X)$
 $E({}^6\text{Li}) = 75 \text{ MeV}$ $\theta_1 = 25^\circ$
 Particle-Particle Coincidences



$\theta_{12} = 9^\circ$

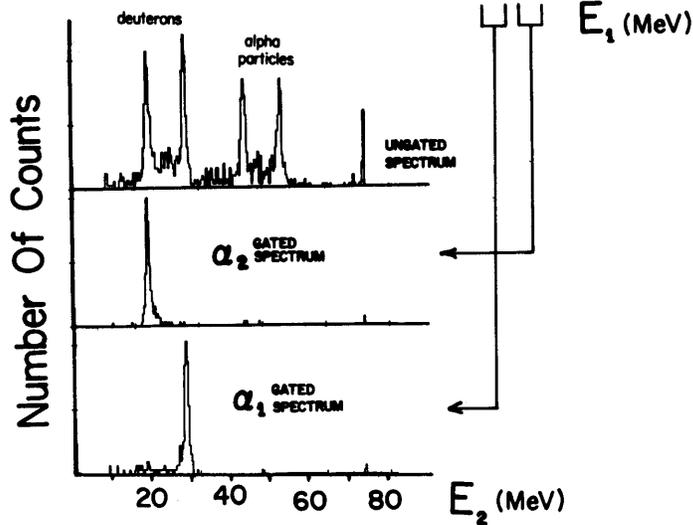


Figure 2. Schematic of the coincidence relationships among the sharp peaks in the coincidence deuteron and α -particle spectra. Inset at the left shows positions of detector telescopes in the scattering chamber.

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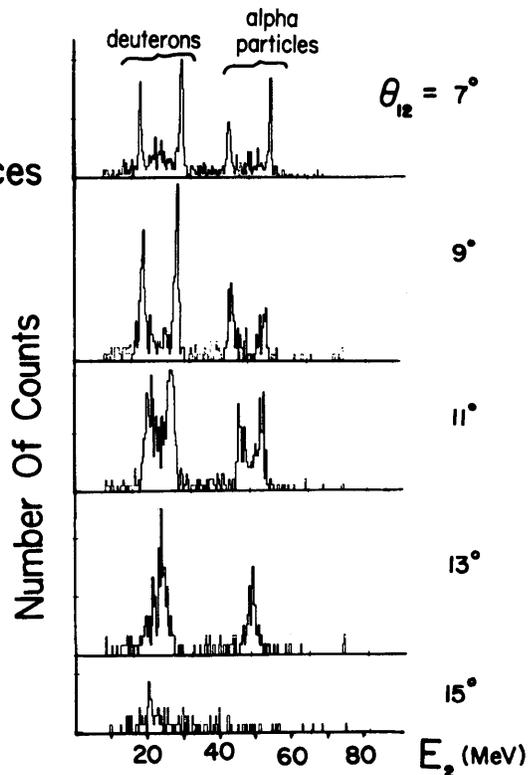
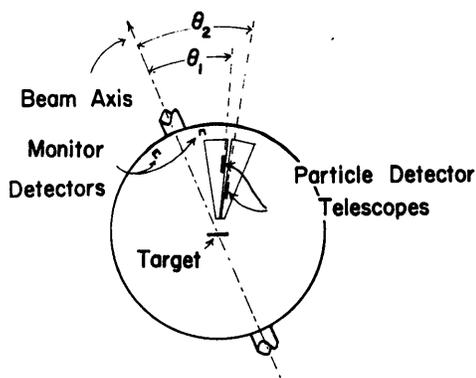


Figure 3. Qualitative view of the characteristics of the particle coincidence spectra for various values of the angular separation of the detector telescopes ($\theta_{12} = \theta_2 - \theta_1$). The dual peaking feature, characteristic of sequential breakup of the ${}^6\text{Li}$ through its 2.18 MeV state, is seen to disappear for $\theta_{12} > 13^\circ$, consistent with the expected limit imposed by the kinematics for this type of decay.

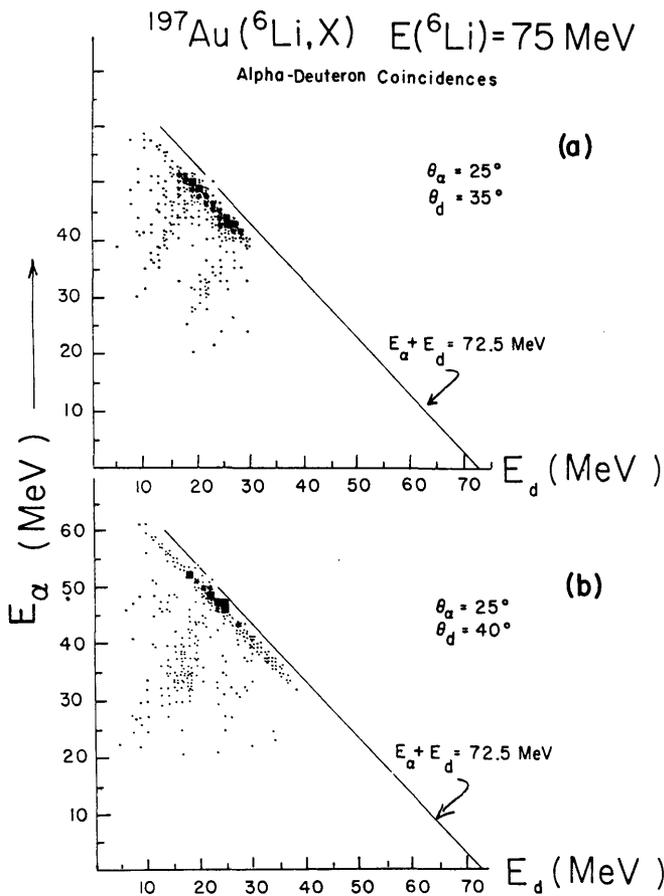


Figure 4. Correlated $E_\alpha - E_d$ spectra for the 75-MeV ${}^6\text{Li}$ bombardment of ${}^{197}\text{Au}$. (a) For $\theta_{12} = 10^\circ$ the dual-peaked character is evident, along with some intensity at high inelasticity. (b) For $\theta_{12} = 15^\circ$ the dual peaking has degenerated into a single peak around beam-velocity values, and a definite inelastic group is evident, corresponding to 17-27 MeV excitation in the residual system. The line $E_\alpha + E_d = 72.5 \text{ MeV}$ corresponds to a kinematic locus equal to the beam energy reduced by the α -d binding energy (1.47 MeV), average beam degradation in the target (0.5 MeV), and average recoil energy loss (0.5 MeV).

attribute these events to direct, non-sequential dissociation, because the α particles and deuterons involved exhibit kinetic energies grouped in single peaks centered approximately at the beam velocity. In Figure 4 are shown two correlated α -d energy spectra for $\theta_{12} = 10^\circ$ (within the sequential cone) and $\theta_{12} = 15^\circ$ (outside the sequential cone). The dual peaking at $\theta_{12} = 10^\circ$ is evident in Figure 4a, and its degeneration into a single-peaked group at $\theta_{12} = 15^\circ$ is clear in Figure 4b. Integration of the α -gated α -d correlation, assuming azimuthal symmetry about the fixed α -particle direction, yields a differential cross section $d\sigma_{\alpha d}/d\Omega_\alpha$ of $143 \pm 22 \text{ mb/sr}$ for production of α particles at 25°

which are correlated with deuterons. Thus, this correlated α -d production accounts for approximately 25% of the singles yield of α particles at 25° ($570 \pm 62 \text{ mb/sr}$). Integration of the same α -d correlation over $\theta_{12} \leq 13^\circ$ gives $d\sigma_{\alpha d}/d\Omega_\alpha \approx 70 \text{ mb/sr}$ at $\theta_\alpha = 25^\circ$, or approximately half of the α -d yield at this geometry.

It is interesting to note that approximately 25% of the α -d coincidence events exhibit large inelasticity, corresponding to excitations in the residual system up to approximately 30 MeV (see Figure 4). Especially interesting is an apparent localization of this excitation at 17-27 MeV (Figure 4b) for $\theta_{12} = 15^\circ$. The present data were not sufficient to explore any features of these inelasticities such as their beam-energy dependence or angular distribution.

In Figure 5 we show the measured α -proton angular correlation. The black dots represent the measured result with the α -particle detector fixed at 25° and the proton detector angle varying, and the open circles represent the p- α correlation with the proton detector fixed. A dramatic feature of the result is the pronounced asymmetry in the α -gated correlation namely the strong preference for the emission of protons between their correlated α -particle's direction and the beam axis.

Shown in Figure 6 are correlated α -p energy spectra for $\theta_{\alpha p} = 15^\circ$ and 25° . The correlated spectra for $\theta_{\alpha p} = 15^\circ$ show dual groups of proton and α -particle energies similar to the sequential ${}^6\text{Li}$ breakup energy distributions (cf. Figure 4a); however the groups are not very highly localized in the α -p case. In addition, this grouping is definitely absent for $\theta_{\alpha p} = 25^\circ$.

Correlated protons and α particles can be produced in a variety of ways. First the ${}^6\text{Li}$ could undergo a 3-body breakup into $\alpha+p+n$. However, $\alpha+p+n$ decay of ${}^6\text{Li}$ has never been observed from any excited state below 25 MeV^3 and the necessarily statistical sharing of energy

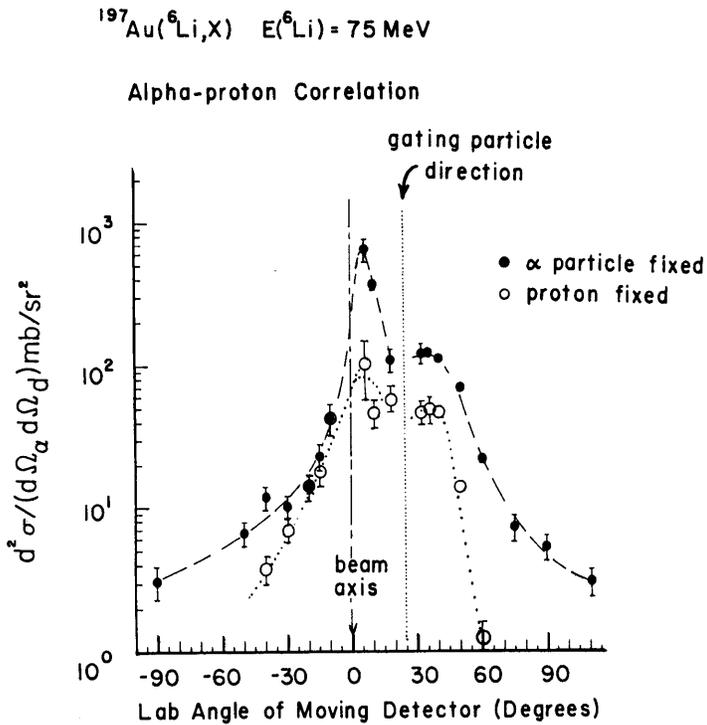


Figure 5. α -proton correlation pattern for the 75-MeV ^6Li bombardment of ^{197}Au . The symbols have the same meaning as in Figure 1, except proton rather than deuteron intensity is being considered.

among the three fragments requires that the energy carried by all the correlated $\alpha+p$ events lie below the kinematic limit shown as curve a in Figure 6 (this curve being determined by the minimum allowed lab energy for the neutron in a 3-body statistical breakup). Second, $\alpha+d$ breakup could be followed by deuteron dissociation, whose kinematic limit for $E_\alpha + E_p$ is given by curve d in Figure 6. The correlated $E_\alpha + E_p$ events are, in fact, concentrated beyond these limits, which tends to rule out both of the above mechanisms. A more plausible mechanism is the single neutron transfer to the target, forming particle-unstable ^5Li , which decays to $\alpha+p$ with a 1.97 MeV Q value and a lifetime of approximately 4.4×10^{-22} sec.³⁾ The kinematic limits for $E_\alpha + E_p$ under neutron transfer to the ground state of ^{198}Au and at the optimum Q-value are denoted by b

$^{197}\text{Au}(^6\text{Li}, X) E(^6\text{Li}) = 75 \text{ MeV}$

Alpha-Proton Coincidences

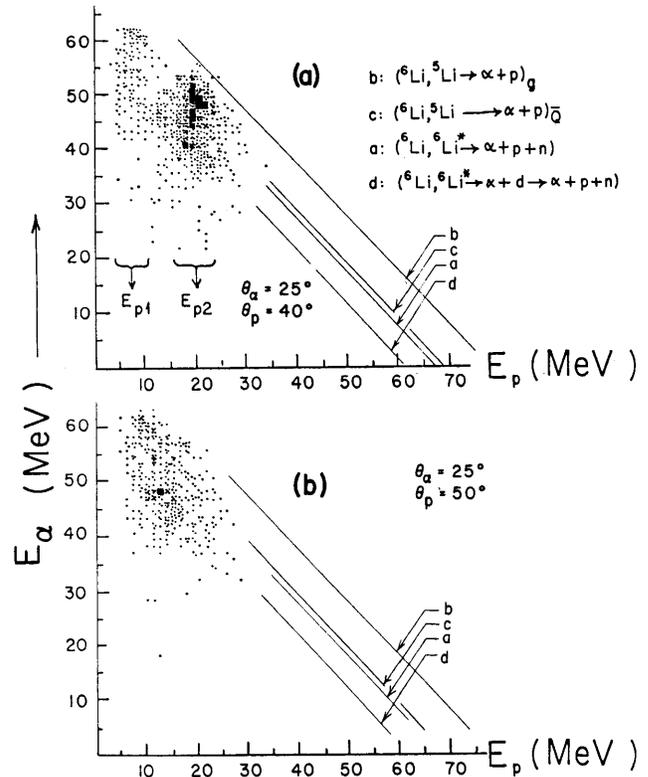


Figure 6. Correlated $E_\alpha - E_p$ spectra for the 75-MeV ^6Li bombardment of ^{197}Au . The diagonal lines represent limits on $E_\alpha + E_p$ imposed by the kinematics of the various reaction mechanisms noted (see text). (a) For $\theta_{\alpha p} = 15^\circ$ distinct double grouping of the events is evident, characteristic of the kinematics of ^5Li breakup. (b) For $\theta_{\alpha p} = 25^\circ$ this double grouping has degenerated into a single group centered at the beam velocity.

and c, respectively in Figure 6. The correlated energy data are much more consistent with the ^5Li formation mechanism, with a preference for the transfer at the optimum Q-value. The +1.97-MeV ^5Li breakup Q-value combines with the beam energy to give a maximum opening angle $\theta_{\alpha p}$ of 23.8 degrees for correlated $\alpha+p$ event from ^5Li breakup. The dual energy groups evident in Figure 6a for $\theta_{\alpha p} = 15^\circ$ occur at energies consistent with their production from ^5Li decay, and the absence of this feature at $\theta_{\alpha p} = 25^\circ$ agrees with the kinematic limits expected for this type of breakup.

Considering once again the correlation pattern shown in Figure 5 with the black dots (α -gated correlation), the enhanced proton production between the

beam axis and the gating α particle can also be understood in the context of the neutron transfer mechanism. It is reasonable to expect that the stripping of a neutron from the ${}^6\text{Li}$ would tend to leave the odd proton in ${}^5\text{Li}$ closer to the target than the α particle. Thus, because of the short lifetime of the ${}^5\text{Li}$ ground state, the direction of the $\alpha+p$ decay products would tend to reflect this orientation, thereby giving the strong enhancement observed.

Finally, integration of the α -gated α -p correlation (assuming azimuthal symmetry about the α particle direction for $\theta_{\alpha p} > 25^\circ$ and arbitrarily taking 25% of the symmetric integration about the α -particle direction for $\theta_{\alpha p} \leq 25^\circ$) is 156 ± 50 mb/sr, which is approximately 27% of the singles α yield at 25° .

The present measurements indicate that charged particles from ${}^6\text{Li}$ -induced reactions on ${}^{197}\text{Au}$ are produced from the following mechanisms (percentage figures apply to the contribution to α particle production at $\theta_\alpha = 25^\circ$):

- (a) cluster transfer to the target (approximately 13%).
- (b) sequential $\alpha + d$ breakup of ${}^6\text{Li}$ through its 2.18-MeV first excited state (approximately 12%)
- (c) direct (non-sequential) ${}^6\text{Li} \rightarrow \alpha + d$ dissociation (approximately 13%)
- (d) Neutron transfer to the target, forming $(\alpha + p)$ -unstable ${}^5\text{Li}$ (approximately 27%).

Other mechanisms which may be present but which could not be observed in the present measurements are:

- (e) Proton transfer to the target, forming $(\alpha + n)$ -unstable ${}^5\text{He}$
- (f) Deuteron pickup from the target, forming $(\alpha + \alpha)$ -unstable ${}^8\text{Be}$.

In summary, we believe that most of the particle-production cross section has been accounted for. The

widely-observed excess of α particles over deuterons in ${}^6\text{Li}$ induced reactions can be understood as the result of the presence of mechanisms which produce α 's and not deuterons. Furthermore, it is clear that the singles spectra and angular distributions are composites of several reaction channels and as such are of marginal use as the sole source of information as the reaction mechanisms present. Further discussion of all of our results in greater detail has been submitted for publication.

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