cays.[1,6]

The $B(M1)$ and $B(E2)$ values between the isobaric analog state in ^{20}Ne and the 7.415-MeV level have not been measured so it is not possible to obtain a quantitative theoretical value for a. We can obtain an estimate of the "weak magnetism" contribution to the interference effect using conserved vector current (CVC) theory by assuming that the $M1$ strength has the single-particle limit and using the experimental $\log ft$ for this transition (4.45) to evaluate the GT matrix element. Using the expression derived by Gell-Mann[7] for $|a|$, a value ~0.004 is obtained, approximately the same as had been calculated and measured for ^{8}Li and ^{8}B, but $\frac{1}{6}$ that observed for ^{20}Na. It is clear that other second-order matrix elements are contributing in this case. If they are associated with the axial-vector interaction only, then it is not possible to estimate their contribution using CVC theory.

An interesting possibility is the contribution from an enhanced second-order vector interaction which is the analog of the $E2$ matrix element.[8] For a nucleus like ^{20}Ne which is a "good rotational nucleus," several enhanced $E2$ transitions have been observed, even for cases where $\Delta T = 1$.[9] A more detailed expression for a incorporating the $E2$ matrix element has been derived by Weidenmüller.[10] This contribution was found to be negligible in the ^{8}Li-B^8 work. For ^{20}Na, the the ratio $B(E2)/B(M1)$ for the transition from the analog state to the 7.415-MeV level would have to be ~5 in order to account for the magnitude of the observed β-α anisotropy. The $M1$ and $E2$ strengths from the analog state to the 7.415-MeV state have not been measured so it is not possible to determine at this time which of the second-order matrix elements are responsible for this relatively large interference effect.

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MECHANISM OF LITHIUM-INDUCED NUCLEAR REACTIONS*

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Peaks in the zero-degree yield curve of the reaction $C^{12}(Li^7,\alpha)N^{15}$ are interpreted as due to resonances in the $C^{12}t\alpha$ system.

Lithium-induced nuclear reactions have been interpreted as primarily direct in character at energies well below[1] and well above[2] the Coulomb barrier. However, they show strong signs of compound-nucleus formation near the Coulomb barrier.[3] The reaction mechanism is of interest in itself but there is an added spur to its understanding caused by the desire to use these reactions as tools in the study of nuclear structure. The Li^7+C^{12} reactions were studied with these interests in mind. The reactions show peaks at zero degrees with a spacing and width similar to that observed[4-7] in other lithium-induced reactions and lead to the suggestion that an extended structure of the lithium nucleus may be the source of these peaks.

Experimental measurements were made with thin (50 keV energy loss to 5-MeV Li^7 ions) self-supporting carbon targets and an E-ΔE detector telescope system. Targets were bombarded with Li^7 ions from the University of Iowa Van de Graaff accelerator. An angular acceptance of 1° was used in the detector system. Pulses were recorded in a ΔE vs E matrix in the memory of

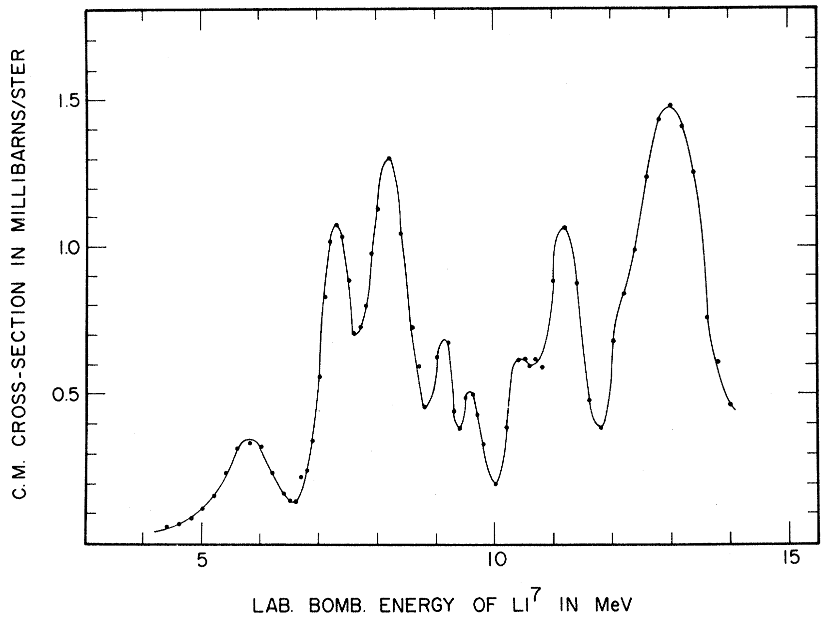

FIG. 1. Center-of-mass cross section for the reaction $C^{12}(Li^7,\alpha_0)N^{15}$ at 0° as a function of laboratory bombarding energy of Li^7.

a general purpose computer. After the run, the various particle types and groups were sorted out and the yields obtained. Measurements were made at 0° and 40° for low-lying groups in the following reactions:

$$Li^7 + C^{12} \to N^{15} + \alpha + 12.382\text{ MeV},$$
$$\to O^{16} + t + 4.694\text{ MeV},$$
$$\to O^{17} + d + 2.597\text{ MeV},$$
$$\to O^{18} + p + 8.401\text{ MeV}.$$

In addition, angular distributions were measured at a number of bombarding energies. Care was taken to check for carbon buildup on the target. The results for the ground-state alpha group at 0° are shown in Fig. 1. Absolute errors in the cross section are less than 10%.

Besides the ground-state alpha-particle group, other alpha-particle groups show similar resonancelike structure, but peaks come at different energies. The ground-state triton group also shows pronounced structure but at about half the cross section. In the case of the protons and deuterons, structure is less pronounced and cross sections are smaller. Data taken at 40° showed the same general character as that taken at 0°, but cross sections were less. Peaks observed at 40° do not, in general, occur at the same energy as those observed at zero degrees; there is little, if any, cross correlation between the particle groups.

An autocorrelation analysis of the data gives a coherence energy of about 0.4 MeV. The compound nucleus is F^{19} with an excitation running from 19 to 25 MeV. For this compound nucleus one would expect a coherence energy of about 0.2 MeV.[8] Because of the large finite-range-of-data error inherent in the present data, one cannot rule out Ericson fluctuations as the explanation of the observations; however, one is led to search for other possible explanations of these peaks.

In addition to the peaks observed in the $Li^7 + C^{12}$ reaction, broad resonancelike peaks have been observed in the yields of a number of lithium-induced reactions: $Li^6 + Li^6$,[4] $Li^6 + B^{10}$,[5] $Li^6 + C^{12}$,[6] and $Li^6 + O^{16}$.[7] The heavier the mass of the target nucleus, the narrower and more closely spaced the peaks are observed to be. Compound-nucleus excitations over a considerable range are contained in these results. This ubiquity can be explained on the basis of high probability of the lithium nucleus existing in an extended state or, in other words, in terms of the cluster structure of lithium.

Figure 2 shows the potential energy of the $C^{12} + Li^7$ and $N^{15} + \alpha$ systems as functions of the distance between the centers of the particles, and the potential energy of the $C^{12} + t + \alpha$ system, considered as three spheres strung out in a line, as a function of distance between the centers of the outermost particles. Coulomb energy and rota-

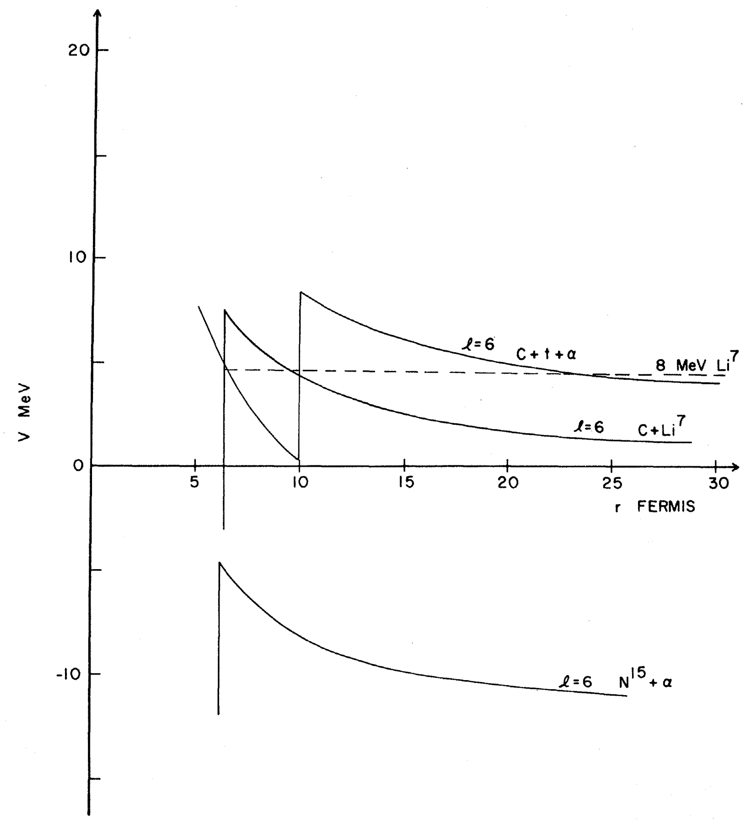

FIG. 2. Potential energy of indicated systems of particles as functions of distance between centers of particles in two-particle cases and between centers of C^{12} and α in three-particle cases. Dashed line indicates position of observed 0° resonance peak and zero-point energy in well.

tional energy are calculated on the basis of point masses and $l = 6\hbar$. Both contributions are significant. Nuclear forces were taken as arising from a square well with a radius of $r_0 A^{1/3}$ ($r_0 = 1.5$ F). In the three-particle case, the triton was positioned approximately midway between the C^{12} and α so that $C^{12}t$ and $t\alpha$ contact occurred at the same time.

Nuclear forces will come into play abruptly when contact is made. This is indicated by the vertical line in each potential curve. For the two-particle case, one would expect the nuclear well to be quite deep, on the basis of the optical model. For the three-particle case, the nuclear force will be weaker and the well shallower because of the reduced amount of contact. The potential rises as the outer particles are brought closer together because of the rotational and Coulomb energy. For some cases, this rise will be sufficiently rapid to define a potential well within which the three-body system can resonate.

A dashed line is drawn in Fig. 2 to indicate an experimental resonance energy. For grazing collisions, this experimental bombarding energy corresponds to the l value indicated on the potential curves. It is expected that grazing collisions will contribute most of the forward-angle cross section. It can be seen that for these grazing collisions there is a barrier for the $Li^7 + C^{12}$ system against compound-nucleus formation but that the energy is appropriate for resonance in the $C^{12}t\alpha$ potential well. If one approximates the well with a harmonic-oscillator shape, the zero-point energy is of the size needed to put the resonant energy at the level of the dashed line.

The peaks observed at 0° in lithium-induced reactions can thereby be explained as due to states in a three-body potential well with an extension of roughly twice the normal nuclear dimensions. There will be a well for each succeeding l value as the bombarding energy increases. The spacing of resonances depends on the moment of inertia of the extended nuclear system. This spacing fits the observed spacing for the indicated nuclear sizes. It is also possible that the complex peak structure may be due to the various modes of oscillation of the three-

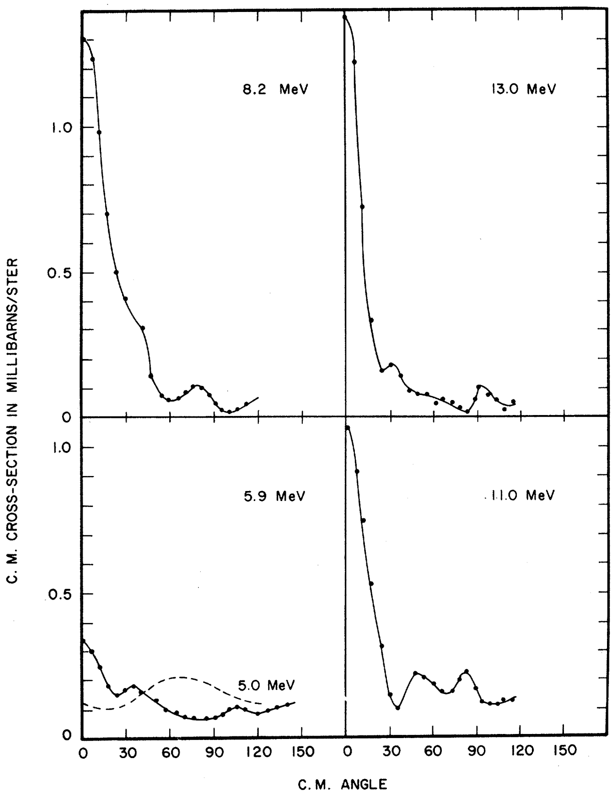

FIG. 3. Center-of-mass cross section for the reaction $C^{12}(Li^7, \alpha_0)N^{15}$ as a function of center-of-mass angle at bombarding energies near peaks in the 0° yield curve. The dashed li e indicates data taken away from the peak.

body system. It also could be due to Ericson fluctuations with a smaller coherence energy.

A resonance is only observed in a particular reaction channel if there is a good overlap with the outgoing channel. In Fig. 2, $N^{15}+\alpha_0$ is the outgoing channel. In order to observe a resonance, the continuum state of $N^{15}+\alpha_0$, at the resonance energy, must have this good overlap.

For angles away from zero degrees, grazing collisions will contribute relatively less to the cross section. For more head-on collisions, or lower l values, the barrier to compound-nucleus formation is reduced and one would expect the cross section for particular high-energy groups to be reduced because of the competition of many exit channels. The resonant yield should, therefore, be forward peaked. This is observed to be the case. Results of measurements of the differential cross section of the ground-state alpha group as a function of angle are shown in Fig. 3 for bombarding energies near peaks on the zero-degree yield curve.

Resonant structure in the forward-angle yield of heavy-ion nuclear reactions would seem to be likely in cases where there is a high probability of breakup of either beam or target into two or more clusters. This will occur when either has a low binding energy for such clusters.

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