Direct Processes in 54-MeV ^{7}Li Breakup Reactions on ^{12}C and ^{197}Au Targets, and the Extraction of Astrophysical Cross Sections

S. B. Gazes, J. E. Mason, R. B. Roberts, and S. G. Teichmann
Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627
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Strong direct processes were observed for elastic breakup in 54-MeV ^{7}Li+^{12}C, ^{197}Au reactions. In the case of ^{12}C, the observed ^{7}Li$\rightarrow \alpha+t$ direct-breakup yield was significantly larger than predicted by a Coulomb-breakup calculation, indicating the importance of the nuclear field. For ^{197}Au, final-state interactions produced a strong distortion in the fragment energy spectra, as well as a modulation of the coincidence efficiency for different detector geometries. Such Coulomb effects are found to severely complicate the extraction of radiative-capture cross sections from direct-breakup data.

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Heavy-ion-induced breakup reactions in the energy region 5–10 MeV/nucleon have been studied for some time [1]. In most cases, the yields are dominated by a sequential, two-step process in which the projectile is inelastically scattered to a particle-unstable state and decays in flight. However, the more exotic process of direct breakup, while difficult to identify unambiguously, is of considerable interest since it reflects the response of the nucleus to large nuclear and Coulomb forces during interaction times of order 10^{-22} s. Such a process has been observed previously in ^{7}Li-induced reactions [2,3], using a close-geometry arrangement of detectors which allowed the direct component of elastic breakup to be kinematically isolated.

More recently, it has been suggested [4,5] that detailed measurements of Coulomb dissociation at small relative kinetic energies ($E_{\rm rel}$) of the outgoing fragments may provide information on time-reversed processes. In the case of (^{7}Li,αt) this would correspond to the astrophysically interesting process of low-energy $\alpha+t$ radiative capture, which is responsible for big-bang nucleosynthesis of ^{7}Li [5]. Some recent work on ^{7}Li breakup [6,7] has attempted to extract such information down to $E_{\rm rel}=0$. In this Letter, we present results from a study of ^{7}Li elastic breakup which indicate that the extraction of radiative-capture cross sections is complicated considerably by both nuclear and Coulomb effects.

The 54-MeV ^{7}Li+^{12}C, ^{197}Au reactions were studied using beams from the upgraded MP tandem at the Nuclear Structure Research Laboratory (NSRL). Emitted α particles were detected in the focal plane of the NSRL's Enge split-pole spectrograph, using a resistive-wire proportional counter to measure particle position and energy loss. The coincident tritons were detected in a Si-ΔE/Si(Li)-E telescope, positioned in close geometry to the opening of the spectrograph. The opening angle between telescope and spectrograph was fixed at $\approx 12°$ and aligned in the breakup reaction plane, with the telescope placed at the larger angle. An absorber foil was used to shield the telescope from the elastically scattered beam. Since the magnetically rigid ^{7}Li elastic particles did not enter the focal-plane detector, this arrangement made it possible to examine reactions well forward of grazing.

The summed energy of the coincident fragments, $E_\alpha+E_t$, was reconstructed and in all cases this spectrum was dominated by a peak at high energies corresponding to the target being left in its ground state (elastic breakup). Analysis proceeded by gating on the elastic peak, since this constraint on the reaction provides selectivity in the exit-channel kinematics. The energy spectrum of the coincident alpha (or triton) is then sufficient for determining the relative kinetic energy of the outgoing fragments (limited by the finite detector solid angles). This, in turn, can be related to an excitation in the primary ^{7}Li.

Such a spectrum is shown in Fig. 1 for alpha particles

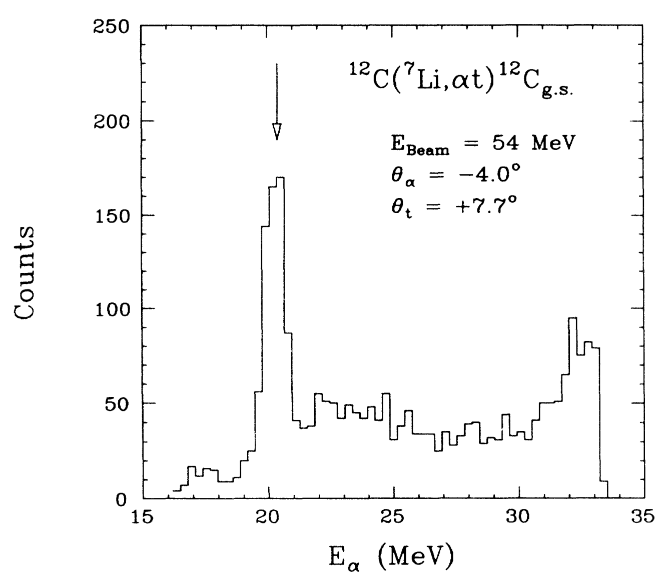

FIG. 1. Energy spectrum of alpha particles emitted in coincidence with tritons in 54-MeV ^{7}Li+^{12}C reactions. Detector angles (laboratory) are indicated. Data are gated on elastic-breakup events, as determined by the summed energies. The arrow indicates the alpha energy corresponding to sequential breakup via the 4.63-MeV state in ^{7}Li.

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emitted in elastic breakup on a ^{12}C target. The prominent peak at $E_\alpha \approx 20$ MeV is associated with the population, and subsequent decay, of the $\frac{7}{2}^-$ (4.63 MeV) state in ^{7}Li. The sharpness of the peak is due to the relatively small opening angle between the detectors, which selects a breakup orientation almost collinear with the primary ^{7}Li involving a forward-emitted triton and backward-emitted alpha particle. It should be noted that the other kinematically allowed solution (i.e., forward-emitted alpha and backward-emitted triton) is not observed in our experiment, due to both the dynamic range of the focal-plane detector and the energy threshold of the shielded telescope.

The yield at energies above $E_\alpha \approx 20$ MeV does not correspond to any states in ^{7}Li, and thus must be ascribed to a direct process involving virtual excitation of the $\alpha + t$ continuum. In order to extract a cross section for this process, the direct yield was taken to be twice the yield observed between the sequential peak and the minimum observable relative energy, $E_{\rm rel}(\min) \approx 0.5$ MeV ($E_\alpha \approx 29$–30 MeV). This was done to roughly account for the missing portion of the breakup spectrum. The extracted yield was then corrected with an energy-dependent coincidence efficiency, derived from Monte Carlo simulations using the experimental detector configurations. These direct elastic-breakup cross sections are plotted in Fig. 2 as a function of the scattering angle of the alpha-triton center of mass.

The cross sections were compared to calculations of breakup in the Coulomb field of the target. This is essentially a Coulomb-excitation calculation [8], involving a

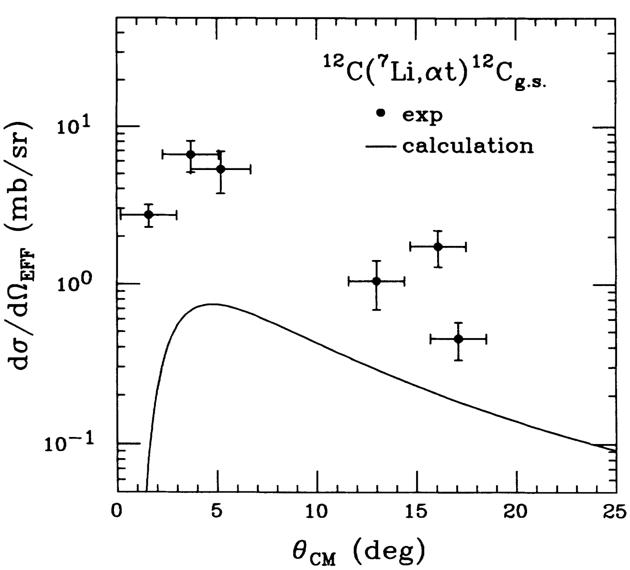

FIG. 2. Experimentally reconstructed cross sections for direct elastic breakup in 54-MeV ^{7}Li+^{12}C reactions. Yields are plotted as a function of the scattering angle (c.m.) of the alpha-triton center of mass. The results of a Coulomb-breakup calculation are shown as a solid curve.

summation over virtual states in the $\alpha + t$ continuum. As was pointed out previously [3], the $B(E1)$ values needed for such a calculation can be extracted from $t(\alpha,\gamma)$-^{7}Li(g.s.) radiative capture by employing detailed balance. Our experimental threshold of $E_{\rm rel}(\min) \approx 0.5$ MeV requires capture cross sections for bombarding energies as low as $E_\alpha = 1.2$ MeV, for which data exist [9].

The results of these calculations are shown in Fig. 2. As can be seen, the experimental yields are significantly larger than the Coulomb-breakup predictions for the region of forward angles probed, indicating the importance of the nuclear field. Such a behavior for low-Z targets is perhaps not surprising, since it has been previously observed in breakup studies [10] of another weakly bound projectile—the deuteron. In order to properly apply detailed-balance arguments to extract capture cross sections, the breakup must be well described as a first-order Coulomb process. Detailed theoretical studies [11] indicate that the spectrum of virtual excitations generated by the Coulomb or nuclear fields are quite different, especially at small $E_{\rm rel}$. Thus, the data taken on a ^{12}C target are unsuitable for such an inversion.

In contrast to ^{12}C, one might expect reactions on a ^{197}Au target to exhibit a stronger Coulomb mechanism. There are, in fact, indications [12] that our measured breakup yields at far-forward angles ($<25°$) are in reasonable agreement with Coulomb-breakup calculations. However, the analysis is substantially complicated by post-breakup Coulomb effects. This is illustrated in Fig. 3(a), which shows the E_α spectrum for elastic breakup in 54-MeV ^{7}Li+^{197}Au reactions.

One would expect the direct elastic-breakup component of the E_α spectrum to be roughly symmetric about an energy corresponding to $E_{\rm rel} = E_{\rm rel}(\min)$ (in this case, $E_\alpha \approx 30$ MeV). Such an approximate symmetry is observed for the reactions on ^{12}C. However, in Fig. 3(a), the direct alpha yield is quite asymmetric, with a strong depletion of lower-energy alphas.

This behavior can be understood by considering final-state interactions with the ^{197}Au target. Because of the different charge-to-mass ratio of the outgoing alpha particle and triton, the two fragments will suffer differential Coulomb accelerations following breakup. For example, a simple calculation of the difference in Coulomb potentials between the ^{197}Au nucleus and each of the outgoing fragments (calculated at the classical distance of closest approach) indicates that, for $\theta_{\rm c.m.} = 20°$, the alpha-particle energy should be boosted by ~ 2 MeV.

However, when the detector geometry is changed (with the angles of the detected alpha and triton essentially switched, yielding the *same* primary scattering angle of $\theta_{\rm c.m.} = 20°$), the energy spectrum looks quite different [Fig. 3(b)]. As can be seen, the depletion at low energies is gone. Furthermore, the direct-breakup yield is significantly enhanced compared to the sequential-breakup peak at 20 MeV.

In order to understand this, the effect of final-state in-

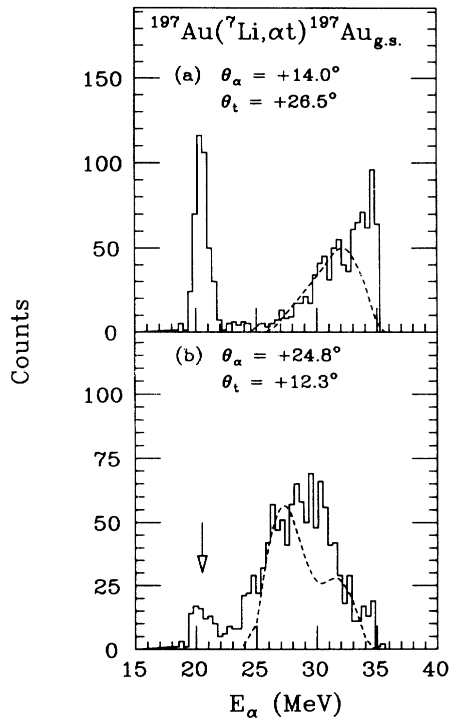

FIG. 3. Energy spectra of alpha particles from elastic breakup in 54-MeV $^7Li+^{197}Au$ reactions. Results are shown for two different orientations of the detectors: (a) alpha particle detected at a smaller angle and (b) alpha particle detected at a larger angle than the coincident triton. In both cases, the fragments are emitted in the reaction plane, and with the same alpha-triton scattering angle. The dashed lines are results of a three-body Coulomb trajectory simulation (see text). The sequential peak is indicated by the arrow.

teractions with the target was investigated in more detail by performing extensive simulations of the three-body Coulomb trajectories following breakup. In these simulations [12], it was assumed that breakup occurred at the distance of closest approach. An important aspect of the simulation was its treatment of the ^7Li as an *extended* object, using realistic α-t potentials from cluster-structure studies [13] of ^7Li as a guide. This introduced an extremely strong sensitivity of the asymptotic fragment energies on breakup orientation of the projectile. In particular, it was found that specific detector geometries preferentially select certain breakup orientations for alpha-triton coincidences.

The results of these simulations are displayed in Figs. 3(a) and 3(b) as alpha energy spectra (dashed lines) which are normalized to the experimentally observed direct-breakup yields. As can be seen, the influence of detector geometry is qualitatively reproduced by these simulations, indicating that the observed structure is largely due to target Coulomb distortion.

Additional evidence for the importance of this final-state interaction can be found by examining the strength of the direct-breakup yield relative to the sequential-breakup cross section. As can be seen by comparing Figs. 3(a) and 3(b), the coincidence efficiency for direct breakup is significantly enhanced (by a factor of ≈ 5) when the geometry requires the alpha particle to be emitted to the larger angle. Such an effect is also seen in our simulations, though the magnitude is sensitive to the presumed distribution of excitations. In particular, for an excitation corresponding to $E_{rel}=0.6$ MeV (where Coulomb-excitation calculations predict a maximum yield), a five-fold increase in effective solid angle is observed for the geometry used in Fig. 3(b). This is another indication of the selectivity of detector geometry to different breakup orientations.

These Coulomb-field distortions are a crucial issue in any attempt to extract astrophysical cross sections. The strong dependence of coincidence efficiency on detector geometry will have a direct effect upon extracted capture cross sections. Furthermore, the distortion of the fragment energy spectra is of great significance since it is the *local* spectrum (at the point of breakup) which contains information about radiative-capture cross sections, and not the asymptotically measured spectrum.

In contrast to these conclusions, another study of ^7Li breakup [6,7] cited yield minima at $E_{rel}=0$ MeV (unshifted by Coulomb effects) as evidence that the breakup took place far from the target. This was supported by the long lifetime inferred from the width of the direct-breakup continuum [6]. However, the stability of relative-energy minima can also arise from the alpha-triton interaction, and thus is not a good measure of final-state interactions with the target. Furthermore, the width of the E_{rel} continuum is determined by transmission coefficients and virtual photon spectra (the latter a reflection of reaction kinematics), and thus cannot be analyzed as a long-lived resonance [14].

In conclusion, we have performed measurements of direct processes in the elastic breakup of 54-MeV ^7Li. Yields on a ^{12}C target are dominated by nuclear contributions, much like the strong "diffractive breakup" observed in earlier studies of the deuteron. The coincident fragment energy spectra on a ^{197}Au target exhibit structure which is understood in terms of final-state interactions with the target Coulomb field, generating distortions in the local breakup spectrum. Moreover, a strong modulation of coincidence efficiency was produced by varying detector geometry, in qualitative agreement with simulations for breakup of an extended object. It is essential that these Coulomb effects be understood in greater detail if one is to extract astrophysically relevant capture cross sections from direct-breakup measurements.

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