Direct Coulomb Breakup of ^{7}Li

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The direct breakup of 70-MeV ^{7}Li scattered from a ^{120}Sn target is investigated at forward angles. Inside the grazing angle, it is found that the breakup is dominated by the Coulomb interaction between projectile and target.

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The study of the breakup of light-ion projectiles such as ^{6}Li and ^{7}Li is of special interest since the simple cluster nature of these nuclei considerably simplifies calculations concerning the breakup process. Thus using the α-t cluster description for ^{7}Li in an adiabatic calculation, Thompson and Nagarajan[1] concluded that the direct breakup of 70-MeV ^{7}Li into the $\alpha+t$ channel was mainly due to the differential nuclear force between the ^{208}Pb target and the projectile fragments. However, a subsequent study of inelastic scattering of 68-MeV ^{7}Li from ^{208}Pb, where a similar cluster-adiabatic calculation was used, showed that the Coulomb interaction becomes increasingly important for smaller angles.[2] This therefore raises the question as to the importance of the Coulomb interaction for projectile breakup at forward scattering angles. In this Letter we present new evidence that, at forward angles, the direct breakup of 70-MeV ^{7}Li on ^{120}Sn is primarily due to the Coloumb interaction between projectile and target.

The experiment was undertaken by use of the 20-MV NSF tandem accelerator at Daresbury. Since we specifically wished to study small relative energies between the emitted α and t fragments, the two solid-state detector telescopes were placed in close vertical geometry.[3] The collimators were 10 mm $\times$ 8 mm and the vertical separation between their centers was 15 mm. The collimators were placed at 115 mm from the target, except at the most forward angle of 11.5°, where they were at 150 mm. The target was isotopically pure ^{120}Sn of 4 mg/cm^2 thickness.

The energy spectra of α particles for events where the total energy of the coincident α and t particles corresponded to the target being left in its ground state are shown in Figs. 1(b)–1(d). The spectra for the more backward angles are dominated by a pair of peaks associated with the kinematic solutions for the reaction ^{120}Sn(^{7}Li, ^{7}Li$^*_{4.63} \rightarrow \alpha + t$)^{120}Sn$_{\rm g.s.}$. The center-of-mass (c.m.) energy of the α-t pair, ϵ_r, for a given α energy, is shown on the top axis.

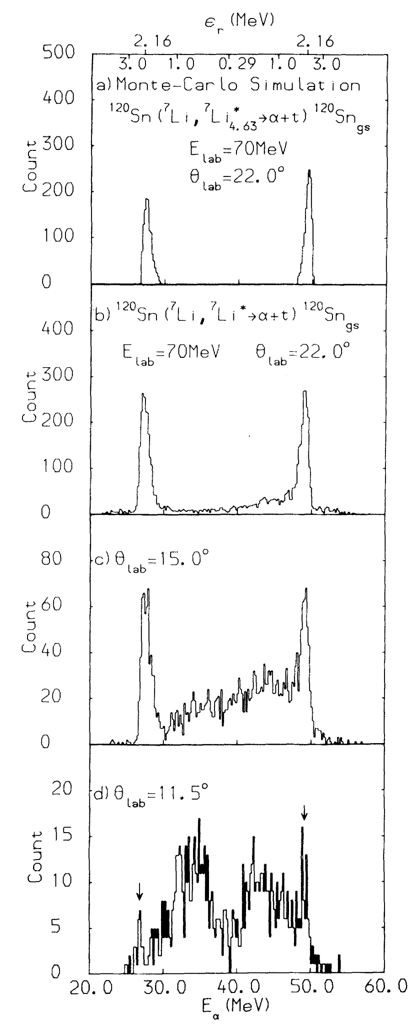

FIG. 1. (a) α-energy spectrum for sequential breakup of ^{7}Li using a Monte Carlo simulation. (b)–(d) Experimental α-energy spectra of the reaction ^{120}Sn(^{7}Li, ^{7}Li* $\rightarrow \alpha + t$)^{120}Sn$_{\rm g.s.}$ at 22°, 15°, and 11.5°.

The position and shape of the two main peaks in Fig. 1 are determined by the geometry of the two collimators in relation to the breakup cone of the two decay particles.[3] To determine the expected shape of these peaks a Monte Carlo–type calculation was undertaken to simulate the sequential breakup of ^{7}Li ions in the reaction ^{120}Sn(^{7}Li,^{7}Li$^*_{4.63}$ $\rightarrow \alpha + t$)^{120}Sn$_{\rm g.s.}$. It is assumed that ^{7}Li breaks up isotropically in its own c.m. system. The calculated α-energy spectrum corresponding to such events is shown in Fig. 1(a). It can be seen from this figure that no events between $E_\alpha = 29$ and 48 MeV would be expected for the sequential breakup of ^{7}Li$^*_{4.63}$. The events observed between these two limits are assumed to be direct breakup as suggested previously.[4]

It can be seen from Fig. 1 that the direct component becomes more intense towards forward angles, and dominates at 11.5°. The shape of this component also changes, becoming more symmetric at the forward angle. Such a change of shape may indicate that final-state interactions vary strongly with α and t energies for larger scattering angles, but only weakly for smaller angles.

The sequential component peaks at the grazing angle [Fig. 2(a)]. By contrast the cross section of the direct component monotonically decreases [Fig. 2(b)]. The behavior of the cross section and spectrum shape of the direct component indicates that the breakup of ^{7}Li at forward angles may be dominated by the Coulomb interaction between projectile and target. In fact, for scattering at 11.5° the closest distance of approach between the two ions is 17 fm, which is somewhat greater than the nuclear interaction distance of 13 fm given by $R_1 + R_2 + \Delta$, where $R_1 = 1.44A^{1/3}$ fm and $\Delta = 2.88$ fm.[5] Of course, this does not rule out the consideration of effects arising from the nuclear field, since orbiting may occur at small impact parameters.[5] Nevertheless it is not unreasonable to investigate the extent to which the observations at forward scattering angles may be explained on the basis of only the Coulomb interaction between the target and projectile. A similar suggestion, using qualitative arguments, has been put forward for ^{6}Li breakup.[6] In normal Coulomb-excitation calculations the excited ion does not break up, and it is assumed that the Coulomb trajectory follows the Rutherford path.[7] For a situation where the projectile does break up, the normal calculation is still assumed to be valid even when the association time of the two ions during the breakup process is not much greater than the collision time. For the breakup situation considered here the association time is $\sim 8 \times 10^{-22}$ s

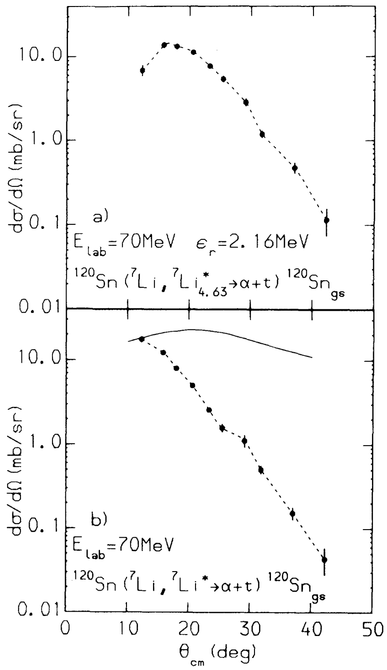

FIG. 2. (a) Angular distribution for the sequential breakup of ^{7}Li on ^{120}Sn. (b) Angular distribution for direct breakup of ^{7}Li on ^{120}Sn. The cross section has been integrated over the range 0.29 MeV $< \epsilon_r < 3$ MeV, excluding the sequential peaks. The solid line represents the Coulomb-breakup calculation. The dashed lines in both figures are a guide to the eye.

[determined from $\Delta E\, \Delta t = \hbar$, with the assumption that $\Delta E \approx 0.8$ MeV (Fig. 3)] and the collision time is $\sim 4 \times 10^{-23}$ s.[5]

Since the ground state of ^{7}Li is a $(\frac{3}{2})^-$ state, the most significant Coulomb multipole term leading to breakup will be $E1$, corresponding to an α-t relative motion of $l = 0$. The cross section for Coulomb breakup to continuum states of energies between ϵ_r to $\epsilon_r + d\epsilon_r$ may therefore be written[7] as

$$d\sigma_{E1} = (Ze/hv)^2 B(\epsilon_r)\, df_{E1}(\theta, \epsilon_r)\, d\epsilon_r, \qquad (1)$$

where Z is the target charge, v is the projectile velocity, and $df_{E1}(\theta, \epsilon_r)$ is the usual Coulomb excitation function. The reduced transition probability $B(\epsilon_r)$ is a function of the relative energy ϵ_r, and may be determined by its relationship to the photodisintegration cross section of ^{7}Li [i.e., ^{7}Li$(\gamma,t)\alpha$]:

$$\sigma_{\gamma,{}^7\rm Li}(E_\gamma) = (16\pi^3/9)(h\omega/ch) B(\epsilon_r), \qquad (2)$$

with $E_\gamma = \epsilon_r + 2.46$ MeV, where 2.46 MeV is the Q value for the reaction. Since there are very little data available for the photodisintegration cross section for this reaction below $E_\gamma \sim 10$ MeV, this reaction cannot provide information concerning $B(\epsilon_r)$

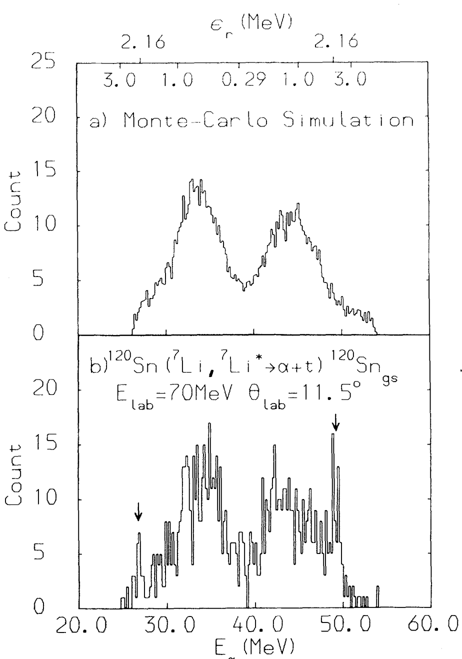

FIG. 3. (a) Simulated α-energy spectrum for Coulomb breakup of ^{7}Li normalized to the experimental parameters for the data shown in (b). (Because of normalization the statistical accuracy of the simulated curve appears higher than the y scale would indicate.) (b) Experimental α-energy spectrum at 11.5°. The arrows indicate the position of the sequential lines.

for the values of ϵ_r relevant to the present experiment. However, the inverse fusion reaction $\alpha + t \rightarrow {}^7\mathrm{Li} + \gamma$ has been measured to low ϵ_r energies. The fusion and photodisintegration cross sections can be related by the reciprocity relationship to give[8]

$$B(\epsilon_r) = \frac{9}{16\pi^3} ch \left(\frac{6}{7}\right) \frac{me^2}{(E_\gamma)^3} \epsilon_r \sigma_{\alpha t,F}(\epsilon_r). \qquad (3)$$

The reduced probability function $B(\epsilon_r)$ can therefore be calculated from the α-t fusion cross section $\sigma_{\alpha t,F}(\epsilon_r)$. The total fusion cross section to the ground state of ^{7}Li was first measured by Holmsgren and Johnston[9] for values of ϵ_r from 0.2 to 0.6 MeV. Further measurements were taken by Tombrello and Phillips[10] for ϵ_r from 0.1 to 1 MeV. Unfortunately these two sets of cross-section data only agree within a factor of 2. However, both sets of measurements gave agreement for the ratio of capture to the first excited state and capture to the ground state. More recently Ottewell[11] has repeated the experiment using a Ge(Li) detector for the capture γ ray which improves the signal-to-background ratio compared to previous measurements. These data ranging from 0.15 to 1 MeV, which agreed reasonably well with those of Ref. 10, were used to calculate $B(\epsilon_r)$, and $d\sigma_{E1}$.

The Monte Carlo program which was used to determine the shape of the sequential peaks [Fig. 1(a)] was used again to determine the expected experimental α-energy spectrum originating from the Coulomb component defined by $d\sigma_{E1}(\epsilon_r)$. To do this the Monte Carlo program was run for a fixed number of events with narrow energy intervals of 3 keV for ϵ_r. The resulting α-energy spectrum for each interval was normalized to $(d\sigma_{E1}(\epsilon_r)d\epsilon_r)$ which is the factor that takes account of the beam charge and target thickness for the particular experimental situation being considered. The simulated and experimental spectra for 11.5° are shown in Fig. 3.

It can be seen from Fig. 3 that there is good agreement between the expected α-energy spectrum shape deduced from the fusion data and the experimental situation. In making this comparison the sequential peaks in the experimental spectra should be ignored. The absolute magnitudes of the two spectra agree within 5%. However, it is estimated that the overall uncertainty in the multiplication factor $(d\sigma_{E1}(\epsilon_r)d\epsilon_r)$ could be as much as 20%. Therefore the close agreement of the two spectra in Fig. 3 should not be automatically taken as evidence that higher-order Coulomb effects, such as virtual excitation to high $E1$ states, are not important.[12]

The calculated Coulomb breakup cross section (integrated over relative α-t energies from 0.29 to 3 MeV) is represented by the solid line in Fig. 2(b). It can be seen that the magnitude of the experimental cross section at the most forward angle closely agrees with the calculated value (this is also evident from Fig. 3). The experimental cross section at the grazing angle falls significantly below the calculated curve. This feature is often seen in other inelastic reactions and simply reflects the increasing dominance of the nuclear force at larger scattering angles. This dominance can also explain the origin of the asymmetric nature of the direct-breaking distribution, seen at larger scattering angles Fig. 1, as due to the scattering of the breakup fragments in the nuclear field which strongly depends upon fragment energy.

It would be interesting to perform calculations of direct breakup combining both the Coulomb and the nuclear forces. However, for a loosely bound projectile such as ^{7}Li the reliability of such calculations at extreme forward scattering angles is open to question.[2] Nevertheless the close agreement at forward scattering angles between the present calculation and the data means that the Coulomb contribution to direct breakup is very significant for 70-MeV ^{7}Li scattered from a ^{120}Sn target. It would clearly be interesting to study the breakup of ^{7}Li from other targets in order to establish the universality of the direct Coulomb breakup process.

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