$^6$Li direct breakup lifetimes

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$\alpha$-$d$ coincidence data were studied for the $^6$Li + $^{59}$Co reaction at $E_{lab} = 29.6$ MeV. By using a kinematic analysis, it was possible to identify which process, leading to the same final state, has the major contribution for each of the selected angular regions. Contributions of the $^6$Li sequential and direct breakup to the incomplete fusion/transfer process were discussed by considering the lifetimes obtained by using a semiclassical approach, for both breakup components.

1. Introduction

The influence of projectile breakup in reactions with stable weakly bound nuclei on fusion cross section has been extensively investigated in the last decade and more recently for reactions involving exotic nuclei [12345678910111213141516]. The light particle spectra measured in ‘singles’ mode display significant contributions from reaction mechanisms other than projectile breakup. This was for example shown very recently for $^6$Li + $^{59}$Co, which can be considered as a benchmark system [35101112131516]. Therefore, coincidence measurements are of crucial importance to disentangling the respective contributions of the non-capture projectile breakup components (both direct and sequential) from other competing mechanisms such as incomplete fusion (ICF) and/or transfer (TR). The contributions of sequential projectile breakup (SBU) and direct projectile breakup (DBU) are both significant and it is necessary to determine which process influences complete fusion (CF) most. In this case, the study of the breakup dynamics could provide decisive information.

2. Experimental Setup

The $^6$Li beam was delivered by the 8 UD Tandem accelerator at the the University of São Paulo Pelletron Laboratory and bombarded a 2.2 mg/cm$^2$ $^{59}$Co target with an
effective energy of $E_{\text{lab}} = 29.6$ MeV. Eleven triple telescopes (ion chamber, a Si surface barrier detector and a CsI detector) \[17\] were used for the detection and identification of the light particles, positioned on both sides with respect to the beam direction with $10^\circ$ angular steps, covering angular intervals from $-45^\circ$ to $-15^\circ$ and $15^\circ$ to $75^\circ$.

3. Results and discussion

The study of $\alpha$ particles and $d$ energy spectra for “single” mode events, performed in our previous work \[15\], indicated a dominant contribution of ICF/TR, more specifically $d$-incomplete fusion ($d$-ICF)/$d$-transfer ($d$-TR) for the case of $\alpha$ spectra and $\alpha$-incomplete fusion ($\alpha$-ICF)/$\alpha$-transfer ($\alpha$-TR) for the $d$ spectra. In each case, the corresponding intermediate nucleus excitation energies were 24.6 MeV and 22.5 MeV for the $^{61}$Ni and $^{63}$Cu nuclei, respectively.

In this work, the contributions of the processes mentioned above, as well as the $^6$Li projectile breakup were identified for different angular regions selected by using the $\alpha$-$d$ coincidence measurements together with a 3-body kinematic analysis. The behavior of the energy centroid of a broad structure present in the energy spectra was studied as a function of the angle. For angular differences within the $^6$Li breakup cone corresponding to the (2.186 MeV, $3^+$) first resonant state, we observe two sharp peaks from the two possible kinematical solutions of the SBU and also a broad structure is observed between them. No other resonant state was observed in the data. For angular differences larger than the SBU cone, we observed only broad structures. These broad structures could be associated either with the decay of nuclei produced in ICF/TR (incomplete fusion and/or transfer) or to $^6$Li DBU to the continuum.

Figure 1 shown the $d$ energy $E_d$ as a function of $\theta_\alpha$ for $\theta_d = 15^\circ$. In this case, if $\alpha$-ICF/TR is dominant, the $d$ energy $E_d$ should be constant, consistent with the 22.5 MeV excitation energy of the $^{63}$Cu intermediate nucleus (dotted line). This behavior would be more evident for angles near the $^{63}$Cu recoil direction, for which we expect the maximum of cross section for the $\alpha$-particle decay. This is indeed observed for angles near the recoiling $^{63}$Cu. For other negative angles we observe instead a trend consistent with a 24.6 MeV excitation energy for the $^{61}$Ni composite system (dot-dashed line). This suggests the dominance of the $d$-ICF/TR process. Therefore, both $\alpha$-ICF/TR and $d$-ICF/TR contributions can be, in principle, mixed together. As shown in \[18,19\], if $^6$Li direct breakup is dominant, the centroid of the broad structure would approximately correspond to the minimum allowed $\alpha$-$d$ relative energy ($E_{\alpha-d}$) for each angular pair. This trend is observed in Fig. 1 (dashed line) and suggests that the $^6$Li DBU dominates in the case of angular pairs for which the broad structure is observed with $\Delta \theta_{ad} = 10^\circ$ and $20^\circ$. For these angular pairs (i.e. for $\theta_\alpha$ angle values ranging between $20^\circ$ and $40^\circ$) the experimental points shown in Fig. 1 correspond to the energies of the SBU peaks.

The dynamics of the SBU and DBU processes were investigated using a semiclassical approach, as the one previously adopted in Ref. \[20\]. Since the Sommerfeld parameter ($\eta \sim 6$) is sufficient large and the relative energies of the breakup fragments are not too high, we can assume that the projectile, as well as the breakup fragments, follow a Coulomb trajectory.

Figure 2 depicts the experimental angular distribution for the SBU process analyzed in
Figure 1. Experimental values for the deuteron energy as a function of the \(\alpha\)-particle detection angle. The 3-body kinematics predictions for ICF/TR and the minimum relative energy \(E_{\alpha d}\) for \(^6\)Li breakup.

Ref. \[15\], as well as for the DBU. The angular distribution for the DBU is shown for \(^6\)Li continuum excitation energies summed between \(E^* = 1.66\) MeV and \(E^* = 2.10\) MeV. The dotted line was extracted from Ref. \[15\] and corresponds to the SBU CDCC calculation \[11,12,13\]. The dashed line represents the DBU CDCC result \[?\, 13\] for a \(^6\)Li excitation energy range from \(E^* = 1.48\) MeV (breakup threshold) to \(E^* = 2.10\) MeV. The curves presented in this figure were used to calculate the relative probability of particle production (function \(f\)) for SBU and DBU processes as a function of the distance of closest approach \(R_{\text{min}}\) as shown in Fig. 3. In the same figure we also present the function \(f\) for the other two DBU excitation energy ranges \(E^* = 2.20\) to 2.40 MeV and \(E^* = 2.41\) to 3.98 MeV not shown in Fig. 2. In the semiclassical calculations we assumed the most probable value of the excitation energy observed experimentally for each energy range \((E^* = 1.7, 2.3\) and 3.2 MeV).

The DBU lifetimes \((\tau_{\text{DBU}})\) due to barrier tunneling were estimated adopting the model of Ref. \[21\] and the calculated \(\tau_{\text{DBU}}\) as a function of \(E_{\alpha d}\) is presented in Fig. 4.

From Fig. 3 one can notice that the most probable value of \(R_{\text{min}}\) are very similar for SBU and DBU. However, for the \(^6\)Li \(3^+\) state with \(E^* = 2.186\) MeV the SBU lifetime is \(\tau_{\text{SBU}} = 2.73 \times 10^{-20}\) s corresponding to \(\Gamma_{\text{SBU}} = (0.024 \pm 0.002)\) MeV \[22\], which is at least one order of magnitude greater than the ones observed in Fig. 4 for DBU. It indicates that sequential projectile breakup occurs very far from the target. On the other hand, for DBU the shorter lifetimes of the continuum ‘states’ cause the breakup process to occur at shorter distances from the target. Therefore, in reactions that have a large ICF/TR cross section (as Refs. \[15,14\], for instance) and a major influence on the complete fusion cross section, the flux diverted from CF to ICF/TR would arise essentially from the DBU.
Figure 3. Function $f$ representing the probability of particle production as a function of the distance of closest approach $R_{min}$ for the SBU and DBU processes.

components (higher excitation energies in the continuum).

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