Study of the influence of projectile breakup on the fusion cross section of $^6,^7\text{Li} + ^{12}\text{C}, ^{59}\text{Co}$


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The recent availability of radioactive nuclei beams motivated the investigation of fusion reactions involving weakly bound nuclei. The cross section enhancement generally observed at sub-barrier energies is understood in terms of dynamical processes arising from couplings to collective inelastic excitations of the target and/or projectile.\(^1\) However, in the case of reactions where at least one of the colliding nuclei has a sufficient low binding energy so that breakup becomes an important process, conflicting experimental and theoretical results are reported in recent papers\(^2\)–\(^7\).

The $^6,^7\text{Li} + ^{12}\text{C}, ^{59}\text{Co}$ fusion reactions are used to investigate the effect of breakup on the fusion cross section.\(^8\) These measurements help to establish the influence of the projectile breakup on the fusion process at near-barrier energies and contribute to the determination of how the mass of the target affects the process, as well as the influence of the incomplete fusion yield.

It is important to have clear the reference used when an enhancement and/or a suppression is defined. In our case,\(^5\) the reaction cross section has been used Experimental results are compared to prediction of Coupled Channel Calculations.

In order to better isolate the effects of possible couplings, the ratio of total fusion cross section $\sigma(^6\text{Li})/\sigma(^7\text{Li})$ is calculated and presented in figure 1 as a function of center of mass energy $E_{cm}$. The solid curve shows the ratio calculated by the Wong model fitted to the data. The other curves represent Coupled Channel calculations\(^3\) performed by CCFULL. One sees that no suppression is observed at energies above the barrier (one should point out that the experimental data presented in this work do not distinguish between CF and ICF) and a sub-barrier enhancement is observed for $^6\text{Li}$. Coupled Channel calculations taking into account the breakup channel (CDCC calculations presented in figure 2)\(^9\) also predict a significant enhancement of $^6\text{Li}$ fusion cross section.

A final tuning for the coupling of the breakup channel, as well as the correct description of the reaction dynamics, requires the explicit measurement of precise elastic scattering data as well as yields leading to breakup itself.\(^10\)–\(^12\) Figure 3 displays the elastic scattering data for the $^6,^7\text{Li} + ^{59}\text{Co}$ systems.

The identification of the breakup products has been achieved measuring the three body final state correlations. Coincidence data displayed in figure 4a show the identification of the process Q-value in order to gate exclusively on the projectile breakup channel. Furthermore, the system excitation energy as well as the projectile fragment relative energy (see figure 4b) are used to identify the exit channel with
Fig. 1. Energy dependence of the ratio $R = \frac{\sigma_{6\text{Li}}}{\sigma_{7\text{Li}}}$ between the fusion cross sections for $^6\text{Li}$ and $^7\text{Li}$ induced reactions. Error bars reflect the large systematic errors. The solid and dashed curves correspond to the case of fits of the experimental data to Single Barrier Penetration Model. Dotted curves correspond to two uncoupled CC-FULL calculations with and without reorientation effects.

Fig. 2. Total fusion excitation functions for $^6\text{Li} + ^{59}\text{Co}$ (full dots) and $^7\text{Li} + ^{59}\text{Co}$ (full triangles), which are normalized with the cross sections in absence of couplings to breakup channels. For each reaction, the incident energy is normalized with the Coulomb barrier $V_B$ of the bare potential. The curves are drawn to guide the eyes.

Fig. 3. Angular distributions of the elastic scattering data for the $^6,^7\text{Li} + ^{59}\text{Co}$ systems.

no ambiguity. Based on those filters, angular correlations (see figure 5) are obtained to identify the several processes. This is complemented by measurements of relative energy of the fragments using different rest frame references (like target, projectile, target + fragment) in order to disentangle the contribution of breakup, incomplete fusion and/or transfer-reemission process. These experimental results are compared
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![Bidimensional plot $E_{\alpha}xE_d$.](image)

Fig. 4. (a) Bidimensional plot $E_{\alpha}xE_d$. (b) Bidimensional plot $E_{d}\times E_{\alpha}$, both at $E_{\text{lab}} = 26\text{MeV}$ for the $^6\text{Li} + ^{12}\text{C}$ system. The lines represents the loci for events leaving $^{12}\text{C}$ in the ground state and the first excited state.

![Bidimensional plot $E_{\alpha}xE_d$.](image)

Fig. 5. Experimental $\alpha$-$d$ and $\alpha$-$t$ angular correlations for the $^6\text{Li} + ^{12}\text{C}$ and $^7\text{Li} + ^{12}\text{C}$ systems respectively.

...to three body kinematics calculations. As an example figure 6 displays the relative energy between $\alpha - d$ for the $^6\text{Li}$ breakup on a $^{12}\text{C}$ target. The region between the dashed vertical lines represent the angular interval in which the three body kinematics predict a constant relative energy. The fact that this experimental trajectory is not constant out of this region indicates the presence of other processes. The fact that the yield for coincidences is not negligible out of this region (see figures 5 and 6) indicates that the other processes producing, as in this case $\alpha - d$ coincidences, are relevant and must be identified. Similar data were taken for $^6,^7\text{Li} + ^{115}\text{In}$. This procedure in unfolding the several light particle emission processes has not been exploited so far in the literature.

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Fig. 6. Relative energy between $\alpha$ and $d$ for the $^{6}\text{Li}$ breakup on the $^{12}\text{C}$ target as a function of the $d$ angle $\theta_d$ for a fixed $\theta_{\alpha} = -25$ degrees. The vertical lines represent the kinematical detection limits for $\alpha$-$d$ decay for the first excited state of $^{6}\text{Li}$ ($E^* = 2.186\text{MeV}$).

References