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Influence of projectile breakup on complete fusion

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Abstract. Complete fusion excitation functions for $^{11,10}B + {}^{159}Tb$ and $^{6,7}Li + {}^{159}Tb$ have been reported at energies around the respective Coulomb barriers. The measurements show significant suppression of complete fusion cross-sections at energies above the barrier for $^{10}B + {}^{159}Tb$ and $^{6,7}Li + {}^{159}Tb$ reactions, when compared to those for $^{11}B + {}^{159}Tb$. The comparison shows that the extent of suppression of complete fusion cross-sections is correlated with the α-separation energies of the projectiles. Also, the measured incomplete fusion cross-sections show that the α-particle emanating channel is the favoured incomplete fusion process. Inclusive measurement of the α-particles produced in $^{6}Li + {}^{159}Tb$ reaction has been carried out. Preliminary CDCC calculations carried out to estimate the α-yield following ^{6}Li breaking up into $\alpha + d$ fail to explain the measured α-yield. Transfer processes seem to be important contributors.

Keywords. Weakly bound nuclei; fusion, breakup.

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1. Introduction

Fusion studies using stable beams have shown [1,2] that at energies near the average fusion barrier, the fusion process is strongly influenced by the structure of the interacting nuclei and the presence of transfer processes. In fact, the coupling between the relative motion of the colliding nuclei and the internal degrees of freedom, like rotation, vibration, and transfer of nucleons, leads to an enhancement of the fusion cross-sections at energies below the average fusion barrier, relative to the cross-sections expected from the single barrier penetration model calculations. However, in the case of reactions where at least one of the colliding nuclei is weakly bound, breakup can become an important process and influence the flux going into fusion. Interest in the investigation of the effect of breakup on fusion at energies around the barrier has received a fillip in recent years, primarily owing to the recent availability of radioactive ion beams in different laboratories around the world. It is known that some of these nuclei away from the stability lines are characterized by halo/skin structure and large breakup probabilities. A detailed understanding of the fusion mechanism with radioactive ion beams is very significant for understanding reactions of astrophysical interest and for the production of new nuclei near the drip lines.

Owing to the low intensities of the radioactive ion beams currently available, experimental studies of reaction mechanisms with unstable beams are still limited [3–7]. However, fusion reactions with high-intensity weakly bound stable beams, like ^{6,7}Li and ^{9}Be, which have significant breakup probabilities, may serve as an important step towards understanding the influence of breakup on fusion mechanism. Besides, the weakly bound stable nuclei, unlike the unstable nuclei, do not have the halo/skin structure and hence it is expected that understanding the influence of breakup on fusion may be less complicated in case of studies with stable nuclei.

In this presentation, the measurements carried out by us to understand the role of breakup in the fusion process, in the $A = 170$ region, will be discussed. Before going into the details of the measurements done, it would be worthwhile to say a few words about how to measure the fusion cross-sections and the different processes associated with the fusion of weakly bound nuclei.

2. Methods to measure fusion cross-sections

Fusion is an amalgamation of two interacting nuclei to form a highly excited, equilibrated compound nucleus, which decays by successive particle emission to produce heavy evaporation residues and/or undergoes fission. The heavy residual nucleus, from which further particle emission is energetically not possible, decays to the ground state by emitting γ-ray cascades. The fusion cross-sections are determined by summing the cross-sections of the evaporation residues and adding them to the fission cross-sections, if any. The cross-sections of the evaporation residue are determined by one of the following methods:

(1) By detecting the prompt γ-rays emitted by the evaporation residues.

(2) By detecting the delayed γ-rays or X-rays from the residual nuclei.

(3) If the residual nuclei are α-active, then the decay αs can be detected to get the cross-sections of the evaporation residues.

(4) The evaporation residues can be directly detected and identified by their charges and masses.

Each method has it's own advantages and disadvantages. So depending on the fusing system and the energy domain of the measurement, the detection technique needs to be chosen.

3. Fusion with weakly bound nuclei

In the study of fusion with weakly bound projectiles, several processes need to be considered that can arise due to the weak binding in the projectile. Figure 1 illustrates the typical reaction mechanisms following the breakup of weakly bound projectiles. When whole of the projectile fuses with whole of the target, the process is known as direct complete fusion (DCF). If prior to fusion, the projectile breaks up and subsequently all the fragments fuse with the target to form a compound nucleus similar to that in the DCF process, then the process is referred to as sequential complete fusion (SCF). As the compound nucleus produced in DCF and SCF are identical, experimentally one cannot differentiate between the two processes, and hence we define complete fusion (CF) as the sum of DCF and SCF processes. Following the breakup of the projectile in the field of the target nucleus, one of the fragments may be captured by the target, while the other escapes with the beam velocity [8]. This process of capture of partial projectile is known as incomplete fusion (ICF). It needs to be noted that an ICF product can also be produced via a transfer reaction. The sum of CF and ICF processes is termed as total fusion (TF). Lastly, if the projectile breaks up prior to fusion, and all the fragments fly off without anyone being captured by the target, then the process is termed as no-capture breakup (NCBU).

It needs to be pointed out that to carry out a meaningful study of the influence of breakup on fusion, one needs to disentangle the CF and ICF events and measure their cross-sections. For light systems, like $^{6,7}\mathrm{Li} + {}^{12,13}\mathrm{C}$ [9–11], $^{6,7}\mathrm{Li} + {}^{16}\mathrm{O}$ [12,13], $^{6,7}\mathrm{Li} + {}^{24}\mathrm{Mg}$ [14], and other systems, CF and ICF events cannot be separated as the ICF products are also produced in the CF process. So for such light systems, TF cross-sections have been reported in [15]. But for heavier systems, like $^{7}\mathrm{Li} + {}^{159}\mathrm{Tb}$ [16], $^{6}\mathrm{Li} + {}^{144}\mathrm{Sm}$ [17], $^{9}\mathrm{Be} + {}^{208}\mathrm{Pb}$ [18], $^{6,7}\mathrm{Li} + {}^{209}\mathrm{Bi}$ [19,20], etc. CF and ICF events have been disentangled. In this presentation, the measurements done with $^{159}\mathrm{Tb}$ will mainly be discussed.

4. Fusion and α-separation energy

To investigate the effect of breakup on fusion, all the reactions studied so far with weakly bound stable beams have been performed using $^{9}\mathrm{Be}$, $^{6}\mathrm{Li}$ and $^{7}\mathrm{Li}$ projectiles that have breakup thresholds ranging from 1.45 to 2.45 MeV. Among the stable nuclei, apart from the $^{6,7}\mathrm{Li}$ and $^{9}\mathrm{Be}$ nuclei, the $^{10}\mathrm{B}$ nucleus also has a fairly low α-separation energy of 4.5 MeV. Therefore, like $^{6,7}\mathrm{Li}$ and $^{9}\mathrm{Be}$, the $^{10}\mathrm{B}$ nucleus may also be expected to break up at low excitation energies, thereby affecting the fusion mechanism at considerably low bombarding energies. To investigate how the α-breakup threshold affects the CF cross-sections, both CF and ICF excitation functions were measured for the systems, $^{11,10}\mathrm{B} + {}^{159}\mathrm{Tb}$ and $^{6,7}\mathrm{Li} + {}^{159}\mathrm{Tb}$ [16,21] at energies around the Coulomb respective barriers. Considering the $^{11}\mathrm{B}$ nucleus with an α-separation energy of 8.66 MeV to behave as a normal strongly bound nucleus at low bombarding energies, $^{11}\mathrm{B} + {}^{159}\mathrm{Tb}$ was chosen to be the strongly bound references system.

Beams of $^{11,10}\mathrm{B}$ in the energy range 38–72 MeV, and $^{6,7}\mathrm{Li}$ in the energy range 28–43 MeV, provided by the 14UD BARC-TIFR Pelletron Accelerator Facility at Mumbai, bombarded a self-supporting $^{159}\mathrm{Tb}$ target of 1.5 mg/cm^2 thickness. The γ-rays emitted by the evaporation residues (ERs) were detected in an absolute efficiency calibrated Compton suppressed clover detector placed at 55° with respect to the beam direction. For $^{6}\mathrm{Li} + {}^{159}\mathrm{Tb}$, the clover detector was placed at 125° with respect to the beam direction. Both on-line and off-line spectra were taken for each exposure. The total charge of each exposure was measured in a 1 m long Faraday cup placed after the target. The target thickness was determined by measuring the Rutherford scattering cross-sections and also by using the 137.5 keV Coulomb excitation line of $^{159}\mathrm{Tb}$. The thickness of the target obtained from the two methods of measurement had very good agreement.

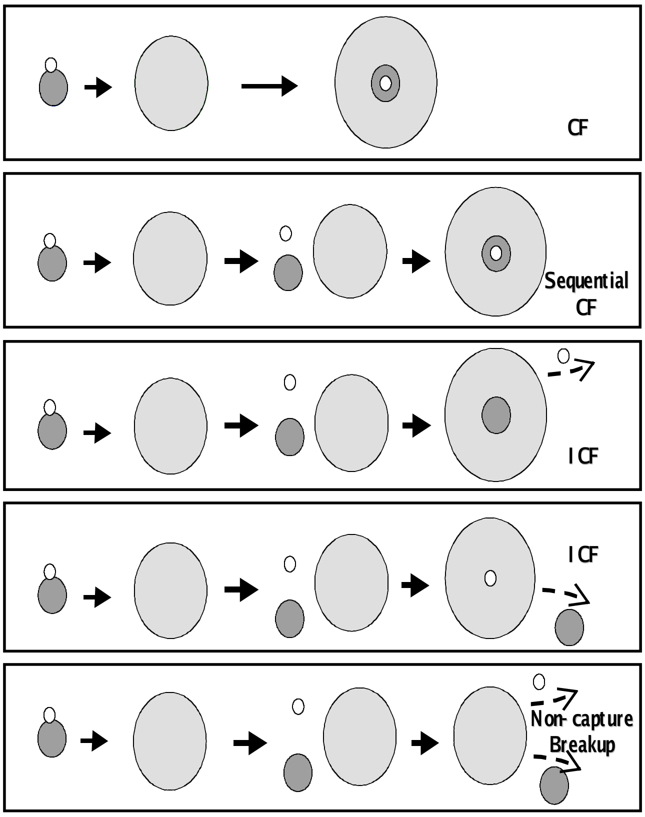

Figure 1. Processes following the breakup of the projectile into two fragments.

The compound nuclei ^{170}Yb, ^{169}Yb, ^{166}Er and ^{165}Er, formed by the fusion reactions $^{11}\mathrm{B} + ^{159}\mathrm{Tb}$, $^{10}\mathrm{B} + ^{159}\mathrm{Tb}$, $^{7}\mathrm{Li} + ^{159}\mathrm{Tb}$ and $^{6}\mathrm{Li} + ^{159}\mathrm{Tb}$ respectively, are expected to decay predominantly by neutron evaporation producing ERs which are all well deformed nuclei. This is also predicted by the statistical model calculations done using the code PACE2 [22]. The CF cross-sections in the B-induced reactions were obtained from the sum of the $3n - 6n$ ER cross-sections and for Li-induced reactions the same were obtained by summing the $3n$–$5n$ ER cross-sections.

To compare the CF cross-sections for the four reactions at the above-barrier energies, they have been plotted in a reduced scale in figure 2. The errors in the data are the statistical uncertainties only. The CF data of Broda *et al* [23] for the $^{7}\mathrm{Li} + ^{159}\mathrm{Tb}$ reaction are shown by the hollow points in the figure. The figure clearly shows in a model independent way, that the CF cross-sections for $^{10}\mathrm{B} + ^{159}\mathrm{Tb}$, $^{7}\mathrm{Li} + ^{159}\mathrm{Tb}$ and $^{6}\mathrm{Li} + ^{159}\mathrm{Tb}$ are suppressed at the above-barrier energies compared to those of $^{11}\mathrm{B} + ^{159}\mathrm{Tb}$. The extent of CF suppression are seen to be consistent with the α-breakup thresholds of the projectiles. As discussed earlier, of the four projectiles, ^{11}B is the most strongly bound nucleus with $Q_\alpha = -8.66$ MeV and ^{6}Li is the most weakly bound nucleus with $Q_\alpha = -1.45$ MeV. The Q_α values for the

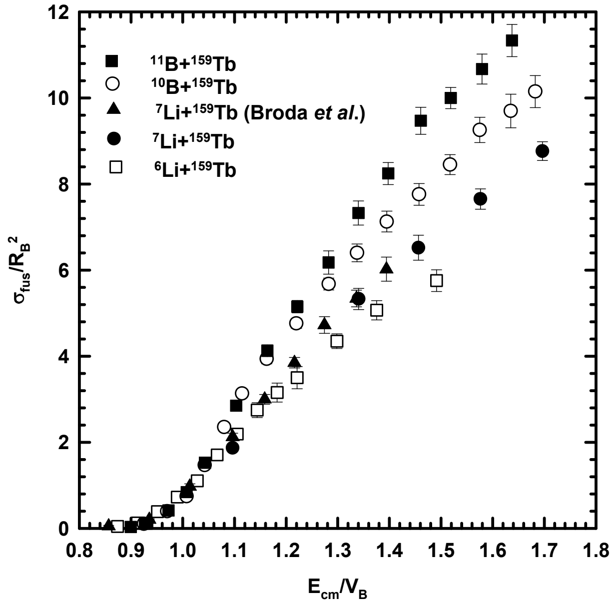

Figure 2. Complete fusion cross-sections in a reduced scale.

other two projectiles lie between these two limits. Thus, from figure 2 it is evident that lower the α-breakup threshold of the projectile, larger is the suppression of CF. Moreover, if one looks carefully into figure 2, one can see that $^{10}\mathrm{B}+{}^{159}\mathrm{Tb}$ CF cross-sections start deviating from those of $^{11}\mathrm{B}+{}^{159}\mathrm{Tb}$, at an energy higher than those of ^{6}Li- or ^{7}Li-induced reaction. Hence we can say that the onset of suppression of CF depends on the α-separation energy of the projectile. Higher the breakup threshold, higher is the energy where the suppression starts. This perhaps explains why ICF products are observed in strongly bound systems at much higher bombarding energies [24,25].

Apart from the γ-ray lines corresponding to the CF ER nuclei, the γ-ray spectra for the $^{10}\mathrm{B}+{}^{159}\mathrm{Tb}$ and $^{6,7}\mathrm{Li}+{}^{159}\mathrm{Tb}$ reactions showed lines corresponding to the ICF products. In $^{7}\mathrm{Li}+{}^{159}\mathrm{Tb}$ and $^{6}\mathrm{Li}+{}^{159}\mathrm{Tb}$ reactions, the contributions from Dy nuclei resulting from the capture of the lighter projectile fragments, t and d respectively, by ^{159}Tb were found to be the dominant ICF contributions, with the contribution from $\alpha+{}^{159}\mathrm{Tb}$ being relatively very small. In the $^{10}\mathrm{B}+{}^{159}\mathrm{Tb}$ reaction, the γ-spectra showed no lines corresponding to the α (lighter fragment) capture by ^{159}Tb. In this reaction, the only ICF contributions which could be observed were from ^{161,162}Er, resulting due to the capture of ^{6}Li (heavier fragment) by ^{159}Tb. This observation cannot be understood from a Coulomb barrier argument, because in the case of ^{6,7}Li-induced reactions, the lighter fragment capture is favoured, while for ^{10}B-induced reaction the heavier fragment capture is favoured. However, this can be conceived, if we consider the Q-value of the reactions. Consideration of the Q-values shows that the channels, where α-particle escapes, with the other fragment being captured by ^{159}Tb is the favoured ICF process.

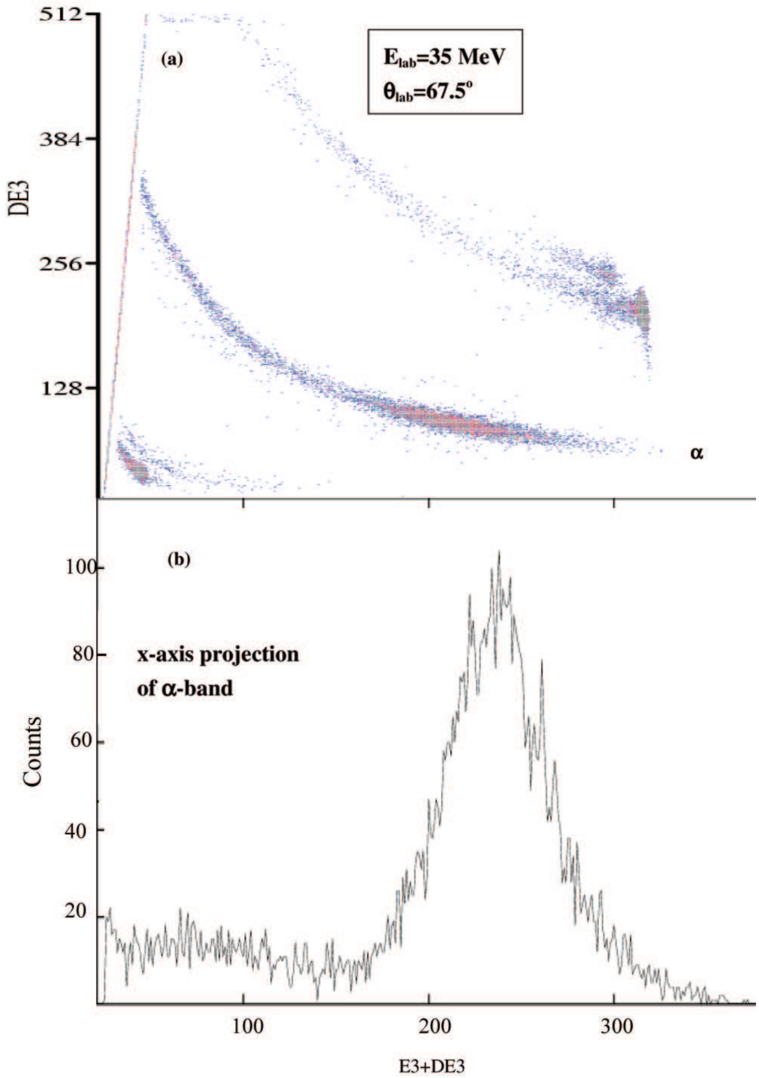

Figure 3. (**a**) A typical two-dimensional $\Delta E - E$ spectrum, (**b**) one-dimensional projection of the α-particle.

5. Inclusive α-yield resulting from ^{6}Li + ^{159}Tb reaction

To have a deeper understanding of the observation that the α-emanating channel is the favoured ICF process, it seemed necessary to detect the outgoing α-particles. Thus we carried out an inclusive measurement of the outgoing α-particles produced in the reaction ^{6}Li + ^{159}Tb, as ^{6}Li is the most weakly bound of the four projectiles considered here.

The experiment was done at the 14UD BARC-TIFR Pelletron accelerator, in Mumbai. ^{6}Li beam bombarded a ^{159}Tb target of thickness 450 μg/cm^2. Four Si

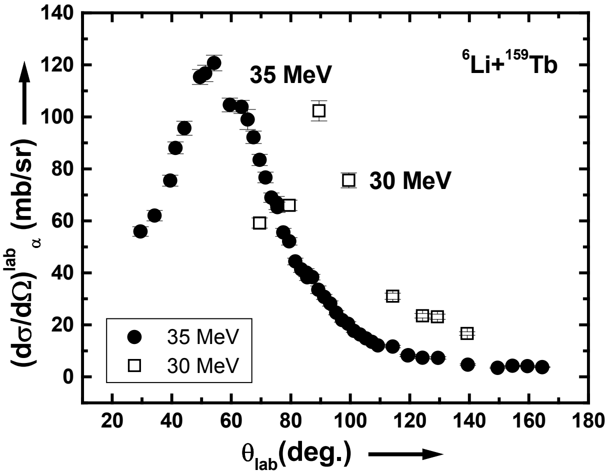

Figure 4. Typical angular distribution plots of α-yields at two different laboratory energies.

$\Delta E - E$ telescopes were used to detect the α-particles produced in the reaction. The ΔE detectors were 25 μ thick, two E-detectors were 3 mm thick, one was 2 mm thick and the other was 500 μ thick. Four telescopes measured the angular distribution of the α-particles in the range 30° to 165°. The measurements were taken at energies $E_{\text{lab}} = 23$, 25, 27, 30 and 35 MeV, that spanned the Coulomb barrier. Figures 3a and 3b show a typical two-dimensional $\Delta E - E$ spectrum and one-dimensional projection of the α-particles at 35 MeV, respectively. Figure 4 shows typical angular distribution plots of the α-yields at two laboratory energies. The total α-production yield at each energy was obtained by integrating the yields over all angles. Figure 5 shows the variation of the total α-yields as a function of the incident energies.

Since this is an inclusive measurement, the measured α-yield will consist of contributions from various processes. For reactions induced by the weakly bound ^{6}Li ($Q = -1.47$ MeV for the $\alpha + d$ breakup), it is natural to assume that an important contributor to the α-yield is the $\alpha + d$ breakup process, as this breakup channel has the lowest Q-value. But other processes producing significant α-yields [26] are also likely to occur. The processes that might contribute significantly to the observed α-yield are:

(1) Breakup of ^{6}Li, which could be either direct or resonant (sequential), i.e. NCBU process.

(2) α-particles resulting from either d-capture by the target, after BU, or a one-step d-transfer.

(3) Single-neutron stripping (or pick-up) from ^{6}Li projectile will lead to unstable ^{5}Li (or ^{7}Li), that will subsequently decay to α plus a proton (or a triton).

(4) Similarly, single-proton transfer can also result in α-particles.

Theoretical calculations need to be done to estimate the α-yield from each of these processes. To estimate the α-particles resulting from the BU process, preliminary continuum-discretized-coupled-channels (CDCC) calculations were carried

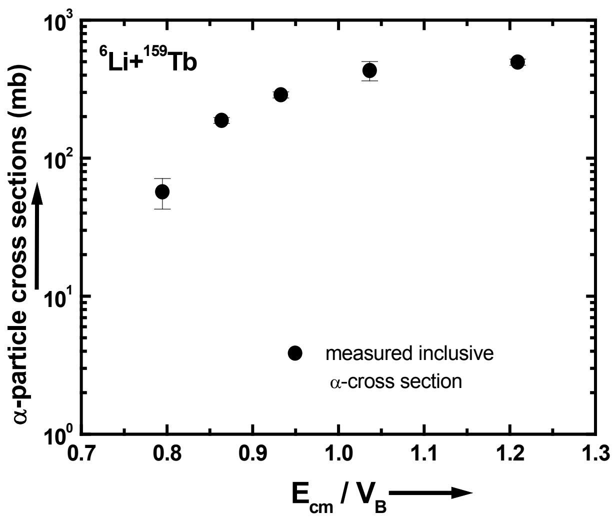

Figure 5. Variation of the total α-yield as a function of incident energies.

out using the code FRESCO [27]. In the CDCC formalism, the breakup process of a weakly bound nucleus is interpreted as an excitation of the nucleus into the continuum energy eigenstates above its breakup threshold. In this method, the breakup continuum states are described in terms of a finite number of discrete states which are suitably constructed from the original continuum states and a coupling among these discretized continuum states are treated exactly in a coupled-channels approach. In the calculations ^{6}Li was taken to be a cluster of $\alpha + d$ for it's bound as well as continuum states. Both direct and sequential BU processes were included in the calculations. The preliminary calculations show that the α-yields resulting from ^{6}Li breaking into α and d lie way below the measured α-yields. So one really needs to calculate the transfer cross-sections which may be important contributors to the α-yield in the reaction.

6. Summary

To summarize, the measurement of CF excitation functions for the $^{11,10}\mathrm{B} + {}^{159}\mathrm{Tb}$ and $^{6,7}\mathrm{Li} + {}^{159}\mathrm{Tb}$ reactions have been presented. Compared to $^{11}\mathrm{B} + {}^{159}\mathrm{Tb}$, the CF cross-sections for $^{10}\mathrm{B} + {}^{159}\mathrm{Tb}$, $^{7}\mathrm{Li} + {}^{159}\mathrm{Tb}$ and $^{6}\mathrm{Li} + {}^{159}\mathrm{Tb}$ are found to show suppressions. The extent of the suppression is found to be correlated with the α-separation energies of the projectiles. Besides, it is also observed that higher the breakup threshold, higher is the onset of suppression.

As α-emanating channel was found to be the dominant ICF process, in all the three reactions showing suppression of CF, α-production in the $^{6}\mathrm{Li} + {}^{159}\mathrm{Tb}$ reaction was measured inclusively at energies spanning the Coulomb barrier. The preliminary CDCC calculations carried out to estimate the α-yield via the $\alpha + d$ breakup process of ^{6}Li largely underestimated the measured α-yield. This indicates that perhaps transfer processes producing α-particles could be important contributors.

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