

Importance of the $1n$ -stripping process in the ${}^6\text{Li} + {}^{159}\text{Tb}$ reaction

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The inclusive cross sections of the α particles produced in the reaction ${}^6\text{Li} + {}^{159}\text{Tb}$ have been measured at energies around the Coulomb barrier. The measured cross sections are found to be orders of magnitude larger than the calculated cross sections of ${}^6\text{Li}$ breaking into α and d fragments, thus indicating contributions from other processes. The experimental cross sections of $1n$ -stripping and $1n$ -pickup processes have been determined from an entirely different measurement, reported earlier. Apart from incomplete fusion and d -transfer processes, the $1n$ -stripping process is found to be a significant contributor to the inclusive α -particle cross sections in this reaction.

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I. INTRODUCTION

Investigation of reactions involving weakly bound projectiles and the influence of their low binding energies on various reaction channels has received a fillip in recent years, especially in the context of the increasing number of radioactive ion beam facilities. To have a proper understanding of the influence of breakup of loosely bound projectiles on the fusion process, one needs to understand the mechanisms of all the competing reaction channels.

Measurements involving weakly bound projectiles, both stable and unstable, with $\alpha + x$ cluster structures show substantially large production cross sections for α particles [1–9], which indicate the presence of mechanisms other than the $\alpha + x$ breakup. Utsunomiya *et al.* showed that for the reaction ${}^7\text{Li} + {}^{159}\text{Tb}$ [9], about half of the α and triton yield originates from the breakup-fusion process, which is more commonly referred to as the incomplete fusion (ICF) process. Evidence of transfer-induced breakup producing α particles in the reaction ${}^7\text{Li} + {}^{65}\text{Cu}$ has also been reported [10]. Our recent works on the systematic measurements of complete and incomplete fusion excitation functions for the reactions ${}^{6,7}\text{Li} + {}^{159}\text{Tb}$ and ${}^{10,11}\text{B} + {}^{159}\text{Tb}$ [11–13] have shown that the complete fusion (CF) cross sections at above-barrier energies are suppressed for reactions with weakly bound projectiles, and the extent of suppression is correlated with the α -breakup threshold of the projectile. The measurements also showed that the α -emitting channel is the favored ICF process in reactions with projectiles having low α -breakup thresholds. A critical insight into these measurements shows that the sum of the CF and the ICF cross sections for each system yields total fusion cross sections which lie very close to the calculated one-dimensional barrier penetration model calculations, at energies above the barrier. This shows that the suppression

in the CF cross sections at above-barrier energies is primarily due to the loss of flux into the ICF channel.

A recent exclusive measurement on the reaction ${}^6\text{Li} + {}^{208}\text{Pb}$ [14] showed that the cross sections of the breakup process following $1n$ stripping (transfer breakup) of ${}^6\text{Li}$ are higher than that for the breakup of ${}^6\text{Li}$ into α and d fragments. By contrast, another recent work on the reaction ${}^6\text{Li} + {}^{209}\text{Bi}$ [15], aimed at disentangling the reaction mechanisms responsible for the large inclusive α -particle cross sections, indicated that the cross sections of the breakup of ${}^6\text{Li}$ into α and d fragments are much higher than those of the breakup following $1n$ stripping of ${}^6\text{Li}$. However, very recently it has been reported [16] that for ${}^{6,7}\text{Li}$ -induced reactions with ${}^{207,208}\text{Pb}$ and ${}^{209}\text{Bi}$ targets, projectile breakup is triggered predominantly by nucleon transfer: n -stripping for ${}^6\text{Li}$ and p pickup for ${}^7\text{Li}$. Based on the observations made in a few reactions, it will perhaps be too optimistic to generalize the dominance of transfer-induced breakup for all ${}^{6,7}\text{Li}$ -induced reactions, as the importance of a transfer reaction depends largely on the projectile-target combination. To conclude whether the observation is a general feature of ${}^{6,7}\text{Li}$ -induced reactions or is true only for specific reactions, it is important to carry out a systematic investigation of ${}^{6,7}\text{Li}$ -induced reactions on various targets, especially medium and light mass targets. In the background of this scenario we chose to carry out an inclusive measurement of the α particles produced at energies around the Coulomb barrier in the ${}^6\text{Li}$ -induced reaction with a ${}^{159}\text{Tb}$ target. The reaction was so chosen because detailed CF and ICF cross sections have already been measured for the system [13].

II. EXPERIMENTAL DETAILS

The ${}^6\text{Li}$ beam with energies $E_{\text{lab}} = 23, 25, 27, 30$, and 35 MeV, from the 14UD BARC-TIFR Pelletron Accelerator Centre in Mumbai, was used to impinge a self-supporting ${}^{159}\text{Tb}$ target foil of thickness $\sim 450 \mu\text{g}/\text{cm}^2$. The beam

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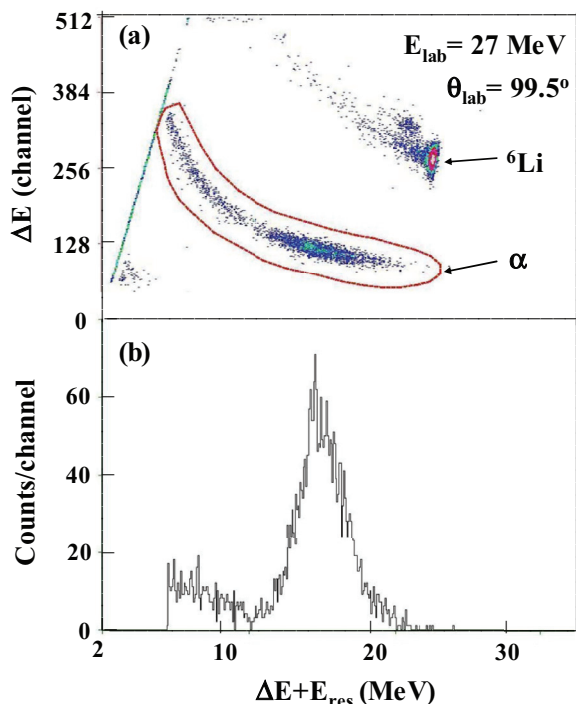


FIG. 1. (Color online) (a) Typical two-dimensional ΔE - E spectrum of the reaction ${}^6\text{Li} + {}^{159}\text{Tb}$ at scattering angle $\theta_{\text{lab}} = 99.5^\circ$ for a beam energy of 27 MeV. The enclosed area shows the α -particle band. (b) The one-dimensional projection of the enclosed area in (a).

energies were corrected for loss of energy in the target material at half-thickness of the target. To detect and identify the α particles produced in the reaction, four ΔE - E telescopes of Si-surface barrier detectors were placed on a movable arm inside a scattering chamber of 1 m in diameter. The thicknesses of the detectors were so chosen that the α particles lose part of their kinetic energies in the first detector (ΔE) and are stopped in the second detector ($E_{\text{res.}}$). The α particles produced in the reaction were measured in the range $30^\circ \leq \theta_{\text{lab}} \leq 165^\circ$ in steps of 2° or 5° depending on the bombarding energy, where θ_{lab} is the scattering angle in the laboratory. Two Si-surface barrier detectors, each of thickness = 500 μm , were placed at angles of $\pm 20^\circ$ with respect to the beam direction for beam monitoring and normalization purposes.

Figure 1(a) shows a typical two-dimensional inclusive ΔE - E ($E = \Delta E + E_{\text{res.}}$) spectrum taken at the laboratory scattering angle $\theta_{\text{lab}} = 99.5^\circ$ for a beam energy of 27 MeV. The enclosed area in the figure shows the α -particle band, and its one-dimensional projection is shown in Fig. 1(b). It shows a broad continuous peak, with centroid nearly equal to $2/3$ the incident beam energy. The contribution of the α particles, emitted mostly at energies corresponding to the beam velocity, is expected to originate from breakup-related processes. It needs to be mentioned here that the heavy compound nuclei formed, following either the CF or ICF process, are expected to decay predominantly by neutron evaporation [13] and this is also predicted by the statistical model calculations done using the code PACE2 [17]. The differential cross sections of

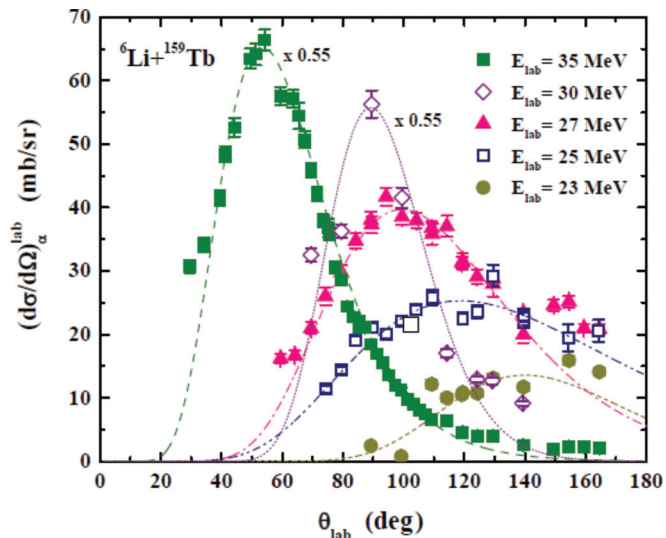


FIG. 2. (Color online) Angular distributions of inclusive α particles for the reaction ${}^6\text{Li} + {}^{159}\text{Tb}$ at energies $E_{\text{lab}} = 23$ – 35 MeV. The lines through the data are fits with Gaussian functions.

the inclusive α particles were obtained by using the formula

$$\frac{d\sigma}{d\Omega} = \left(\frac{Y_\alpha}{Y_{\text{mon}}} \right) \left(\frac{\Delta\Omega_{\text{mon}}}{\Delta\Omega_{\text{Tele}}} \right) \left(\frac{d\sigma}{d\Omega} \right)_{\theta_{\text{mon}}}^{\text{Ruth}}, \quad (1)$$

where Y_α and Y_{mon} are the number of counts under the broad continuous peak of the α particles (Fig. 1) and the average number of counts in the monitor detectors, respectively. The quantities $\Delta\Omega_{\text{mon}}$ and $\Delta\Omega_{\text{Tele}}$ are the solid angles subtended by the monitor detectors and the ΔE - E telescope, respectively, and θ_{mon} is the angle of the monitor detector. For all five bombarding energies, the broad peak in each of the α -particle energy spectra was well separated from the low-energy small peak (Fig. 1) at all scattering angles. The α particles in the low-energy peak, which is indeed a very small contribution at all the bombarding energies, could be due to target impurities, such as C and O.

The measured angular distributions of the inclusive α particles for the five incident energies are shown in Fig. 2. The angular distribution at each of the bombarding energies was obtained by considering the counts within the main peak of the α spectrum. With the exception of the low-energy 23-MeV data, each of the distributions shows a clear maximum that shifts to lower laboratory angle with the increase of beam energy. The angular distribution data were fitted with Gaussian functions and are shown by the lines in Fig. 2. The total angle-integrated α -particle cross sections obtained from the angular distribution data at each of the incident energies are plotted in Fig. 3.

III. DISCUSSION

Because the present work is an inclusive measurement, the α -particle cross sections are expected to have contributions from various processes. For reactions induced by the weakly bound projectile ${}^6\text{Li}$ ($Q = +1.47$ MeV for the $\alpha + d$ breakup), it is natural to assume that an important contributor to the

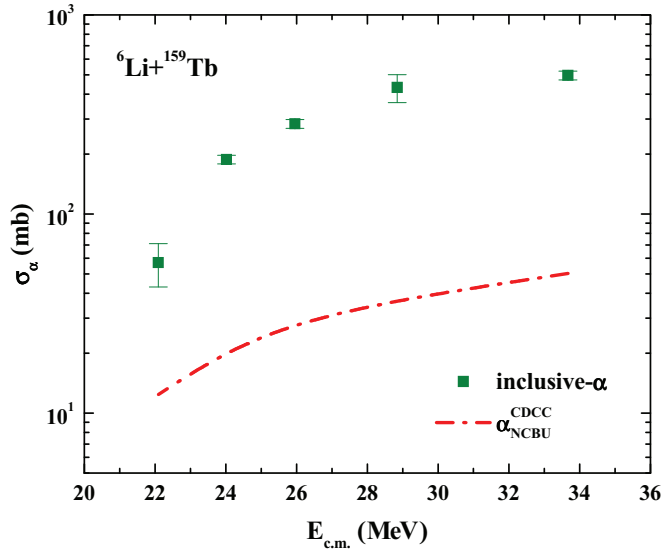


FIG. 3. (Color online) Measured inclusive α -particle cross sections for the reaction ${}^6\text{Li} + {}^{159}\text{Tb}$. The dash-dotted line shows the NCBU cross sections obtained from the CDCC calculations.

α -particle cross sections is the breakup of ${}^6\text{Li}$ into α and d fragments. Besides, other processes producing significant α -particle cross sections are also likely to occur. The processes that might contribute significantly to the inclusive α -particle cross sections are the following: (i) breakup of ${}^6\text{Li}$ into α and d fragments, which could be either direct or resonant (i.e., sequential) or both, where both fragments escape without being captured by the target, i.e., a no-capture breakup (NCBU) process, (ii) α particles resulting from d capture by the target (d -ICF), following the breakup of ${}^6\text{Li}$ into α and d , or a one-step d transfer to the target, (iii) single-proton stripping from ${}^6\text{Li}$ to produce unbound ${}^5\text{He}$ that decays to an α particle plus a neutron, (iv) single-neutron stripping from ${}^6\text{Li}$ to produce an α -unstable ${}^5\text{Li}$, which will subsequently decay to an α particle plus a proton, and (v) single-neutron pickup from ${}^6\text{Li}$ to produce ${}^7\text{Li}$, which breaks into an α particle and a triton if ${}^7\text{Li}$ is excited above its breakup threshold of 2.45 MeV.

In order to understand the origin of the large inclusive α -particle cross sections obtained in the reaction ${}^6\text{Li} + {}^{159}\text{Tb}$, measurements and/or theoretical calculations are necessary to estimate the contribution from each of the above processes.

A. Breakup cross sections: Continuum-discretized-coupled channels calculations

To estimate the contribution from the NCBU process (i), exclusive measurements between the breakup fragments α and d are needed. As only inclusive measurements were taken in the present work, the NCBU cross sections have been estimated theoretically in the framework of the continuum-discretized-coupled channels (CDCC) method [18,19]. The CDCC calculations were performed with the coupled channels code FRESKO [20] (version frxx.09j), by assuming ${}^6\text{Li}$ to have an $\alpha + d$ cluster structure for its bound and continuum states. Following Ref. [21], we discretized the α - d continuum into a

series of equally spaced momentum bins, each of width $\Delta k = 0.25 \text{ fm}^{-1}$ in the range $0.0 \leq k \leq 0.75 \text{ fm}^{-1}$, corresponding to the ${}^6\text{Li}$ excitation energy of $1.47 \leq E_x \leq 10.27 \text{ MeV}$ with respect to the ${}^6\text{Li}$ ground-state energy. The contribution from higher excited states is expected to be negligible. Each momentum bin was treated as an excited state of the ${}^6\text{Li}$ nucleus with excitation energy equal to the mean energy of the bin and having spin J and parity $(-1)^L$. The angular momenta are related by $\mathbf{J} = \mathbf{L} + \mathbf{s}$, where \mathbf{s} is the spin of the deuteron and \mathbf{L} is the relative angular momentum of the $\alpha + d$ cluster system. In the calculations, L is limited to 0, 1, and 2. The contribution from higher L is negligible. Couplings to the 3^+ ($E^* = 2.18 \text{ MeV}$), 2^+ ($E^* = 4.31 \text{ MeV}$), and 1^+ ($E^* = 5.65 \text{ MeV}$) resonant states as well as couplings to the nonresonant $\alpha + d$ continuum were included in the calculations. In order to avoid double counting, the bin width was suitably modified in the presence of resonant states. The $\alpha + d$ binding potentials were taken from Ref. [22]. The cluster-folding model potentials for the interactions, α target, and d target were evaluated at $2/3$ and $1/3$ of the incident energy of the ${}^6\text{Li}$ beam, respectively. As no experimental elastic scattering angular distribution data for $\alpha + {}^{159}\text{Tb}$ and $d + {}^{159}\text{Tb}$ reactions are available in the literature, the global optical model potential parameters [23,24] were used in describing the interactions at the corresponding energies. The couplings from the ground state to continuum and continuum to continuum states were included in the calculations. Both Coulomb and nuclear couplings were incorporated. The results of the NCBU cross sections thereby calculated are plotted in Fig. 3 by the dash-dotted curve, and they are seen to largely underestimate the measured α -particle cross sections. This shows that the α particles from sources other than breakup are important and need to be accounted for. This feature has also been observed for other heavy systems, such as ${}^6,7\text{Li} + {}^{208}\text{Pb}$ [8] and ${}^6\text{Li} + {}^{209}\text{Bi}$ [15].

B. Contribution of α -particle cross sections from the d -ICF process

The α -particle cross sections resulting from the d capture by the ${}^{159}\text{Tb}$ target [d -ICF, process (ii)], followed by xn evaporation, were determined from the γ -ray spectra recorded in the fusion cross sections measurement of the ${}^6\text{Li} + {}^{159}\text{Tb}$ reaction [13]. The cross sections of the resulting residual nuclei ${}^{160}\text{Dy}$, ${}^{159}\text{Dy}$, and ${}^{158}\text{Dy}$ were already reported in Ref. [13]. However, for the sake of convenience, the cross sections of the αxn channels, following the d -capture ICF, along with the total d -capture cross sections ($\Sigma \alpha xn$), are plotted in Fig. 4. As already mentioned in the earlier work, the ICF cross sections thus measured also include contributions due to the d transfer from ${}^6\text{Li}$ to ${}^{159}\text{Tb}$, if any, since in the γ -ray measurement it was not possible to distinguish between the two types of events.

Also, the single-proton stripping process (iii) ${}^{159}\text{Tb}({}^6\text{Li}, {}^5\text{He}){}^{160}\text{Dy}$ ($Q = +2.836 \text{ MeV}$), if it occurs, will lead to the ${}^{160}\text{Dy}$ nuclei in excited states. The ${}^{160}\text{Dy}$ nuclei following the $1p$ -stripping process will then decay by xn evaporation to produce Dy isotopes and will be included in the αxn channel cross sections of the d -ICF process.

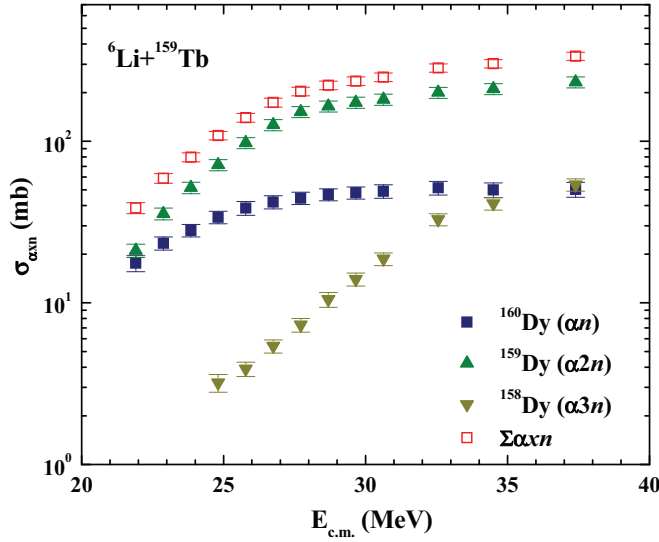


FIG. 4. (Color online) Cross sections of ^{160}Dy , ^{159}Dy , and ^{158}Dy nuclei produced in the reaction ${}^6\text{Li} + {}^{159}\text{Tb}$. The hollow points are the sum of the cross sections of the three Dy isotopes, i.e., the total d -ICF cross sections for the reaction. See Sec. III B for details.

C. Contribution of α -particle cross sections from n -transfer processes

The contributions due to processes (iv) and (v), i.e., the single-neutron stripping reaction ${}^{159}\text{Tb}({}^6\text{Li}, {}^5\text{Li}){}^{160}\text{Tb}$ ($Q = +0.711$ MeV) and the single-neutron pickup reaction ${}^{159}\text{Tb}({}^6\text{Li}, {}^7\text{Li}){}^{158}\text{Tb}$ ($Q = +0.883$ MeV), leading to the γ rays of ${}^{160}\text{Tb}$ and ${}^{158}\text{Tb}$, respectively, have been measured from the γ -ray spectra [13] of the ${}^6\text{Li} + {}^{159}\text{Tb}$ reaction. For the former case, the production cross section of the 63.68-keV (1^-) state of ${}^{160}\text{Tb}$ was obtained from the measured cross section of the 63.68-keV γ ray, after correcting for its internal conversion coefficient (α_T) of 15.1. In the γ -ray spectra, this was the only γ ray of ${}^{160}\text{Tb}$ that could be identified. Besides, because this is a fairly low energy γ ray, special care was taken to estimate the area under this γ -ray peak. The 63.68-keV γ ray is an $E2$ transition that feeds the ground state of ${}^{160}\text{Tb}$. As this γ -ray has a fairly large internal conversion coefficient, the reliability of the cross sections of ${}^{160}\text{Tb}$ may be questioned. The large value of $\alpha_T = 15.1$, though theoretically calculated, is expected to be a reliable estimate since theoretically calculated values of α_T , especially for $E2$ transitions, are known to agree well with the experimentally measured values. For example, the measured value of α_T for the 75.26-keV transition in ${}^{160}\text{Gd}$ is 7.41 ± 0.21 while the calculated value varies between 7.24 and 7.51; the measured α_T value for the 73.39-keV transition for ${}^{164}\text{Dy}$ is 8.92 ± 0.19 while the calculated value varies between 8.80 and 9.12; the measured α_T value for the 53.2-keV transition for ${}^{230}\text{Th}$ is 229 ± 7 and the calculated value lies between 227.6 and 234.2 [25]. Also, although the cross section of the 63.68-keV γ ray is small, the corresponding peak in the γ spectrum is fairly clean, thereby yielding γ -ray cross section with small uncertainty. Nevertheless, an uncertainty of 10% in the theoretical value of α_T has been assumed while obtaining the cross sections of the ${}^{160}\text{Tb}$ nuclei shown in Fig. 5. It should be emphasized here that, in this method

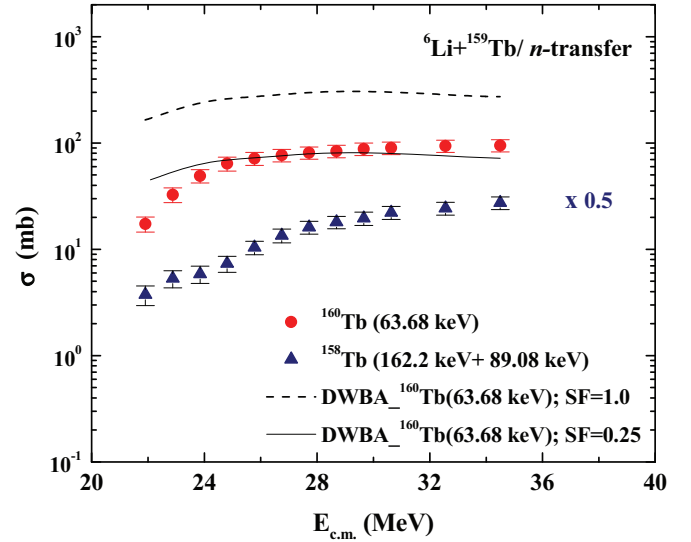


FIG. 5. (Color online) Measured cross sections of $1n$ -stripping and $1n$ -pickup processes populating the excited states of ${}^{160}\text{Tb}$ and ${}^{158}\text{Tb}$ nuclei, respectively, in the reaction ${}^6\text{Li} + {}^{159}\text{Tb}$. The dashed and solid curves are the distorted wave Born approximation calculated cross sections, with spectroscopic factors of 1 and 0.25, respectively, assumed for the 63.68-keV state.

of extraction of n -stripping cross sections from the γ -ray spectra, the contribution of transfer to the ground state of ${}^{160}\text{Tb}$ cannot be determined. So within the constraints of the present technique, only excited state transfer cross sections could be obtained.

Similarly, the total cross sections of the $1n$ -pickup process populating the excited states of ${}^{158}\text{Tb}$ nuclei were obtained by summing the measured cross sections of the 162.2- and 89.08-keV γ rays after appropriate correction for their respective internal conversion factors, and these are shown in Fig. 5. In this case also, the ground-state transfer cross sections could not be determined.

In order to compare the measured cross sections for the n -stripping process with theory, we attempted to calculate the cross sections for the single n transfer to the first excited 63.68-keV (1^-) state of ${}^{160}\text{Tb}$ nuclei for the five bombarding energies of 23, 25, 27, 30, and 35 MeV. The transfer cross sections were calculated in the distorted wave Born approximation (DWBA) framework, using the computer code FRESKO. The n - ${}^{159}\text{Tb}$ and n - ${}^5\text{Li}$ binding potentials were taken from Refs. [26] and [27], respectively. The required potential parameters for the entrance channel ${}^6\text{Li} + {}^{159}\text{Tb}$, the exit channel ${}^5\text{Li} + {}^{160}\text{Tb}$, and the ${}^5\text{Li} + {}^{159}\text{Tb}$ core-core interaction were taken to be the global optical model potential parameters of Ref. [28] with modifications such that these potentials fit the measured elastic scattering angular distributions at the five bombarding energies of 23, 25, 27, 30, and 35 MeV. Depth parameters have been adjusted to reproduce the binding energy of the neutron to the core ${}^{159}\text{Tb}$. The spectroscopic factor (SF) for ${}^6\text{Li} \rightarrow {}^5\text{Li} + n$ was taken from Ref. [27]. The experimental SF for the 63.68-keV (1^-) state in ${}^{160}\text{Tb}$ is not available in the literature. Nevertheless, the transfer cross sections have been calculated by assuming the SF to be 1.0 for the 63.68-keV (1^-)

state. The cross sections thereby calculated are shown by the dashed curve in Fig. 5, and they are seen to largely overpredict the measured cross sections. It was found that the DWBA calculations done with a SF of 0.25 gave an overall fit to the measured cross sections at the higher energies. The resulting calculations are shown in the figure by the solid curve.

Due to the unavailability of relevant SFs, no better DWBA calculation could be done for the $1n$ -stripping process. Therefore, no further attempt was undertaken to calculate the cross sections for the $1n$ -pickup process.

D. Total contribution to measured α -particle cross sections from various processes

The measured d -ICF (i.e., $\Sigma\alpha xn$) cross sections, the $1n$ -stripping cross sections (excluding the ground-state transfer contribution), and the sum of the cross sections from these two processes are compared with the measured inclusive α -particle cross sections in Fig. 6. The calculated NCBU cross sections are also shown in the figure by the dash-dotted line. It is observed that the $1n$ -stripping cross sections (excluding the ground-state transfer contribution) are much larger than the calculated NCBU cross sections, in contradiction to that reported for the ${}^6\text{Li} + {}^{209}\text{Bi}$ reaction [15] but in agreement with the observation of Luong *et al.* [14,16]. It had been

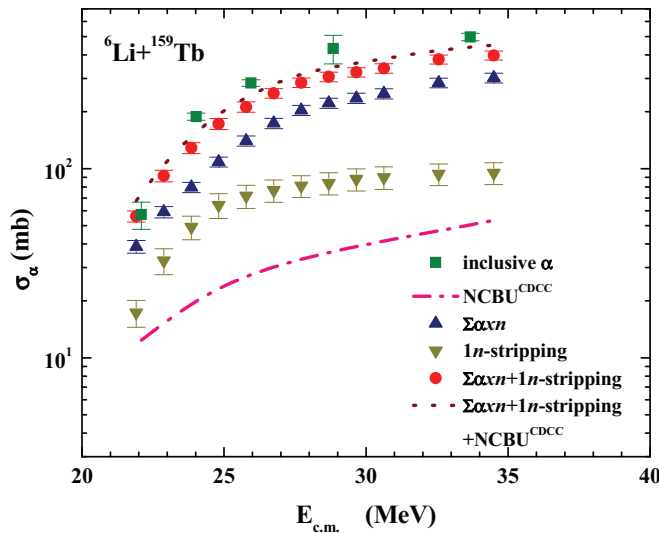


FIG. 6. (Color online) Contributions to the α -particle cross sections originating from various processes in the reaction ${}^6\text{Li} + {}^{159}\text{Tb}$. The squares are the measured inclusive α -particle cross sections. The up triangles are the $\Sigma\alpha xn$ channels, corresponding to the d -ICF process (including d transfer and $1p$ stripping, if any). The down triangles are the contributions from the $1n$ -stripping process (excluding ground-state transfer), corresponding to the instantaneous decay of the resulting α -unstable ${}^5\text{Li}$ nuclei into α and p . The circles are the sum of the d -ICF and the $1n$ -stripping cross sections. The cross sections resulting from the breakup of ${}^6\text{Li}$ into α and d (NCBU process), as determined from the CDCC calculations, are shown by the dash-dotted line. The dotted curve shows the trend of the cross sections, if the calculated NCBU cross sections are added to the measured cross sections of d -capture ICF and $1n$ -stripping processes.

mentioned in Ref. [15] that the measured exclusive cross sections of $\alpha + p$ in the ${}^6\text{Li} + {}^{209}\text{Bi}$ reaction, following n stripping of ${}^6\text{Li}$, are possibly the lower limit. This may be because the detector configuration used to measure the $\alpha + p$ breakup cross section [29] did not cover the whole range of the relative momentum, thereby leading to the underestimation of the cross section. Though the relative importance of reaction mechanisms largely depends on the target-projectile combination, the present observations, in conjunction with those reported in Refs. [14,16], in fact do show that the n -stripping process is more important than the NCBU process in ${}^6\text{Li}$ -induced reactions with targets such as ${}^{159}\text{Tb}$, ${}^{207,208}\text{Pb}$, and ${}^{209}\text{Bi}$.

It can be seen from Fig. 6 that the sum of the cross sections resulting from d -ICF (including d transfer and $1p$ stripping, in any) and $1n$ stripping (excluding ground-state transfer) reactions, shown by the solid circles, lie very close to the measured total inclusive α -particle cross sections. Here the yield of the α particles due to the ground-state transfer in the $1n$ -stripping process and also following the breakup of ${}^7\text{Li}$ nuclei produced via the n -pickup process have not been considered. The α -breakup threshold of ${}^7\text{Li}$ is 2.45 MeV, and hence ${}^7\text{Li}$ nuclei can break up only if they are excited above 2.45 MeV. Therefore, the $1n$ -pickup reaction will contribute to the total α -particle cross sections, depending on the excitation energy of the ${}^7\text{Li}$ nuclei. At lower bombarding energies, this process may not be a significant contributor, but at higher bombarding energies, the ${}^7\text{Li}$ nuclei may be excited to energies above the breakup threshold, thereby resulting in a small contribution. However, it is obvious from the figure that for this reaction, over the energy range of the present measurement, the $1n$ -pickup process is certainly not a very significant contributor to the total α -particle cross sections. The dotted curve in the figure shows that if we add the CDCC-calculated NCBU cross sections to the measured d -ICF and $1n$ -stripping cross sections, the inclusive α -particle cross sections are nearly reproduced. Thus, the d -ICF (including d transfer and $1p$ stripping, if any) and the $1n$ -stripping processes are the dominant contributors, with the NCBU process being a relatively small contributor, to the total α -particle cross sections in the ${}^6\text{Li} + {}^{159}\text{Tb}$ reaction at energies around the Coulomb barrier.

IV. SUMMARY

In summary, the inclusive α -particle cross sections for the reaction ${}^6\text{Li} + {}^{159}\text{Tb}$ have been measured at energies around the Coulomb barrier. The NCBU cross sections calculated using the CDCC formalism are found to be only a small fraction of the inclusive α -particle cross sections. Other reaction mechanisms contributing to the large α -particle cross sections have been disentangled, using data from our earlier work [13] based on an entirely different technique, e.g., the γ -ray method. The $1n$ -stripping cross sections are found to be much larger than the calculated cross sections of the NCBU process, in contradiction to the observation reported for the reaction ${}^6\text{Li} + {}^{209}\text{Bi}$ [15]. The d -ICF, including d transfer and p stripping if any, and the $1n$ -stripping processes are found to be the dominant contributors to the total α -particle

cross sections in the ${}^6\text{Li} + {}^{159}\text{Tb}$ reaction. However, due to the lack of appropriate spectroscopic factors, proper DWBA calculations could not be performed. Experiments aimed at measuring such spectroscopic factors need to be carried out in the near future. Besides, as transfer-induced breakup seems to be an important process in reactions with loosely bound projectiles, both inclusive and exclusive measurements in other systems, especially lighter systems and systems involving halo and skin nuclei, would be very valuable to obtain a clear picture of the transfer-breakup process. Identification and subsequent determination of the absolute cross sections of different multistep reaction processes involved in reactions

with weakly bound nuclei may pave the way for theorists to come up with a proper theoretical description of such processes, which is indeed a challenging task.

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