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STUDY OF FUSION AND TRANSFER REACTIONS IN THE ^{7}Li + ^{205}Tl SYSTEM*

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The complete fusion (CF), incomplete fusion (ICF), and neutron transfer ($1n$ stripping, $2n$ stripping, and $1n$ pickup) cross sections for the ^{7}Li + ^{205}Tl system were measured at energies around the Coulomb barrier by the online γ-ray detection technique. The measured CF cross sections were found to be suppressed at above-barrier energies compared to the one-dimensional barrier penetration model (1DBPM) as well as coupled channel (CC) calculations. However, measured CF cross sections at below-barrier energies are found to be enhanced compared to 1DBPM and are in reasonable agreement with the CC calculations. The suppression observed in CF cross sections at above-barrier energies is found to be commensurate with the measured total ICF cross sections. Among ICF cross sections, t-capture is found to be dominant over α-capture at all the measured energies. It is also observed that ICF is dominant at below-barrier, while CF dominates at above-barrier energies. Measured neutron transfer cross sections were compared with coupled reaction channel (CRC) calculations and found to be in agreement. The cumulative sum of all measured observables CF, ICF, and neutron transfer cross sections was found to agree with the estimated reaction cross sections.

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1. Introduction

The reaction mechanism studies with weakly bound stable and unstable nuclei have received tremendous attention in the last few decades [1–13]. With the advent of new radioactive ion beam (RIB) facilities around the world, the nuclei away from the line of stability are produced and accelerated, which further boosted these studies. It is now fairly well established that the fusion cross sections with weakly bound stable projectiles are suppressed at energies above the Coulomb barrier when compared to predictions based on coupled channels calculations. However, there are limited studies for fusion with RIBs due to low beam intensities. Additionally, measurement of direct nuclear transfer reactions involving the weakly bound stable projectiles have been performed and the significance of nucleon transfer in the reaction dynamics has been investigated in several studies [14–18].

In the present work, we report on the measurement of CF, ICF, and neutron transfer cross sections for the $^{7}\mathrm{Li} + {}^{205}\mathrm{Tl}$ system around the Coulomb-barrier energies using the online γ-ray detection technique.

2. Experimental details

The experiment was performed using the $^{7}\mathrm{Li}$ beam from the BARC-TIFR Pelletron LINAC Facility, Mumbai, India at ten energy points in the energy range of $E_{\mathrm{beam}} = 25$–40 MeV. The target $^{205}\mathrm{Tl}$ of 1 mg/cm^2, evaporated on 25 μg/cm^2 carbon backing was placed inside a compact chamber made of aluminium alloy, surrounded by the Indian National Gamma Array (INGA) setup [19]. The array consisted of nine Compton-suppressed High Purity Germanium (HPGe) Clover detectors for detection of γ-rays from the residues populated in the $^{7}\mathrm{Li} + {}^{205}\mathrm{Tl}$ system. Inside the chamber, three charged particle detector telescopes ($\Delta E = 25$–40 μm, $E = 1000$ μm) were placed at 70°, 120°, and 140°, respectively, for detection of elastic and α-particle events mainly. In addition, two Si surface barrier detectors with thickness of 300 μm, acting as monitor detectors were also placed at $\pm 25°$ for absolute normalisation purpose. The time-stamped data were collected using a digital data acquisition system with a sampling rate of 100 MHz [19]. Standard calibrated radioactive $^{152}\mathrm{Eu}$ and $^{133}\mathrm{Ba}$ sources were used for efficiency and energy calibration of the clover detectors. Figure 1 shows the typical γ-ray add-back spectrum from all the clover detectors measured at $E_{\mathrm{beam}} = 38$ MeV for the $^{7}\mathrm{Li} + {}^{205}\mathrm{Tl}$ system. The prompt γ-rays from complete fusion ($^{208,209}\mathrm{Po}$), incomplete fusion ($^{206,207}\mathrm{Pb}$ from t-capture, $^{207,208}\mathrm{Bi}$ from α-capture), one-neutron stripping ($^{206}\mathrm{Tl}$), two neutron stripping ($^{207}\mathrm{Tl}$), and one-neutron pickup ($^{204}\mathrm{Tl}$) channel were identified from Refs. [20–25] and are labelled.

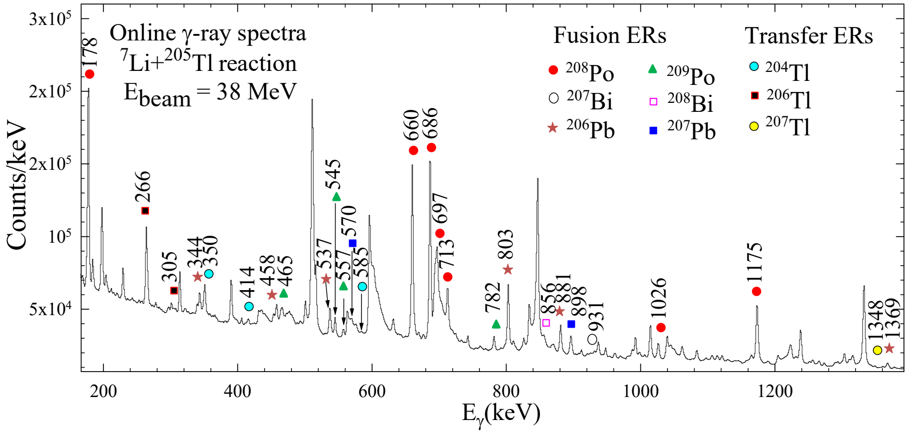

Fig. 1. γ-ray add-back spectrum from all the clover detectors obtained in the ^{7}Li + ^{205}Tl system at beam energy $E_{\mathrm{beam}} = 38$ MeV. The γ lines from the possible evaporation residues (^{208,209}Po) following CF, α-capture channel (^{207,208}Bi), and t-capture channel (^{206,207}Pb) are labelled. Also, the γ lines following the neutron transfer channel (^{206}Tl from $1n$ stripping, ^{207}Tl from $2n$ stripping, and ^{204}Tl from $1n$ pickup) are marked.

3. Results and discussion

3.1. Data reduction

The cross sections for all the residues formed in CF (^{208,209}Po), ICF (^{207,208}Bi, ^{206,207}Pb), and neutron transfer (^{204,206,207}Tl) were determined considering all the ground and metastable states. The γ-ray yield and its absolute efficiency, elastic yield at the monitor detector, its solid angle, and the Rutherford cross section were utilised for extracting the cross section of a particular γ-ray.

3.2. Fusion cross sections

The cross sections for all the residues from CF and ICF are shown in Fig. 2 (a). The residue cross sections from ^{208,209}Po were added to get the CF cross sections. Similarly, the total t-capture and total α-capture cross sections are obtained by adding the individual residue cross sections. The total t-capture cross sections are found to be much larger than α-capture at all the measured energies. Figure 2 (b) shows the comparison of CF, ICF, and total fusion (TF = CF + ICF) data. As can be seen, CF cross sections are larger than ICF at above-barrier energies, while ICF overtakes CF at below-barrier energies.

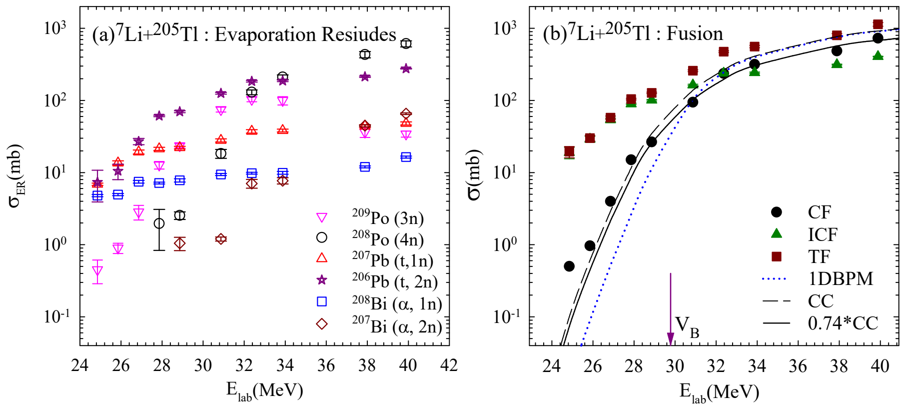

Fig. 2. (a) ER cross sections: ^{209,208}Po (complete fusion), ^{208,207}Bi (α-capture) and ^{207,206}Pb (t-capture); (b) Fusion: CF, ICF, and TF cross sections in the ^{7}Li$+^{205}$Tl system.

For understanding the fusion behaviour, coupled channel (CC) calculations were performed using the modified version of CCFULL [26], which can include the effect of projectile ground-state spin and its excitation in addition to the target excitation. The Akyüz–Winther (AW) potential [27] parameters were used in the calculation. The full couplings include the coupling of the projectile ground state ($3/2^-$) and first excited state ($1/2^-$, 0.478 MeV). As the target is the odd-A nucleus ^{205}Tl, the excitation energies and deformation parameters were taken to be the averages of those of the neighbouring even–even nuclei ^{204}Hg and ^{206}Pb.

The results from the uncoupled (1DBPM) and CC calculations are shown in Fig. 2 (b) by dotted and dashed lines, respectively. It was observed that at sub-barrier energies, the calculated fusion cross sections with the couplings are enhanced compared to the uncoupled values. However, at above-barrier energies, the calculated values of fusion with or without couplings are higher than the measured CF values and in agreement with TF values. CC calculations scaled by a factor of 0.74 are found to match with measured CF values at above-barrier energies as shown in Fig. 2 (b) by the solid line. Hence, it can be concluded that CF cross sections in this region are suppressed by $26 \pm 4\%$ compared to the prediction of CCFULL calculations. The uncertainty of 4% in the suppression factor was estimated from the uncertainties in V_b and CF cross section. This suppression factor is similar to earlier studies with the ^{7}Li projectile [4] on various targets which confirms that the CF suppression is target-independent. However, at below-barrier energies, the measured cross sections are found to be enhanced compared to 1DBPM and in reasonable agreement with the CC calculations. These results are reported in detail in our recent work [28].

3.3. Neutron transfer cross sections

The measured neutron transfer (^{204,206,207}Tl) cross sections are plotted in Fig. 3. One-neutron stripping cross sections are found to be larger than two-neutron stripping and one-neutron pickup cross sections. Coupled Reaction Channel (CRC) calculations were performed to understand the mechanism of neutron transfer. A detailed discussion of this kind of calculations was given in our earlier works [14]. These calculations were performed using the Fresco code (version FRES 2.9) [29].

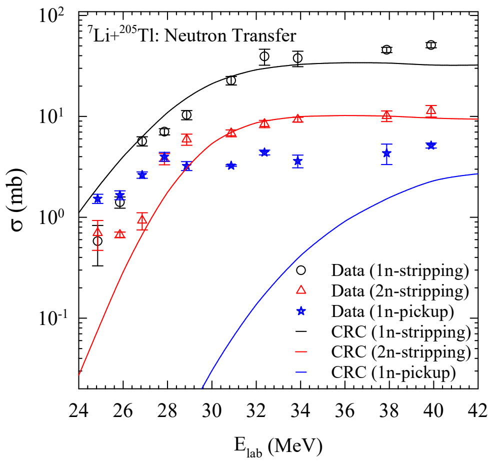

Fig. 3. Comparison of measured cross sections for $1n$ stripping, $2n$ stripping, and $1n$ pickup transfer in the $^{7}\mathrm{Li} + {}^{205}\mathrm{Tl}$ system with CRC calculations.

CRC calculations for one-neutron stripping, two-neutron stripping, and one-neutron pickup were performed by using the global phenomenological optical model potentials parameters which were taken from Refs. [30, 31]. The potentials binding the transferred particles were of the Woods–Saxon volume form, with radius $1.25A^{1/3}$ fm and diffuseness 0.65 fm, with A being the mass of the core nucleus. The depths were adjusted to obtain the required binding energies of the particle–core composite system. The single-particle states along with spectroscopic factors (C^2S) taken from [32–36] were considered in the calculations. For the $^{7}\mathrm{Li} \to {}^{6}\mathrm{Li}$ transfer, both the $1p_{3/2}$ and $1p_{1/2}$ components of the neutron bound to ^{6}Li were included with spectroscopic factors of $C^2S = 0.43$ and 0.29, respectively, taken from Cohen and Kurath [37]. Similarly for the $^{7}\mathrm{Li} \to {}^{8}\mathrm{Li}$ transfer, both the $1p_{3/2}$ and $1p_{1/2}$ components of the neutron bound to ^{7}Li were included with spectroscopic factors of $C^2S = 0.98$ and 0.056, respectively, taken from Cohen and Kurath [37]. The spectroscopic factor for the $^{7}\mathrm{Li} \to {}^{5}\mathrm{Li}$ transfer is taken as 1.0.

The finite range Distorted Wave Born Approximation (DWBA) formalism in the post form for stripping and prior form for pickup was used. Calculations were carried out including the full complex remnant term.

The CRC calculations for one-neutron stripping, two-neutron stripping, and one-neutron pickup are shown in Fig. 3. One-neutron and two-neutron stripping calculations are found to explain the data satisfactorily, while the one-neutron pickup calculations underpredict the data. These results are reported in detail in our recent work [38].

4. Complete reaction mechanism in the ^{7}Li + ^{205}Tl system

For complete understanding of the reaction mechanism in the ^{7}Li + ^{205}Tl system, the measured CF, ICF, and transfer cross sections and their sum are compared with the deduced reaction cross sections from the present calculations as shown in Fig. 4. A reasonably good agreement of reaction cross sections with the sum was observed at all the energies.

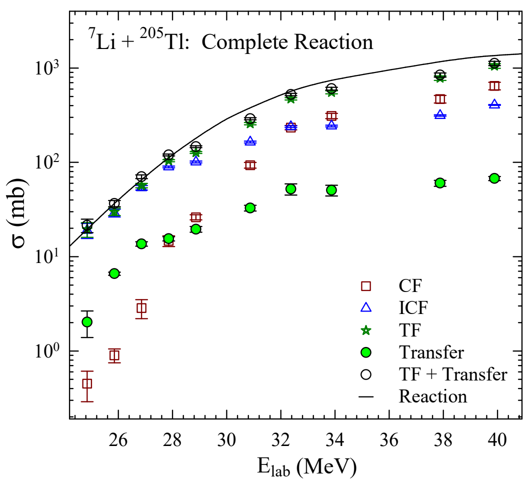

Fig. 4. Comparison of measured cross sections for CF, ICF, neutron transfer, and their cumulative with the reaction cross sections in the ^{7}Li + ^{205}Tl system.

5. Summary

The fusion and neutron transfer cross sections in the ^{7}Li + ^{205}Tl system were measured in the energy range of $0.80 < V_b < 1.34$ by the online γ-ray measurement method. The measured complete fusion cross sections at above-barrier energies were found to be suppressed by a factor of $26 \pm 4\%$ in comparison with the coupled channel calculations, which is in agreement with the literature data for the ^{7}Li projectile on various targets. Measured t-capture cross sections are found to be significantly more than the α-capture cross sections at all the energies. One-neutron and two-neutron stripping calculations are found to explain the data satisfactorily, while the one-neutron pickup calculations under-predict the data. Further, a cumulative of measured CF, ICF, and neutron transfer cross sections shows reasonable good agreement with estimated reaction cross sections.

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