Influence of projectile breakup on fusion with ^{159}Tb target

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The recent increasing availability of beams of radioactive nuclei has caused a great interest in investigating the fusion mechanism involving weakly bound nuclei, both stable and unstable [1]. The effect of breakup process on fusion involving such nuclei, particularly ^{6,7}Li and ^{9}Be, have been studied extensively in different target mass regions From literature survey one finds that for medium & light systems like ^{6,7}Li+^{59}Co, ^{9}Be+^{27}Al, ^{6,7}Li+^{24}Mg, ^{6,7}Li+^{16}O *etc*., where complete fusion (CF) and incomplete fusion (ICF) events cannot be separated and only the total fusion (TF=CF+ICF) cross sections were measured, it was observed that there is no significant effect of breakup on TF at energies around the Coulomb barrier. Whereas fusion measurement for heavy systems like ^{6,7}Li+^{209}Bi, ^{9}Be+^{208}Pb, ^{7}Li+^{165}Ho *etc*., shows that the CF cross sections are substantially suppressed at above barrier energies compared to the predictions of the one dimensional barrier penetration model (1D BPM) calculations. In this context to see what happens in the mass region between the medium, light and heavy mass systems, we have carried out fusion cross section measurement with ^{159}Tb target. We mention here that since in this mass region, the compound nuclei decay predominantly by neutron evaporation, the residual nuclei produced following the CF and ICF processes are different, hence separate measurement of CF and ICF cross sections are possible.

Now to investigate the effect of breakup on fusion, all the reactions studied so far with weakly bound stable beams have been performed using ^{6}Li, ^{7}Li and ^{9}Be projectiles that have breakup thresholds ranging from 1.45 to 2.45 MeV. Among the stable nuclei, apart from the ^{6,7}Li and ^{9}Be nuclei, the nucleus ^{10}B, also has a fairly low α-separation energy of 4.5 MeV. So like ^{6,7}Li and ^{9}Be, the nucleus ^{10}B may also be expected to breakup at low excitation energies, thereby affecting the fusion mechanism at considerably low bombarding energies. To investigate how the α-breakup threshold affects the fusion mechanisms, both CF and ICF cross sections were measured by the characteristic γ-ray method for the systems ^{11}B+^{159}Tb, ^{10}B+^{159}Tb, ^{7}Li+^{159}Tb and ^{6}Li+^{159}Tb [2,3] at energies around the respective Coulomb barriers. Here ^{11}B+^{159}Tb was chosen to be the strongly bound reference system as the nucleus ^{11}B having α-separation energy of 8.66 MeV, is comparatively strongly bound among the projectiles ^{11}B, ^{10}B, ^{7}Li and ^{6}Li.

Beams of ^{11,10}B in the energy range 38-72 MeV and ^{6,7}Li in the energy range 23-43 MeV, provided by the 14 UD BARC-TIFR Pelletron Accelerator Facility at Mumbai, bombarded a self-supporting ^{159}Tb target. The γ-rays emitted by the product nuclei were detected in a clover detector placed at 55^{o} with respect to the beam direction. For ^{6}Li+^{159}Tb, the clover detector was placed at 125^{o} with respect to the beam direction. Both in-beam and off-beam γ-spectra were taken for each beam 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}Tb.

The CF cross sections in the ^{11}B, ^{10}B-induced reactions were obtained from the sum of the 3*n*-6*n* channel evaporation residues (ER) cross sections and for ^{7}Li, ^{6}Li induced reactions the same were obtained by summing the 2*n*-5*n* channel ER cross sections. The measured CF excitation functions for the four reactions are compared with the predictions of 1D BPM calculations done using the code CCFULL [4] in the no coupling limit. We find that all the four reactions show significant enhancement of CF cross sections at below barrier energies compared to the 1D BPM calculations. The 1D BPM calculations reproduced the measured CF cross sections at above barrier energies, for

^{11}B+^{159}Tb, but fail to reproduce the measured CF cross sections for ^{10}B+^{159}Tb, ^{7}Li+^{159}Tb and ^{6}Li+^{159}Tb reactions. Since the target ^{159}Tb is a well-deformed nucleus, the effect of deformation on fusion is considered by coupled channels (CC) calculations done using the code CCFULL. The CC calculations are found to be in reasonably good agreement with the measured CF cross sections at below barrier energies for all the four reactions, thereby showing that the sub-barrier enhancement is primarily due to the effect of target deformation. At above barrier energies, the CC calculations are found to be in very good agreement with the measured CF cross sections for ^{11}B+^{159}Tb, while for ^{10}B+^{159}Tb, ^{7}Li+^{159}Tb and ^{6}Li+^{159}Tb, the measured CF cross sections are found to be suppressed by 14±5%, 26±5%, 34±5% respectively. The extent of CF suppression for these three reactions is found to be corelated with the α-breakup threshold of the projectiles. Lower the α-breakup threshold, larger is the extent of CF suppression. In addition to the CF measurement, we have also measured the cross sections of various channels corresponding to the ICF process for the ^{10}B+^{159}Tb, ^{7}Li+^{159}Tb and ^{6}Li+^{159}Tb reactions. As expected for ^{11}B+^{159}Tb, from the γ-spectra, we have not observed any γ-rays corresponding to the ICF process. From the measured ICF excitation functions for the three reactions ^{10}B+^{159}Tb, ^{7}Li+^{159}Tb and ^{6}Li+^{159}Tb, we found that ICF process with α-emitting channels are the dominant ICF process and this observation is found to be consistence with the Q-value of the reactions. In the context of this observation, we felt it would be interesting to carry out an inclusive measurement of the outgoing α-particles. For this measurement, we chose the ^{6}Li+^{159}Tb reaction, as ^{6}Li has the lowest α-breakup threshold among the four projectiles considered here.

The experiment was performed at the 14 UD BARC-TIFR Pelletron Accelerator at Mumbai. A set of four ΔE-E telescopes of Si-SBD was used to detect the light charged particles. Measurement of inclusive α-particle angular distribution was carried out in the angular range 30^{o} to 165^{o} for each of the five bombarding energies 23, 25, 27, 30 and 35 MeV. Each of the measured angular distribution of the inclusive α-particles is integrated to obtain the total cross sections of the inclusive α-particles [5]. Since this is an inclusive measurement, the measured inclusive α-particle cross sections is expected to have contributions from various processes. These are: (i) non capture breakup (NCBU) process; since we have not performed any exclusive measurement, we have estimated their cross sections in the continuum discretised coupled channels (CDCC) formalism using the code FRESCO [6]. The CDCC predicted cross sections of the NCBU process is found to be much less than the measured inclusive α-particle cross sections. So definitely there are contributions from other processes. (ii) *d*-capture ICF process; contribution of α-particles coming from this process is measured from the γ-ray spectra as mentioned in the measurement of ICF process in the ^{6}Li+^{159}Tb reaction. (iii) Contribution of α-particles coming from the single-neutron stripping process was obtained by measuring the cross sections of ^{160}Tb nuclei from the γ-ray spectra of fusion excitation measurement for ^{6}Li+^{159}Tb. (iv) contribution of α-particles coming from the single- proton stripping process if any is already included in the measured cross section of α*n* channel of *d*-ICF process. From the comparison of cross sections of α-particles coming from the processes considered above, we found that *d*-capture ICF and single neutron stripping process are the dominant contributors to the total inclusive α-particle cross sections at energies around the Coulomb barrier for the ^{6}Li+^{159}Tb reaction [7].

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