Effect of breakup on complete fusion of weakly bound ^{6,7}Li projectiles with ^{144,152}Sm targets

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Introduction

Study of nuclear reactions involving weakly bound (stable or radioactive) projectile has been a subject of recent experimental and theoretical interest [1,2]. Although sub-barrier fusion involving strongly bound stable nuclei is well understood, there are different conclusions about the enhancement or suppression of the fusion cross section (σ_{fus}) over the predictions of single barrier fusion model around the Coulomb barrier, when one of the collision partners is a weakly bound nuclei such as ^{6,7}Li and ^{9}Be. There are theoretical calculations that predict either suppression of the complete fusion (CF) cross sections due to breakup of loosely bound nucleus or enhancement of the same due to coupling of the relative motion of the colliding nuclei to the breakup channel. An understanding of breakup and fusion is directly relevant to produce nuclei near the drip line and possibly superheavy nuclei. Experimentally such studies are limited because of the low intensities of unstable beams currently available. But the stable weakly bound projectiles like ^{6,7}Li and ^{9}Be available with large intensities are ideal for the quantitative testing of theoretical models and for use as a comparator for fusion measurements with other unstable beams.

With this motivation, we performed several measurements on the fusion cross sections for four reactions involving Lithium beams with Samarium targets i.e., ^{6,7}Li + ^{144,152}Sm reactions. The aim of the present thesis was not only to study the effect of projectile breakup on fusion, but also its dependence on breakup threshold as well as target structure. First measurement was made for ^{6}Li beam on ^{144}Sm target which is spherical [3]. Next set of measurements were made with the same beam but a deformed target (^{152}Sm) to see the effect of target deformation in the presence of projectile breakup [4]. To investigate how CF excitation function varies with the projectile breakup threshold, measurements were also made with the same targets but with ^{7}Li (with larger breakup threshold energy) as a projectile [5].

Measurements

The fusion cross sections for ^{6,7}Li + ^{144,152}Sm reaction have been measured at energies near and above the barrier (V_B), in steps of 1-2 MeV, using ^{6,7}Li beams from 14UD BARC-TIFR pelletron facility at Mumbai. Targets of thickness ~ 400-800 μg/cm^2 were made by electro-deposition on Al backing.

Fusion of ^{6,7}Li+^{A}Sm leads to excited compound nuclei $^{(A+6/7)}$Tb* which de-excite mainly by neutron evaporation. The unstable evaporation residues (ERs) decay to Gd isotopes by electron capture. The cross sections for the individual ER channels were measured by offline counting of the gamma rays emitted from the corresponding Gd nuclei.

Results and discussions

To understand the measured ER cross sections, statistical model (SM) calculations were performed using the code PACE [6] with default potential parameters. For all the energies the SM calculations were carried out by feeding the *'l'* distributions obtained from simplified coupled-channels calculations using CCFULL [7]. ER excitation functions as well as the relative cross sections of the dominant ER channels were reproduced by the SM calculations with suitable value of the level density parameter. The combined contribution of measured xn channels was found to be ≥ 90% of the total fusion cross sections for all the four reactions. The remaining contributions were estimated from SM predictions and added to the measured ER cross sections to obtain the total experimental complete fusion cross sections (σ_{CF}^{expt}).

Fusion barrier distributions were obtained using the expression "$d^2(\sigma E)/dE^2$" from which the centroid was taken to be the average experimental barrier. Coupled-channels (CC) calculations were performed using the potential parameters that can reproduce the above experimental barrier. Results of the CC calculations for both fusion excitation function and barrier distribution were compared with the experimental data. It was observed that the behavior of σ_{CF}^{expt} is different at above and below the Coulomb barrier energies. CF cross sections are found to be suppressed at above barrier energies and enhanced at sub-barrier energies compared to the calculations with uncoupled barrier. Simplified CC calculations including the target excitations as well as bound excited state of the projectile (if any) could reproduce the σ_{CF}^{expt} at sub-barrier energies for reactions involving spherical target i.e., ^{6,7}Li+^{144}Sm. However, at above-barrier energies, the calculations with/without inelastic couplings always over-estimate the σ_{CF}^{expt} implying that the measured CF cross sections are suppressed in this region. It was also observed that the σ_{CF}^{expt} is suppressed by a similar factor as compared to the CF data available in the literature for the reactions involving tightly bound projectiles but forming similar compound nuclei. Thus, CF suppression at above barrier energies for the present reactions was confirmed [3].

To see the dominance of projectile breakup versus target deformation, the σ_{CF}^{expt} for ^{6}Li+^{144}Sm were compared with those for ^{6}Li+^{152}Sm. Cross sections for the latter at sub-barrier energies were found to be much enhanced compared to the former. This implies that the qualitative effect of the target deformation on sub-barrier fusion is enhancement which is independent of whether the projectile is weakly or strongly-bound. On the other hand, at above barrier energies, the CC calculated CF was found to overestimate the σ_{CF}^{expt} for ^{6}Li+^{152}Sm. And the CF was found to be suppressed almost by a factor similar to that of ^{6}Li+^{144}Sm due to loss of incident flux by projectile breakup. Hence, it was concluded that the effect of projectile breakup and target deformation can co-exist and their effects are prominent at two different energy regions: one at sub-barrier and the other at above barrier energies [4].

To investigate the projectile breakup threshold dependence of the CF suppression factor, we measured CF cross sections for two reactions involving ^{7}Li as a projectile (having higher breakup threshold) but with the same targets i.e., for ^{7}Li+^{144,152}Sm reactions. Comparison showed that CF suppression factors are smaller for ^{7}Li+^{144,152}Sm compared to those for ^{6}Li+^{144,152}Sm. Suppression factors are obtained by comparing the data with CCFULL predictions as well as the ones calculated using proximity potential. CF suppression factors at above barrier energies for measured reactions are given in the Table below.

Table: CF Suppression factors

Reaction	Suppression
^{6}Li+^{144}Sm	32±4%
^{6}Li+^{152}Sm	28±5%
^{7}Li+^{144}Sm	24±4%
^{7}Li+^{152}Sm	25±4%

A systematic study for several reactions involving weakly bound projectiles shows that the CF suppression factor decreases with the increase in breakup threshold [5].

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