Investigations of Incomplete and Total fusion in reactions with weakly bound nuclei

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Vishwajeet Jha is the recipient of the DAE Scientific & Technical Excellence Award for the year 2015

Abstract: The incomplete fusion (ICF) process, in which only a part of the nucleus fuses with the target, plays a crucial role in the reaction dynamics of weakly bound nuclei at the energies around the Coulomb barrier. We have developed a new quantum mechanical method to calculate the ICF cross sections based on the break-up of the projectile nucleus and subsequent absorption of its fragments. The present method enables us to study the coupling effects of break-up continuum and transfer on the total fusion cross sections and provides a consistent description of experimentally observed systematic behavior of the complete fusion suppression.

Introduction
Fusion using weakly bound nuclei present exciting opportunity for the synthesis of new nuclei away from the valley of stability and would possibly enable the production of the super-heavy nuclei in island of stability - the holy grail of nuclear physics. In addition, studies of fusion using weakly bound nuclei at low energies provide crucial information for the reactions of astrophysical interest. The fusion of two nuclei at energies around the Coulomb barrier is represented as the quantum mechanical tunneling phenomena through a multi-dimensional potential barrier. However, the couplings of various reaction processes to the internal degrees of freedom at energies around the barrier energies affects the fusion process.
Due to the low breakup threshold, the weakly bound projectile nuclei can easily break into fragments in the nuclear or Coulomb field and this has a significant influence on the fusion process [1]. The breakup may be followed by subsequent fusion of only a part of the projectile leading to incomplete fusion (ICF). The fusion process is classified as the complete fusion (CF), which refers to fusion of the whole projectile or all its fragments, and the total fusion (TF), where the ICF processes are also included. Experimentally, the measured CF cross sections in reactions induced by weakly bound projectiles show suppression compared with the theoretical calculations that explain the fusion cross sections involving tightly bound projectiles very well. Despite several theoretical efforts separate calculation of CF and ICF within a fully quantum mechanical model has been an open problem. The breakup process can be accounted for in a detailed way by using the continuum discretized coupled channel (CDCC) formalism, where breakup effects are modelled as excitation to the projectile continuum and its coupling effects on the fusion process are explicitly taken into account. We have developed a new method, which uses varied absorptions for the projectile fragments within the CDCC approach to evaluate the contributions of the ICF cross sections. Using this new method of calculation, we have carried out several investigations to understand the reaction mechanisms of the stable weakly bound projectiles, 6,7Li and 9Be, on a range of target nuclei and explain the experimentally observed features in the data, notably the fusion suppression in reactions with weakly bound nuclei. Some of the important results of the measurements and calculations are discussed here.

ICF calculations in 6Li and 7Li induced reactions:
For a comprehensive understanding of the fusion process with weakly bound nuclei, the separate contribution of the ICF and CF at energies around the Coulomb barrier needs to be calculated. The
breakup and transfer are the dominant direct processes which may contribute significantly at energies around the Coulomb barrier. The effect of couplings arising from breakup can be incorporated with the CDCC approach, while the transfer processes can be described by Coupled-reaction channel (CRC) calculations. A combined CDCC-CRC approach can be utilized to study the dynamic effects arising due to couplings of breakup and transfer. Earlier, the CDCC-CRC calculations have been utilized to provide the good descriptions of certain observables such as the total fusion (i.e., the sum of ICF and CF), elastic, and non-capture breakup cross sections [2, 3, 4]. Because, the ICF can be effectively defined as the absorption following the breakup, the breakup absorption model can be utilized for calculating the ICF components.

We have performed the detailed CDCC calculations to study the fusion process for the $^6\text{Li}$ and $^7\text{Li}$ nuclei on several targets [5]. An $\alpha$-d cluster structure for the $^6\text{Li}$ [6] and $\alpha$-t cluster structure for the $^7\text{Li}$ [7] were assumed for calculation of breakup. The continuum above break-up threshold were discretized and summed over momentum bins of sufficiently small widths with respect to the momentum of the relative motion of the clusters. The momentum bins were truncated at sufficiently high value of energy and angular momentum. In $^6\text{Li}$, couplings to the $1^+$, $2^+$ and $3^+$ resonances and $L = 0, 1, 2, 3$ $\alpha$-d continuum were included. For the $^7\text{Li}$ to $1/2^-$ first excited state, the $5/2^-$ and $7/2^-$ resonances, and the $L = 0, 1, 2, 3$ $\alpha$-t continuum was taken. The wave functions for generating the ground state, resonance states and continuum state of the projectile nuclei using the well known binding potentials for the clusters.

The radial wavefunctions $R^{\alpha}_d(r)$ of the projectile-target system are obtained by solving the coupled equations of the form [8, 9],

$$\left[ -\frac{\hbar^2}{2\mu_{PT}} \frac{d^2}{dr^2} - \frac{L(L+1)}{r^2} + U_{PT} + E_{\alpha} - E \right] R^{\alpha}_d(r) = \sum_{\alpha'} i^{L'-L} V^{J'}_{\alpha\alpha'} R^{J'}_{\alpha'}(r)$$

where, the required coupling potentials $V^{J'}_{\alpha\alpha'}$ were generated in the cluster-folding (CF) model, which used $\alpha$-Target and d-Target potentials for the $^6\text{Li}$, $\alpha$-Target and t-Target potentials for the $^7\text{Li}$. The total fusion cross sections were calculated as the absorption of the flux from the coupled channels set by employing a short-ranged imaginary part of the complex ion-ion potential ($U_{PT}$) that describes the interaction of nuclei. The absorption represents the irreversible loss from the coupled channels set and is equivalent to the incoming wave boundary condition applied at the radius where the potential forms the pocket. The TF cross sections are taken as absorption cross sections and obtained from the $S$-matrix elements given by

$$\sigma_R = \sigma_D + \sigma_{abs} = \frac{\pi}{k^2} \sum_l (2l + 1)(1 - |S_l|^2).$$

where, $\sigma_{abs}$ is total reaction cross section and $\sigma_D$ is cross section of all explicitly included direct reaction channels and $\hbar k$ represents the relative momentum of the two nuclei in the entrance channel. The ICF is subsequently calculated as the total absorption from the breakup channel only using the full CDCC wave function.

The results of the calculations for the TF, CF, and ICF cross sections are shown in Fig. 1 with long-dashed, short-dashed, and dotted lines, respectively, along with the available measured data for $^6\text{Li} + ^{209}\text{Bi}$ systems, respectively. The bare calculations (without breakup couplings) were also performed and the calculated fusion cross sections are denoted by dash-dot-dotted lines in the above-mentioned figures. The Coulomb barrier positions are marked by arrows in figures. It is seen that at energies above the Coulomb barrier, the calculations which include the couplings and calculations that omit them have negligible difference, but at energies below the barrier, the coupled TF cross sections are enhanced in comparison to bare TF cross sections. This behaviour of enhancement of fusion cross sections due to inclusion of breakup couplings at energies below the Coulomb barrier is similar to coupling effects due to inelastic processes in tightly bound nuclei. The model calculations are able to describe the CF and ICF cross sections very well. From the calculations it is evident that the difference between the TF and CF cross sections at higher energy can be almost entirely ascribed due to the ICF cross sections. Hence, ICF cross sections can be taken as the measure of the suppression of the CF cross sections with respect to the calculations. The other important feature is the observation of dominance of
ICF process over the CF process at energies below the barrier, while the reverse is true at energies above the barrier.

Systematical behavior of ICF and fusion suppression in $^{6,7}$Li and $^9$Be induced reactions:
There have been conflicting experimental results and theoretical interpretations regarding the suppression or enhancement of fusion cross sections for the weakly bound nuclei when the results are compared with the simplistic coupled-channel calculations. A large suppression of CF cross sections ($\sim 30\%$) has been inferred from most measurements in $^{6,7}$Li induced reactions on different targets. Since the CF suppression observed in experiments with respect to coupled-channel calculations compares well with the ICF cross section, an indirect measure of CF suppression factors ($F_{CF}$) is obtained from the ICF probability ($P_{ICF} = 1 - F_{CF}$), which is defined as $P_{ICF} = \sigma_{ICF}/\sigma_{TF}$. Based on the ICF measurement for $^9$Be on heavy targets, it was predicted that the complete fusion suppression factor will decrease with target charge. Even for the $^6$Li and $^7$Li projectile, the $F_{CF}$ was expected to decrease with the target charge. Therefore, fusion measurements are necessary for light mass systems to study the systematic behavior of the CF suppression.

The CF cross sections at energies around the Coulomb barrier for the $^6$Li + $^{90}$Zr around the barrier [11]. The above barrier CF cross sections were found to be suppressed by $34 \pm 8\%$ at all energies as compared to the conventional coupled-channel calculations. As shown in Fig. 2, a constant CF suppression from heavy to medium mass nuclei is observed. The calculations for ICF shown earlier are consistent with the suppression factors observed in the experimental data and a universal behavior of $P_{ICF}$ and $F_{CF}$ can be deduced. A larger body of experimental data for CF and ICF separately for $^9$Be induced reactions on different

Fig. 1: The data of complete fusion (CF), incomplete fusion (ICF), and total fusion, (TF) = CF + ICF + fission, for $^{6,7}$Li + $^{209}$Bi reaction taken from Ref. [10] are compared with the calculations. The arrow indicates the position of Coulomb barrier.

Fig. 2: Universal complete fusion suppression factor ($F_{CF}$) for $^6$Li projectile with different targets [Ref. 11 and references therein].
targets are available with the conflicting claim that the $P_{ICF}$ and $F_{CF}$ may monotonically decrease with the target charge $Z_T$ [12, 13]. We utilize the experimental fusion cross section data available for fusion of $^9$Be with $^{28}$Si, $^{89}$Y, $^{124}$Sn, $^{144}$Sm, and $^{208}$Pb targets at energies around the Coulomb barrier. As the 1n-transfer is found to have a large contribution for the $^9$Be induced reactions we studied the effect of 1n-transfer couplings along with the breakup using the CDCC-CRC calculations [14]. A $^9$Be + n cluster model has been found to correctly describe the low energy reaction dynamics of $^9$Be [3]. The significant contributions of 1n transfer are obtained for the $^9$Be + $^{208}$Pb and $^9$Be + $^{28}$Si systems, specially at the lower energies.

Fig. 3: Calculated ICF probabilities ($P_{ICF}$) are compared with the suppression factors derived from the experimental data [Ref. 14 and references therein]. The behavior of ICF contribution due to transfer is included by adding $P_{ICF,TR}$ to $P_{ICF,n} + P_{ICF,a}$. For comparison, the calculations using the simplistic earlier model described in Ref. [13] are also plotted.

The ICF probabilities due to breakup ($P_{ICF,n} + P_{ICF,a}$) and 1n transfer ($P_{ICF,TR}$) are in good agreement with the behavior of measured complete fusion suppression factors. The CF suppression factors calculated as the ICF probabilities show a systematic behavior with respect to different target masses and they remain approximately constant at energies above the barrier for all the systems considered. The ICF contribution due to transfer varies depending on the structure of the target and the residual nuclei.

Summary:
The simultaneous explanation of the measured experimental data for the CF, ICF, and TF cross sections over the entire energy range is obtained for the first time using calculations in the full quantum mechanical approach. The ICF probability, which signifies the suppression of CF in TF, is found to be constant at above-barrier energies and it is in agreement with the available data for several systems. The CF suppression factors calculated as the ICF probabilities show a systematic behavior with respect to different target masses and they remain approximately constant at energies above the barrier for all the systems considered. The exclusive measurements of ICF and CF cross sections with different weakly bound projectiles, especially in the light-target-mass region, wherever possible, are needed to further verify this proposition.

Acknowledgements:
I thank all my collaborators of this research work.

References: