Study of Nuclear Coupling Effects on CF, ICF and TF Excitation Functions for ^{6}Li + ^{96}Zr System

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In the last few decades, there has been a notable rise in focus on fusion reactions that involve weakly bound nuclei [1]. The extended nuclear density tail in some of very weakly bound nuclei decreases the Coulomb barrier and thereby enhances the fusion cross sections. But the dynamic effects arising from channel couplings can either enhance or suppress various fusion cross sections.

The fusion reaction induced by weakly bound nuclei may occur through various mechanisms. For instance in Direct Complete Fusion (DCF), the entire projectile fuses with the target, while in Sequential Complete Fusion (SCF), the fragments from projectile breakup are absorbed one after another. In the case of Incomplete Fusion (ICF), only one fragment of the projectile is absorbed, while the other fragment remains unabsorbed. Experimentally, it is challenging to differentiate between SCF and DCF since both lead to the creation of the same compound nucleus. However, recent studies have successfully measured the cross sections for CF and ICF individually.

Various theoretical frameworks, including classical, semi-classical and quantum mechanical models, have been developed to calculate the Complete Fusion (CF) and Incomplete Fusion (ICF) cross sections individually. In this study, we utilized a semi-classical model [2-3], incorporating both Coulomb and nuclear couplings [4] to analyze the excitation functions of CF, ICF, and TF processes for the ^{6}Li + ^{96}Zr system at near-barrier energies.

Within this semi-classical framework, the relative motion between the projectile and the target is governed by classical equations, while the intrinsic motion of the clusters within the projectile is described quantum mechanically. One solves the Alder-Winther (AW) equations [6]

$$i\hbar\, \dot{a}_{\alpha}(l, t) = \sum_{\alpha} \langle \Phi_{\alpha} | \mathrm{U}(\mathrm{r}, t) | \Phi_{\beta} \rangle e^{-i(\varepsilon_{\alpha}-\varepsilon_{\beta})t/\hbar}\, a_{\beta}(l,t)$$

with the initial condition $a_{\alpha}(l, \mathrm{t} \rightarrow -\infty) = \delta_{\alpha 0}$, indicating the projectile starts in its ground state before the collision. The probability of populating channel α with angular momentum l is given $P_l^{(\alpha)} = | a_{\alpha}(l, \mathrm{t} \rightarrow -\infty) |^2$.

One of the important ingredients needed to solve these equations is the coupling potential which consists of Coulomb and nuclear parts whose form factors are given by

$$F^C(\mathrm{r}) = \begin{cases} \frac{r}{R_C^3}\left(4 - \frac{3r}{R_C}\right) & r < R_C \\ \frac{1}{r^2} & r \geq R_C \end{cases}$$

with $R_C = 1.2\,(A_P^{1/3} + A_T^{1/3})$ and

$$F^N(\mathrm{r}) = \frac{e^x\,(1 - e^x)}{a_0^2\,(1 + e^x)^3}$$

with $x = \frac{(r-R)}{a_0}$ and R and a_0 represent the range and diffuseness parameter respectively.

In this method, the fusion cross section is estimated by approximating the fusion probability as the product of $\overline{\mathrm{P}}_l^{(\alpha)}$, the probability of the system being in channel α at the closest approach on the classical trajectory and the tunneling probability $\mathrm{T}_l^{(\alpha)}(\mathrm{E}_{\alpha})$, through the potential barrier in channel α that is $P_l^F(\alpha) \simeq \overline{\mathrm{P}}_l^{(\alpha)}\, \mathrm{T}_l^{(\alpha)}(\mathrm{E}_{\alpha})$. The tunneling probability $\mathrm{T}_l^{(\alpha)}(\mathrm{E}_{\alpha})$ is well approximated by the Hill-Wheeler formula which is applied under the parabolic approximation of the effective potential barrier and is written as

$$T_l(E) = [1 + \exp\{\tfrac{2\pi}{\hbar\omega_l}(B_l - E)\}]^{-1}$$

where B_l and ω_l are the height and curvature of the fitted parabola respectively.

The fusion cross section is given as

$$\sigma_F = [\, \tfrac{\pi}{k^2} \sum_l (2l + 1)\, P_l^F(\alpha)\,]$$

The label α = 0 refers to the ground state of the projectile and is associated only with CF events. In contrast, α ≠ 0 represents breakup states, treated as a single effective bound state, and contributes only to ICF events. The Total Fusion (TF) cross-section is obtained by adding the contributions from both Complete Fusion (CF) and Incomplete Fusion (ICF) events that is $\sigma_{TF} = \sigma_{CF} + \sigma_{ICF}$.

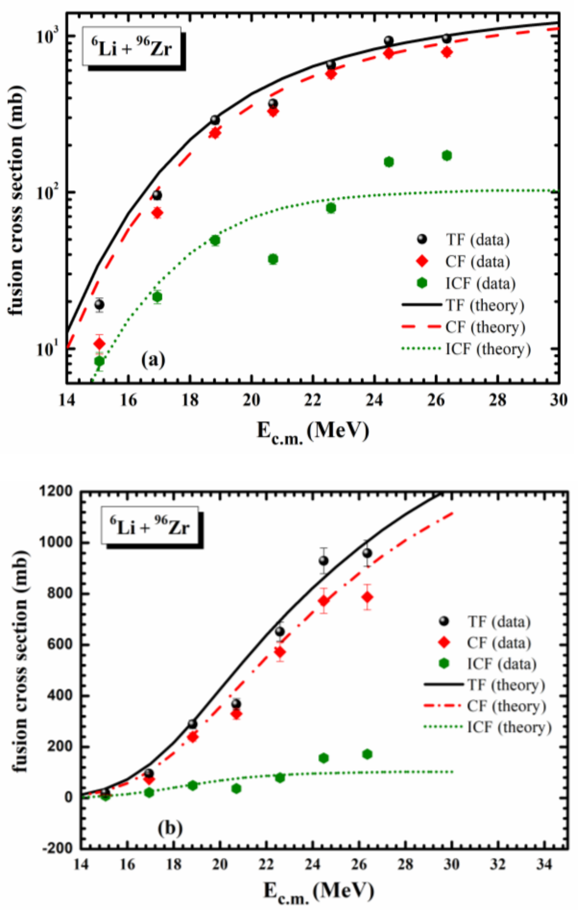

Fig. 1 Fusion excitation functions for CF, ICF and TF processes for ^{6}Li + ^{96}Zr reaction are compared with the corresponding experimental data taken from Ref. [5].

Fig.1 compares the fusion excitation functions for CF, ICF, and TF processes induced by ^{6}Li projectile on ^{96}Zr target at near-barrier energies ($V_B \approx$ 20MeV) with the corresponding experimental data taken from Ref. [5]. To compare the experimental data with predictions for various fusion cross sections at energies ranging from below barrier to above the barrier, the logarithmic and linear graphs are presented in Figs.1 (a) and (b) respectively. Figure 1(a) shows that the theoretical cross sections for CF and TF are in reasonable agreement with the experimental data, except in the deep sub-barrier energy region, where the theory significantly overestimates the data. This overestimation arises from the extended nature of the imaginary potential's tail, which results in absorption occurring not only at the barrier radius but also extending beyond it. A simple physical interpretation of this effect is very conspicuously given in [7]. Further the authors suggested to adopt phenomenological imaginary potential consistent with the nature of fusion processes and the main trends of the data. Thus in order to fix the optimised values of the potential parameters comparison with a larger ensemble of data is required and the work in this direction is in progress.

Figure 1(b) shows that at energies well above the barrier, the predicted ICF cross section is lower than the measured values, leading to the theoretical CF cross section exceeding the observed data. This discrepancy between the data and predictions may be attributed to the various approximations used in the present approach, particularly to the fact that the continuum is approximated by a single effective channel.

References

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