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Fusion suppression/fusion enhancement around the Coulomb barrier

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ABSTRACT

This work explored the fusion dynamics of ${}^{6}_{3}Li+{}^{59}_{27}Co$, ${}^{9}_{4}Be+{}^{124}_{50}Sn$, ${}^{9}_{4}Be+{}^{208}_{82}Pb$, ${}^{40}_{20}Ca+{}^{124}_{50}Sn$ and ${}^{12}_{6}C+{}^{208}_{82}Pb$ reactions by using energy dependent Woods–Saxon potential model (EDWSP model) and coupled channel model. The roles of projectile breakup channel on fusion process are directly reflected from fusion mechanism of ${}^{6}_{3}Li+{}^{59}_{27}Co$, ${}^{9}_{4}Be+{}^{124}_{50}Sn$ and ${}^{9}_{4}Be+{}^{208}_{82}Pb$ reactions. Whereas, the impacts of collective excitations and/or nucleon transfer channels on fusion process are evident from analysis of ${}^{40}_{20}Ca+{}^{124}_{50}Sn$ and ${}^{12}_{6}C+{}^{208}_{82}Pb$ reactions. The total fusion data (sum of complete and incomplete fusion data) of ${}^{6}_{3}Li+{}^{59}_{27}Co$ reaction is reasonably recovered by the EDWSP model calculations which in turn indicate that total fusion excitation function data is not suppressed with reference to theoretical predictions. In contrast, for ${}^{9}_{4}Be+{}^{124}_{50}Sn$ (${}^{9}_{4}Be+{}^{208}_{82}Pb$) reaction, the above barrier fusion data is suppressed with respect to the expectations of coupled channel approach and single barrier penetration model by 28% (32%). However, the EDWSP model based calculations reduce the magnitude of suppression factor by 8% (12%) for ${}^{9}_{4}Be+{}^{124}_{50}Sn$ (${}^{9}_{4}Be+{}^{208}_{82}Pb$) reaction and consequently the fusion data at above barrier energies is inhibited for both reactions by 20% with reference to the EDWSP model calculations. This fusion suppression can be correlated with loosely bound nature of the projectile. On the other hand, the above barrier fusion data of ${}^{40}_{20}Ca+{}^{124}_{50}Sn$ and ${}^{12}_{6}C+{}^{208}_{82}Pb$ reactions is not inhibited with respect to the predictions of coupled channel approach and EDWSP method, henceforth, confirms stability of projectiles against breakup effects.

1. Introduction

The availability of radioactive beams has been considerably increased scientific interest to explore the realm of nuclear interactions as well as nuclear structure of exotic nuclei lying far from valley of stability. In recent time, the understanding of fusion dynamics of weakly bound and/or halo nuclei at near and sub-barrier energies, which exhibits quite different characteristics in comparison to that of tightly bound systems, has become one of the most intriguing and challenging problems on theoretical as well as experimental front. For tightly bound systems, the coupling of intrinsic channels associated with the fusing nuclei to their relative motion causes a splitting of the Coulomb barrier into a distribution of barriers of different weight and height [1,2]. On the other hand, due to low breakup threshold, the weakly bound systems breakup before

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reaching the fusion barrier, henceforth, regulates the suppression of above barrier fusion data with reference to the theoretical predictions. In other words, for weakly bound systems, the breakup channel dramatically affects fusion cross-section and related quantities in domain of Coulomb barrier and various theoretical methods have been extensively used to explore the role of breakup channel on fusion process. However, different theoretical approaches result in controversial statement with regard the enhancement or suppression of fusion cross-section due to breakup effects and therefore further investigations are still needed for its clarifications [1–13]. The authors [14,15] have shown that coupling to breakup channel enhances fusion cross-section at below-barrier energies while it inhibits fusion data at above barrier energies. Such fusion suppression can be understood in terms of breakup of projectile in vicinity of target isotope.

This article contributes to the investigations of role of projectile breakup channel on fusion process by studding fusion dynamics of ${}^{6}_{3}Li + {}^{59}_{27}Co$, ${}^{9}_{4}Be + {}^{124}_{50}Sn$, ${}^{9}_{4}Be + {}^{208}_{82}Pb$, ${}^{40}_{20}Ca + {}^{124}_{50}Sn$ and ${}^{12}_{6}C + {}^{208}_{82}Pb$ reactions [5–7,16–23]. The theoretical calculations of fusion excitation function of chosen reactions are performed using the EDWSP model [24–27] and coupled channel model [28]. In case of ${}^{9}_{4}Be$ -induced reactions, the projectile is weakly bound system and may breaks up in the field of heavy target isotope (${}^{124}_{50}Sn$, ${}^{144-154}_{62}Sm$, ${}^{197}_{79}Au$, ${}^{208}_{82}Pb$, ${}^{209}_{83}Pb$, ${}^{238}_{92}U$). This breakup may be mediated by the Coulomb field or nuclear field of target isotope and consequently maintains the inhibition of fusion data at above barrier energies with reference to the theoretical predictions. The calculations based on coupled channel approach suggested that the above barrier fusion data of ${}^{9}_{4}Be + {}^{124}_{50}Sn$ reaction is suppressed by 28% while for ${}^{9}_{4}Be + {}^{208}_{82}Pb$ reaction; it is inhibited by 32% [16–18]. However, in EDWSP model based calculations, the magnitude of suppression factor can be reduced up to 8% (12%) for ${}^{9}_{4}Be + {}^{124}_{50}Sn$ (${}^{9}_{4}Be + {}^{208}_{82}Pb$) reaction. For both reactions, the fusion data at above barrier energies is inhibited by 20% with respect to the expectations of the EDWSP model while the sub-barrier fusion enhancement of these reactions has been reasonably explained by the theoretical approaches. In case of ${}^{6}_{3}Li + {}^{59}_{27}Co$ reaction [5,7], the total fusion data (sum of complete fusion data and incomplete fusion data) is not suppressed with reference to predictions of the EDWSP model. Although, the projectile (${}^{6}_{3}Li$) has low breakup threshold (1.475 MeV) in comparison to that of ${}^{9}_{4}Be$ -nucleus. Since the suppression effects are generally observed due to Coulomb breakup and in lighter target, the nuclear breakup dominates over Coulomb breakup. Therefore, in fusion of ${}^{6}_{3}Li + {}^{59}_{27}Co$ reaction [5,7], the nuclear breakup instead of Coulomb breakup may predominant and hence does not result in suppression of fusion data at above barrier energies.

On the other hand, the heavier projectiles (${}^{12}_{6}C$ and ${}^{40}_{20}Ca$) are stable against breakup channel and mirrors absence of breakup effects in fusion dynamics of ${}^{40}_{20}Ca + {}^{124}_{50}Sn$ and ${}^{12}_{6}C + {}^{208}_{82}Pb$ reactions [19–23]. The lighter target isotope (${}^{124}_{50}Sn$) is magic nucleus while the heavier target isotope (${}^{208}_{82}Pb$) is doubly magic nucleus and hence facilitates the low lying vibrational states as dominant mode of couplings. In case of ${}^{12}_{6}C + {}^{208}_{82}Pb$ reaction, the collective excitations are dominant mode of couplings and coupling to such states enhances the magnitude of sub-barrier fusion excitation function over the single barrier penetration model calculations. In fusion of ${}^{40}_{20}Ca + {}^{124}_{50}Sn$ reaction, in addition to inelastic surface excitations, the couplings to neutron transfer channel is essentially required to reproduce the observed fusion data. The predictions of theoretical methods (EDWSP model and coupled channel approach) reasonably explained the energy dependence of fusion cross-section of ${}^{40}_{20}Ca + {}^{124}_{50}Sn$ and ${}^{12}_{6}C + {}^{208}_{82}Pb$ reactions in the domain of Coulomb barrier. This clearly suggested that the EDWSP model and coupled channel model induce similar kinds of barrier modification effects in heavy ion fusion reactions.

2. Theoretical formalism

2.1. Single channel description

The partial wave analysis gives following expression of total fusion cross-section

$$\sigma_F = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)T_\ell^F \tag{1}$$

The tunneling probability (T_ℓ^F) due to Hill and Wheeler [29] can be obtained by using the parabolic approximation of interaction potential and is given by the following expression

$$T_\ell^{HW} = \frac{1}{1+\exp\left[\frac{2\pi}{\hbar\omega_\ell}(V_\ell - E)\right]} \tag{2}$$

Wong using the following approximations for barrier position, barrier curvature and barrier height [30] modified the above expression.

$$R_\ell = R_{\ell=0} = R_B$$
$$\omega_\ell = \omega_{\ell=0} = \omega$$
$$V_\ell = V_B + \frac{\hbar^2}{2\mu R_B^2}\left[\ell+\frac{1}{2}\right]^2 \tag{3}$$

where, V_B is Coulomb barrier associated with $\ell = 0$. Using all these approximations into Eq. (2), and solving Eq. (1), one gets the following expression for one dimensional Wong formula [30].

$$\sigma_F = \frac{\hbar\omega R_B^2}{2E}\ell n\left[1 + \exp\left(\frac{2\pi}{\hbar\omega}(E - V_B)\right)\right] \tag{4}$$