Nuclear Fusion Reactions Involving Weakly Bound Nuclei at Near Barrier Energies

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The studies on nuclear fusion reactions involving loosely bound nuclei around barrier energies have attracted significant attention since last almost three decades [1, 2]. One of the primary aim of these studies is to investigate the role of unique characteristics features of nuclei lying in the close vicinity of drip lines in determination of the fusion cross section. The static effects arising because of large spatial extension of some highly neutron-rich or proton-rich nuclear isotopes have been found to enhance the fusion cross section due to barrier lowering. However regarding the role of various channel coupling dynamical effects in the description of fusion reactions conflicting results have been observed. In particular, owing to low breakup threshold coupling to the breakup and transfer channels have been identified as playing a key role in the analysis of fusion induced by weakly bound nuclei. Thus we have investigated theoretically the effects of breakup and transfer coupling on the fusion cross sections for reactions induced by ^{6}He and ^{6}Li on various targets in near barrier energy regime. For theoretical analysis of any nuclear reaction the optimum form of nucleus-nucleus potential is an important ingredient. Because of the simplicity and wider acceptability for fusion process we have assumed the proximity potential as the nuclear interaction potential which may be written as [3, 4]

$$V_p = 4\pi\gamma b \frac{C_1 C_2}{C_1 + C_2} \Phi(s_0)$$

where b is the nuclear surface thickness and C_i are the Süssmann central radii.

The nuclear surface tension coefficient, γ, is given by

$$\gamma = 0.951\left[1 - 1.7826(N-Z)^2 / A^2\right] \ \text{MeVfm}^{-2}$$

N, *Z* and *A* refer to neutron, proton and mass number of colliding nuclei.

The universal proximity potential function Φ which depends on the minimum separation distance s_0 is approximated by the following “cubic-exponential” pocket formula

$$\Phi(s_0) = \begin{cases} \frac{-1}{2}(s_0 - 2.54)^2 - 0.0852(s_0 - 2.54)^3 \ for s_0 \le 1.2511 \\ -3.437\exp(-s_0/0.75) \ for s_0 \ge 1.2511 \end{cases}$$

where

$$s_0 = R - X_1 - X_2 = R - R_1(\alpha_1)\cos(\theta_1 - \alpha_1) - R_2(\alpha_2)\cos(180 + \theta_2 - \alpha_2)$$

For the description of reaction mechanism the quantum diffusion model is employed wherein the capture probability is given by [5]

$$P_{cap} = \frac{1}{2} erfc\left[\left(\frac{\pi s_1(\gamma - s_1)}{2\mu\hbar(\omega_0^2 - s_1^2)}\right)^{1/2} \frac{\mu\omega_0^2 R_0/s_1 + P_0}{[\gamma\ln(\gamma/s_1)]^{1/2}}\right]$$

and the cross section for the formation of dinuclear system is written as

$$\sigma_c(E_{c.m.}) = \sum_L \sigma_c(E_{c.m.}, L) = \pi\bar{\lambda}^2 \sum_L (2L+1) P_{cap}(E_{c.m}, L)$$

In order to include the breakup effects this equation is multiplied by survival probability of projectile against breakup and it becomes

$$\sigma_{total}(E_{c.m.}) = \pi\bar{\lambda}^2 \sum_L (2L+1) P_{cap}(E_{c.m}, L) \times (1 - P_{bu}(R_{\min}))$$

The breakup probability $P_{bu}(R_{\min})$ for a fixed energy and impact parameter is given by the following exponential function of distance of closest approach [6]

$$P_{bu} = A\exp(-\alpha R_{\min}).$$

The parameters A and α are determined to reproduce the measured breakup probability, if available at two different energies in near barrier energy. If the experimental data are not available for some projectile-target combinations then the breakup probability calculated through CDCC approach may be used for the purpose of evaluating *A* and *α*. Using this formalism, we have calculated the fusion excitation functions of various projectile-target combinations with a special emphasis on the role of projectile breakup and of the transfer channel in description of near barrier fusion reactions. We have found that the projectile breakup does not influence the fusion reactions involving ^{6}He and it suppresses the fusion cross section of reactions induced by ^{6}Li [7]. The possible explanation of these observations lies in the facts that ^{6}He is a neutron halo nucleus. As a result of halo structure of ^{6}He the dominant factors which affect the fusion cross section are large spatial extension and two neutron transfer process while in case of ^{6}Li these effects are absent and the breakup effects are much more pronounced.

Further, the effects of deformation and two neutrons transfer on fusion cross sections for ^{6}He+^{64}Zn, ^{6}He+^{68}Zn, ^{6}He+^{206}Pb, ^{6}He+^{209}Bi and ^{6}He+^{238}U reactions involving ^{6}He as a projectile around barrier energies have been found to be dominant in the sub barrier energy region. It is observed that when there is a noticeable change in the value of deformation parameter and change of shape occurs then the deformation effects dominates over the neutron transfer effects [8]. On the other hand, if the influence of deformation effects is negligible then the neutron transfer effects lead to sub barrier enhancement of fusion cross section. Finally, it is worth mentioning here that besides the channel coupling effects, disentangling relative contribution of incomplete fusion and complete fusion in total fusion is a debatable issue and needs investigation.

References

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