Effect of vibrational coupling on sub-barrier fusion of ${}^{38}_{20}Ca + {}^{92}_{40}Zr$ system

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Introduction

Since last few decades, a lot of interest had been shown in heavy ion fusion reactions mainly because of the fact that these are major source of energy production in stars and are responsible for the formation of super heavy elements [1]. Also, the heavy ion fusion reactions facilitate the understanding of the nuclear structure and interaction. In a simplistic model, the process of nuclear fusion is governed by quantum mechanical tunneling through the Coulomb barrier and is described by a one dimensional barrier penetration model. But the observed sub-barrier enhancement in the fusion cross-section over the expectation of one dimensional barrier penetration model suggested a link with the intrinsic degrees of freedom of projectile and target nuclei. The coupling between the relative motion and the internal degrees of freedom such as static deformation, vibration of nuclear surface, zero point motion, rotations of nuclei during collision, neck formation, nucleon transfer reactions etc. results in the splitting of the uncoupled coulomb barrier into distribution of barriers of varying heights. The sub-barrier enhancement of the fusion cross-section may be ascribed to the barrier of height smaller than that of uncoupled Coulomb barrier [2]. Theoretically the standard way to address the effect of nuclear intrinsic degrees of freedom on the fusion cross-sections is to solve numerically the coupled channel equations that determine the wave functions of the relative motion of projectile-target systems. In the present work, we have investigated the effects of coupling of low lying vibrational 2^+ and 3^- states of projectile and target and their mutual coupling for ${}^{38}_{20}Ca + {}^{92}_{40}Zr$ system using the code CCFULL[3].

Results and Discussions

We have calculated the fusion cross-sections, barrier distributions and the average angular momentum for ${}^{38}_{20}Ca + {}^{92}_{40}Zr$ system by using the code CCFULL and have investigated the effects of coupling to the low lying vibrational states on these quantities. The so obtained fusion cross-sections have been compared with the calculations of the one dimensional barrier penetration model based on Wong's formula. In particular we have studied the effects of coupling of low lying 2^+ and 3^- vibrational states of projectile and target nuclei and their mutual couplings. The main ingredients needed in the coupled channel calculations are the deformation parameters (β_λ) and the energy (E_λ) of the vibrational states [4,5]. The values of these parameters ($\beta_\lambda; E_\lambda$) for $\lambda = 2$ multipolarity are (0.125; 2.206MeV) and (0.103 ; 0.934MeV) for ${}^{38}_{20}Ca$ and ${}^{92}_{40}Zr$ nuclei respectively and that of ($\beta_3; E_3$) for ${}^{92}_{40}Zr$ nucleus is (0.19; 2.340 MeV).

In Fig.1, we have plotted the fusion excitation functions of ${}^{38}_{20}Ca + {}^{92}_{40}Zr$ fusion reactions as calculated by one dimensional barrier penetration model and by the code CCFULL with and without coupling. The results obtained by using the Wong formula and that of CCFULL without any coupling coincide with each other. It is clear from Fig.1 that there is a substantial enhancement in the fusion cross-section when coupling to the 3^- state of the target is taken into account and the enhancement further increases when the coupling to 2^+ and 3^- states of the target is considered simultaneously.

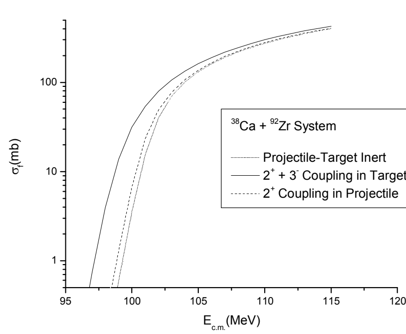

Fig.1 Fusion excitation function of ${}^{38}_{20}Ca + {}^{92}_{40}Zr$ system corresponding to various couplings.

The barrier distributions corresponding to the fusion excitation functions are shown in Fig.2. It is found that the barrier height is reduced due to the coupling of various vibrational states of the projectile and target. The shape of barrier distribution is very sensitive to the coupling between relative motion and intrinsic degrees of freedom and nuclear structure of the colliding nuclei. Further the reduction in barrier height is more pronounced when highly deformed and very low lying state of the target is included and is responsible for the observed large enhancement in fusion cross-section.

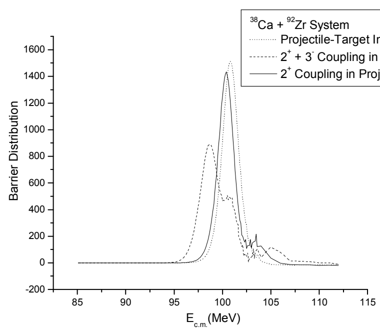

Fig.2 Barrier distributions for $^{38}_{20}Ca + ^{92}_{40}Zr$ system corresponding to various couplings.

In Fig.3 the average angular momentum of the compound nuclei formed in $^{38}_{20}Ca + ^{92}_{40}Zr$ fusion reaction is plotted as a function of centre of mass energy. It is found that the coupling to 2^+ and 3^- state of $^{92}_{40}Zr$ and 2^+ state of $^{38}_{20}Ca$ lead to the formation a bump in the low energy region.

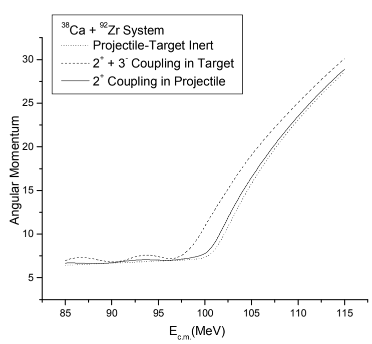

Fig.3 The variation of angular momentum with centre of mass energy for $^{38}_{20}Ca + ^{92}_{40}Zr$ system.

Conclusions

We have investigated the effects of the coupling of low lying surface vibrational states of the projectile and the target nuclei on the sub-barrier fusion cross-section for $^{38}_{20}Ca + ^{92}_{40}Zr$ system through the coupled channel approach by using the code CCFULL. It has been found that the coupling of low lying vibrational states with the relative motion of interacting nuclei enhances the sub-barrier fusion cross-section to large extent as compared with the one dimensional barrier penetration model calculations. Further, the extent of enhancement of the sub-barrier fusion cross-section has been found to be very sensitive to the deformation parameter and the energy of the states included in the analysis. The enhancement in the fusion cross-section is found to be significantly large in case of highly deformed nucleus having a very low lying vibrational state.

References

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