Energy dependent interaction potential and evidence of shape transition effects in sub-barrier fusion dynamics of $^{27}Al+^{70,72,74,76}Ge$ reactions

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The quantum tunneling with many internal structure degrees of freedom have been received significant attention over last three decades due the fact that experimentally measured fusion cross-sections data are strongly influenced by the nuclear structure degrees of freedom like inelastic surface excitations and nuclear deformation and/or nucleon transfer channels [1]. In this regards, this work emphasized the dominance of the collective excitations and/or nuclear shape deformation of the collision partners on fusion dynamics of $^{27}Al+^{70,72,74,76}Ge$ reactions [2]. The target isotopes lie in the region of weak deformation and expected to display shape transition effects [3] and consequently attracts the researchers to explore their fusion dynamics with different projectiles. The theoretical analysis of the chosen reactions has been done by adopting the energy dependent Woods-Saxon potential (EDWSP) model [4-5] and coupled channel code CCFULL [6]. In coupled channel model, the standard Woods-Saxon potential has been used for the numerical calculations and is defined as

$$V_N(r)=\frac{-V_0}{\left[1+\exp\left(\frac{r-R_0}{a}\right)\right]}$$

where, V_0 is depth of nuclear potential, r is the range and a is the diffuseness parameter of the nuclear potential. Generally, the parameters of the standard Woods-Saxon potential are defined by fitting the experimental data of a given reaction under consideration. In distinction, in EDWSP model [4-5], the parameters of the above potential are modified and are defined as

$$V_0=\left[A_P^{\frac{2}{3}}+A_T^{\frac{2}{3}}-(A_P+A_T)^{\frac{2}{3}}\right]\left[2.38+6.8(1+I_P+I_T)\frac{A_P^{\frac{1}{3}}A_T^{\frac{1}{3}}}{\left(A_P^{\frac{1}{3}}+A_T^{\frac{1}{3}}\right)}\right]\ MeV$$

where $I_P=\left(\frac{N_P-Z_P}{A_P}\right)$ and $I_T=\left(\frac{N_T-Z_T}{A_T}\right)$ are the isospin asymmetry of the participating nuclei. In EDWSP model, the diffuseness parameter $a(E)$ is taken as energy dependent and is defined as

$$a(E)=0.85\left[1+\frac{r_0}{13.75\left(A_P^{-\frac{1}{3}}+A_T^{-\frac{1}{3}}\right)\left(1+\exp\left(\frac{\frac{E_{c.m.}}{V_{B0}}-0.96}{0.03}\right)\right)}\right]fm$$

$E_{c.m.}$ is the incident energy in center of mass frame, V_{B0} is height of the Coulomb barrier and r_0 is the range parameter that describes the radii of participating nuclei.

In the coupled channel analysis of $^{27}Al+^{70,76}Ge$ reactions, the no-coupling calculations, wherein the colliding nuclei are treated as inert, are strongly under predicted by the experimental data. The lighter target (^{70}Ge) is spherical in shape, therefore, the influences of low lying inelastic surface excitations are expected to dominate in the fusion dynamics of $^{27}Al+^{70}Ge$ reaction. The consideration of one phonon 2^+ in target alone is unable to reproduce the fusion cross-section data at below barrier energies. The inclusions of one phonon 2^+ and 3^- vibrational states of target improves the results but still there is large discrepancies between model predictions and experimental fusion data. Since, projectile is odd-A nucleus and it facilitates large number of low lying odd-A spin states and these quantum states are added in quadrature in the coupled channel calculations. Thus, by including all odd-A spin states of projectile along with the 2^+ and 3^- vibrational states of target reasonably recovers the observed fusion dynamics of $^{27}Al+^{70}Ge$ reaction as evident from Fig.1a.

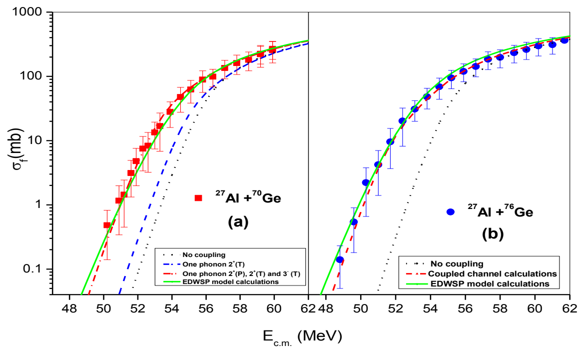

Fig.1. Fusion excitation functions of $^{27}Al+^{70,76}Ge$ reactions obtained by using the EDWSP model and coupled channel code CCFULL [6]. The theoretical calculations are compared with the available experimental data taken from Ref. [2].

On the hand, in EDWSP model, as consequence of the energy dependence in the nucleus-nucleus potential it becomes more attractive in the sub-barrier energy regimes. The enhanced attractive features of the EDWSP model induce gross potential modulation effects and subsequently modify the barrier profile and barrier characteristics of the interaction barrier between the participant nuclei. As a result, the theoretical predictions made by using the EDWSP model along with the one dimensional Wong formula [7] predicts substantially larger fusion cross-sections and thus adequately explored the sub-barrier fusion anomalies of the studied reaction as depicted in Fig.1a.

The heavier target isotope (^{76}Ge) is statically deformed in its ground state [2-3, 8], therefore, it is fruitful to consider the rotational states instead of the vibrational states of the target isotope in the coupled channel analysis. For $^{27}Al+^{76}Ge$ reaction, the inclusion of rotational state up to 6^+ spin state of the ground state rotational band along with the odd-A spin state associated with projectile in coupled channel approach, the model calculations reasonably reproduced the fusion dynamics of $^{27}Al+^{76}Ge$ reaction as shown in Fig.1b. While in case of the EDWSP model, the barrier lowering effects introduced due to energy dependence in the nucleus-nucleus potential reduces the effective fusion barrier between the fusing nuclei. In that sense, the energy dependent interaction potential fairly recovers the observed fusion dynamics of the given reaction. Since the channel coupling effects in the coupled channel analysis and the gross-potential modulation induced due to energy dependence of the nucleus-nucleus potential in the EDWSP model modifies the barrier profile and leads the reduction of the effective fusion barrier between colliding nuclei and thus both models reflects similar behavior of the heavy ion fusion reactions. In other words, one can say that the energy dependence in the nucleus-nucleus potential artifact the various channel coupling effects induced due to nuclear structure of the fusing nuclei.

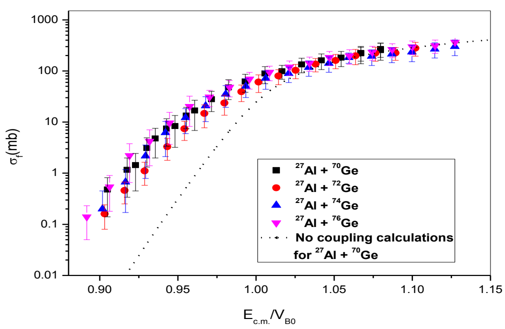

Fig.2. Fusion excitation functions of $^{27}Al+^{70,72,74,76}Ge$ reactions obtained by using the EDWSP model [4-5] and coupled channel code CCFULL [6] and results are compared with the experimental data taken from Ref. [2].

In literature, it has been pointed out that for a given projectile the magnitude of the fusion cross-section data increases with the increase of the deformation of the target isotope. In case of Ge-isotopes, which lie in the region of weak deformation, there is a change of the shape of nucleus from spherical symmetry to permanent deformed shape as one move from lighter target isotope (^{70}Ge) to heavier target isotope (^{76}Ge). In other words, there is gradual change in the shape of target isotope with the increase of neutron richness. Consequently, the magnitude of the fusion cross-sections data increases as one move from lighter target to the heavier target isotope as evident from the Fig.2

In summary, the fusion dynamics of $^{27}Al+^{70,72,74,76}Ge$ reactions have been analyzed within the view of the EDWSP model and the coupled channel model. The collective excitations are found to be dominant in lighter target while there is dominance of the rotational degrees of freedom of the target in the heavier isotope and such nuclear structure degrees of freedom leads to the substantially large enhancement of the fusion cross-section data at sub-barrier energies. In addition, there is a gradual change of the shape of target isotope from spherical shape to statically deformed shape as one move from lighter target to heavier target isotope. Furthermore, the channel coupling effects produced due to nuclear structure effects of the participant nuclei in the coupled channel calculations represents similar results as inferred from the energy dependence of the nucleus-nucleus potential. This unambiguously identifies that energy dependence in the nucleus-nucleus potential mocks up the dominant channel coupling effects induced due to nuclear structure of the fusing pairs.

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