Influence of elongated and compact hexadecapole deformed nuclear configurations on the fusion dynamics

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Introduction

Heavy ion induced reactions are used as a probe to study the nuclear structure effect and also the synthesis of heavy and super-heavy compound nuclei. The synthesis of superheavy nuclei (SHN) has been explored mainly through the hot and cold fusion nuclear mechanisms [1, 2]. These fusion phenomena has been described successfully when either or both the colliding nuclear partners are quadrupole deformed [3]. Along with deformation degree of freedom, the orientation degree of freedom shows significant influence on the fusion barrier characteristics and subsequently plays important role in the nuclear fusion dynamics. Thus, it would be interesting to analyze the relevance of higher-order deformations in the formation of SHN at different scale of incident energies.

In view of this, we are examining the influence of higher-order deformations (up to hexadecapole (β_4)) and orientations corresponding to the elongated (or cold) and compact (or hot) configurations of deformed shapes in the formation of SHN. This analysis is done in terms of capture cross-sections (σ_{cap}), obtained using the extended ℓ-summed Wong model [4], over a wide range of center of mass energies ($E_{c.m.}$) lying across the Coulomb barrier. To carry forward this idea, ^{238}U (β_{21}=0.236, β_{41}=0.098)+^{27}Al (β_{22}=-0.392, β_{42}=0.193) and ^{32}S (β_{22}=0.221, β_{42}=-0.095) pairs of projectile-target (p-t) combinations are taken into consideration. To analyze the effect of β_4-deformation and respective optimum orientations mainly at the below- and near-barrier regions, we have obtained σ_{cap} for the spherical ($\beta_2 = \beta_4 = 0$), quadrupole ($\beta_2 \neq 0, \beta_4 = 0$) and hexadecapole deformed ($\beta_2 \neq 0, \beta_4 \neq 0$) cases, and also compared the results with the available experimental data [5].

Methodology

To deal with the projectile-target nuclei which lead towards the formation of superheavy nuclei, the modified nuclear proximity potential, i.e. Prox88 (mod) [6], has been taken into account, as given below

$$V_N(R) = 4\pi\overline{R}\gamma b\phi(s_0), \quad (1)$$

here, γ and b are the surface energy constant and the surface thickness terms, which are having values 1.65 and 0.99 fm respectively. $\overline{R}$ is the mean curvature radius which incorporates the deformation and orientations degrees of freedom.

The fusion barrier characteristics obtained with the addition of nuclear and Coulomb potentials [7] are used further as input in the calculation of capture cross-sections (σ_{cap}). Here, σ_{cap} is calculated using the extended ℓ-summed wong model [4] and given as

$$\sigma_{cap}(E_{c.m.}) = \frac{\pi}{k^2}\sum_{\ell=o}^{\ell_{max}}(2\ell+1)P_\ell(E_{c.m}, \theta_i), \quad (2)$$

where $k = \sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}}$, $E_{c.m}$ is the center-of-mass energy. μ is the reduced mass, ℓ_{max} is the maximum angular momentum calculated by sharp cut-off approximation method for above barrier energies and extrapolated it for below barrier region. P_ℓ is the transmission coefficient for ℓ^{th} partial wave calculated by Hill-Wheeler approximation and describes the penetration probability of the barrier.

Results and Discussion

In the present work, we have analyzed the role of hexadecapole deformation (up to β_4) and respective optimum orientations (θ_{opt}), which correspond to the elongated (or cold) and compact (or hot) configurations of deformed nuclei, in determining the capture cross-sections σ_{cap} as a function of center of mass energies $E_{c.m.}$. Both of the considered choices of projectile-target nuclei (^{238}U+^{27}Al and ^{32}S) are hexadecapole deformed and the respective values of deformations up to β_4 are given in Fig.1. The obtained results are shown in comparison with the experimental data for the above said reactions. However, the data is available for the above barrier energies. Thus, to analyze the nuclear structure effects, we have done

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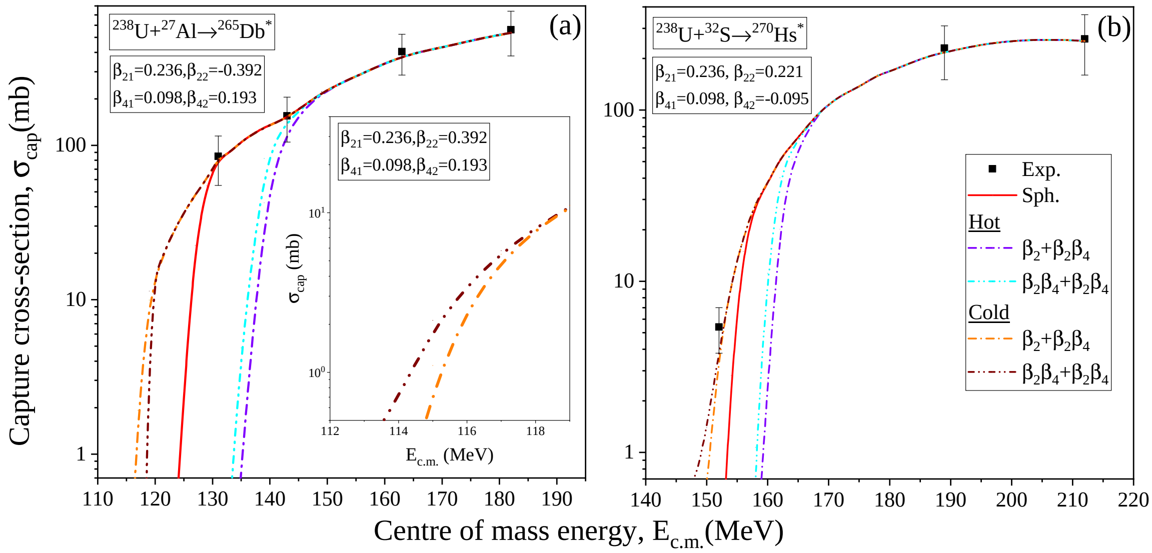

FIG. 1: The capture cross-section, σ_{cap} (mb), is shown as a function of center of mass energy $E_{c.m.}$ (MeV), which is lying across the Coulomb barrier, for (a) $^{238}U+^{27}Al\rightarrow^{265}Db^*$ and (b) $^{238}U+^{32}S\rightarrow^{270}Hs^*$ reactions.

the theoretical calculations at the energies, which are near and below the Coulomb barrier. As it is known that the nuclear structure effect plays a prominent role at below and near the barrier energies. However, these structural effects disappear at the above barrier energies as centrifugal potential starts dominating over the nuclear proximity potential.

Initially, we have determined $\sigma_{cap}(E_{c.m.})$ for the above said reactions by considering (i) spherical ($\beta_2 = \beta_4 = 0$) case, then introduced (ii) β_2 in projectile and up to β_4 in the target nucleus ($\beta_2 + \beta_2\beta_4$) and then (iii) incorporated the value of β_4 for both the colliding nuclei ($\beta_2\beta_4 + \beta_2\beta_4$). For these cases, it has been noticed from Fig.1 for the elongated (cold) configuration that, the cross-sections obtained due to incorporation of deformations get enhanced from that of the spherical case, otherwise, get hindered for the compact (or hot) configuration. Further, in reference to $\beta_2 + \beta_2\beta_4$ case, the value of $\sigma_{cap}(E_{c.m.})$ always increase independent of the choice of hot and cold optimum cases. However, the above result is not true for the cold configuration of $^{238}U+^{27}Al$ reaction, due to unusual larger magnitude of oblate deformation (i.e. β_2=-0.392) possessed by the target nucleus. In view of this, we have done an exercise by considering the positive value of β_2-deformation for ^{27}Al and analyzed enhancement in cross-sections for $\beta_2\beta_4 + \beta_2\beta_4$ from that of $\beta_2 + \beta_2\beta_4$ case. The related results are shown in the inset of Fig.1(a).

Therefore, one may conclude that, the presence of β_4-deformation in both the colliding nuclear partners, give relatively enhanced probability of fusion from that of β_2 deformation, mainly at the below and near barrier regions. The above result is independent of the choice of compact and elongated fusion configurations.

References

[1] Y. T. Oganessian, J. Phys. G **34**, R165 (2007).
[2] S. Hofmann *et al*, Eur. Phys. J. A **14**,147 (2002).
[3] R. K. Gupta, A. Sandulescu and W. Greiner, Z. Natureforsch **32a**, 704-707 (1977).
[4] R. Kumar, M. Bansal, S. K. Arun and R. K. Gupta, Phys. Rev. C **80**, 034618 (2009).
[5] W. Q. Shen *et al.*, Phys. Rev. C **36**, 1 (1987).
[6] R. Kumar, Phys. Rev. C **84**, 044613 (2011).
[7] C. Y. Wong, Phys. Rev. Lett. **31**, 12 (1973).