A study of exotic compound nuclear systems and subsequent fragments emission using Skyrme Energy Density Formalism

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Introduction

The semiclassical Skyrme Energy Density Formalism (SEDF) approach based nuclear potential expressed in terms of the Skyrme Hamiltonian density function depends on the nuclear density ρ, kinetic energy density τ and spin-orbit density $\vec{J}$ terms. Here, τ and $\vec{J}$ obtained within the framework of extended Thomas-Fermi approach (ETF) are also density dependent terms [1]. This motivates us to understand the exchange and non-exchange effects among the colliding nuclear partners, by employing the density approximations. Here, different density approximations: sudden, modified-sudden, frozen and relaxed-density, have been employed within the SEDF [2] and phenomenological potentials [3] and analyzed the corresponding effects in terms of the fusion barrier characteristics and subsequently on the fusion cross-sections, at below, near and above the Coulomb barrier energies, for the considered choices of projectile-target (P-T) combinations. In addition to this, the relative change in the tail region of density profile, due to two- and three-parameter density functions, imparts respective modifications in the fusion dynamics. This analysis prompts to make a better choice of density distribution function for addressing the fusion hindrance phenomena of the mass-symmetric and asymmetric nuclear partners. Also, the calculated fusion cross-sections using the Wong formula [4] and its extended version [5] are compared with the available experimental data, for the incident energies lying across the Coulomb barrier. Such comparative analysis motivates to empathize the importance of nuclear structure effects especially in the sub-barrier region.
In addition to the above, the incorporation of deformations (up to β_3) and orientation effects within the SEDF and phenomenological based potentials aid to understand the significance of symmetry-breaking pear shapes in the nuclear fusion as well as the decay mechanisms. The results obtained from the above analysis have been discussed in reference to that of the quadrupole deformed and spherical shape nuclei. The mass and charge distributions of compound nuclear systems, formed via heavy-ion induced reactions, have also been examined by including deformations (up to β_3) and related optimum orientations effects within the collective clusterization approach of Dynamical Cluster-decay Model (DCM) [6], developed on the basis of Quantum Mechanical Fragmentation Theory (QMFT). Also, in the above analysis, the role of different Skyrme forces has been analyzed via the mass and charge dispersion of light- and heavy-mass isotopes of actinide, at the low excitation energies.

Calculation and results

Within the framework of Skyrme Energy Density Formalism, the effect of different nuclear density approximations, i.e. sudden, modified sudden and frozen density, has been analyzed in terms of the fusion barrier characteristics and subsequently on the fusion cross-sections for a variety of compound nuclei, formed via ^{58}Ni-based reactions, over a wide range of incident energies [7]. For comparative analysis, the phenomenological Woods-Saxon potential parameterized under the relaxed-density approximation has been used for the above mentioned reactions. In results, for the selected choices of projectile-target combinations (^{18}O, ^{40}Ca, ^{58}Ni and ^{132}Sn+^{58}Ni), the frozen density approximation is found to give relevant details of the fusion barrier characteristics (barrier position R_B, barrier height V_B and barrier curvature $\hbar\omega_B$), which in turn, address the available experimental data across the Coulomb barrier energies.
Further, with the use of the semiclassical SEDF approach, the corresponding effect of two- (2pF) and three-parameter (3pF and 3pG) density functions has been explored in the calculation of fusion barrier characteristics (due to relative change in the tail and nearby region of nuclear density) [8]. The collective effect of V_B, R_B and $\hbar\omega_B$ has been analyzed in determining the fusion cross-sections using the extended ℓ-summed Wong model for mass-symmetric (^{58}Ni+^{58}Ni) and

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asymmetric (^{8}B, ^{18}O and ^{132}Sn+^{58}Ni) choices of ^{58}Ni-based reactions. The obtained results are compared with the available experimental data for the above said colliding nuclear partners over a wide range of incident energies. For the symmetric reaction (^{58}Ni+^{58}Ni), the 2pF density function reduces the fusion hindrance and gives better agreement with the data using SLy4 Skyrme force. On the other hand, for the case of mass-asymmetric nuclear reaction partners (^{8}B, ^{18}O and ^{132}Sn+^{58}Ni), the 3pF and 3pG density functions are found to give better comparison of fusion cross-sections with the data, especially at the below barrier energies. It is worth mentioning that the tail and nearby region of the density distributions play an important role in the heavy-ion induced reactions.

In further study, the relevance of deformation (up to β_3) and orientation degrees of freedom has been explored in synthesizing heavy and superheavy nuclei via hot and cold fusion processes. Initially, the optimum orientations (θ_{opt}) corresponding to the 'elongated or cold' and 'compact of hot' fusion configurations of octupole (β_3) deformed nuclei [9] were obtained. These orientations are dependent on +/- signs as well as the magnitude of β_3-deformation. On the basis of this analysis, the impact of soft- (with small β_3-deformation) and rigid-pear shapes (with strong β_3-deformation) of octupole deformed nuclei has been investigated on the fusion barrier characteristics. In results, the cold fusion configuration of octupole deformed nuclei shows relatively larger impact on the fusion barrier and subsequently on the fusion cross-sections [10]. Such analysis reinforces that the nuclear structure effects play an important role in nuclear fusion dynamics. Consequently, it can be said that the octupole deformed nuclei can be used for the synthesis of heavy and superheavy elements.

Furthermore, in the de-excitation process of light- and heavy-mass isotopes of Thorium, i.e. ^{222,224,226,228,230}Th*, the role of deformations up to β_3 and related cold optimum orientation has been explored within the framework of the DCM [11]. To carry forward with this idea, the mass and charge dispersions of chosen 'Th' isotopes have been analyzed by including deformations (up to β_3) and related cold optimum orientations within the DCM, which is based on the collective clusterization approach of the QMFT. The analysis is worked out at the low excitation energy, which correspond to the cold synthesis criteria. In the decay of light-mass isotopes of Th, i.e. ^{222,224}Th*, the near-symmetric fission is preferred, possibly due to deformed magic number of neutrons (N = 62) of the quadrupole deformed fragment. However, the asymmetric fission involving an octupole deformed fragment (Z = 56; ^{144}Ba and in its vicinity) is found to be prominent in the case of heavier isotopes of Th, i.e., ^{226,228,230}Th*. From the above analysis, the near-symmetric and asymmetric fission modes observed in the decay of Th isotopes, due to involvement of deformations (up to β_3) and related cold optimum orientation, are in agreement with the experimental data.

In conclusion, the effective nuclear interaction potential derived using SEDF approach helps in understanding the amalgamation process of colliding nuclear densities and the role of deformations and orientations degrees of freedom in the fusion-fission dynamics at the low-energy regime. In future work, it would be interesting to study the relevance of proton- and neutron-drip line nuclei in reaction dynamics within the framework of Skyrme Energy Density Formalism, especially at deep sub-barrier energies.

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