Collective clusterization in ground and excited states of nuclear systems at low energies

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Introduction

The formation and decay of an equilibrated compound nucleus (CN) has been a topic of great interest and is supposed to impart important information in context of reaction mechanism at low energies. The CN can decay in number of ways by emitting multiple light particles (n, p, α) and γ-rays (constituting the evaporation residue, ER), fusion-fission (ff, consisting of intermediate and heavy mass fragments, and the asymmetric or near-symmetric, and symmetric fission fragments), and many a times a non-compound, quasi-fission (qf), or incomplete fusion (ICF) process. Generally, for heavy nuclear systems ($A_{CN} \sim 200$), the fission mode dominate, however evaporation residue process contribute most in case of a light compound systems. Interestingly a significant contribution of ER is measured in a few heavy systems as well.

In the present work, possible decay modes of a variety of nuclear systems formed in heavy ion reactions alongwith the decay of ground state trans-lead nuclei have been studied using the collective clusterization method. Various current nuclear phenomenon related to static and dynamic deformations and orientations, barrier modification, structure/substructure of fission fragments, shell effects, angular momentum, entrance channel and fission anisotropies etc have been investigated extensively.

Calculations and discussion

The basis of this study is the Dynamical Cluster-decay model (DCM) [1], which is an extension of Preformed Cluster-decay Model (PCM) [2] for ground-state (temperature T=0) decays. The PCM is based on the well known Quantum Mechanical Fragmentation Theory (QMFT) [3]. The deformation and orientation effects are duly incorporated in PCM as well as in DCM.

As a first application, the DCM is used to study the odd-mass nuclear systems ^{213,215,217}Fr* [4]. The entrance channel effects in the decay of ^{215}Fr* nucleus, formed via two asymmetric reaction channels ^{11}B+^{204}Pb and ^{18}O+^{197}Au reactions, is studied. This study confirms the entrance-channel independence of the decay of ^{215}Fr*, in agreement with experimental observations and statistical model (PACE2) calculations. The role of sticking versus non-sticking moment of inertia is found important for fixing the limiting angular momentum ℓ_{max}, since fission anisotropy is found to support the non-sticking limit, whereas the sticking limit is best suited for fusion (consisting mainly of fusion-fission) excitation functions.

For the decay paths of compound systems ^{213,217}Fr*, formed in ^{19}F+^{194,198}Pt reactions, a small hump/ shoulder is seen for the two systems in their respective preformation yields due to the deformed magic shell around $Z_2 = 36$ and spherical magic shell around $Z_1 = 50$, which is somewhat stronger for ^{213}Fr* (with neutron number $N = 126$) decay than in the case of ^{217}Fr* ($N = 130$). The same magic shell closure effects are prevalent in ^{215}Fr* compound system which, for this system, need further investigations. Another important result for all the three ^{213,215,217}Fr* systems is that, with the inclusion of deformation and orientation effects of nuclei, the mass fragmentation changes from symmetric to asymmetric, with the above noted humped structure sug-

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gesting the presence of structure effects in the fission products of ^{213,215,217}Fr* nuclei.

Though DCM has been applied to investigate decay path via CN channel, its application in reference to incomplete fusion (ICF) and subsequent decay processes along with complete fusion (CF) process is studied [5] in reference to the dynamics of ^{10,11}B + ^{209}Bi reaction forming compound systems ^{219,220}Ra*. The main contribution to CF cross-section comes from the fission cross-section at higher energies and evaporation residues contribute more at lower incident energies. The evaporation residue cross-sections consist of significant contribution from the neutron evaporation cross-sections along with smaller contribution from other charged particle evaporation residues produced through the αxn and pxn ($x = 2, 3, 4$) emission channels in ^{219}Ra system. The calculated CF and ICF cross-sections for ^{219}Ra system compare nicely with experimental data at all the reported energies, which allow us to conclude that DCM can also be applied for ICF process along with its well established application in CF process.

Next, in order to investigate the role of dynamic deformations, the decay of hot and rotating compound system ^{241}Pu*, at both below-and above-barrier energies, is studied using DCM. So far only the static deformations of Möller and Nix are used in the framework of DCM to understand the heavy ion reactions. The interesting feature of this study is that although the potential energy surface in the fissioning region are different, the distribution yield remains asymmetric independent of static and dynamic deformations effects studied up to quadrupole β_2 or for higher order hexadecapole deformations. However some symmetric fragments start appearing particularly for static deformed case, whose contribution seems more prominent for higher order deformations (β_2-β_4) and at higher incident energies. This emergence of symmetric mass distribution along with observed asymmetric fragmentation provides the possibility of fine-or sub-structure in the fusion-fission of ^{241}Pu* nucleus.

Besides heavy ion reactions, the role of higher-multipole deformations and orientations of nuclei is investigated in reference to ground state decays of heavier nuclei. These effects are duly incorporated in PCM [6] for investigating spontaneous emission of ^{14}C clusters, observed in decays of certain parent nuclei in the trans-lead region, specifically, from ^{221}Fr to ^{226}Th. We notice that whereas penetrability and assault frequency are almost independent of the choice of deformation and orientation effects, the preformation probability changes strongly and become much larger for the case of deformations and orientations included, as compared to spherical nuclei. The calculated decay half-lives and branching ratios of ^{14}C clusters with respect to α-decay, are found to be in good agreement with measured values for the calculation performed with higher-multipole deformations (β_2,β_3,β_4), with "compact" orientations of cold elongated configurations. However $T_{1/2}$ values of all the measured clusters except ^{14}C could be fitted with β_2-deformations effects alone.

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