Abstract

The subject of this thesis is a theoretical study of heavy ion collisions for the formation and decay of super-heavy elements, using deformed and oriented nuclei. By applying the Dynamical Cluster-decay Model (DCM) based on Quantum Mechanical Fragmentation Theory (QMFT), to these reactions, we have studied the role of static deformation and compact orientation of target nucleus in measured fusion, fusion-fission and capture cross-sections. Also, using the same formalism, we have tried to explore the Island of Stability for superheavy nuclei and locate its center. This thesis is divided into 6 chapters.

Chapter 1, outlines a brief introduction to the experimental and theoretical studies related to the synthesis of super-heavy elements. An overview of the historical background and current status of the related research in nuclear physics in general and Island of Stability for superheavy elements in particular has been discussed in this chapter. This chapter also includes the details of synthesis of superheavy elements, the challenges faced by experimentalists and the ways how these have been overcome.

Chapter 2, gives the details of the methodology used in this thesis. Brief overview of the QMFT is given. The methods of calculating the collective fragmentation potentials and kinetic energy part of the Hamiltonian are discussed, together with the solution of the stationary Schrödinger wave equation. The role of changing magic numbers on shell corrections and binding energy is analyzed. For the case of collisions between deformed and oriented nuclei, we derive the proximity potential
for nuclei colliding in one plane (co-planar). The details are given for the effect of deformed and oriented nuclei in the Coulomb and angular momentum potentials. Here also the deformation and orientation effects of daughter and clusters are duly incorporated. Finally, the DCM which is used to calculate the decay properties such as decay cross sections, kinetic energies, etc., of compound nuclei, has been discussed in detail.

In Chapter 3, the DCM extended for deformations and orientation degrees of freedom of the incoming nuclei and outgoing fragments included, is used to study the excitation functions of the “equatorial” compact hot fusion reaction $^{244}\text{Pu}+^{48}\text{Ca} \rightarrow ^{292}114^* (\theta_c=90^\circ \text{ for } ^{244}\text{Pu})$. Considering the higher multipole deformations up to hexadecapole deformation $\beta_4$ and configurations with “compact” orientation $\theta_c$, the role of static deformation and compact orientation of target nucleus in measured fusion, fusion-fission and capture cross-sections of this reaction is studied. The capture, equivalently, quasi-fission is also considered as a “cold” process with an elongated “polar” configuration (taking $\theta_c=0^\circ$ for $^{244}\text{Pu}$). The fusion or light particle decay channel cross-sections for collisions between nuclei with static deformations at their respective compact orientations are shown to be much more than for the case of the nuclei taken to be spherical, signifying the increase in fusion threshold for an intermediate hot fusion reaction to be associated with the static deformation of the target nucleus and its orientation at the point of collision in its path toward the (spherical) compound nucleus. The shell effects in both the potential and kinetic energy (the mass parameters) terms of the Hamiltonian are shown to be important. In addition to the $^{48}\text{Ca}+^{244}\text{Pu}$ reaction valley, a number of other new reaction valleys (target-projectile combinations) are shown to arise for the “optimally oriented hot” fusion process. The experimental data is reproduced within one parameter description, i.e., the neck length parameter $\Delta R(T)$, using the “compact” orientations of the deformed nuclei. The free parameter $\Delta R$ is shown to depend strongly on limiting angular momentum, which in turn depends on the use of sticking or non-sticking moment of inertia for angular momentum effects.
In Chapter 4, first the DCM, with deformation effects up to hexadecapole deformations and “compact” orientations included, is used to calculate the fusion evaporation residue cross sections $\sigma_{ER}$ for 3 and 4-neutrons emission in a hot fusion reaction $^{48}\text{Ca}+^{238}\text{U}\rightarrow^{286}112^{*}$ at various incident energies, taking three different proton magic numbers $Z=114, 120$ or 126 and $N=184$ for the superheavy region. In each case, the shell corrections are obtained from an “empirical” formula, with the corresponding liquid drop energies adjusted to give the experimental binding energies. This is done for all possible mass (and charge) fragmentations of the compound system. The DCM gives a good description of the measured fusion excitation function, $\sigma_{ER} (=\sigma_{3n} + \sigma_{4n})$ as a function of the compound nucleus excitation energy $E^{*}$, within one parameter fitting, the neck length $\Delta R(E^{*})$.

Next we study the effect of changing the magic numbers in superheavy region, on the fragmentation potential and the preformation and penetration probabilities, in particular for the emitted neutrons ($A_{2}=1-4$), of the compound system $^{286}112^{*}$. A change in the fragmentation potentials is shown to occur only in cases where one of the nucleus in target-projectile combinations ($A_{1}, A_{2}$) is close to the new magic numbers. There is no change in penetrability since the scattering potential does not depend on shell effects. In other words, no change is expected to take place for pairs in the neighborhood of symmetric fragments, as is shown to be the case for fragments beyond the light fragment masses $A_{2} > 70$. For $A_{2} < 70$, some of the minima change (due to the heavy fragment $A_{1}$), in particular their relative depths, as the proton closed shell for superheavy mass region is changed. The interesting result of our calculations is that the fusion evaporation cross section remains the highest for the case of $Z=126, N=184$, and the lowest for the case of $Z=114, N=184$, independent of the fitting procedure, as well as of excitation energy $E^{*}$. Thus our study of fusion evaporation residue alone seems to support the island of stability for superheavy nuclei to center around $Z=126, N=184$, rather than around $Z=114, N=184$, with $Z=120, N=184$ as the second best possibility.
In Chapter 5, considering different magic shells such as Z=126, 120 or 114, N=184 or Z=120, N=172 for the superheavy mass region, the dynamical cluster-decay model (DCM), with deformation and orientation degrees of freedom of colliding nuclei or decay fragments included, is used to study the complete excitation functions i.e. evaporation residue, fusion-fission and quasi-fission processes, of a "non-equatorial" compact hot-fusion reaction $^{48}\text{Ca}+^{238}\text{U}\rightarrow^{286}112^*$ (orientation angle $\theta_e=72^\circ$ for $^{238}\text{U}$ compared to $\theta_e=90^\circ$ for "equatorial" compact). For the higher multipole deformations taken up to hexadecapole deformations $\beta_4$, and configurations with "compact" orientations $\theta_d$, the DCM gives a good description of the individual light-particle decay channels $\sigma_{xn}$ ($x=3$ and 4 neutrons), and other decay channels, the fusion-fission $\sigma_{ff}$ and quasi-fission $\sigma_{qf}$ cross-sections at various incident energies or compound nucleus excitation energies $E^*$, within a single parameter description, the neck-length parameter $\Delta R$. Within the Strutinsly renormalization procedure, in each case, the shell corrections are obtained from an "empirical" formula with the corresponding liquid drop energies adjusted to give the experimental binding energies. This is done for all the mass (and charge) fragmentations of the compound system. Of all the four choices of magic numbers considered, the evaporation residue cross-sections ($\sigma_{ER} = \sigma_{3n} + \sigma_{4n}$, the sum of light-particle, neutron-channel cross-sections) remain the largest and nearly the same for Z=126, N=184 or Z=120, N=184, but the fusion-fission cross-sections $\sigma_{ff}$ are always the highest for Z=120, N=184. Noting that the quasi-fission process is not affected by the magicity of shells, this study supports Z=120 and N=184 as the strongest magic numbers for the center of island of stability for superheavy elements. In other words, combined with the results of chapter 4, our study supports the relativistic mean field result of Z=120 and N=184 as the strongest candidate for the center of island of stability for superheavy mass region.

Finally, in chapter 6, we summarize our results and give an outlook of our work for further studies.