Chapter 1

Introduction

1.1 Introduction

Our Earth is home to 83 stable elements, including slightly fewer than 300 stable isotopes. Other nuclei found in nature, although bound to the emission of protons and neutrons, are radioactive. That is, they eventually capture or emit electrons and positrons, alpha particles, or undergo spontaneous fission. Each unstable isotope is characterized by its half-life ($T_{1/2}$) - the time taken for half of the sample to decay. Isotope half-lives range from less than a thousandth of a second to billions of years. Many radioactive nuclei may have half-lives comparable to or longer than the age of the Earth (4.5 billion years). Examples are the actinide nuclei $^{232}$Th ($T_{1/2}=11010$ years), $^{235}$U ($T_{1/2}=7108$ years), or $^{239}$U ($T_{1/2}=4108$ years). Short-lived isotopes cannot be found naturally on Earth because they have long decayed since our planet was formed. Yet, thousands of short-lived isotopes are continually created in the cosmos and they play a crucial role in the ongoing formation of the elements in the Universe. The properties of most rare isotopes are unknown and can be only inferred, with considerable uncertainty, from theoretical calculations.

The valley of stability, Figure 1.1, comprises stable nuclear systems in the Z-N landscape, popularly known as “nuclear landscape”, a chart plotted as a function of proton number Z and neutron number N. It is relevant to mention here that 7-8 thousand combinations of proton and neutron are possible (between neutron and...
proton “drip lines”, beyond which nuclear binding is zero) of which our knowledge is restricted to 2-3 thousand only. In other words, number of stable nuclei is very small (shown by black squares) in comparison to large number of possible unstable nuclei. The existence of stable/bound nuclei depends on the sensitive balance between repulsive Coulomb forces and attractive, short range nuclear forces. The search for super-heavy elements (\(Z > 100\)) explores the borderline of the nuclear chart towards its upper end where the strong Coulomb force acting between the many protons dominates the nuclear stability and finally terminates the number of elements by instability against fission. The superheavy elements (SHEs) mark the limit of nuclear mass and charge; they inhabit the upper right corner of the nu-
clear landscape, but the borderlines of their territory are unknown. The SHEs allow nuclear physicists to explore concepts such as “magic numbers” and the “island of stability”, which help us understand why some nuclei are more stable than others. They can also be used to test the predictions of different models of the nucleus and, ultimately, they may help us to understand why nature contains only a finite number of elements.

The quest for superheavy nuclei began in the 1940’s with the synthesis of atomic nuclei with a number of protons greater than uranium (Z=92). In 1940, neptunium (Z=93) and plutonium (Z=94) were discovered. This was followed by the synthesis of americium (Z=95) and curium (Z=96) in 1944, berkelium (Z=97) in 1949, californium (Z=98), einsteinium (Z=99) and fermium (Z=100) in 1952, and mendeleevium (Z=101) in 1955. All these elements were produced by intense neutron irradiations or by proton, deuteron, or helium (alpha particle) bombardment in a cyclotron. Some of these isotopes have been produced in sizable amounts. Einsteinium and fermium were discovered in the debris from the thermonuclear explosion conducted at Eniwetok Atoll in the Pacific Ocean. Still heavier elements (transuranium) were produced in heavy-ion accelerators by fusing heavy actinide targets (plutonium-californium) with light ions of carbon (nobelium, Z=102, 1958; ruthefordium, Z=104, 1969), boron (lawrencium, Z=103, 1961), neon (dubnium, Z=105, 1967), and oxygen (seaborgium, Z=106, 1974). Most of the heaviest elements were found in three “heavy element factories”: Lawrence Berkeley Laboratory in Berkeley (USA), Joint Institute for Nuclear Research in Dubna (Russia), and Gesellschaft für Schwerionenforschung (GSI) near Darmstadt (Germany). But the exciting new discoveries brought new players to the “superheavy” community: RIKEN (Japan) and GANIL (France). Chemical studies of transactinides are also being carried out at PSI and JAERI (Japan).

The lifetimes of the heaviest elements were found to be very short. For instance, element Z=112, investigated using the reaction $^{70}Zn + ^{208}Pb \rightarrow ^{277}Cn + In$, turned out to have a half life of only about 280 $\mu$sec. The corresponding fusion cross section is extremely small, 1 pb. Since the production cross section was found to be rapidly
Figure 1.2: Target-projectile combinations and the measured cross-sections with cross-section limits for the experimentally synthesized SHEs both for cold, hot and very hot fusion reactions.

Element number
decreasing with the atomic number, (see Figure 1.2), it was then concluded that it would be very difficult to reach still heavier elements. This happens because the disruptive electrostatic forces between the positively charged protons grow faster than the cohesive nuclear forces that hold the nucleons (protons and neutrons) together. The large electrostatic forces cause heavy nuclei to decay rapidly by the emission of alpha particles (helium nuclei) and by spontaneous fission. But this instability of SHEs does not seem to be inevitable. The island of stability describes the possibility of elements with particularly stable “magic numbers” of protons and neutrons. This would allow certain isotopes of some transuranic elements to be far more stable than others i.e., is, decay much more slowly (with half lives of at least minutes or days, compared to fractions of a second; some have even suggested the possibility of half lives of the order of millions of years).

The idea of the island of stability for SHEs was first proposed by Glenn T. Seaborg. He thus spoke of a sea of instability – the increasingly and sometimes fantastically unstable elements from 101 to 111 – that one would somehow have to leap over if one was ever to reach what he called the island of stability (an elongated island stretching from Elements 112 to 118, but having in its center at the “doubly magic” isotope of Z=114). The hypothesis is that the atomic nucleus is built up in “shells” in a manner similar to the electron shells in atoms. In both cases shells are just groups of quantum energy levels that are relatively close to each other. Energy levels from quantum states in two different shells will be separated by a relatively large energy gap. So when the number of neutrons and protons completely fill the energy levels of a given shell in the nucleus, the binding energy per nucleon will reach a local maximum and thus that particular configuration will have a longer lifetime than nearby isotopes that do not have filled shells.

There is no consensus among theorists with regard to the center of the shell-stability in the superheavy region. Since the pioneering work of late 1960’s of Lund Group, using one center oscillator, and that of Frankfurt School, using two center shell model, it is established that the center of island of stability for SHEs (the next magic numbers beyond Z=82, N=126) lies at Z=114, N=184. Experimentally,
however, we have not yet succeeded in identifying such a region, though the nucleus Z=114 with somewhat lower N=178 is already synthesized and experiments have gone up the ladder with Z=118, N=179. Furthermore, the recent Dubna data [1] on Qα-values for 294116 and 294118 decay chains do not show any (shell) structure effects of the Z=114 magicity [2]. In this context, it is relevant to remind that the above mentioned predictions for the region of stability did not enjoy any concrete experimental or microscopic theoretical information. The calculations relied mainly on the available structure information for lower mass regions of stable and radioactive nuclei up to Z=100 or so. Recently, many microscopic mean field models have been developed and their applications in the region of SHEs predict Z=120 and N=172 or 184 as the next magic nucleus [3,4]. Also, Z=126, N=184 have been used/predicted as magic numbers [5-7]. On the other hand, there is no available shell model that predicts Z=120 as the next magic charge number. The challenge presented to experimental nuclear physicists is clear: they need to create the super-heavy nuclei and measure their properties to put these theoretical predictions to test.

The method that is being successfully used for the synthesis of super-heavy elements is that of complete fusion reactions. In complete fusion reactions, two colliding nuclei merge with each other to form a compound nucleus, giving utmost a few atoms of SHEs. In the 1970s, “cold fusion” reactions involving medium-mass projectiles with even-even Z = 20-24 (Calcium, Titanium and Chromium) and lead or bismuth targets were introduced and replaced “hot fusion” reaction with actinide targets. Later on, the same method enabled the discovery of seaborgium (Z=106, 1976), hassium (Z=108, 1984), meitnerium (Z=109, 1982), Darmstadtium (Z=110, 1994), Roentgenium (Z=111, 1994), and Cooperium (Z=112, 1996). Theoretically, “Cold fusion” reactions correspond to lowest interaction barriers, largest interaction radii and non-compact, elongated nuclear shapes, with the excitation energy of the compound nucleus formed to lie between 10-20 MeV. These reactions are weakly exothermic reactions. At excitation energies of 10-20 MeV, 1-2 neutrons are emitted from the compound nucleus. Cold synthesis of SHEs was first proposed theoretically by Greiner, Gupta and collaborators at Frankfurt [8]-[19] as early as
in 1974-75, more than three decades back, on the basis of Quantum Mechanical Fragmentation Theory using the two center shell model as an average two-body potential within the Strutinsky macro-microscopic method. They suggested the use of cold compound systems that were formed for all target-projectiles systems that lie at the bottom of the potential energy minima. Four such reaction valleys were always found to exist, namely with: (i) symmetric or nearly symmetric nuclei, (ii) asymmetric nuclei with one or both deformed nuclei, (iii) very asymmetric nuclei with Pb nucleus (or the neighboring Bi nucleus for odd Z compound systems) always as one of the reaction partners, and, (iv) super-asymmetric target-projectiles (such as C, N, O and Ne) and heavy deformed targets. The excitation energy is lowest for the case (i) of symmetric target-projectile combinations, but the above information on reaction valleys, when optimized by the requirements of cold fusion reactions (smallest interaction barrier, largest interaction radius and non necked nuclear shapes), singled out the use of of the reaction partners of case (iii) above, i.e. Pb (or Bi) as one of the reaction partners always, for the cold synthesis of super heavy elements. Experimentally, however, it became possible to identify the true signatures of cold fusion phenomenon only in late 1990’s.

Thus, we can ascend the ladder of SHEs by fusion of nuclei. Fusion is a process in which two nuclei are brought together to form a compound nucleus (CN). A substantial energy barrier, due to mutual repulsion between the two nuclei, opposes the fusion reaction. This barrier consists of the Coulomb and the nuclear potentials. However, the long range Coulomb repulsion between the nuclei is offset by stronger, but short range, attractive nuclear force. Then, the problem is to bring the nuclei sufficiently close so that the Coulomb barrier can be crossed over, say, via tunneling. Hence, the two nuclei are required to collide with sufficient kinetic energy to overcome their mutual electrostatic repulsion (or fusion threshold barrier) and subsequently to bring into effect the role of strong but short range attractive nuclear force. In other words, the simplest picture of fusion is that of quantum tunneling through a one dimensional barrier formed by the long range Coulomb potential, the centrifugal potential and the short range nuclear potential. It means
that the knowledge of interaction potential, forming barrier, between two nuclei is extremely important in order to have a systematic study of a nuclear reaction. The inclusion of deformation and orientation effects of the colliding nuclei leads to lowering of its barrier height [20]-[24]. This means that the interaction potential and hence the fusion cross-sections are largely influenced by the nuclear structure effects of the target and projectile nuclei and their relative orientations. The collisions between deformed as well as oriented nuclei have been studied theoretically and experimentally to establish the effect of deformation and orientation on fusion reactions [20]-[26].

The study [22] based upon Quantum Mechanical Fragmentation Theory (QMFT) by Gupta and collaborators shows that the interaction barrier (height as well as its position) is greatly affected by deformed and oriented colliding nuclei. This study gives the optimum orientations for fusion of deformed nuclei based on the quadrupole deformations alone and also investigated the role of hexadecupole deformation in fusion reactions. The optimum orientations are given for “cold, non-compact”
Figure 1.4: Schematic diagram for dynamics of the colliding nuclei playing around Coulomb as well as nuclear interaction potential.

and “hot, compact” fusion configurations corresponding to largest interaction radius/lowest barrier and smallest interaction radius/highest barrier, respectively. The details can be seen in Table 1 of [22]. However a schematic diagram is illustrated in Figure 1.3, only for prolate-prolate and oblate-oblate deformed colliding nuclei along collision axis for both “cold, elongated” and “hot, compact” configurations.

The compound nuclei (CN) formed in low-energy heavy-ion reactions are highly excited and carry large angular momentum (Figure 1.4). The compound systems so formed decay by emitting multiple light particles, LPs (n, p, α) and γ-rays. For light compound systems with $A_{CN} \sim 40 - 80$, the light-particles (LPs) emission is always accompanied by intermediate mass fragments, the IMFs (with $2 < Z < 10$ and $5 < A < 20$). In this mass region the IMFs contribution is very small of the order of 5-10%, in comparison to LPs contribution. However, for the heavy nuclear systems $A_{CN} \sim 200$, the most probable decay mode of the compound nucleus is fission ($20 \leq A \leq A/2$), due to its instability against centrifugal repulsion, with small
contribution from neutrons and $\gamma$-rays emissions, just in contrast to decay process of light compound systems. Then there are other processes which may contribute to decay products, e.g., deep-inelastic collisions and quasi-fission, etc., depending upon the reaction conditions. The quasi-fission (or capture cross-section), characterized by a few nucleon transfer occurs at the early stage of the fusion process where both the target and projectile can be considered to have not yet lost their identity since there is no compound nucleus formation [27,28]. Thus, the measured compound nucleus decay or fusion cross-section in this case consists of the promptly emitted light particles cross-section, called residue cross-section $\sigma_{ER}$, the IMFs cross-section $\sigma_{IMF}$, the fusion-fission $\sigma_{ff}$ and the non-compound quasi-fission $\sigma_{qf}$, i.e., $\sigma_{Exp}^{Exp} = \sigma_{ER} + \sigma_{IMF} + \sigma_{ff} + \sigma_{qf}$. The different terms in this expression contribute in different mass regions of CN.

In order to study the decay of a hot and rotating compound system (i.e. having angular momentum, $\ell \neq 0$ and temperature, $T \neq 0$), we have used the Dynamical Cluster-decay Model (DCM) of Gupta and collaborators [29]-[45] which is a reformulation of preformed cluster model (PCM) [46]-[49] of Gupta and collaborators for ground-state decays (i.e. $\ell=0$ and $T=0$). In DCM, decay of excited compound nuclei is studied as a collective clusterization process for emissions of the LPs, as well as the IMFs and fission fragments, in contrast to the statistical models in which each type of emission is treated on different footing. It is relevant to mention here that in statistical model, the Hauser-Feshbach (HF) analysis (LILITA or CASCADE codes) is used to study LPs decay, whereas the fission model is developed to study IMFs/fission decay of CN formed in different mass regions, like BUSCO code [50] for $2 < Z < 20$, extended HF Scission-Point Model [51] and saddle-point “transition-state” fission model [52] for $A < 80$, GEMINI code based on Moretto’s fission model [53] for $A > 100$. Another advantage of using the DCM is that the structure effect of CN is also included via the preformation of the fragments with relative probabilities, before penetrating the interaction barrier, a useful information which is missing in the statistical fission models.
1.2 Organization of thesis

The thesis is organized as follows.

Chapter 2 contains the details of the methodology that we have applied for studying the synthesis of super-heavy elements and for the calculations of the fusion cross-sections. The work is based on the Quantum Mechanical Fragmentation theory proposed by Greiner, Gupta and collaborators at Frankfurt [8]-[19] as early as in 1974-75 using two center shell model as an average two body potential in Strutinsky macro-microscopic method. The key ingredient of this theory is the shell effects in fragmentation potentials, which means using at least one spherical closed shell nucleus as the reaction partner, referring to the minima of the potential energy surface (PES), $V(\eta, R)$, in relative separation coordinate $R$ and mass asymmetry $\eta$ (defined later) for a given compound nucleus. Apparently, the significance of closed shells in selecting reaction partners for synthesizing SHEs raises the question of the role of deformed closed shells. In view of this we have extended this theory to include the effects of deformations and orientation degrees of freedom, in order to study the collisions between any two symmetric or asymmetric mass, deformed nuclei. As it is a quantum mechanical theory, the deformation and orientation effects are introduced through both the ion-ion potentials and mass parameters defining the kinetic energy term. Thus a brief description of the scattering and fragmentation potentials used in this theory is given. The nuclear proximity potential based on Blocki et al. [54] pocket formula is extended to include the deformations and orientations of the colliding nuclei. The classical hydrodynamical mass parameters are calculated. The preformation probability and penetration probability of the outgoing fragments are calculated by solving Schrödinger wave equation and their contributions to the compound nucleus decay cross-section are discussed. The role of changing magic numbers on shell corrections and hence binding energy is analyzed. For the calculations of fusion cross-sections, the dynamical cluster decay model (DCM) of Gupta and collaborators [29,31-34,55,56] based on the Quantum Mechanical Fragmentation Theory (QMFT), which, in binary fragmentation, uses a collective mass transfer
process. The DCM is achieved from the PCM (Preformed Cluster Model) of Gupta and collaborators [46,47,49] by making all its terms as temperature-dependent and using the temperature-dependent binding energies. The DCM treats the CN decay of light particles LPs, intermediate mass fragments IMFs and heavy mass fragments HMFs or symmetric fission SF on equal footings, in contrast to statistical models which uses the HF analysis for LPs and binary fission for all other processes. For the decay of the hot and rotating compound nucleus the angular momentum is included using the temperature-dependent centrifugal potential.

In Chapter 3, we have used the dynamical cluster-decay model (DCM) of Gupta and collaborators [29,31–45,55,56], extended for the first time to include the deformations and orientation degrees of freedom of the colliding nuclei. The model is used to calculate the fusion evaporation cross-sections and other decay channels, the fusion-fission and quasi-fission cross-section (equivalently, capture) with in one parameter fitting, the the neck length $\Delta R$, for $^{242,244}$Pu+$^{48}$Ca fusion reaction, synthesizing $Z=114$ element [27,57]. The quasi-fission is also considered as a “cold process” with an elongated “polar” configuration. The effect of the deformation and orientation degree of freedom of the colliding nuclei on the fusion cross-sections is studied. The light particle decay channel cross-sections (the evaporation residue 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 free parameter $\Delta R$ of the model 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. For the sticking moment of inertia, the evaporation residue (neutron emission) is shown to occur almost promptly (largest $\Delta R$), followed by the competing (hot/ cold) quasi-fission and ending finally...
with fusion-fission of hot compound nucleus. Different $\Delta R$'s (equivalently, relative separations) for the three processes means to predict that the processes ER, ff and qf happen in different time-scales, in agreement with the indications of experiments.

In Chapter 4, we have used the dynamical cluster-decay model (DCM), with deformation effects up to hexadecapole deformations and "compact" orientations included, to calculate the fusion evaporation residue cross sections $\sigma_{ER}$ for 3 and 4-neutrons emission in a hot fusion reaction $^{48}$Ca+$^{238}$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. The liquid drop energies are taken from the work of Davidson et al. [58], based on Seeger's mass formula [61]. For $T=0$, Seeger [61] obtained the constants, $\alpha$, $\beta$, $\gamma$ and $\delta$ by fitting all even-even nuclei and 488 odd-A nuclei available at that time (in 1961). For the large amount of data available now on ground-state binding energies, these constants of liquid drop energy needed refitting, which was done by some of us [29,31] to get the experimental binding energies [62] with shell corrections determined from Myers and Swiatecki [5]. Wherever the experimental data were not available, the theoretically estimated binding energies of Möller et al. [60] were used. The magic numbers used for the superheavy region, both in fitted constants of $V_{LDM}(T=0)$ [29,31] and shell corrections [5], were $Z=126$, $N=184$. Evidently, the same job of fitting the constants of $V_{LDM}(T=0)$ to give the experimental binding energy $B$ for shell corrections with new proton magic numbers at $Z=120$ or 114, respectively, need be re-done if the magicity at $Z=126$ is to be changed to that of the new ones at $Z=120$ or 114, the shell corrections in each case are calculated from the "empirical" formula of Myers and Swiatecki [5].

The $T$-dependent liquid drop energy of Davidson et al.[58] with its constants at $T=0$ refitted by some of us[29,31,36,45] to give the experimental binding energies. The shell corrections $\delta U$ used here are the "empirical" estimates of Myers and Swiatecki $\delta U$(MS)[5], also taken $T$-dependent, with $T_0=1.5$ MeV[59]. We have also studied the effect of using a different prescription for $\delta U$, like that of Möller et al.$\delta U$(MN)[60], calculated for $Z$ $\geq$8. Similar to that for $\delta U$(MS), for $Z$ $<$8 we calcu-
late the $\delta U(MN)$ by subtracting from experimental binding energy $B_{\text{Expt}}$, the $V_{\text{LDM}}$ [58]. We notice that the calculated cross-sections for use of these different prescriptions for shell corrections do not change much, but that the shell effects in masses (to what ever extent they are present in hydrodynamical masses) play an important role. First of all, 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. Also, penetrability is independent of the magic numbers used, since it is exactly the same for $Z=126, 120$ or 114. Whereas preformation probability decreases with increase in angular momentum($\ell$), the contribution of penetration probability goes on increasing as $\ell$-value increases. So we have here an upper ($\ell_{\text{max}}$) as well as a lower ($\ell_{\text{min}}$) limit on $\ell$-values, an $\ell$ window that contribute to the cross section. The DCM gives a good description of the measured fusion excitation function, $\sigma_{\text{ER}} (=-\sigma_{3n} + \sigma_{4n})$ as a function of the compound nucleus excitation energy $E^*$, within one parameter fitting, the neck length $\Delta R(E^*)$. Of all the three choices of magic numbers, the fusion evaporation residue cross section remains the largest for the case of $Z=126, N=184$, and the lowest for the $Z=114, N=184$ case independent of the fitting procedure, as well as of excitation energy, thereby clearly suggesting that $Z=126, N=184$ are the strongest magic numbers (largest shell corrections), and $Z=114, N=184$ are the weakest (smallest shell corrections), with $Z=120, N=184$ lying in between. Thus, on the basis of fusion evaporation residue cross sections alone, the present study 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.

However, for the reaction $^{48}\text{Ca}+^{238}\text{U} \rightarrow ^{286}_{112}$, in addition to $\sigma_{\text{ER}} (=-\sigma_{3n} + \sigma_{4n}$, the sum of neutron-channel cross-sections) at higher excitation energies of $E^* \approx 30-40$ MeV, the excitation functions for fusion-fission ($\sigma_{ff}$) and capture ($\sigma_{\text{cap}}$, equivalently,
quasi-fission ($\sigma_{qf}$) are also measured in another Dubna experiment [27], though at lower excitation energies of $E^* \approx 20-40$ MeV. In Chapter 5, we consider the total data [27, 57] on three cross-sections ($\sigma_{ER}$, $\sigma_{ff}$ and $\sigma_{qf}$) simultaneously for a best fit of the only parameter of the model, the neck-length $\Delta R(E^*)$. The quasi-fission (qf) channel is characterized (see, e.g., [41] and the discussion of results in this chapter) by the formation of highly asymmetric mass fragments due to a few nucleon transfer (light mass fragment $A_2 \approx 76-86$, and the corresponding heavy mass fragment $A_1 \approx 200-210$, for the above said reaction), occurring most probably at the early stage of the fusion process when the compound nucleus is still strongly deformed and the target and projectile nuclei can be considered to have not yet lost their identity. On the other hand, the symmetric or near symmetric ff channel (fragment mass $A_i = A/2 \pm 20$, $i = 1, 2$) is the last stage of the process where the strongly deformed complex develops in to the neck formation. Of course, the evaporation residue occur almost promptly (largest neck-length parameter $\Delta R$, see below).

We consider all the four cases of magic $Z=114$, 120 or 126 with $N=184$ and $Z=120$, $N=172$ for obtaining the shell corrections from the “empirical” formula of Myers and Swiatecki [5] with the corresponding liquid drop energies obtained from Seeger’s mass formula [61] based work of Davidson et al. [58]. While studying the effect of changing the magic numbers in superheavy region, on the fragmentation potential and the preformation and penetration probabilities, 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. One such important change is in the minima at $3n$ and $4n$ clusters (plus the corresponding heavy fragments). The neck-length parameter $\Delta R$ as a function of CN excitation energy $E^*$ for the simultaneous best fit to the data on cross-sections for the three processes of ER, qf and ff, considered for the cases of four magic pairs of $Z$, $N$ ($Z=126$, 120 or 114, $N=184$ or $Z=120$, $N=172$), is plotted. Interestingly, due to the changed magic numbers, as expected, the largest change in $\Delta R$ occurs
for ER, the $3n$ and $4n$ emissions, since the complementary heavy fragments lie in the neighborhood of superheavy region, and the $\Delta R$ for ff is nearly the same since they refer to symmetric and nearly symmetric fragments, i.e., far away from superheavy magic shells. The qf process is independent of the magicity of shells since it refers to incoming channel alone. The important result is that the neck-length parameter $\Delta R$ (equivalently, relative separation $R_a$) is different for the three processes, which means to predict that the three processes of ER, qf and ff happen in different time-scales, in agreement with the indications of experiments [1, 3]. The evaporation residue cross-sections (which are strongly dependent on the choice of magic shells due to the complementary heavy residue) are the largest and nearly indistinguishable for $Z=126$, $N=184$ or $Z=120$, $N=184$, but the fusion-fission cross-sections, independent of $E^*$, are always favoured (highest) for $Z=120$, $N=184$. Thus, our detailed calculations and a close look at the results suggests $Z=120$, $N=184$ as the strongest magic numbers (largest shell corrections) which should form a doubly-magic spherical nucleus at the center of island of stability of superheavy nuclei.

Finally, in Chapter 6, summary of the thesis is presented with an outlook of this work.
Bibliography


