Chapter 1

Introduction

Nuclear physics is the branch of physics that studies the building blocks and interactions of atomic nuclei. Few things that come to mind of a layman, when talked about nuclear physics, are nuclear power and nuclear weapons, but the research has provided wider applications, including those in medicine (nuclear medicine, magnetic resonance imaging), materials engineering (ion implantation) and archaeology (radiocarbon dating). Nuclear physics enables us for the better understanding of the nature. The traditional goal of nuclear physics is to understand the properties of atomic nucleus in terms of the bare interaction between pairs of nucleons, or nucleon-nucleon forces.

The field of nuclear physics includes the field of low energy particle physics, as it got evolved from the nuclear physics. The discovery of the electron by J. J. Thomson was the first indication that the atom had internal structure. At the turn of the 20th century the accepted model of the atom was J. J. Thomson’s “plum pudding” model. This model account for the stability of atoms, but unable to account for the discrete wavelengths observed in the spectra of light emitted from excited atoms. Neither could it explain the results of a classic series of experiments started in 1911 by Rutherford and continued by his collaborators, Geiger and Marsden. These consisted of scattering α-particles by very thin gold foils. In the Thomson model, most of the α particles would pass through the foil, with only a few suffering deflections through
small angles. Rutherford suggested that they look for large-angle scattering and
indeed found that some particles were scattered through very large angles, even
greater than \(90^\circ\). Rutherford showed that this behavior was not due to multiple
small angle deflections, but could only be the result of the \(\alpha\) particles encountering
a very small positively charged central nucleus. To explain the results of these
experiments Rutherford formulated a planetary model, where the atom was likened
to a planetary system, with the electrons (the planets) occupying discrete orbits
about a central positively charged nucleus (the Sun). Because photons of a definite
energy would be emitted when electrons moved from one orbit to another, this
model could explain the discrete nature of the observed electromagnetic spectra,
when excited atoms decayed.

Later on physicists had also discovered three types of radiations coming from
atoms, which they named as alpha-, beta-, and gamma- radiations. Experiments
in 1911 by Otto Hahn, and by James Chadwick in 1914 discovered that the beta
decay spectrum was continuous rather than discrete that were observed in gamma
and alpha decays. In 1905, Albert Einstein formulated the idea of mass-energy
equivalence. While the work on radioactivity by Becquerel, Pierre and Marie Curie
predates this, an explanation of the source of the energy of radioactivity had to
wait for the discovery that the nucleus itself was composed of smaller constituents,
the nucleons. Also the naturally occurring elements were postulated to consist of a
mixture of different isotopes, giving rise to the observed masses. The explanation of
isotopes had to wait twenty years until a classic discovery by Chadwick in 1932. He
refined and extended the earlier experiments by Irene Curie (the daughter of Pierre
and Marie Curie) and her husband Frederic Joliot and demonstrated that they im-
plied the existence of an electrically neutral particle of approximately the same mass
as the proton. He had discovered the neutron \((n)\) and in so doing had produced
almost the final ingredient for understanding a nucleus. After neutron discovery,
H. Yukawa in 1934, made attempt to explain the nature of the nuclear force and
suggested that massive bosons mediate the interaction between two nucleons. Historically, it was a formidable task to describe the nuclear force phenomenologically, and the first semi-empirical quantitative models came in the mid-1950s. Most basic questions were settled in 1960s and 1970s. Some times the nuclear force is called residual strong force, in contrast to the strong interactions which are now understood to arise from quantum chromodynamics after the verification of quark model. Two-nucleon systems such as the deuteron, the nucleus of a deuterium atom, as well as proton-proton or neutron-proton scattering are ideal for studying the NN force. Such systems can be described by attributing a potential (like Yukawa potential) to the nucleons and using the potentials in Schrödinger equation. A successful way of describing nuclear interactions is to construct one potential for the whole nucleus instead of considering all its nucleon components. This is called the macroscopic approach. For example, scattering of neutrons from the nuclei can be described by considering a plane wave in the potential of the nucleus, which comprises a real and an imaginary part. This model is often called optical model.

A nucleus can have many nucleons depending upon the mass number A, so with some approximations it can be treated as a classical system, rather than a quantum-mechanical one. In liquid-drop model, the nucleus has an energy contributed by volume, surface tension, electrical repulsion of the protons, and asymmetry of neutrons and protons. Also a correction term that arises from the tendency of proton pairs and neutron pairs to occur is also included. The liquid-drop model is able to reproduce many features of nuclei, including like the behavior of binding energy with respect to mass number, as well as the phenomenon of nuclear fission of heavy nuclei. Later on Mayer gave the shell model. This model can explain, why nuclei with certain numbers of neutrons and protons (the magic numbers 2, 8, 20, 28, 50, 82, 126, ...) are particularly stable, because their outer shells are filled. Other more complicated models for the nucleus have also been proposed.

Current research in nuclear physics is mostly related to the study of nuclei under extreme conditions such as high excitation energy and spin, and the decay of the
compound nuclei formed in various reactions. Extension of Periodic table i.e. synthesis of superheavy elements is also the hot topic. Nuclei may also have different shapes or different neutron-to-proton ratios. Experimentalists can create such nuclei by artificially induced fusion or nucleon transfer reactions, employing ion beams from accelerators. Beams with even higher energies can be used to create nuclei at very high temperatures.

There are 80 elements which have at least one stable isotope, and in total there are about 300 such stable isotopes. However, there are thousands of other isotopes which are unstable. These radioisotopes may be unstable and decay in all timescales ranging from fractions of a second to weeks, years, or many billions of years.

1.1 Heavy ion reactions

Heavy ion reactions is a fast growing subject of nuclear physics. Heavy ions are the nuclei equal to or heavier than the $\alpha$-particle i.e. nuclei with $Z \geq 2$ and $A \geq 4$. Thus, $\alpha$-particle can be called as the lightest heavy ion. Heavy ion collisions give new possibilities to examine the form of the ion-ion interaction potential which is one of the most important ingredient in the investigation of the stability or decay of nuclei, elastic or inelastic scattering, fusion reactions and the estimation of cross-sections for the synthesis of heavy and superheavy elements, for low energy reactions. The long range part of the interaction potentials are determined from the Coulomb and centrifugal interactions, and the short distance behavior strongly depends upon the nuclear surface properties and the readjustment of combined nuclear system, resulting in potential pockets which determine the characteristics of the compound system formed due to the collision between the two nuclei. Thus for a better understanding of the world around us, the more accurate and microscopic methods for calculating the ion-ion interaction, between the colliding nuclei, should be exploited.

Different models have been developed to describe the interaction potential of
the two colliding nuclei. Though the Coulomb interaction plays an important role but is not enough to describe the formation of a compound nucleus. The nuclear interaction also plays an important role in the formation of a compound nucleus.

The various approaches for calculating the ion-ion potentials are:

(i) Phenomenological models like that of Bass [1,2], who introduced a simple analytical expression for the potential. Similarly, Blocki et al. [3] introduced a simple formula for nucleus-nucleus interaction energy as a function of separation distance between the surfaces of the two colliding nuclei, known as the “pocket formula” of proximity potential. Other proximity potentials are given in refs. [4,5]. The proximity formula for the interaction potential is free from any adjusting parameter and uses the measured values of surface tension and surface diffuseness. However to relate the separation between the surfaces of the colliding nuclei with the distance between the center of the approaching nuclei, we need the accurate knowledge of nuclear radii. Then, there are potentials obtained from the folding procedure with a phenomenological Yukawa-plus-exponential [6–10], etc. Some of these potential have been fitted to the experimental fusion barrier height and have been very successful in describing scattering data.

(ii) Semi-microscopic and fully microscopic calculations such as macro-microscopic methods [10–12], the asymmetric two center shell model [13] and other mean field calculations [14,15].

The interaction potentials based on the semi-microscopic approach are usually done under two extreme physical assumptions:

(a) The approximation under which the collision being so slow that at each stage of the collision the nucleons of the two ions reach the equilibrium configuration, called the ‘adiabatic approximation’.

(b) The approximation under which the collision is so fast that the internal structure of the two ions is unmodified and the nuclear density overlap without changing their shapes, called ‘sudden density approximation’ that includes the effect of exchange
terms due to anti-symmetrization. The sudden density approximation excluding the effect of exchange terms is also known as frozen density approximation [16]. These two extreme pictures may be considered in energy density formalism (EDF) as well as in a method of double folding of the projectile and target nuclei density with either realistic or effective nucleon-nucleon interaction. The Hartree-Fock method (HF) can be considered as the microscopic background to built up the EDF model but, in the sudden density approximation, the full HF calculations are not available in EDF model due to the impossibility of expressing the kinetic energy density $\tau$ of the compound nucleus at HF level. To overcome this difficulty, semiclassical approaches to this quantity based on the Thomas-Fermi (TF) method or its extensions (extended Thomas Fermi model) have been used for obtaining $\tau$ in the compound system. The extended Thomas Fermi (ETF) approach of Grammaticos and Voros [17] starts from the semiclassical expansions in the powers of $\hbar^2$ of the density matrix where $\tau$ is obtained as a function of the local density $\rho$, for spin independent potentials. For an isolated nucleus, the ground state density is found from the energy density by a variational approach. To correct the deficiencies of the lowest-order term TF and to provide a more accurate description of the nuclear surface, higher order, $\hbar^2$ and $\hbar^4$ corrections to kinetic energy density $\tau$ containing inhomogeneity and nonlocal effects have been taken. Brack et al. [18] have shown that for finite nuclei the ETF approximation, taking into account the $\hbar^2$ and $\hbar^4$ corrections, leads to a nice description of the global quantities like binding energies or root mean square radii of the density distribution of nuclei in comparison with the results of Hartree-Fock method. The one-body Hamiltonian considered in [17], which can be of interest in nuclear structure calculations, does not contain any spin dependent term. It is however well known, after the success of traditional Shell-Model, that the single-particle nuclear Hamiltonian must incorporate a spin-orbit part in order to account for the observed nuclear properties correctly. Thus the spin-orbit part is incorporated in the later work of Grammaticos and Voros, [19], by
extending their semiclassical expansions to the realistic case where the effective one-body Hamiltonian for nucleons contains spin-dependent terms. In this work they give spin-induced corrections to the kinetic energy density and surface energy of the nucleus, and expression to the spin-dependent densities in the nucleus up to fourth order of $\hbar^4$. The spin is an effect of the order of $\hbar$ and thus gives no contribution in the classical limit. However as soon as we consider the higher order $\hbar$-expansions the effects of spin starts coming into play. Jennings et al. [20] has also examined the spin-dependent Hamiltonian by computing the level density to one body Hamiltonian including a spin-orbit part. Some other authors [21] have considered the spin-dependent Hamiltonian, but their spin-orbit potential was of the same order in $\hbar$ as the rest of the Hamiltonian. These authors [21] arrived at conclusions which are not directly applicable in the case of a system of nucleons.

It has been shown that the models based on macroscopic approach, like the liquid drop model and Extended Thomas-Fermi (ETF) models are able to reproduce the fusion data correctly. Therefore, out of a large number of available interaction potentials, we use here the energy density formalism in semiclassical ETF approach [17–19, 22] which provides a convenient basis for the calculation of the interaction potential between the two colliding nuclei. Within the energy density formalism, two different energy density functional are available, one due to Bruckner et al. [23–26] and the other due to Vautherin and Brink [27] which uses the density dependent Skyrme interactions [28]. Here in this thesis, we used the later one in semiclassical ETF approach, due to its main advantage of explaining and reproducing the ground state properties of a large number of nuclei.

In energy density formalism, the nucleus-nucleus interaction potential, as a function of separation distance, is defined as the difference of the energy expectation value of the colliding nuclei that are overlapping (at a finite separation distance $R$) and are completely separated (at $R=\infty$) [26, 29]. Brink et al. [30] used the Hartree Fock density as well as the two parameter Fermi density in the Skyrme energy density
functional (SEDF) \cite{27} for the calculation of nucleus-nucleus interaction potential. Chattopadhyay and Gupta \cite{31} introduced the nuclear proximity potential in form of a universal function, first for Thomas-Fermi nuclear densities and later for two parameter Fermi densities \cite{32}. The universality of such a universal function was later tested by Gupta and collaborators \cite{33,34} and simple analytical expressions were given to represent the universal function of proximity potential. The consistency of SEDF with proximity potential was already tested by Brink and Stancu \cite{30}. However, such functional forms could be worked out for spin-saturated ($\tilde{J}=0$) nuclei or, equivalently, the spin-orbit density independent part of the interaction potential $V_p(R)$ only, since the spin-orbit density dependent interaction potential $V_J(R)$ in this formalism depends on the filling of shell model states and hence only a simple analytical functional form of $V_J(R)$ has been possible \cite{33,34}.

Since the semiclassical ETF approach allows us to express the kinetic energy density $\tau(\vec{r})$ and spin-orbit density $J(\vec{r})$ as functions of nucleon density $\rho(\vec{r})$ and its derivatives, used in self-consistent variational approach with nucleon densities as the variational quantities, the Skyrme energy density becomes a functional of the nucleon densities alone, and hence eliminates completely the use of single particle wave functions. The (variational) nucleon densities are taken as the Hartree-Fock (HF) densities, Hartee-Fock-Bogoliubov (HFB) densities, or simply the modified (two-parameter) Fermi density with an additional parameter \cite{14,15,18,22,35}. The kinetic energy density $\tau(\vec{r})$ and spin-orbit density $J(\vec{r})$ are taken up to second order, although the higher order contributions to both the kinetic energy density $\tau(\vec{r})$ and spin-orbit density $J(\vec{r})$ \cite{18,19,22} are available in the semiclassical approach at the ETF level, for reasons of their being enough for numerical convergence \cite{22}. In the present work, we use the surface diffuseness and nuclear radii, the two parameters of two parameter Fermi-density, obtained from a polynomial fit to the experimental data \cite{38,39}. In earlier calculations \cite{15,22,35}, these parameters were determined self-consistently. All of these calculations (the HF, the ETF and the SM) give
similar densities, and are comparable with Fermi density at T=0, at least in the
tail/surface region of interest for heavy ion collisions. This is illustrated later in
Fig. 2.7 for two nuclei (one light and other heavy) where HF and ETF density
calculations are available in the literature [22, 27]. For 208Pb, the Fermi density
(2.91) is compared with the HF density, calculated for two different Skyrme forces
SI and SII [27], and the ETF density for Skyrme SkM* force [22]; and for 16O with
HF density for Skyrme SI force and the shell model (SM) density. Since nuclear
densities are the main input in the semiclassical ETF model, apparently, our use of
the SM wave functions, instead of the HF equations, and the Fermi density, instead
of the self-consistent HF/ETF densities, are quite reasonable.

Since the compound systems formed are hot, the inclusion of temperature is
also important. Semiclassical ETF approach is also extended to nuclear systems at
finite temperatures [18, 40], but for the free energy and entropy density functionals
only. Here in this present work, we include the temperature effects via the nuclear
density [41], taken as the two-parameter Fermi density. This follows from the fact
that at higher temperatures the HF density takes nearly a shape of Fermi-type,
i.e. become flat in the interior region of small r-values [42]. Furthermore, the
Fermi density distributions and shell model density distributions, as well as the
spin-orbit density interaction potentials based on them, are found to be nearly the
same [32, 33, 43], at least in the surface region of relevance for heavy ion collisions.
In this way, we have included the temperature effects in the semiclassical ETF
formalism.

Normally, in heavy ion collisions, the compound nucleus formed has high excitation
energy and carries large angular momentum. Depending on the mass, the
compound nucleus looses its excitation energy either by loosing a couple of neutrons
and go to ground state, or it decays by emitting multiple light particles (LPs) n, p, α and γ-rays and then it undergoes fission (called, fusion-fission) or alternatively
the fusion-cluster decay; both the processes are advanced in this work (see Fig. 1.1).
Figure 1.1: Coulomb-plus-nuclear potential and dynamics of the colliding nuclei.

The two colliding nuclei may also undergo quasi fission where two nuclei interact strongly, dissipating considerable energy, exchange energy and nucleons, while the surfaces of the colliding nuclei overlap for a brief period corresponding to a partial rotation of the nuclear molecule.

In low-energy heavy-ion collisions, when two nuclei come together, the mutual Coulomb repulsion between them opposes the formation of a compound nucleus (CN). However, the Coulomb interaction alone is not enough to describe the formation of a compound nucleus. Also, as discussed earlier, the nuclear interactions play an important role in the formation of a compound nucleus. The nuclear interactions are the strongest attractive interactions, though short ranged, and thus to form a compound nucleus the colliding nuclei should have sufficient kinetic energy to overcome the Coulomb barrier in order to come into the range of nuclear attraction. This can be done, depending on the kinetic energy of the colliding nuclei, either by the passing over or by the quantum mechanical tunnelling of the Coulomb barrier.
The compound nucleus so formed has charge and mass number equal to the sum of the charges and masses of the colliding partners.

Theoretically, various models have been developed to describe the above mentioned particle emission or decay process. The first model that explained the $\alpha$-decay was given by Gamow and, independently by Gurney, by applying the then newly developed quantum tunnelling. In this model, it was assumed that the $\alpha$-particle is already formed inside the decaying nucleus and that keeps on assaulting the surface of the nucleus with certain frequency ($\approx 10^{21}\text{s}^{-1}$) till it tunnels through the potential barrier of the nucleus with certain probability. This approach for understanding the $\alpha$-decay of nuclei forms the basis of almost all the models developed later for studying various ground state nuclear decays. Mainly there are two different types of models [44] based on Gamow's theory: One type of models, due to Gupta and collaborators [45-47], is known as Preformed Cluster Models ($PCM$), in which not only the $\alpha$-particle but also all the clusters of different sizes are considered to be preformed in the mother nucleus with different probabilities depending on the mass of the considered cluster. After this, the penetration of the barrier is similar to Gamow's penetration for $\alpha$-particle. In the second type of models, known as Unified Fission Models ($UFM$s), the penetration is considered without bothering about the clusters being preformed or not inside the mother nucleus. Sândulescu, Poenaru and Greiner [48] were the first to do a theoretical calculation for cluster decay by using such a unified fission model, called Analytical Super Asymmetric Fission Model ($ASAFM$). These UFMs do not carry the necessary structure information. Alternatively, the $PCM$ [45-47] contains the structure information of the decaying nucleus via the preformation factor. The $PCM$ is further developed by Gupta et al. [49-51] to the study of decay of hot and rotating compound system formed in heavy ion reactions and the model is known as the Dynamical Cluster-decay Model ($DCM$). The DCM, based on quantum mechanical fragmentation theory (QMFT) [52–54], is worked out in terms of only one parameter, namely the neck-length parameter,
which is related to the total kinetic energy $TKE(T)$ or effective Q-value $Q_{eff}(T)$ at temperature $T$ of the hot CN, defined in terms of the CN binding energy and ground-state binding energies of the emitted fragments [49].

The emission of the multiple LPs, also called light particle evaporation residue, is best understood as the statistically equilibrated CN emission in Hauser Feshbech (HF) analysis [55,56], resulting in CN fusion cross sections. Apparently, the decay process must depend on temperature and angular momentum dependent potential barriers [57]. For light compound systems with $A_{CN} \geq 40$, the above noted LP emission is always accompanied by intermediate mass fragments, the IMFs of $Z>2$ and $4<A<20$, also called “complex fragments” or “clusters”, whose contribution, though small of the order of 5 to 10%, is to be included in the CN fusion cross section. The CN fusion cross section then become equal to the sum of the cross section due to the LP emission and due to the fission-like IMF emission. It has been observed that the IMFs are emitted above a certain temperature, e.g., in the experiment of $^{58}Ni + ^{58}Ni \rightarrow ^{116}Ba^*$ [58–60], the IMFs are observed at $E_{lab} > 200$ MeV. Then, the temperature- and spin-dependent potentials must also be mass-asymmetry dependent. In other words, the structure effects of the compound system become important. In the more recent experiments of the decay of compound nuclei $^{118,122}Ba^*$, formed in the reaction $^{40}Ca + ^{78,82}Kr$ [61], all the possible fragments are observed i.e IMFs and heavy IMF’s denoted as HMF.

In order to understand the production of IMF and HMF, not only the HF analysis is extended to include the fragments heavier than $\alpha$-particle in the BUSCO code [62] or in the Extended Hauser-Feshbach scission-point model [56], but also other statistical fission model descriptions [57] have been used that are based on either the scission-point or saddle-point configuration, in the GEMINI code [55], or the saddle-point “transition-state” model (TSM) [57,63–66], respectively. Thus, the two processes of LP and IMF emissions are considered separately on two different models (the HF analysis and Fission Models). However the fission and cluster decay
are competing processes with later being more prevalent for lighter fragments [44].

Recently, Gupta et al. [49, 50, 67, 68] have proposed that the process of cluster-decay can be used to explain the IMF production and fusion-fission (ff), along with the process of multiple particle emission from the hot and rotating compound systems. Thus, in their dynamical cluster decay model (DCM), the emission of the LPs, IMFs, and ff, are treated as the collective mass motion of preformed clusters through the barrier. In terms of the barrier picture, a cluster-decay process is in fact a fission process with structure effects of the CN also included via the preformation of the fragments, but without any phase space arguments (i.e. with no level density calculations). Alternatively, the dynamical fission process has been considered by some authors [52, 53] simply as a continuous deformation of the CN [69–73].

The DCM is applied to both negative as well as for positive Q-value ($Q_{out}$) systems, with complete angular momentum and charge dispersion effects included. Interesting enough, the light particles, though treated within the same dynamical collective cauternization process, are found to possess different characteristic properties [74–76]. DCM also has the in-built characteristics of barrier modification through the only parameter of the model, the neck length parameter. Wong formula [77] is also a special case of the DCM with preformation probability $P_2=1$ [68].

It may be relevant to mention here that the nucleus-nucleus interaction potential used in the DCM is so far the nuclear proximity potential of Blocki et al. [3]. An alternative to the pocket formula of proximity potential [3], one can use the Skyrme Energy Density formalism (SEDF) [32]. In this work, we use this more microscopic SEDF as well for calculating the nuclear-nuclear interaction potential for the decay of compound nucleus formed in heavy ion reactions.

In DCM, with the temperature dependent proximity potential, the temperature effects in the proximity potential of Blocki et al. [3] are included through the nuclear radii [78] and surface width [79], and in semiclassical ETF approach of SEDF.
these are taken through the parameter of Fermi density distribution, following [80].
Thus, the temperature dependent interaction potential, calculated in the semiclassical Extended Thomas Fermi approach of Skyrme energy density formalism, is used as an alternate to the temperature dependent nucleus-nucleus interaction potential of Blocki et al. in DCM.

Also Wong formula [77] and Sharp cut-off model can be used for the calculation of fusion reaction cross-sections. It is noted that Sharp cut-off model is valid only for above barrier energies.

In this thesis, following problems are studied:

- In order to test the DCM, it is employed to analyze the recent data on decay of the compound systems $^{118,122}$Ba$^*$, at a relatively low bombarding energy of 5.5 MeV/A formed in $^{40}$Ca$+^{78,82}$Kr, using the proximity potential of Blocki et al. [3].

- The nucleus-nucleus interaction potential, calculated in Skyrme energy density functional method by using the SETF approach, is expressed in terms of the universal function of proximity potential and then an application of the resulting interaction potential and its parameterized universal functions of nuclear proximity potential to fusion excitation functions for $^{64}$Ni$+^{64}$Ni reaction is made.

- Barrier modification effects, in sub-barrier heavy-ion fusion reactions, is studied within the extended-Wong model using proximity potential obtained by using the semiclassical ETF approach in SEDF under frozen density approximation.

- Application of DCM is also made to study the decay of $^{164}$Yb$^*$, formed in $^{64}$Ni$+^{100}$Mo reaction, which is known for the hindrance phenomena in coupled channel calculations, using nuclear potential from ETF approach.
The above mentioned theoretical study in different CN mass regions, explained in later chapters, give us information on reaction mechanisms of heavy ion reactions.

1.2 Organization of the thesis

The thesis is organized as follows:

Chapter 2 describes the details of the preformed-clusters based dynamical cluster-decay model (DCM), based on the Quantum Mechanical Fragmentation Theory (QMFT) for binary fragmentation, using a collective mass transfer process. The process of binary-decay like the $\alpha$-decay and other cluster decays, is treated in two steps: First step is the quantum mechanical preformation probability of the cluster in the mother nucleus and the second step is the penetration of the cluster through the interaction barrier. In this model the preformation probability of all possible clusters within the mother nucleus is calculated. The temperature dependence of the proximity potential, Coulomb interaction potential, rotational energy and binding energies are also discussed. Details of the Skyrme energy density formalism (SEDF) of Vautherin and Brink \cite{27}, used to calculate the interaction potential between the two colliding nuclei is also described. The semiclassical extended Thomas-Fermi (ETF) approach in SEDF, which uses the density dependent Skyrme interactions, for the calculations of interaction potential in terms of the proximity potential is given. The two parameter Fermi-density with its parameters obtained from a polynomial fit to the experimental data \cite{38,39}, are used to calculate the nuclear density at zero and at finite temperatures. Furthermore, the use of the semiclassical ETF approach in SEDF to obtain the proximity potential in terms of dimensionless universal functions and their temperature dependence is discussed. Details of Wong’s formula and its extended version are also given in this chapter.

In Chapter 3, application of the DCM is made to the recent data on decay of the compound systems $^{118,122}$Ba* at a relatively low bombarding energy of 5.5
MeV/A. The same model has been successfully applied earlier to the intermediate mass fragments (IMFs) data of $^{116}\text{Ba}^*$, observed at medium and higher incident energies. For the heavier $^{118,122}\text{Ba}^*$ systems, however, a complete mass fragmentation spectrum is observed experimentally. Except for a small narrow region of heavier mass fragmentation ($8 \leq Z_L \leq 15$), the DCM gives an overall good description of the observed data on cross-sections, better than for the two statistical model calculations based on BUSCO and GEMINI codes. Furthermore, the DCM shows an interesting in-built characteristic of presenting different behaviors for different mass regions of decay products, namely, the light intermediate mass fragments (IMFs), the heavy mass fragments (HMFs) and the symmetric and near symmetric fission fragments (SF and nSF), required to be assumed in the above mentioned two statistical model calculations. In DCM, this property is assimilated via the neck-length parameter, which fixes the maximum angular momentum, used as a parameter in the BUSCO and GEMINI codes.

In Chapter 4, the universal function of nuclear proximity potential is obtained for the Skyrme nucleus-nucleus interaction in the semiclassical Extended Thomas-Fermi approach. This is obtained as a sum of the spin-orbit density independent and spin-orbit density dependent parts of the Hamiltonian density, since the two terms behave differently, the spin-orbit density independent part mainly attractive and the spin-orbit density dependent mainly repulsive. The semiclassical expansions of kinetic energy density and spin-orbit density are allowed up to second order and the two parameter Fermi density, with its parameters fitted to experiments, is used for the nuclear density. The universal functions or the resulting nuclear proximity potential reproduces the "exact" Skyrme nucleus-nucleus interaction potential in semiclassical approach, with in less than $\sim 1$ MeV of difference, both at the maximum attraction and in the surface region. An application of the resulting interaction potential to fusion excitation functions shows clearly that the parameterized universal functions of nuclear proximity potential substitutes completely the “ex-
act” potential in Skyrme energy density formalism based on semiclassical Extended Thomas-Fermi method, including also the modifications of interaction barriers at sub-barrier energies in terms of modifying the constants of the universal functions.

In Chapter 5, the nuclear proximity potential, obtained by using the semiclassical extended Thomas Fermi approach in Skyrme energy density formalism, is shown to give more realistic barriers in sudden approximation without including exchange effects, i.e., in frozen density approximation, as compared to the sudden approximation with exchange terms included. By taking advantage of the fact that, in ETF method, different Skyrme forces give different barriers (height, position and curvature), we use for cross-sections, the $\ell$-summed extended-Wong model under frozen densities approximation, where the Skyrme force is chosen with proper barrier characteristics, not-requiring additional “barrier lowering” or “barrier narrowing”, for a best fit to data at sub-barrier energies. The method is applied to the capture cross-section data from $^{48}$Ca+$^{238}$U, $^{244}$Pu, and $^{248}$Cm reactions and to fusion-evaporation cross-sections from $^{58}$Ni+$^{58}$Ni, $^{64}$Ni+$^{64}$Ni, and $^{64}$Ni+$^{100}$Mo reactions, with effects of deformations and orientations of nuclei included, wherever required. Interestingly, whereas the capture cross-sections in $^{48}$Ca+$^{238}$U and $^{48}$Ca+$^{244}$Pu reactions could be fitted to any force, such as SIII, SV and GSki, by allowing a small change of couple of units in deduced $\ell_{\text{max}}$ values. On the other hand, the fusion-evaporation cross-sections in Ni-induced reactions required different Skyrme forces for the best fit to data. In other words, just as for the pocket formula of nuclear proximity potential [15], for the ETF-based proximity potential also, no barrier modification effects are required for the Ca-based capture cross-sections in $\ell$-summed extended-Wong model, but the same are essential for the fusion-evaporation cross-sections in Ni-based reactions displaying fusion-hindrance, taken care here by the use of different Skyrme forces for different reactions. Note, however, that no single Skyrme force was able to reproduce the data simultaneously for all the above mentioned three Ni-based reactions, though more than one Skyrme force could fit equally well the
same data.

In Chapter 6, the decay of hot and rotating compound nucleus $^{164}$Yb*, formed in heavy ion reaction $^{64}$Ni+$^{100}$Mo at both below- and above-barrier energies, is studied on the basis of the DCM, with the semiclassical extended Thomas Fermi approach in Skyrme energy density formalism with Skyrme force SIII and GSkI used for calculating nuclear proximity potential under frozen approximation of addition of densities for compound system, with effects of deformations and orientations of nuclei included in it. The effect of Skyrme forces on barrier modification is also studied. There is only one parameter in this model, namely, the neck-length parameter, which varies smoothly with temperature of the compound nucleus at both below and above-barrier energies, and its value remains within the range of validity of proximity potential. The emission of light particles ($x\pi$, $x$-neutrons, $x=1-4$) as well as the energetically favored symmetric fission (SF) channel ($(A/2) \pm 17$), are considered as the dynamical collective mass motions of preformed fragments or clusters through the barrier. The SF, constituting the fusion-fission ($ff$) cross-section, contribute only at above-barrier energies, and is compatible with the CASCADE analysis of experimental data. A best fit to data is obtained for two different neck-length parameters, one for light-particles (LPs) and another for all other decay channels, the $ff$ cross-section. The barrier height corresponding to the neck length parameter for LPs, gives “barrier lowering” in a straight-forward way for the best fitted fusion-evaporation cross-sections in DCM with Skyrme force SIII and GSkI, and, contrary to the (statistical model) analysis of experimental data, results in largest contribution for In emission. A further study is called for both the LPs and $ff$ channels.

Finally, Chapter 7, presents a summary and outlook of the work.
Bibliography


