Chapter 1

Introduction

The discovery of radioactivity in 1896 heralded a new era in the study of physics, the dawn of nuclear physics. The atom was no longer considered indivisible. It was understood that the atom was made up of smaller particles which rearranged themselves spontaneously in radioactive transformation. In 1911, Rutherford conducted a series of experiments in which he bombarded a piece of gold foil with positively charged particles emitted by radioactive material and showed that atom consists primarily of empty space surrounding a well defined central core called "nucleus" with a radius of about 10^{-12} cm. The discovery of neutron in 1932 by Chadwick led Heisenberg to suggest that nuclei are made up of protons and neutrons. Thus the nuclear physics as we know today dates back to no further than 1932. The forces that hold a nucleus together cannot be ordinary electrostatic forces since the (electrically neutral) neutrons are bound in the nucleus. The nuclear forces, unlike the forces which hold an atom together have no analogy in classical physics. The fundamental step in the exploration of nuclear forces was taken by Wigner who showed that they must have a short range of action but must be very strong within that range. Heisenberg and Majorana showed that the nuclear forces must be saturated which means that not all pairs of nucleons within a nucleus can exert attractive force upon each other.

After the discovery of radioactivity which is a spontaneous process, the next step was almost ordained, that is the deliberate rearrangement of the constituents of the nucleus in a nuclear reaction. In 1919 Rutherford was able to demonstrate that alpha particle could knock proton out of nitrogen nuclei and fuse with what was left. It follows then that Rutherford had successfully carried through the first man made nuclear reaction.

$$^{14}\mathrm{N} +^{4}\mathrm{He} \ = \ ^{17}\mathrm{O} +^{1}\mathrm{H}$$

Later he carried out a number of other reactions involving alpha particles. However he was limited because of the unavailability of other energetic particles. Thus was born the idea of particle accelerators. The first particle accelerator, the Cock-croft Walton device was accomplished in 1929. Since then there has been tremendous growth in the development of heavy ion accelerators which has been aptly matched by the development in the detection techniques, leading to an immense growth in our understanding of nuclear physics.

During the past decades, a major research effort has gone into the study of nuclei by means of probes which excite them in a moderate way mainly by bombardment with light ions such as protons, neutrons and alpha particles. This investigation has unraveled the richness of nuclear phenomena. However, when two heavy systems are brought in contact in a heavy ion collision one is entering a totally new regime of nuclear physics. The availability of precise beams of almost any species has opened up new horizons in the study of heavy ion physics. The reactions involving heavy ions tend to differ from the light ion induced reactions in many ways. Though there is no well defined borderline between light and heavy ions, the α particle has sometimes been referred to as the "lightest heavy ion". The features that characterise heavy ion induced reactions are enumerated below :

1. The Coulomb interaction plays a much more important role, especially when one is concerned with lower energies where the effects of nuclear structure are most likely to manifest themselves.

2. The de Broglie wavelength associated with the relative motion of the inter-

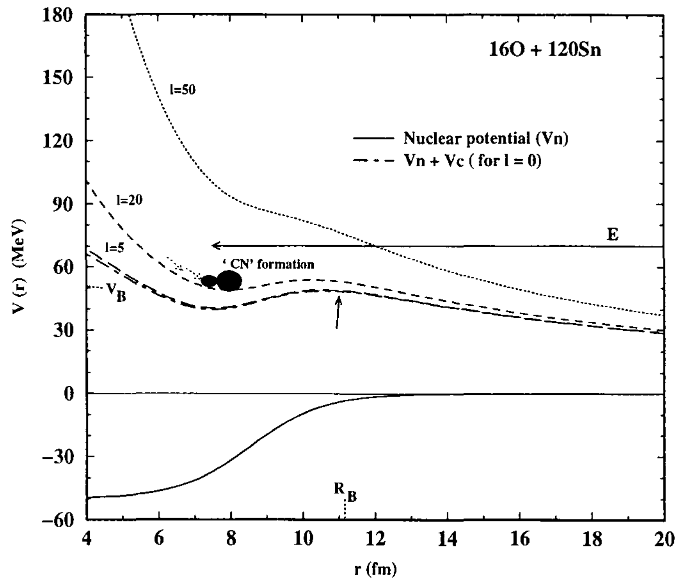

Figure 1.1: The effective potential $V(r)$ for the system ^{16}O + ^{120}Sn. The effective potential for different values of ℓ is shown, also shown is the nuclear potential (Woods-Saxon form). The arrow marks the interaction barrier. V_B and R_B indicate the height and position of the Coulomb barrier.

acting ions is much shorter than for the light projectiles, typically an order of magnitude smaller than the size of the nuclei. Thus classical approximations tend to have more validity.

3. Because of its large mass, the angular momentum of a heavy ion with respect to the centre of mass is very large.

4. Since a heavy ion is a multi nucleon system, the probability of a reaction taking place is increased very rapidly. In a very crude picture one would argue that the mean free path of a heavy ion of **A** nucleons in nuclear matter should be $\approx \frac{1}{\mathbf{A}}$ times the mean path of a nucleon with the same velocity.

In any nucleus-nucleus collision the dynamics of the reaction is strongly governed by the ion-ion potential. Understanding of the nucleus-nucleus potential is thus important in the study of heavy ion collisions as the potential contains information

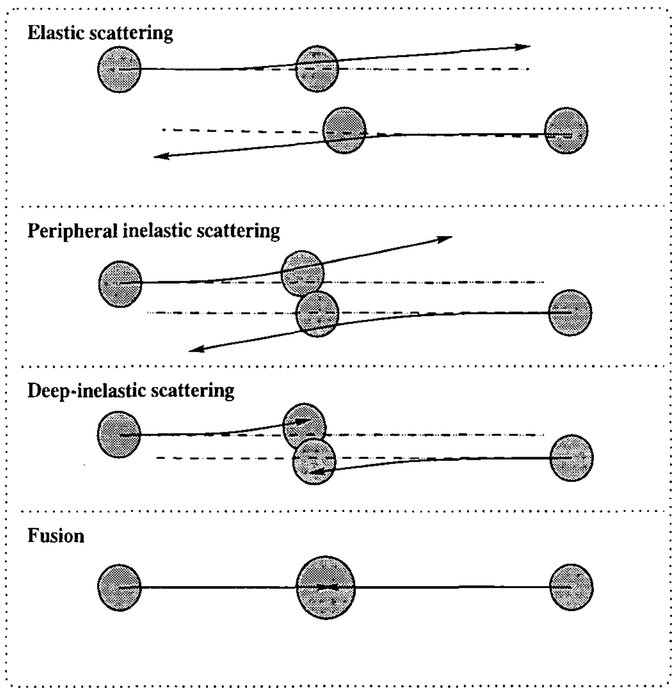

Figure 1.2: Examples of the kinds of nuclear interactions that occur in collisions at different values of the impact parameter, **b**. The impact parameter describes how close to head on (b = 0) the collision is.

about the nuclear matter distribution and the nucleon-nucleon interaction. When the nuclei are separated by a distance more than the range of the nuclear interaction, the inter-nuclear interaction is purely Coulombic. On the other hand, when they have sufficient overlap of the nuclear matter, the attractive nuclear potential comes into picture. Thus the total potential is the sum of the Coulomb and the nuclear potentials. Apart from this there is a centrifugal potential which also contributes to the total. The total or 'effective' potential governing the radial motion for an interacting system is shown in Fig. 1.1. As can be seen, there exists a barrier in the total potential, referred to as the interaction barrier. The barrier for the ℓ=0 partial wave is called the Coulomb barrier, V_B at a distance R_B. The effective potential, in general, is characterised by strong absorption, large Coulomb barrier and a potential pocket interior to the Coulomb barrier for most of the significant partial waves. The position, height and curvature of the potential barrier are important in characterising the different aspects of the nucleus-nucleus collision.

A great variety of phenomena can arise in heavy ion collisions which depend on the properties of the two nuclei and the relative motion energy of the interacting system. Broadly speaking, the relative contributions of these processes to the total reaction cross section depends on the velocity or energy per nucleon of the system. If the energy is low, the time required for the two nuclei to cross each other is more than the average time of particle collisions inside the nucleus (10^{-22}sec) and so the incident particle is absorbed. The incident energy and momentum is distributed among all the nucleons. This leads to the formation of a highly excited compound nucleus. In contrast to this at high energies, the incident particle interacts with some constituents of the target nuclei only. Such reactions are called direct reactions and are accompanied by the excitation of few degrees of freedom. Both direct and compound nuclear reactions are the limiting cases, in reality there may occur reactions of intermediate nature.

Keeping in mind the "near classical nature" of heavy ion reactions, one can easily classify the types of reactions in terms of a quantity called the impact parameter, "b" (Fig. 1.2), which is the perpendicular distance between the centre of force and the direction of the incident particle. The quantity 'b_{gr}' is defined as the impact parameter for a grazing trajectory where the the two nuclei just start touching. For values of $b > b_{gr}$, the particle interact only through the repulsive Coulomb force. In such distant collisions one observes only elastic scattering and Coulomb excitation. For $b \approx b_{gr}$, the tails of the nuclear wave functions start overlapping. The effect of the nuclear interaction is felt and peripheral reactions like few nucleon transfer and excitation of collective modes are observed. For close collisions, $b < b_{gr}$ the nuclear attraction overtakes the Coulomb repulsion and more prolific reactions like deep inelastic scattering occur where there is a substantial conversion of incident energy to heating of the nucleus. Finally, an approximately head-on collision (very small

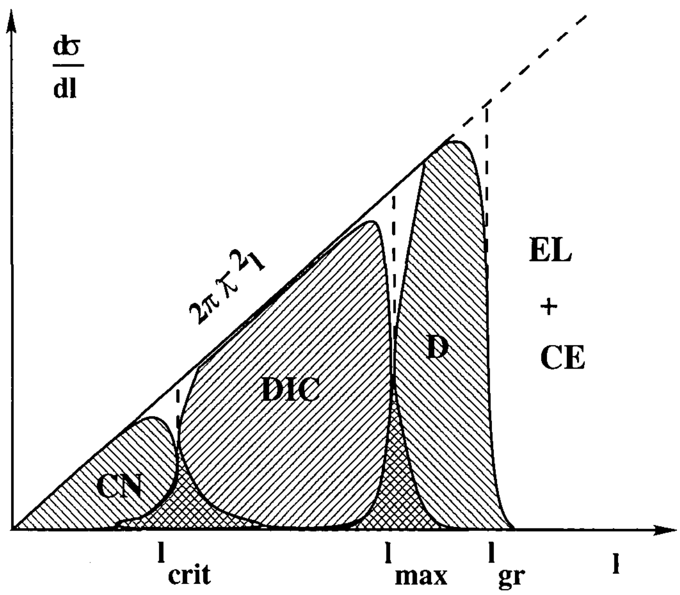

Figure 1.3: Schematic illustration of the ℓ dependence of the partial cross section for compound nucleus (CN), deep inelastic collisions (DIC), direct (D), Coulomb excitation (CE) and elastic (EL) processes. The straight line represents the geometrical partial cross section $d\sigma/d\ell = 2\pi\lambda\!\!\!^{-2}\ell$. Vertical dashed lines indicate the extensions of the various ℓ windows in the sharp cut off model.

impact parameter) can cause the colliding nuclei to fuse, forming a single "compound nucleus" that lives long enough for the nucleons to reach a totally equilibrated system. In any heavy ion interaction, all impact parameters are possible leading to different kinds of reaction products and each partition of the interaction is referred to as a "reaction channel". The channel serves to define the asymptotic state of the system of colliding partners far away from the region of interaction both before and after the collision called entrance and exit channel respectively. Though in principle many exit channels may be possible only those energetically allowed are 'open', rest are closed channels.

The reaction cross-section σ_R can be given in terms of the critical impact parameter b_{gr} where the nuclear reactions start as,

$$\sigma_R = \pi b_{gr}^2 = \pi R_B^2[1 - \frac{V_B}{E_{c.m.}}]$$

where V_B is the barrier height and R_B is the position of the barrier. The decomposition of the reaction cross section with respect to the impact parameter is usually displayed by considering the differential with respect to 'b' or equivalently with respect to $\ell(= kb)$

$$\frac{d\sigma}{d\ell} = k^{-1}\frac{d\sigma}{db} = \frac{2\pi\ell}{k^2}$$

where 'k' is the asymptotic wave number. The partial cross section, $d\sigma/d\ell$ as a function of ℓ is plotted in Fig. 1.3. The straight line is the unitarity limit. As can be seen from the figure the different regions overlap in ℓ, however the extent of the overlap is not known clearly.

The energy region around the Coulomb barrier is very interesting because of many open reactions channels like elastic scattering, inelastic scattering, transfer and fusion. There is a strong interplay between these channels leading to interesting observations. Elastic scattering takes place in the presence of many open reaction channels. The very presence of these open reaction channels, the sum total of which is related to elastic scattering by the quantum property of unitarity, causes substantial depletion of flux in the elastic channel. This absorption being strong over most of the interaction region with a rather well defined surface is called quantal diffraction which drastically modifies the semi-classical behaviour of the scattered wave. The classical scattering can be best described by the deflection function which connects the impact parameter 'b' and the scattering angle 'Θ' and is given by

$$\Theta(b) = \pi - 2\int_a^\infty \frac{b}{r^2\sqrt{1 - \frac{v(r)}{E} - \frac{b^2}{r^2}}}dr$$

The classical scattering cross section is given by

$$\frac{d\sigma}{d\Omega} = \frac{b}{sin\theta|d\theta/db|}$$

The deflection function for a partly attractive and partly repulsive potential is given in Fig. 1.4. Most of the interesting features of the scattering process can be inferred from this.

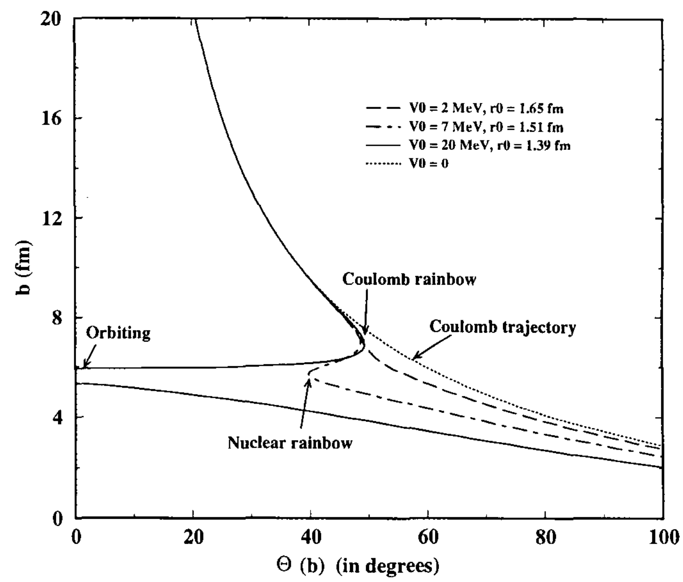

Figure 1.4: Typical deflection function for partly repulsive and partly attractive forces. (^{16}O + ^{58}Ni at E_{lab} = 60 MeV) The deflection functions were calculated using Woods-Saxon potentials having the same diffuseness a_R=0.6 fm but different values of the real potential V_0 and radius parameter r_0. The values are indicated in the figure. When the nuclear attraction is weak, the deflection function is only slightly changed from the Coulomb; in case of strong nuclear interaction a maxima occurs in the deflection function causing a singularity in the classical cross section known as rainbow scattering; if the nuclear attraction is so strong as to compensate the Coulomb plus centrifugal potentials for a given ℓ, orbiting occurs and the deflection function tends to have negative angles.

Here we will discuss some of the intriguing features of heavy ion fusion reactions at energies around the barrier as it forms the object of study of this thesis. The possibility of inducing complete fusion of heavy nuclei has been a particularly fascinating aspect of heavy ion research for many years. Large scale efforts in this field have been motivated by the desire to synthesise new nuclear species "the super heavy elements" beyond the known region of stable or radioactive nuclide. Another unique aspect of fusion with heavy projectiles is associated with the high angular momentum which can be imparted to the compound nucleus. This offers the possibility to study nuclear states in the vicinity of the "yrast line". Fusion is generally identified with the trapping of the interacting system in the pocket of the effective potential for a sufficiently long time so that the two nuclei fuse to form a equilibrated compound system. The fusion cross section σ_{fus} as a function of the projectile energy E generally increases until it reaches a maximum and remains constant and then begins a slow decline as the projectile energy increases further. This is due to the fact that there is a critical angular momentum above which fusion does not occur because of the disappearance of the pocket in the potential curve.

At bombarding energies below the Coulomb barrier, complete fusion is classically forbidden but still can occur due to the quantum mechanical tunneling. This process has been studied extensively for light projectiles to as low energy as 40 % below the barrier. For heavier systems not only higher bombarding energies are necessary, but the cross sections are also expected to decrease more rapidly with decreasing energy below the barrier. The physical motivation for studying low energy fusion cross section has been largely provided by the astrophysical implications. Another important aspect of sub-barrier fusion, which is related to the astrophysical application, but of more general significance, is the possibility to deduce information on the nucleus-nucleus potential. At a given incident energy and angular momentum the probability of penetration through the potential barrier will depend both on the height and on the shape and position of the barrier. One may therefore hope to obtain by measuring sub-barrier fusion excitation functions precisely over a large energy range, a rather detailed mapping of the potential barrier and hence the nuclear potential.

Measurement of sub-barrier fusion of heavy ions is experimentally difficult because of the low cross sections involved. Still pioneering studies have been carried out during the past years overcoming these difficulties [1, 2]. The experiments have been extended to energies very much below the classical Coulomb barrier and the cross sections measured span up to six orders of magnitude from few hundreds of millibarns down to sub-microbarn level. In order for two nuclei to fuse together it is necessary to achieve sufficient overlap of the nuclear matter so that the attractive nuclear force can offset the repulsive Coulomb potential. At sub-barrier energies this large overlap suggests that fusion can be associated with a simple local potential barrier penetration process. From the vast amount of experimental data collected for a wide range of target and projectile combinations the following inferences emerged:

1. more sub-barrier fusion (by orders of magnitude) was observed than that could be associated for in terms of a simple one dimensional barrier penetration picture (Fig. 1.5).

2. there were pronounced variations among excitation functions for fusion of neighbouring nuclei. Even in the fusion of a series of isotopes with a common projectile, the cross sections showed a systematic variation.

3. the associated angular momentum distribution was broad extending to very large ℓ's .

These differences were more pronounced for heavy and symmetric systems.

It became clear that the simple picture of tunneling in a one dimensional potential involving only the radial separation is highly unrealistic and underestimates the sub-barrier fusion cross-sections by orders of magnitude. Thus one has to go beyond the one dimensional potential model to reproduce the data. This was demonstrated in a work by Balantekin [3] in which an effective one-dimensional potential was extracted directly from the fusion data. The potential obtained for heavy systems has a inner edge with a negative slope which is unphysical. Thus the data cannot be fitted by manipulating the parameters or forms of the potentials. One has to think in terms of additional degrees of freedom like shapes of the nuclei or inelastic excitations and quantum tunneling in this multi-dimensional configuration space. Another way to look at the same effect is in the form of coupled channels framework, where it is proposed that the two nuclei at the time of fusing need not be in their ground states

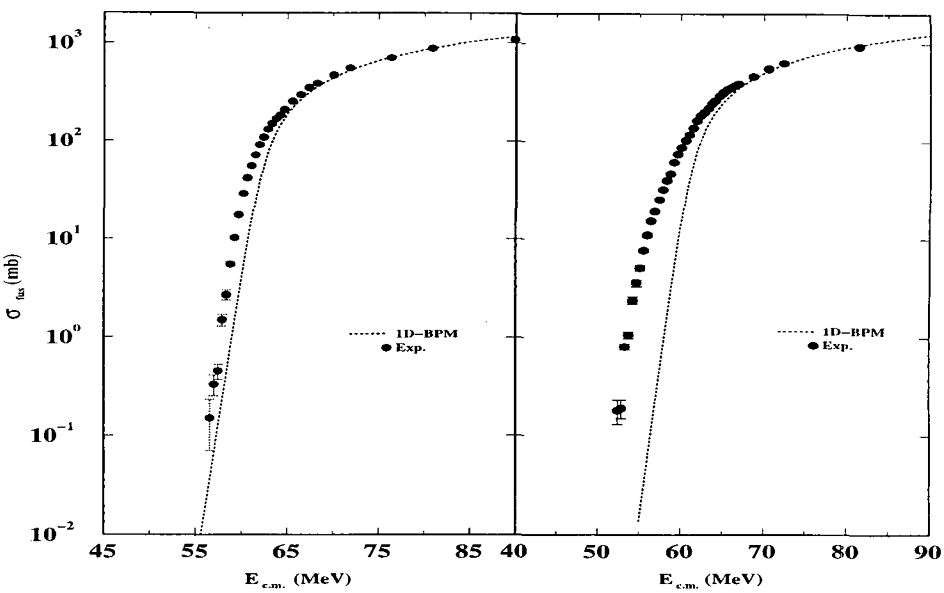

Figure 1.5: Experimental fusion cross sections for the systems ^{16}O + $^{144,154}Sm$ [8] shown along with the predictions of the one dimensional barrier penetration model (1D-BPM). The failure of the 1D-BPM is clearly visible. Also the 'isotopic dependence' can be seen in this case *i.e.* more enhancement for the heavier isotope.

but in a quantum state which is a linear combination of the excited states of the two nuclei. This is the basis of the coupled Schrödinger equations.

The systems ^{16}O + $^{148,150,152,154}Sm$ were studied by Stokstad [2] in 1980 and it was found that the cross sections increased as the neutron number of Sm increased. He suggested the increasing static quadrupole deformation of the Samarium isotope to be responsible for the measured enhancement. Here the target is prolate deformed, the interaction barrier will depend on the orientation of the deformed nucleus relative to the direction of approach of the reaction partner. If the approach is along the axis of symmetry of a prolate deformed nucleus, the barrier is lowered and fusion is enhanced. If the approach is along the direction perpendicular to the symmetry axis then the barrier is increased and fusion is reduced. The net effect of this on the barrier transmission at sub-barrier energies is to enhance the cross section. This is a particularly simple and physically transparent example of the effect of coupling to another degree of freedom (nuclear shape degree of freedom) to the relative motion in the entrance channel. Quantum mechanically this is equivalent to the coupling of the ground state to the rotational states of the deformed nuclei.

The comparison of experimental excitation functions for symmetric systems reveals another possible origin of the sub-barrier fusion enhancement. To understand this, it may be assumed that the enhancement is entirely caused by the nuclear structure of the colliding nuclei. If it is presumed that the contributions to the enhancement of the two nuclei are independent from each other, the excitation function for the system A + B should be an average of the excitation functions of the symmetric systems A + A and B + B, where A and B are the reactants. This has been tested for the isotopes ^{58}Ni and ^{64}Ni [1]. All three possible combinations of these two isotopes show sub-barrier fusion enhancement. However, the excitation function for the asymmetric system has not been found to be an average of the two excitation functions for the symmetric systems, but in fact, exceeds both considerably. This comparison shows that some mechanism is responsible for a part of the enhancement in which the two reactants are not independent but interact with each other. Since the symmetry in neutron to proton ratio for the ^{58}Ni + ^{64}Ni favours transfer of neutrons from the heavier to the lighter isotope, it suggests that neutron flow or particle transfer in general may provide a path for fusion.

Thus the data suggest that the important channels among the additional degree of freedom are associated with rotational and vibrational excitations of the nuclei and particle transfer between the nuclei. However inclusion of any additional degree of freedom leads to qualitatively the same modifications of the sub-barrier cross section. Therefore as long as we do not perform entirely parameter free calculations, any inference from a fit to the data as to the relevance of that particular coupling remains questionable. That is, of course, not surprising considering the rather structure-less shape of the fusion excitation functions.

Quantum tunneling through a potential barrier is a very general problem in physics. The motion of particle which is a part of many particle system tunneling through a barrier will be affected by the environment formed by the other particles. This coupling to other degrees of freedom of a many body system can both aid or hinder the tunneling process. If the number of degrees of freedom is limited or some of them are dominant with respect to others, then the Hamiltonian describing the motion may be truncated to include only the strong coupling. The sub-barrier fusion problem presents such a scenario. The reaction channels apart from fusion like inelastic excitations and transfer couple strongly to the entrance channel and enhance the tunneling probability. This can be treated elegantly in the coupled channels formalism [4, 5]. Here the Hamiltonian is modified to include a coupling interaction. The Schrödinger equation is solved with the ingoing wave boundary conditions. The effect of coupling is to replace the single one dimensional barrier with a spectra of "n+1" barriers of different heights and positions where "n" is the number of channels coupled. It can be shown, that there is at least one barrier which is below the uncoupled barrier. It follows then that it is tunneling through these low energy barriers which is responsible for the sub-barrier enhancement.

It was realised by Rowley [6, 7] that it was in principle possible to obtain direct information on the distribution of barriers by taking the second derivative of the product of the centre of mass energy E and σ_{fus} with respect to energy. It was shown in their paper that

$$D(B) = \frac{1}{\pi R_B^2} \frac{d^2(E\sigma_{fus})}{dE^2}|_{E=B}$$

would essentially give the underlying distribution of barriers D(B), smoothened over a energy range of about 2 MeV by quantal barrier penetration effects. It is relatively easy to show that the width of the distribution should be of the order of the coupling strengths. This showed that little specific information could be obtained for weak couplings whereas for strong couplings detailed structure information might be obtained. Obviously one needs rather high precision data to be able to numerically calculate the second derivative of the excitation function. However soon such

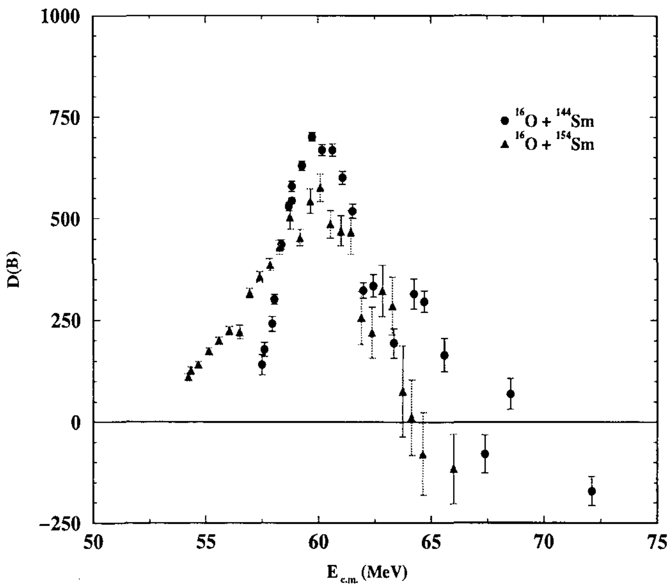

Figure 1.6: Barrier distribution for the systems ^{16}O + $^{144,154}Sm$ [8] extracted from measured fusion cross sections for these systems. The barrier distribution is vastly different for the two systems thus acting as a 'fingerprint'.

high quality data became available. The results [8] revealed that the 'experimental barrier distribution' could be qualitatively different providing a 'fingerprint' of the relevant coupling (Fig. 1.6). The existence of such clear fingerprints is an extremely important result, and has initiated lot of work in this direction.

The extraction of barrier distribution requires high precision data, however even with a high precision it becomes difficult to get a meaningful distribution at higher energies as the errors on the second derivative grow with energy. Alternative methods were sought of where the error could be reduced. It was suggested that information about the barrier distributions may be contained in the quasi-elastic scattering excitation functions at backward angles. Timmers *et al.,* [9] presented a method to extract a representation of the fusion barrier distribution from quasi-elastic excitation function. They found that although this representation of the quasi elastic-scattering data indeed shows the general features of the fusion barrier distribution, its sensitivity is reduced at higher energies. More recently it has been shown that the effects of strong coupling are present in the barrier distributions from the elastic scattering, but are smoothened out since different eigen barriers have phase differences. Furthermore the effects are also smoothened by weak coupling, which appear in first order in the elastic scattering but only in the second order in fusion cross section.

The coupled channels calculations and the concept of barrier distribution has been extremely successful in explaining the data for light and asymmetric systems. The analysis of fusion data in these systems displayed the rich interplay between reaction dynamics and nuclear structure. The nuclear structure effects coming in play in the fusion process could be pin pointed. The specific effect of vibrational coupling, rotational coupling or nucleon transfer could be deciphered. Indeed for light and asymmetric systems the basic framework of the coupled channel calculations is justified. Here the Coulomb potential is relatively weak and so the barrier is formed at a large radial separation where the two nuclei do not touch each other. Hence while tunneling through the barrier the individual nuclei preserve their character and one can talk about coupling of the states in the nuclei to the tunneling process. As the experiments were extended to heavier and more symmetric systems large discrepancies were observed. These can be related to basically two effects, the approximations that went into the simplified coupled channels calculations used for the analysis and the neglect of other effects like neck formation which may play an important role here.

The analysis of the ^{58}Ni + ^{60}Ni system measured by Stefanini *et al.,* [10] unmasked the limitations of the simplified coupled channels calculations which were successful in explaining the experimental data like the ^{16}O + ^{144}Sm case. The main approximation of the simplified approach was that the coupling potential was included to first order only in the linear coupling approximation. Moreover the model space for the surface vibrational degree of freedom was included up to one phonon level only. It is reasonable to doubt that such type of restricted basis would be able to describe the evolution of two heavy strongly coupled nuclei towards the fused state. The barrier distribution for the ^{58}Ni + ^{60}Ni was a three peaked structure and it required all order coupling up to the mutual double excitation of the quadrupole states of the target and projectile in order to explain the data.

Thus the coupled channels calculations have been successful in describing the fusion of light systems reasonably well, however as the systems get heavier the coupled channels description becomes less accurate. A problem arising in the coupled channels description has to do with the expansion of the nuclear potential in terms of the deformation parameters in order to obtain the coupling potential. Usually only the terms linear in the deformation parameters are taken into account. It was however shown by Esbensen and Landowne [11] that second order terms play a non-negligible role in describing the fusion excitation function. This raises the question of the convergence of the potential. Full coupled channels calculations have been performed by Hagino *et al.,* [12] including coupling to all orders and taking into account the finite excitation energies of the different excited states. Such calculations give better agreement with the experimental data in contrast to the simplified calculations [13].

A key input to any coupled channels calculation is the parameters defining the nuclear potential between the interacting nuclei, which is generally taken to be of Woods-Saxon form. These parameters are obtained by fitting the high energy fusion data using a single barrier. The calculated cross sections at these energies are very sensitive to the average barrier height and position but are relatively insensitive to the form or magnitude of the coupling. However, since there exists some sensitivity of the calculated high energy fusion cross sections to the couplings [8], the parameters may not be realistic. Also one should realise that fusion probes the potential at distances much closer to the fusion barrier radius, where the information derived from elastic scattering analysis may not be accurate. A striking feature of the parameters extracted from such fits is the large value of the diffuseness parameter, 'a', compared with the average value of 0.65 fm extracted from elastic scattering data [14]. This inconsistency demonstrates the problem inherent in considering specific channels in isolation [8, 15]. Only when all relevant channels are considered simultaneously in a full coupled channels calculation, that the 'bare' interaction potential can be calculated. Some difference in the value of 'a' is expected on the basis of the different treatment of higher partial waves associated with peripheral reactions in the fusion and elastic scattering process [8]. The fusion potential must scatter such partial waves to prevent them from contributing to the fusion cross section, while for scattering these high partial waves must pass over the barrier and be absorbed to prevent them from appearing in the elastic channel. So the barrier should be higher for the high partial waves in the case of fusion while for elastic scattering it should be lower. The diffuseness parameter determines how the barrier heights vary with angular momentum and a large value of 'a' gives a barrier which increases rapidly with ℓ, which is consistent with the requirement of high barrier for large ℓ for fusion. Further work is required to determine the diffuseness of the nuclear potential appropriate to the analysis of precise fusion data [16].

Another aspect which needs to be considered is the role of multi-nucleon transfer. As mentioned before particle transfer mainly neutrons is one of the cause of the observed sub-barrier enhancement. In the weak coupling limit, such channels can be modelled by fictitious inelastic states, but multi-nucleon transfer as has been observed in the ^{40}Ca + ^{96}Zr [17] case has a large effect on the reaction dynamics. The reduction of the lowest barrier may be so dramatic that it becomes appropriate to think of the formation of a neutron neck. In such cases more detailed calculations or the construction of some appropriate macroscopic model may be required. The coupled channels calculations as of now do not treat nucleon transfer in a satisfactory manner. In general, the number of reaction channels rises when the size of the system increases. In particular increasingly more transfer channels become accessible in heavier systems. One may therefore, expect the number of fusion barriers to multiply when the product Z_pZ_t increases, so that eventually individual barriers are not resolved. This is where 'microscopic' channel coupling and 'macroscopic' neck formation may be expected to be equivalent. Thus the understanding of the effects of multi-neutron transfer on the fusion process should be crucial in identifying this correspondence between the 'microscopic' and 'macroscopic' aspects of heavy-ion fusion.

We have come a long way from the first observation of sub-barrier fusion enhancement. In the past years considerable progress have been made both in terms of high precision experiments and more accurate coupled channels calculations to explain the data. Still a consistent picture is yet to emerge which would be valid over a wide range of target and projectile combination. There remain many open problems like the role of transfer in the fusion process and the lack of unambiguous identification of the coupling scheme. The recent analysis of the ^{16}O + ^{208}Pb data has posed such a problem [16]. In this case coupling to the single- and 2-phonon states of ^{208}Pb correctly taking into account the excitation energy and the phonon character of these states, particle transfers, and the effects of varying the diffuseness of the nuclear potential, were all explored. However, no satisfactory description of the experimental barrier distribution and fusion excitation function could be obtained. In view of the good quality of the data and the detailed calculations performed the disagreement between theory and experiment indicates that we have not yet uncovered the intricacies of the dynamics of the heavy ion fusion process. The effort now should be to perform high precision experiments to isolate individual effects and analyse the data comprehensively to get a complete picture of the fusion process.

In the light of what is said above we report in this thesis measurements which are an effort to understand the fusion mechanism for heavy ions. The idea was to study systems where specific effects could be analysed without ambiguity like coupling of multi-phonon states and qualitative identification of the role of transfer coupling in the fusion process. One of the main emphasis of this work was to perform the experiments with a high level of precision, the high quality data thus obtained can be a good testing ground for the different theoretical predictions. We have analysed our data in the framework of the exact coupled channels calculations. The measurements that we have performed are the fusion cross sections for the systems ^{37}Cl + ^{116}Sn, ^{16}O + ^{112,116}Sn and ^{32}S + ^{112,116,120}Sn. The energy range covered the region around the Coulomb barrier roughly 10 % above to 10 % below the barrier. From the measured cross sections the second derivative was extracted which is related to the barrier distribution. We have also attempted to extract the fusion barrier distribution from back angle quasi-elastic scattering data. We measured quasi-elastic excitation function for the systems ^{16}O + ^{120}Sn and ^{32}S + ^{120}Sn. Our measurements for quasi-elastic scattering were performed at the extreme back angle of 180°. There is a need to measure extreme back angle cross sections as then the distortions (oscillations) due to Fresnel diffractions effects are minimised. Such oscillations are very prominent for relatively lighter systems which have smaller Sommerfeld parameters.

In all our measurements we have concentrated on Sn isotopes, the reason for that being their ambiguous behaviour. In the fusion of Sn isotopes with different projectiles it was observed that there is no isotopic dependence [18, 19] which is at variance with other systems where strong isotopic dependence was seen. From the isotopic studies available in literature generally the heaviest target shows more enhancement. In the majority of cases studied, across an isotopic series the target deformation increases while the neutron separation energy decreases with the isotopic mass. Smaller values of neutron separation energies lead to relatively more positive Q-value neutron transfer reactions. Both these factors are found to enhance fusion. Though there may be ambiguities as to the reason, whether collective vibrations or neutron transfer or flow, there is a strong isotopic dependence observed in most of the cases with the heavier isotope showing more enhancement. In the case of Sn isotopes there are no major differences in either the energy levels or the deformation values for the different isotopes. All the isotopes are spherical with similar shell structures, the lowest quadrupole and octupole states are collective in nature and may be expected to play a similar role in the fusion dynamics. There is some experimental evidence of multi phonon states also in these isotopes, the role of which can also be investigated. Since the Sn isotopes are very similar in nature, strong isotopic dependence is not expected, to look for the subtle differences we performed the ^{16}O + ^{112,116}Sn measurement. Here the projectile does not play an active role in the fusion process hence any small difference in the two systems may be deciphered by comparing the barrier distribution for the two systems. The absence of any positive Q-value transfer channels in these systems makes the comparision quite straight forward. One can easily establish whether at all there is any difference in the vibrational coupling in these systems. In order to see the effect of positive Q-value neutron transfer channels we studied the systems ^{32}S + ^{112,116,120}Sn, here we can look for isotopic dependence in the presence of transfer channels. The system ^{32}S + ^{120}Sn is particularly interesting to study as it has many +Q-value transfer channels. It offers the possibility of studying the effect of multi-neutron transfer on the fusion process and the shape of the barrier distribution for this system will be a clear indication as to how these transfer channels affect the fusion process. The other system studied ^{37}Cl + ^{116}Sn, offered the possibility to study the influence of proton transfer channels, whether they affect the fusion process or not.

The quasi-elastic scattering cross sections were measured for the systems for which the fusion excitation function was also measured. Our motivation here was two fold, one was to study the feasibility of measuring 180° scattering cross sections and secondly to see how closely the barrier distribution extracted from quasi-elastic data follows that extracted from the fusion data.

The experimental work reported in this thesis work has been carried out at the Nuclear Science Centre, New Delhi, using the heavy ion beams provided by the 15

UD Pelletron accelerator. The recoil mass separator HIRA (Heavy Ion Reaction Analyser) has been used in the fusion and quasi-elastic scattering measurements.

The organisation of the thesis is as follows;
The Second chapter discusses briefly about fusion reactions in general and sub-barrier fusion in particular. Different models put forward to explain the sub-barrier fusion enhancement are briefly described in this chapter. A brief account of the ion-ion potential is also given. Chapter 3 deals with the coupled channels formalism used in explaining the sub-barrier fusion data. The coupled channel formalism used in this work is briefly explained here, with some details of the computer codes CCMOD and CCFULL. Chapter 4 discusses the concept of barrier distribution and how it can be extracted from experimental data. Some of the important measurements and the success of coupled channel calculations in explaining the data are also reviewed. Chapter 5 discusses the experimental techniques used in the present work for the measurement of the relevant observable. The details of the experiments performed are given in this chapter. Data reduction methods and results are given in the Chapter 6. Details of the coupled channel calculations and analyses are discussed in the Seventh Chapter. Chapter 8 gives a summary of all the measurements and concludes the thesis with the important inferences, open problems and future outlook.

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