Chapter 1

Introduction

Contents

1.1 Overview of Nuclear Reaction Models

It is now well established, that a nuclear reaction is not a simple and well-defined,single-stage or two-stage phenomenon but on the contrary it is, in general, a complicated multi-step process [1]. The traditional single-stage "direct reaction" and the two-stage "compound nuclear reaction" are just the two extreme cases of otherwise very complicated and "long" process of nuclear excitation in which either a very small or a very large number of degrees of freedom can be excited during the projectile-target interaction. If we consider the nuclear excitation process in detail, we find that it proceeds by a series of stages in which successively more and more nucleons are excited. At each stage, there is a definite probability that the reaction will proceed at once to the final state.

Fast direct reactions are expected to take place at very high energies where the incident particle wavelength is no more than the size of a nucleon. Direct reactions in nuclear physics are scattering reactions with a peaked angular distribution for the scattered particle, characterized by typical forward-peaked diffraction like pattern and a small energy transfer to the target nucleus. At comparatively lower energies, similar characteristics are observed in the other direct reactions like stripping, pickup and inelastic scattering. Direct reactions may be very well understood in most cases by the optical model for elastic scattering and by the various distorted wave Born approximation theories for other reactions [2,3].

At still lower energies, the compound nuclear reactions dominate [4]. This other extreme type of reaction, proceeding through a large number of intermediate states of the compound nucleus, can be treated very well by statistical theories, of which the most successful is that due to Hauser and Feshbach [5], with several later refinements. Here the projectile wavelength being much larger than nuclear dimensions, the incident particle energy is distributed over so many nucleons at the very first projectile-target collision that none of the excited nucleons has enough energy to escape the system immediately and a statistical equilibrium is reached due to strong interactions between the nucleons. Subsequently after a relatively long time, on nuclear time scale, particle are emitted by the process called "evaporation", which is analogous to the evaporation of molecules from a heated liquid drop. The energy spectra for such reactions are Maxwellian and angular distributions of the emitted particles are symmetric about 90° in compound nuclear reactions.

In the decade of 1980 and thereafter, there were great advancements made in the area of accelerator technology and nuclear radiation detectors, which brought a drastic change in the area of nuclear reactions. Variable

energy accelerators capable of delivering a variety of particles beams up to very high energies and high resolution semiconductor detectors provided an excellent scope for research in the study of various nuclear properties.

One such study, quite often made, is that of the variation of reaction cross-section with bombarding energy, widely known as the "Excitation function" for the particular reaction. While it helps to optimize the production of useful radioactive isotope by maximizing the yield of the desired product and minimizing the radioactive impurities, it also contains very valuable information on the time-scale and mechanism of the reaction. For example, the narrow resonances observed in the excitation functions indicates the relatively long life time of the compound nuclear states [6, 7]. Likewise, the so called "high energy tails" (less rapid decrease of cross-section with energy than predicted by compound nucleus theory) observed in the excitation functions of a variety of reactions in the energy range of 20-200 MeV, pointed out to some new physics coming into play in this energy region of excitation. Similarly, the ejectile energy spectra showed continuous but forward-peaked hard components which did not fit with direct reaction theories. Particles emitted symmetrically about 90° , as in compound nucleus reactions, showed non-Maxwellian energy distribution.

These strange experimental features [8, 9], apparently related to, but subtly differing from the well-known characteristics of direct and compound nucleus reactions, seem to provide a linkage between the two extreme models. They point out to reaction modes, intermediate in time scale as well as in the number of degrees of freedom, as compared to the conventional direct and compound nucleus processes. In the target-projectile composite system, if the first stage interaction represents a direct reaction and the last stage represents an equilibrated compound nucleus, then the intermediate stages through which the composite system equilibrates are chronologically called "Pre-equilibrium" stages(Fig 1.1).

Thus, a comprehensive view formed of a nuclear reaction may be that for a given excitation, it is a multi-step process, which the target-projectile composite system, passes through a series of intermediate stages of increasing complexity and reaches the final stage of a compound nucleus having a statistical equilibrium, with a large number of degrees of freedom excited. The most noteworthy point is that the reaction may come to an end, by the emission of particles leaving behind the residual nucleus, at any point in the above sequence. If this happens at the very first interaction, it is a direct reaction; if in one of the intermediate stages, it is a pre-equilibrium reaction; or if it occurs only at the end of the last stage, then it is a familiar compound nucleus reaction. Multi-particles reactions may, however, span several stages of the equilibration sequence.

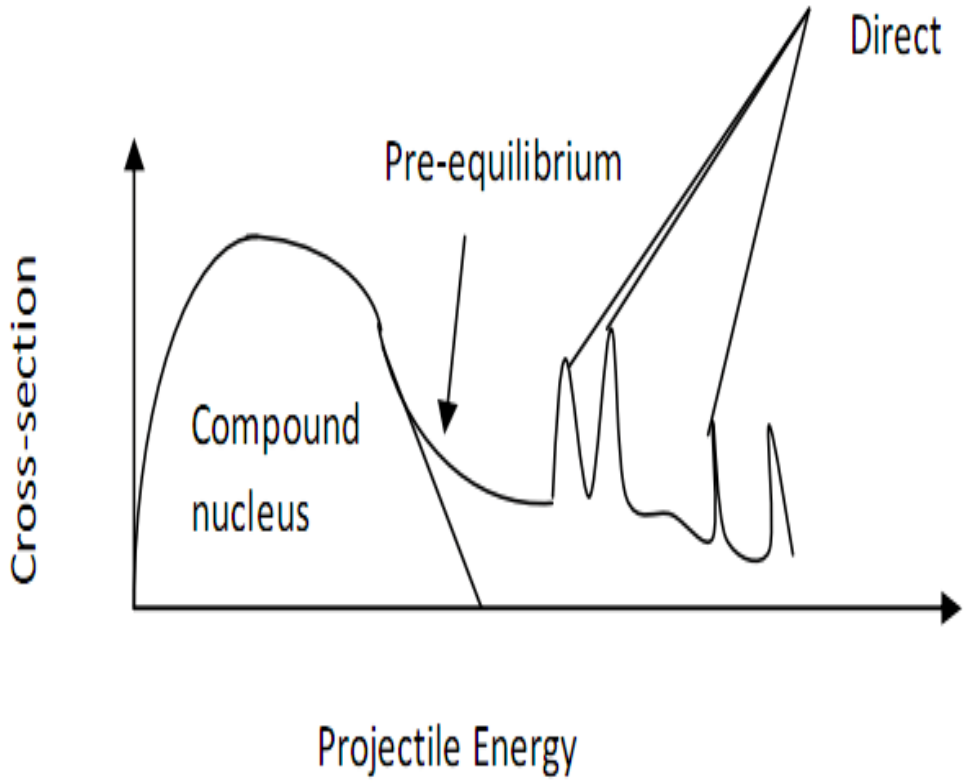

Figure 1.1: A typical neutron emission spectrum showing contributions of different reaction mechanisms in nuclear reaction

1.2 Description of the Pre-equilibrium models

During the last few decades, many nuclear reaction models have been developed to treat the pre-equilibrium phase of reactions leading to the formation of the compound nucleus. Although a variety of approaches and computational techniques have been employed, most of these models utilize, in one way or other, one or both of the two basics concepts ingrained in the Intranuclear Cascade (INC) model [10–12] and the Statistical model of intermediate structure (SMIS) first proposed by Griffin [13, 14]. The idea of Intranuclear Cascade approach is to treat the equilibration as a series of quasi-free scattering processes of independent nucleons in the nuclear environment and to follow these processes explicitly in a geometric fashion in the nuclear volume. Nucleon-nucleon kinematics and cross-sections are employed and emission is assumed to occur whenever a nucleons follows a trajectory out of the composite nucleus without undergoing another collision.

On the other hand, Griffin considered the equilibrating system as a

whole, envisioning it to pass through increasingly complex configurations of single particle excitations. His model exploits the idea of two-body nature of elementary thermalizing process implicitly, in that it groups the single particle configurations according to the single particle degrees of freedom participating in the total excitation. It further assumes that, at each stage, all possible single particle configurations are equally likely, so that the occurrence of configurations capable of particle emission into continuum may be estimated on a statistical basis. A fraction of these configurations, which are similar to virtual states, may emit particles. All such "pre-compound" particles coming from each of the preceding stages to the formation of the compound nucleus, qualitatively explain the non-Maxwellian part of the particle spectrum, or the "intermediate structure", as called by Griffin. In its original form, the model does not explicitly treat the competition between particle emission and intranuclear collisions and so it does not predict the absolute cross-sections, as the Intranuclear Cascade model does. It is however a very transparent model, worked out as simple analytical formulae, as compared to the Monte-Carlo calculations required by the Intranuclear Cascade approach.

Basically Griffin's model offers a time-dependent description of a multi-step reaction process. A more detailed time-dependent version is provided by the "Fermigas equilibration model" developed by Harp, Miller and Berne [15]. This is widely known as HMB model. The guiding idea of this model is that if one believes in the success of the compound nucleus model and the idea that the particles in the nucleus can be thermalized like any quantum or classical gas, then one should look for the equation which describes this thermalization process in statistical physics. Such description is given by Boltzmann master equation in classical physics. So, employing Boltzmann-like master equations for a Fermi gas system, Harp, Miller and Berne treated the nucleus as a box filled with Fermi gas at zero temperature forming a Fermi sea. For example, in describing the reaction induced by a nucleon, it is assumed that at the initial moment(t=0), the incident particle is inserted into the box and placed in one of the empty high energy levels above the Fermi gas. For computational simplicity, all the energy space of the single particle levels is divided into bins of certain width, allowing the particles to collide with one another and exchange energy. The fractional occupation of each energy bin is followed as a function of time. The particle flux is divided in proportion to the rate at which the particle may be emitted versus the rate at which it may make an internal transition. Redistributions of populations are governed by master equation approach in which the free nucleon-nucleon collision cross-sections are used to predict the absolute cross-sections of reactions involving only nucleon emission. The practi-

cal disadvantage of this parameter-free model is its complexity and the necessity of solving a number of coupled differential equations.

In later years, much effort has therefore been devoted to combining the advantages of both the Intranuclear cascade model and Griffin's statistical model of intermediate structure into a simple formalism capable of calculating the absolute pre-equilibrium emission cross-sections and yet retaining the simplicity of statistical description of the intermediate structure. As a result, a number of formulations, the Hybrid model of Blann [16–18], the Exciton model of Gadioli *et. al.* [19,20] and many other models [21–25] later on have emerged as descendants of Griffin's statistical model of intermediate structure. All the models have common feature that they group the many body states of the equilibrating system according to exciton numbers and employ particle-hole densities to estimate the occurrence of configurations capable of pre-compound particle emission. In addition, these models treat the competition between particle emission and intranuclear transitions during the equilibration phase explicitly and evaluate the rates at which such intranuclear transitions takes place. The particle emission rates into the continuum are invariably calculated from the reciprocity theorem while the internal transition rates are derived either from free nucleon-nucleon cross-sections or from the imaginary part of the optical potential or from average matrix elements obtained by semiempirical fits to the experimental data. Also there are some conceptual differences between the models. Many debates and arguments were made regarding these differences and most of them were resolved to a large extent finally [26].

Attempts were made to include pre-equilibrium emission of complex particles within the framework of Exciton model by introducing a new idea of "correlated emission". Cline and others [27,28] visualised the formation of complex particles at the time of emission. They considered the emission of, for example, alpha particle as an event of "correlated emission" of four nucleons in such a way that they appear as an alpha particle to the outside world. Combining both the aspects of complex particle emission and angular distributions in the framework of generalized exciton model, Machner developed an "Exciton coalescence" model [29].

Most of the above "excitation models", are semi-empirical in nature, lacking in quantum theoretical foundation. To make up for this, Agassi *et. al.* [30] in 1975 proposed the "Generalized exciton model" based on quantum statistical approach. In 1980, Feshbach, Herman and Koonin [23] proposed a full fledged quantum mechanical formalism called the "Multistep direct and multistep compound" theory. The basic physics of the relaxation process is the same in these theories, as in the Exciton model. In the theory of Feshbach *et. al.* there is a clear distinction between states having atleast

one nucleons in bound and continuum states. The continuum component of these states form P-space while the Q-space contains all the states with bound nucleons. Particle emission is only possible from the P-space. A nuclear reaction proceeding only through the P-space is called a multistep direct reaction (MSDR). Decay from Q-space is impossible by definition, however, particles may be emitted after decay from Q-space to P-space. Such a reaction is called multistep compound reaction (MSCR).

The P-space interactions take place rapidly and the pre-equilibrium particles retain some memory of the incident direction of the projectile, giving forward-peaked angular distributions. On the other had, the Q-space interactions take place much more slowly as at each stage there are many interactions that exchange energy but do not alter the exciton number. A quasi-equilibrium is established, giving rise to an angular distribution that is symmetric about 90° but with a life time that is shorter and a nuclear temperature that is higher than the fully equilibrated compound nucleus. The proportion of the reactions going through P and Q spaces depends strongly on the incident energy. At high energies, it is quite likely that throughout the reaction there is atleast one particle in the continuum. In this case the reaction will proceed by multistep direct process represented by the P-space. At lower energies, most of the states are bound and the reaction is caused by the Q-space through the multistep compound mechanism. At any energy both these processes contribute incoherently so that the corresponding cross-sections can be added together for comparison with experiment. But in theory, in this above mentioned form, was applied only to nucleon induced reactions involving nucleon emission only. One of the major sources of uncertainty in the calculations were the lack of knowledge of the compound state and final states densities. Later on the theory was extended to treat complex particles in the incident as well as outgoing channels.

The statistical and pre-equilibrium models discussed upto this point assume that all the states collected in a configuration, be it an exciton one or the entire compound nucleus, are somehow mixed with one another so that their energy is distributed statistically. Although this seems to be a good approximation at low energies, it certainly does not remain so as the energy increases. At sufficiently high energies, the velocity of an incident nucleon can be over four times that of the fastest nucleon in the nucleus. In such cases, models that go to the other extreme and assume no configuration mixing at all, become relevant. Among models of this type are Intranuclear cascade model [10–12], as well as Hybrid model [17, 18, 31] and the hybrid Monte-Carlo simulation [32–34] of M. Blann.

The Monte Carlo pre-equilibrium model that has been developed pro-

gressively by M. Blann and others, offers some advantages in conforming nuclear reactions and generating various nuclear databases. The initial decay model formulated by Blann was subsequently expanded further to give angular and energy distributions of ejectile and later on a treatment of cluster-induced reactions was also incorporated. This approach made it possible to accurately model a variety of nuclear reaction mechanism occurring at projectile energies ranging upto few hundred MeV. Precompound models based on an assumed equilibration sequence of intranuclear two body interactions have proven valuable as a tool in the interpretation of a variety of nuclear reactions. There were few short comings in the model, pointed out by Bisplinghoff and others, one of which was in the treatment of multiple emissions from precompound nucleus and in treatment of exclusive reactions for differential cross-sections. These short comings were removed subsequently for nucleon and heavy ion induced reactions by successful application of Monte Carlo algorithms, in what we today know as Hybrid Monte Carlo Simulation (HMS).

The HMS models treats only the 2p-1h configurations, which have been shown to be a good approximation to the distribution that results from a nucleon-nucleon collision in nucleus. For each particle in a 2p-1h configuration, an energy above the Fermi energy is attributed randomly. If the particle energy is above the binging energy, it may either escape or rescatter to form another 2p-1h pair, which it again does randomly. If it escapes, the remaining energy of the 1p-1h pair is divided randomly between the particle and the hole and the new particle is tested for escape or rescattering. This goes on until all the particles are bound. Hence, here, each successive scattering of a nucleon is treated as producing a new 3-exciton configuration, consistent with the 2-body assumption. This approach helps in avoiding the use of higher order exciton densities, which, as demonstrated by Bisplinghoff, were inconsistent with population by a 2-body mechanism. Because of this approach, Blann's HMS model allows unlimited emission of pre-equilibrium particles and it can be used to compute exclusion reactions where specific correlations between the ejectiles are of interest.

1.3 Review of the results of pre-equilibrium emissions

Let us review some of the results obtained for pre-equilibrium emissions using this HMS model. As an example, an angle-integrated spectra for the reaction of protons incident on Zirconium at 80, 160 and 256 MeV is shown here in Fig 1.2 [35]. This result illustrates the importance of

multiple pre-equilibrium emission with increasing incident energy. At 80 MeV, the contribution from all precompound nucleons emitted after second is less than 10%. AT 160 MeV, this contribution(all nucleons emitted after second) increases to approximately 30% and it increases further at 256 MeV. In the figure "N" represents that there are N-1 nucleons emitted before the emission of the N^{th} nucleon, for which the spectrum is being shown. Another example of HMS prediction of emission spectrum at various angles is shown in Fig 1.3 [35]. These plots show the neutron spectra for the reaction of 256 MeV protons incident on ^{208}Pb. The general features of the experimental spectra are well reproduced using the new theoretical approach. From these two examples we can say that the theory not only accounts for the energy dependence of the spectra but also accounts for the angular dependence of the pre-equilibrium ejectiles. As seen in this example, the forward peaking of the spectra for the pre-equilibrium ejectiles with increasing emission energy can be seen clearly.

As mentioned earlier, later on the model was extended to include the algorithm for cluster induced reactions in attempt to extend the benefits of the Monte Carlo approach. One example of this implementation is shown in Fig 1.4 [35] where the results of HMS are compared with experimental results of alpha particles incident on Niobium at energies of 30.5, 42 and 55 MeV. For the calculated results, total reaction cross-section were used as starting point, without reduction, by the authors. But in the literature, it has been previously demonstrated that there are significant amount of low momentum transfer reactions, presumably due to higher partial waves of the entrance channel. In a detailed analysis of these type of reactions, E. Gadioli *et. al.* [39] concluded that only 60 to 70% of the reaction cross sections lead to the collisions in which the alpha might "dissolve" in the field of the nucleus. Also, it has been found empirically that for odd A targets, alpha induced reactions are best represented by initial 5 exciton configurations. Results presented in Fig 1.4, therefore were calculated assuming a 3 proton, 2 neutron set of initial excitons. After all the above considerations, we see excellent agreement between calculated and experimental results for the shapes of the spectra at 42 and 55 MeV. Further, if we reduce the reaction cross-sections by 40%, to take into account Gadioli's conclusion, agreement with the experimental results gets still better.

There has been many improvements and additions made to the original code developed by Blann and many version of them are available today. In the present work we have used ALICE-2014 version of the HMS code which is further developed and refined by Blann and others. The code is intended to be relatively fast in execution and easy to use. The ease of use is facilitated by several library files which must be present at time of

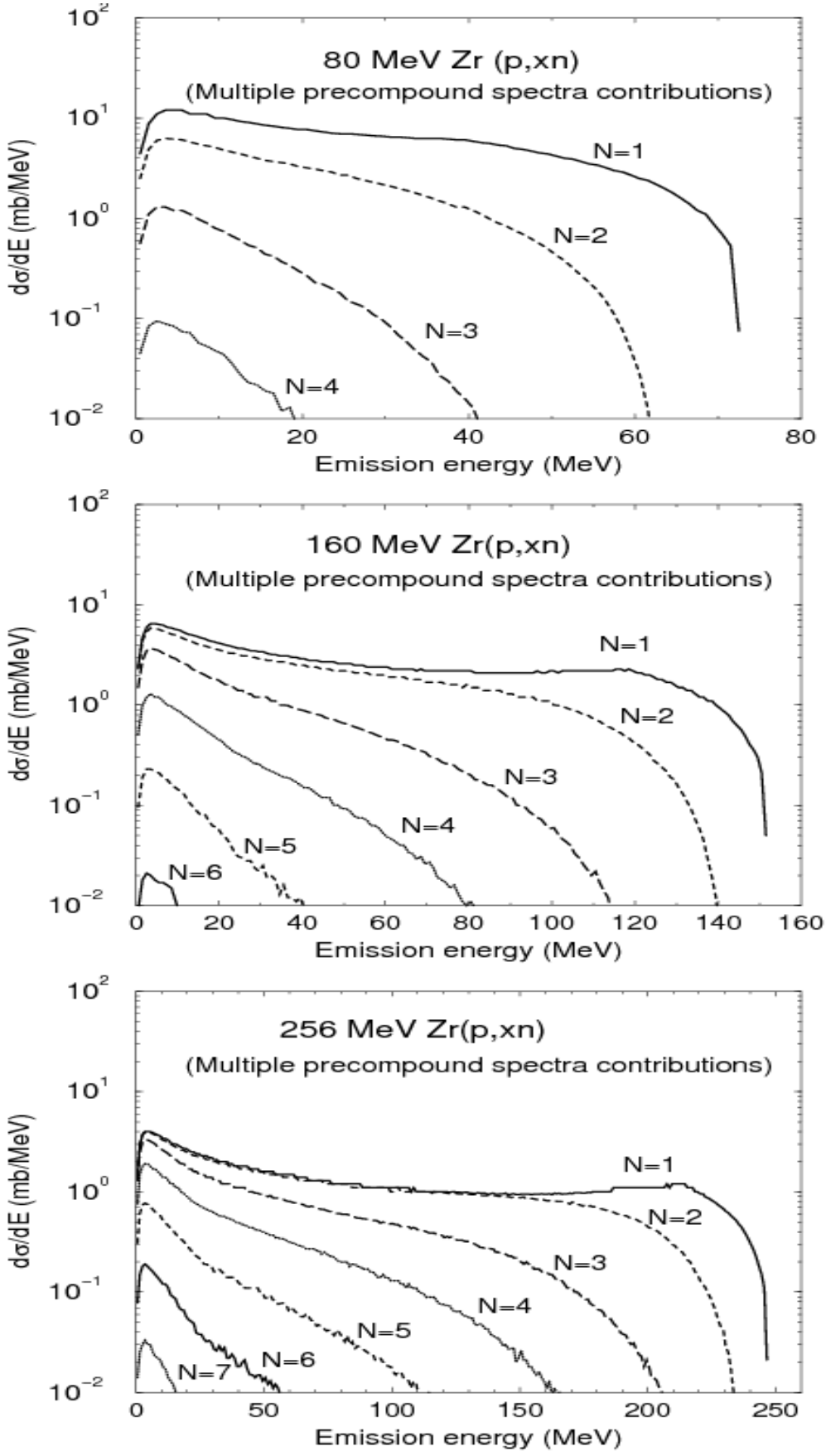

Figure 1.2: Calculated pre-equilibrium spectra, including contributions from multiple pre-equilibrium processes.

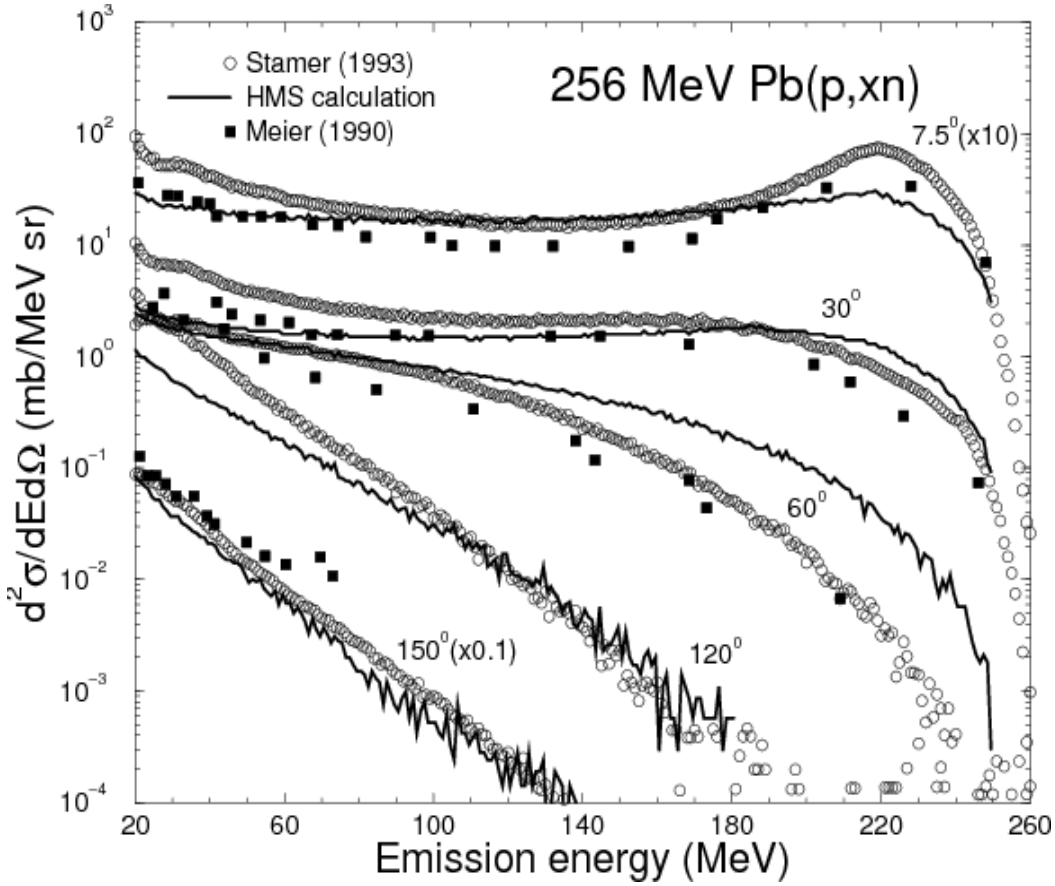

Figure 1.3: Neutron emission spectra at various angles for 256 MeV p + ^{208}Pb, compared with data.

execution, internal data files and subroutines to prepare data necessary for the calculations. The present code version accepts incident particles of photons, neutrons, protons and heavy ions. Many other capabilities exist in the present code version over pre-HMS and even early HMS versions. Such as, light excited nuclei may be given the Fermi breakup option in decay, precompound+compound emission of ^{2}H, ^{3}H, ^{3}He, ^{4}He, and ^{7}Be may be requested, isomer ratios may be calculated for product yields, isomer targets as well as naturally occurring isotopic targets may be used, for fission the mass and charge yields of the fission products are calculated along with their excitations, etc. There is also option provided to select the level density from Fermi gas densities, Kataria-Ramamurthy and Obninsk model.

1.4 Motivation and Objectives

We have also used another code PACE4 [40], which is a fusion-evaporation code, to compare it with the calculated results from ALICE-2014 and experimental results. This comparison helps us to estimate the contribution in

the total reaction cross-section from equilibrium and non-equilibrium emission. This statistical model code Projection-Angular-Momentum-Coupled-Evaporation (PACE) is derived from the original code called JULIAN, which is the Hillman-Eyal evaporation code [41] which used Monte Carlo simulation to determine the decay sequence of an excited nucleus using the Hauser-Feshbach formalism [5].

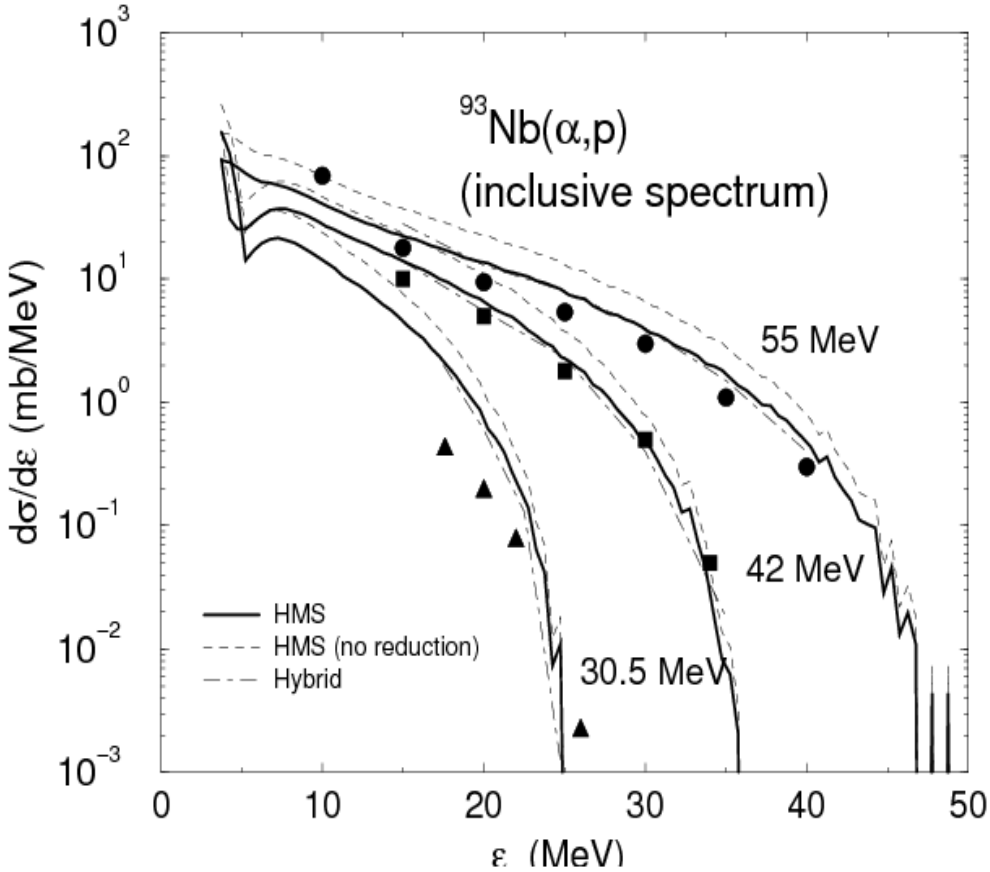

Figure 1.4: Experimental and calculated spectra on ^{93}Nb. Solid lines are the results of the HMS Monte Carlo simulation after the reduction by a factor of 0.6. The HMS results without any such reduction are shown as dashed lines.

The Monte Carlo calculations provides the correlations between various quantities, such as particles and gamma-rays, or angular distribution of particles. Sequential decays are considered until any further decay is prohibited due to the energy and angular momentum conservation laws. A random number selection determines the actual final state to which the nucleus decays to and the process is, then repeated for other cascades until all the nuclei reach the ground state. The transmission coefficients for light particle emission are determined using optical model potentials [42]. The code also provides event by event trace back of the entire decay sequence from the compound nucleus into any one of the exit channels. The fusion

cross-sections are obtained from the Bass model [43]. PACE4 can provide information on energy and angular distributions of evaporated particles.

Considerable efforts are actually being made to create databases of experimental data and theoretical predictions which could be used for interdisciplinary purposes. Examples of such work and of calculations performed for nucleon induced reactions are available in the literature [36–38]. However, for heavy ion reactions comparable information is still lacking, in spite of its increasing importance for applications in interdisciplinary fields. The work planned here as a part of the thesis is aimed at acquiring data which could produce the required comprehensive information and thereby aid in developing phenomenological theories which are able to provide a quantitative account of all measured observables in reactions induced by lighter heavy ions, such as ^{14}N and ^{19}F. Also we want to identify the dominant reaction mechanism which contributes towards the emission of nucleons and alpha particles. Especially, since we know that in heavy ion reactions the compound nucleus mechanism is competing with non-equilibrium and direct reaction processes which are even more dominant at high energies. Experiments have clearly indicated that in such non-equilibrium and direct reactions, alpha particles comprise a major contribution to the emission cross section of all the outgoing particles. Apart from studying the reaction mechanisms in heavy ion reactions, we also want to make a general test of ALICE-2014 and thereby a test of all the new additions and improvements that has been made in the code over the years, over a fairly wide range of bombarding energies.
Keeping this in mind our focused objective for the experiments are as follows:

1. To study the emission of alpha particles in the reaction of ^{14}N on heavy targets like Rh, Co, Nb and Au at incident energies going from Coulomb barrier to several tens of MeV/nucleon.

2. To study the emission of neutrons in the reaction of ^{19}F with targets like Ta, Y and V at incident energies of several tens of MeV/nucleon.

3. We also wish to study the excitation functions of the residues emitted in these reactions.

Targets are selected from various regions of periodic table in order to understand effect of mass number on the reaction mechanism and on mode of decay.

1.5 Overview of the present work

In the present work, in order to explore some of the important issues related to the heavy ion reaction dynamics at energies ranging from Coulomb barrier and above, several experiments have been performed at iThemba LABS, South Africa and TIFR, Mumbai. At both of these facilities desired ion beams of required energies, target making facilities and radiation counting facilities were available. The study of the equilibrium and non-equilibrium emissions in heavy ion reactions is done with the help of the following measurements:

- Study of emission of alpha particles was done for the system $^{14}N + ^{59}Co, ^{93}Nb, ^{197}Au$ at bombarding energies of 250 and 400 MeV. The experiment was done using general purpose scattering chamber (GPSC). Beam was bombarded on self-supporting targets and charged particles were identified using silicon $\Delta E - E$ telescopes having thickness $30\mu m/500\mu m$, mounted inside GPSC. The angular distribution measurements of the emitted charged particles was carried out in the angular range of 20° to 170° in the angular interval of 2° to 5°.

- Neutron emission from the reaction in the systems $^{19}F + ^{181}Ta$, ^{89}Y, ^{51}V was studied in the energy region of 100 to 150 MeV. The detection and energy measurements of the emitted neutron was done at Bhabha Atomic Research Centre–Tata Institute of Fundamental Research (BARC-TIFR) Pelletron-LINAC facility, Mumbai using time of flight technique. This facility has about fifteen liquid scintillator neutron detectors (NE213) arranged at three different azimuthal angle at a distance of 65 to 82 cm from the target at the center. Neutrons were identified using PSD and TAC modules and neutron spectra were obtained using the same with help of LAMPS-VME software. Efficiency measurements of the neutron detectors were done using ^{252}Cf source.

- Excitation functions for the residues emitted in the reactions $^{14}N + ^{103}Rh$ were measured using the activation technique in conjunction with off-line γ-ray spectroscopy. Several targets of thickness around 500 $\mu g/cm^2$ were used for the purpose of irradiation. Irradiation time was decided according to the half-life of the emitted residues. The induced activity in the target and a catcher in close contact with it were subsequently measured for several weeks. Depending upon how easily beam energy could be changed, irradiation were done at energy intervals of 5 to 10 MeV. Activities were measured using calibrated

HPGe detectors. The residues were identified using their characteristic gamma lines and using their half-life by measuring decrease in activity.

The large body of experimental data measured in this work is compared with theoretical predictions obtained from ALICE-2014 and PACE4 codes, to test the underlying physics of the models incorporated in these codes and to judge their limits of validity. The results from the experiments and the conclusions drawn from the results are presented in this thesis in the subsequent chapters. The detailed plan of the thesis is given below:

Chapter 1- This chapter deals with the introduction of the heavy ion reaction mechanism giving special emphasis on pre-equilibrium reaction process.

Chapter 2- This chapter will give the complete description of the experimental work carried out for study of excitation functions of various residues produced in the reaction of ^{14}N with ^{103}Rh at projectile energies ranging from threshold up to 400 MeV by means of activation method in conjunction with γ-ray spectroscopy. The chapter will present in detail the procedure, data analysis and calculations of experimental cross-sections as well as theoretical calculations followed by uncertainty analysis and results obtained.

Chapter 3- This chapter will contain complete description and experimental findings about neutron emission in reactions of ^{19}F with ^{181}Ta, ^{89}Y, ^{51}V at beam energies ranging from 130 to 150 MeV. The chapter will contain details of the time-of-flight technique and pulse-shape discrimination method that was used to measure the neutron spectra. This will be followed by details of ALICE and PACE calculations and their comparison with experimental data, and finally the discussion of the results obtained.

Chapter 4- This chapter will give the details about the experiment performed for the measurement of non-equilibrium emission of alpha particles in the interaction of ^{14}N with ^{59}Co and ^{93}Nb at incident energies of 250 and 400 MeV. The data were collected in wide angular range using silicon surface barrier detectors. The chapter will give details of the experiment and theoretical calculations performed using modified PACE code, followed by results and discussion.

Chapter 5- This will be the final chapter which will contain the summary and conclusions obtained through all the three experiments. There are still

some unexplored territories in this field which needs some investigation. The chapter will also describe, in brief, the need and scope for such kind of work for other systems to fully understand the heavy ion reaction dynamics.

✠ ✠ ✠ ✠

Bibliography

[1] P. E. Hodgson, Contemp. Phys. **29**, 457 (1988).

[2] N. Austern, "Direct Nuclear Reaction Theories", Wiley-Interscience, New York (1970).

[3] G. R. Satchler, "Direct Nuclear Reactions", Clarendon Press, United Kingdom (1983).

[4] P. E. Hodgson, Brazilian Jour. of Phys. **2**, 61 (1972).

[5] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

[6] R. J. Charity, Eur. Phys. J. Plus **131**, 63 (2016)

[7] C. M. Perey, F. G. Perey, J. A. Harvey, N. W. Hill, N. M. Larson, R. L. Macklin and D. C. Larson, Phys. Rev. C **47**, 1143 (1993).

[8] M. Blann, Ann. Rev. Nucl. Sci. **25**, 123 (1975).

[9] H. Machner, Phys. Rep. **127**, 309 (1985).

[10] M. L. Goldberger, Phys. Rev. **74**, 1269 (1948).

[11] N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller and G. Friedlander, Phys. Rev. **110**, 185 (1958).

[12] H. W. Bertini, Phys. Rev. **131**, 1801 (1963).

[13] J. J. Griffin, Phys. Rev. Lett. **17**, 478 (1966).

[14] J. J. Griffin, Phys. Rev. B **24**, 5 (1967).

[15] G. D. Harp, J. M. Miller and B. J. Berne, Phys. Rev. **165**, 1166 (1968).

[16] M. Blann, Phys. Rev. Lett. **21**, 1357 (1968).

[17] M. Blann, Phys. Rev. Lett. **27**, 337 (1971).

[18] M. Blann, Phys. Rev. Lett. **28**, 757 (1972).

[19] E. Gadioli, E. Gadioli Erba, P.G. Sona, Nucl. Phys. A **217**, 589 (1973).

[20] E. Gadioli, E. Gadioli Erba, Nucl. Inst. and Meth. **146**, 265 (1977).

[21] C.K. Cline, Nucl. Phys. A **210**, 590 (1973).

[22] E. Betak and J. Dobes, Z. Phys. A **279**, 319 (1976).

[23] H. Feshbach,, A. Kerman, S. Koonin, Ann. Phys. **125**, 429 (1980).

[24] A. Iwamoto, K. Harada, Phys. Rev. C **26**, 1821 (1982).

[25] H. Nishioka, H.A. Weidenmuller, S. Yoshida, Ann. Phys. **183**, 166 (1988).

[26] J. Bisplinghoff, Phys. Rev. C **33**, 1569 (1986).

[27] C.K. Cline, Nucl. Phys. A **193**, 417 (1972).

[28] I. Ribanský, P.Obložinský, Phys. Lett. B **45**, 318 (1973).

[29] H. Machner, Phys. Rev. C **21**, 2695 (1980).

[30] D. Agassi, H.A. Weidenmüller and G. Mantzouranis, Phys. Rep. **22**, 145 (1975).

[31] M. Blann, Nucl. Phys. A **213**, 570 (1973).

[32] M. Blann, Phys. Rev. C **54**, 1341 (1996).

[33] M. Blann and M.B. Chadwick, Phys. Rev. C **57**, 233 (1998).

[34] M. Blann and M.B. Chadwick, Phys. Rev. C **62** , 034604 (2000).

[35] M.B. Chadwick, M. Blann and S. Hilaire, *International Conference on Nuclear Data for Science and Technology* **ND2007**, 11 (2007) and references therein.

[36] M.B. Chadwick, P.G. Young, S. Chiba, S.C. Frankle, G.M. Hale, H.G. Hughes, A.J. Koning, R.C. Little, R.E. MacFarlane, R.E. Prael and L.S. Waters, Nucl. Sci. and Eng. **131**, 293 (1999).

[37] A. Gandini, G. Reffo (Eds.), Nuclear Reaction Data and Nuclear Reactors—Physics, Design and Safety, World Scientific, Singapore, 1999.

[38] A.J. Koning, J.P. Delaroche, Nucl. Phys. A **713**, 231 (2003).

[39] E. Gadioli, E. Gadioli Erba, J.J. Hogan and B.V. Jacak, Phys. Rev. C **29**, 76 (1984).

[40] A. Gavron, Phys. Rev. C **21**, 230 (1980).

[41] M. Hillman and Y. Eyal, textitJULIAN: a Monte-Carlo Hauser–Feshbach program for evaporation from compound nuclei. (1977) https://www.osti.gov/servlets/purl/7210482.

[42] C.M. Perey and F.G. Perey, Atm. Nucl. Data Tables **17**, 1 (1976).

[43] R. Bass, Phys. Rev. Lett. **39**, 265 (1977).