THE STUDY OF SIGNITURES OF PRE-EQUILIBRIUM REACTIONS IN $^{12}C +^{197} AU$ SYSTEMS

By

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DEDICATED TO

My Mother Sinke Abebe and My Brother Zelalem Adugna.

MY MOM:

You are sunlight in my day,

You are the moon I see far away.

You are the one that makes troubles be gone.

You are the one who taught me life,

How not to fight, and what is right.

You are the words inside my song,

You are my love, my life,my mom.

You are the one who cares for me,

You are the eyes that help me see.

You are the one who knows me best,

When it's time to have fun and time to rest.

You are the one who has helped me to dream,

You hear my heart and you hear my screams.

Afraid of life but looking for love,

I'm blessed for God sent you from above.

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Abstract

In this work C-12 induced reaction on Gold(^{197}Au) in the energy range of 59Mev to 91Mev have been studied. Excitation function for four reactions of the type $^{197}Au(^{12}C, 3n)^{206}At$, $^{197}Au(^{12}C, 4n)^{205}At$, $^{197}Au(^{12}C, 5n)^{204}At$ and $^{197}Au(^{12}C, 6n)^{203}At$ were studied in these reactions. For theoretical excitation function the computer code COMPLET have been used. The theoretical results are compared with the experimental excitation functions obtained from EXFOR data source,IAEA to verify signatures of pre-equilibrium decay.The study shows that at intermediate energy, carbon induced reactions on high weight nuclei occurs through pre-equilibrium and equilibrium(compound) nucleus stages and not only by compound nucleus formation.

Chapter 1

Introduction

The study of nuclear reaction induced by heavy ion has attracted the attention of many nuclear physists because it provides knowledge about the nature of nuclear forces, nuclear structure and to explain many other phenomena related to nucleus[1-9]. Many efforts have been generated during the last decade by nuclear physists.In recent years intensive efforts have been made to understand the mechanism involved in heavy ion(HI) induced reaction. These study have a vital application in the field of medical science; research centers uses heavy ion beams for cancer treatment. Instead of x-ray radiation, carbon ions are used to irradiate the patient. The technique allows tumors which are close to vital organs to be treated; wich is not possible with x-rays.

One of the most important aims of this research is to improve the basic understanding of the reaction mechanism. These reactions are described by different models which depend on the energy of the projectiles. The most investigated range of energies is 0 to 200Mev.In this energy range one can determine different reactions mechanisms which are called, direct reaction, incomplete fusion, compound nuclear reaction, pre-equilibrium nuclear reactions,etc. The direct reactions take place in the time the projectile takes to pass over (traverse) the target nucleus and it is the fastest. The direct reaction which includes the 'stripping' and 'pick-up' reactions are characterized by certain angular distributions of the scattered or the outgoing particles and forward peaking. Those particles can be understood by regarding the reactions as having involved only the interaction between

the incident particle and the outer nucleons of the target nucleus.

The second stage of nuclear reaction(compound nucleus) is historically proposed by Niles Bohr. The initiation to develop the compound nucleus theory is the problem for resonance peak of nuclear reactions. According to this theory the sharp peak of the reaction cross section is due to the existence of the quasi-stable nuclear state for particular value of resonance energy. When particle x with this resonance energy approaches the target nucleus X, within the range of nuclear forces, a compound nucleus is formed. In compound nucleus reactions the energy of the projectile shared among the nucleons of the compound nucleus until it reaches the state of statistical equilibrium and it is the slowest reaction.This compound nucleus will then disintegrate into two or more products Y and y. Thus this type nuclear reaction is regarded as consisting of two successive steps,the formation and the decay stages. More detailed discussion is given in section 2.2.

Between these extreme processes there are the pre-equilibrium reactions.To explain this theory different pre-equilibrium nuclear reaction models have been developed. The first model developed by J.J Griffin was the exciton model [10]. The model was further modified and developed by M.Blan [11] et al. In the pre-equilibrium theories of nuclear reaction it is assumed that interaction is due to successive nucleon-nucleon interaction in a series of stages. Each interaction produces a particle-hole (p-h) pair and the particle-hole pair is called an exciton.

In the thesis other two related pre-equilibrium models are presented. In this thesis the carbon-particle is the projectile or the bombarding particle and Gold are the target. The different reaction channels studied are: ${}^{197}_{79}Au({}^{12}_{6}C, 3N)^{206}_{85}At$, ${}^{179}_{79}Au({}^{12}_{6}C, 4N)^{205}_{85}At$, ${}^{179}_{79}Au({}^{12}_{6}C, 5N)^{204}_{85}At$ and ${}^{179}_{79}Au({}^{12}_{6}C, 6N)^{203}_{85}At$. The objective of this thesis is to investigate the signitures of pre-equilibrium reaction of carbon-particle induced reaction on Gold with the help of computer code COMPLET[12-13]. In chapter four of the thesis the computer code COMPLET and the formulation for the code is discussed. COMPLET computer code is among the many computer codes available to compute the pre-equilibrium and

equilibrium excitation functions. The different channels are the results of the projectile energies. In this work the measurement of the cross section is one of the main tasks in the field of 59Mev to 91Mev energy range nuclear reactions. To calculate the cross-section in model of compound nucleus and in pre-equilibrium models, the most important ingredients are the exciton number and the level density parameter. The theoretical results are compared with the experimental data obtained from EXFOR data source,IAEA[14]. These are plotted together for comparison.

The nuclear data for the accelerator driven technologies are required for a large number of the target elements covering almost entire periodic table over a wide range of energies.Therefore, more detailed and accurate measurements are needed to fulfill this requirement of data. The nuclear data required for these applications are obtained mainly from the nuclear scattering and from the reaction model calculations which depend on the optical models, whose parameters are determined by elastic scattering and the total cross-section data.

Many efforts have been made to obtain the estimates of basic nuclear reaction cross-section both experimentally and theoretically.Though, considerable data is available in cross-section data taken by high resolution detectors of better efficiency.

Theoretically it may be possible to explain the measured excitation function (EFs) for a given reaction channel individually using a certain theoretical code.However, a consistent analysis requires reproduction of excitation function for all open channels simultaneous using the same code. There are several codes which are used for the theoretical calculations of cross section like ALICE91,CASCADE,PACE4, COMPLET,etc. These code calculates the EFs of light and heavy-ion induced reactions. The configurations of these codes predict the total cross section only for the population of the residual nuclei. At moderate excitation energies, reactions induced by heavy-ions are found to proceed through compound nucleus as well as pre-equilibrium emission. As a result, precise measurement of EFs for such cases and their analysis may be used to find out the relative contribution

of equilibrium and PE processes. With a view to provide a large set of cross section data and to study the mechanism of PE emission a program of precise measurement and analysis of cross sections for heavy-ion induced reaction is necessary. These measurements are important for testing the capability of theoretical model codes with respect to experiment. The details of result and discussion of carbon reaction on Gold are given in section 5 of the thesis.

Chapter 2

THEORIES OF NUCLEAR REACTION

2.1 Description of nuclear reaction

One important field of research to understand nuclear properties is study of nuclear reactions. Most of our knowledge of the atomic reaction has been based on the results of collision experiments between a target and various projectiles like electron , nucleon ,heavy nuclei, etc. Nuclear reaction is a process that occurs when a nuclear particle (nucleon or nucleus) gets in to close contact with another. Generally in experimental conditions the target is at rest and is bombarded with a beam of projectiles. However, it may be mentioned that in colliding beam experiments, both the colliding particles are in motion. Such experiments have become common in high energy physics. Here we shall restrict ourselves mainly to a class of nuclear reactions in which both the target and projectile nuclei are heavy nuclei having mass number A>4[1].

Most of the known nuclear reactions are produced by exposing different materials to a beam of accelerated nuclear particles. Usually a strong energy and momentum exchange takes place and the final products of the reaction are one, two or more nuclear particles leaving the point of close contact in various directions. The products nuclear reaction occurs between an energetic reaction partner, called the projectile or bombarding particle, and one that is at rest, called the target, some particles are emitted, and one or more

nuclei are formed [2].

Nuclear reactions are quantum mechanical phenomenon involving strong and electromagnetic interaction and they obey a set of conservation laws. Let us formally represent a nuclear reaction involving two nuclei in the initial and final states as follows:

$$A + B \Longrightarrow C + D + Q \tag{2.1.1}$$

Where

A=bombarding particle

B=target (at rest in the lab.system)

C=light reaction product

D= heavy reaction product

Q=the energy released or absorbed

To shorten the notation a reaction of the type (2.1.1) is designated by:

$$B(A, C)D \tag{2.1.2}$$

It should be realized that in general the number of reaction products can be more than two. A typical reaction,which illustrates equation (2.1.1) is:

$${}^{16}_{8}O + {}^{12}_{6}C \longrightarrow {}^{24}_{12}Mg + {}^{4}_{2}He + Q(6.478Mev) \tag{2.1.3}$$

The study of nuclear reactions had its beginnings in experiments performed in 1919 by Rutherford. Nitrogen, bombarded with 7.69 Mev alpha particles from ^{214}Po, was found to eject protons, identifiable as such by their range exceeding that of the initiating alpha particles. Since Rutherford's pioneer experiment may be written as:

$${}^{4}_{2}He + {}^{14}_{7}N \longrightarrow {}^{1}_{1}H + {}^{17}_{8}O \tag{2.1.4}$$

or contracted to

$$^{14}N(\alpha, p)^{17}O$$

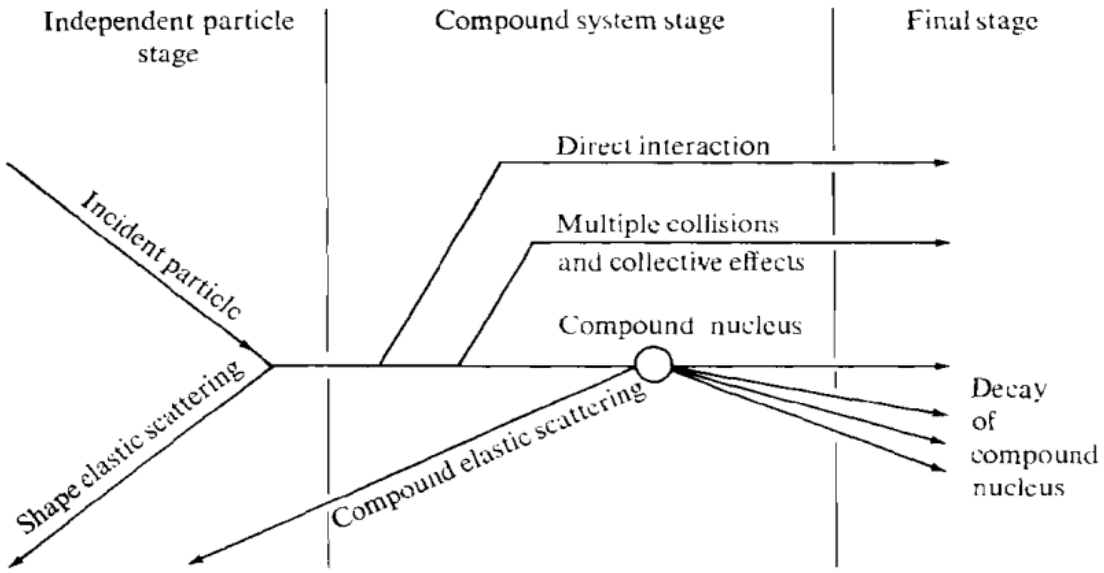

Figure 2.1: sequence of stages in a nuclear reaction according to Weisskopf.Ref[3]

And 1939, When fission was discovered (Hahn and Strassman , Meitner and Frisch), nearly all known nuclear process which could be initiated with bombarding energies up to approximately 10Mev were found.

Detailed theories of nuclear reaction were patterned after the two, apparently contradictory, models of nuclear structure; the liquid-drop model and the shell model. In one theory, it was assumed (Bohr,1936) that a nuclear projectile incident on a nucleus would interact strongly with all the nucleons in the nucleus and quickly share its energy with them. The compound nucleus so created would decay in a manner independent of its mode of formation. In the reaction theory based on the shell model (Bethe,1940;Fernbach,Serber,and Taylor,1949;Feshbach,porter,and Weisskopf.,1954), it was proposed that an incident nucleon would interact with the nucleus via the shell-model potential and that the probability of absorption into the compound nucleus would be relatively small. These different aspects of nuclear reaction can be unified into a single theory (Weisskopf,1957 ;Feshbach,1958)[3].

2.2 Conservation laws in nuclear reactions

In every type of nuclear reaction the total charge before the nuclear reaction is same as the total charge after the reaction. That is the total charge number is conserved. The other is conservation of mass number; according to this law the total number of nucleons before and after the collision must be same. This result together with the law of conservation of charge implies that the total number of nucleons is also conserved. The total angular momentum J before the reaction is the vector sum of the spin angular momenta (I_1,I_2) and the relative orbital angular momenta(l) i.e $J = I_1 + I_2 + l$. In any nuclear reaction this total angular momentum J is conserved, i.e. the total angular momentum quantum number J before the nuclear reaction is same as after the nuclear reaction. And the total parity is also conserved. The law of conservation of total linear momentum, states that the total momentum before the nuclear reaction is same as the total momentum of the system after nuclear reaction [1].

2.3 Energetics of nuclear reactions

Since from previous conservation laws the number of protons remains unchanged in a reaction, all masses can be written as atomic masses. Conservation of energy gives for the reaction (2.1.1)

$$M_A C^2 + T_A + M_B C^2 = M_C C^2 + T_C + M_D C^2 + T_D \tag{2.3.1}$$

Where the projectile and target have masses M_A and M_B, the light and heavy products masses M_C and M_D respectively. T_A, T_C and T_D represent the (lab.) kinetic energy of each particle. The masses of A and B are ground state masses. On the other hand, many reactions leave D in excited states; in that case M_D represents the total mass energy of that state.

The Q value of reaction is defined as the difference between the final and initial kinetic

energies [3].

$$Q = T_C + T_D - T_A \tag{2.3.2}$$

$$Q = [M_A + M_B - (M_C + M_D)]C^2 \tag{2.3.3}$$

Q may be positive or negative. If Q is positive, the reaction is said to be exoergic; if Q is negative, it is endoergic. A reaction cannot take place unless particles C and D emerge with positive kinetic energies, that is:

$$T_C + T_D > 0 \tag{2.3.4}$$

or

$$Q + T_A > 0$$

Although this condition is necessary, it is not sufficient. The Q value is an important quantity in a nuclear reaction. It can be determined from mass spectroscopy [Eq. (2.3.3)] or by measuring kinetic energies [Eq. (2.3.2)]

2.4 Wave Mechanical Theory for Single Entrance and Exit Channels

Nuclear reaction cross-sections may be explained using wave mechanical theory under general assumptions[13]. Let us consider a particle approaching a nucleus parallel to the Z-axis with velocity v. This particle can be represented by a plane wave assuming negligible diffraction effects.

$$\psi_{inc} = e^{ikz} \tag{2.4.1}$$

Here the wave amplitude is unity so that there is only one particle per unit volume and in the incident beam there are v particles per unit area per second,where v is the velocity of the incident particle. Since the particles position with respect to x,y axes can not be precisely specified,the angular momentum value of the particle, $l\hbar$ may take any value. To solve this problem the plane waves must be transformed into a superposition of spherical

waves each of which represents a particle of definite angular momentum. Let us find an expression for equation (2.4.1) in terms of expansion of partial waves. It can be seen that e^{ikz} is a solution with axial symmetry of the wave equation

$$\nabla^2\psi + k^2\psi = 0 \tag{2.4.2}$$

This equation can be solved in spherical polar coordinates and the solutions with axial symmetry are of the form

$$\psi_l = g_l(r)p_l(cos\theta) \tag{2.4.3}$$

Where l is an integer $p_l(cos\theta)$ is a Legender polynomial and $g_l(r)$ is that solution of the equation

$$\frac{1}{r^2}\frac{d}{dr}r^2(\frac{dg}{dr}) + (k^2 - \frac{l(l+1)}{r^2})g = 0 \tag{2.4.4}$$

Which is bounded at the origin. The most general solution of equation (2.4.3) is given by

$$\psi = \sum_{l=0}^{\infty} A_l g_l(r)p_l(cos\theta) \tag{2.4.5}$$

Where A_l are arbitrary constants. The terms in the infinite series are the partial waves. Hence,

$$e^{ikz} = e^{ikrcos\theta} = \sum_{l=0}^{\infty} A_m g_m(r)p_l(cos\theta) \tag{2.4.6}$$

Multiplying both sides by $P_l cos\theta sin\theta d\theta$ and integrating with the limits from 0 to infinity of equation (2.4.6) and letting $cos\theta = t$ we get,

$$\int_{-1}^{1} e^{ikrt}p_l(t)dt = \frac{2}{2l+1}A_l g_l(r)$$

$$\frac{2}{2l+1}A_l g_l(r) = \frac{1}{ikr}(e^{ikr} - (-1)^l e^{-ikr}) - \frac{1}{ikr}\int_{-1}^{1} e^{ikrt}p'(t)dt \tag{2.4.7}$$

The second term of equation (2.4.7) is of the order of $\frac{1}{r^2}$ which may be seen after integration by parts once more. For large value of r,

we get

$$\frac{2}{2l+1}A_l g_l(r) \sim \frac{1}{ikr}(e^{ikr} - e^{-il\pi}e^{-ikr})$$

$$= \frac{1}{ikr}(e^{\frac{il\pi}{2}}[e^{i(kr-\frac{l\pi}{2})} - e^{-i(kr-\frac{l\pi}{2})}])$$

$$= \frac{2i^l}{kr}sin(kr - \frac{l\pi}{2}) \tag{2.4.8}$$

Now $g_l(r)$ can be defined completely by requiring that,

$$A_l = (2l+1)i^l Hence,$$

$$g_l(r) = \frac{1}{kr}sin(kr - \frac{l\pi}{2})$$

The required expression is then given by

$$e^{ikz} = e^{ikrcos\theta} = \sum_{l=0}^{\infty}(2l+1)i^l g_l(r)p_l(cos\theta) \tag{2.4.9}$$

It can be seen that $g_l(r)$ is a spherical Bessel function with an asymptotic expression. That is,

$$g_l(r) = \sqrt{\frac{\pi}{2kr}}J_{l+\frac{1}{2}}(kr) \tag{2.4.10}$$

Where the asymptotic form of the spherical Bessel function is expressed as,

$$J_{l+\frac{1}{2}}(kr) = \frac{1}{(2l+1)!!}\sqrt{\frac{2}{\pi}}(kr)^{l+\frac{1}{2}}, r \ll 1$$

$$J_{l+\frac{1}{2}}(kr) = \sqrt{\frac{2}{\pi}}sin(kr - \frac{l\pi}{2}), r \gg 1 \tag{2.4.11}$$

The incident wave function is then expressed using equation (2.4.10) and equation (2.4.11) as

$$\psi_{inc} = \frac{1}{kr}\sum_{l=0}^{\infty}(2l+1)i^l p_l(cos\theta)sin(kr - \frac{l\pi}{2})$$

$$\psi_{inc} = \frac{1}{kr}\sum_{l=0}^{\infty}(2l+1)i^l p_l(cos\theta)[\frac{e^{i(kr-\frac{l\pi}{2})} - e^{-i(kr-\frac{l\pi}{2})}}{2i}] \tag{2.4.12}$$

From equation (2.4.12),it can be seen that $\frac{1}{r}e^{-i(kr-\frac{l\pi}{2})}$ represents a spherical wave converging (going onto) the nucleus and $\frac{1}{r}e^{+i(kr-\frac{l\pi}{2})}$ represents a spherical wave diverging or

going out from the nucleus.If the out going waves are affected in amplitude as well as in phase, we have an inelastic process which can be represented by the wave equation,

$$\psi_l(r) = \frac{1}{2ikr}\sum_{l=0}^{\infty}(2l+1)i^l p_l(cos\theta)(\eta_l e^{i(kr-\frac{l\pi}{2})} - e^{-i(kr-\frac{l\pi}{2})}) \tag{2.4.13}$$

Where η_l is a complex constant which contains the effects of the scattering center.Its real part gives the change in amplitude and its imaginary part gives the change in phase. η_l can be represented by

$$\eta_l = |\eta_l|e^{2i\delta_l} \tag{2.4.14}$$

The scattered wave is itself the superpositions of partial waves and may be written as

$$\psi_{sc} = \frac{f(\theta)}{r}e^{ikr} \tag{2.4.15}$$

where $f(\theta)$ is the scattering amplitude.Thus the number of particles crossing unit area per second in the scattered beam is given by

$$v|\psi|^2 = v|f(\theta)|^2 d\Omega \tag{2.4.16}$$

Where $d\Omega$ is an element of solid angle. The value for the scattering amplitude $f(\theta)$ is obtained using equation (2.4.13) and equation (2.4.15)

$$f(\theta) = \frac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)(\eta_l - 1)p_l(cos\theta) \tag{2.4.17}$$

The two types of reactions,elastic and inelastic,may be inferred from the discussion above. For elastic scattering where there is no loss of incident particles $|\eta_l|^2$ =1.It means there is no change in amplitude between the incident and the scattered wave,which implies no change in the real part of η_l . η_l is now written as $e^{2i\delta_l}$. Then the scattering amplitude is expressed as

$$f(\theta) = \frac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)(e^{2i\delta_l} - 1)p_l(cos\theta) \tag{2.4.18}$$

δ_l is the phase shift in the asymptotic form of the partial wave 1. For the inelastic reaction $|\eta_l|^2$<1,that is there is a change in amplitude and δ_l is complex. The cross section for

the scattered particle may be obtained by applying the probability current density of the scattered wave function ψ_{sc} . The number of scattered particles (N_{sc}) through a solid angle $d\Omega$ is defined as

$$N_{sc} = \frac{\hbar}{2im}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(\frac{\partial\psi_{sc}}{\partial r}\psi_{sc}^{*} - \frac{\partial\psi_{sc}^{*}}{\partial r}\psi_{sc})r_o^2 d\Omega$$

$$N_{sc} = v\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|f(\theta)|^2 d\Omega \tag{2.4.19}$$

where m is the mass of the scattered particles and r_0^2 is the radius of a sphere with solid angle $d\Omega$. The scattered cross section is given by

$$\sigma_{sc} = \frac{N_{sc}}{Flux}$$

$$= \frac{v\int\int|f(\theta)|^2 d\Omega}{v}$$

$$= \int\int|f(\theta)|^2 d\Omega$$

$$= \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)|1-\eta_l|^2 \tag{2.4.20}$$

The reaction cross section may be obtained in the same way but using a negative sign before the probability current to indicate the direction of current onto the nucleus.

$$\sigma_r = \frac{N_r}{v} = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)(1-|\eta_l|^2) \tag{2.4.21}$$

From equation (2.4.21) it is clear that if $|\eta_l| = 0$,that is no change in amplitude of the wave,there is no reaction ($\sigma_r = 0$) but scattering may be there.On the other hand if $\eta_l = 1$,both reaction and scattering are not possible.If $\eta_l = 1$,there is no reaction but there is maximum scattering.If $\eta_l = 0$,then there is maximum reaction and also some scattering.The total cross section is obtained by adding equation (2.4.20) and equation (2.4.21).

$$\sum_{0}^{\infty}\sigma_{l,t} = \sum_{0}^{\infty}\frac{2\pi}{k^2}(2l+1)(1-Rel\eta_l)$$

$$\sigma_t = \frac{4\pi}{k^2}\sum_{0}^{\infty}(2l+1)sin^2\delta_l \tag{2.4.22}$$

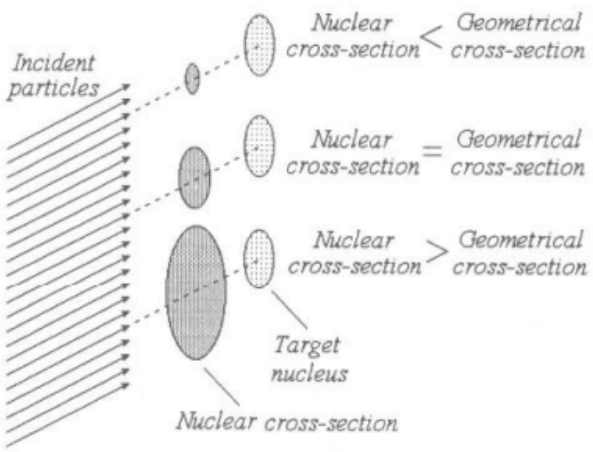

Figure 2.2: Nuclear cross-section viewed as the area effectively presented to the incident beam by each target nucleus. The larger the nuclear cross-section the greater the probability that an incident particle will react with a nucleus.

2.5 Nuclear reaction cross section

The probability that a nuclear reactions will occur is expressed in terms of a parameter called the nuclear reaction cross-sections ;the larger the nuclear cross sections the more probable the reactions .This factor can be viewed as the target area effectively presented to the incident particles by each nucleus. such that if the incident particle passes through this area reaction will take place. The cross-section of a reaction is defined by :

$$\sigma = \frac{number\ of\ events\ of\ given\ type\ per\ unit\ time\ per\ nucleus}{number\ of\ incident\ particles\ per\ unit\ area\ per\ unit\ time} \tag{2.5.1}$$

Nuclear cross sections are measured in a unit called the barn: $1b = 10^{-28}m^2$.They may be larger or smaller than the geometric cross-section of the target nucleus, though in most cases they are of the same order of magnitude and it is shown in Fig(2.2). Nuclear cross-sections generally depend on two factors:

(i) the energy of the projectile particle ;

(ii) the nature of the nuclear reaction.

In general, the reduction, ΔI, in the intensity of a particle beam of intensity I on passing through a slice of homogeneous material of thickness, Δx, is given by

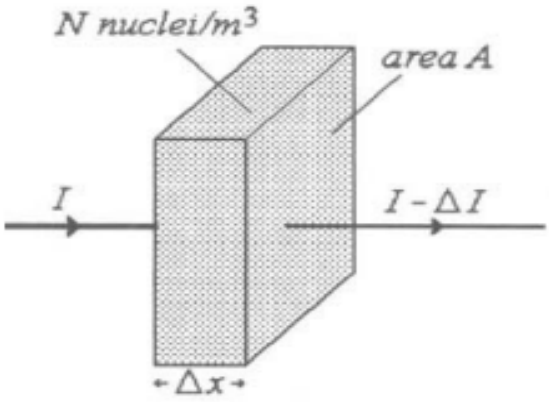

Figure 2.3: The attenuation of a beam of particles by a slice of a material containing N reacting nuclei per cubic meter.The slice effectively presents an imprevious 'wall'of area $AN\sigma\Delta x$.

$$\Delta I = -\mu I.\Delta x \tag{2.5.2}$$

μ is the macroscopic cross-section or linear attenuation coefficient. If each unit volume of the material contains N nuclei that can interact with the particles in the beam and if each such nucleus presents a target of area σ to the incident particles, then a slice of frontal area A effectively presents a 'wall' of interacting nuclei of area $AN\sigma\Delta x$ to the beam (Fig 2.3). The relative attenuation, $\frac{\Delta I}{I}$, of the beam resulting from its passage through the slice will be:

$$\frac{\Delta I}{I} = \frac{-AN\sigma\Delta x}{A} = -N\sigma\Delta x \tag{2.5.3}$$

From equetions (2.5.2) and (2.5.3), the relationship between the nuclear cross-section, σ, and the macroscopic cross-section, μ , is simply:

$$\mu = N\sigma \tag{2.5.4}$$

Chapter 3

REACTION MECHANISMS

In a projectile target nucleus interaction either of two things may happen. The projectile may simply be deflected by the target nucleus potential and change its direction without any change in the center of mass energy. This is shape elastic scattering. On the other hand, the projectile may interact with target particle, lose energy to it and thus be removed from the entrance channel to be absorbed by the target nucleus. After the absorption nuclear reaction may occur by any of three processes, viz, direct reaction mechanism, compound nuclear emission or by pre-equilibrium emissions. If the projectile enters the nucleus and interacts with one nucleon (or a cluster) and both of them are ejected after a single interaction this is called direct reaction. If the projectile interacts with a limited number say 2 to 5 nucleons, before the striking projectile and or the ejectiles come out, this is a case of pre-compound reaction mechanism. On the other hand, the incident projectile may interact with a large number say thousands or more of the nucleons, inside the nucleus in some sequence and the energy of the incident particle is shared by a very large numbers of nucleons, so that only after a lot of interactions including many reflections from the surface, some nucleons (or clusters) find enough energy and get emitted. This scenario corresponds to the compound nucleus formation [5].

In general,these reactions can be classified according to the time scale on which they occur, and the degree to which the kinetic energy of the incident particle is converted into internal excitation of the final products. The interaction of a projectile with a nucleus

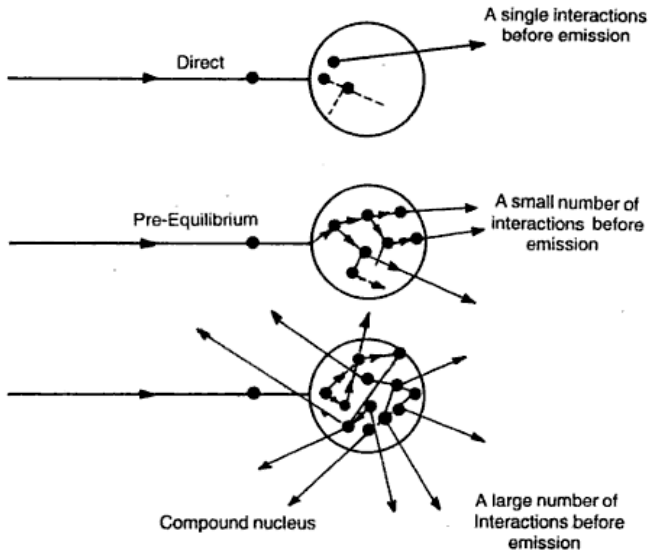

Figure 3.1: Three models of reaction mechanism. In the direct mode, there is only one interaction; in pre-compound 2-4 or 5 and in compound several thousand interaction before emission.

may exhibit several effects. An overview of all possible nuclear reaction mechanisms is given by in Fig(3.2)

The simplest form is the formation of the compound nucleus which can be described by statistical mechanics as being in a state of statistical equilibrium. The energy distribution of the components of the system is Maxwellian. A component of this system may get a large amount of energy as a result of the statistical fluctuation. This amount of energy may enough to cause the decay of the compound nucleus. Being a statistical process, the evaporation of particles favors the escape of nucleons having the minimum possible energy. In case of charged particles, this minimum energy is the Coulomb barrier of the compound nucleus. When the compound nucleus has reached statistical equilibrium, it is said to have been thermalized.

If the nuclear reactions proceed directly from the entrance channel to the exit channel without the formation of an intermediate state, they are said to be direct reactions. If the internal states of the two colliding systems do not change, we have elastic scattering

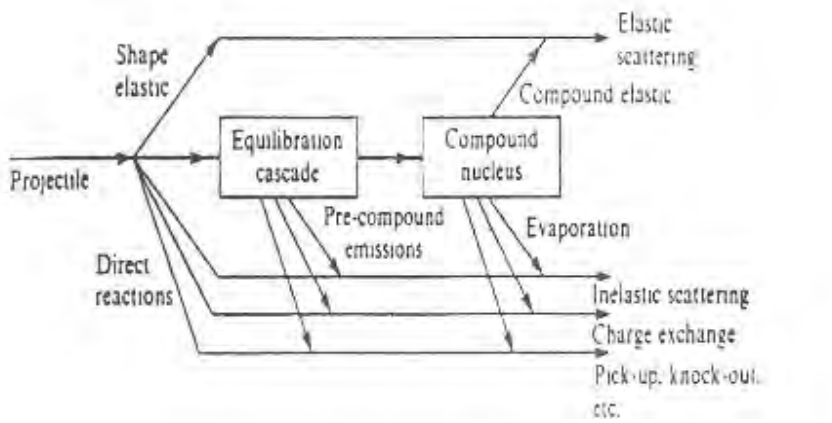

Figure 3.2: An overview of all possible nuclear reaction mechanisms

and if one or both systems are excited in the exit channel, it is inelastic scattering.

3.1 Direct reaction mechanism

A direct reaction takes place when the projectile interacts with a target nucleon or a cluster of nucleons and excites it. The incoming particle has sufficiently high energy so that after the collision either the projectile or the target particle has enough energy to escape from the target-projectile composite nucleus. Alternately, the projectile might pick-up one or more nucleons from the target nucleus, or, if it is a composite particle, it might lose one or more nucleons to the target nucleus. In any case the projectile interacts with only a small portion of the nucleus with the consequence that the ejectile takes up a substantial part of the projectile momentum. The projectile energy is then high and the residual nucleus is left at comparatively low excitation where the nuclear states are discrete. The ejectile spectrum is, therefore, also discrete. One property which distinguishes this type of reaction,direct reaction, from the compound nucleus reaction is that it proceeds much more rapidly, in time of the order of the nuclear transit time about 10^{-21}s.

Unlike compound nucleus theory,experiments show that the differential cross section of certain type of reaction is strongly peaked in the forward direction. This may be accounted for if it is assumed that some of the incident particles interact with nucleons in the

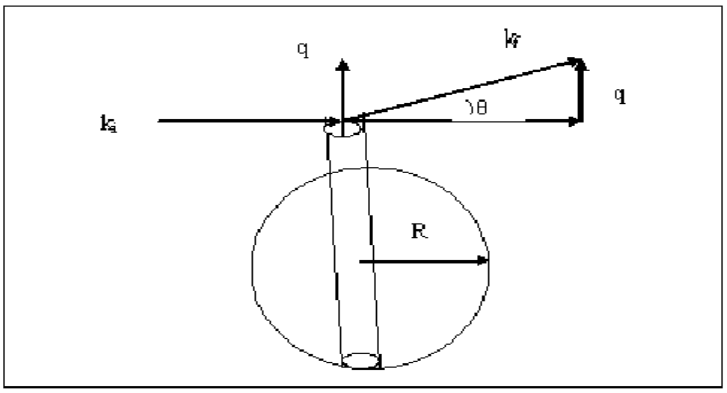

Figure 3.3: Interference in direct interaction in the surface of the nucleus Ref[13]

equatorial rim of the target nucleus. In doing so they loose some energy and are deflected through a small angle but not captured into the compound nucleus. When the incident particles are positively charged,some of them which also interact with the interior of the nucleus will be reflected back by the Coulomb barrier until they are captured into the compound nucleus [12].However,this compound nucleus will decay predominantly through the emission of neutron, so that the compound process is dominant in the (p,n) reaction. The direct reaction process involves a single-step interaction between the projectile and a target particle (single nucleon or cluster). The wave functions involved are comparatively simple and standard one body wave equations can be used to analyze the ejectile spectrum and angular distribution. Also, since the projectile energy and momentum govern the kinematics of the interaction leading to direct emissions, the ejectile angular distribution is strongly forward peaked [1]. If we take the target nucleus to be moderately absorptive so that direct reaction takes place throughout the nuclear surface, the interference in the surface of the nucleus may be studied with a simple geometrical representation.

Let K_i be the incident wave vector and K_f is the wave vector of emitted particle at an angle θ from the initial direction. Then the angular momentum transfer vector is $L = \hbar q \times r = \hbar(K_i - K_f) \times r$ where r is the position vector at the point of interaction of the incident and the target particle(nucleons) and q is the linear momentum transfer.

From the vector diagram as shown in the figure(3.3), we can write

$$q^2 = K_i^2 + K_f^2 - 2K_iK_fcos\theta \tag{3.1.1}$$

for stripping reaction like (d,p) the q may be the linear momentum transferred to target nucleus by absorbed neutron.we can write $K_i = K_d, K_f = K_p$ and $q = K_n$

We can write Eqn.(3.1.1) for (d,p) reaction

$$K_n^2 = K_d^2 + K_p^2 - 2K_dK_pcos\theta \tag{3.1.2}$$

The angular momentum transfer by absorbing neutrons is given by:

$$L_n = \hbar(K_n \times r) \tag{3.1.3}$$

L_n must be an integral value(integer multiple of $\hbar$) i.e.$L_n = l_n\hbar$ where l_n=0,1,2,.....

As r is perpendicular to the linear momentum vector K_n,we can write:

$$K_nr = K_nRsin\beta = l_n$$

or

$$\frac{l_n}{K_n} = Rsin\beta$$

for $\beta = 90$

$$\frac{l_n}{K_n} \leq R \tag{3.1.4}$$

0r

$$\frac{K_n^2}{l_n^2} \geq \frac{1}{R^2} \tag{3.1.5}$$

$$\frac{K_d^2 + K_p^2 - 2K_dK_pcos\theta}{l_n^2} \geq \frac{1}{R^2} \tag{3.1.6}$$

or

$$cos\theta \leq \frac{K_d^2 + K_p^2}{2K_dK_p} - \frac{l_n^2}{2K_dK_pR^2} \tag{3.1.7}$$

For given values of the energy of the deutron and proton which determines the value of K_d and K_p for a given nucleus(given R). Eqn.(3.1.7) can calculate the emission angle

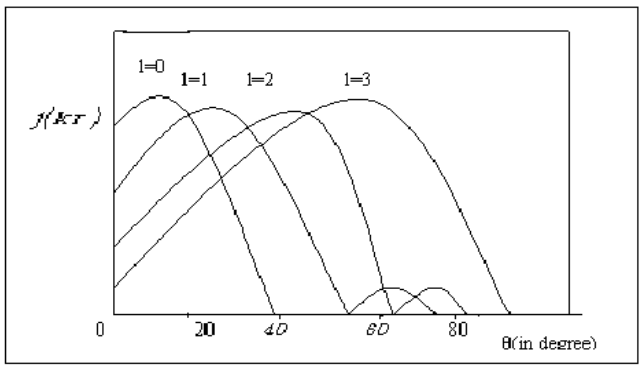

Figure 3.4: Direct interaction angular distributions

of proton and sets an upper limit to the value of $cos\theta$ or lower limit to θ,the angle at which proton is emitted. In Eqn.(3.1.7) if $K_d^2 + K_p^2 \geq 2K_dK_p$ the first term more than 1.suppose the second term is zero due to $l_n = 0$ and if the first term is 1,$\theta = 0$. The angle of emission of proton is $\theta = 0$. But if $l_n = 1, 2, 3, ..,$ second term give some negative contribution which will make $cos\theta$<1 and angle θ increases from 0.

The angle θ is increasing with l_n value,i.e. angular momentum transfer to the nucleus.The quantum mechanical theory of direct reaction was given by N.Austerts and S.T.Butlar. They have shown that the differential cross-section is proportional to the modules square of spherical Besseles function[7].i.e.

$$\sigma \propto |j(KT)|^2 \tag{3.1.8}$$

where $j(KT)$ is spherical Bessel function.Some direct interaction angular distributions are shown in Fig.(3.4) taken from Ref.[4].

3.2 The compound reaction

At the other extreme we have the compound nuclear reactions these reactions are important at comparatively low incident energies. In this case there is no emission after a single interaction. Instead both the projectile and the excited nucleon (or cluster) remain

inside the nucleus and undergo further interactions inside the nuclear matter. Through successive interactions the energy and momentum brought in by the projectile are diffused through the nucleus and eventually transferred to the composite nucleus as a whole. During the process of energy-momentum sharing more and more degrees of freedom are excited after each interaction with the consequence that the nuclear state becomes more and more complex. After certain relaxation time a condition of statistical equilibrium is reached when the average number of excited degrees of freedom becomes constant .At statistical equilibrium, different nuclear configurations arise and decay in to other configurations. A certain fraction of the equilibrium configuration consists of configurations in which sufficient energy is concentrated on a single nucleon (or cluster) so that it may be emitted from the nucleus.

A compound nucleus is formed when the composite nucleus attains statistical equilibrium and emissions taking place through statistical fluctuations from the equilibrium configuration are called compound nuclear emissions. A nuclear reaction of this type is described as: $x + X \rightarrow C^* \rightarrow Y + y$. On nuclear time scale this takes a considerable time, which is about $(10^{-13} - 10^{-16}\text{s})$. Once equilibrium is reached the compound nucleus retains no memory of its mode of formation and the decay modes of the compound nucleus are the very general ones. The ejectiles come out with low energies the residual nucleus is left with comparatively high excitation where the density of nuclear levels is large. So the ejectile spectrum is continuous.

According to the Bohr assumption, We can Write the probability of formation of compound nucleus $\sigma_c(a)$ and the probability of a decay of compound nucleus Y and emitted particles b of a nuclear reactions X (a,b)Y in the form

$$\sigma(a, b) = \sigma_c(a) G_c(b) \tag{3.2.1}$$

Where, $\sigma_c(a)$ is the cross sections for the formation of a compound system by particle a incident up on the target nucleus X. Gc (b) is the probability that the compound system C, once formed , decay by emission of a particles b, leaving a residual nucleus Y. Gc (b)

is a pure number; the compound system C must decay eventually in some way; $G_C(b)$ is the probability of this special way of decay. It can also be referred to as the branching ratio of the reaction in to the emission of b.

Evidently

$$\sum G_c(b) = 1 \tag{3.2.2}$$

if the sum is extended over all particles b which C can emit.

It is useful to specify the reaction X (a,b) Y in greater detail, by considering the cross section $\sigma(\alpha, \beta)$ corresponding to a specific entrance channel α and specific exit channel β. In other words, we specify the quantum states of all reactions partners before and after the reaction [7].

We therefore write

$$\sigma(\alpha, \beta) = \sigma_c(\alpha) G_c(\beta) \tag{3.2.3}$$

Where $\sigma_c(\alpha)$ is the cross section for the formation of C channel α, and $G_c(\beta)$ is the probability that C decays through channel β.

According to the Bohr assumption, the disintegration of the compound system in to the different channels β, γ, etc.,depends only on the energy E_c, the angular momentum J_c , and the parity of the compound system.

In order to simplify our present consideration, the dependence of the properties of the compound system on the angular momentum J and the parity Π will be ignored in this section. We now introduce a few magnitudes which describe the disintegration of the com pound system C. We begin with the mean life time $\tau(E_c)$ of C before disintegration and define the magnitude.

$$\Gamma(E_c) = \frac{\hbar}{\tau(E_c)} \tag{3.2.4}$$

Which is $\hbar$ times the rate of disintegration per unit time.

Γ is an energy and, later on, will play the role of a level width. We therefore call it the total width of the state of C with an excitation energy E_c. C can decay in to several

channels, and its total decay rate Γ can therefore be subdivided in to decay rates referring to specific channels.

$$\Gamma(E_c) = \sum \Gamma_\beta(E_c) \tag{3.2.5}$$

Where the sum is extended over all channels in to which C can decay, i.e., over all open channels. The specific decay rate $\Gamma(E_c)$ is also a function of E_c and is called the partial width for the decay in to channel .

The magnitude Γ_β can also be defined as follow:

If an assembly of N equal samples of the compound system C is arranged in such away that, on the average, N system constant in time (i.e. as many compound systems decay as are produced), then the number of decays in to channel β per unit time is given by

$$\frac{N\Gamma_\beta}{\hbar} \tag{3.2.6}$$

We can now express the branching probability in terms of the decay rates by the relation

$$G_c(\beta) = \frac{\Gamma_\beta}{\Gamma} \tag{3.2.7}$$

The reaction time for compound nuclear emissions is of the order of the relaxation time. A perturbation of nuclear matter has a typical propagation velocity of the average nucleon velocity inside the nuclear matter.

If v and l be the average nucleon velocity and the mean free path respectively, inside the nucleus, then the average number of interactions per unit time is v/l. If N interactions are necessary to reach the statistical equilibrium then Nl/v is the time taken to form the compound nucleus. The relaxation time may then be expected to be one or two orders of magnitude longer than the time taken for direct reactions. The direct and compound nuclear reactions taken together can account for the greater part of the nuclear reaction cross-sections. However, these are not the only mechanisms by which particle emission can occur in nuclear reactions[1].

3.3 Pre-equilibrium reaction

Particle emission is also possible while the composite nucleus is proceeding towards statistical equilibrium. Emissions taking place after the first projectile-target particle interaction are direct emissions. Emissions from the second interaction onwards in the non-equilibrated system belong to the category of pre-equilibrium or pre-compound nuclear reactions. The pre-equilibrium reactions are at one end of the nuclear reaction time scale.

Many recent heavy-ion experiments have provided evidence for non-equilibrium particle emission. In order to interpret the physical message of the experimental observations it is necessary to have an appropriate reaction model. Suitable models for heavy-ion pre-compound decay phenomena may provide the necessary bridge in understanding the transition between low energy compound nucleus reaction and the fragmentation reactions of higher incident energies. Some of these models are discussed in the following sub-sections.

3.3.1 Exciton model

The exciton model, first introduced by Griffin[10] and later modified by many workers, the composite nucleus states are characterized by the number of excited particles and holes (the exciton) at every stage of the nucleon-nucleon cascade. In this model the equilibration between target and projectile is achieved by the succession of nucleon-nucleon interactions. The initial configuration is fixed by the nature of the projectile. For example in the case of a nucleon-induced reaction, it is a two-particle and one-hole configuration due to the interaction of the incident nucleon with a nucleon of the target which is excited from a state below to a state above Fermi energy. Additional nucleon-nucleon interactions give rise to a sequence of states characterized by increasing exciton numbers, eventually leads to a fully equilibrated residuals nucleus. A typical graph illustrating the simple exciton model is illustrated in fig 3.5. Initially the target nucleus is in the ground state.

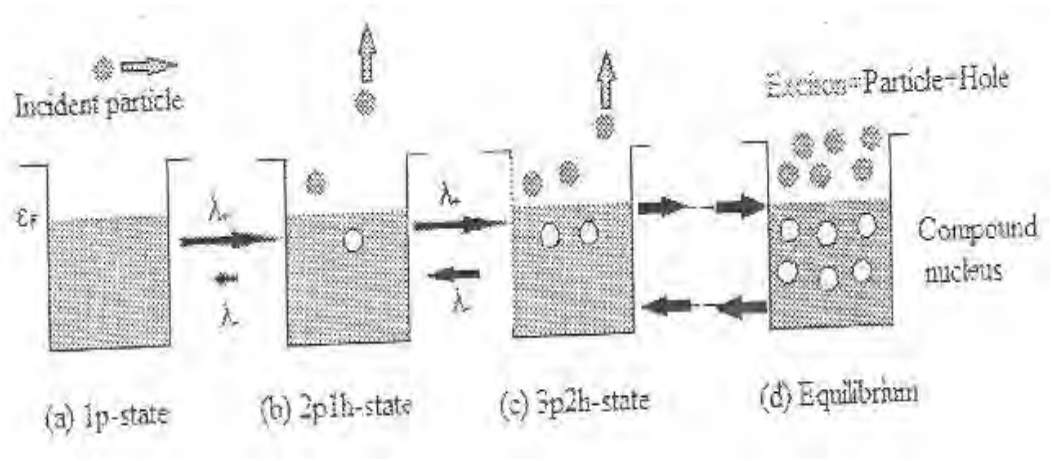

Figure 3.5: A typical diagram illustrating a nucleon-induced Exciton model.

All the levels below the fermi energy are filled and all the levels above are vacant.

The projectile nucleons enter the target nucleons with a given energy and form 1 particle - 0 hole (1p0h) states. In this case n=1 as can be seen in fig 3.5(a) at this stage, the projectile has entered the nuclear force field but has not been absorbed by the target. It is still in the entrance channel and can leave the nuclear force field without interacting with any individual target nucleon. Since all levels below the fermi energy are filled, the first interaction (absorption by the target) between the projectile and target nucleon will rise the later above the fermi energy and leave a hole below. Thus 2p1h state is formed i.e., a state with exciton number n=3 state either of the excited particles may be emitted if it has sufficient energy to escape. If however, particle emission does not take place, and then there will be a further two body interaction either between one of the excited particle and a nucleon below fermi sea or between the two excited particles themselves. The first process leads to the formation of n=5 (3p2h) state while the second would produced a new state n=3 (2p1h) state having different energy configuration of the hole and particles, or back to the original n=1 exciton state. Restrictions to two-body interactions lead to the following selections rules concerning the possible variation of the number of particles p, holes h, and exciton n=p+h, in the course of the cascade of interactions: $\Delta p = 0, \pm 1, \Delta h = 0, \pm 1, \Delta n = 0, \pm 2$.

The states which are excited in the course of this interaction cascade are very unstable. In exciton model intermediate states play significant role in dealing PE processes. Single particles densities are often used to calculate the exciton level densities, assuming the nucleus to be distinguishable fermi gas with equidistance level[9]. The transition rates are proportional to level density of the final accessible states (Fermi Goldens rule). Ericson's[11] level density result, at a given exciton number n, with excitation energy E_{ex} is:

$$\rho_n(E_{ex}) = \frac{g(gE_{ex})^{p+h-1}}{p!h!(p+h-1)!} \tag{3.3.1}$$

In this equation g is the one-particle state density, E_{ex} is the excitation energy, and p and h are the numbers of excited particles and holes. Wiliam[8] gave expression for the particle-hole density by considering the effect of the pauli Exclusion principle in the uniform spacing model as

$$\rho_n(E_{ex}) = \frac{g(gE_{ex} - A(p,h))^{p+h-1}}{p!h!(p+h-1)!} \tag{3.3.2}$$

Here $A(p,h) = \frac{1}{2}(p^2 + h^2 + p - h) - \frac{1}{2}h$

The probability of decay from an n exciton state $P_n(E_{ex})$ is defined as the ratio of the emission rate from n to the rates of all transitions (including emission) from n. If $\lambda_c^n(\varepsilon)$ be the emission rate with energy ε (in the interval $d\varepsilon$) from the n exciton state and $\lambda_{\pm},_0^n$ the rates for the transitions corresponding to the change of the exciton number $\Delta n = \pm 2, 0$

$$P_n(\varepsilon) = \frac{\lambda_c^n(\varepsilon)}{\lambda_+^n + \lambda_-^n + \lambda_0^n + \int d\varepsilon \lambda_c^n(\varepsilon)} \tag{3.3.3}$$

The exciton model assumes that

i) at each stage of the cascade all the states with the same configuration and the same total energy are equiprobable, and

ii) at each stage of the cascade all the processes which may occur are also equiprobable . The first assumption implied that partitioning of energy occurs with equal apriori probability. Hence emission rates are summed over all ε in the denominator to obtain $P_n(\varepsilon)$.

The emission rate as obtained from the principle of detailed balance is given by

$$\lambda_c^n(\varepsilon) = \frac{(2s+1)}{\hbar}[\frac{\rho_{n'}(u)}{\rho_n(E_{ex})}]m\varepsilon\sigma_{inv}(\varepsilon) \tag{3.3.4}$$

Here s and m are the intrinsic spin and reduced mass of the ejectile,n' is the exciton number after emission of ejectile with v nucleons: $n' = n - v$, u is the residual excitation energy given by $u = E_{ex} - B - \varepsilon$, with B the ejectile separation energy, σ_{inv} is the inverse cross-section. Using Fermi's-golden rule the transition rates are defined as

$$\lambda_+^n = \frac{2\pi}{\hbar}|M_+|^2\rho_{n+2}, \Delta n = +2 \tag{3.3.5}$$

$$\lambda_-^n = \frac{2\pi}{\hbar}|M_-|^2\rho_{n-2}, \Delta n = -2 \tag{3.3.6}$$

$$\lambda_0^n = \frac{2\pi}{\hbar}|M_0|^2\rho_n, \Delta n = 0 \tag{3.3.7}$$

Here $|M_{0,\pm 2}|$ are the matrix element of the corresponding transitions ρ_{n+2} , ρ_{n-2} and ρ_n are the density of states available in the n+2, n-2 and n exciton states after $\Delta n = 2, -2$ and 0 transitions. The estimation of the transition matrix element proves to be one of the most crucial points in the model. A common estimation is to assume $M_+ = M_- = M0 = M$. Using the assumption and the consequent restriction imposed on the density of final states, the transition states were given by Williams[11] as

$$\lambda_+ = \frac{2\pi}{\hbar}|M|^2\frac{g^3E^2}{2(n+1)}, \Delta n = +2 \tag{3.3.8}$$

$$\lambda_- = \frac{2\pi}{\hbar}|M|^2 gph(n-2), \Delta n = -2 \tag{3.3.9}$$

$$\lambda_0 = \frac{2\pi}{\hbar}|M|^2 g^2 E\frac{3n-2}{4}, \Delta n = 0 \tag{3.3.10}$$

Where E is the excitation energy of the system.The matrix element is evaluated empirically.The most common form of $|M|^2$ empirical results for nucleon-nucleon scattering is given by Kalbach [17].

$$|M|^2 = \frac{k\sqrt{\frac{e}{7Mev}}\sqrt{\frac{e}{2Mev}}}{eA^3} \tag{3.3.11}$$

for $e < 2Mev$

$$|M|^2 = \frac{k\sqrt{\frac{e}{7Mev}}}{eA^3} \tag{3.3.12}$$

for $2Mev \leq e \leq 7Mev$

$$|M|^2 = \frac{k\sqrt{\frac{15Mev}{e}}}{eA^3} \tag{3.3.13}$$

for $e \geq 15Mev$

where $e = \frac{E}{n}$ and $k = 135Mev^3$

Compound nuclear equilibration is attained when the rate of creation of p-h pairs approximately equals the annihilation rates of such pair, so that the exciton number $n = \bar{n}$ remains unchanged. Assuming that λ_{n+2}=λ_{n-2}=λ_0 at equilibrium i.e.,$n = \bar{n}$ it follows

$$\bar{n} \cong \sqrt{2gE} \tag{3.3.14}$$

At low excitation energy, it is reasonable to assume energy independent matrix element. While at higher excitation energies, energy dependent matrix elements are used. The analysis of a large body of data indicates that a mass and energy dependence of the average square matrix for nucleon-nucleon interaction given by kalbach's estimate , according to which $|M|^2$ has the following mass number (A) and energy (E_{ex}) dependent

$$|M|^2 = KA^{-3}E_{ex}^{-1} \tag{3.3.15}$$

Where K is an adjustable parameter ranging from 95-700 Mev^3

3.3.2 The Hybrid model

The Hybrid model was proposed by Blann [11].Predictions of pre-equilibrium decay in heavy ion reaction where made a decay ago using the hybrid model.The pre-equilibrium decay probability is given by

$$P_v(\varepsilon)d\varepsilon = \sum_{n=n_o,\Delta n=+2}^{\bar{n}} [\frac{nX_nN_n(\varepsilon,u)}{N_n(E)}]gd\varepsilon * [\frac{\lambda_c^n(\varepsilon)}{\lambda_c(\varepsilon)+\lambda_+(\varepsilon)}]D_n \tag{3.3.16}$$

Here $P_v(\varepsilon)d\varepsilon$ is the number of particles of the type v emitted in to the unbounded continuum with channel energy between ε and $\varepsilon + d\varepsilon$.

The quantity in the first bracket of Eq (3.3.16) represents the number of particles to be found (per Mev) at a given energy ε (with respect to continuum) for all scattering processes leading to an "n" exciton configuration. The nucleon-nucleon scattering energy partition function $N_n(E)$ is identical to the exciton state density $\rho_n(E_{ex})$ and $N_n(E)$ represent number of combination with which n exciton may share E_{ex}.

The second set of bracket in Eq (3.3.16) represents the fraction of the v type particles at energy ε which should undergo emission in to the continuum, rather than making an inter-nuclear transition. The D_n represents the average fraction of the initial population surviving to the exciton number being treated. The H model calculates the nucleon-nucleon interaction rate $\lambda_+(\varepsilon)$ from the nucleon-nucleon scattering cross-section. Blann gave the empirical expression for the two-body interaction rates[11] as follows:

$$\lambda_+^n = [1.4 * 10^{21}(\varepsilon + B_{sp}) - 6 * 10^{18}(\varepsilon + B_{sp})^2]k^{-1} \tag{3.3.17}$$

Where ε is the particle energy outside the nucleus i.e., ejectile energy and B_{sp} its separation energy k is an adjustable constant and λ_+^nrepresents the rate at which a nucleon at a given energy $\varepsilon + B_{sp}$ above the Fermi energy undergoes two-body interactions.

3.3.3 Geometry Dependent Hybrid model

Geometry dependent hybrid (GDH) model have been reasonably successful reproducing a broad range of data. This was accomplished with several choices of parameter options. The geometry dependent hybrid model is a variant of the HM in which the nuclear geometry effects are considered. GDH model takes in to account the reduced matter density and hence also the shallow potential. In this way the diffused surface properties sampled by higher impact parameter were incorporated in to the pre-compound decay formalism in the geometry dependent hybrid model.

The nucleon density distribution in the nuclear skin can affect the pre-equilibrium decay in two ways. First the mean free path in the intranuclear transitions is greater in the diffused edges and secondly the Fermi energy will be lower in that region so that the hole depth is limited. Considering these effects the Hybrid model for the cross sections was reformulated as a sum of contributions over impact parameter[11].

$$\sigma_v(\varepsilon)d\varepsilon = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)T_l P_v(\varepsilon)d\varepsilon \tag{3.3.18}$$

Where $P_v(\varepsilon)$ is the pre-equilibrium decay probability calculated as a function of nuclear density and T_l is the transmission coefficient. The differential emission spectrum is given in the GDH model as

$$\frac{d\sigma_v(\varepsilon)}{d\varepsilon} = \pi\lambda^2\sum_{l=0}^{\infty}(2l+1)T_l P_v(l,\varepsilon) \tag{3.3.19}$$

Where $P_v(l,\varepsilon)d\varepsilon$ is as for $P_v(\varepsilon)d\varepsilon$, but evaluated for the l^{th} partial wave. T_l is the transmission coefficient for the l^{th} partial wave, and λ is the reduced de-Brolie wave length.For the calculation of the nuclear density the Fermi distribution may be applied as used by M. Blann [11].

$$d(R) = \frac{\bar{d}}{[e^{\frac{R-c}{z}}+1]} \tag{3.3.20}$$

Where $d(R)$ is the nuclear matter density at radius R, $\bar{d}$ is the central nuclear density,c is the charge radius with

$$c = 1.07A^{\frac{1}{3}}fm$$

and $z = .55fm$. The transition rates in the Hybrid model in each region is multiplied by $\frac{\bar{d}}{<d(r)>}$ to include all impact parameters. Where $< d(R) >$ represent the average density for the impact parameter taken into consideration.

3.4 Heavy-ion reaction

The study of the interaction of two heavy ions is a subject of growing interest in nuclear physics. Because of the heavy mass of the incident heavy ion, a lot of energy and angular

momentum can be imparted to the target nucleus giving rise to new phenomenon, e.g fusion-fission, etc. Any nuclide heavier than alpha (He^4) may be called heavy ions. The word ion is used because in experimental studies, it is a positively charged ion, with many electrons removed from the neutral atom, which is either say in a tandem electrostatic, accelerator or in a cyclotron. So any ion from He^4 up to Pb^{208} or U^{238} is a heavy ion.Reactions have been studied using a large number of heavy ions as projectiles. Very commonly used heavy ions are: Li^6, C^{12},N^{14}, O^{16}, Ne^{20}, Mg^{24}, Al^{27}, S^{32}, Ca^{40}, Cr^{52}, Ni^{58}, Sn^{120}, Pb^{208},etc.

The heavy ion induced reaction is somewhat complex because of the complexity of the incident projectile. The complex nature of the projectile makes it possible that a number of new reactions occur, and also when the projectile fuses with the target nucleus creating a compound nucleus one has to consider the special features of the heavy-ion reaction due to the large angular momentum carried in by the projectile.

At low energies two heavy ions interact only through their Coulomb fields, and can scatter elastically or inelastically with coulomb excitation. Nuclear reactions can only take place if the two-ion energy E_{cm} in their center of mass system is high enough to overcome the Coulomb barrier, and then the associated wave length $\lambda = h/\sqrt{2ME_{cm}}$ is much less than the nuclear dimensions. In such circumstances the interaction shows semiclassical features, and in particular it is appropriate to consider the ions moving along their classical orbits [9]. This semiclassical nature of the heavy-ion interactions makes it possible to give an overall description in terms of the minimal distance between the two interacting ions r_{min} which is simply related to the impact parameter b by

$$r_{min} = \frac{b}{\sqrt{1 - \frac{V(r_{min})}{E_{CM}}}} \tag{3.4.1}$$

Where $V(r_{min})$ is the nuclear potential acting between the two ions. Even though such a description is only qualitative and a full treatment must take account of the quantum mechanical nature of the process, it is possible to distinguish four regions where the

different reaction mechanism predominates as the minimal distance between the two ions increases:

(1)the fusion or compound nucleus formation region, with $0 \leq r_{min} \leq R_F$;

(2)the deep inelastic and the incomplete fusion region with $R_F < r_{min} \leq R_{DIC}$;

(3)the grazing region with $R_{DIC} < r_{min} \leq R_N$;

(4) the Coulomb region with $r_{min} > R_N$, where R_N is the distance above which nuclear interactions are negligible.

The ion orbits corresponding to these regions are schematically shown in fig.3.6. Nuclear reactions, induced by heavy ions below but near Coulomb barrier are useful for exciting the collective model of excitation of the target nuclei.

Because Coulomb barrier is comparatively high in heavy ion-induced reactions and the projectile energies generally available are of the same order as the Coulomb barrier, the Coulomb barrier energy becomes very good reference energy to describe the reactions. Further, one can decide the reactions according to the impact parameter (R_1) in a semi classical manner. It may be noted, that the impact parameter is the closest distance of approach of the projectile as indicated in fig 3.6.

One, then,has the following possibilities:

i)If $R1_1 >> R = R_1 + R_2$, the projectile passes quite away from the nuclear range of interaction of the two nuclei and only Coulomb interaction is possible between the projectile and the target. Then only Rutherford elastic scattering takes place, or the target and/or projectile may be internally excited, through Coulomb excitation giving rise to inelastic scattering of the projectile. This is shown in trajectory (1) in fig 3.6.

ii)If $R1_2 is \approx R_1 + R_2$, i.e. the outer surface of the incident projectile just grazes along the surface of the target nucleus, then the edges of the nuclear ranges of the nuclei just touch, so that only the outer portions of the skins of the two nuclei interact. Then only the extremely outer lying nucleus in the two nuclei comes within the nuclear range of interaction. This may, lead to one or two nucleon-transfer from one nucleus to the other

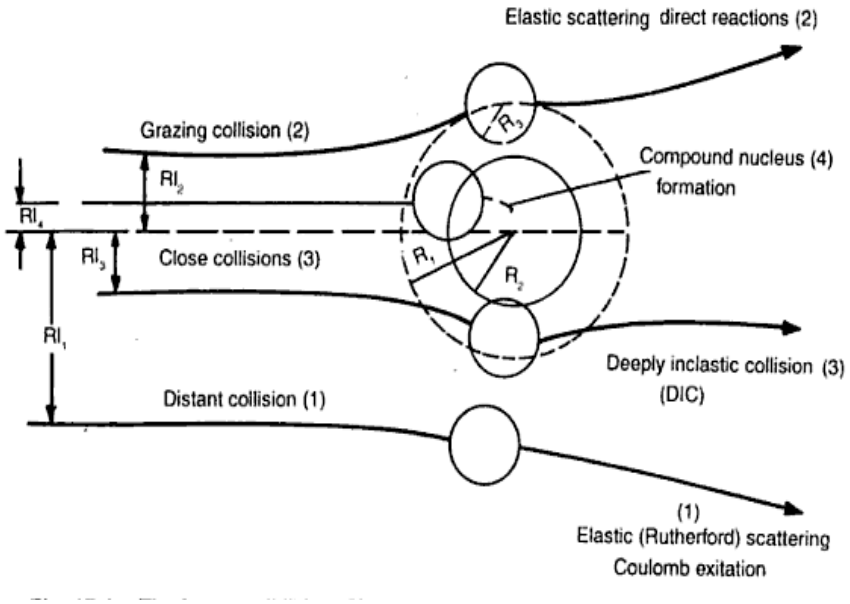

Figure 3.6: The four possibilities of heavy ion interactions, as seen classically showing the trajectories, corresponding to distant collision (Trajectory1), grazing (Trajectory2), close collisions (Trajectory3), and for compound nucleus formation (Trajectory4).

or only elastic scattering or inelastic scattering may take place when any one of the two nuclei are internally excited, either via Coulomb excitation or nuclear interaction. This is induced by trajectory (2) in fig 3.6.

iii)If $R1_3 \leq R_1 + R_2$, i.e. the incident projectile just enters the nuclear range of the interaction of the two nuclei. This is a case, where nuclear interaction is prominent and elastic scattering is nearly absent. Then deep inelastic collisions predominate. Here a few nucleons from one to five or six nucleons can get transferred from one nucleus to the other.

iv)If $R1_4 << R_1 + R_2$ and the energy of the incident projectile is high enough, so that it can penetrate the Coulomb barrier, the projectile, then enters the nuclear body much beyond the nuclear skin. Then the interaction of the nucleons in the incident nucleus will be very strong with the nucleus in the target nucleus giving rise to various phenomena, e.g. (1) fusion: so that the two nuclei completely merge into each other giving rise to the highly excited state of the compound nucleus, which decays through gamma emission. (2)

fusion-neutron Evaporation: In this case, the compound nucleus may decay to another nuclear species, by the evaporation of many neutrons from the compound nucleus. This may lead to exotic nuclei. (3) fusion-fission: so that after the compound nucleus formation, it fission into two less heavy nuclei-according to laws of fission.

As the projectile is heavy and target nucleus also heavy, therefore there is involvement of large mass (large number of nuclei) in nuclear reaction. As a result, in nuclear reactions induced by heavy ions:

(a)There may be transfer of huge mass or large number of nucleons. From a single nucleon transfer to large number of nucleon transfer may take place.

(b)Transfer of very large energy and momentum takes place. In these reactions we get highly excited states with large angular momentum transfer.

(c)We can also populate nuclei which are far away from the stability line. Such nuclei which either have large number of neutrons or protons (not available in nature) can be produced which are called Exotic nuclei.

(d)Due to large amount of mass transfer and also in the decay (after reaction) we may have emission of several types of systems, i.e. light particles, nucleons and also heavy elements (heavy fragments). The measurement of decay products is not an easy task. It involves certain special types of detecting or analyzing systems.

Chapter 4

THE COMPUTER CODES AND FORMULATION

4.1 Nuclear data Evaluation

The Nuclear data evaluation is carried out by the experimental data and theoretical model of calculations. It is difficult to measure the necessary cross-section for all the isotopes produced by the intersection of heavy ions for a wide range of energies. This is due to economical problem and the experimental difficulty. Nuclear reaction models are always needed to get the estimates of the particle-induced reaction cross-section. This reaction model is very important when the experimental data are not available or if it is impossible to measure the cross-section due to the experimental difficulty. Therefore,nuclear reaction calculations play an important role in the nuclear data calculation.

4.2 Formulation

In the pre-equilibrium emission calculations,the initial exciton configurations and level density parameters are very essential quantity. The nuclear level density influences the shape and the height of the calculated excitation functions. The level densities of the

nuclide involved in the evaporation chain may be calculated from the Fermi density distribution[18].

$$\rho(E) = \frac{\pi^{\frac{1}{2}} e^{2\sqrt{aE}}}{12 a^{\frac{1}{4}} E^{\frac{5}{4}}} \tag{4.2.1}$$

Where 'E' is the excitation energy and 'a' the level density parameter. The level density parameter obtained by experiment shows a linear dependent with the mass number of the compound nucleus. In general it is given by an expression,

$$a = \frac{ACN}{K} \tag{4.2.2}$$

Where 'ACN' is the mass of the compound nucleus and 'K' is the free constant. In the thesis the level density parameter $a = \frac{ACN}{10}$ is used for all the reactions,which is the best fit to experimental results. The theoretical calculations in this thesis is done using the exciton $n_0 = 12(6p+6n+0h)$. These excitons interact independently with the particles below the Fermi level,creating new particle-hole configuration in the second stage or getting emitted into the continuum.

4.3 Complet code

The code COMPLET is a nuclear reactions code which was designed for versatility and ease of use in the bombarding energy range of a few Mev to several hundred Mev.The code COMPLET is based on same philosophy as the former code INDEX (15). It applies the statistical model of compound nucleus decay developed by weisskopf-Ewing (12) and the hybrid and geometric dependent hybrid model of Blann (11) and the further simplification and improvement by J.Ernst (16).

It predicts the yield of residual nuclei in nuclear reaction with excitation energy up to 225Mev taking in to account two mechanisms. Pre-equilibrium emission is accompanied in the frames of the model of independently interacting exciton. An approximation concerning pre-equilibrium angular momentum removal is included. The equilibrium part formerly based on Weisskopf-Ewing evaporation formula is also modified to include full

angular momentum decoupling regarding emission of light particles with $A \leq 4$. In COMPLET code a pre-equilibrium process in two stages is assumed. The particles in the initial configuration (n_o=EX1+ EX2+ EX3) can be neutron, proton or alpha particle, represented by the exciton numbers EX1, EX2 and EX3 respectively. It is customary to use the initial exciton number n_o separated in to proton and neutron above and holes below the fermi level as a fit parameter to match theoretical prediction with experimental excitation function. The requirement of detailed input parameters was sacrificed to achieve this goal. The code COMPLET provides yields and spectra for all reactions populated by all combinations of n, p, d, α and can provide all input parameters internally. The running time of the code is very short. This code includes damping of fission widths above a critical temperature R_o. The used code is a further simplification of the formula due to Paul and Thoennessen in Ann.Rev.Nucl and particle science 44(1944).

This version needs about 2 megabyte memory. Therefore the option of calculations of particle-residual nucleus correlations as well as the option for calculating inclusive p-and n-spectra. The code COMPLET includes pre-equilibrium neutrons, protons and alpha emission up two particle, as well as evaporation of neutron protons, α, deuterons, tritons and hellions. Originally, this code has been developed out of the code OVERLAID ALICE by M.Blann. while some standard routines remained practically unchanged (like FISROT,LMASS,PUNCH,PLT, PARAP, OVER1, OVER2 and TLJ) others have been substantially modified (like MAIN, SHAFT, NUCMFP,etc) or are completely new (like, INDEX, PARDEN, TRAPRO, ANGULAR, etc)the underlying PE-MODEL is described in Z.Phys.A328 (1989).It is contained in subroutine INDEX.

The INPUT is described below. The notion “card“ from the old FORTRAN input is still kept but now corresponds to lines. Free formats, the input values should be separated by ”,” or “CR”.

CARD 1

General input data: definition of scattering system and calculation method.

Symbol description

AP - Projectile mass number

AT - Target mass number

ZP - Projectile charge

ZT - Target charge

QVAL - Reaction Q value = AP+AT-ACN.

= 0: calculated from M and S mass formula.

= 1: calculated from mass excesses of 1990 nuclear wallet cards

CLD- ratio of single particle level densities $\frac{af}{an} = 0$:$\frac{af}{an} = 1$.

If parameter ISOT is nonzero, CLD is isotopic abundance input default value =1.0

If =0, use rotating finite range fission barriers due to A.J.sierk

BARFAC- multiplies the rotating drop fission barrier by this value.

BARFAC = 0: BARFAC=1

ROFFAC - multiplies the rotational energy by this value. = 0:ROTFAC=1.

RO- critical temperature above onset of retarded fission

GI - nuclear friction parameter from equilibrium deformation to saddle

GO - nuclear friction parameter from saddle to scission point

NA - the number of nuclides of each z to be included in the calculation. Up to 21 neutrons may be emitted (maximum NA=22)

NZ - the number of Z- values to be calculated in the emission process. up to 8 protons may be emitted (maximum NZ=9). For correct PE calculations binding energies are calculated for all nuclei with IZ, $IA \leqq 5$ (17.7.91)

MC-Shell correction option for masses subroutine.

MC = 0, masses incl. Shell correction.

MC = 1, masses without shell correction term

MC = 2, BE values will be supplied as input.

MC>2, BE values are calculated from 1990 nuclear wallet cards.

MP- pairing correction to masses.

MP = 0: no pairing term in masses.

MP = 1: pairing term in masses, ldgs calculated from msl formula and applied back shifted

MP =2: masses are from nuclear wallet cards;

MP =3: pairing correction in masses, NOTE: changes are not corrections in only level densities

IPA - pairing corrections in level densities

IP= -1, no corrections

IP =0, standard correction i.e multiplier =12

IPA>0 multiplier is IPA

M3- number and type of particles to be emitted from each nuclide

If = 1: N only;= 2:N and p;=3 or =0:N,p and Alpha;=4:N,p,alpha and Deuteron.

If = 5: N, p, Alpha, Deuteron and Triton;=6: N,P, Alpha, Deuteron, Triton and hellion (3HE)

IF =7: as before incl. Gammas. Calculations until gamma emission is finished important for isomeric ratio calculations.

INVER inverse cross section parameters.

If = 0 user supplied:

If 1: results by O.M subroutines as ALICE/85/300,

If = 2 O.M for N, p as in old ALICE

If =3: sharp cutoff values for inverse cross sections

Option Inver =2 greatly reduces total cpu time

IKE if = 1 no particle spectra will be printed:

If= 2 equilibrium spectra for each nuclide will be printed:

If =3 pre-compound spectra will be printed

If = 5 PE and summed equilibrium spectra will be (separately) printed:

If IKE = -2 to -5: reduced output with spectra as IKE =ABS(IKE)(yields are printed after negative energy input)

If $IKE \leqq 0$ or $IKE \geqq 6$ most reduced output

emitting nuclides and all partial waves) of pre-compound plus equilibrium spectra. To print gamma spectra, increase the IKE value selected by 5.

If IPCH =1 or =2, fission barriers are to be read in after this first record IPCH - = 1: inverse cross sections will be readout for possible future use in separate output file.

= 0: or NE from 1.no printout

KPLT - number of decades to be plotted as excitation function on line printer. If

KPLT = 0: no plotting

Card 2

Title -80 columns

If MC = 2 on CARD 1, read user supplied n, p,alpha, deuteron triton and helion binding energies here, Format for IA =1 to NA, IZ=1 to NZ.

If INVER =0 on CARD1, read the n, p, alpha, deuteron triton, helion and gamma inverse cross sections here.

In ascending channel energy, first value = 0.1 Mev, incremented by 1Mev, 48 values per particle type in sequence N,P,A,D,T,3HE, and gamma depending on value of M3.

CARD 3

ENERGY and COMPOUND NUCLEUS and PRE-EQUILIBRIUM OPTION

Symbol Description

IKEN - projectile kinetic energy in the laboratory system.

If = 0: A new problem will begin at CARD1.

If <0: previously calculated excitation functions will be printed (if KPLT=0, EKIN values were run in ascending order they are plotted).

If EKIN=0 on two successive cards, a normal exit will occur for negative target mass on

card 1.

RCSS = 0: reaction cross section is calculated from subroutine (for pi-induced reactions: if RCSS (input) =0, RCSS=100 mb)>: number of T(l) values to be read from the next card

JCAL

= 1, weisskopf-ewing evaporation calculation

= 2, S- wave approximation, liquid drop moment of inertia

= 3, S- wave approximation, rigid body moment of inertia (only if entrance channel cross sections calculated by parabolic approximation, i.e.. ZP>1 and RCSS= 0.)

=0, evaporation-fission competition, partial wave by partial wave.

JFRAC- direct- semi-direct capture gamma ray estimate :<0: no emission>0: approach of kalka

JANG -JANG + 1 = maximum number of contributing incoming partial waves.

-Usually use the maximum: JANG =99. Otherwise, JANG can be used for cutoff on L- values provided by subroutines OVER1 and 2

All other parameters on this card are for the pre-compound calculation options. Put TD-values to zero, if no pre-compound calculation is wanted.

TD - Initial exciton number =p+h

EX1 - Initial excited neutron number

EX2 - Initial excited proton number

EX3 - Initial alpha particle exciton number

POT - Fermi energy in Mev

If = 0: POT is calculate from nucl.matter value= 37.8 Mev;

AV - if AV = 0: =1 OPTICAL MODEL mean free paths are used in routine MFP.

Not to be used above 55 Mev.

If AV = 1: Nucleon-Nucleon mean free paths are used in NUCMFP.

ALF - probability that newly created exciton particle from first stage exciton gets an

alpha particle in the second stage.

(1-ALF): complementary probability

If ALF>1 calculation for two initial exiton numbers

A)ATD=TD-3 (min.1.5) AEX1=AEX2=0. AEX3=2;ATD=TD-6 for TD>9 with weight ULF=INT (ALF)100

B)Weight = (1-ULF), with initial exciton numbers.

CMFP - mean free paths are multiplied by CMFP.if CMFP =0:multiplier is 1

GDO - critical angular momentum. GDO>0: partial waves with L>GDO are not taken in to account in line of isotone cross sections while cross sections for partial waves with L>GDO are accounted for in the line below

N.B For $GDO \leq +0.5$ No cut-off.

In these interactions the original exciton type is assumed to be conserved. The newly created exciton may be α particle, α -hole state formed with probability (1-ALF). The value of ALF = 0.2 is found to be the best choice.

The Q-value for the formation of the compound nucleus and the emitted nucleons binding energies in the evaporation chain have been calculated using Myres and swiatecki mass formula[15]. The mean free path multiplier for intra nuclear transition rates are calculated from optical potential parameters.

Chapter 5

RESULT AND DISCUSSION

In the present work the excitation functions for four evaporation residues(ERs) were studied. These are: $^{197}Au(^{12}C, 3N)^{206}At$, $^{197}Au(^{12}C, 4N)^{205}At$, $^{197}Au(^{12}C, 5N)^{204}At$ and $^{197}Au(^{12}C, 6N)^{203}At$, carried out in the 59Mev to 91Mev carbon incident energy range. The measured excitation functions were compared with the theoretical predictions obtained from the code COMPLET. The Experimental cross-section is obtained from IAEA data source , EXFOR Library[14]. The theoretical and experimental cross-sections are plotted against the projectile energy and are shown in figure 5.1 to 5.6. The theoretical calculation is performed for two cases. These are for pre-equilibrium plus compound nucleus decay excitation function and for only compound nucleus decay excitation function. The excitation function for the pre-equilibrium reaction and the excitation function for compound reaction is calculated by the COMPLET code.The excitation function for pre-equilibrium plus compound reaction is shown by the green color and the excitation function for compound reaction is shown by red color. And also the excitation function for the experimental results with errors are shown by the triangle points of black color. COMPLET code is an extension of the code ALICE-91 and INDEX. These two codes employ the Weisskopf-Ewing model for the statistical part and geometry dependent hybrid model of M.Blann for the pre-equilibrium emission. The code COMPLET gives the result of both compound reaction and compound nucleus plus pre-equilibrium reaction. The projectile energy is measured in Mega electrovolt (Mev) and

the cross-section are measured in millibarn(mb). The experimental data for the reaction $^{197}Au(^{12}C, 3N)$,$^{197}Au(^{12}C, 4N)$, $^{197}Au(^{12}C, 5N)$ and $^{197}Au(^{12}C, 6N)$ is taken from the Author S.BABA,K.HATA, S.ICHIKAWA, T.SEKINE, Y.NAGAME, A.YokoYAMA, M. SHOJI, T.SAITO,N.TAKASHI, H.BABA, I.FUJIWARA [19]. Energy range selected from the data is same with theoretical. The cross-section of theoretical and experimental with the energy range are given in table 5.1 to 5.4

The various parameters are used for calculations of excitation functions. However, the

Table 5.1: Theoretical and Measured cross-section for the reaction $^{197}Au(^{12}C, 3N)^{206}At$

$E - Lab$	$\sigma(Exp)$	Err	$\sigma(compound)$	$\sigma(pre - compound + compound)$
59	62	4.7	6.53	15.8
66	21	1.36	25.27	81.76
69	9	1.03	2	81.32

Table 5.2: Theoretical and Measured cross-section for the reaction $^{197}Au(^{12}C, 4N)^{205}At$

$E - Lab$	$\sigma(Exp)$	Err	$\sigma(compound)$	$\sigma(pre - compound + compound)$
59	38	3	34.98	24.23
60	87	5	76.74	53.4
64	361	33	286.6	199.1
67	443	40	338.3	238.5
70	448	34	253.8	231.5
76	233	14	50.04	217.2
78	182	10	50.79	253.6
80	90	6	28.88	224.4
84	32	2.1	8.91	205.6

initial exciton number is found to play an important role in the theoretical predictions. In this thesis the initial exciton number n_o with configurations (6p+6n+0h) has been taken to 12 for ^{12}C projectile, which interact independently with particles below the fermi level creating either new particle-hole configuration in the second stage or getting emitted in to the continuum. The other important thing is about level density parameter (a). It can be seen for $a = \frac{ACN}{9}$ and $a = \frac{ACN}{10}$. The excitation function for these level density parameter are almost similar. However, in this thesis the theoretical calculation is performed by the

Table 5.3: Theoretical and Measured cross-section for the reaction $^{197}Au(^{12}C, 5N)^{204}At$

$E - Lab$	$\sigma(Exp)$	Err	$\sigma(compound)$	$\sigma(pre-compound+compound)$
66	29	2.24	16.43	21.91
70	104	6.74	205.4	183.4
72	238	12.82	270.9	227.8
76	341	29.83	642.6	372.4
78	463	24.93	687.1	383
83	332	21.54	516.1	358.4
86	181	11.75	344.1	345
87	145	19.48	298.4	340.6
91	35	2.29	197.8	336.4

Table 5.4: Theoretical and Measured cross-section for the reaction $^{197}Au(^{12}C, 6N)^{203}At$

$E - Lab$	$\sigma(Exp)$	Err	$\sigma(compound)$	$\sigma(pre-compound+compound)$
75	3	0.44	2.8	4.3
77	28	5.03	19.7	26.15
78	20	3.46	17.61	25.82
79	41	7.94	35.71	47.75
80	80	8.89	66.69	78.59
81	105	19.11	104	114.7
83	104	20.22	223.4	198.7
86	153	26.06	451.6	302.1

level density parameter $a = \frac{ACN}{10}$ for pre-equilibrium reaction because it best fits with the experimental excitation function.

5.1 The production of ^{206}At

^{206}At is produced when a particle (^{12}C-particle) strike target element Gold (^{197}Au) and emits three neutron (3N). The signatures of pre-equilibrium and compound reaction are seen in the excitation functions of $^{197}Au(^{12}C, 3N)^{206}At$ reactions by comparing the calculated values with the experimental result [19].

As can be seen from the figure above, at the lower energy (58-66Mev) there is no formation of compound reaction for the reaction $^{197}Au(^{12}C, 3N)^{206}At$ and calculations have

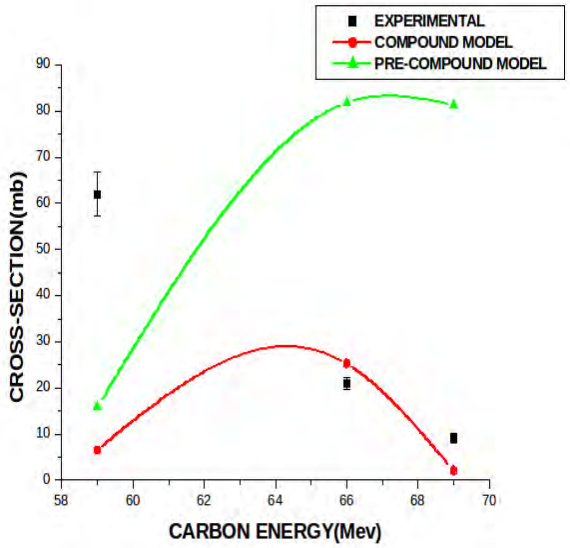

Figure 5.1: Experimental and theoretical excitation function for the reaction $^{197}Au(^{12}C, 3N)^{206}At$

be done by using consistent set of parameters. In this energy range there is also no pre-equilibrium reaction. In the reaction of $^{197}Au(^{12}C, 3N)^{206}At$ at the incident energy 59Mev of carbon the experimental values is very large than the calculated value.This is far apart from the compound nucleus values and also pre-equilibrium results. But at the higher energy range(66-70Mev) the experimenat value are very close to the compounnd nuclear emission. Therefore, now it is concluded that in the reaction $^{197}Au(^{12}C, 3N)^{206}At$ there is no signatures of pre-equilibrium reaction and only compound nucleus formation is taking place.

5.2 The production of ^{205}At

In this reaction ^{205}At is produced by releasing four neutron (4N) when a particle (^{12}c-particle) bombarded with target element Gold (^{197}Au).

From the above graph, at the lower energies around 60Mev experimental values are very simillar to both the compound nucleus reaction and pre-equilibrium reaction calculations,but it is more close to compound nuclear emission. At the higher energies around

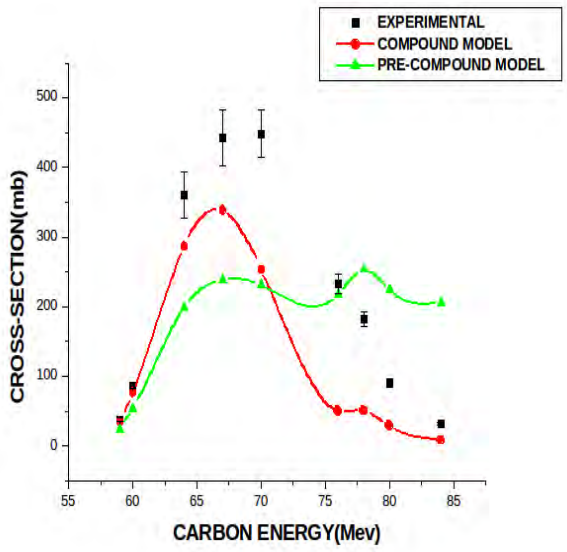

Figure 5.2: Experimental and theoretical excitation function for the reaction $^{197}Au(^{12}C, 4N)^{205}At$

80MeV and above experimental values are very close to compound nuclear calculations confirming the formation of compound nucleus;pre-equilibrium trend is far apart.In general compound nucleus formation theory satisfies the results. In this energy range no signatures of pre-equilibrium formation are obtained.

5.3 The production of ^{204}At

^{204}At is produced from reaction of target nucleus Gold (^{197}Au) with carbon (^{12}C) particle by emitting five neutrons (5N). In fact, in the $^{197}Au(^{12}C, 5N)^{204}At$ reaction in the energy range 65-77MeV the measured values are closer with pre-equilibrium results and these are lower than the compound nucleus results. The higher compound nucleus values shows no compound nulear emission and pre-equilibrium emission is giving better result. In the energy region higher than 77MeV the experimental values are far apart from both equilibrium and pre-equilibrium calculations,but their trend is similar to compound nuclear theory.And hence in this reaction signatures of Pre-equilibrium decay are seen in the lower energy range.Only at higher energy both the calculations are far apart and reaction is not

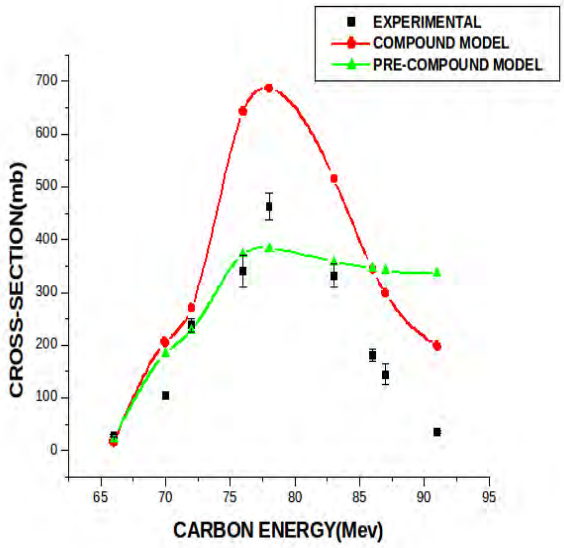

Figure 5.3: Experimental and theoretical excitation function for the reaction $^{197}Au(^{12}C, 5N)^{204}At$

taking place by these channels.

5.4 The production of ^{203}At

In the $^{197}Au(^{12}C, 6N)^{203}At$ reaction there is production of ^{203}At by emitting six neutron (6N). Similar to the previous reactions the formation of compound nuclear and pre-equilibrium nuclear reaction both give the results closer to experimental value. As can be seen from figure 5.4 one can say that both compound nuclear reaction and pre-compound nuclear reaction are possible in the incident energy range of 75 to 81 Mev. In the $^{197}Au(^{12}C, 6N)^{203}At$ reaction in the incident energy range of greater than 81Mev, calculated values both compound and pre-compound reaction theory are much larger than the experimental value. This channel is not populated by pre-equilibrium or equilibrium reactions followed by evaporation of six neutron. Therefore, in the incident energy greater than 81Mev of the $^{197}Au(^{12}c, 6N)^{203}At$ reaction there is a great difference between the excitation functions of experimental result and the pre-compound nuclear reaction. This show that in this energy range there is no signatures of pre-equilibrium reaction. But

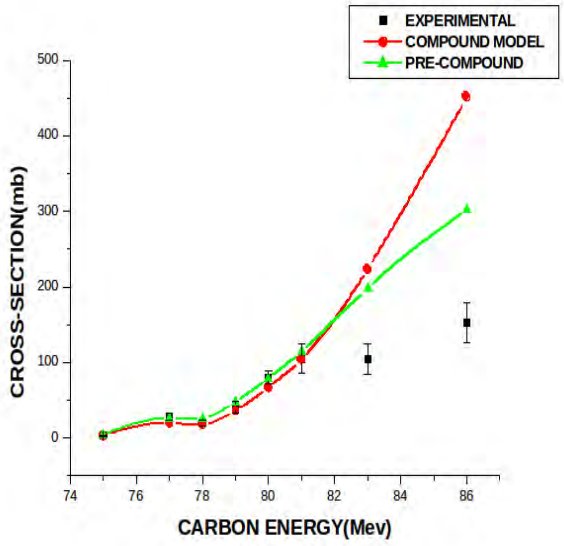

Figure 5.4: Experimental and theoretical excitation function for the reaction $^{197}Au(^{12}C, 6N)^{203}At$

there is signatures pre-equilibrium reaction in the energy range of 75Mev to 81Mev.

As the initial exciton number has an effect in the excitation function of the pre- equilibrium stages of the nuclear reaction,exciton number $n_0 = 12$ and $n_0 = 13$ are taken for the comparison in the reaction channel $^{197}Au(^{12}C, 6N)^{203}At$. The theoretical and the experimental excitation functions for these exciton numbers are shown in Fig.(5.5). It can be seen from the figure that for the pre-equilibrium stage the exciton number $n_0 = 12$ and $n_0 = 13$ both fits the experimental curve even though the value $n_0 = 12$ is used throughout the thesis. Another comparison is done to see the effect of the level density parameter(a) on the excitation function. The level density parameter $a = \frac{ACN}{10}$ which is taken for all calculations in the thesis is compared with level density parameter $a = \frac{ACN}{9}$ for the reaction channel $^{197}Au(^{12}C, 6N)^{203}At$. The theoretical cross-sections for the two level density parameters and the experimental cross-sections are shown in Fig.(5.6). The figure show that the value for the level density $a = \frac{ACN}{10}$ better fits the experimental curve in the pre-equilibrium region than the level density value $a = \frac{ACN}{9}$.

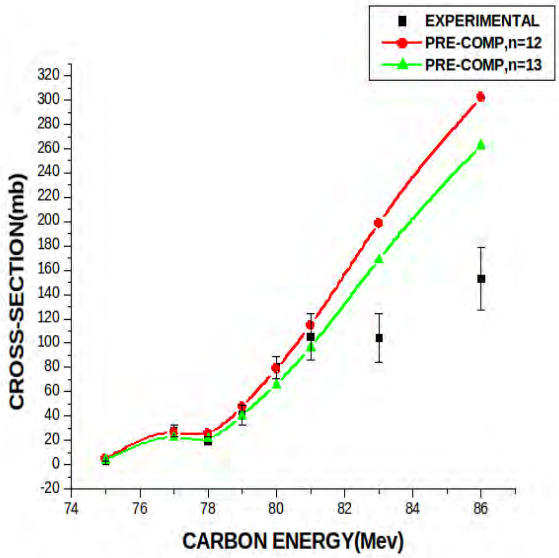

Figure 5.5: Experimental and theoretical excitation function for the reaction $^{197}Au(^{12}C, 6N)^{203}At$ for two exciton numbers.

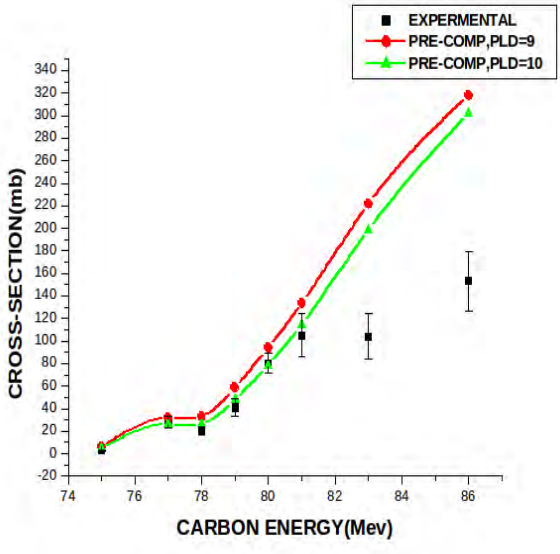

Figure 5.6: Experimental and theoretical excitation function for the reaction $^{197}Au(^{12}C, 6N)^{203}At$ for two level density parameters

Chapter 6

CONCLUSION

Nuclear reactions with intermediate projectile energies occurs at two stages. These two stages are the pre-compound and the compound(equilibrium) nucleus stages. In this study, contribution from direct reaction process is not expected. In the compound nucleus reactions,the projectile is captured by the target nucleus and its energy is shared and re-shared among the nucleons of the target until it reaches a state of statistical equilibrium. After a time much longer than the nuclear transit time, a nucleon or a group of nucleons near the surface receive enough energy to escape just as a molecule evaporates from the heated liquid drop.A compound nucleus is formed when the composite nucleus attains statistical equilibrium and emissions taking place through statistical fluctuations from the equilibrium configuration are called compound nuclear emissions.

Particle emission is also possible while the composite nucleus is proceeding towards statistical equilibrium.This is called pre-equilibrium emission. The pre-equilibrium reactions are at one end of the nuclear reaction time scale. For explaining these reaction nuclear physics needs models. some of these models are exciton model,hybrid model and Geometry dependent hybrid model.

In the present thesis, signatures of pre-equilibrium reactions of C-12 on Gold (^{197}Au) were studied. The $(^{12}C, xn)$ cross-section values for ^{197}Au target nuclei have been calculated for 59Mev to 91Mev incident energy ranges. The calculation results on the excitation functions and the intermidiate energy ranges for reaction process are given in figure 5.1-5.4.

In the thesis, for the study of carbon induced reaction on Gold, the reaction is studied using both the Weisskopf-Ewing model and the pre-equilibrium model of particles using the geometry dependent hybrid model with an improved computer code COMPLET. Using the code complete the theoretical excitation functions are computed by supplying standard input parameters of the problem and also the adjustable free parameters for both the compound and pre-equilibrium calculations. The experimental excitation functions are obtained from the EXFOR data source,IAEA. The theoretical and experimental excitation functions for the reaction channels ${}^{197}_{79}Au({}^{12}_{6}C, 3N)^{206}_{85}At$, ${}^{179}_{79}Au({}^{12}_{6}C, 4N)^{205}_{85}At$, ${}^{179}_{79}Au({}^{12}_{6}C, 5N)^{204}_{85}At$ and ${}^{179}_{79}Au({}^{12}_{6}C, 6N)^{203}_{85}At$ are plotted together. The results show that at lower energies around 60-80Mev compound as well as pre-compound nucleus theory are giving results which are closer to experimental value. some signatures of pre-equilibrium are obtained at low energies.As the energy increases both the calculation are not satisfying the experimental values,may be something else like incomplete fusion of projectile.Also there is no appreciable effect of changing exciton number from 12 to 13.The level density parameter $a = \frac{ACN}{10}$ gives in the better results.Finally it is concluded that in current high energy range no signatures of pre-equilibrium decay is obtained but at lower energies reaction may take place through both the process;compound nucleus as well as pre-compound plus compound nucleus.

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Declaration

This thesis is my original work, has not been presented for a degree in any other University and that all the sources of material used for the thesis have been dully acknowledged.

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