



**PRE-EQUILIBRIUM EVAPORATION OF
NEUTRONS FROM SOME $\alpha + {}^{93}\text{Nb}$ SYSTEMS AT
CYCLOTRON ENERGIES**

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Abstract

In this study, calculations of the excitation function of $^{93}\text{Nb}(\alpha, n)^{96}\text{Tc}$, $^{93}\text{Nb}(\alpha, 2n)^{95}\text{Tc}$, $^{93}\text{Nb}(\alpha, 3n)^{94}\text{Tc}$ reactions have been carried out in the incident alpha energy range from 10-42 MeV. In these calculations, the pre-equilibrium effects have been investigated. Some of the most widely used pre-equilibrium nuclear models are Intra-Nuclear-Cascade(INC) model, Harp-Miller-Berne(HMB) model, Exciton model and Hybrid/Geometry Dependent Hybrid(GDH) models. The calculations were done using ALICE-91 computer code, which is based on GDH model and various parameters were changed to see the effects on the excitation function. The calculated results have been compared with experimental data taken from data EXFOR library.

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Chapter 1

Introduction

Working with Geiger and Marsden, Rutherford devised an experiment to investigate the scattering of beam of alpha particles by thin foil of gold. After performing the experiment he was observing the effects of shooting a narrow beam of small α particles at a thin gold foil and noticed when α particles struck the thin metal, some of them scattered instead of continuing straight through. From Rutherford's discovery came the realization of the idea of the nucleus as a small, dense concentration of charge and mass. In Rutherford's day, there were no particle accelerators providing a ready supply of particle beams, and so he had to look around for a nuclear probe which might yield information about atomic structure. Later the accelerators were invented by Cock Croft and Walton which generates high energy particles for higher and higher nuclear reactions(1).

Nuclear reactions provide various information about nuclear size, nuclear forces, nuclear excited states, and nuclear models using nuclear probes. Neutron is one of the important particle to get information about the nucleus. The neutron is a subatomic particle with no net electric charge and a mass slightly larger than that of proton. The neutron has been the key to nuclear power production after it was discovered in 1932 by James Chadwick. During nuclear reactions neutrons are produced using α -radioactive isotopes and suitable targets. Some radioactive gamma sources having energy $E_\gamma > 1.6$ MeV produce neutrons with ${}^9\text{Be}$ target and some gamma sources having energy $E_\gamma > 2.22$ MeV produce neutrons from D_2O target. Accelerated charged particles produce neutrons of mono-energy

with different targets but for this purpose we need accelerators such as Cyclotron, Pelletron, Betatron, etc that produce high energy particle beam.

Nuclear reaction is the process in which two nuclei, or else a nucleus of an atom and a subatomic particle (such as a neutron, or high energy electron) from outside the atom, collide to produce products different from the initial particles. It is the process in which the incident particle is absorbed or scattered, same particles or some other particles or particle are emitted in different directions. It is the process in which the target nucleus is bombarded by a particle and results in another nucleus with emitted particle. When a nuclear particle or particles is in closer contact with another nucleon or nucleus, the interaction takes place in which energy momentum transfer may take place. If an incident projectile hits the target nucleus, a nuclear reaction takes place as a result there is a new nucleus and an outgoing particle. Many kinds of nuclear reactions occur in response to the absorption of particles such as neutrons or protons. Other types of reactions may involve the absorption of gamma rays or the scattering of gamma rays.

To understand how scientists have developed our present picture of the atom, with electrons orbiting a central nucleus, we must think back to the state of atomic theory at the turn of the 20th century. Scientist working with cathode ray tube had identified positively and negatively charged particles. In a famous experiment, J.J. Thomson had succeeded in measuring the charge- to- mass ratio of cathode rays. He identified these rays as a beam of electrons. Later in 1911 Rutherford decided to direct a beam of alpha particles at a metal foil consisting of many atoms. Alpha particles are natural product of many radioactive substances, and their properties had been under investigation for over a decade. It consists of two protons and two neutrons; it therefore has charge $+2e$. It is the same as the nucleus of a helium atom, ${}^4_2\text{He}$. From the study of the properties of radiations emitted in the natural radioactivity, it is proved that alpha particle is doubly ionized helium atom, ${}^4_2\text{He}^{++}$. The energy of alpha particle obtained from natural radioactive nuclei distributes to all parts and discrete in nature and appreciably smaller than the coulomb barrier and they are

not suitable to have nuclear reactions effectively. However, the alpha particles from the accelerator machine have continues and higher energy and they are frequently used for the study of the nuclear reaction mechanisms of different isotopes. Modern accelerators play an important role in nuclear reactions, for they produce radioactive isotopes that have various applications in applied fields of science as a residue of nuclear interaction between projectiles and targets.

In my present case alpha particle from accelerators is used to produce nuclear reaction with stable Niobium isotope and study its outcome. When alpha particle makes nuclear reaction with stable isotopes of Niobium, we get Technetium (Tc) isotopes of different mass number with different excitation energy and half life and even with different properties.

Niobium is a shiny, white, ductile metal. In air an oxide layer forms whose color depends on its thickness. Shades of blue, green and yellow are typical. Niobium resists corrosion due to the oxide film. The metal starts to oxidize rapidly in air at 200⁰C. Niobium's chemical properties are very similar to those of tantalum. Niobium is one of the five major refractory metals (metals with very high resistance to heat and wear). Niobium has 28 isotopes whose half-lives are known, with mass numbers from 83 to 110. Of these, one is stable, ⁹³Nb (100 %).

When alpha particle beam comes to Niobium, nuclear reactions take place between the nucleus of the incident alpha particle and the nucleons of the Niobium gives an outgoing particle. Therefore, the studies have been made to compare the excitation function of reaction in the isotopes of natural Niobium (⁹³Nb) which is stable. The excitation functions for the reactions ⁹³Nb(α , n)⁹⁶Tc, ⁹³Nb(α , 2n)⁹⁵Tc and ⁹³Nb(α , 3n)⁹⁴Tc have been analyzed at different alpha particle energies. The shape of the excitation functions reveals the reaction mechanisms of nuclear reactions.

Depending upon the time at which they occur, the nuclear reactions are of two types;

- **Compound nucleus reaction, and**
- **Direct reactions**

When the projectile enters the target nucleus, it interacts with a number of nucleons and energy-momentum transfer takes place. The system so formed is called compound nucleus C^* (which is in excited state). The nucleon which have got energy move further with incoming projectile and further interact with other nucleons and large number of nucleons get involved in the energy-momentum transfer. Compound nucleus so formed has life time of about 10^{-16} seconds.

Direct reactions occur without the formation of compound nucleus. A projectile comes very close to the nucleus and interact with the few surface nucleons may be the one or two protons or neutrons. The rest of the core is not taking part in the interaction. It is faster interaction as compared with compound nucleus formation. The interaction time is about 10^{-21} seconds.

In the present work there are some reactions that do not qualify neither as direct nor as compound nucleus. These are called 'pre-equilibrium' or 'pre-compound reactions'. The experimental results of early 1950, showed that the nuclear reaction mechanism has also an intermediated character between one step direct reactions in which few degrees of freedom are involved and the compound nucleus reaction in which all the energy of the projectile is distributed among all nucleons of the compound nucleus in a completely statistical manner. Thus during the 1960's, evidence was accumulated indicating that in some conditions it is possible for particles to be emitted after the first stage of a nuclear interactions but before the attainment of statistical equilibrium. All the intermediate processes are called pre-equilibrium reactions.

There are different types of pre-compound nuclear reaction models.

These are(2-5)

- Intra-nuclear cascade (INC) Model
- Harp-Miller-Bern (HMB) model
- Exciton model
- Hybrid/geometry dependent hybrid (GDH) Models

Numerous models have been developed to account for the high-energy pre-equilibrium particles that make up the "continuum" region of the secondary particle emission spectra above the evaporation peak (for incident energies above approximately 10 MeV). Beginning in the 1940's, intra-nuclear cascade (INC) models were developed that use Monte Carlo techniques to simulate nucleon- nucleus reactions in terms of individual successive nucleon-nucleon collisions.

Harp, Miller and Berne(4) have developed a model which can be applied to nucleon-induced reactions at high incident energies. This model is considered as HMB model and it takes into account the scattering process among nucleons excited above the Fermi level.

Other widely used semi-classical pre-equilibrium reaction models are the exciton (Griffin, 1966)(5) and hybrid/geometry dependent hybrid (GDH)(Blann, 1971)(6) models. Griffin's work provided an explanation of the high energy emitted particles first observed in the measurements of Wood et al. (1965). These models also picture the evolution of the nuclear reaction in terms of successive nucleon-nucleon collisions, but do so within a particle-hole, or "exciton", formalism (nucleons excited from within the Fermi sea leave a hole). The exciton and hybrid models differ in terms of the statistical postulates made to treat the evolution of the reaction (Hodgson and Gadioli, 1992)(2). In these models the reaction is usually followed in energy space, which simplifies the calculations and leads to closed-form deterministic equations. Emission probabilities from particle-hole excitations

are obtained by applying detailed balance, making use of inverse reaction cross sections and the phase space of particle-hole excitations. The bulk of our calculations were performed using the exciton model for the pre-equilibrium phase of the reaction; its predictive capability for reactions up to a few hundred MeV is rather good, and it requires a relatively small amount of computer time. We note, however, that these models deal with reaction probabilities instead of amplitudes coming from solution of the wave equation, and therefore observable that are sensitive to interference effects in the scattering, such as angular distributions, are often not calculated accurately.

In recent years, quantum mechanical theories have been developed to describe pre-equilibrium processes. Various theories have been proposed which differ in the underlying quantum statistical assumptions made. The most widely studied theory is that of Feshbach, Kerman, and Koonin (FKK) (1980)(7), due to its relatively straightforward computational structure. This theory partitions the reaction process into two types of scattering: multi-step compound (important at the lowest incident energies), and multi-step direct (important at higher incident energies). The multi-step direct reaction mechanism, which is generally most important, predicts multi-step scattering cross sections in terms of a convolution of the 1-step scattering cross section, an attractive result that follows from the statistical assumptions (particularly the random phases of matrix elements) made by FKK. The 1-step cross section is obtained by extending direct reaction distorted wave Born approximation (DWBA) theory into the continuum. One of the main advantages of quantum mechanical theories is that they accurately predict the angular distributions of pre-equilibrium ejectiles, which are governed by inherently quantum effects, such as diffraction and refraction. In most cases, semi-classical exciton models can only compete in predictive power with the FKK theory because they use angular distributions from phenomenological systematics based on measurements. For some of the nuclei that we calculated, the FKK theory was used. However, the long computer time required for its computation makes it somewhat impractical for large-scale calculations. The FKK

theory is, however, useful for comparisons with exciton model results to help validate the exciton model predictions.

In this thesis work the theoretical calculations of excitation functions or cross-sections(σ) for some reactions for stable Niobium induced by alpha particle is made by using the Alice-91 computer code based on hybrid or geometry dependent hybrid models. The calculated values are compared with the experimental results which are obtained from data EXFOR(25) library and conclusions of the pre equilibrium evaporation of neutrons from alpha-Niobium ^{93}Nb reactions at cyclotron energies are made. The effect of changing level density parameter a , ($a=A/9$ to $A/10$) is also seen together with the effect of changing its initial exciton number $n_0 = 4$ or $(4p+0h)$ to $n_0 = 6$ or $(5p+1h)$

Chapter 2

Nuclear Reaction Theories

2.1 Nuclear Reaction

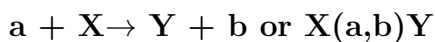
A process that occurs as a result of interactions between atomic nuclei when the interacting particles approach each other to within distances of the order of nuclear dimensions. While nuclear reactions occur in nature, understanding of them and use of them as tools have taken place primarily in the controlled laboratory environment. In the usual experimental situation, nuclear reactions are initiated by bombarding one of the interacting particles, the stationary target nucleus, with nuclear projectiles of some type, and the reaction products and their behaviors are studied.

Nuclear reactions and nuclear scattering are used to measure the properties of nuclei. Reactions that exchange energy or nucleons can be used to measure the energies of binding and excitation, quantum numbers of energy levels, and transition rates between levels. A particle accelerator produces a beam of high-velocity charged particles (electrons, protons, alpha, or "heavy ions"), which then strikes a target nucleus. Nuclear reactions can also be produced in nature by high-velocity particles from cosmic rays, for instance in the upper atmosphere or in space. Beams of neutrons can be obtained from nuclear reactors or as secondary products when a charged-particle beam knocks out weakly-bound neutrons from a target nucleus. Nuclear reactions can also be produced by beams of photons, muons, and neutrinos.

In order for a nuclear reaction to occur, the nucleons in the incident particle, or projectile, must interact with the nucleons in the target. Thus the energy must be high enough to overcome the natural electromagnetic repulsion between the protons. This energy "barrier" is called the Coulomb barrier. If the energy is below the barrier, the nuclei will bounce off each other. Early experiments by Rutherford used low-energy alpha particles from naturally radioactive material to bounce off target atoms and measure the size of the target nuclei.

When a collision occurs between the incident particle and a target nucleus, either the beam particle scatters elastically leaving the target nucleus in its ground state or the target nucleus is internally excited and subsequently decays by emitting radiation or nucleons.

In order to write an equation for a nuclear reaction, we must first establish some basic rules. Each of the elements involved in the reaction is identified by the chemical symbol and two numbers are attached to the symbol. One of them is the mass number, also known as the A number. The 'A' number describes the atomic weight of the atom and identifies the number of protons and neutrons in the nucleus. The second number is the atomic number, or Z number. The 'Z' number describes the number of protons in the nucleus and determines the type of atom. If a target nucleus X is bombarded by a particle 'a' and results in a nucleus Y with emitted particle 'b', this is commonly written in one of two ways as.



where,

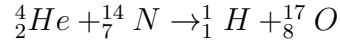
a-is a projectile

b-is an emitted particle

X-is target nucleus and

Y-is the residual nucleus.

For example, the first nuclear reaction observed by Rutherford in 1919 was(1) :



When an alpha strikes a nitrogen nucleus, ${}^{14}\text{N}$, to produce a proton, ${}^1\text{H}$, and an isotope of oxygen, ${}^{17}\text{O}$. In this case Rutherford bombarded alpha particle to nitrogen-14 nuclei and obtained a new nucleus that is oxygen-17 with proton as emitted particle. Hence a nuclear reaction is described by identifying the incident particle, target nucleus, and reaction products.

We can characterize the energetics of the reaction with a reaction energy Q , defined as the energy released in the reaction. The Q is positive if the total mass of the products is less than that of the projectile and target, indicating that the total nuclear binding energy has increased. The Q -value can be written in equation form as

$$Q = (M_X + M_a - M_Y - M_b)C^2 \quad (2.1.1)$$

where,

M_X -is the mass of target nucleus

M_a -is the mass of the projectile

M_Y -is the mass of the residual nucleus and

M_b -is the mass of the emitted particle

2.2 Reaction Mechanisms

An incident particle, such as a nucleon, may enter and leave the nucleus at different angles, but with the same energy (elastic scattering). The nucleon may collide directly with a nucleon of the nucleus; in this case, if either or both of the nucleons have an energy greater than that required to leave the nucleus, they may leave without interacting with any of its other nucleons (direct process). There also exist more complex direct reactions, in which the energy of the incident particle is transferred directly to one nucleon or a small

group of nucleons in the nucleus. If the energy introduced by the incoming particle is gradually distributed among many nucleons of the nucleus, the nuclear states will become increasingly more complex. However, after a certain time, dynamic equilibrium will be reached: different nuclear configurations will arise and decay in the resultant system, called a compound nucleus. The compound nucleus is unstable and rapidly decays into the final products of the nuclear reaction. If the energy of one of the nucleons in some configurations is sufficient for ejection from the nucleus, the compound nucleus decays with the emission of a nucleon. On the other hand, if the energy is concentrated in a few groups of particles, existing for a short time in the compound nucleus, then there may be the emission of alpha particles, triton, deuteron, and the like. At excitation energies of the compound nucleus that are lower than the energy for the ejection of particles, the only reaction path is the emission of gamma quanta. Sometimes particles are ejected before equilibrium is reached, that is, before the formation of a compound nucleus (the mechanism of pre-equilibrium decay).

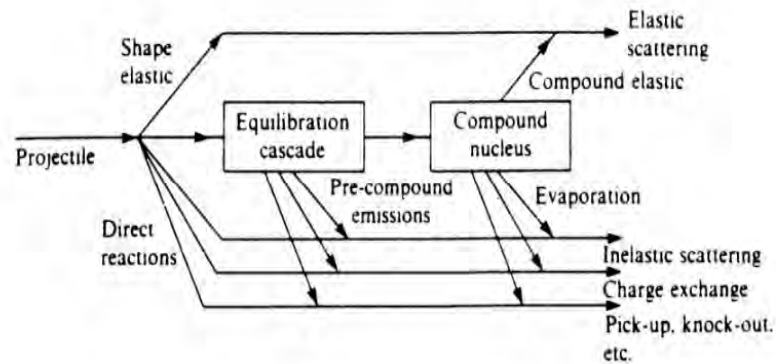


Figure 2.1: an overview of reaction mechanisms

At low energies of the incident particles, the major mechanism of nuclear reactions, as a rule, is the formation of a compound nucleus, with the exception of nuclear reactions with deuteron. Direct processes predominate at high energies. The nature of the dependence of the effective cross sections σ of nuclear reactions on the energy ε of the incident particles $\sigma(\varepsilon)$ differs for different mechanisms of nuclear reactions. For direct processes, the dependence $\sigma(\varepsilon)$ exhibits monotonic behavior. In the case of nuclear reactions resulting in the formation of compound nuclei, maxima are observed in $\sigma(\varepsilon)$ at low particle energies; these maxima correspond to the energy levels of the compound nucleus. In the high-energy region ($\varepsilon \geq 15$ MeV for intermediate-mass and heavy nuclei), the energy levels of the compound nucleus overlap, and the cross section depends monotonically on energy. The energy spectrum of the decay products of a compound nucleus in the region of higher energies consists of separate lines, and in the low-energy region the emitted particles have a broad maximum.

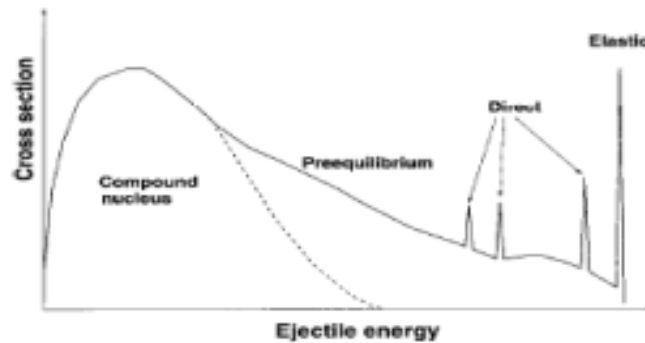


Figure 2.2: Neutron emission spectrum showing contributions of different reaction mechanisms in a nuclear reaction

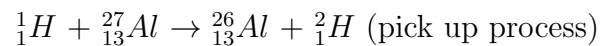
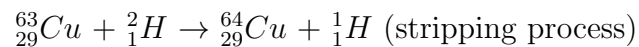
The sharp peaks at high energies correspond to direct reactions, the broad peak at low energies shows compound formation and the region between the two is the pre-equilibrium region.

2.2.1 Direct reactions

An intermediate energy projectile transfers energy or picks up or loses nucleons to the nucleus in a single quick (10^{-21} second) event. Energy and momentum transfer are relatively small. These are particularly useful in experimental nuclear physics, because the reaction mechanisms are often simple enough to calculate with sufficient accuracy to probe the structure of the target nucleus. To qualify as a direct reaction, both the target nucleus and the internal structure of the cluster transferred must be undisturbed by the reaction. The residual nucleus is simply the coupled product of the cluster and the ground state of the target nucleus. This condition is generally difficult to meet for transfer reaction involving large numbers of nucleons.

The reaction proceeds directly from the entrance channel to the exit channel without the formation of an intermediate state (short glancing collision). If the internal states of the colliding systems do not change, we have elastic scattering. If one or both systems are excited in the exit channel, we have inelastic scattering. If one or more nucleons are transferred from one nucleus to the other, we have a transfer reaction. If a nucleon or light nucleus is ejected from the target while the projectile continues free, we have quasi-elastic scattering.

The stripping and pick up reactions, are interactions with surface nucleons (few nucleons), are examples of direct reactions which take place at the higher energies. In such reactions the projectile picks up a nucleon from target nucleus and some times the projectile is stripped off a nucleon by the target nucleus (1).For example,

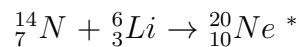
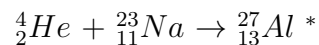


The main characteristics of direct reactions

- i) The emission of much larger number of high energy particles than expected from evaporation model.
- ii) The angular distributions of emitted particles show a forward picking($\theta=0^\circ$). Almost all the particles are emitted in forward direction (around $\theta=0^\circ$ or within 10°).
- iii) A monotonic decrease of cross-section with energy.
- iv) Direct reactions usually take place at high energy of projectiles.

2.2.2 Compound Nucleus Formation

Either a low energy projectile is absorbed or a higher energy particle transfers energy to the nucleus, leaving it with too much energy to be fully bound together. On a time scale of about 10^{-16} seconds, particles, usually neutrons, are "boiled" off. That is, it remains together until enough energy happens to be concentrated in one neutron to escape the mutual attraction. Charged particles rarely boil off because of the coulomb barrier. The excited quasi-bound nucleus is called a compound nucleus. For example,



The compound nucleus forgets the history of formation. Hence it doesn't remember how it was formed (what was the entering projectile and what energy E_c^*). The compound nucleus is excited to an energy states with;

$$E_c^* = \epsilon_\alpha + \text{B.E}$$

The compound nucleus has life time $\sim 10^{-16}$ second and it will decay into different channel but it will depend only on the energy of excitation, angular momentum and parity. The

decay will not depend upon the mode of formation of compound nucleus. It will depend only on the Quantum mechanical parameters of state (Energy, angular momentum etc).

The compound nucleus can be described by statistical mechanics as being in a state of statistical equilibrium. The energy distribution of the components of the system is given by a Maxwellian distribution. A component of this system may receive a large amount of energy as the result of a statistical fluctuation. This amount of energy can be enough to cause the decay of the compound nucleus. Being a statistical process, the evaporation of particles favors the escape of nucleons near the smallest possible energy. In the case of charged particles, this minimum energy is the Coulomb barrier of the compound nucleus. When the compound nucleus has reached statistical equilibrium, we say that it has been thermalized.

2.2.3 Pre-equilibrium Decay in Nuclear Reactions

Pre equilibrium reaction is neither direct nor compound nuclear reaction but in some conditions it is possible for particles to be emitted after the first stage of a nuclear interaction but before the attainment of statistical equilibrium or compound nucleus formation. In pre-equilibrium reactions, the emission of particles from the excited target nucleus is neither by statistical decay of the compound nucleus nor by the prompt emission after collision. The emission of a particle by the target nucleus happens neither immediately after the collision nor by the statistical decay of the compound nucleus. The projectile shares its energy among a small number of nucleons in the target. The struck nucleons initiate a cascade of reactions within the target, at the course of which a particle can be emitted (before the compound nucleus has reached a state of statistical equilibrium). The pre-equilibrium effects start manifesting themselves at energies around 20 MeV, and at excitation energies above 50 MeV their contribution starts becoming significant. It is assumed that all possible ways of distribution of the excitation energy between all different particle-hole configurations with the same exciton number have equal probability to

occur. The exciton number changes during the nuclear reaction as a result of intra-nuclear two-body collisions. At each stage of the reaction there may be a non-zero probability that a particle is emitted. If this happens at an early stage, we speak of pre-equilibrium (PE) emission.

The pre-equilibrium models became rather popular tool to analyze and understand nuclear reactions at excitation energies ranging from several tens of MeV up to the GeV regions. There are different types of pre-compound nuclear reaction models. These are(2-5);

- Intra-nuclear cascade (INC) Model
- Harp-Miller-Bern (HMB) model
- Exciton model
- Hybrid/geometry dependent hybrid (GDH) Models

Among these models, the hybrid and geometry dependent hybrid (GDH) models have been reasonably successful in reproducing a broad range of experimental data.

Intra-nuclear Cascade (INC) Model

The intra-nuclear cascade model (INC) was first proposed by Serber in 1947 (8). He noticed that in particle-nuclear collisions the de-Broglie wavelength of the incident particle is comparable (or shorter) than the average intra-nucleon distance. Hence, a description of interactions in terms of particle-particle collisions is justified. The first calculations of pre-equilibrium angular distributions were performed with this model using the quasi-free scattering inside the nucleus. The INC model traces the individual nucleon trajectories in three- dimensional geometry. The trajectory of an excited particle is followed until some arbitrary energy generally considerably above the average equilibrium value has been attained by the nucleon. Particles reaching the nuclear surface with sufficient energy to be emitted are assumed to be emitted.

When all particles of a given cascade have been traced, the total energy of the residual nucleus, its identity, and the energies and angles of the emitted particles are shared, and a new cascade with new impact parameter is calculated. With the help of such an approach, the time evolution of the reaction can be generated but after few collisions the actual calculation becomes too much complicated. The INC model is a realistic model but in general, the model predictions are not satisfactory at backward angles and in some forward angles also.

The process classes use model classes to determine the secondaries produced in the interaction and to calculate the momenta of the particles. Here we present a collection of such models which describe a medium-energy intra-nuclear cascade. The basic steps of the INC model are summarized as follows:

- 1.The space point at which the incident particle enters the nucleus is selected uniformly over the projected area of the nucleus,
- 2.The total particle-particle cross sections and region-dependent nucleon densities are used to select a path length for the projectile,
- 3.The momentum of the struck nucleon, the type of reaction and the four-momenta of the reaction products are determined, and
- 4.Exciton model updated as the cascade proceeds
- 5.If the Pauli exclusion principle allows and $E_{particle} > E_{cutoff} = 2$ MeV, step (2) is performed to transport the products.

Harp-Miller-Berne (HMB) Model

Harp,Miller and Berne (4) have developed a model which can be applied to nucleon-induced reactions at high incident energies. This model is considered as HMB model and it takes into account the scattering process among nucleons excited above the Fermi level.

This model calculates the occupation probability of an average state in the i -th bin as a function of time using Fermi gas distribution. At the initiation of the reaction, at the time

$t=0$ all the levels below Fermi energy are filled up (as the target is in ground state), and the projectile is in an excited state. This gives the fractional occupation probability at time $t = 0$. Two-body interaction then lead to a redistribution of probabilities. Unfortunately we cannot directly compare the experimental value with the theoretical value because the HMB model does not formulate a calculating method of angular distributions.

After calculating the relative probabilities of scattering into and out of each bin and the emission from bins above the particle binding energies, populations of all bins are changed accordingly. The calculation is repeated until a steady state configuration is reached. At each time during the equilibrium process the energy spectrum of emitted nucleons are calculated and a net spectrum obtained. Later Harp and Miller suggested minor modification in HMB model. They considered the nucleus to be composed of independent proton and neutron Fermi gases. Therefore, the proton and neutron occupation numbers for the single particle states of these gases completely specifies the internal configuration of the nucleus at any time. Further it is also assumed that the mechanism for the equilibrium of the gases takes place through binary nucleon-nucleon collisions. Correspondingly a new set of master equations is obtained, the solution of which gives the proton and neutron occupation numbers.

Exciton Model

The Exciton model was proposed by Griffin (5) for explaining various experimental nuclear reaction data. In this model the equilibration between target and projectile is achieved by the succession of two body interactions and the composite nucleus states are characterized by the number of excited particles and holes (the exciton) at any stage of the nucleon-nucleon cascade. The initial configuration is fixed by the nature of the projectile. The exciton number(n), $n=p+h$; where p is number of particles and h is the number of holes.

An excited nucleus is considered as a gas of quasi-particles i.e., particle-hole degree freedom is included, taking into account residual hh , ph and pp interactions. In this

the nuclear potential is shown with equally spaced single particle levels, i.e., levels whose occupancy is either 0 or 1. Initially the target nucleus is in ground state. All the levels below the Fermi energy are filled and all the levels above are vacant. The projectile nucleon enters the target nucleus with a given energy and forms a 1 particle 0 hole (1p-0h) state, i.e., a state with exciton number $n = 1$. 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 the levels below the Fermi energy are filled, the first interaction between the projectile and target nucleon will raise the latter above the Fermi energy and leave a hole below. Thus a 2p-1h state is formed. In other words, the absorption of the projectile nucleon by the target leads to the formation of $n = 3$ exciton state.

After formation of the $n = 3$ state either of the excited particles may be emitted if it has sufficient energy to escape. If however, particle emission does not take place, then there will be a further two body interaction either between one of the two excited particles and a particle below the Fermi surface or between the two excited particles themselves. The first results in the formation of $n = 5$ exciton state or 3p-2h state while the second would lead to a new 2p-1h state having different energy configuration of the particles and holes, or back to the original $n = 1$ exciton state. Hence a two body interaction will lead to transitions in which the change in the exciton number $\Delta n = \pm 2, 0$.

The Hybrid/Geometry Dependent Hybrid (GDH) Model

The intra-nuclear cascade calculation results indicated that the exciton model deficiency resulted from a failure to properly reproduce enhanced emission from the nuclear surface. In order to provide a first order correction for this deficiency the hybrid model was reformulated by Blann and vonach (9). In this model, multi pre-equilibrium particle emission along with equilibrium decay is considered whereas the spectra of emitted particles are calculated for each step in the energy dissipation process induced by the interaction between projectile and target nucleons. The pre-equilibrium emission cross-section of the

type ν (proton or neutron) in the hybrid model is given by (9)

$$\sigma(\epsilon) = \sigma \sum_{n=n_0, \Delta n=+2}^{\bar{n}} D_n P_n(\epsilon) \quad (2.2.1)$$

Where $P_n^\nu(\epsilon)$ is the emission probability of ν with energy ϵ from the n exciton states.

The pre-equilibrium decay probabilities in this model is given by

$$P_\nu(\epsilon)d\epsilon = \sum_{n=n_0, \Delta n=+2}^{\bar{n}} \left[\frac{{}^n X_\nu N_n(\epsilon, U)}{N_n(E)} \right] g d\epsilon * \left[\frac{\lambda_c(\epsilon)}{(\lambda_c(\epsilon) + \lambda_+(\epsilon))} \right] D_n \quad (2.2.2)$$

where $P_\nu(\epsilon)d\epsilon$ is the number of the type ν emitted into the unbound continuum with channel energy between ϵ and $\epsilon + d\epsilon$ (MeV). The quantity in the first set of square brackets represents the number of particles to be found (per MeV) at a given energy ϵ (with respect to continuum) for all scattering process leading to an n exciton configuration. The second set of square brackets represents the fraction of the ν type particles at energy ϵ , which should under go emission into the continuum, rather than making an intra nuclear transition. The D_n represents the average fraction of the initial population surviving to the exciton number being treated. The hybrid model also calculates $\lambda_+(\epsilon)$ from N-N scattering cross-sections.

The geometry dependent hybrid (GDH) model is a variant of the hybrid model in which the nuclear geometry effects are considered. In hybrid model calculations the nuclear matter density is taken as uniform throughout the nucleus while GDH model takes into account the reduced matter density and hence also the shallow potential at the nuclear surface. In this way the diffused surface properties sampled by higher impact parameters were incorporated into the pre-compound decay formalism in the geometry dependent hybrid model. Therefore the differential pre-equilibrium cross-section for particle emission in the GDH model is given by

$$\frac{d\sigma_\nu(\epsilon)}{d\epsilon} = \frac{\lambda^2}{4\pi} \sum_{l=0}^{\infty} (2l+1) T_l P_\nu(l, \epsilon) \quad (2.2.3)$$

Where $P_\nu(l, \epsilon)$ is same as $P_\nu(\epsilon)d\epsilon$ but evaluating for the l -th partial wave. T_l is the transmission coefficient for l -th partial wave, and $\frac{\lambda}{2\pi}$ is reduced De-Broglie wavelength.

When the system is equilibrated, its de-excitation is followed by the Weisskopf-Ewing(20) evaporation model, While level density $\rho(U)$ is calculated using Fermi gas level density formula.

The statistical properties of excited nuclear levels have been a matter of concern and study for more than fifty years. One of the basic statistical properties of levels is their density. For the description of the level densities the Fermi-gas and constant temperature models are used frequently with parameters obtained from fitting of some experimental data. But the physical assumptions upon which both these models are based are not sophisticated enough to allow them to account properly for variations of level densities over wide energy interval from the ground state to energies much higher than the neutron separation energy. This is not surprising, as the models discussed were initiated more than fifty years ago, when nuclear physics was not so developed and computer based. Some of the most important concepts, upon which current understanding of the structure of low-lying nuclear levels is based, include shell effects, pairing correlations and collective phenomena. All these concepts have been incorporated into the Generalized Super fluid Model (GSM) developed by many authors over the last 20 years. The phenomenological versions of the model convenient for an analysis of experimental data were developed intensively during the last years. Now a days microscopic models for the level density are emerging but at the present stage their applications are limited. For practical applications of the statistical model it is very important to obtain parameters of the level density description from reliable experimental data. The cumulative numbers of low-lying levels and the average distances between neutrons resonances are usually used for such data.

The nuclear level density distribution in geometry dependent hybrid model is given by employing a Fermi density distribution function as

$$d(R_l) = d_s[\exp(R_l - C)/0.55fm + 1]^{-1} \quad (2.2.4)$$

Where ρ_s =saturation density of the nuclear matter and C is the charge radius given by

$$C = 1.07A^{1/3}fm \quad (2.2.5)$$

taken from electron scattering results. This value of charge radius C has been replaced in the present parameterization by a value characteristic of matter (rather than charge) radius based on the droplet model work of Myers (21) plus an ad-hoc projectile range parameter $\frac{\lambda}{2\Pi}$,

$$C = 1.18A^{1/3}[1 - (1/1.18A^{1/3})^2] + \lambda \quad (2.2.6)$$

The radius for the l -th partial Wave Was defined by

$$R_l = \frac{\lambda}{2\Pi}(l + 1/2) \quad (2.2.7)$$

In the hybrid model the average nuclear density is calculated by integration and averaging of equation between $R = 0$ and $R = C + 2.75fm$. The Fermi energy (ϵ_f) is assumed to vary as the average density to the third power. The value of ϵ_f so evaluated is used in defining the single particle level density "g" for all calculations, hybrid and GDH, as this should be a property of the average potential. The single level density have been defined by

$$g_n = \frac{N}{20} \left[\frac{\epsilon_f + B_n + \epsilon}{\epsilon_f} \right]^{1/2} \quad (2.2.8)$$

$$g_p = \frac{N}{20} \left[\frac{\epsilon_f + B_p + \epsilon}{\epsilon_f} \right]^{1/2} \quad (2.2.9)$$

Where,

E_f =Fermi energy

B_n, B_p =Binding energy of neutron and proton number of compound nucleus respectively.

Chapter 3

Computer code

A number of models have been proposed to understand nuclear reaction mechanisms using a variety of computer codes. These computer codes are used to predict and analysis different products of nuclear decay. In addition to these they are used to verify the reaction mechanism, to aid in the identification of compound nucleus formation and decay, to determine angular momenta and to search for non-statistical aspects of nuclear structure at higher excitation energies and higher angular momentum.

The types of calculations and computer code may be classified as single step (SS) calculations and multi-step (MS) calculations. In SS calculations the excited nucleus has energy sufficient for one decay or it is only the emission of the first particle that is of interest. However, in case of MS calculations the spectra of gamma rays and light particles contains contributions from successive decays and the distribution of heavy residues is arrived at through several or many successive decays. This problem can be treated in two ways namely Multi Step Gridded Method (MSGR) and Multi Step Monte Carlo (MSMC) method. In MSGR a grid is constructed in Z and A and, for each nucleus, a population distribution over a two dimensional grid in excitation energy and angular momentum. The advantage of the grid calculation is that the yield of very weakly populated residual nuclei may be calculated with precision. However, such codes generally do not calculate the angular distributions of emitted particles or residues.

The size of the grid in Z and A continues to expand for successive daughter nuclei until further decay is energetically forbidden. However, MSMC method follows the decay of individual compound nuclei in an initial ensemble by Monte Carlo techniques until the residual nucleus can no longer decay. The great advantage of the Monte Carlo method is that it can predict energy spectra, angular distributions and multi particle correlations in laboratory system.

I have used the Alice-91 computer codes out of various available statistical codes for the calculation of excitation functions and to compare the experimental values with the calculated one.

3.1 Alice-91 computer code

Alice-91 is an improved version of the earlier codes Alice and Overlaid code. The pre-equilibrium calculations in this code may be performed in the frame work of hybrid(10) model or geometry dependent hybrid (11) model. Very few parameters are required to be given as input data for pre-equilibrium calculation. The input data are required, neutron and proton number of target and projectile, the initial exciton number n'_o , level density parameter 'a' and the mean free path multiplier. In pre-equilibrium emission calculations the initial exciton configuration and level density parameter a are very crucial quantity. The mean free path multiplier for intra nuclear transition rates may be calculated either from the optical potential parameters of Becchetti and Greenless (12) or from Pauli corrected nucleon-nucleon cross-sections (16).

The inverse reaction cross sections are calculated from the optical model subroutine which uses the Becchetti and Greenless (12) optical parameter, however, there is an option of classical sharp cut off model also. The level density parameter influences the shape as well as the height of calculated excitation functions.

In this the level densities of the nuclide involved in the evaporation chain can be calculated from the Fermi gas model (9) as

$$\rho(U) = (U - \delta)^{\frac{-5}{4}} \exp(2\sqrt{a(U - \delta)}) \quad (3.1.1)$$

where, U is the excitation energy of the nucleus and δ is the pairing term. in general for the level density parameter a value of $a = A/K$ is applied, where A denotes the nucleon number of the compound nucleus and not the residual nucleus and K, a constant for which values spread over a wide region.

The following summarize input requirements for the full operation of the program and find the best calculated values in order that it fits to experimentally observed results of pre equilibrium neutron evaporation from alpha -Niobium reaction at cyclotron energies.

Card 1 General input data

ap - projectile mass number

at - target mass number

zp - projectile charge

zt - target charge

qval - reaction q-value= $ap+at-acn$. d=calculated from Myers swiatecki/Lyseki (msl) mass formula.

pld - level density parameter a, $a=acn/8$, $a=acn/9$ and $a=acn/10$.

cld - ratio of single particle level densities af/an . d=1.0

barfac -scales liquid drop or finite range fission barrier;d=1.If input parms na,nz ,mc,mp are all centered as alanck or zero then default will set na=11, nz=9, mc=3, and on card(s)3, jcal=1(Weisskopf calculation) and geometry dependent hybrid (gdh) pre-compound decay, these are suggested for beginners, in this mode, ike=4 inver=2 are also selected.

na - number of nuclide of each z to included in calculation.

nz - number of z to be calculated in the emission process.

mc - shell correction option for masses subroutine.mc = 0, shell correction,

mc = 1, no shell correction,

mc = 2, msl masses incl. shell correction, but separation energies and or ldgs atleast partly provided by user.

**if mc is increased by 10, Alice will substitute 1971 gove mass table masses formsl masses whereavailable and (ifso selected by mc=11 ormp=0) subtract pairing or shell correction
mp - pairing option mp = 0.no pairing terms in masses

; mp=1: pairing terms in masses,ldg calculated from msl formula and applied back shifted

;mp =2,as mp=1 but shell correction also included in ldgs;

mp = 3, normal pairing shift, zero for odd-even nuclei, delta added to excitation for odd-odd nuclei,etc recommend values mc=10,mp=3,

Idopt if zero, Fermi gas level density;

if Idopt=1, kataria Ramamurthy formula with shell correction due to difference of experimental mass and liquid drop correction;

if Idopt=2, Ignalyuk level density.

if Idopt=3, Gilbert-Cameron level density.

inver - inverse cross-section parameter

=0,results supplied by optical model subroutine,

=1,user supplies;

=2,sharp cutoff values each z.

**Option inver=2 greatly reduces total central processing unit(CPU) time.

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, =5: n, p, alpha, deuteron and triton;

When m3=3 is default value recommended pld=0, kplt=0, m3=0, blank=0 ike -is energy bin mersh size in MeV

If=0: no particle spectra will be printed;If=1: Equilibrium spectra for each nuclide will printed;If=2: only pre-equilibrium will be printed; If=3: as 1+2; If =4: pre-equilibrium plus summed equilibrium spectra will be printed;

**to print gamma spectra, increase ike value selected by 5

ipch if ipch =1 or =2 ,fission barrier may be read in after card number 1 as bexp (ia,iz), one card for each barriers are independent of angular momentum for ipch=1, and are scaled as rldm barriers for ipch=2.

**this option should be used with care as abuses are not disallowed.

kplt-if kplt is 1 and the last energy input line is followed by -1 in column 1-5, excitation function will be plotted on standard output.

card 2 title card-80 columns

1.If mc=2 or 12 on card 1, read user supplied n, p, alpha, deuteron, binding energies and or ldgs here, one line per nuclide, order((ia=1,na+2),iz=1,nz+2) when ever non zero binding energy is detected, Alice will use user provided binding energies for this nuclide, same convention for ldgs.

2.If inver=1 on card 1, read n, p, alpha, deuteron inverse cross-section here, in ascending channel energy, 1st value for 0.1 MeV channel energy, then in 1 MeV steps, 48 values for each particle type, sequence n, p, alpha, deuteron

. Card.3 energy/option card.

this card (and card(s) 4 if selected) is repeated for each energy for a given target + projectile

If the na, nz, mc, mp=0 default mode was used on card 1, enter only ex. on this card. eq1. projectile kinetic energy in the laboratory system.

if=0, a new problem will begin at card 1.

if=-1, previously calculated excitation functions will be plotted, if kplt=1 was selected and if eq values were run in ascending order if eq=0 on two successive cards, a normal exit will occur.

rcss- reaction cross-section. If left blank, the cross-section will be internally by the optical

model subroutine for incident n or p ,and by the parabolic model routine for all other projectiles. If rcss is read in,this value entered for rcss will be used. If a geometry dependent hybrid model and or fission calculation is selected and if one wishes to enter transmission coefficient for entrance channel, then the negative of the number of t(1) to be read must be entered for rcss; the t(1) will then be read on card(s)4

iadst if=0, no angular distribution,

if=1, yes for neutrons;

=2, yes for pritons;

=3, for neutrons using Kalbach systematics;

=4, for protons using Kalbach systematics;

ifr-choice for refraction with angular distributions

If ifr=0, no refraction

If ifr=1/2, entrance channel refraction

If ifr=3, Heisenberg entrance and exit refraction

If ifr=2, Heisenberg exit channel and std entrance refraction

i3d-If=0, three dimensional folding for angular ditribution, else2-D

jcal-is i2 14 type of calculation option

jcal.=1, Weisskopf-Ewing evaporation calculation

jcal=2, s-wave with liquid drop moment of inertia

jcal=3, s-wave with rigid body

jcal =0, evaporation fission compitition,partial wave by partial wave

**If fission is to be calculated using zero barrier for all j.gt.jcrit, increase jcal by 10.

adist-energy increment for calculating angular distributions (f3.0) if adist=1, default value is 5 MeV.

Jfrac-if fission calculation is to be only in a specified angular momentum range, this is the lower limit.

Jupper-is upper limit of angular momentum, if the range is to be restricted

jang-is option of emitted particles decreasing angular momentum.If=1, yes;If=0, no.

1.If jang is greater than 100(less than 200) loop over angular momenta will before increments of jang-100 and 'no' option on removal of angular momentum holds. if jang is greater than 200, delta l 'yes' option holds, and loop is incremented by jang-200. use jang.gt.100 with jcal=0 and td=0 only

All additional parameters on this card are for pre-compound option.leave remaining columns blank if no pre-compound calculation selected

1.If 'td' is positive and 'ex1"ex2'are blank, default parameters will be selected.The gdo option may still be selected.for default pre-compound hybrid model, use td=1, remaining variables zero for gdh calculation,enter td=1,tmx=1, and leave all other variables after td blank.

td - initial excitation number =p+h.

ex1 - initial excited neutron number.

ex2 - initial excited proton number.

ex3 - initial alpha particle exciton number.

tmx-if-0 hybrid model, if eq.1, gdh.

av-if av=0, optical model transition rates; these values should not be used above 55 MeV.

2.if av=1, nucleon-nucleon mean free paths are used

'gav'-No longer used.

3.cost-is mean free paths are multiplied by cost+1.

4.gdo-if=1, 'gdh' calculation (if any) restricted to initial exciton number,hybrid calc.for higher exciton numbers.

5.ij-if ij=1, isospin pre-compound option is selected.

if so the next card '3a' will be containing (p, n)_q values qp_n(1),qp_n(2), and qp_{nc},qp_{nc} is(p, n)_q value for making compound nucleus by a (p, n) reaction; qp_n(i) is for nucleus populated by emission of particle i,1=n, 2=p.

qp_{nc}=bp(at+ap+1, zt+zp)-bn(same), and

qpn(1)=bp-bn of (at+ap, zt+zp), and

qpn(2)=bp-bn of (at+ap, zt+zp-1)

4 entrance channel

Transmission coefficients $t(1)$ needed only, if `rcsss.lt.0`, Alice will try to read as many $t(1)$ as indicated by the absolute value of `rcss`(i.e. it may expect several cards here).

The Alice-91 computer code is used to calculate all the calculations internally; so the core of the computer is divided into chart of nuclides. The pre equilibrium emission of neutrons at some cyclotron energies and with some cross-sections uses the geometry dependent hybrid (GDH) model calculations with 1 MeV grid size to perform the emission of neutrons, proton, alpha and deuteron storing the residual nucleus population into the appropriate bin.

Chapter 4

Experimental Techniques for measurement of excitation functions

Nuclear reactions induced by alpha particles at intermediate energy are characterized by pre equilibrium (PE) particle emission followed by equilibrium (EQ) decay. As the projectile energy increases, the pre equilibrium particle emission becomes more and more pronounced. Hence the tail portion in the excitation function may not be explained unless the pre equilibrium particle emission is taken into account. The excitation function for alpha-Niobium reactions were measured up to alpha particle energy of about 42 MeV using the stacked foil activation techniques and GeLi gamma ray spectroscopy. Detector efficiency is defined as the percentage of ionizing radiations hitting the detector that is measured. Gamma-ray detection efficiency can be calculated with the help of 100cm^2 High Purity Germanium (HPGE) Detector.

The variation of efficiency with energy for detectors of roughly the same size and shape is quite similar even though the absolute values may differ. The Monte Carlo approach is the best method of calculation for the detector efficiency. It is desirable to decide detector efficiency experimentally. The experiment was performed at the Variable Energy Cyclotron Center (VECC), Calcutta using an alpha particle beam, Spectroscopically pure (SPECPURE) natural Niobium metallic foils were used for investigation. The stack was

comprised of fifteen Niobium foils interspersed with aluminum foils, which served as energy degrader, to get desired alpha particle energy incident on the individual target foil. The α -particle incident on each foil in the stack was calculated using α -particle energy stopping power Tables of Northcliffe and Schilling(15). Theoretical calculations of the excitation functions based on the geometry dependent hybrid (GDH) model, proposed by Blann(6) have been made and a comparison with this model shows that the model gives a satisfactory reproduction of the experimental excitation functions. Efforts have been made to develop a fully quantum mechanical picture of PE reaction in the framework of multi-step theories(16-18).

4.1 Formulation

When a very thin sample is irradiated, the rate of activation is directly proportional to the neutron flux. Thick samples perturb the neutron flux and depress the rate of activation. While any sample is being activated, it is also decaying. When N_0 is the initial number of target nuclei present in the sample, and irradiated by the beam of incident flux ϕ . Then the rate of production of a particular activity is given by

$$R_p = N_0\phi\sigma \quad (4.1.1)$$

and the expression for N_0 can be given as

$$N_0 = \frac{mN_A f}{A_0} \quad (4.1.2)$$

Where,

m-is the mass of the target foil in grams,

N_A -is the avogadro number ($=6.023 \times 10^{23}$),

f-is the percentage abundance of the isotopes in the target,

A_0 -is the atomic weight of the target material.

Given the large number of nuclei comprising the sample or radioisotope, there is a definite probability that some particular proportion of disintegrations will occur in a given time interval. Hence the rate of disintegration is proportional to the number of radioactive nuclei initially present. The decay rate can be expressed mathematically as

$$\frac{\Delta N}{\Delta t} = \lambda N \quad (4.1.3)$$

where,

$\frac{\Delta N}{\Delta t}$ - is the decay rate, also called the activity of the isotope,

N-is the number of radioactive nuclei present,

t-is the time and,

λ is the proportionality constant, called the decay constant, which is characteristic of the particular isotope.

The decay constant λ is the probability that a single nucleus will decay in a given period of time (usually seconds). (These explanations of what the decay constant, the activity, and the number of radioactive nuclei present would make excellent questions on a pop quiz). In words, how many decays occur depends on two things the probability that any one atom will decay and the number of atoms that could decay that are present in the sample to start with.

In the limit of shrinking time intervals the above equation becomes;

$$\frac{dN}{dt} = \lambda N \quad (4.1.4)$$

The rate of change in N is the difference between the rate of activation and the rate of decay:

$$\frac{dN}{dt} = R_P - \lambda N \quad (4.1.5)$$

where,

R_P -is the rate of activation cross-section

N-is the total number of radioactive nuclei present

Thus

$$\frac{dN}{dt} = \sigma\phi N_O - \lambda N \quad (4.1.6)$$

But Well-known activation equation is

$$\left(\frac{dN}{dt}\right)_t = \sigma_r\phi N_0[1 - \exp(-\lambda t_1)]. \exp(-\lambda t) \quad (4.1.7)$$

Where,

the factor $[1 - \exp(-\lambda t_1)]$ is called the saturation correction factor.

λ is the decay constant of the residual nucleus and

$$\lambda = \frac{.693}{t_{1/2}}$$

Where

$t_{1/2}$ is the half-life of residual nucleus.

The number of decay of the induced activity is small time interval (dt) can be written as-

$$dN = \sigma_r\phi N_0[1 - \exp(-\lambda t_1)]. \exp(-\lambda t)dt \quad (4.1.8)$$

Then the number of nuclei decay in time t_2 to $(t_2 + t_3)$ is given as

$$\begin{aligned} C &= \int dN \\ &= \sigma_r\phi N_0[1 - \exp(-\lambda t_1)] \int_{t_2}^{t_2+t_3} \exp(-\lambda t)dt \\ C &= \frac{\sigma_r\phi N_0[1 - \exp(-\lambda t_1)][1 - \exp(-\lambda t_3)]}{\lambda \exp(-\lambda t_2)} \end{aligned} \quad (4.1.9)$$

If A is the observed counts rate and C is the absolute count rate is related as-

$$C = \frac{A}{G.\epsilon.\theta.K} \quad (4.1.10)$$

Where,

ϵ = Detector efficiency

G = Geometry dependent factor

θ = Branching ratio of the particular γ -rays

K = Correction factor for γ -ray self absorption in the target and is given by

$$K = \frac{[1 - \exp(-\mu d)]}{\mu d} \quad (4.1.11)$$

Where, μ is the γ -ray absorption coefficient for the target in cm^2/g and d is the thickness of the target foil in g/cm^2 . Thus relating equations (4.1.9) and (4.1.10) the experimentally measured reaction cross section(σ_r)at a given energy has been calculated using the expression (16)

$$\sigma_r = \frac{A.\lambda \exp(\lambda t_2)}{N_0.\phi.\theta.(\epsilon G).K[1 - \exp(-\lambda t_1)][1 - \exp(-\lambda t_3)]} \quad (4.1.12)$$

The above equation is used to measure the activation cross-section for a particular reaction product.

Where, A = Counts under the photo peak of the characteristic gamma-ray, λ = Decay constant of the residual radio isotope, N_0 = Number of nuclei in the sample, θ = Absolute intensity of the characteristic gamma-ray, ϵG = Geometry dependent efficiency of the High Purity Germanium detector, ϕ = Average flux of the incident beam, t_1 , t_2 , t_3 are irradiation time, time lapse between stopping the beam and start of counting and Counting time respectively.

4.2 Experimental Results

The activation cross-sections for the given reactions were determined from the intensities of various identified γ -rays of sufficient intensity. The spectroscopic data used in the cross-section measurement are taken from the Table of Isotopes(14). In the reaction $^{93}\text{Nb}(\alpha, \text{n})^{96}\text{Tc}$, $^{93}\text{Nb}(\alpha, 2\text{n})^{95}\text{Tc}$ and $^{93}\text{Nb}(\alpha, 3\text{n})^{94}\text{Tc}$, the product nuclei is the same, so all the decay parameters are the same and differ in half- life, energies of emitted particles etc. As the result, the observed activity in the irradiated sample is the composite activity due to the reaction in the same set and will be the total of the activities produced due to these reactions.

Chapter 5

Calculations for various (α , xn) reactions on Niobium

The cross-section calculations were performed for pre-equilibrium nuclear reactions using GDH model for analyzing the reactions. In order to perform these calculations Alice-91 computer code is used. Firstly the theoretical calculation is done by taking the initial exciton number $n_o=4$ with configuration $(2n+2p+0)$ and pld-the level density parameter, $a=acn/pld=9$.

Later the value of the parameters are changed to the level density parameters 'a'=10 and exciton number $n_o=6$ to see the effect of excitation functions. The excitation functions for the reactions ${}^{93}\text{Nb}(\alpha, n)$, ${}^{93}\text{Nb}(\alpha, 2n)$ and ${}^{93}\text{Nb}(\alpha, 3n)$ are shown in fig below.

5.1 Comparisons of calculated results with the Experimental values.

From the graphs below it is suggested that most of the experimentally measured values and the theoretically calculated values of the cross-sections of the pre-compound nuclear reaction on Niobium at lower energies are comparable and fits to each other.

But at higher energies the theoretically calculated pre-compound nuclear reaction cross-sections are far apart from the experimentally measured values. Thus the theoretical calculation of compound nuclear reaction cross-section is required to check whether it fits the experimental result or not. Weisskopf-Ewing option is used for the compound nucleus reaction.

The comparison of the experimentally measured values and the theoretically calculated values of cross-sections is done using nearly comparable energy range of the projectile, nearly from 10 MeV to 42 MeV and for ^{93}Nb (α , 3n) reaction the energy of projectile is extended to see the peak of the graph from where it starts to fall down until the cross-section of the compound nucleus reaction becomes zero. The energy ranges of the theoretically calculated values and the experimentally measured values are kept constant to make the comparison process simple. In general theoretically calculated cross-sections of a nuclear reaction, obtained using Alice-91 computer code, showed the consistency among the experimental results.

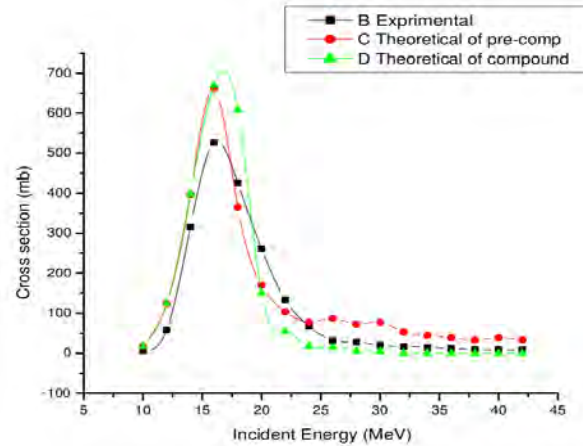
1. $^{93}\text{Nb}(\alpha, n)$ 

Figure 5.1: graph shows excitation function of $^{93}\text{Nb}(\alpha, n)$.

B-Experimental

C-Theoretical of Pre-comp nuclear reaction

D-Theoretical of compound

The theoretically calculated values of pre-equilibrium nuclear reactions cross-section starts from the energy of projectile at about minimum energy of 10 MeV with 17.8 mb and reaches its maximum peak at about 16 MeV with 662 mb and starts to fall down for increasing value of energy of projectile by making a long tail. Similarly the Experimental value indicates that the excitation function starts at about minimum energy of projectile and reaches its maximum peak at about 627 mb and falls down with increasing energy of projectile making a long tail. At lower energies the calculated values of pre-equilibrium cross-section fits with the experimentally measured values. However, at higher energies the calculated values of pre-equilibrium excitation function is far away from the experimental values and forms along tail. For this reason the compound nucleus cross-section calculation is done and gives better result which fits with the experimentally measured values as compared to pre-compound.

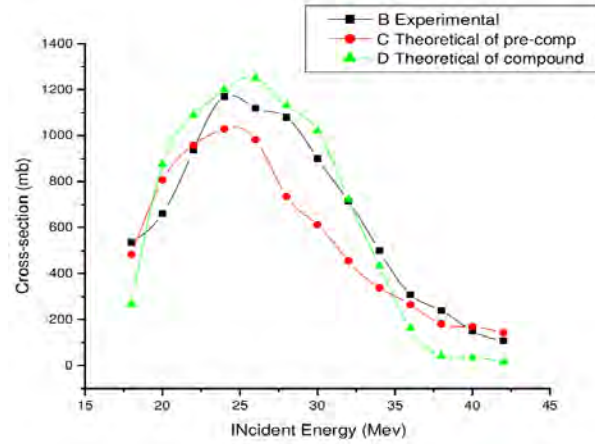
2. $^{93}\text{Nb}(\alpha, 2n)$ 

Figure 5.2: graph shows excitation function of $^{93}\text{Nb}(\alpha, 2n)$.

B-Experimental

C-Theoretical of Pre-comp nuclear reaction

D-Theoretical of compound

From the theoretical calculations, the reaction cross-section of pre-equilibrium nuclear reaction values starts at minimum energy of the projectile about 18 MeV with 483 mb and reaches its maximum peak at energy about 24 MeV with 1030 mb and then falls down for increasing value of projectile energy by making a long tail. In the same manner the experimental result shows that the reaction cross-section value starts at about minimum energy of projectile and reaches its maximum peak and then it falls down by making a long tail for the higher energy of projectile. Comparatively the experimental and theoretical pre-compound nuclear reaction excitation functions resemble, give better fit and have similar features at the lower and higher energies. But the compound nucleus reaction excitation function is closer to the experimental result at the energy range from 24 MeV to 34 MeV with their cross-sections of 1200 mb to 434 mb respectively.

3a. $^{93}\text{Nb}(\alpha, 3n)$

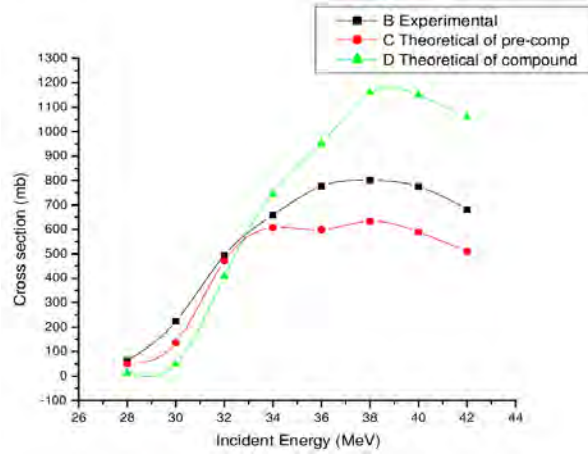


Figure 5.3: graph shows excitation function of $^{93}\text{Nb}(\alpha, 3n)$ at lower energies.

B-Experimental

C-Theoretical of Pre-comp nuclear reaction

D-Theoretical of compound

3b. $^{93}\text{Nb}(\alpha, 3n)$

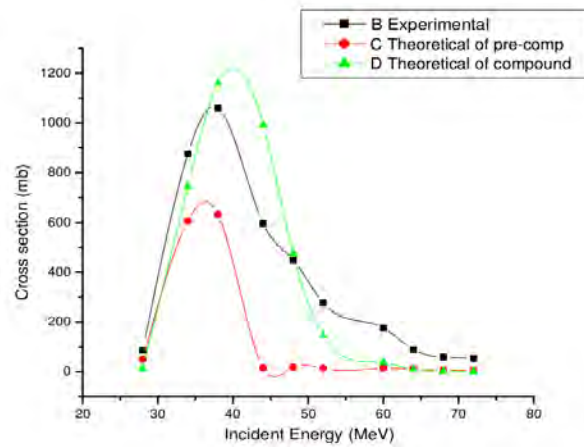


Figure 5.4: graph shows excitation function of $^{93}\text{Nb}(\alpha, 3n)$ at higher energies.

B-Experimental

C-Theoretical of Pre-comp nuclear reaction

D-Theoretical of compound

The excitation function of pre-compound nuclear reaction starts at energy about 28 MeV with 50.2 mb and reaches its maximum maximum peak value at energy about 38 MeV with 633 mb and falls down for some increasing projectile energies. At lower energies the pre-compound nuclear reaction excitation function fits with the experimental excitation function up to its peak value of cross-section. As the energy increases the compound nucleus reaction excitation function becomes closer to the experimental excitation function. In this reaction at higher energies both the pre-compound and compound nucleus excitation functions almost equally fit to the experimental results.

The exciton number ' n_o ' and level density parameter ' a ' are the most important parameters for the pre-equilibrium calculations. In the present calculations the initial exciton number $n_o = 4$ with configuration (2p+2n+0h) gives the best fit for the reproduction of experimental data. The level density parameter ' a ' is taken as $a=A/9$ where A is the mass number of compound nucleus. With the above set of appropriate input parameters which give the best reproduction of experimental data, the theoretical calculations have been performed. In the figures 5.1-5.8 the theoretical excitation functions are plotted along with the experimental excitation functions. The green line represents the calculations based on the compound nucleus reaction. The red line represents the calculations based on pre-equilibrium nuclear reaction and the black line represents the experimental excitation function.

The changing of pld-the level density parameter in calculating the cross-sections of nuclear reactions have no appreciable effect (i.e the excitation functions have similar characteristics). However, the change of exciton number ' n_o ' has a considerable change on excitation function of nuclear reactions (for $n_o=4$, the excitation function of pre-compound nuclear reaction starts to fall down below the experimental result with its peak cross-section of 1030 mb and fits the experimental results at higher energies). In contrast to this for $n_o=6$ the excitation function of pre-compound nuclear reaction starts to fall down above the experimental results with its peak cross-section of 1170 mb and far apart from the experimental result at higher energies. The variation in excitation function with pld and n_o is given in figures 5.5-5.8 below.

The relation of excitation function and the level density parameter (pld), considering the nuclear reaction of $^{93}\text{Nb}(\alpha, 2n)$ is shown in figures 5.5-5.6 below.

a) for $\text{pld}=A/9$

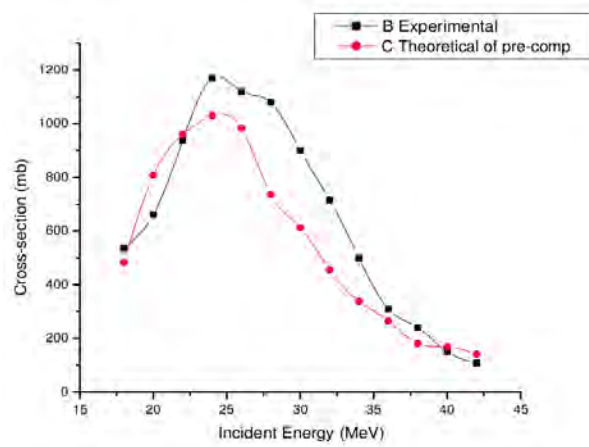


Figure 5.5: Experimental and theoretical excitation functions for $\text{pld}=A/9$.

B-Extrapolated experimental value of $^{93}\text{Nb}(\alpha, 2n)$

C-Theoretically calculated value

b) for $\text{pld}=A/10$

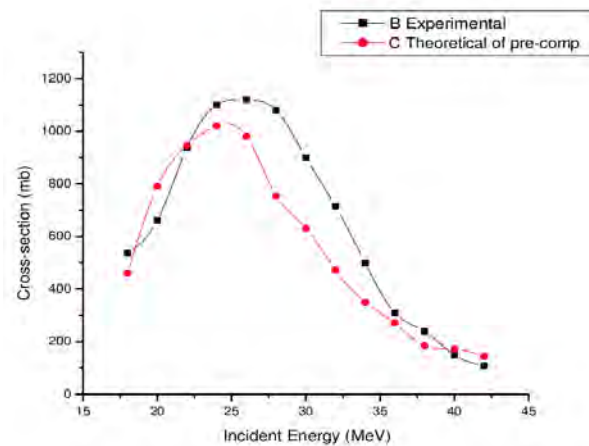


Figure 5.6: Experimental and theoretical excitation functions for $\text{pld}=A/10$.

B-Extrapolated experimental value of $^{93}\text{Nb}(\alpha, 2n)$

C-Theoretically calculated value

The relation of excitation function and exciton number is shown again using the nuclear reaction of $^{93}\text{Nb}(\alpha, 2n)$ in fig 5.7-5.8 below.

a) for $n_o=4(2n+2p+0h)$

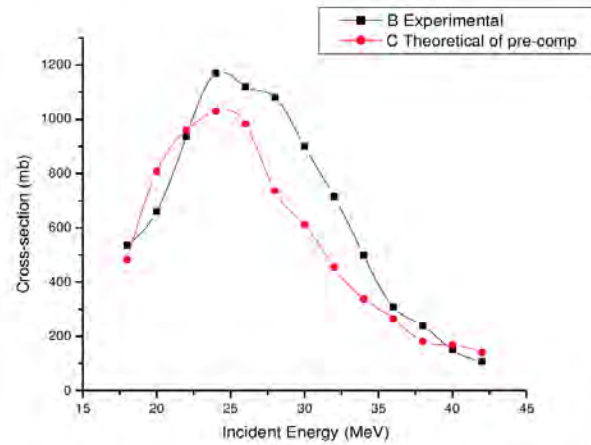


Figure 5.7: Experimental and theoretical excitation functions for $n_o=4$.

B-Extrapolated experimental value of $^{93}\text{Nb}(\alpha, 2n)$

C-Theoretically calculated value

b) for $n_o=6(3p+2n+1h)$

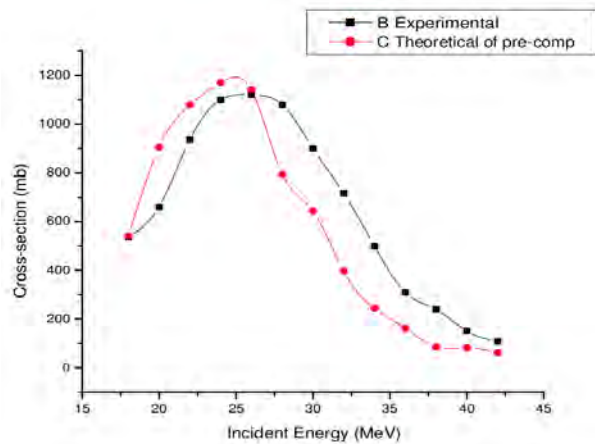


Figure 5.8: Experimental and theoretical excitation functions for $n_o=6$.

B-Extrapolated experimental value of $^{93}\text{Nb}(\alpha, 2n)$

C-Theoretically calculated value

5.2 Conclusion.

From the above analysis it may be concluded that α particle induced excitation functions have a tail in the high energy region, which cannot be accounted for by the compound reaction mechanisms, and that the pre-equilibrium emission must be considered along with the compound nucleus decay.

The calculated values from the geometry dependent hybrid model of pre-equilibrium nuclear reaction agree with the experimentally measured excitation functions of alpha induced reaction on Niobium at lower energies. But from above figures it is clear that at higher energies in this case both pre-equilibrium and only equilibrium cross-sections are closer to experimental value. So it is not 100 percent correct to say that only compound nucleus theory is not valid. But in these reactions it is particularly observed that pre-equilibrium contribution is not up to appreciable amount. May be in some other reactions where α particle emission also takes place, pre-equilibrium emission may be predominant. But it was not possible to compare as experimental values were not available.

Theoretical and experimental results have no appreciable change with the variation of 'pld' values in pre-equilibrium region. But the theoretical excitation function values changes considerably with the change of exciton number, showing that the excitation function dependence on the exciton number. In my calculation of excitation function of alpha induced reactions on Niobium, the choice of exciton number $n_o=4$ with configuration $(2p+2n+0h)$ for the pre-equilibrium system gives satisfactory results that really coincides with the experimental results in the long tail portion.

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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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Place and time of submission: Addis Ababa University, June 2011

This thesis has been submitted for examination with my approval as University advisor.

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