STUDY OF REACTION MECHANISM IN $P + ^{133}CS$ SYSTEMS AT VARIOUS ENERGIES OF PROTONS

By

Konjit Asresahagn Angdasaw

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The undersigned hereby certify that they have read and recommend to the school of Graduate Studies for acceptance a thesis entitled "STUDY OF REACTION MECHANISM IN P + ^{133}Cs SYSTEMS AT VARIOUS ENERGIES OF PROTONS"by konjit asresahagn angdasaw in partial fulfillement of the requirements for the degree of MASTERS OF SCIENCE IN PHYSICS.

Dated:JUNE 2013

Supervisor: _____

Prof.A.K.Chaubey

Examiners: _____

Dr.Tilahun Tesfaye

_____

Prof.P.Singh

ADDIS ABABA UNIVERSITY

Date: **JUNE 2013**

Author: **Konjit Asresahagn Angdasaw**

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Abstract

In this thesis proton induced reaction on Cesium ^{133}Cs for various energy of protons have been studied. Excitation function (EFs) for five reactions of the type $^{133}Cs(p,n)^{133}Ba$, $^{133}Cs(p,n+p)^{132}Cs$, $^{133}Cs(p,3n)^{131}Ba$, $^{133}Cs(p,5n)^{129}Ba$ and $^{133}Cs(p,6n)^{128}Ba$ were studied. Theoretical calculations have been carried out by using code COMPLET includes both compound nucleus (CN) as well as pre - compound (PC). The theoretical results are compared with the experimental excitation functions obtained from EXFOR data source,IAEA. The study shows that high energy parts of excitation functions are dominated by pre - equilibrium reaction mechanism where as the low energy parts are dominated by compound nucleus reaction mechanism. The percentage of pre - equilibrium factor contribution is found to increase with normalized projectile energy and when the incident proton energy increases the pre - equilibrium reaction is more signficant.

Chapter 1

INTRODUCTION

The study of nuclear reactions induced by protons has again attracted the attention of nuclear physicists. One of the main reasons for this is the requirement of precise nuclear data needed for the development of recently proposed Accelerator Driven Sub-critical (ADS) reactors [1]. Further, the data also have verity of applications including the field of medical sciences, environmental sciences, transmutation of nuclear waste etc. One of the important aim of the study of such reactions is to enhance the basic understanding of the reaction mechanism. The reaction mechanism of nucleon induced reactions particularly proton induced reactions is still not well understood. There are indications that compound and pre-compound reaction processes play an important role at moderate excitation energies. 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. As such, 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. Efforts have been made to obtain the estimates of basic nuclear reaction cross-sections both experimentally as well as theoretically. Though, considerable data is available in literature on proton induced reactions but the cross-section values measured

by different groups of workers for the same reaction, generally, do not agree. Further, earlier measurements were done mostly by using detectors and electronics of low resolution and poor efficiency. As such, it has been realized that there is a great need of new, reliable and self consistent cross-section data taken by high resolution detectors of better efficiency. It may not be out of place to mention that 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. Fitting of excitation function for an individual channel may improve the description of the data for the partial channel at the cost of other open channels however, it is unacceptable from the point of view of physics. Several phenomenological as well as quantum-mechanical models have been launched to explain the pre-equilibrium (PE) reaction mechanism. All these models describe the method by in which projectile energy gradually gets redistributed among the constituent nucleons of the composite system through a series of residual two-body interactions. It is interesting to obtain in the analysis, simultaneously, a best description of all existing experimental data for all open channels, as this approach is considered to be internally consistent, detailed and complete. Several models like ALICE-91 , CASCADE , PACE2 , ACT, COMPLET [2] etc., are available in the literature and are generally used for theoretical calculations of EFs for light and heavy-ion induced reactions. In all the codes except ACT , the configuration of the codes is such that they predict the total cross-section only for the population of the residual nuclei. However, the code ACT calculates the cross-sections for the production of both the ground as well as isomeric states. In the work reported[3], the code ACT based on the lines of codes STAPRE was used using consistently the same set of parameters. At moderate excitation energies, reactions induced by nucleons and light-heavy ions are found to proceed through CN as well as PE emission [3]. As such, 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 programme of precise measurement and analysis of cross-sections for proton, alpha-particles and heavy-ion induced reactions is going on at many places. These measurements may provide a broad database for testing the capability of theoretical model codes with respect to calculating ratio-isotope production. The experimental details are given in section 4, while the details of result and discussion of proton induced reaction on cesium i.e $^{133}Cs(p,n)^{133}Ba$, $^{133}Cs(p,n+p)^{132}Cs$, $^{133}Cs(p,3n)^{131}Ba$, $^{133}Cs(p,5n)^{129}Ba$ and $^{133}Cs(p,6n)^{128}Ba$ are given in section 5 of the thesis. Using these measured values, the calculated values were compared and some important conclusions were drawn.

Chapter 2

THEORIES OF NUCLEAR REACTION

2.1 Description Of Nuclear Reaction

One important field of reseach to understand nuclear physics is nuclear reactions. The study of nuclear reactions is extremally important almost all the properties of the nucleus such as mass, size, charge distribution, etc. have been obtained from this study. Further, this study provides information about the nature of nuclear force and reaction mechanisms.

The process of bombarding a target nucleus by fast moving projectile and the subsequent interaction between the two which alters the composition, energy, etc. of the target nucleus is known as Nuclear Reaction. This is also known as transmutation of one element in to another.

Typically, Nuclear reaction occures between an energetics reaction partner called the projectile or bombarding particles and one that is at rest called the target, some particles are emitted. Nuclear reactions can be written down in a manner similar to chemical reaction equations. If a target nucleus X is bombarding by particle a. During this process a new nucleus Y is formed and particle b is emitted, then this nuclear reaction is written as

$$a + X \longrightarrow Y + b$$

In shorthand way to denote the above reaction is

$$X(a,b)Y$$

If more than one particles say b_1, b_2 and b_3 are emitted then the reaction is written as

$$a + X \longrightarrow Y + b_1 + b_2 + b_3$$

It denoted as

$$X(a, b_1 b_2 b_3)Y$$

Generally, Nuclear reactions are taken to be reactions in which particles interact with nuclides and end up giving rise to nuclides and particles[4].

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.

The first study of nuclear reaction was performed by Ernest Rutherford in 1917. He was able to accomplish transmutation of nitrogen in to oxygen at the university of manchester, using alpha particles directed at nitrogen as follows

$${}^{14}_{7}N + \alpha \longrightarrow {}^{17}_{8}O + {}^{1}_{1}H$$

This reaction rewritten as more compact form as

$${}^{14}_{7}N(\alpha, p){}^{17}_{8}O$$

This was the first observation of an induced nuclear reaction that is a reaction in which particles from one decay are used to transform another atomic nucleus. Eventually, In 1932 at cambridge university a fully artifical nuclear reaction and nuclear transmutation was achived by Rutherford's collagues John cockcroft and Ernest Walton , who used artifically accelerated protons against lithium -7, to split the nucleus in to two alpha particles. The feat was popularly known as splitting the atom although it was not the modern nuclear fission reaction later discovered in heavy elements in 1938.

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

2.1.1 Types Of Nuclear Reactions

There are many ways of classifying nuclear reactions. Depending on its energy, the incoming particle can produce different types of reactions (reaction channels). Some of them are:

Elastic scattering

The projectile a after interaction is emitted with some energy. The target X is also in the initial Quantum mechanical state. In this type of reaction the entering projectile and emitted particles are the same.

Example;

$$^{1}_{0}n + ^{208}\,pb \longrightarrow ^{208}\,pb + ^{1}_{0}\,n$$

When no energy is transferred between the target nucleus and the incident particle, the process is known as ^{208}pb elastic scattering. Target nucleus and residual nucleus is the same. There is no appreciable energy loss. So system remains in the same ground state. No excitation,i.e Target nucleus remains in ground state.

Inelastic scattering

Here the emitted particle is the same as the initial projectile but its energy is reduced. Some energy is taken by target nucleus and it goes in the excited state.

$$a + A \longrightarrow A^* + a$$

energy is decrease. a is in excited and when comes in ground state γ-rays are emitted, This means $A^* \longrightarrow A + \gamma$.

Example;

$${}^1_0n + {}^{208}\,pb \longrightarrow {}^{208}\,pb^* + {}^1_0\,n, \text{ Hence } {}^{208}pb^* \rightarrow {}^{208}\,pb + \gamma$$

Disintegration process

$a + A \rightarrow b + B \rightarrow c + C$, When the projectile enters the target nucleus new system is formed. This may decay to residual nucleus B and particle b is emitted or this may decay to a system C and particle c is emitted. (Its decay is depending up on the energy of the reaction product.)

Radioactive capture

The projectile is captured by target nucleus and a few system is formed in the excited state. which will come down in the ground state by emitting γ-radiation. After capture of projectile only γ-radiations are emitted.

Example;

$${}^1_1H + {}^{26}_{13}\,mg \longrightarrow {}^{27}_{13}\,Al^*, \text{ then } {}^{27}_{13}Al^* \longrightarrow {}^{27}_{13}\,Al + \gamma$$

Many body reaction

Depending up on energy of excitation of the system produced after capture of projectile, this may decay by the emission of many particles b_1 ,b_2 , b_3 , b_4 etc. and finally γ-radiations are emitted when the energy of excitation is well below the binding energy of a nucleon. Number of particles are emitted depending up on the projectile energy.

Example;

$$^{16}O(p,2p)^{15}N, \quad ^{16}O(p,3p)^{14}C$$

Photodisintegration

Incident projectile is not a nucleon but γ-radiation. This incident γ depending up on the energy may have disintegration of target nucleus.

Example;

$\gamma +^{2}_{1} H \rightarrow^{1}_{1} H +^{1}_{0} n$, Photodisintegration of Deuteron.

Stripping and Pick up reaction

When the projectile and the target nucleus exchange nucleons and the projectile gains nucleons from the target the reaction is said to be Pick up and if the projectile losses nucleons(the target gains nucleons) the reaction is called Stripping. Since both processes involve nucleons exchange between the target and the projectile the reaction also called nucleon transfer reaction. Both pick up and stripping reactions are direct reaction because the nucleons involved in the reaction process enter or leave the target nucleus with out disturbing the other nucleons of the target nucleus. Interaction with only surface nucleons takes place not with the nucleus as a whole.

Depending up on the energy of the projectile the interaction is possible in which the projectile is stripped off a nucleon (stripping) or projectile is pick up a nucleon from target nucleus. These reactions are different than the other previous reactions.

Example;

$$^{63}_{29}Cu +^{2}_{1} H \longrightarrow^{64}_{29} Cu +^{1}_{1} H \quad \text{(stripping)}$$

$$^{1}_{1}H +^{27}_{13} Al \longrightarrow^{26}_{13} Al +^{2}_{1} H \quad \text{(pickup)}$$

Heavy Ion Reactions

The study of the interaction of two heavy ions is the 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 (^4He) considered as heavy ions. So any ion from ^4He up to ^{208}pb or ^{238}U is a heavy ion. Reactions studied using a large number of heavy ions as projectile.

2.1.2 Conservation Laws in Nuclear Reactions

In analyzing nuclear reaction we apply conservation laws. Conservation of energy, momentum and angular momentum are all derived from classical mechanics. Nevertheless, all remain true in quantum mechanics and relativistic mechanics, which have replaced classical mechanics as the most fundamental of all laws.

In ordinary nuclear reaction the following conservation laws are conserved: conservation of charge (total charge before the reaction is the same as the charge after the reaction), momentum, angular momentum, energy, nucleon number (Baryon number) and lepton number. At higher energies we still conserve total nucleon (baryon) number, but at low energy we conserve separately proton number and neutron number.

Conservation of parity is also conserved i.e In nuclear reaction proceding through strong interaction, parity is conserved. But in nuclear reaction proceding through weak interactions, parity is violated.

2.1.3 Energtics of Nuclear Reactions

Conservation of total relativistic energy in our basic reaction gives as

$$M_X C^2 + T_X + M_a C^2 + T_a = M_Y C^2 + T_Y + M_b C^2 + T_b \tag{2.1.1}$$

Where $T_X = 0$ because the target is at rest, T_a, T_Y, T_b are kinetic energies for each particle and M_X, M_a, M_Y and M_b are rest masses of projectile, target,residual and emitted particle. We define the reaction Q - values (the energy released or absorbed in a nuclear reaction), with radioactive decay Q - values, as initial mass energy minus the final mass

energy.

$$Q = (M_{inital} - M_{final})C^2 \tag{2.1.2}$$

$$Q = [M_X + M_a - M_Y - M_b]C^2 \tag{2.1.3}$$

which is the same as the excess kinetic energy of the final products:$Q = T_{Final} - T_{Initial}$, the Q - value may be postive, negative or zero.

If $Q > 0(M_{inital} > M_{final})$ or $(T_{final} > T_{inital})$ the reaction is said to be exoergic or exothermic, in this case nuclear mass or binding energy is released as kinetic energy of the final products.

If $Q < 0(M_{inital} < M_{final})$ or $(T_{final} < T_{inital})$ the reaction is endoergic or endothermic, and inital kinetic energy must is conserved in to nuclear mass or binding energy. the changes in mass and energy must of course be related by the familiar expression from special relativity, $\Delta E = \Delta MC^2$ - any change in the kinetic energy of the system of reacting particles must be balanced by an equal change in its rest energy.

2.1.4 Nuclear Reaction Cross - Section

Aquestion often a rises that when some projectiles are bombarded on a target, an interaction or reaction between these two takes places, then how many nuclei are taking part in this reaction? Is this number small or large? Depending upon the numbers, the probabilitity of a particular reaction becomes small or large. There must be a quantitative measure of this probabilitity. This quantity should be easily measurable and also theoretically calculable, so that we can compare the experimental results with the theoretical calculations.

The quantity which defines the probabilitity of a given reaction is called the nuclear reaction cross - section and it is denoted as σ.

The reaction cross - section can be visualized as an effective area around the nucleus such that if the incident particles cross the area, a nuclear reaction takes places, otherwise not. This area is also known as effective area. It is not exactly same as the geometrical

area(πr^2), where r is the radius of the nucleus. This effective area could be larger, smaller or equal to the geometrical area of the nucleus. Thus, nuclear reaction cross - section is a measure of the probabilitity that bombarding particles at a particular energy would interact with the target.

Let us consider abeam of particles of flux I (number of particles passing a unit area per unit time) incident on a thin sheet of a material having thickeness dx and face area A. Let us also assume that thickness is so small that none of the nuclei of the thin sheet overlap each other. Thus, each nucleus has an equal probability to cause a nuclear reaction with the incident beam. Let σ be the effective area of the target nucleus as stated earlier, this area is such that when the incident particle crosses this area the reaction always takes place. Let n be the number of target nuclei per area in this thin sheet.

Number of nuclei in the sheet per unit face area = $n \times dx$

Total number of nuclei in the sheet = $A \times n \times dx$

Since each nucleus has an effective area σ, so the total effective area available for the reaction = $A \times n \times \sigma \times dx$

Fractional effective area f = $\frac{\sigma \times A \times n \times dx}{A}$

$= \sigma \times n \times dx$

When a projectile takes part in a nuclear reaction. it is absorbed by the target nucleus, so the flux of incident particles decreases. If the fractional effective area (f) if large, then the corresponding decrease in the flux(I) will be large and vice versa. This can be summarized that fractional change in flux is equal to f. i.e

$$\frac{dI}{I} = -n \times \sigma \times dx \tag{2.1.4}$$

The negative sign has been introduced because as dx increase the flux decrease.

Assuming that at x = 0, $I = I_0$ integrating equation with respect to x, we get

$$I = I_0 e^{-n\sigma x} \tag{2.1.5}$$

Thus, the flux of the incident beam exponentially decrease as the thickeness of the sheet increase.

Units of reaction cross - sections are the unit of area. These cross - sections are normally very small $\sim 10^{-27}$ to $10^{-28}m^2$. since this value is small so it is convenient to use a unit called *barn*. $1barn(b) = 10^{-28}m^2$ and Smaller units of cross sections are millbarn (mb), microbarn (μb), etc

Different Types of Cross - Section

In nuclear reaction we come across different types of reaction cross - section. They are

1) Partial reaction cross - section

For a given energy and target projectile combination, several nuclear reactions such as elastic scattering, inelastic scattering, capture reaction, disintegration reactions, etc are possible simultaneously. There is a definite reaction cross - section for each such reaction denoted by $\sigma_1, \sigma_2, \sigma_3$,... etc. These cross - sections are known as partial reaction cross - sections.

2) Total reaction cross - section

As stated earlier, for a given energy and target projectile combination, many partial cross - sections may exist simultaneously , sum of all such partial cross - sections is known as total reaction cross - section σ. $\sigma = \sigma_1 + \sigma_2 + \sigma_3 + ...$

Quantum Mechanical plane wave analysis of reaction cross - section

Nuclear reaction cross-section may be explained using wave mechanical theory under general assumptions[6]. Let us consider a collimated beam of neutrons taking on the target, the beam is moving in Z-direction. This neutron beam can be consider as a plane wave exp(ikz).

$$\psi_{inc} = e^{ikz} \tag{2.1.6}$$

The plane wave can be explained in terms of bessel's functions and spherical harmonic of various values of ℓ.

$$e^{ikz} = \sum_{\ell=0}^{\infty} i^{\ell}(2\ell+1)j_{\ell}(kr)P_{\ell}(cos\theta) \tag{2.1.7}$$

$$j_{\ell}(kr) = \frac{sin(kr - \frac{\ell\pi}{2})}{kr} \tag{2.1.8}$$

$$P_{\ell}(cos\theta) = \sqrt{\frac{4\pi}{2\ell+1}}Y_{\ell,0}(\theta) \tag{2.1.9}$$

For $r \to \infty$ then the Bessel function $j_{\ell}(kr) = \frac{sin(kr - \frac{\ell\pi}{2})}{kr}$

$$e^{ikz} = \psi_{inc} \tag{2.1.10}$$

$$\psi_{inc} = \frac{1}{kr}\sum_{\ell=0}^{\infty} i^{\ell}(2\ell+1)sin(kr - \frac{\ell\pi}{2})P_{\ell}(cos\theta) \tag{2.1.11}$$

$$\psi_{inc} = \frac{1}{2ikr}\sum_{\ell=0}^{\infty} i^{\ell}(2\ell+1)[e^{i(kr-\frac{\ell\pi}{2})} - e^{-i(kr-\frac{\ell\pi}{2})}]P_{\ell}(cos\theta) \tag{2.1.12}$$

$$\psi_{inc} = \frac{1}{2kr}\sum_{\ell=0}^{\infty}(2\ell+1)i^{\ell+1}[e^{-i(kr-\frac{\ell\pi}{2})} - e^{i(kr-\frac{\ell\pi}{2})}]P_{\ell}(cos\theta) \tag{2.1.13}$$

The 1^{st} term $e^{-i(kr-\frac{\ell\pi}{2})}$ is ingoing wave and the 2^{nd} term $e^{i(kr-\frac{\ell\pi}{2})}$ is outgoing wave. In the presence of a nucleus the amplitude of outgoing wave is modified.

$$\psi(r) = \frac{1}{2kr}\sum_{\ell=0}^{\infty}(2\ell+1)i^{\ell+1}[e^{-i(kr-\frac{\ell\pi}{2})} - \eta_{\ell}e^{i(kr-\frac{\ell\pi}{2})}]P_{\ell}(cos\theta) \tag{2.1.14}$$

$\eta_{\ell} =\mid \eta_{\ell} \mid e^{i\delta_{\ell}}$, Where $e^{i\delta_{\ell}}$ represents phase and $\mid \eta_{\ell} \mid$ is the amplitude.

If $\mid \eta_{\ell} \mid$ is changing, it means amplitude is decreasing, reaction is taking place. If δ_{ℓ} is changing then scattering is taking place.

If $\mid \eta_{\ell} \mid$ is not changing, it means no attenuation of amplitude and hence no reaction. If

the phase is changing (phase shift) then scattering is taking place.

The scattered wave can be written as

$$\psi_{sc} = \psi(r) - e^{ikz} \tag{2.1.15}$$

$$\psi_{sc} = \sum_{\ell=0}^{\infty} \frac{1}{2kr}(2\ell+1)i^{\ell+1}(1-\eta_\ell)(e^{i(kr-\frac{\ell\pi}{2})})P_\ell(cos\theta) \tag{2.1.16}$$

The scattered wave can be also written in terms of scattering amplitude as follows

$$\psi_{sc} = f(\theta)\frac{e^{ikr}}{r} \tag{2.1.17}$$

$f(\theta)$ is the scattering amplitude, then to get the value of $f(\theta)$ simply compare the above two equations.

$$f(\theta)\frac{e^{ikr}}{r} = \sum_{\ell=0}^{\infty} \frac{1}{2kr}(2\ell+1)i^{\ell+1}(1-\eta_\ell)(e^{i(kr-\frac{\ell\pi}{2})})P_\ell(cos\theta) \tag{2.1.18}$$

$$f(\theta) = \sum_{\ell=0}^{\infty} \frac{i^{\ell+1}}{2k}(2\ell+1)e^{\frac{-i\ell\pi}{2}}(1-\eta_\ell)P_\ell(cos\theta) \tag{2.1.19}$$

For any value of ℓ, $i^\ell e^{\frac{-i\ell\pi}{2}} = 1$, then the above equation becomes

$$f(\theta) = \frac{1}{2ik}\sum_{\ell=0}^{\infty}(\eta_\ell - 1)P_\ell(cos\theta)(2\ell+1) \tag{2.1.20}$$

To get the scattering cross-section, we consider a sphere of radius r_0 enclosing the scatterer. The values of r_0 is very much larger than the nuclear force range.

The number of scattered particle through the solid angle $d\Omega$ is equal to the number of particles scattered through $r_0^2 d\Omega$.

N_{sc} can be calculated using the expression of the probability of current density.

$$N_{sc} = \frac{\hbar}{2mi}\int (\frac{d\psi_{sc}}{dr}\psi_{sc}^* - \frac{d\psi_{sc}^*}{dr}\psi_{sc})_{r=r_0}^{r_0^2 sin\theta d\theta d\phi} \tag{2.1.21}$$

Where $k = \frac{\sqrt{2mE}}{\hbar}$, hence $\frac{\hbar k}{m} = \hbar\frac{\sqrt{2mE}}{\hbar m} = \frac{\sqrt{2mE}}{m}$ and $v = \frac{\sqrt{2E}}{\sqrt{m}} = \frac{\sqrt{2mE}}{m}$ the above equation

becomes

$$N_{sc} = \frac{\hbar k}{m} \int \mid f(\theta) \mid^2 sin\theta d\theta d\phi \tag{2.1.22}$$

Where m is the mass number of incident particle

$$N_{sc} = v \int \mid f(\theta) \mid^2 d\Omega \tag{2.1.23}$$

$$N_{sc} = \frac{v\pi}{k^2} \sum_{\ell=0}^{\infty} (2\ell + 1) \mid 1 - \eta_\ell \mid^2 \tag{2.1.24}$$

Due to orthogonality of normalization of spherical harmonics and legendere polynomial

$$P_\ell(cos\theta) = \sqrt{\frac{4\pi}{2\ell + 1}} Y_{\ell m} \tag{2.1.25}$$

$$\sigma_{sc} = \frac{N_{sc}}{Incident\ flux} \tag{2.1.26}$$

Incident flux for a plane wave e^{ikz} moving with velocity v

$$\int \psi\psi^* d\tau = 1 \tag{2.1.27}$$

Particle density in a plane wave is the flux of plane wave number of particle per second per unit area=v then

$$\sigma_{sc} = \frac{N_{sc}}{Incident\ flux} \tag{2.1.28}$$

$$\sigma_{sc} = \frac{N_{sc}}{v} = \frac{\pi}{k^2} \sum_{\ell=0}^{\infty} (2\ell + 1) \mid 1 - \eta_\ell \mid^2 \tag{2.1.29}$$

Where, from the relation $P = \frac{\hbar}{\lambda} = \hbar k$

$$\sigma_{sc} = \pi\lambda^2 \sum_{\ell=0}^{\infty} (2\ell + 1) \mid 1 - \eta_\ell \mid^2 \tag{2.1.30}$$

$$\sigma_{sc,\ell} = \pi\lambda^2(2\ell+1) \mid 1-\eta_\ell \mid^2 \tag{2.1.31}$$

Then let calculate the reaction cross-section using the probablity current density expression. Now first let calculate number of particles going in

$$N_r = -\iint \frac{\hbar}{2mi}(\frac{d\psi_r}{dr}\psi_r^* - \frac{d\psi_r^*}{dr}\psi_r)r_0^2 sin\theta d\theta d\phi \tag{2.1.32}$$

In place of ψ_{sc} we have ψ_r

$$N_r = \frac{\hbar\pi}{mk}\sum_{\ell=0}^{\infty}(2\ell+1)(1- \mid \eta_\ell \mid^2) \tag{2.1.33}$$

$$\sigma_r = \frac{N_r}{incident flux} = \frac{N_r}{v} \tag{2.1.34}$$

$$\sigma_r = \sum_{\ell=0}^{\infty}\sigma_{r,\ell} = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)(1- \mid \eta_\ell \mid^2) \tag{2.1.35}$$

$$\sigma_r = \pi\lambda^2\sum_{\ell=0}^{\infty}(2\ell+1)(1- \mid \eta_\ell \mid^2) \tag{2.1.36}$$

Then the total cross section $\sigma_{t,\ell}$ is given as

$$\sigma_{t,\ell} = \sigma_{sc,\ell} + \sigma_{r,\ell} \tag{2.1.37}$$

$$\sigma_{t,\ell} = \pi\lambda^2(2\ell+1)[1- \mid \eta_\ell \mid^2 + \mid 1-\eta_\ell \mid^2]$$

$$\sigma_{t,\ell} = \pi\lambda^2(2\ell+1)[1-\eta_\ell\eta_\ell^* + (1-\eta_\ell)(1-\eta_\ell^*)]$$

$$\sigma_{t,\ell} = \pi\lambda^2(2\ell+1)[2-\eta_\ell-\eta_\ell^*] \tag{2.1.38}$$

$$\sigma_{t,\ell} = \pi\lambda^2(2\ell+1)[2-(Re\eta_\ell + Img\eta_\ell) - (Re\eta_\ell - Img\eta_\ell)] \tag{2.1.39}$$

$$\sigma_{t,\ell} = \pi\lambda^2(2\ell+1)[2-2Re\eta_\ell] \tag{2.1.40}$$

$$\sigma_{t,\ell} = 2\pi\lambda^2(2\ell+1)[1 - Re\eta_\ell] \tag{2.1.41}$$

Total cross section is given by only $Re\eta_\ell$, $\eta_\ell =\mid \eta_\ell \mid e^{2i\delta_\ell}$, If $\mid \eta_\ell \mid= 1$, $\eta_\ell = e^{i2\delta_\ell} = cos2\delta_\ell + isin2\delta_\ell$ then the real part of $\eta_\ell = Re\eta_\ell = cos2\delta_\ell$, Hence $1 - Re\eta_\ell = 2sin^2\delta_\ell$

$$\sigma_{t,\ell} = 2\pi\lambda^2(2\ell+1)2sin^2\delta_\ell \tag{2.1.42}$$

$$\sigma_{t,\ell} = 4\pi\lambda^2(2\ell+1)sin^2\delta_\ell \tag{2.1.43}$$

$$\sigma_{r,\ell} = \pi\lambda^2(2\ell+1)(1- \mid \eta_\ell \mid^2) \tag{2.1.44}$$

$$\sigma_{sc,\ell} = \pi\lambda^2(2\ell+1) \mid 1 - \eta_\ell \mid^2 \tag{2.1.45}$$

For $\eta_\ell = 1$ then $\sigma_{sc,\ell} = 0$, $\sigma_{r,\ell} = 0$, For $\eta_\ell = -1, \sigma_{r,\ell} = 0$, $\sigma_{sc,\ell} = 4\pi\lambda^2(2\ell+1)$, For $\eta_\ell = 0, \sigma_{r,\ell} = \sigma_{sc,\ell} = \pi\lambda^2(2\ell+1)$ and For $\mid \eta_\ell \mid= 1$ then $\sigma_{r,\ell} = 0$, $\sigma_{sc,\ell} = finite$

When reaction cross-section is zero, scattering is also zero, when reaction cross-section is maximum at $(\eta_\ell = 0)$ scattering cross-section is equal to reaction cross-section and when scattering is maximum, reaction is zero.

Infact, Reaction is zero when scattering is maximum. Scattering is possible with out reaction but no reaction is possible with out scattering.

$$\sigma_{r,\ell} = \sum_{\ell=0}^{\infty} \pi\lambda^2(2\ell+1)(1- \mid \eta_\ell \mid^2) \tag{2.1.46}$$

$$\sigma_{r,max} = \sum_{\ell=0}^{\infty} \pi\lambda^2(2\ell+1) \qquad |\eta_\ell| = 0| \tag{2.1.47}$$

$$\sigma_{sc} = \sum_{\ell=0}^{\infty} \pi\lambda^2(2\ell+1) \qquad |\eta_\ell| = 0| \tag{2.1.48}$$

$$\sigma_{total} = \sigma_{r,max} + \sigma_{sc} = 2\pi\lambda^2 \sum_{\ell=0}^{\ell_m} (2\ell + 1) \tag{2.1.49}$$

$$\sigma_t = 2\pi\lambda^2(\ell_m + 1)^2 \qquad Where \;\; \ell_m = \frac{R}{\lambda} \tag{2.1.50}$$

$$\sigma_t = 2\pi\lambda^2(\frac{R}{\lambda} + 1)^2 = 2\pi\lambda^2 \frac{(R+\lambda)^2}{\lambda^2} \tag{2.1.51}$$

$$\sigma_t = 2\pi(R + \lambda)^2 \tag{2.1.52}$$

For high energy $R >> \lambda$

$$\sigma_t = 2\pi R^2 \tag{2.1.53}$$

Total cross-section is twice of the geometrical cross-section of the nucleus. In the figure below, the vertical axis represents $\frac{\sigma_{sc,\ell}}{\pi\lambda^2(2\ell+1)^2}$ and the horizontal axis represents $\frac{\sigma_{r,\ell}}{\pi\lambda^2(2\ell+1)^2}$

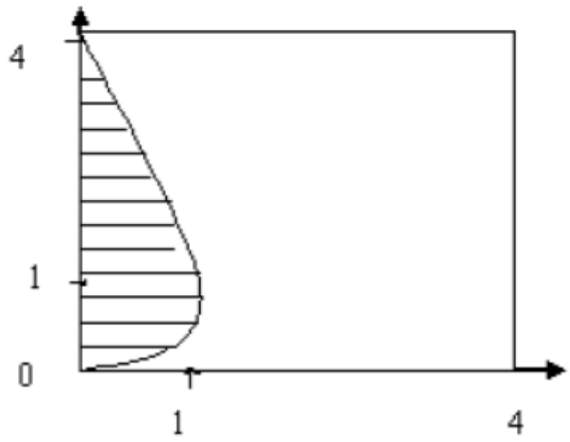

Figure 2.1: it shows possible values of scattering and reaction cross-section

2.1.5 Nomenclature of Nuclear Reaction

Projectile Particles

Projectile Particles are two types

(1) Charged nuclei, including ${}_1^1H(p)$,${}_1^2H(d)$,${}_2^4He(\alpha - particle)$ and heavier ions such as ${}_6^{12}C$, and

(2) γ rays and unchanged particles, including neutrons.

A number of devices for accelerating changed particles have been designed. Among the earliest of these is the cyclotron other accelerates includes synchroton, the linear accelerator and various heavy ion accelerator.

In this thesis the target element is Cesium - 133. Cesium (chemical symbol Cs) is a metal that may be stable (nonradioactive) or unstable (radioactive). The most common radioactive form of cesium is cesium - 137. Another fairly common radioisotope is cesium - 134. Cesium - 137 is much more significant as an environmental contaminant than cesium - 134. It is also very useful in industry for its strong radioactivity.

In 1860, Gustav Kirchhoff and Robert Bunsen discovered nonradioactive cesium in mineral water in Germany. Radioactive cesium-137 and many other radionuclides that are used in nuclear medicine, was discovered in the late 1930s.

Nonradioactive cesium occurs naturally in various minerals. Radioactive cesium - 137 is produced when uranium and plutonium absorb neutrons and undergo fission. Examples of the uses of this process are nuclear reactors and nuclear weapons. The splitting of uranium and plutonium in fission creates numerous fission products. Cesium-137 is one of the more well-known fission products.

Cesium, as well as Cesium - 137, is a soft, malleable, silvery white metal. The half-life of cesium-137 is 30 years. It decays by emission of a beta particle and gamma rays to barium - 137m (m means metastable) stablilizes it self by emitting an energitic gamma ray with a half - life of a bout 2.6 minutes. It is this decay product that makes cesium an external hazard (that is a hazard with out being taken in to the body). cesium is naturally present as the isotope 133 in various ores and to a lesser extent in soil.

Cesium - 137 is one of the most common radioisotopes used in industry. Thousands of devices use cesium - 137, it also used in medical therapy to treat cancer.

Chapter 3

REACTION MECHANISM

Various reaction models have been extremely successful in describing certain classes or types of nuclear reaction process. In general, all reactions can be classified according to the time scale on which they occur and degree to the kinetic energy of incident particle is converted into internal excitation of the final products. A large fraction of the reactions observed has properties consistent with those predicted by two reaction mechanisms. which represents the extremes in this general classification. These are the mechanism of compound nucleus formation and direct reaction. The interaction of a projectile with a nucleus may exhibit several effects. An overview of all possible nuclear reaction mechanisms is given in the figure below. The simplest form is the formation of the compound nucleus which can be described by stastical mechanics as being in a state of statistical equilibrium. The energy distribution of the components of the system is maxwellian. A components of this system may get a large amount of energy as a result of the statistical fluctuation. This amount of energy may be 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 coulomb barrier of the compound nucleus. When the compound nucleus has reached stastical equilibrium. it is said to have been thermalized. If the nuclear reactions proceed directly from entrance channel to the exit channel without the formation of an intermedidate state, they are said to be direct reactions. If the internal states of the two

colliding systems do not change, we have elastic scattering and if one or both systems are excited in the exit channel, it is inelastic scattering.

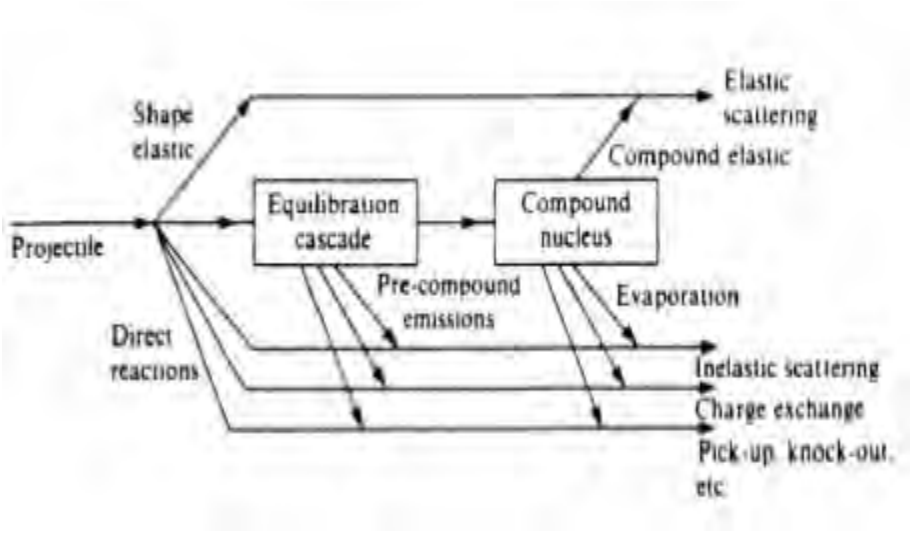

Figure 3.1: An overview of all possible nuclear reaction mechanisms

In compound nuclear reactions, the excitation energy is shared uniformly among the constituent nucleons. The compound nuclear reaction models are the Weiskoff - Ewing and Hauser - Feshbach models. The second most important mechanism is the direct interaction. This reaction occurs without the formation of an intermediate state and proceeds directly from the entrance to an exit channel. The direct reaction can be elastic scattering, inelastic scattering, knock-out and transfer or pick-up reaction. If the internal states of both systems are conserved, it will be elastic scattering while inelastic scattering occurs when one or both systems are excited in the exit channel. During the nuclear reaction, transfer of one or more nucleons happen from one nucleus to the other, it is known as a transfer or pick-up reaction.

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 commonly used pre-equilibrium models are the exciton model and the hybrid model. Both these are semi-classical models and originate from the paper by Griffin

[7] and later development. 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. If the emission does not occur at an early stage, the system eventually reaches the equilibrium or evaporation stage. This stage is described by the Weisskopf-Ewing formalism or more clearly by the Hauser-Feshbach formalism which explicitly treats vector coupling of spins and parities between compound and residual nuclei and projectiles. The time scale for direct interaction is $\sim 10^{-21}$ sec, for pre-compound emission $\sim 10^{-18}$ sec and for compound nucleus evaporation $\sim 10^{-15}$ sec.

In general, The low energy region up to about 10 MeV mostly statistical processes dominate. The pre-equilibrium effects start manifesting themselves at energies around 20 MeV and at excitation energies above 50 MeV their contribution starts becoming significant. The Pre-equilibrium models have been widely used in modeling nuclear cross sections below 200 MeV, i.e. till the spallation process becomes dominant. it provided an adequate description of the high energy tails(i.e. the region between the evaporation peak and the discrete states)of the outgoing particle spectra.

3.1 Compound Nucleus Reaction

Compound Nucleus Theory due to Bohr

The compound nucleus hypothesis of N.Bohr is probably the most often used concept for the description of nuclear reactions. Bohr divided this reaction in two - step process.

1) Formation of compound nucleus

The formation of compound nucleus is a slow process (10^{-15} to 10^{-16} sec) as compared with the time taken by a normal nucleon (few Mev) projectile, which is called nuclear

time. it is around 10^{-21} to 10^{-22} sec.

During formation of compound nucleus interaction taking with incoming projectile and nucleons present in the target, lot of energy momentum is transfered and this is shared by almost all the nucleus in this much large time. If the projectile happens to be a nucleon, it will be impossible to distinguite it from the other nucleon. After large number of collision between nucleons a stastical thermodynamic equilibrium is established. And we can say that the compound nucleus forgets the way in which it was formed.

When a projectile a is incident over a target nucleus X it enters the target nucleus and forms a new system C^*. $a + \mathrm{X} \rightarrow C^*$, Where C^* is a compound system in excited state. This process takes to much time, that the system C^* formed forgets the history of its formation. i.e C^* does not know what was the projectile a and what was the target X.

Suppose we want to form a system of compound nucleus ${}^{27}_{13}Al^*$

$${}^{4}_{2}He(\alpha) + {}^{23}_{11}Na \longrightarrow {}^{27}_{13}Al^* \ (\alpha \text{ - particle as a projectile})$$

$${}^{1}_{1}H(P) + {}^{26}_{12}mg \longrightarrow {}^{27}_{13}Al^* (\text{proton as a projectile})$$

$${}^{1}_{0}n + {}^{26}_{13}Al \longrightarrow {}^{27}_{13}Al^* (\text{neutron as a projectile})$$

By incoming channel $(a + X)$ the compound nucleus is formed.

2) Decay of Compound Nucleus

Due to this forget fullness of the compound nucleus, the second step is independent and unrelated to the first step. i.e ${}^{27}_{13}Al^*$ can decay to various outgoing or emitted channel by emitting different partices like p, n, d, α, γ.

The decay mechanism of the compound nucleus will depend only upon the energy of excitation of the compound nucleus not on the mode of formation.

In general, Compound nucleus model works best for low energies(10MeV - 20MeV). Where the incident projectile has a small chance of escaping from the nucleus with its identity and most the energy interact. It also works best for medium weight and heavy nuclei,Where the nuclear interior is large enough to absorb the incident energy.

Another characterstics of compound nucleus reactions is the angular distribution of the products. Because of random interactions among the nucleons, we expect the outgoing particle to be emitted with a nearly isotropic angular momentum. If heavy ion is the incident particle, large amounts of angular momentum can be transfered to the compound nucleus and to extract that angular momentum the emitted particles tend to be emitted at right angular momentum and thus preferentially at 0 and 180 degree. With light projectiles, this effect is negligible. The evaporation analogy mentained previously is really quite approprate. In fact,the more energy we give to the nucleus, the more particles are likely to evaporate.

In 1950 the first experiment was done in USA by an indian S.N.GHOSLAL. In the experiment two projectiles as $\alpha-$ particle and proton were selected to make compound nucleus of ${}^{64}_{30}Zn^*$. For alpha-particle the target was ${}^{60}_{28}Ni$ and for proton the target was ${}^{63}_{29}Cu$ is selected.

$$\begin{array}{lll} p + {}^{63}Cu \searrow & & \nearrow {}^{63}Zn + n \\ & {}^{64}Zn^* & \longrightarrow {}^{62}Cu + n + p \\ \alpha + {}^{60}Cu \nearrow & & \searrow {}^{62}Zn + 2n \end{array}$$

If the idea of the compound nucleus is valid and if one chooses the energy of the proton and of the incident α-particle to produce the same excitation energy, then the cross section for each one of the three exit channels should be independent of the way the compound nucleus is formed. That is, the properties of the compound nucleus do not have any relationship with the nuclei that formed it. where one can see clearly that the cross sections depend practically only on the exit channels.

Limitation for Bohr's hypothesis

1) Mean free path of the collision (Λ), it has some correlation between mean free path(Λ) and nuclear radius (R), $\Lambda \ll R$, The mean free path of collision of the projectile must be very much smaller than the nuclear radius so that projectile remains inside the nucleus

and interacts goes on till the thermal equilibrium is established. The mean free path increase with increases of kinetic energy (ε) of the projectile so for low energy projectile Λ will be small. At thermal energies it is smallest so this condition of $\Lambda \ll R$ will be valid at low energies and this may be not be true at higher energies. This may be correct ($\Lambda \ll R$), ($\Lambda < R$), ($\Lambda \approx R$) upto few tens of MeV energy. so compound nucleus formation may be valid upto $\sim$ 50MeV energy or less.

2) Decay time of the excited state of the system shoud be large enough. so that system forgets the history of formation. During the formation of compound nucleus, if there is concentration of more energy on one or two nucleon and these aquire higher energy may be emitted out. $E_c = \varepsilon + E_B$, ($\frac{\varepsilon+E_B}{A}$) $\ll S_a$, Where S_a is separation energy, E_B is the binding energy $S_a \approx E_B$ and ($\frac{\varepsilon+E_B}{A}$) is energy per nucleon in the compound nucleus.

$$\varepsilon + E_B \ll S_a A \qquad \text{Hence, } E_B \sim S_a \sim S$$

$$\varepsilon + S_a \ll S_a A \quad \text{this implies} \quad \varepsilon \ll (A-1)S$$

So far the kinetic energy of projectile is much smaller than (A - 1) S, the compound nucleus is formed. For light nuclei the compound nucleus theory may be valid at low energies $\sim$ 10 - 50 MeV but if one considers heavy nuclei, the compound nucleus theory may be valid at higher energies upto 100MeV.

3.1.1 Nuclear Reaction Cross - Section

Due to 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 particle b of a nuclear reaction X (a,b) Y in the form

$$\sigma(a,b) = \sigma_c(a) G_c(b) \tag{3.1.1}$$

Where $\sigma_c(a)$ is the cross - section for the formation of compound nucleus by the particle a striking nucleus X and $G_c(b)$ is the probability that C decays by emission of b, leaving Y as the residual nucleus, $G_c(b)$ is a pure number. The compound system C must decay eventually in some ways; It can also refered to as the branching ratio of the reaction in

to the emission of b, evidently

$$\sum_b G_c(b) = 1 \tag{3.1.2}$$

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 reaction partners before and after the reaction.

The above equation can be written as[14]

$$\sigma(\alpha, \beta) = \sigma_c(\alpha) G_c(\beta) \tag{3.1.3}$$

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, Y, 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 properties of the compound system on the angular momentum J_c and the parity will be ignored in this section.

Now introduce a few magnitudes which describe the disintegration of the compound system C. We begin with the mean life time $\tau(E_c)$ of C before disintegration and define the magnitude.

$$\Gamma(E_c) = \frac{\hbar}{\tau(E_c)} \tag{3.1.4}$$

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 can therefore call it the total width of the state of C with an excitation energy E_c. C can decay in to various channels and its total decay rate Γ can be subdivided in to decay rates refering to specific channels.

$$\Gamma(E_c) = \sum_\beta \Gamma_\beta(E_c) \tag{3.1.5}$$

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 β. 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 are produced), then the number of decays in to channel β per unit time is given by

$$\frac{N\Gamma_\beta}{\hbar} \tag{3.1.6}$$

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

$$G_c(\beta) = \frac{\Gamma_\beta}{\Gamma} \tag{3.1.7}$$

3.1.2 The Reciprocity Theorem For Nuclear Reaction

If a reaction is taking place by a channel (α, β) which is called actual direct process. we can write its cross - section as $\sigma(\alpha, \beta)$. If the reaction takes place in the reverse channel the cross - section is $\sigma\ (\beta, \alpha)$ for such type of process we have a theorem known as Reciprocity Theorem.

The relation is quite universal and depends only on the channels λ_α and λ_β it is expressed by

$$\frac{\sigma(\alpha,\beta)}{\lambda_\alpha^2} = \frac{\sigma(\beta,\alpha)}{\lambda_\beta^2} \tag{3.1.8}$$

The channel wave number $K_\alpha = |K_\alpha|$ and the channel wave length λ_α are related as $K_\alpha = \frac{1}{\lambda_\alpha}$

$$K_\alpha^2\sigma(\alpha,\beta) = K_\beta^2\sigma(\beta,\alpha) \tag{3.1.9}$$

$$K_\alpha^2\sigma_c(\alpha)G_c(\beta) = K_\beta^2\sigma_c(\beta)G_c(\alpha) \tag{3.1.10}$$

$$K_\alpha^2\sigma_c(\alpha)\frac{\Gamma_\beta}{\Gamma} = K_\beta^2\sigma_c(\beta)\frac{\Gamma_\alpha}{\Gamma} \tag{3.1.11}$$

$$K_\alpha^2\frac{\sigma_c(\alpha)}{\Gamma_\alpha} = K_\beta^2\frac{\sigma_c(\beta)}{\Gamma_\beta} = U(E_c) \tag{3.1.12}$$

where $U(E_c)$ is constant. Decay probabilitity of compound nucleus becomes

$$G_c(\beta) = \frac{\Gamma_\beta}{\Gamma} = \frac{K_\beta^2\sigma_c(\beta)}{\Gamma U(E_c)} \tag{3.1.13}$$

$$\frac{K_\beta^2\sigma_c(\beta)}{\Gamma U(E_c)} = \frac{K_\beta^2\sigma_c(\beta)}{U(E_c)[\Gamma_\alpha + \Gamma_\beta + ... + \Gamma_\gamma]} \tag{3.1.14}$$

since α and β can be any pair of channels which lead to the compound system C , the function $U(E_c)$ must be independent of the channel and we obtain(3.1.15).The probability $G_c(\beta)$ of the disintegration through a specific channel β can be written in the form of

$$G_c(\beta) = \frac{\Gamma_\beta}{\Gamma} = \frac{K_\beta^2\sigma_c(\beta)}{\sum_\gamma K_\gamma^2\sigma_c(\gamma)} \tag{3.1.15}$$

Where the sum is extended over all channels γ in to C can decay. Hence the cross - sections for the reaction $\sigma \rightarrow \beta$ can be computed if the cross-section $\sigma_c(\gamma)$ for the formation of the compound system by all possible channels are known and if the bohr assumption is valid.

$$\sigma(\alpha, \beta) = \sigma_c(\alpha) = \frac{K_\beta^2\sigma_c(\beta)}{\sum_\gamma K_\gamma^2\sigma_c(\gamma)} \tag{3.1.16}$$

This last equation tells as if the compound nucleus formation cross - section through all possible channels is known then it is possible to obtain the decay probability through a given channel.

3.1.3 Resonance in a Compound Nucleus Reaction

Information about excited states of nuclei can be gained from a nuclear reaction as well as from a radio active decay. The presence of excited state can be detected by the pulse peak in the cross-section vs energy curve of a particular reaction. Such a peak is called resonance. A compound nucleus more likely to be formed when the excitation energy provided exactly matches with one of the energy levels than if the excitation energy have some other values. The uncertainty principle in the form

$$\Delta E \Delta t = \hbar \tag{3.1.17}$$

Where $\Delta E = \Gamma$, and $\Delta t = \tau$ (mean life time of the CN), enable us to relate Γ and τ as

$$\tau = \frac{\hbar}{\Gamma} \tag{3.1.18}$$

3.2 Pre - equilibrium Reaction

The experimental results of early 1950s 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 reactions in which all the energy of the projectile is distributed among all nucleons of the compound nucleus in a completely statistical manner. All the intermediate processes are called pre-compound or pre-equilibrium reaction.

A typical example of neutron emission spectrum showing contributions of different re-

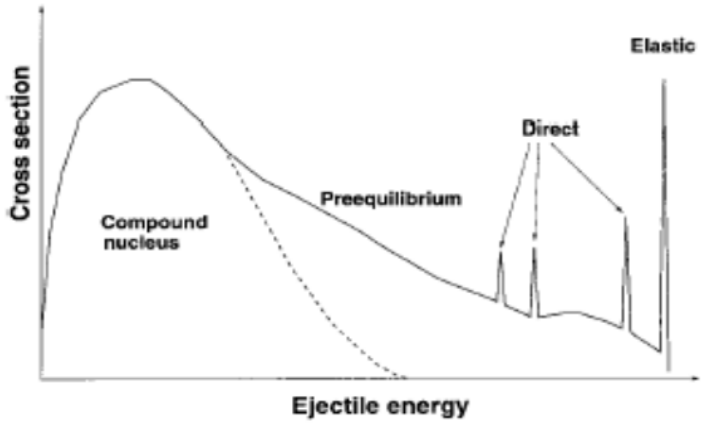

Figure 3.2: Neutron emission spectrum showing contributions of different reaction mechanisms in a nuclear reaction

action mechanisms in a nuclear reaction are shown in Fig. 3.2. We observe that the two most important reaction mechanisms are compound and the direct. The pre-equilibrium mechanism fills the gap between them. The existence of pre-equilibrium reactions was revealed by a study of the excitation functions of nuclear reactions showing long tails beyond the maximum. If we consider a heavy target nucleus which is non-fissionable, the significant contribution to the compound nucleus decay is neutron evaporation. The observation leads to the fact that as soon as the evaporation of x-neutrons becomes energetically possible there is an extremely rapid increase of cross section of (p,xn) reaction, p being the projectile. At an energy that exceeds the threshold by an amount equal

to the next neutron binding energy, this cross-section should reach a value almost equal to that of reaction cross-section. A further increase in excitation energy should lead to an exponential decrease of the cross-section, the excitation functions for (p,xn) reactions have high energy tails which slowly decrease with increasing energy. This experimental fact can also be observed in case of light nuclei. This observation gives the evidence of pre-equilibrium reactions.

At incident energies above 10MeV it is possible for particle emission to take place after the direct stage, but long before the attainment of statistical equilibrium. Their time scale is intermediate between the very fast direct reactions and the relatively slow compound nucleus formation reactions. More direct evidence for pre-equilibrium reaction is provided by the energy spectra of emitted particles .

Most pre-equilibrium reactions takes place at energies high enough for it to be no longer possible to resolve the individual final states. With increasing projectile energy (above 10 MeV) sometimes a particle emission can occur even before the whole energy could distribute evenly among the nucleons of the compound nucleus.

Nuclear reaction mechanisms at intermediate excitation energy is now supposed to proceed through equilibrium as well as pre-equilibrium emission of particles. The high energy tail observed in excitation functions of light charged particles contains important information about the reaction mechanisms. For explaining different observations nuclear physics needs models. The developed models are checked with experimental data to see the extent how much they can reproduce these data. In this thesis some related pre-equilibrium models are presented. exciton model and hybrid model are the commonly used pre-equilibrium models. These models are applied to study proton induced reaction on cesium isotopes.

3.2.1 Exciton Model

The Exciton model proposed by J.J Griffin[7] for the formation and decay of the average compound nuclear state. The nuclear state is characterized by the excitation energy of the composite nucleus and the exciton number, which is the total number of particles(p) above and holes(h) below the fermi surface.

According to this model the interaction of a projectile with a target nucleus, gives rise to a simple initial configuration characterized by small number of exciton's (excited particles and holes). Successive two body interactions increase the number of exciton's and lead to a fully equilibrated residual nucleus. Griffin[7] introduced two basic hypothesis to describe each stage of composite nucleus.

1) All the states having the same particle - hole configuration, the same total energy and parity have equal probablity.

2) All the decay mode is equiprobable.

The first hypothesis gives the energy distribution of the exciton. The second hypothesis simplifies the evaluation of transition rates obtained as suitable average over all the possible energies of the exciton's in each configuration. In exciton model, any exciton creates a new particle - hole pair, exciton structure of the system is changed and it shifts to the next reaction stage. It takes into account the single pre-equilibrium emission in its standard formulation. Griffins model has widely been used and amplified by many authors. All the efforts put in the development and elaboration of this model made it a recognized and well establised calculational mode for nuclear interactions. It is very useful to analyze the spectra of emitted particles and excitation functions of reactions up to hundreds of MeV energy.

The pre-equilibrium exciton model is governed by the set of master equation which describes both competing processes, the equilibrium of the nucleus and the emission. In the most simple case, when we consider just one possible excitation energy and only the

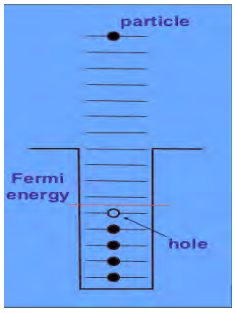

Figure 3.3: exciton (particle and hole) and Fermi energy

composite system prior to and including the first emission, this set reads

$$\frac{dP(n,E,t)}{dt} = P(n-2,E,t)\lambda^{+}(n-2,E)+P(n+2,E,t)\lambda^{-}(n+2,E)-P(n,E,t)[\lambda^{+}(n,E)+L(n,E)] \tag{3.2.1}$$

Where P(n,E,t) is the occupation probability of finding the nucleus with the excitation energy E in an n - exciton state at time t , $\lambda^{\pm}(n,E)$'s are the decay rate from an n - exciton to the (n$\pm$2) exciton state and L(n,E) is the emission (integrated over out going energies and summed over all possible ejectiles).

3.2.2 Geometry Dependent Hybrid Model

This model was proposed by Blann[9]. The semi-classical pre - equilibrium models exciton model and hybrid model both have similar mathematical form but the physical back grounds are different. In hybrid model, exciton has two probabilities

1) To be emitted

2) To create a particle - hole pair, independent of the rest of exciton's

Each exciton is treated separately so the next exciton stage has 3 times more exciton than the original one. The hybrid model allows multi-particle emission in equilibration phase. In this model, multi-pre-equilibrium particle emission a long with equilibration decay is considered where as the spectra of emitted particles are calculated from each step in the energy dissipation process induced by the interaction between projectile and target nucleons.

The hybrid model for pre-compound decay is given by Blann and Vonach[9] as

$$\frac{d\sigma_v(\varepsilon)}{d\varepsilon} = \sigma_R P_v(\varepsilon) \tag{3.2.2}$$

and

$$P_v(\varepsilon)d\varepsilon = \sum_{n=n_0}^{n'} [\frac{nX_v N_n(\varepsilon, U)}{N_n(E)}] g d\varepsilon [\frac{\lambda_c(\varepsilon)}{\lambda_c(\varepsilon) + \lambda_+(\varepsilon)}] D_n \tag{3.2.3}$$

Where σ_R is the reaction cross - section, nX_v is the number of particle type v (neutron or proton) emitted into the unbound continuum with channel energy between ε and $d\varepsilon$. The quantity in the first set of square brackets of equation above represents the number of particles to be found (per MeV) at a given energy ε for all scattering processes leading to an n exciton configuration. $\lambda_c(\varepsilon)$ is emission rate of particle into the continuum with channel energy ε and $\lambda_+(\varepsilon)$ is the intranuclear transition rate of a particle. The second set of square brackets in above equation represents the fraction of the v type particles at a energy which should undergo emission into the continuum, rather than making an intranuclear transitions. The D_n represents the average fraction of the initial population surviving to the exciton number being treated.

Early comparisons among experimental results, pre-compound exciton model calculation, and intranuclear cascade calculations indicated that the exciton model gave too few pre-compound particles and that these were too soft in spectra distribution for the expected initial exciton configurations. The intranuclear cascade calculations 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. In this way the diffuse surface properties sampled by the higher impact parameters were crudely incorporated in to the pre-compound decay formalism, in the geometry dependent hybrid model (GDH). The differential emission spectrum is given in the GDH as

$$\frac{d\sigma_\nu(\epsilon)}{d\epsilon} = \pi\lambda^2 \Sigma_{l=0}^{\infty} (2l+1) T_l P_\nu(l, \epsilon) \tag{3.2.4}$$

Where λ is the reduced de Broglie wavelength of the projectile and T_l represents transmission cofficient for l^{th} partial wave. Using the total pre-equilibrium neutron emission spectrum $\frac{d\sigma_n(\varepsilon)}{d\varepsilon}$, the cross-section which could be involved in the emission of neutrons is calculated as

$$\sigma_n = \int_{U=0}^{E-B_n} \frac{d\sigma_n(\varepsilon)}{d\varepsilon} d\varepsilon \tag{3.2.5}$$

Where B_n represents the neutron binding energies. The geometry dependent influences are manifesting in two distinct manners in the formulation of the GDH model. The more obvious is the longer mean free path predicted for nucleons in the diffuse surface region. The second effect is less physically secure, yet seems to be important in reproducing experimental spectral shapes. The nuclear density distribution used in the GDH model as a Fermi density distribution function, $\rho(R_l) = \rho_s[\frac{exp(R_l - C)}{0.55 f_m + 1}]^{-1}$, Where ρ_s is the density at the center of nucleus, and C = $1.07A^{1/3}f_m$ taken from electron scattering results. The radius for the l^{th} entrance channel partial was defined by $R_l = \lambda(l + 1/2)$. In the GDH model, the fermi energies and nuclear densities are defined to impact parameters R_l.

Many other semi-classical pre-equilibrium models have been proposed, most of them under estimate the experimental data. To overcome this deficiency, quantum mechanical models are formulated. These models are based on the theory of nuclear scattering .Two important reactions mechanisms are multi-step compound (MSC) and multi-step direct (MSD). One excited partice must be above the binding energy (in contnuum of levels) in MSD while all the particles are bound in potential well in case of MSC mechanism. The angular distributions are forward peaked in MSD and the particles emitted from MSC chains are symmetric around 90 degree. The MSD reaction models use the DWBA approach to the continuum of levels and to the multiple scattering. Different formulations of MSD and MSC have been proposed. The most important point in using these models is that both MSC and MSD shoud be applied simultaneously in calculations as one is the necessity of the other.

Equilibrium emission is according to Weisskopf-Ewing(WE) model[14] by neglecting angular momentum. In the evaporation, the basic parameters are binding energies, inverse cross-section, the pairing and the level-density parameters. The reaction cross-section for the incident channel a and exit channel b can be written as

$$\sigma_{ab}^{WE} = \sigma_{ab}(E_{inc}) \frac{\Gamma_b}{\sum_{b'} \Gamma_{b'}} \tag{3.2.6}$$

Where E_{inc} is the incident energy. In the above equation Γ_b can be also expressed as

$$\Gamma_b = \frac{2s_b + 1}{\pi^2 \hbar^2} \mu_b \int d\varepsilon \sigma_b^{inv}(\varepsilon) \varepsilon \frac{\omega_1(U)}{\omega_1(E)} \tag{3.2.7}$$

Where U, $\mu_b, s_b, \sigma_b^{inv}$ are the excitation energy of the residual nucleus, the reduced mass, the spin and the inverse reaction cross-section respectively. The total single-particle level density it taken as

$$\omega_1(E) = \frac{1}{\sqrt{48}} \frac{exp[2\sqrt{\alpha(E-D)}]}{E-D} \tag{3.2.8}$$

Where E,D and g are the excitation energy of compound nucleus, the pairing energy and the single particle level density respectively.

3.3 Direct Reaction

The reactions which takes without the formation of compound nucleus are called direct reaction. this are fast reactons which roughly take to about 10^{-22} to 10^{-20}sec. These interactions takes place with only few nucleons (or nucleon) and projectile. In this reaction the projectile interacts with a nucleon, a group of nucleons or the whole nucleus and emission takes place immediately.

When the projectile energy is high, it enters the nucleus of the target; as it interacts with one or more surface nucleons and some energy must be lost so that the emitted particle leaves the system with energy slightly less than that of the projectile. The interaction takes place with very small portion of the target nucleus (just outside the closed shell) and it takes very small time for the process in the order of 10^{-22} to 10^{-23}sec.

3.3.1 Characteristics of Direct Reaction

Basic characteristics of direct reaction are

(a) The energy distribution of emitted particles is not like compound nucleus. there are much more high energy particles emitted in the direct reactions.

(b) These reactions takes place at high energy of projectile where compound nucleus theory gives low cross-section results.

(c) The angular distributions of emitted particles shows a forward peaking not isotropic or symmetric distribution as is observed in compound nucleus. The reason of forward peaking may due to large energy momentum transfer on a few nucleon.

(d) Monatomic change at reaction cross-section with energy of projectile, no resonances are observed (no maxima and minim observe), i.e. as the threshold energy of a certain reaction is reached the cross section decreases. Exchange of nucleon is the typical feature of direct reactions as in the case of stripping and pick up reaction.

Examples of direct reaction

Elastic scattering is the simplest direct reactions which leave the target nucleus in its ground states. Inelastic scattering of high energy protons,in which a proton of high energy is incident to wards nucleus and it interact with few surface nucleus. That is outer most shell nucleon(inner shell model core do not take part in the reaction) interact with incoming project and a proton of reduced energy is emitted.

Stripping reaction in which say deutron as a projectile (deutron is alosely bound systems.ϵ_B $\sim$ 2MeV) interact with a nucleon. the deutron is broken in to n and p, n is absorbed in the nucleus and p is emitted in the same direction or proton is absorbed and a neutron is emitted. this means (d,p) and (d,n) reaction.The other example of direct reaction is pick-up reaction (p,^{3}He),(d,t) and (d,^{3}He) in all these reactions, the projectile absorbs (pick-up) a nucleon from nucleus.

Chapter 4

THE COMPUTER CODES AND FORMULATION

4.1 Nuclear Data Evaluation

Nuclear data evaluation is carried out on the basis of the experimental data and theoretical model of calculations. It is both practically and economically impossible to measure the necessary cross-section for all the isotopes in the periodic table for a wide range of energies. 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 unable to measure the cross-sections due to the experimental difficulty. Therefore, nuclear reaction calculations play an important role in the nuclear data evaluation.

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[13].

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

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

$$a = \frac{A_{CN}}{K} \tag{4.2.2}$$

Where 'A_{CN}' is the mass of the compound nucleus and 'K' is the free constant. Theoretical calculations in this thesis done by using the level density parameter $a = \frac{A_{CN}}{8}$,$a = \frac{A_{CN}}{9}$ and $a = \frac{A_{CN}}{10}$ are used for all the reactions but $a = \frac{A_{CN}}{10}$ is the best fit to experimental results and exciton number $n_0 = 1$ and $n_0 = 3(2p+h)$ are used but $n_0 = 3$ is found to give satisfactory reproduction of the experimental data. 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 to use in the bombarding energy range of a few MeV to several hundred MeV. 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, alpha, deuterons, tritons and hellions.

4.4 Description of parameters selected as input

The code COMPLET is based on same philosophy as the former code INDEX (17). It applies the statistical model of compound nucleus decay developed by weisskopf-Ewing (15), the hybrid and geometric-dependent hybrid model of Blann (9) further simplification and improvement by J.Ernst (16).

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, 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 thesis describes new calculations on the excitation functions of five reactions were studied. These are: $^{133}Cs(p,n)^{133}Ba$, $^{133}Cs(p,n+p)^{132}Cs$, $^{133}Cs(p,3n)^{131}Ba$, $^{133}Cs(p,5n)^{129}Ba$ and $^{133}Cs(p,6n)^{128}Ba$ carried out in the 10MeV to 100MeV proton incident energy range. In the theoretical calculation, the code COMPLET have been used. The code COMPLET gives the results of both equilibrium reaction and pre-equilibrium reaction. The experimental cross-section is obtained from EXFOR data source, IAEA[17]. The theoretical and experimental cross-sections are plotted against the projectile energy are shown in figure 5.1 to 5.11. The projectile energy is measured in Mega electroVolt (MeV) and the cross-section are measured in millibarn (mb). The experimental data for the reaction $^{133}Cs(p,n)^{133}Ba$ and $^{133}Cs(p,5n)^{129}Ba$ is taken from the Author (F.Tarkanyi,A.Hermanne,S.Takacs,F.Ditroi,B.Kiraly,H.Yamazaki,M.Baba,A .Mohammadi,A.V.Ignatyuk) and data for $^{133}Cs(p,n+p)^{132}Cs$ and $^{133}Cs(p,6n)^{128}Ba$ is taken from the Author (C.Deptula,Kim Sen Han,O.Knotek,S.Mikolajewski,L.M.Poplnenkova, E.Rurarz,N.G.Zaitseva) but data for$^{133}Cs(p,3n)^{131}Ba$ is taken from the two Authors (C.Deptula,Kim Sen Han,O.Knotek,S.Mikolajewski,L.M.Poplnenkova, E.Rurarz,N.G.Zait seva) and (F.Tarkanyi,A.Hermanne,S.Takacs,F.Ditroi,B.Kiraly,H.Yamazaki,M.Ba ba,A. Mohammadi,A.V.Ignatyuk). Also energy range selected from the data is same with theoretical. This makes easy for comparison. The cross-section of theoretical and experimental

with the energy range are given in the table 5.1 to 5.5. The errors quoted in the production of cross-sections arise mainly from unceritanties in the target thickness, detecter efficiency, the beam current integration and counting statstics. proper care must be taken in order to keep the beam current constant. however all the fluctuations that were identified during the irradiation time. The overall error in the measured cross-section is found to be less than 18 percent.

In this thesis various input parameters are used for calculations of excitation functions. which play an important role in the theoretical predictions. The initial exciton number n_o, for pre-equilibrium emission,the particles in the initial configuration can be neutron,proton or alpha-particle. These exciton interact independently with particles below the fermi level creating either new particle-hole configurations in the second stage or getting emitted into the continuum. An initial exciton number has an effect in the excitation function of the pre-equilibrium stages of the nuclear reaction, exciton number $n_o = 1$ and $n_o = 3$ are taken for comparison for the reactions $^{133}Cs(p,n)^{133}Ba$ and $^{133}Cs(p,5n)^{129}Ba$. The theoretical and experimental excitation functions for the exciton numbers $n_o = 1$ and $n_o = 3$ are shown in figure 5.2 and 5.5 respectivly. It can be seen from the figure that exciton number $n_o = 3$ is best fits with the experimental curve, hence all theoretical data is taken only for $n_o = 3$. Another input parameter is level density parameter a defined as $a = \frac{A_{CN}}{K}$, where A_{CN} is the mass of the compound nucleus and K is an adjustable constant. Comparison is done to see the effect of level density parameter (a) on the excitation functions. The level density valve $a = \frac{A_{CN}}{8}$, $a = \frac{A_{CN}}{9}$ and $a = \frac{A_{CN}}{10}$ are taken for the reaction $^{133}Cs(p,n)^{133}Ba$ and $^{133}Cs(p,5n)^{129}Ba$. The theoretical cross-section for the three level density values and experimental cross-section are shown in the figure 5.1 and 5.4 respectivly. The figure shows that level density $a = \frac{A_{CN}}{10}$ give best fits with the experimental curve, hence all theoretical data is taken by $a = \frac{A_{CN}}{10}$. The last important input parameter is mean free path multiplier MFP, Comparison is done to see the effect of mean free path on the above two reaction for MFP = 0.5 , 1 and 2. The figure (5.3 and

5.6) shows that MFP = 2 is best fits with the experimental curve, hence all theoretical data is done by MFP = 2. Changing the above three input parameters affects the pre - equilibrium nuclear reaction part. Therefore, the first six graph below show the effects of level density parameters, exciton number and MFP mean free path, excitation function done for $^{133}Cs(p,n)^{133}Ba$ and $^{133}Cs(p,5n)^{128}Ba$. And the figures 5.7 to 5.11 shows production of Barium and cesium isotope by reaction of proton with target nucleus cesium. when a target is bombardment by beam of particles, it is common for nuclear reactions to take place leading to radioactive residual nucleus. The last figure (5.12) show that the percentage fraction of pre-equilibrium reaction contribution at higher projectile energy.

For $^{133}Cs(p,n)^{133}Ba$

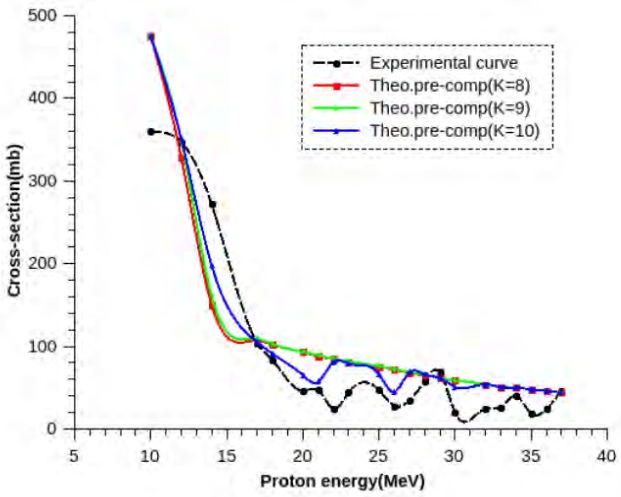

Figure 5.1: Experimental and theoretical excitation function for the reaction $^{133}Cs(p,n)^{133}Ba$ for three level density parameters

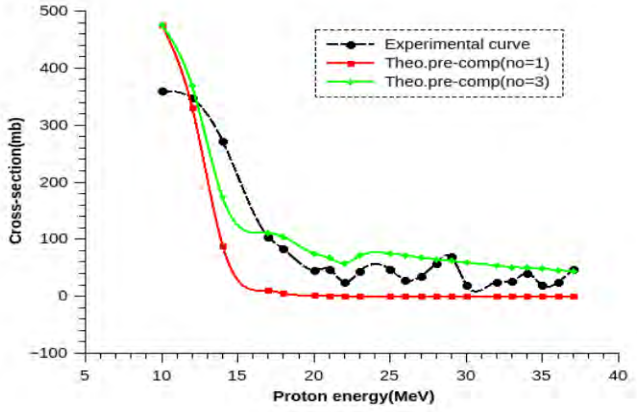

Figure 5.2: Experimental and theoretical excitation function for the reaction $^{133}Cs(p,n)^{133}Ba$ for two exciton numbers

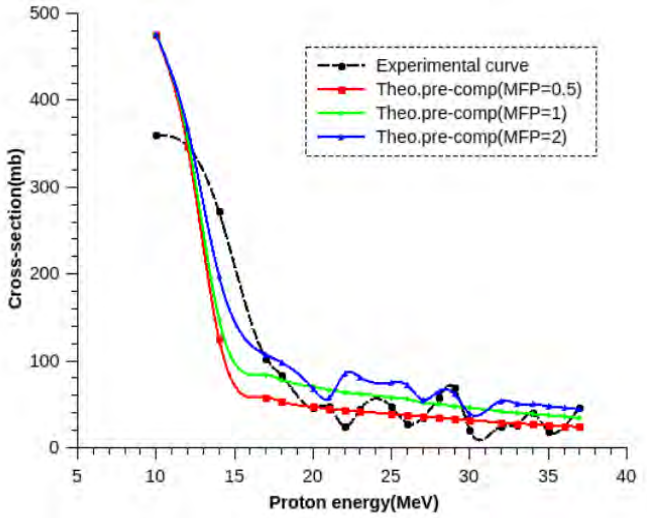

Figure 5.3: Experimental and theoretical excitation function for the reaction $^{133}Cs(p,n)^{133}Ba$ for three mean free path

For $^{133}Cs(p,5n)^{128}$

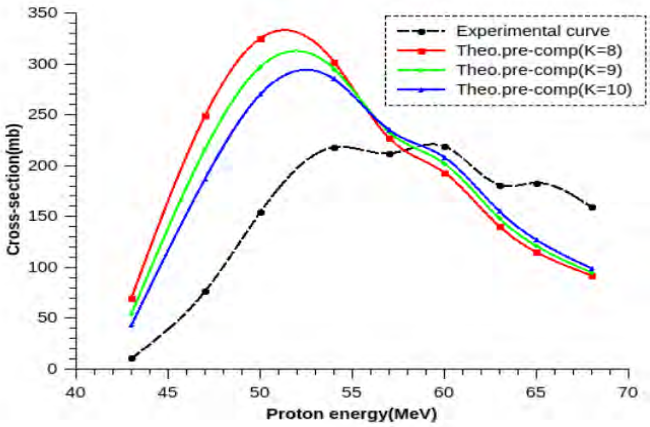

Figure 5.4: Experimental and theoretical excitation function for the reaction $^{133}Cs(p,5n)^{128}Ba$ for three level density parameters

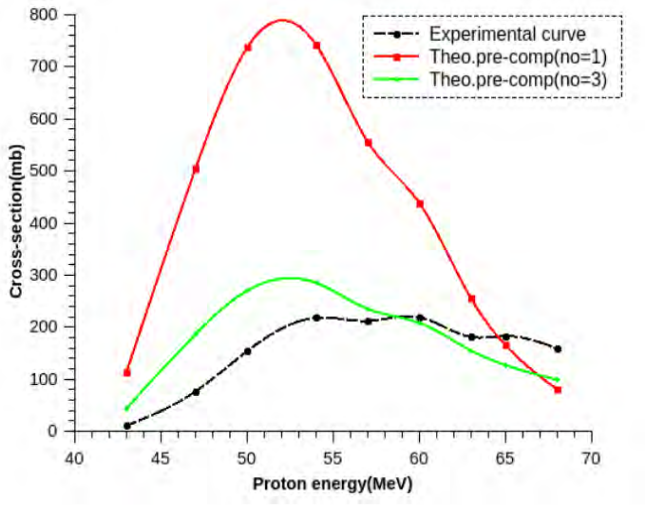

Figure 5.5: Experimental and theoretical excitation function for the reaction $^{133}Cs(p,5n)^{128}Ba$ for two exciton numbers

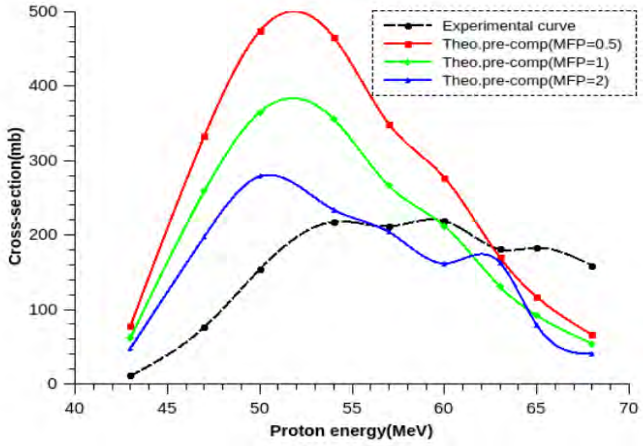

Figure 5.6: experimental and theoretical excitation function for the reaction $^{133}Cs(p,5n)^{129}Ba$ for three mean free path

5.1 Production of ^{133}Ba

^{133}Ba is produced when a projectile (proton particle) strike a target element cesium (^{133}Cs) and emits single neutron (n). The theoretical calculated excitation functions of $^{133}Cs(p,n)^{133}Ba$ reaction is compared with the experimental result.

Table 5.1: Theoretical and Measured cross-section for the reaction $^{133}Cs(p,n)^{133}Ba$

$E-Exp$	$E-err$	$\sigma(Exp)$	$\sigma-err$	$\sigma(pre-compound)$	$\sigma(compound)$
10	2.1	360	38	474.9	476.8
12	1.9	347	16	347.3	331.5
14	1.5	272	24	173.1	89.13
17	1.2	103.8	9.8	107.3	10.29
18	1.2	83.3	4.4	78.52	5.022
20	1	46.4	5.2	46.45	1.171
21	1	47.1	5.6	44.99	0.575
22	0.9	25.3	4.2	43.34	0.288
23	0.8	44.1	7.1	42	0.147
25	0.7	47	17	39.4	0.03986
26	0.7	28	3.1	37.9	0.02076
27	0.6	34.7	6.1	36	0.01084
28	0.7	58	3.1	50.7	0.005691
29	0.6	69	13	62	0.002891
30	0.6	20	8.6	31	0.001555
32	0.5	25	12	29	0.0004663
33	0.4	26.3	6.8	27.8	0.0002589
34	0.4	40.2	9	39.3	0.0001443
35	0.4	19.1	6.7	26.25	0.0000808
36	0.3	24.1	4.9	25	0.0000454
37	0.3	46.7	9.7	44	0.00000257

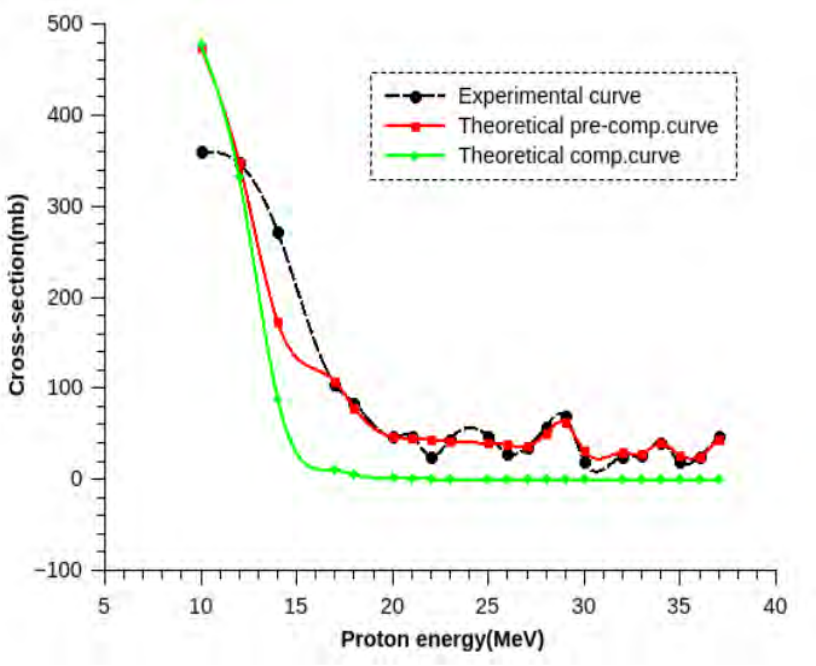

Figure 5.7: Experimental and Theoretical excitation function for the reaction $^{133}Cs(p,n)^{133}Ba$

As can seen from figure above, experimentally measured and theoretically calculated excitation function for $^{133}Cs(p,n)^{133}Ba$, calculations have been done by using different set of input parameters. At Low energy tail theoretical pre-compound and theoretical compound start at the same point but high energy tail theoretical pre-compound fit with the experimental result.

Compound nucleus reaction gives best result up to 20MeV. After this energy pre-equilibrium nuclear reaction dominates and it is shown by long tail. It is clear that the theoretical result obtained by using a computer code COMPLET agree with the experimental result obtained from the EXFOR data. Basically, theoretical result have been calculated by using different set of input parameters, exciton number $n_o = 3$, level density parameter pld $= \frac{A_{CN}}{10}$ and mean free path multiplier MFP $= 2$. Which plays a key role in the theoretical calculation.

5.2 Production of ^{132}Cs

^{132}Cs is produced when a projectile (proton particle) strike a target element cesium (^{133}Cs) and emits single proton plus single neutron (n+p). The calculated excitation functions of $^{133}Cs(p, n + p)^{132}Cs$ reaction is compared with the experimental result.

Table 5.2: Theoretical and Measured cross-section for the reaction $^{133}Cs(p, n + p)^{132}Cs$

$E - Exp$	$\sigma(Exp)$	$\sigma(pre - compound)$	$\sigma(compound)$
18	25	36.57	35.35
22	81	79.96	63
24	120	119.6	64
29	113	125.6	19.92
33	125	127.9	3.694
39	122	123.6	0.2090
45	120	119.8	0.01307
47	115	115	0.005030
50	137	161	0.001159
54	135	155	0.0001877
58	150	130	0.00003243
63	152	156.9	0.000007745
68	115	100	0.0000008908
69	110	99	0.0000005769
74	118	138	0.00000006295
80	122	128.9	0.000000004100
84	129	124	0.0000000007374
89	130	107	0.00000000007541
93	123	102	0.00000000001278
98	118	97	0.000000000001459

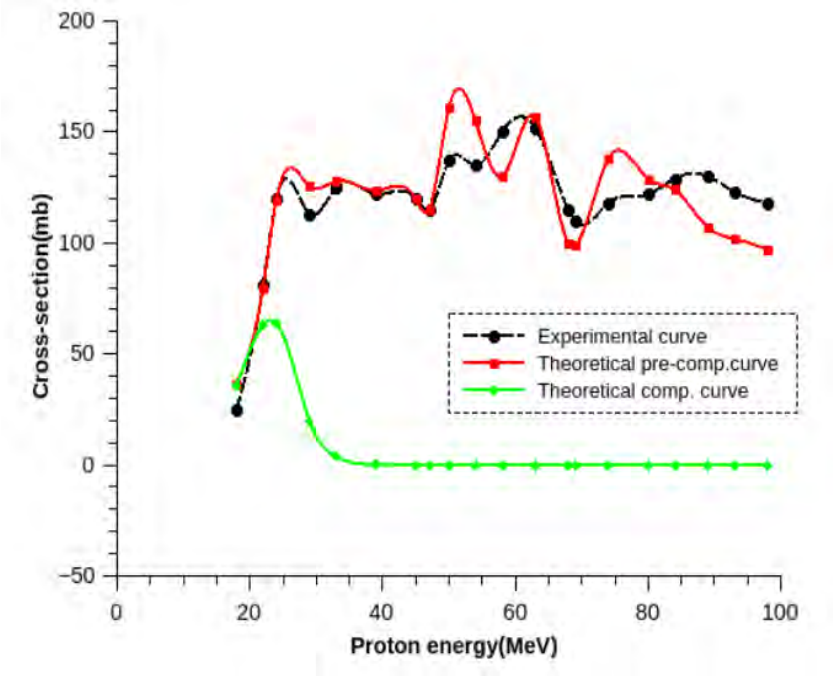

Figure 5.8: Experimental and Theoretical excitation function for the reaction $^{133}Cs(p, n+p)Cs^{132}$

As can seen from the above figure the experimentally measured and theoretically calculated excitation function for $^{133}Cs(p, n + p)Cs^{132}$, At low energy range up to 25Mev there is formation of compound nucleus reaction. but when projectile energy increase theoretical pre - compound reaction give best fits with the experimental result obtained from the EXFOR data. The theoretical calculation obtained from computer code COMPLET by using different input parameters,exciton number $n_o = 3$, pld $= \frac{A_{CN}}{10}$ and MFP=2. And from the above graph we can observe that at higher projectile energy there is no formation of compound nucleus. it is dominated by pre - compound reaction. also the above figure is different from other because of emission of two different particles (neutron and proton), which change the shape of the graph.

5.3 Production of ^{131}Ba

^{131}Ba is produced when a projectile (proton particle) strike a target element cesium ^{133}Cs and emits three neutron (3n). The calculated excitation functions of $^{133}Cs(p,3n)^{131}Ba$ reaction is compared with the experimental result.

Table 5.3: Theoretical and Measured cross-section for the reaction $^{55}Cs(p,3n)^{131}Ba$

$E-Lab$	$\sigma(Exp)$	$\sigma(pre-compound)$	$\sigma(compound)$
24	509	557.7	873
25	604	667	1013
26	796	741	1121
29	767	821	1290
32	826	752.9	1132
34	670	667.9	735
39	501	310	189
41	241	238.9	89
45	146	139.9	18
47	139	124.9	8.176
50	135	143	2.382
53	118	129	0.6818
54	125	125.9	0.4507
61	118	113	0.02488
68	89	89.7	0.001449
69	91	88	0.0009628
74	77	76	0.0001351
78	74	68	0.00002691
84	82	57.8	0.000001778
89	68	51	0.000000171
93	53	46	0.00000002398
98	55	41	0.000000002548

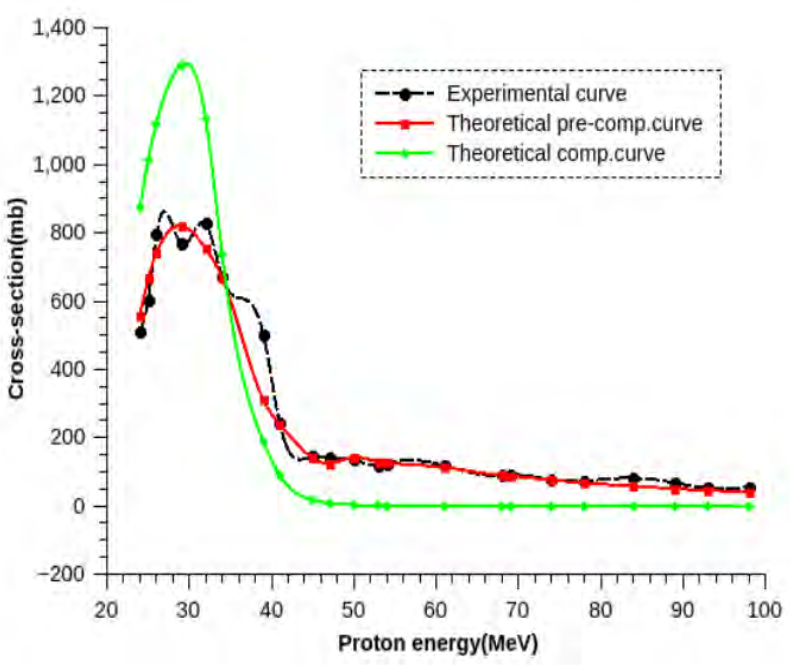

Figure 5.9: Experimental and Theoretical excitation function for the reaction $^{133}Cs(p,3n)^{131}Ba$

As can seen from the above figure the experimentally measured and theoretically calculated excitation function for $^{133}Cs(p,3n)^{131}Ba$, At low energy range there is formation of compound nucleus reaction up to 40MeV but when the incident proton energy increase pre - compound reaction dominate. i.e there is no formation of compound nucleus reaction at higher energy.

The graph also shows that theoretical pre - compound reaction is best fit with experimental result, which is obtained from the EXFOR data source. Also theoretical calculations obtained from computer code COMPLET by using different input parameters.

For this reaction the pre-equilibrium contribution is very nicely explain the experimental valves while compound nucleus gives much larger valve.

5.4 Production of ^{129}Ba

^{129}Ba is produced when a projectile (proton particle) strike a target element cesium ^{133}Cs and emits five neutron (5n). The calculated excitation functions of $^{133}Cs(p,5n)^{129}Ba$ reaction is compared with the experimental result.

Table 5.4: Theoretical and Measured cross-section for the reaction $^{133}Cs(p,5n)^{129}Ba$

$E-Exp$	$E-err$	$\sigma(Exp)$	$\sigma-err$	$\sigma(pre-compound)$	$\sigma(compound)$
43	1.8	10.9	2.3	43	114
47	1.6	76.4	9.1	187	504
50	1.4	154	19	270	737
54	1.2	218	25	285	742
57	1	212	25	227	556
60	0.8	219	25	208	438
63	0.6	181	24	186	255
65	0.5	183	22	170	165
68	0.3	159	20	122.6	80

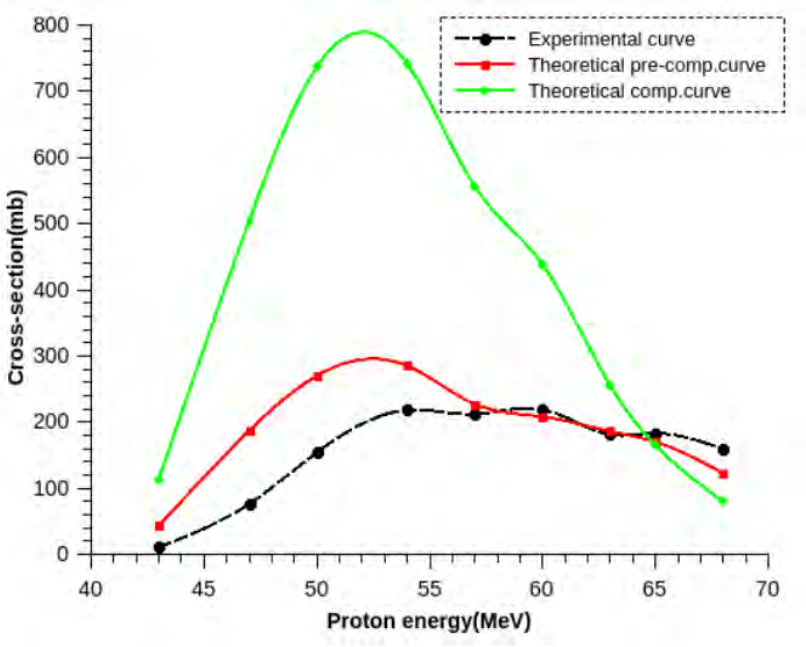

Figure 5.10: Experimental and Theoretical excitation function for the reaction $^{133}Cs(p,5n)^{129}Ba$

As can seen in the above figure, there is no compound nucleus decay for this composition in the given energy range because its theoretical calculation of excitation function is not comparable with experimental one. Therefore, we have only pre - compound nuclear reaction in the given energy range. It is seen that for larger number of neutron emission the reaction is taking place by pre - equilibrium decay even at the low energy end side. The compound nucleus theory is not valid for larger number of neutron emission, as its value is much larger than the experimental value.

5.5 Production of ^{128}Ba

^{128}Ba is produced when a projectile (proton particle) strike a target element cesium ^{133}Cs and emits single neutron (6n). The calculated excitation functions of $^{133}Cs(p,6n)^{128}Ba$ reaction is compared with the experimental result.

Table 5.5: Theoretical and measured cross-section for the reaction $^{133}Cs(p,6n)^{128}Ba$

$E-Exp$	$\sigma-Exp$	$\sigma(pre-compound)$	$\sigma(compound)$
47	7	0	0
50	8	0.388	0.2487
53	22	4.081	12.5
54	46	14.98	27
57	112	55.5	103
58	158	84.94	158.5
59	185	109	181
61	197	156.9	238.9
67	260	186	332
71	164	147	224
74	144	121	147
75	128	110.9	122
78	105	80.58	101.7
79	107	73	85
81	102	59	56.7
83	98	46.73	35.8
84	92	46.73	28.8
85	91	42.84	24.5
88	81	35.93	12.5
89	88	34	9.88
90	84	32.56	7.789
91	78	31	6.150
93	74	28.5	3.695
95	70	24	2.098
97	68	23	1.269
98	60	22.72	0.9827

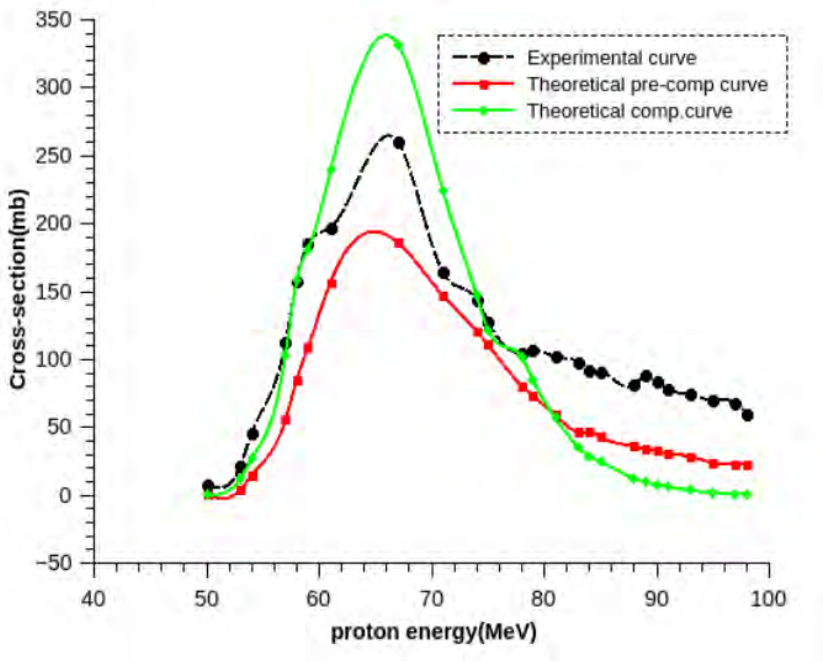

Figure 5.11: Experimental and Theoretical excitation function for the reaction $^{133}Cs(p,6n)^{128}Ba$

From the above figure we can seen that the more energy we give to the compound nucleus, the more particles are likely to evaporate. At higher incident energies,it is more likely that additional neutrons will evaporate from the compound nucleus. All figure above shows that the cross section for (p,xn) reactions. where x = 1,3,5 and 6. For each reaction, the cross section increase to a maximum and then decreases at higher energy makes it more likely for an additional neutron to be emitted. As observed from the above graph, the reaction (p,6n) started from around 47MeV, this indicates that energy needed to emit six neutron is greater than energy needed to emit one neutron,three neutron and five neutron. Again from energy range 54MeV to 74MeV projectile energy compound nucleus reaction takes place. After proton energy of 74MeV pre - compound nuclear reaction dominates the region and it shown by long tail.

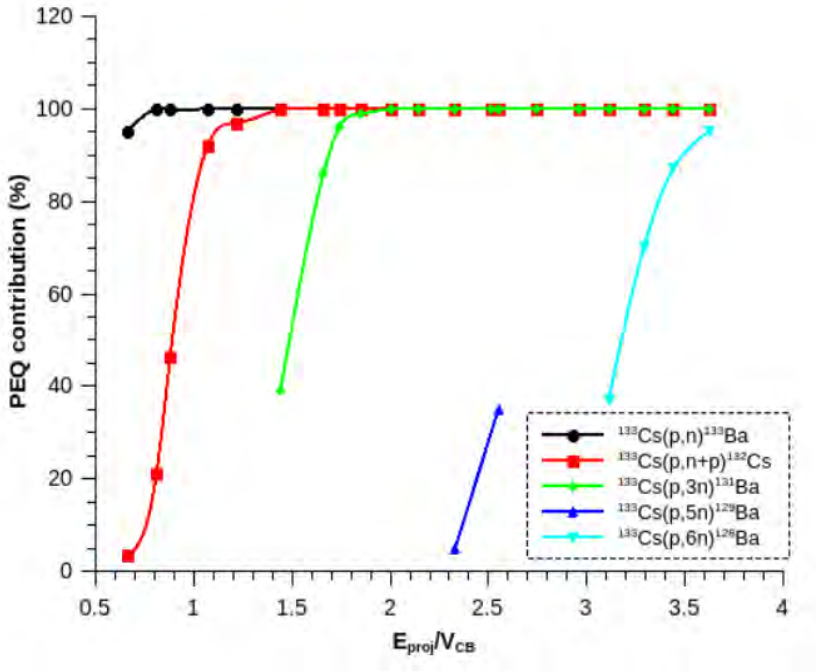

Figure 5.12: The percentage of pre-equilibrium contribution as a function of normalized projectile energy

The above graph shows that contribution of pre-equilibrium reaction in higher projectile energy range. The percentage fraction of pre-equilibrium reaction is defined as $\frac{\sigma_{pre-equ}-\sigma_{comp}}{\sigma_{pre-equ}} \times 100$, which is the y-axis and the normalized projectile energy is defined as $\frac{E_{projectile}}{potential\ \ coulomb\ \ barrier}$ $(E_{projectile}/V_{CB})$ is the x-axis.

Generally, It can be seen clearly from the above graph the percentage of pre-equilibrium contribution is found to increase with normalized projectile energy and when the incident proton energy increase pre-equilibrium reaction has high contribution, this implies at higher energy the contribution of pre-equilibrium reaction is signficant. Also the dependence of pre-equilibrium factor on the projectile energy and finally all the above reaction becomes almost constant around 100 percent.

Chapter 6

CONCLUSION

In this thesis, Excitation functions for five reactions in $p+^{133}Cs$ system have been studied by using equilibrium and pre-equilibrium reactions mechanism, These are $^{133}Cs(p,n)^{133}Ba$, $^{133}Cs(p,n+p)^{132}Cs$, $^{133}Cs(p,3n)^{131}Ba$, $^{133}Cs(p,5n)^{129}Ba$ and $^{133}Cs(p,6n)^{128}Ba$ have been calculated for 10MeV-100MeV incident proton energy ranges. The theoretical calculation results on the excitation functions and the optimum energy ranges for reaction process are given in the figures 5.7 - 5.11.

Broadly, nuclear reaction is understood in terms of three kinds of reactions. Namely, equilibrium (Compound), pre - equilibrium (pre - compound) and direct reaction. compound nucleus reaction is formed when incoming projectile energy is shared between all the nucleus in the target nucleus and equilibrium emissions occurs due to statistical fluctuation in energy. Direct reaction is a single step process that occurs due to large momentum transfer from the projectile to the target nucleus. this results in high energy ejectile emission leaving residual at lower excited states. Between this two extremities i.e between compound and direct reaction, pre - equilibrium reaction plays a signficant role having features of both cross section of the product nuclei corresponding to a particular reaction is the resultant of all the reaction mecanism involved. In this study, contribution from direct reaction process is not expected.

Generally, The theoretical calculations based on COMPLET computer code with suitable input parameters, nuclear level density $a = \frac{A_{CN}}{10}$, Exciton number $n_o = 3$ (2p+h) with the

mean free path mulitplier MFP = 2 give best result. All reactions are in good agreement with the experimental data obtained from EXFOR data source.

Also as can be seen in the figures 5.7-5.11, the high energy part of the experimental excitation functions can not account for the equilibrium decay mechanism and the pre - equilibrium emission must be considered along with compound nucleus decay. Besides, the pre - equilibrium effects increases as the incident proton energy increases. The percentage of pre - equilibrium factor calculated and plotted in the figure 5.12 it shows the dependence of pre-equilibrium factor on the projectile energy. percentage of pre - equilibrium factor contribution is found to increase with normalized projectile energy and when the incident proton energy increase pre - equilibrium reaction has high contribution, this implies at higher projectile energies contribution of pre - equilibrium is more signficant. It is seen that pre - equilibrium factor first increases very fast with projectile energy and at higher energies it becomes almost constant around 100 percent.

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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.

Name: konjit Asresahagn Angdasaw

Signature:

Place and time of submission: Addis Ababa University, 2013

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

Name: Prof.A.K.CHAUBEY

Signature: