# CALCULATION OF REACTION CROSS SECTION FOR PROTON INDUCED $[(P,\gamma),(P,N),(P,2N),(P,3N)]$ ON MOLYBDENUM (MO-95) IN DI DIFFERENT ENERGY REGIONS

Ibsa Beyene

A Thesis Submitted to

The Department of Physics

PRESENTED IN FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE
JIMMA UNIVERSITY
JIMMA, ETHIOPIA
OCTOBER 2017

JIMMA UNIVERSITY
DEPARTMENT OF
PHYSICS

This is to certify that the thesis prepared by **Ibsa Beyene** Graduate Studies entitled "**CALCULATION OF REACTION CROSS SECTION FOR PROTON INDUCED** $[(p,\gamma),(p,n),(p,2n),(p,3n)]$ **ON MOLYBDENUM (MO-95) IN DI DIFFERENT ENERGY REGIONS** " in fulfillment of the requirements for the degree of **Master of Science** complies with the regulations of the University and meets the accepted standards with respect to originality and quality. .

Dated: October 2017

Supervisor: ______________________
Dr. T Tessema

Readers: ______________________
Mr. xxxx

______________________

JIMMA UNIVERSITY

Date: **October 2017**

Author: **Ibsa Beyene**

Title: **CALCULATION OF REACTION CROSS SECTION FOR PROTON INDUCED** $[(p,\gamma),(p,n),(p,2n),(p,3n)]$ **ON MOLYBDENUM (MO-95) IN DI DIFFERENT ENERGY REGIONS**

Department: **Physics**

Degree: **M.Sc.** Convocation: **October** Year: **2017**

Signature of Author

*To my family.*

# Table of Contents

**Table of Contents** **v**

**Abstract** **viii**

**Acknowledgements** **ix**

**1 Introduction** **2**
- 1.1 Background . . . . . 2
- 1.2 Statement of the problem . . . . . 4
- 1.3 Objective of the study . . . . . 6
  - 1.3.1 General objective . . . . . 6
  - 1.3.2 Specific objective . . . . . 6
- 1.4 Significance of the study . . . . . 6
- 1.5 Limitation of the study . . . . . 7

**2 Literature Review** **8**
- 2.1 Introduction . . . . . 8
- 2.2 Conservation laws . . . . . 18
- 2.3 Cross section($\sigma$) . . . . . 20
  - 2.3.1 Partial wave analysis . . . . . 21

**3 Material and Methodology** **27**
- 3.1 Materials . . . . . 27
- 3.2 Methodology . . . . . 27
  - 3.2.1 Analytical Method . . . . . 27
  - 3.2.2 Computational Method . . . . . 28

**4 Result and Discussion** **34**
- 4.1 The reaction $^{95}Mo(p,\gamma)^{96}Tc$ . . . . . 35

4.2 The reaction ${}^{95}Mo(p,n){}^{95}Tc$ . . . . . . . . . . . . . . . . . . . . . . . . . 37
4.3 The reaction of ${}^{95}Mo(p,2n){}^{94}Tc$ . . . . . . . . . . . . . . . . . . . . . . . 39
4.4 The reaction of ${}^{95}Mo(p,3n){}^{93}Tc$ . . . . . . . . . . . . . . . . . . . . . . . 41

**5 Conclusion** **44**

**Bibliography** **45**

# Abstract

In this work calculation cross section reaction of Proton induced nuclear reaction [ $^{95}Mo(p,\gamma)^{96}Tc$, $^{95}Mo(p,n)^{95}Tc$, $^{95}Mo(p,2n)^{94}Tc$, and $^{95}Mo(p,3n)^{93}Tc$] at different energy ranges have been studied. The main contributing process for the formation of Technitium( Tc) radionuclide which are short half- life isotope. For theoretical excitation function the computer code COMPLET have been used. The theoretical results are compared with the experimental cross-sections obtained from EXFOR data source for the formation of compound nucleus. The present measurement over this energy range confirms the earlier published data. The used theoretical nuclear model codes can describe well the investigated reaction in the whole interested proton energy range. In this study, using nuclear reaction code (complet)-an Alice-91 based code experimental compound nucleus cross-sections are approximately reproduced. Then justifies the agreement between theoretical and experimental.

# Acknowledgements

First of all I would like to thank the almighty of God. I am deeply indebted to my instructor and advisor, Dr.Teklemariam Tessema for his academically support and help in every aspect of my research activities. I am also thankful to him for giving me opportunities to indulge myself in this wonderfully intriguing research field, guiding me to the right research direction. I am thankful to graduate office of Jimma University for their ideal and constructive comment in my all research activities. I would like to thank the Department of Physics for facilitating all the necessary materials while I am conducting my research. I am thankful to my Co-advisor Mr.Abreham Alemu for his valuable comment and suggestion. I would like to express my thanks to my mother, Beliyu Tolera and my sisters Werkinesh Beyene, Hawi Beyene and and all my family members for their endless support and love.

# List of Figures

2.1 Pictorial representation of a typical nuclear reaction induced by an intermediate energy proton. . . . . . . . . . . . . . . . . . . . . . . . . 11

2.2 Diagram of Intra nuclear cascade model(taken from Direct Nuclear Reaction Theories, John Wiley ) . . . . . . . . . . . . . . . . . . . . . . 14

2.3 Schematic diagram of pre few stages of a nucleon-induced reaction in the exciton model . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15

4.1 Experimental and theoretical excitation function for the reaction $^{95}Mo(p,\gamma)^{96}Tc$ . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 37

4.2 Experimental and theoretical excitation function for the reaction $^{95}Mo(p,n)^{95}Tc$ . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39

4.3 Experimental and theoretical excitation function for the reaction $^{95}Mo(p,2n)^{94}Tc$ 41

4.4 Experimental and theoretical excitation function for the reaction $^{95}Mo(p,3n)^{93}Tc$ 43

# Chapter 1

# Introduction

## 1.1 Background

Many efforts have been generated during the last decade by nuclear physicist. In recent incentive works have been made to understand the information that nuclear reaction provide knowledge about nature of nuclear force, nuclear structure ,size,shape and other parameters related to the nucleus. Whenever energetic particle projectile fall up on the bulk matter there is a probability that nuclear reaction can take place [1] and Rutherford was the first physicist who perform nuclear reaction. The disintegration of a nitrogen atom by $\alpha$-particle represented by an equation

$$^4_2He +^{14}_7 N \rightarrow [^{18}_9F] \rightarrow^{17}_8 O +^1_1 H$$

The symbol in brackets stands for the unstable nucleus formed as a result absorbtion $\alpha$-particle of by nitrogen nucleus; this kind is often called a compound nucleus [6]. In nuclear physics, a nuclear reaction is a process in which two particles or nuclear particles collide to produce products either different from the initial particles or particles itself in excited state or ground state. In principle, a reaction can involve the collision of two nuclei or subatomic particles, but the probability of three or more particles colliding at the same time is extremely small, and such an event is exceptionally rare. The other utility of this research is also to improve the basic understanding of the nuclear reaction mechanism which are described by experiment using a theoretical approach. Nuclear reaction can be classified in to two [2] depending on time of reaction, energy width, cross section reaction.

1) Direct nuclear reaction; Is a type of nuclear reaction which can takes in the peripheral of the target nucleus in a short period of time ($\approx 10^{-22}s$) [1]. This nuclear reaction the projectiles have enough energy and as energy of incident particle is increased, its de Broglei wave length($\lambda_D$) decrease until becomes more likely to interact a nucleon sized object than nucleus sized object [2]. Because of this reason a projectile nucleon collide either with a nucleon or a few nucleons in which wave length was comparable with nucleon dimension.

2) Compound nuclear reaction; Is a type of nuclear reaction the incoming particle or projectile and target nucleus equally sharing of energy before the out going particle is ejecting [2]. This nuclear reaction leads to the sharp peak of the quasi-stable nuclear state for particular value of resonance energy. Reaction that proceeds through the compound nucleus to be a two step process [3];

i) the formation of compound nucleus

ii) the decay of compound nucleus

More or less random collisions occur and statistical distribution in energies and small probability for a single nucleon to gain a large enough share of the energy to escape as much molecules evaporate from hot liquid. Particles in the initial channel coalesce to form a compound nucleus and decay process is independent of the entrance channel.

The decay of compound nucleus is independent of how it is formed. The peculiar characters nuclear reaction emphasis was then production of new nuclear species and give quantitative aspects of mass and energy balance [4]. The study of nuclear reaction has a number of pros due to different reasons. It gives some information about the nucleus like decay probability rate, excitation, resonance, charge of the nucleus, distribution of charges in the nucleus and different clues of the nucleus. This implies in nuclear physics nuclear reaction was give a dynamic response to those problems. The possibility of nuclear reaction taking place whenever energetic particle fall up on bulk matter [5]. The ever since known as Rutherford scattering which able to observe change of transmutation and evidence for the existence atomic nuclei. Information about relative probabilities of different reaction provides clues about the problem structure and offers a testing ground about nuclear force. Any nuclear transmutation process leads to an excited state of product of decay schemes. The excitation of nucleus by varying the energy of incident particle was discovering some important features. The calculation of the reaction cross section for proton induced reactions [(p,$\gamma$),(p,n); (p,2n); (p,3n)] on Molybdenum (Mo-95) in different energy regions used to particle production and describe the theoretical and experimental value.

## 1.2 Statement of the problem

Spontaneous disintegration of longlived,a naturally occuring isotopes provides information on nuclei. However,only a limited number of nuclei accessible for study by this process and then only under narrow range of circumstance [6]. To get out of this difficulty nuclear reaction can be induced in the myriad of pair of wise combinations provided by stable or longlived nuclei over the wide range of energies provided by accelerators in laboratories. This provides the greatest volume and widest range of nuclear data. It is practically and economically impossible to measure necessary cross section for all isotopes in the periodic table for a wide range of energies. Nuclear reaction models are frequently needed to provide estimates. Nuclear reaction emphasis was the production of new nuclear species and give quantitative aspects of mass and energy balance. The possibility of nuclear reaction taking place whenever energetic particle fall up on bulk matter study has a number pros to illuminates the nuclear hidden facts. Rutherford scattering which able to observe change of transmutation and evidence for the existence atomic nuclei. Information about relative probabilities of different reaction provides clues about the problem structure and offers a testing ground about nuclear force. Any nuclear transmutation process leads to an excited state of product of decay schemes. The excitation of nucleus by varying the energy of incident particle was discovering some important features. It is both practically and economically impossible to measure necessary cross section for all isotopes in periodic table for a wide range of energies and nuclear reaction models are frequently need to provide estimates. Then nuclear reaction model calculations play an important role in the nuclear data evaluation. The research questions are; (the questions which will be investigate in this works are as follows)

1. What are the calculated values of cross section $[(p,\gamma),(p,n)(p,2n),(p,3n)]$ of proton induced nuclear reaction cross section on molybdenum?

2. What experimental data review available of cross section $[(p,\gamma),(p,n)(p,2n),(p,3n)]$ proton induced nuclear reaction cross section on Molybdenum($^{95}$Mo) in the data center?

3. Is there a satisfactory agreement between experimental value and the experimental

data?

## 1.3 Objective of the study

### 1.3.1 General objective

The main objective of this study is to theoretically examine the the nuclear reaction cross-section of proton induced reaction on $^{95}_{42}Mo$ at different energy ranges by using FORTRAN based computer code called complet. Thereby compare the theoretical result with experimental.

### 1.3.2 Specific objective

The specific objectives of studies are;

- To calculate cross section of $[(p, \gamma), (p, n)(p, 2n), (p, 3n)]$ proton induced nuclear reaction cross section on $^{95}_{42}Mo$ using a reaction code.
- To compare the calculated cross section of $[(p, \gamma), (p, n)(p, 2n)(p, 3n)]$ of proton induced nuclear reaction cross section on $^{95}_{42}Mo$ with the data obtained from Nuclear Data base (EXFOR) and give justification of the experimental cross-section data.

## 1.4 Significance of the study

The main use of the research is in order to the validate experimental cross-section of some proton induced reactions on molybdenum by theoretical calculations.
Such reaction are useful to produce a short half-life radio isotope technetium(Tc) and can be used in nuclear medicine.

In addition this thesis can be used as a reference to gain deeper understanding of proton induced nuclear reaction on molybdenum ${}^{95}_{42}Mo$ by other users of nuclear reaction on molybdenum ${}^{95}_{42}Mo$ who interested in.

## 1.5 Limitation of the study

Due to time constraint, the scope of the study is limited to few channels of calculation cross section $[(p,n)(p,2n)(p,\gamma)(p,3n)]$ of proton induced nuclear reaction on Molybdenum (Mo-95).

# Chapter 2

# Literature Review

## 2.1 Introduction

When energetic particle falls up on the matter and overcome the coulomb barrier nuclear reaction take place in a the nucleus dimension [7]. Nuclear reaction is physical process in a which there is a change of atomic nucleus taking place. Nuclear reaction models are frequently needed to provide estimates of the particle-induced reaction cross-sections, especially if the experimental data are not available or unable to measure the cross-sections due to the experimental difficulty. Several microscopic models have been constructed in order to describe the first stage of proton - nucleus reaction. All of them have the same basis, they describe the reaction as a cascade of nucleon - nucleon collisions, but employing different assumptions. The main difference concerns implemented potential of nucleon - nucleus interaction. Is a process of the production of nuclei and elementary particles in a nuclear reaction of particles(projectile) and target nuclei. The different circumstance is convenient to classify nuclear reactions by the type of bombarding particle, target, bombarding energy and reaction product [1]. The projectile is absorbed by the target nucleus and a compound nucleus is formed and thermodynamic equilibrium is established. Then after emitting particles and/or radiations. Decay of compound nucleus assumed to be depends only on the excitation energy and other good quantum numbers of the compound nucleus and is totally independent of its mode of formation [6]. This is called 'independent hypothesis'. In another case, at relatively higher excitation energies, the forward peaked angular distribution of particles indicates the presence of direct reaction. The result of recent measurement indicates the presence of reaction process which is intermediate between these two extreme reaction as a result of succussive interaction of the projectile and nucleons of the target nucleus and emission may takes place at any stage even before the establishment of thermodynamic equilibrium known as pre-equilibrium nuclear reaction. Nuclear reaction occurs in different mechanism:

A) **Direct Nuclear Reaction;** projectile make glancing contact and separate immediately losing some energy either one or more nucleons transferred from or to it [8]. Target particle most likely to interact to one or very few valence nucleons near the surface of the target and the remaining nucleons of the target serving as a passive spectator. In such type of reactions might remove or insert single nucleon from a target and the processes occurred very rapidly. In this type of reaction there is nucleon-nucleon interaction peripherally [9]. Most commonly the energy share or the interaction of the projectile particle and target is compared to the nuclear natural time ($t = \frac{2R}{v_p}$) when, R-radius of target particle, $v_p$ -velocity of projectile, is the time taken to cross the target nucleus. Direct reaction can be classified as;

i) Stripping reaction; is a type of direct nuclear reaction in which one or more nucleons are transferred to a target nucleons from passing particle

ii)Pickup reaction; in this type of reaction one or more nucleons are transferred from a target nucleons to a projectile particle.

iii) Breakup reaction; is a type of reaction which a break up of a projectile into two or more fragments.

iv) Knock-out reaction; a reaction in which a single nucleon or light cluster is removed from the projectile by a collision with the target.

**B) Compound Nuclear Reaction;** As Bohr(1936) The incident particle absorbed by a target or a projectile and a target nucleus interact, creating a composite nucleus, the energy initially concentrated on a few nucleons (nucleon) spreads through the composite nucleus which involves toward state of equilibrium and disintegrates by ejecting a particle (proton, neutron , alpha particle etc) the compound nucleus disintegration is independent of the in which the latter is formed [10]. The appropriate formalism for the description of compound-nuclear reactions is a statistical one. Weisskopf and Ewing developed calculation of reaction cross-section regarding to Bohr's picture using partial wave analysis but no taken account of conservation of angular momentum and parity [11]. The model postulates strong interaction between nucleons that causes immediate dissipation of the energy of the incident nucleon among many nucleons in the target nucleus. As a result, none of the nucleons has enough energy to escape from the compound state and a compound nucleus is formed and takes a time ($\approx 10^{-15}s$) compared with. It is a quasi-bound state that lasts until the energy re-concentrates onto a small number of nucleon(s) that are then emitted from it [6]. More or less, random collisions occur and statistical distribution in energies and small probability of for a single nucleon to gain a large enough share of energy to escape much as gas evaporate from hot liquid.The projectile can add material, energy, angular momentum to the target nucleus. Such type of reaction involves the compound nucleus to be two-step process; the formation and then the subsequent

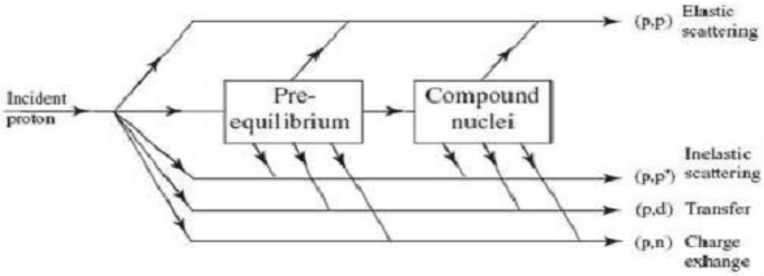

Figure 2.1: Pictorial representation of a typical nuclear reaction induced by an intermediate energy proton.

decay of the compound nucleus. The Bohr hypothesis allows the cross section to be written as the product of the two factors, the cross section $\sigma_a$ for formation of the compound nucleus and the probability $P_b$ will be decay in to the channel b

$$\sigma_{ab} = \sigma_a P_b \tag{2.1.1}$$

The compound nucleus formation cross section at a particular at a particular orbital angular momentum $\ell$ is given by

$\sigma_a = \pi\lambda_a^2(2\ell + 1)T_a$,where $\lambda_a$-reduced wave length in the incident channel($k^{-1}$)and $T_a-$ transmission coeffecient for entrance channel a. Weisskopf and Ewing develop theoretical calculations of reaction cross-sections according to Bohr's model using partial wave analysis but parity and angular momentum not taken in to account never the less it provides good estimate for the magnitude of the cross-section [6]. The existence of quantum states in the Compound nucleus requires an explanation [12]. One might expect that the spectrum of the Compound nucleus is continuous if the excitation energy E is higher than binding energy. Then the system is excited sufficiently to emit a particle (namely the bombarding particle) and its spectrum should correspond to the spectrum of an atom above the ionization energy, which is continuous. The excitation energy of the Compound nucleus created by the bombarding particle is always higher than binding energy so that we should expect a continuous spectrum and no resonances [1].

Compound-nuclear reactions play a crucial role in many areas of basic and applied nuclear science. The production of heavy elements in various astrophysical environments, for instance, involves compound reactions and the resulting observable abundance patterns depend, sometimes very sensitively, on the associated reaction cross sections. Similarly, a proper description of nuclear fuel cycles for energy applications requires data on various types of compound reactions. The term ”compound nucleus” was introduced by Bohr to describe a resonant composite of (At + A.) nucleons in thermal equilibrium; its most familiar experimental signature is a CM angular distribution of unpolarized decay products, symmetric about $90^0$.

**C) Pre Compound Nuclear Reaction;** Is another important class of nuclear reactions is that proceeding by a small number of direct processes, each of which can be calculated in a familiar way. The Statistical model of intermediate structure emerged easily and naturally from these idea [13]. It provided separate, closed algebraic expressions for the energy distributions of compoundand of precompound (later to become pre-equilibrium) particle emissions, and these combined to yield an excellent description of some (p,n) data. Nuclear reaction models based on totally quantum mechanical and semiclassical theories are proposed for pre-equilibrium emission mechanism[13].Most commonly used quantum models are Feshback, Kerman and Koonin

(FKK) model and Nishioka, Verbaarshot, Weidenmuller and Yoshida (NVWY)model or Hydelbergmodel.

**Intra-Nuclear-Cascade(INC)model**; is a nuclear reaction model that incorporated pre-equilibrium emission which is proposed by Serber. The projectile enters the target nucleus with a given impact parameter 'b', after traveling a certain a distance inside the nucleus it interacts with a target nucleon and excites it above Fermi sea [14]. Each scattered particles then travel through the nucleus interacting with the other nucleons. The Intra-nuclear cascade model traces the individual nucleon trajectories in three-dimensional geometry. The trajectory of an excited particle is followed until some arbitrary energy, generally considerably above the average equilibrium value, has been attained by the nucleon.

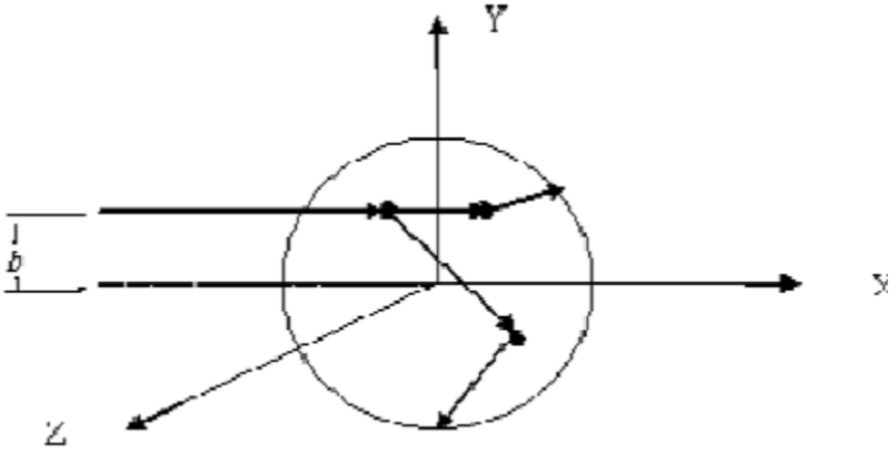

Figure 2.2: Diagram of Intra nuclear cascade model(taken from Direct Nuclear Reaction Theories, John Wiley )

When all particles of a given cascade have been traced,the total energy of the residual nucleus, its density, and the energies and angles of the emitted particles are shared and a new cascade with new impact parameter is calculated. This model is realistic but the predictions are not satisfactory back and forward angles[15]. In this model, mean free paths and energy transfers in the assumed two-body scattering processes are based on experimental nucleon-nucleon (N-N) scattering cross sections and angular distributions, with collisions in which either partner has a final energy less than the Fermi energy being forbidden by the Pauli principle. For each scattering event, the position of collision within the nucleus and the energies and directions of each particle are followed explicitly in three-dimensional geometry. Several microscopic models have been constructed in order to describe the first stage of proton - nucleus reaction. All of them have the same basis, they describe the reaction as a cascade of nucleon - nucleon collisions, but employing different assumptions. The main difference concerns implemented potential of nucleon - nucleus interaction. One can

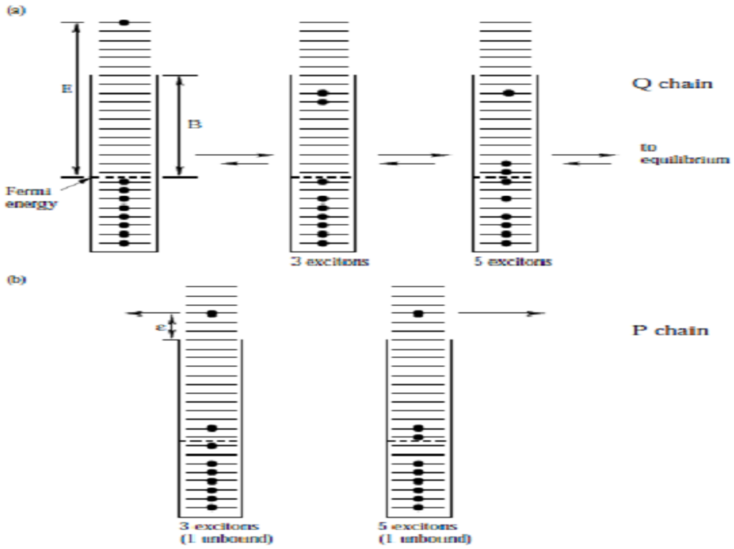

Figure 2.3: Schematic diagram of pre few stages of a nucleon-induced reaction in the exciton model

distinguish the simplest models, which neglect features of the mean field dynamics and employ constant static potential, like a class of Intra - Nuclear Cascade (INC) models. Other, more sophisticated approaches comprise dynamically changing field and minimal fluctuations obtained due to use of test particle method.

**Exciton model;** Is presented by Griffin it is logically simple and modified. In this model the incoming projectile interacting with the target nucleus, gives rise to a simple initial configuration characterized by a small number of excited particles and holes called excitons (n=p+h) [17]. Horizontal lines indicate equally spaced single-particle of potential well and solid circles are particles. In (a) nucleon-nucleon interaction leading to equilibrium, (b) interaction leading to configurations in which at least one particle is unbound and thus may be emitted in to continuum. Successive two-body residual nucleus interactions rise to an intranuclear cascade through which a sequence of states an increasing exciton number, eventually leads to a fully equilibrated residual nucleus. For number of n excitons, particles p,and holes h

$\triangle n = 0, \pm 2; \triangle p = 0, \pm 1; \triangle h = 0, \pm 1$

At each stage of this equilibrium process the decay mode of the composite nucleus can compete. Exciton model assumes

1).At each stage of the cascade all of the states with the same configuration and the same total energy are equiprobable.

2).At each stage of the cascade all the process which may occur are also equiprobable.

The first assumption try to predict the energy distribution of the excitons. The exciton number between energy $\varepsilon and \varepsilon + d\varepsilon$ in a configuration of p particles and h holes and total energy E is $dN_p(p, h, E, \varepsilon)$ and the remaining p-1 particles and h holes have the energy $E - \varepsilon$ is given by

$$dN_p(p, h, E, \varepsilon) = \frac{\rho_{p-1,h}(E - \varepsilon) g d\varepsilon}{\rho_{p,h}(E)} \tag{2.1.2}$$

$g = \frac{1}{d}$, density of single particle,Fermi gas model $g = \frac{3A}{2\varepsilon_F}$

If $\rho_{ph}(E) and \rho_{p-1,h}(U)$ are the state densities for the composite and the residual nuclei. The escape width for emission of a particle $\upsilon$ with energy between $\varepsilon_\upsilon$ and $\varepsilon_\upsilon + d\varepsilon_\upsilon$

$\Gamma^{\uparrow}(\upsilon, \varepsilon_{\upsilon|E,p,h}) = W\hbar(\upsilon, \varepsilon_\upsilon \mid E, p, h) d\varepsilon_\upsilon$

Where W-is decay rates

Griffin proposed the exciton model of pre-equilibrium emission to explain an excess of high energy neutrons relative to those from the compound nucleus observed in (p,n) reactions. The projectile enters the nucleus and collides with a nucleon, producing a two-particle one-hole excitation. The secondary particles can themselves interact, producing three-particle two-hole excitations and so on. The exciton can be stated as 2s+1 which noticed the shell-shifted equispacing model with active and passive particles and/or holes. In pre-equilibrium calculations we are interested only in particles (holes) which represent degrees of freedom; that is those which have permutable excitation energy. Passive particles (holes) which are fixed adjacent to the Fermi level are not counted. Rather, they contribute to the Pauli energy. In a proton-induced reaction, a collision of the proton with the nucleus leads to a 2p-1h state, in which the incident particle has excited a target particles, creating a particle-hole pair. When the equilibrium state is reached, the pre-equilibrium model is replaced by evaporation model.

## 2.2 Conservation laws

In nuclear reaction several conservation laws contributes whereby two nuclei (projectile a and target A) to produce emitting particle b and residue B[19].

(a+A → b+ B) OR in compact form A(a,b)B

Where; a- Incident particle

A-Target nucleus

B- residue nucleus

b- emitted particle

Therefore any three of the reactant is uniquely determine the forth by the following conservation laws;

1)Baryonic number; In all decays and reactions the total baryonic number is conserved.By assign B=+1for baryons, B=-1 for ant baryons and B=0 to non-baryon the summation of B's must be conserved. Depending on different energy range of the projectile either number of nucleons are conserved in high energy range or number of neutron and proton separately.

2)Charge; Similar fashion with baryon number, the number of charges or lepton is conserved.

3)Energy and momentum; Nuclear reaction and decays obey the conservation of energy (including their rest mass) and momentum [6]. Conservation of energy for stationary target is

$$M_a \times c^2 + T_a + M_A \times c^2 = M_b \times c^2 + T_b + M_B \times c^2 \tag{2.2.1}$$

By using conservation of linear momentum and the target is at rest

$P_a = P_B + P_b \rightarrow M_a V_a = M_B V_B \cos\varphi + M_b V_b \cos\theta$

Rearrannging the above two equation one can calculate the Q value of the equation which is defined as the difference between the final and initial kinetic energies including rest energy of the particles.

$Q = T_B + T_b - T_a$

$$Q = T_b(1 + \frac{M_b}{M_B}) - T_a(1 - \frac{M_a}{M_B}) - \frac{2}{M_b}(M_a M_b T_a T_b)^{\frac{1}{2}} \cos\theta \qquad (2.2.2)$$

In order to not violate to physics laws both linear and angular momentum are conserved. Angular momentum transfer in the nuclear reaction from projectile to the target. This angular momentum comes from the transfer at the point of contact and it affects the out going particle.

$P_A = P_a - P_b$

$P_A^2 = P_a^2 + P_b^2 - 2P_a P_b \cos\theta$ (cosine law)

$P_A^2 = (P_a - P_b)^2 - 4P_a P_b \sin^2 \frac{\theta}{2}$

The transferred angular momentum by semiclassical is given by

$(L = \sqrt{\ell(\ell + 1}\hbar \leq P_A R)$ for direct reaction,$P_a = P_b = P$,then

$$\sin\frac{\theta}{2} = \frac{P_A}{2P} \geq \frac{\sqrt{\ell(\ell+1)}}{2PcR}\hbar c \qquad (2.2.3)$$

By equation above any one can calculate the scattering angle of the out going particle. Given energies of outgoing and projectile have direct relationship between $\theta$ and $\ell$ particles emerging at a certain angle should correspond to its angular momentum of orbiting particle [19]. For the interacting particles have spin,the cross section have to spin weight factors appropriately.

4) Parity; These conservation laws are a significant in nuclear physics as else where, but there is another symmetry and conservation law which is of particular importance in quantum system such as the nucleus; reflection symmetry and parity. A single

particle wave function $\psi(r)$ is said to be have parity +1 ($\psi(-r) = +1\psi(r)$) if it is even under reflection of particle coordinates and -1, ($\psi(-r) = -\psi(r)$) for odd.

Parity is an important concept because the laws of the electromagnetic and of the strong interactions. Wave function for the system can be chosen to have a definite parity which does not change as the wave function evolves in time according to Shrodinger equation [6].

## 2.3 Cross section($\sigma$)

Cross section is a measure of relative probability for nuclear reaction occurrence is commonly expressed instead of the concept of cross section [1]. Let the current of incident particle beam $I_a$ per unit time a nd let the target show to the beam N target nuclei per unit area. If the outgoing particles appear at a rate $R_b$, then the reaction cross section is

$$\sigma = \frac{R_b}{I_a N} \tag{2.3.1}$$

In the literature, it is often called $\sigma(\theta, \phi)$ or $\sigma(\theta)$. The reaction cross section $\sigma(\theta)$,by integrating all angles

$\sigma = \int_0^{\pi} \sin\theta d\theta \int_0^{2\pi} d\phi \frac{d\sigma}{d\Omega} d\Omega$

One can write simple nuclear reaction cross section in terms of interaction radius

$\sigma = \pi R^2$ ,where $R = R_2 + R_1$ or$R = 1.2(A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}})$

Interaction radius is the summation of radii of projectile particle and target nuclei [19]. Nuclear reaction take place if the colliding nuclei come with in the range of nuclear force;

$r \leq R \rightarrow$ nuclear reaction take place

$r > R \rightarrow$ no reactions occur.

At the distance of closest approach ,the initial kinetic energy E appears partly as reduced kinetic E' and partly as coulomb potential energy B. Then

$$E = E' + B \tag{2.3.2}$$

$B = \frac{Z_1 Z_2 e^2}{4\Pi\varepsilon_0 R} \approx \frac{1}{2} A^{\frac{2}{3}} Mev$ -is coulomb potential for proton induced reaction on a target nucleus of A mass. From conservation of angular momentum gives,

$\vec{L} = Pb = p'R$

$\frac{E'}{E} = (\frac{P'}{P})^2 = (\frac{b}{R})^2$

The mass of the target is assumed to be large compared with the projectile mass.

$$\sigma = \pi R^2 \frac{E'}{E} = \pi R^2 (1 - \frac{B}{E}) \tag{2.3.3}$$

where $E_{cm} = \frac{EM}{m+M}$

Thus k can be written in terms of wave number $k(= \frac{P}{\hbar})$

$\sigma = \pi (\frac{L}{P})^2 = \frac{\pi \ell(\ell+1)\hbar^2}{(\hbar k)^2}$

$$\sigma \approx \frac{\pi \ell^2}{k^2} \tag{2.3.4}$$

Cross section falls to zero when $E = B$ and it remains there at lower energies, but the nuclei are always out of contact with each other even in head on collision. Even the particle classically remain out of range,$(E < B)$ there is a probability of the coulomb barrier penetrated and the reaction taking place.

### 2.3.1 Partial wave analysis

In this section any one going to calculate the cross section with out placing any limitation on the strength $V(\vec{r})$. In quantum mechanics, the wave nature of matter allows the wave function $\psi$ to penetrate in to the classically forbidden region under a finite barrier [21]. Inside the barrier the less energy region of the incident the wave function $\psi$ is decaying exponenttially. Barrier penetration means that there will be some probability that two hydrogen nuclei can come in to contact and fuse even when,classically,there is not enough energy to do so [22]. The coulomb barrier for charged particle is not rebounced back. A particle with a reduced mass $\mu$ which moves in the potential $\hat{\mathrm{V}}(\overrightarrow{r})$ is by Schrodinger equation

$-\frac{\hbar^2}{2\mu}\overrightarrow{\nabla}^2\Psi(\overrightarrow{r})+\hat{V}(\overrightarrow{r})\Psi(\overrightarrow{r})=E\Psi(\overrightarrow{r})$

By taking Z-axis to be the direction of incident beam and it can be represented by a plane wave $e^{ikz}$ corresponding to momentum $p=\hbar k$ and outgoing spherical wave.

$$\psi_{in}=Ae^{ikz} \tag{2.3.5}$$

$\psi_{in}(r)=A\Sigma_0^\infty i^\ell(2\ell+1)\jmath_\ell p_\ell(\cos\theta)$

A-appropriate chosen by normalization constant.

General $S-wave(\ell=0)$

$\psi_{sc}(r)=\frac{(\eta-1)}{2ikr}e^{ikr}$

$$\psi_0(r)=\frac{1}{2ikr}(-e^{-ikr}+\eta e^{ikr}) \tag{2.3.6}$$

We have account for the scattering amplitude $f(\theta,\phi)$ which plays a central role in the theory of scattering of the incident wave. Although it determines the differential cross section [1]. By integrated flux of incident wave,

$R^{in}=\frac{i\hbar}{2m}(\psi_{in}\nabla\psi_{in}^*-\psi_{in}^*\nabla\psi_{in}$

In the same manner to flux of scattered wave

$R_{in}=A^2\frac{\hbar k_0}{m}$ ,and $R_{sc}=A^2\frac{\hbar k}{mr^2}|f(\theta,\phi)|^2$,$R_{out}=\frac{|\eta|^2}{k}piv$

Cross section ,the S-wave elastic scattering cross section $\sigma_{sc,o}$ is the integrated flux of scattering particles per unit flux of the incident wave $F_{in}$

$\sigma_{sc,o} = \frac{R_{sc}}{F_{in}} = \pi\frac{|\eta-1|^2}{k^2}$ and $\sigma_{r,0} = \frac{R_{in}-R_{out}}{F_{in}} = \pi\frac{(1-|\eta|^2)}{k^2}$

reaction cross section is maximum whenever $|\eta|^2 = 0$ which consist equation for $\ell = 0$ and for elastic scattering $|\eta| = 0$

This is analogous to the situation in optics where the loss of light by a purely absorbing disc gives rise to diffraction with light appearing at a finite angles away from the direction of incident beam [19]. The wave function of the nuclear surface by boundary condition $(R = r)$ interior and exterior wave function and its derivative must be continuous $[U_{(r)} = r\psi_{(r)}]$

$f = R[\frac{dU_o(r)/dr}{U_o(r)}]_{r=R}{=}R[\frac{dU_i(r)/dr}{U_i(r)}]_{r=R}$

$$f = ikR(\frac{\eta e^{ikR} + e^{-ikR}}{\eta e^{ikR} - e^{ikR}}) \tag{2.3.7}$$

This implies a particular model allow us to calculate f and,hence,the cross sections. These can be compared with experiment in order to test the model or,if the model proves to be successful,it can be used to predict cross sections [23]. If a particle enters or leaves the nucleus, it must penetrate a surface at which its wave number changes suddenly from a low value k out side to a high value K inside, or vice versa.

$$\sigma_{r,0} = \pi\lambda^2\frac{4Kk}{(K+k)^2} \tag{2.3.8}$$

Such sudden change of wave number is connected with a reflexion, so that this surface is only partially penetrable for the particle. The penetrability T can be easily calculated for an uncharged particle. (The passage of charged particles is hindered by the Coulomb barrier which increases the reflexion effect). Wave mechanics shows that the ratio T of the penetrating particles to the incident ones from a region in which the wave number is k to a region in which it is K (or vice versa) is given by $(\frac{4kK}{(k+K)^2})$. A compound nucleus model, which assumes that particles reaching the inside region fuse with the target nucleus and do not reappear [24]. Compound nucleus has too much energy to be stable and it will survive for a relatively long time compared with the duration of a direct reaction even decay occurs some time later when, by chance a nucleon or a part of nucleon to escape. Any excited state decays with a probability $\lambda = \frac{1}{\tau}$,where $\tau$,is its mean life time. The shape of resonance can be obtained by expanding the phase shift about the value $\delta_\ell = \frac{\pi}{2}$. From

$$\sigma_{sc} = \sum_{0}^{\infty} 4\pi\lambda^2(2\ell+1)\sin^2\delta_\ell \tag{2.3.9}$$

There will be scattered resonance where $\eta_\ell = -1$ corresponding shift $\delta_\ell = \frac{\Pi}{2}$. To better convergence of Taylor series

$\delta_\ell(E) = \cot\delta_\ell(E_R) + (E - E_R)(\frac{\partial\cot\delta_\ell}{\partial E})_{E=E_R} + \frac{1}{2}(E - E_R)^2(\frac{\partial^2\cos\delta_\ell}{\partial E^2})_{E-E_r} + ..$

Defining $\Gamma = 2(\frac{\partial\delta_\ell}{\partial E})^{-1}_{E=E_R}$

The second term vanishes and thus (neglecting higher order terms)

$\cot\delta_\ell = -(\frac{E-E_R}{\frac{\Gamma}{2}})$ and $\sin\delta_\ell = \frac{\frac{\Gamma}{2}}{[(E-E_R)^2+\frac{\Gamma^2}{4}]^{\frac{1}{2}}}$

$\sigma_{sc} = \frac{\pi}{2}(2\ell+1)\frac{\Gamma^2}{(E-E_R)^2+\frac{\Gamma^2}{4}}$

When the bombarding E in the entrance channel is close the energy $E_R$ for exciting a state in the compound nucleus the cross section for the reaction $(a + A \rightarrow C^* \rightarrow b + B)$takes the Lorentz distribution and is given by the Breit-Wigner equation.

$$\sigma_{\alpha,\beta} = g_\alpha(J)\frac{\pi}{k_\alpha^2}\frac{\Gamma_\alpha\Gamma_\beta}{(E - E_r)^2 + (\frac{\Gamma}{2})^2} \tag{2.3.10}$$

$\alpha$ -entrance channel $(a + A)$

$\beta - exit$ channel $(b + B)$

$k_\alpha$ -wave number in entrance channel

$g_\alpha = \frac{2J+1}{(2i_a+1)(2i_A+1)}$-spin quantum number of incident particle($i_a$),target nucleus($i_A$) and compound nucleus(J)and it may be reduced to $(2J + 1)$ for spinless incident particle and target nucleus.

The relative probabilities of of the different decay branches depend on the amount available excitation energy [20]. Certain nuclei, known as a fissile nuclei,will under go fission when bombarded with low energy (thermal)neutrons,a process that is of particular nuclear reactors. Slow neutron was used to isotopes production in this manner energy appropriate to de Broglei wave length ($\lambda_D \propto \frac{1}{\sqrt{E}}$). It should be slow neutrons to be fuse with the target, becuase it has not face coulomb barrier and high probability to made compound nucleus. On the other hand Feshbach and Hauser treated the compound nucleus in a more detailed way and have explicitly taken in to account the conservation of parity and angular momentum [8]. The compound nucleus formation cross section at a particular angular momentum $\ell$ is

$$\sigma_a = \pi\lambda_a^2(2\ell + 1)T_a \tag{2.3.11}$$

The transmission coefficient $T_a$ for the entrance channel a is, $T_a = 1- \mid Saa \mid^2$ ,where $S_{aa}$-is average S-matrix. Relating a cross section to its inverse

$\lambda_a^2\sigma_{ab} = \lambda_b^2\sigma_{\hat{a}\hat{b}}$, $\hat{a}$ and $\hat{b}$ are refer to time-reversed states and combining equations

$T_aP_b = T_{\hat{b}}P_{\hat{a}} \Longrightarrow \frac{P_{\hat{a}}}{T_a} = \frac{P_b}{T_{\hat{b}}} = \xi$ (constant) ,Therefore

$P_b = \xi T\hat{b} = \frac{T\hat{b}}{\sum_a T_a}$ ,Thus we get

$$\sigma_{ab} = \pi\lambda_a^2(2\ell + 1)\frac{T_aT_b}{\sum_c T_c} \tag{2.3.12}$$

This is Hauser-Feshback equation provides the cross section of compound nuclear

reaction determined from a single incident channel a to single outgoing channel in absence of spin and specific angular momentum state($\ell$). One can calculate the transmission coefficient from the appropriate optical model potential. Any interacting particles have spin for reaction A(a,b)B
$a^i + A^I \rightarrow^{\ell} (C)^{J*} \rightarrow^{\ell} b^{\acute{i}} + B^{\acute{I}}$ ,orbital angular momentum $\ell$ and spin angular momentum to form total nucleus angular momentum J. The probability spin i and I combine is $P(s) = \frac{2s+1}{(2i+1)+(2\ell+1)}$ and the same fashion the probability of s combine with $\ell$ to give J; $P(J) = \frac{2J+1}{(2s+1)+(2\ell+1)}$ ,The partial waves by $(2\ell + 1)$ the cross section given by

$$\sigma_{ab}^{HF}(E) = \pi \lambda_a^2 \sum \frac{2J+1}{(2i+1)+(2I+1)} \frac{T_a T_b}{\sum_c T_c} \tag{2.3.13}$$

Many of the more recent important developments which are still in progress are left out. In particular, pre-equilibrium processes in light and heavy ion reactions to be the subjects of great interest in recent years, and much relevant to the present symposium. Intensive studies, both experimental and theoretical are being made. Hopefully in the near future, they will be understood as well as direct and compound nucleus processes, and a unified picture of nuclear reactions will emerge that quantitatively describe all stages of nuclear reactions from shape elastic scattering to compound nucleus decay. Quantum equilibration is a dephasing process, operating among states nearly degenerate in energy. In an infinite system this near-degeneracy merely corresponds to the continuous spectrum of excitation energies. In a finite nucleus, where the spectrum is discrete, the "degeneracy" is due to the overlapping of resonances, and the number of "degenerate" states, $\frac{\Gamma}{D}$, is an essential parameter in any description of their relaxation.

# Chapter 3

# Material and Methodology

## 3.1 Materials

During this research the following material has been used.

- Experimenta data from Exfor
- Fortran 77 based nuclear reaction code , complet
- Computer, flash, printer and Stationary materials and different reference

## 3.2 Methodology

### 3.2.1 Analytical Method

This approach is used to solve the reaction cross-section equation using Schrodinger equation of partial wave. The calculation of reaction cross-section is determined by the projectile energy and analytically solve cross-section as a function of energy.

### 3.2.2 Computational Method

Nuclear reaction cross-section data is being collected using nuclear reaction code per a given projectile energy. Due to lack of senior laboratory to experimentally determine the nuclear reaction cross-sections, experimental data has been taken from nuclear reaction data base, EXFOR.

The nuclear reaction code used in this thesis is a fortran-77based computational code called complet.

#### Code Complet

The code COMPLET is a nuclear reactions code which was designed for validity and ease use in the bombarding energy range of a few Mev to several hundred Mev.The code COMPLET is based on same philosophy as the former code INDEX (25). It applies the statistical model of compound nucleus decay developed by both the hybrid and geometric dependent hybrid model of [18] Blann, exciton of weisskopf-Ewing [13] and also the rather further simplification and improvement by J.Ernst (16).

The COMPLET CODE 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 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 nuclide 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 5 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 5 0 or IKE = 6 most reduced output emitting nuclides and all partial waves) of pre-compound plus equilibrium spectra. To print gamma spectra, increase the IKE value selected by 5.

If IPCH =1 or =2, fission barriers are to be read in after this first record IPCH - = 1: inverse cross sections will be readout for possible future use in separate output file. = 0: or NE from 1.no printout KPLT - number of decades to be plotted as excitation function on line printer. If KPLT = 0: no plotting

Card 2 Title -80 columns

If MC = 2 on CARD 1, read user supplied n, p,alpha, deuteron triton and helion binding energies here, Format for IA =1 to NA, IZ=1 to NZ. If INVER =0 on CARD1, read the n, p, alpha, deuteron triton, helion and gamma inverse cross sections here. In ascending channel energy, first value = 0.1 Mev, incremented by 1Mev, 48 values per particle type in sequence N,P,A,D,T,3HE, and gamma depending on value of M3.

CARD 3

ENERGY and COMPOUND NUCLEUS and PRE-EQUILIBRIUM OPTION

Symbol Description

IKEN - projectile kinetic energy in the laboratory system.

If = 0: A new problem will begin at CARD1. $If < 0$: previously calculated excitation functions will be printed (if KPLT=0, EKIN values were run in ascending order they are plotted).

If EKIN=0 on two successive cards, a normal exit will occur for negative target mass on card 1. RCSS = 0: reaction cross section is calculated from subroutine (for pi-induced reactions: if RCSS $(input) = 0, RCSS = 100mb) >$: 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 = +0.5 No cut-off. In these interactions the original exciton type is assumed to be conserved. The newly created exciton may be a particle, a -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[25]. The mean free path multiplier for intra nuclear transition rates are calculated from optical potential parameters.

# Chapter 4

# Result and Discussion

Here the cross section of nuclear reaction of outgoing channels were calculated using a computational code, complet. These are: $^{95}Mo(p,\gamma)^{96}Tc$, $^{95}Mo(p,n)^{95}Tc$, $^{95}Mo(p,2n)^{94}Tc$, and $^{95}Mo(p,3n)^{93}Tc$ at different energy ranges. The reference used to determine the energy ranges of each channel is the data of International Atomic Energy Agency(IAEA) experimental data of proton induced nuclear reaction on Molybdenum ($^{95}Mo$) to produce Technetium(Tc) radionuclide isotopes. Theoretical cross section of nuclear reaction generated by complet computational code calculation were compared with the experimental values taken from EXFOR data library [26]. These code employ the Weisskopf-Ewing model for the statistical part and geometry dependent hybrid model of M.Blann for the pre-equilibrium emission. The code COMPLET gives the result of cross-section for the reaction of $^{95}Mo(p,\gamma)^{96}Tc$, $^{95}Mo(p,n)^{95}Tc$, $^{95}Mo(p,2n)^{94}Tc$, and $^{95}Mo(p,3n)^{93}Tc$.

The experimental cross-section data in EXFOR, used for comparison are as given by the authors,T.Sauter and F.Kappeler, M.Izumo,T.Matsuoka,T.Sorita,Y.Nagame, T.Sekine, K.Hata, S.Baba,V.N.Levkovski. The result obtained in each of the reaction was as discussed in the following section.

## 4.1 The reaction $^{95}Mo(p,\gamma)^{96}Tc$

In this reaction a proton energy in the range 1.695Mev to 2.895Mev is used.

In this energy range, Cross-section of the reaction for energies 1.695Mev, 1.988Mev, 2.141Mev, 2.39Mev, 2.494Mev, 2.673Mev, 2.845Mev, 2.895Mev as shown in the table 4.1 was calculated using complet nuclear reaction code.

Table 4.1: Theoretical and Measured cross-section for reaction $^{95}Mo(p,\gamma)^{96}Tc$

| E(Mev) | Exp(mb) | Calc(mb) |
|---|---|---|
| 1.695 | 0.00058 | 0.0000541 |
| 1.988 | 0.00729 | 0.00719 |
| 2.141 | 0.0179 | 0.0175 |
| 2.39 | 0.0425 | 0.0430 |
| 2.494 | 0.108 | 0.108 |
| 2.673 | 0.132 | 0.189 |
| 2.845 | 0.156 | 0.246 |
| 2.895 | 0.128 | 0.145 |

As can be seen from the table (table 4.1) and the graph of energy versus $\sigma$ (graph 4.1) is being plotted. The theoretically calculated data using the complet code is a little bit higher than the experimental data. The error of deviation from experimental data increase when projectile energy gets higher. The reaction cross section of $^{96}Tc$ is shown in fig 4.1 $^{96}Tc$ produced in capture nuclear reaction. Both total cross section and the cross-sections of the experimental reaction and theoretical calculation are similar. We have observed here good agreement between the measured and experiment in the given energy ranges of 1.695Mev to 2.895Mev. The measured values are consistent with at the given energy ranges. However, the knowledge of the (p, $\gamma$) cross sections is valuable since it allows to determine $(\gamma, p)$-reaction. Our measured values show very good agreement with the latest data reported by T.Sauter and F.Keppeler with the recommended values shown in Fig 4.1 and that fact confirms the high reliability of the measured cross-section values of $^{95}Mo(p,\gamma)^{96}Tc$,$(T_{\frac{1}{2}} = 4.28d)$ production in the whole investigated energy range of the present measurement.

Our measured reaction cross-section of $^{96}Tc$ radionuclides along with the values of model calculation using the complet code are shown in fig 4.1. The theoretically calculated values of production are completely supporting the experimental values,

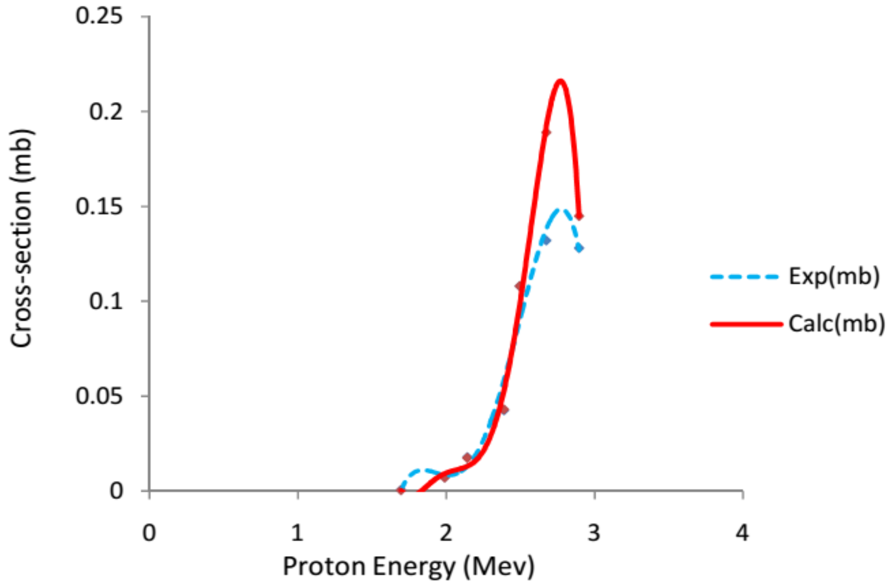

Figure 4.1: Experimental and theoretical excitation function for the reaction $^{95}Mo(p,\gamma)^{96}Tc$

both in shape and magnitudes.

## 4.2 The reaction $^{95}Mo(p,n)^{95}Tc$

The reaction $^{95}Mo(p,n)^{95}Tc$ channel have been plotted and interpolated from threshold energy to 28.19Mev of the incident proton(projectile) energy as shown in fig 4.2. In this reaction proton projectile energy is between 5.05Mev and 28.19Mev. The cross-section for the formation of the compound nucleus is calculated using a computational code complet. The result of the calculation displayed in the table 4.2 together with the experimental data. From the table 4.2 and graph 4.2 we see that there is a good agreement between calculated and experimental values of cross-section for the the formation of compound nucleus. For The reaction $^{95}Mo(p,n)^{95}Tc$channel have been plotted and interpolated from threshold energy to 30Mev of the incident

Table 4.2: Theoretical and Measured cross-section for reaction $^{95}Mo(p,n)^{95}Tc$

| Energy(Mev) | Exp(mb) | Calc(mb) |
|---|---|---|
| 5.05 | 18.4 | 19.87 |
| 6.93 | 144 | 43 |
| 8.05 | 271 | 217.6 |
| 10.48 | 489 | 484.1 |
| 13.0 | 517 | 524 |
| 15.1 | 257 | 187 |
| 16.31 | 107 | 81.47 |
| 23.29 | 18.6 | 25.4 |
| 28.19 | 16 | 14.11 |

proton(projectile) energy as shown in fig 4.2.

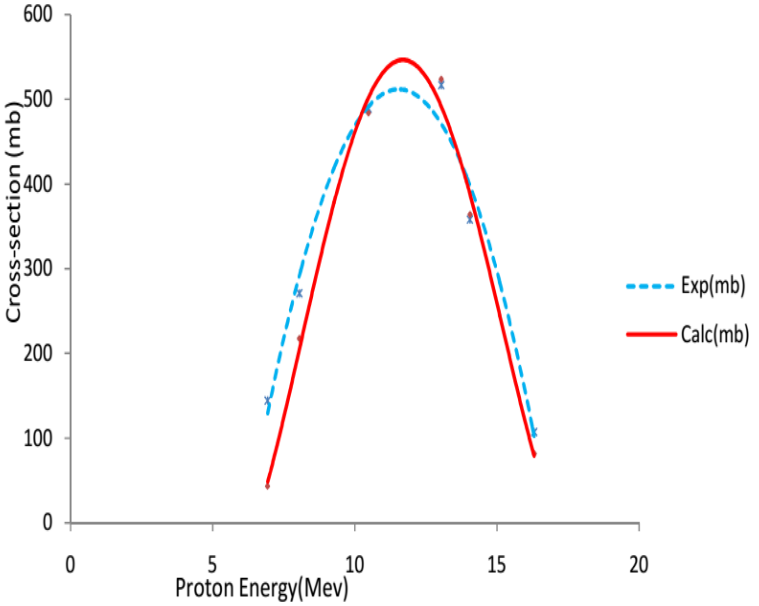

Figure 4.2: Experimental and theoretical excitation function for the reaction $^{95}Mo(p,n)^{95}Tc$

From the table 4.2 and graph 4.2 we see that there is good agreement between calculated and experimental values of cross-section for the formation of compound nucleus. In this graph the calculated cross-section values show good agreement with the latest data reported by M.Izumo,T.Matsuoka,T.Sorita,Y.Nagame,T.Sekine,K.Hata, S.Baba, and very good satisfactory between 16Mev to the recommended values shown in fig 4.2 and that fact confirms the high reliability of the measured cross-section values of $^{95}Tc(T_{\frac{1}{2}} = 20hr)$ production in the whole investigated energy range of the present measurement.

## 4.3 The reaction of $^{95}Mo(p,2n)^{94}Tc$

In this reaction proton projectile energy is between 5.05Mev and 28.19Mev. The cross-section for the formation of the compound nucleus is calculated using a computational code complet. The result of the calculation displayed in the table 4.3 together with

Table 4.3: Theoretical and Measured cross-section for reaction $^{95}Mo(p,2n)^{94}Tc$

| E(Mev) | Exp(mb) | Calc(mb) |
|---|---|---|
| 12.8 | 32 | 34 |
| 15.8 | 325 | 328 |
| 18.3 | 487 | 491 |
| 21.4 | 557 | 566.5 |
| 24 | 415 | 411 |
| 27.6 | 282 | 262 |
| 29.5 | 152 | 148 |

the experimental data.

The theoretical cross section is very good agreement with a recommended data published by V.N.Levkovski at the energy range 12.8Mev to 29.5Mev as shown in fig 4.3. The calculated nuclear reaction cross section of $^{94}Tc(T_{\frac{1}{2}} = 4.883hr)$ radionuclide with the given energy range values of model calculation using the complet code are plotted and interpolated are completely supporting the experimental values in both shape of graphic and numeric. $^{95}Mo(p,2n)^{94}Tc$ is examined the complet code calculation has provided a full harmony with experimental data at proton energies around 13Mev to 20.6Mev. It is interesting to note that the degree of matching between theoretical and experimental values is improved when the total cross section taken into account. Our measured values show very good agreement with the latest data reported by V.N.Levkovski and the recommended values shown in fig 4.3 and that fact confirms the high reliability of the measured cross-section values of $^{94}$Tc production in the whole investigated energy range of the present measurement.

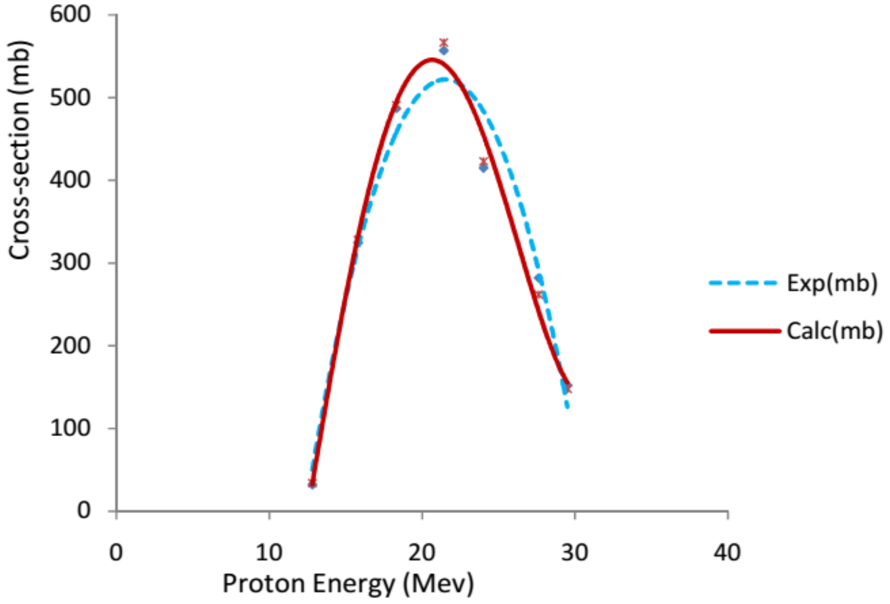

Figure 4.3: Experimental and theoretical excitation function for the reaction $^{95}Mo(p,2n)^{94}Tc$

## 4.4 The reaction of $^{95}Mo(p,3n)^{93}Tc$

In this reaction a proton projectile of energy is the range 24Mev to 29.5Mev is used. In this energy range, cross-section of the reaction for energies 24Mev, 24.8Mev, 25.7Mev and 26.6mev as shown in the table was calculated using complet nulear reaction code.

Table 4.4: Theoretical and Measured cross-section for reaction $^{95}Mo(p,3n)^{93}Tc$

| E(Mev) | Exp(mb) | Calc(mb) |
|---|---|---|
| 24 | 13 | 15.2 |
| 24.8 | 25 | 24.5 |
| 25.7 | 36 | 38.28 |
| 26.6 | 47 | 49.09 |

$^{93}Tc$ is produced from reaction of target nucleus Molybdenum($^{95}Mo$) with proton particle projectile by emitting three neutrons (3n).

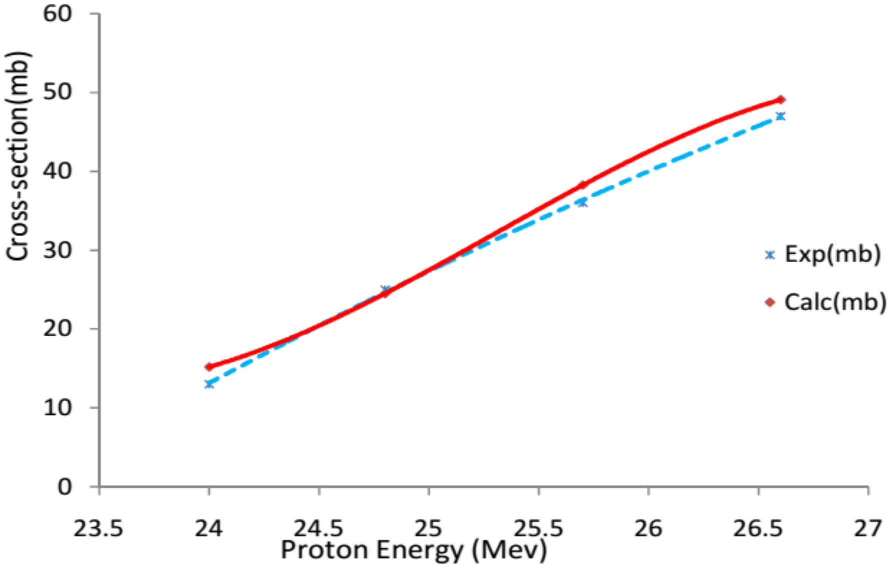

Figure 4.4: Experimental and theoretical excitation function for the reaction $^{95}Mo(p,3n)^{93}Tc$

' In fact, in the $^{95}Mo(p,3n)^{93}Tc$ reaction in the energy range 24Mev-29.5MeV the measured values of total cross-sections are closer with the recommended data by V.N.Levkovski around 24Mev energy. Because of the short half-life and the existence of numerous reaction channels are available for $^{93}Tc(T_{\frac{1}{2}} = 2.75hr)$ production from a natural $^{95}Mo$ target.The present results were compared with the earlier reported experimental data by V.N.Levkovski and theoretical data taken from the complet code, and found satisfactory agreement.

# Chapter 5

# Conclusion

This work describes calculations cross section of proton induced nuclear reaction (the excitation functions) of [$^{95}Mo(p,\gamma)^{96}Tc$, $^{95}Mo(p,n)^{95}Tc$, $^{95}Mo(p,2n)^{94}Tc$, and $^{95}Mo(p,3n)^{93}Tc$] on Molybdenum[Mo-95] at different proton energy ranges. In this thesis we have studied the collaboration of the theory or model of nuclear reaction codes and experiment.The calculation cross-sections and integral yields obtained in the present work would be useful to upgrade theoretical codes, for estimation of the activity for future pioneer accelerator developments and other radiation safety problems,for checking the yield on enriched target for medical isotope production. Theoretical calculations can provide the initial guidance allowing for extensive investigations or used to test Tc isotopes production which medical radioisotopes at little cost.

# Bibliography

[1] K.S.Krane, Introductory Nuclear physics(john wiley and sons,New York,1988)

[2] B. R. Martin Nuclear and Particle , John Wiley and Sons(2006)

[3] Norman K Glendenning Direct Nuclear Reactions, World Scientific Publishing Co. Ltd(2004)

[4] Introduction to Nuclear Science, Compound nuclear Reaction (Simon Fraser University, NUCS, spring 2011)

[5] Das and T. Ferbel, Introduction to Nuclear and Particle Physics, John Wiley and Sons, 1994;

[6] IRVING KAPLAN, Introduction to nuclear physics 2nd edition(1962)

[7] McGraw.Hill,Elements of Nuclear Physics,(1967) Condon University of Colorado.

[8] H.S.HANS,Nuclear physics:Experimental and Theoretical,New age international publishers(2001)

[9] P.E.Hodgson,E.Gadioli and E.Gadioli Erba,Introductory Nuclear physics,Oxford University press(1977)

[10] Brett V.Carlson,Jutta E.Escher and Mahir S.Hussein 'Theoretical description of Compound-Nuclear Reaction'(Open Challenges and Problems).

[11] Feshbacb H, Kennan A and Koonhi S.The statistical theory of multi-step compound and direct reactions. Ann. Phys. NY 125:429-76, 1980.

[12] Phsical Review 'Systematic study of neutron capture including the compound, pre-equilibrium, and direct mechanisms'C 90,024604 (2014)

[13] FeSHbacb H, Kennan A and Koonhi, The statistical theory of multi-step compound and direct reactions. Ann. Pit ss. NY 125:429-76, 1980.

[14] R. Serber, Phys. Rev., 72(1947)1114.

[15] Friedman W A. Hussein M S. McVo, K W and Meilo P A. Preequilibrium reactions: statistical fluctuations and doorways. Phys. Rep.Rev.Sect. Phy:. Let:. 77:47-119. 1981.

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

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

[18] M. Blann and H. K. Vonach, Phys. Rev., C28(1983)1475

[19] J. S. Lilley, Principle and Application of nuclear physics, Department of physics and Astronomy, University of Manchester, Wiley.

[20] W.N.COTTINGHAM,D.A.GREENWOOD, Introduction to N uclear physics 2nd edition.

[21] N. Austern, Direct Nuclear Reaction Theories, John Wiley and Sons, Inc., 1976

[22] Nouredine Zettili,Introduction to Quantum Mechanics,2nd edition John Wiley and sons.

[23] Griffiths,David J, Introduction to Quantum Mecchanics(1995)by prentile Hall,Inc

[24] Victor F. Weisskopf.Compound nucleus and nuclear resonances,Massachusetts Institute of Technology (Cambridge). (7. X.1949.)

[25] J.Ernest,W.Friedland H.Stockhrest,Z.phys,A-Atomic nuclei 328,333(1987)

[26] EXFOR data source IAEA,Vienna(2008)

# JIMMA UNIVERSITY
# COLLEGE OF NATURAL SCIENCES
# PERFORMANCE CERTIFICATE FOR MASTER'S DEGREE

Name of Student: **Ibsa Beyene** ID No. **SSMSC 00910/06**

Graduate Program: **Summer, MSc.**

1. Course Work Performance

| Course Code | Course Title | Cr. hr | Number Grade | Rank ** | Remark |
|---|---|---|---|---|---|
| **Phys699** | **MSc. Thesis** | **6** | | | |

** Ecellent, Very Good, Good, Satisfactory, Fail.

Thesis Title

**CALCULATION OF REACTION CROSS SECTION FOR PROTON INDUCED** $[(p,\gamma),(p,n),(p,2n),(p,3n)]$ **NUCLEAR REACTION ON MOLYBDENUM (Mo-95) IN DIFFERENT ENERGY REGIONS**

2. Board of Examiners decision Mark × in one of the boxes. Pass ☐ Failed ☐

If failed, give reasons and indicate plans for re-examination.

________________________________________________________

________________________________________________

3. Approved by: Name and Signature of members of the examining Board, and Deans, SGS

| Committee member | Name | Signature | Date |
|---|---|---|---|
| Chairman | ____________ | ____________ | ____________ |
| External Examiner | ____________ | ____________ | ____________ |
| Internal Examiner | ____________ | ____________ | ____________ |
| Major Advisor | ____________ | ____________ | ____________ |

| | | |
|---|---|---|
| ____________________ | ____________ | ____________ |
| Dean, School of Graduate Studies(SGS) | Signature | Date |

# School of Graduate Studies
# Jimma University
# College of Natural Sciences
# MSc. Thesis Approval Sheet

We the undersigned, number of the Board of Examiners of the final open defense by **Ibsa beyene** have read and evaluated his/her thesis entitled "**CALCULATION OF REACTION CROSS SECTION FOR PROTON INDUCED** $[(P,\gamma),(P,N),(P,2N),(P,3N)]$**NUCLEAR REACTION ON MOLYBDENUM (Mo-95) IN DIFFERENT ENERGY REGIONS** " and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfilment of the requirements for the degree Master of Science in **Physics (Nuclear Physics)**.

| | | |
|---|---|---|
| Name of the Chairperson | Signature | Date |
| Name of Major Advisor | Signature | Date |
| Name of Internal Examiner | Signature | Date |
| Name of External Examiner | Signature | Date |

**SCHOOL OF GRADUATE STUDIES**

# DECLARATION

I hereby declare that this Msc dissertation is my original work and has not been presented for a degree in any other University and that all source of materials used for the dissertation have been duly acknowledged.

Name: Ibsa Beyene

Signature: __________________
email:

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

Name:Dr.Teklemariam Tessema

Signature: ____________________

Place and date of submission:

Department of Physics

Jimma University

October, 2017