CALCULATION OF ALPHA INDUCED REACTIONS $[(\alpha, n), (\alpha, 2n), (\alpha, p)]$ CROSS SECTION ON IRON ^{54}Fe IN DIFFERENT ENERGY REGIONS

A THESIS SUBMITTED TO THE DEPARTMENT OF PHYSICS IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN PHYSICS (NUCLEAR PHYSICS)

Amare Gebrewold

JIMMA UNIVERSITY
JIMMA, ETHIOPIA
OCTOBER 2017

JIMMA UNIVERSITY
DEPARTMENT OF
PHYSICS

This is to certify that the thesis prepared by **Amare Gebrewold** Graduate Studies entitled "**CALCULATION OF ALPHA INDUCED REACTIONS** $[(\alpha, n), (\alpha, 2n), (\alpha, p)]$ **CROSS SECTION ON IRON** ^{54}Fe **IN DIFFERENT ENERGY REGIONS**" in fulfillment of the requirements for the degree of **Master of Science in physics(Nuclear physics)** complies with the regulations of the University and meets the accepted standards with respect to originality and quality. .

Dated: October 2017

Supervisor: _____
Dr. Teklemariam Tessema

Readers: _____

_____

JIMMA UNIVERSITY

Date: **October 2017**

Author: **Amare Gebrewold**

Title: **CALCULATION OF ALPHA INDUCED REACTIONS** $[(\alpha, n), (\alpha, 2n), (\alpha, p)]$ **CROSS SECTION ON IRON** ^{54}Fe **IN DIFFERENT ENERGY REGIONS**

Department: **Physics**

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

Permission is herewith granted to Jimma University to circulate and to have copied for non-commercial purposes, at its discretion, the above title upon the request of individuals or institutions.

Signature of Author

To my family.

Table of Contents

Table of Contents **v**

Abstract **ix**

Acknowledgements **x**

1 Introduction **1**
- 1.1 Statement of the problem 4
- 1.2 Objectives 4
  - 1.2.1 General Objectives 4
  - 1.2.2 Specific Objectives 5
- 1.3 Significance of the study 5
- 1.4 Limitation of the study 5

2 Literature Review **7**
- 2.1 Nuclear reactions 7
- 2.2 Reaction Mechanisms 9
  - 2.2.1 Direct Reactions 10
  - 2.2.2 Compound Nucleus Reactions 12
  - 2.2.3 Pre-equilibrium Reaction 13
- 2.3 cross-section 16
- 2.4 Differential cross-section 17
- 2.5 Classical estimation of cross-sections 20
- 2.6 Quantum mechanical considerations of cross-sections 24
- 2.7 General s-wave ($\ell = 0$) elastic scattering and absorption 25
  - 2.7.1 Matching the wave function at the nuclear surface 27
- 2.8 Scattering via a compound nucleus 28

3 Materials and Methodology **30**
3.1 Materials 30
3.2 Methodology 31
3.2.1 Analytical Method 31
3.3 Computational Method 31
3.4 Analysis with Computer code COMPLET 31

4 Result and Discussion **33**
4.1 Reaction cross-section of $^{54}_{26}Fe(\alpha, n)^{57}_{28}Ni$. 33
4.2 Reaction cross-section of $^{54}_{26}Fe(\alpha, 2n)^{56}_{28}Ni$ 35
4.3 Reaction cross-section of $^{54}_{26}Fe(\alpha, p)^{57}_{27}Co$ 36

5 Conclusion **38**

Bibliography **39**

List of Figures

2.1 *Shows overview of reaction mechanisms [6]* 11

2.2 *Geometry of the differential cross-section [14]* 19

2.3 *Diagram showing two nuclei with effective interaction radii R_1 and R_2. [15]* 21

2.4 *Classical grazing trajectory of a charged particle [15]* 22

2.5 *: Angular momentum zones for an incident beam directed perpendicular to the plane of the figure. Particles with a given angular momentum quantum number l, relative to the center, are mainly confined to the ring-shaped zone corresponding to that value of l.* 25

4.1 *Graph shows the excitation function of* ${}^{54}_{26}Fe(\alpha,n)^{57}_{28}Ni$ 34

4.2 *Graph shows the excitation function of* ${}^{54}_{26}Fe(\alpha,2n)^{56}_{28}Ni$ 35

4.3 *Graph shows the excitation function of* ${}^{54}_{26}Fe(\alpha,p)^{57}_{27}Co$ 37

List of Tables

4.1 The table shows excitation function of ${}^{54}_{26}Fe(\alpha, n)^{57}_{28}Ni$ 34
4.2 The table shows excitation function of ${}^{54}_{26}Fe(\alpha, 2n)^{56}_{28}Ni$ 35
4.3 The table shows excitation function of ${}^{54}_{26}Fe(\alpha, p)^{57}_{27}Co$ 36

Abstract

In this thesis, calculations of the excitation function of alpha induced ${}^{54}_{26}Fe(\alpha, n)^{57}_{28}Ni$, ${}^{54}_{26}Fe(\alpha, 2n)^{56}_{28}Ni$, ${}^{54}_{26}Fe(\alpha, 3n)^{55}_{28}Ni$ and ${}^{54}_{26}Fe(\alpha, p)^{57}_{27}Co$ reaction on iron ${}^{54}Fe$ in different energy regions have been carried out. The theoretical calculation were done using code COMPLET and compared with experimental nuclear data. The cross-sections were calculated for the production of ${}^{56,57}Ni$ and ${}^{57}Co$ in ${}^{54}Fe(\alpha, Xn)$ where $X = 1, 2$ and ${}^{54}Fe(\alpha, P)$ respectively. The graph of energy versus cross-section (σ) is being plotted. It is observed that theoretical cross-sections are in good agreement with experimental data taken from EXFOR.

Acknowledgements

First, I would like to thank the Almighty GOD. It is only due to His blessings that I have been able to accomplish this work.

Next, I would like to express my gratitude, appreciation and respect to my advisor, Dr. Teklemariam Tessemma for his guidance, invaluable advice and kindness throughout this study.

Also, I would like to express my heartfelt appreciation and respect to my coadvisor Ato Chali Yadeta, for his unreserved support while carrying out this research work.

I would like to thank my brothers Teshome Gebrewold , Tigistu Gebrewold and my sisters Birhane Gebrewold , Bizunesh Gebrewold and Abezash Gebrewold for their moral and financial supports during my study. Without their help this work would not have been possible.

Last but not least, I am grateful to all my friends and colleagues who in one way or another has advised and supported me during my study.

Amare Gebrewold

Oct., 2017

Chapter 1

Introduction

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

The Exciton model was proposed by Griffin [1] for explaining various experimental nuclear reaction data. In this model the equilibration between target and projectile is achieved by the succession of two body interactions and the composite nucleus states are characterized by the number of excited particles and holes (the exciton) at any stage of the nucleon-nucleon cascade. The exciton number (n),n=p+h ; where p is number of particles and h is the number of holes. Reactions that exchange energy or

nucleons can be used to measure the energies of binding and excitation [1]. The initial configuration is fixed by the nature of the projectile. Nuclear reactions and nuclear scattering are used to measure the properties of nuclei. A particle accelerator produces a beam of high-velocity charged particles (electrons, protons, alpha, or "heavy ions"), which then strikes a target nucleus. 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. When a collision occurs between the incident particle and a target nucleus, either the beam particle scatters elastically leaving the target nucleus in its ground state or the target nucleus is internally excited and subsequently decays by emitting radiation or nucleons [2].

In order to understand the special place that iron holds in stellar evolution, it is important to consider the complete chain of events that lead up to the formation of iron nuclei. Iron plays a key role in the normal evolution of stars and is further produced in vast quantities in the subsequent explosive event at the end of the process of stellar evolution, which gives rise to the metals we see in the Universe today, including those found on earth. It is no exaggeration to say that the process of stellar evolution is arguably the most important chain of events in the Universe that we know of [3].

Elemental natural iron has four stable isotopes with following abundances: $^{54}Fe(5.8)$, $^{56}Fe(91.72)$,^{57} $Fe(2.2)$ and $^{58}Fe(0.28)$. Iron is used in many industrial application because of its ductility, strength, and relative abundance [4].

Alpha particles are natural product of many radioactive substances, and their properties had been under investigation for over a decade. It consists of two protons

and two neutrons; it therefore has charge $+2e$. It is the same as the nucleus of a helium atom, ${}_2^4He$. From the study of the properties of radiations emitted in the natural radioactivity, it is proved that alpha particle is doubly ionized helium atom, ${}_2^4He^{++}$. The energy of alpha particle obtained from natural radioactive nuclei distributes to all parts and discrete in nature and appreciably smaller than the coulomb barrier and they are not suitable to have nuclear reactions effectively. However, the alpha particles from the accelerator machine have continues and higher energy and they are frequently used for the study of the nuclear reaction mechanisms of different isotopes. Modern accelerators play an important role in nuclear reactions, for they produce radioactive isotopes that have various applications in applied fields of science as a residue of nuclear interaction between projectiles and targets.

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

$$Q = (M_X + M_a - M_Y - M_b)c^2 \tag{1.0.1}$$

Where,

M_X-is the mass of target nucleus

M_a-is the mass of the projectile

M_Y-is the mass of the residual nucleus and

M_b-is the mass of the emitted particle

1.1 Statement of the problem

To study the nuclear reaction cross section of alpha induced reactions on iron Fe-54 important for number of reasons . Nuclear reaction takes place when ever energetic particle fall up on bulk matter. In this study alpha induced reactions on iron Fe-54 $[(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p)]$ in different energy regions have been studied.

The main intent of the research is to calculate excitation function of alpha induced reaction on iron Fe-54 in different energy regions. it also needed to construct the research project to generate data for alpha induced reactions on iron Fe-54 and plot energy versus cross-section.

The research questions are:

• What are the nuclear data available for alpha induced reactions $[(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p)]$ on iron Fe-54 ?

• What are the theoretical value of the excitation function of alpha induced $[(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p)]$ on iron Fe-54 ?

• Is there good agreement between theoretical values and experimental values?

1.2 Objectives

1.2.1 General Objectives

The general objective of this work is:

• To calculate the nuclear reaction cross section of alpha induced reactions on iron Fe-54 $[(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p)]$ at different energy regions by using computer code COMPLET.

1.2.2 Specific Objectives

The specific objectives of the study are:

- To calculate reaction cross section of some alpha induced reactions on iron Fe-54.
- To analyze reaction cross section of some alpha induced reactions on iron Fe-54 and compare the result with experimental values.
- To compare calculated cross-section of alpha induced reactions $[(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p)]$on iron Fe-54 in different energy regions

1.3 Significance of the study

My study contributes to theoretical Calculation of alpha induced reactions $[(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p)]$ cross section on iron Fe-54 in different energy regions.

The study helps to develop the basic understanding of theoretical calculation of excitation function of alpha induced reaction on iron Fe-54. Alpha induced reaction on iron isotopes provide clues to understand the nuclear structure and offers a good testing ground for the ideas about nuclear force and used as a reference to gain deeper understanding of excitation function of alpha induced reaction on iron Fe-54 .

1.4 Limitation of the study

Due to time constraint, the scope of the study is limited to few channels of calculation cross section $[(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p)]$ of alpha induced nuclear reaction on iron Fe-54 .

Chapter 2

Literature Review

2.1 Nuclear reactions

The study of nuclear reactions is important for a number of reasons. Progress in the understanding of nuclear reactions has occurred at a faster pace and generally a higher level of sophistication has been achieved compared to similar studies of chemical reactions [2]. The approaches used to understand nuclear reactions are of value to any chemist who wishes a deeper insight into chemical reactions. There are certain nuclear reactions that play a preeminent role in the affairs of man and our understanding of the natural world in which we live. For example, Life on earth would not be possible without the energy provided to us by the sun. That energy is the energy released in the nuclear reactions that drive the sun and other stars [2]. For better or worse, the nuclear reactions, fission and fusion, are the basis for nuclear weapons, which have shaped much of the geopolitical dialog for the last 50 years. Apart from the intrinsically interesting nature of these dynamic processes, their practical importance would be enough to justify their study [2]. Nuclear reactions and nuclear scattering are used to measure the properties of nuclei. Reactions that exchange energy or nucleons can be used to measure the energies of binding and

excitation. To discuss nuclear reactions effectively we must understand the notation or jargon that is widely used to describe them. Let Us begin by considering the nuclear reaction a particle accelerator produces a beam of high-velocity charged particles (electrons, protons, alpha, or "heavy ions"), which then strikes a target nucleus [2]. Nuclear reactions can also be produced in nature by high-velocity particles from cosmic rays, for instance in the upper atmosphere or in space. Beams of neutrons can be obtained from nuclear reactors or as secondary products when a charged-particle beam knocks out weakly-bound neutrons from a target nucleus. Nuclear reactions can also be produced by beams of photons, and neutrinos. In order for a nuclear reaction to occur, the nucleons in the incident particle, or projectile, must interact with the nucleons in the target. Thus the energy must be high enough to overcome the natural electromagnetic repulsion between the protons. This energy "barrier" is called the Coulomb barrier [1, 5]. If the energy is below the barrier, the nuclei will bounce off each other. Early experiments by Rutherford used low-energy alpha particles from naturally radioactive material to bounce off target atoms and measure the size of the target nuclei. When a collision occurs between the incident particle and a target nucleus, either the beam particle scatters elastically leaving the target nucleus in its ground state or the target nucleus is internally excited and subsequently decays by emitting radiation or nucleons. In order to write an equation for a nuclear reaction, we must first establish some basic rules [2, 5]. Each of the elements involved in the reaction is identified by the chemical symbol and two numbers are attached to the symbol. One of them is the mass number. The mass number describes the atomic weight of the atom and identifies the number of protons and neutrons in the nucleus. The second number is the atomic number. The atomic number describes the number

of protons in the nucleus and determines the type of atom. If a target nucleus X is bombarded by a particle $'a'$ and results in a nucleus Y with emitted particle $'b'$, this is commonly written in one of two ways as.

$$a + X \rightarrow Y + b \quad or \quad X(a,b)Y \tag{2.1.1}$$

where, a-is a projectile (bombarding particle)(incident particle),

b-is an emitted particle (outgoing particle),

X-is target nucleus and

Y-is the residual nucleus (recoil nuclus) [2], [5].

2.2 Reaction Mechanisms

In nuclear reaction, there are three mechanisms of nuclear reaction [6]. These are direct reaction, compound nucleus reaction and pre-equilibrium reaction. The direct reaction takes place in the time the projectile takes to traverse the target nucleus ($\sim 10^{-22}s$). In this reaction, the projectile may interact with a nucleon, a group of nucleons or with the whole nucleus and emission takes place immediately [6].

The compound nucleus reaction takes place when the projectile is captured by the target nucleus. In this reaction, the energy and momentum of the projectile is shared and re-shared among the nucleons of the compound nucleus until it reaches a state of statistical equilibrium. This transfer of energy and momentum takes so much time ($\sim 10^{-15}s$) that the incoming projectile becomes part of the system because there is a thorough mixing of all the nucleons energy .

The pre-equilibrium reaction is a reaction mechanism where a particle is emitted neither immediately after the interaction of the projectile with a nucleon or with a group of nucleons of the target nucleus, as in a direct reaction, nor after a long time

by the statistical decay of the compound nucleus. The projectile may share its energy among a small number of nucleons which may further interact with other nucleons, and this cascade of nucleon-nucleon interactions through which the energy of the incident particle is progressively shared among the target nucleons, a particle may be emitted long before the attainment of statistical equilibrium.

All these reactions are subject to the conservation laws of energy, momentum, mass number, spin, total charge, parity, lepton number, baryon number, etc. The relative importance of these three reaction mechanisms depends on the type of interacting particles and their relative energy [6].

In these different types of reaction mechanisms, after the first interactions, the nucleon may leave the nucleus immediately by a direct reaction or it may interact with a nucleon in the nucleus and start a cascade of nucleon-nucleon interaction from which pre-equilibrium emission may occur. During this cascade, the energy is shared among an increasing number of nucleons until eventually the compound nucleus is formed. The compound nucleus may decay into the elastic or any of the reaction channels that are allowed energetically. The shape elastic and compound elastic processes combine to give the measured elastic scattering cross-section. In a similar way the direct, pre-equilibrium and compound nucleus processes combine to give the inelastic cross-sections and all the other non-elastic reactions. This shows the connection between the different reaction mechanisms.

2.2.1 Direct Reactions

A direct reaction [7] occurs when the projectile interacts primarily with the nucleons in the surface of the target nucleus. The interaction is with one or two nucleons. Energy and momentum transfer is very small and the transfer is to only few nucleons, and

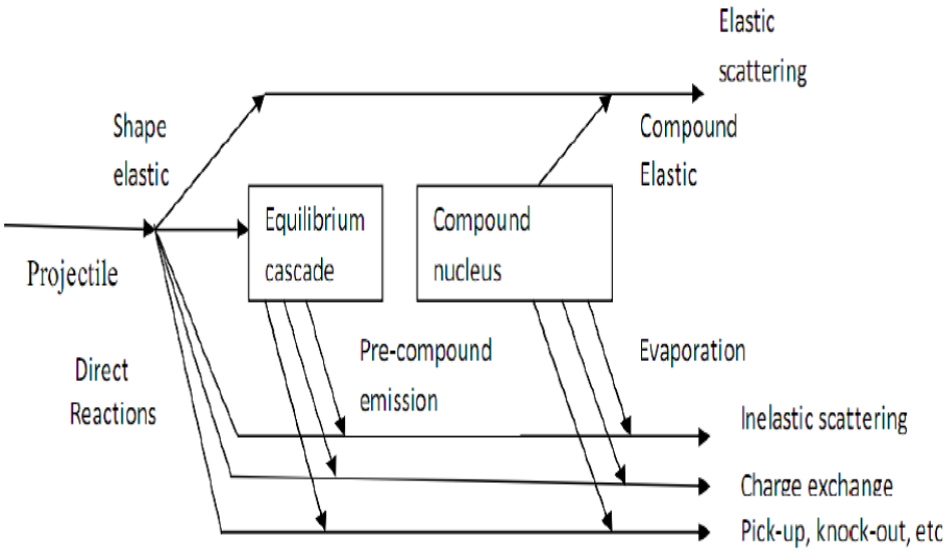

Figure 2.1: *Shows overview of reaction mechanisms [6]*

emission of the particle most probably is in the direction of motion of the projectile.

The main characteristics of direct reactions are: first the emission of much larger number of high energy particles than expected on the basis of evaporation model. Second, the angular distribution of emitted particles shows a forward peaking. This is may be because the direct reaction takes place with surface nucleons. The third main characteristic of direct reaction is a monotonic change of cross-section with energy, no resonances are observed. Direct reactions take place, generally, at higher energies.

There are a number of reactions categorized under the direct reaction. The simplest direct reaction is elastic scattering, which leaves the target nucleus in its ground state. Inelastic scattering occurs when a projectile interacts with a target nucleus and gives it some of its energy, raising it to an excited state. Measurement of the loss

of energy gives the energy of the excited state.

2.2.2 Compound Nucleus Reactions

A compound nucleus reaction is an extreme example of a multi step reaction in which the detailed complexity of the successive steps is lost [7]. In compound nucleus reaction a transfer of energy and momentum takes so much time that the compound nucleus formed forgets the history of formation. If the same compound nucleus is formed by different projectile interactions, it cannot remember the mechanism of its formation .

A compound nucleus state is excited, and gives resonances when the energy brought in by the projectile, plus the capture Q-value coincides with energy of one of its states. These states are excited one by one as the energy increases, and each corresponds to resonance [8].

It is difficult to give a rigorous description of the process of formation of the compound nucleus. It is a good approximation to assume that, in the sequence of nucleon-nucleon interactions, all the states corresponding to the various configurations are excited with equal probability. When eventually the long-lived compound nucleus is created, all the possible states corresponding to a given set of quantum numbers E, J, M, π, form the single-particle to the complex many-particle states, are equally likely. The compound nucleus is then in statistical equilibrium since the probability of occurrence of a given configuration is simply proportional to its statistical weight.

In compound nucleus reactions, after a time much longer than the time required by the projectile to cross the nucleus, a nucleon or a group of nucleons near the surface may, by statistical fluctuation, receive enough energy to escape, just as a molecule may evaporate from a heated drop of liquid. This statistical process favors

the evaporation of the particles with energy near the smallest possible energy, which in the case of charged particle is the height of the coulomb potential at the nuclear surface, the coulomb barrier. If the excitation energy of the compound nucleus is high enough, several particles may evaporated in sequence and the process continues until the energy of the nucleus is below the threshold for the particle emission, and then the nucleus emits -rays until it reaches the ground state. The decay of the compound nucleus is independent of the way it is formed.

2.2.3 Pre-equilibrium Reaction

Pre-equilibrium reaction is neither direct nor compound nucleus reaction. In this types of reactions particles are emitted after the first stage of a nuclear interaction (direct reaction) but long before the attainment of statistical equilibrium (compound nucleus formation). Their time scale is intermediate between the very fast direct reactions and the relatively slow compound nucleus formation [7].

In pre-equilibrium reactions, the emission of particles from the excited target nucleus is neither by statistical decay of compound nucleus nor by the prompt emission after collision. In these reactions, the projectile shares its energy among a small number of nucleons in the target; the struck nucleons initiate a cascade of reactions with the target, at the course of which a particle can be emitted before the compound nucleus was reached a state of statistical equilibrium.

The energy of the projectile is shared among the nucleons of the target by a cascade of nucleon-nucleon interactions that excites particle-hole state of increasing complexity. A pre-equilibrium reaction corresponds to emission of an unbound particle from one of these particle-hole states when the composite nucleus is not yet equilibrated.

Most pre-equilibrium reactions take place at energies high enough for it to be no longer possible to resolve the individual final state. The cross-sections are those of reactions to a continuum of final states, and the absence of fluctuations in these continuum spectra shows that to a high degree of accuracy one may assume that there are no interference effects so that pre-equilibrium cross-sections can be evaluated by adding incoherently the contributions from each stage of the nucleon-nucleon interaction cascade. The total cross-section for pre-equilibrium emission is then the sum of the cross-sections for emission from each stage of the cascade.

The pre-equilibrium models became rather popular tool to analyze and understand nuclear reactions at excitation energies ranging from several tens of MeV up to the GeV regions. There are different types of pre-compound nuclear reaction models. These are [9]- [12]

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

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

Intra-nuclear Cascade (INC) Model

The intra-nuclear cascade model (INC) was first proposed by Serber in 1947 [13]. He noticed that in particle-nuclear collisions the de-Broglie wavelength of the incident particle is comparable (or shorter) than the average intra-nucleon distance. Hence, a description of interactions in terms of particle-particle collisions is justified. The first calculations of pre-equilibrium angular distributions were performed with this

model using the quasi-free scattering inside the nucleus. The INC model traces the individual nucleon trajectories in three- dimensional geometry. The trajectory of an excited particle is followed until some arbitrary energy generally considerably above the average equilibrium value has been attained by the nucleon. Particles reaching the nuclear surface with sufficient energy to be emitted are assumed to be emitted.

When all particles of a given cascade have been traced, the total energy of the residual nucleus, its identity, and the energies and angles of the emitted particles are shared, and a new cascade with new impact parameter is calculated. With the help of such an approach , the time evolution of the reaction can be generated but after few collisions the actual calculation becomes too much complicated. The INC model is a realistic model but in general, the model predictions are not satisfactory at backward angles and in some forward angles also. The process classes use model classes to determine the secondaries produced in the interaction and to calculate the momenta of the particles. Here we present a collection of such models which describe a medium-energy intra-nuclear cascade. The basic steps of the INC model are summarized as follows:

• The space point at which the incident particle enters the nucleus is selected uniformly over the projected area of the nucleus,

•The total particle-particle cross sections and region-dependent nucleon densities are used to select a path length for the projectile

•The momentum of the struck nucleon, the type of reaction and the four-momenta of the reaction products are determined, and

•Exciton model updated as the cascade proceeds

•If the Pauli exclusion principle allows and $E_{particle} > E_{cutoff} = 2MeV$, step [9] is

performed to transport the products.

2.3 cross-section

cross-section is a measure of the relative probability for reaction to occur. Let the current of incident particles be I_a particles per unit time and let the target shows to the beam N target nuclei per unit area. If the out going particles appear at a rate R_b then the reaction cross-section is

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

For scattering reactions, the appropriate observable is the cross-section. In a typical scattering experiment, a beam of particles is allowed to hit a target and the rates of production of various particles in the final state are counted. It is clear that the rate will be proportional to: (a) the number N of particles in the target illuminated by the beam, and (b) the rate per unit area at which beam particles cross a small surface placed in the beam at rest with respect to the target and perpendicular to the beam direction. The latter is called the flux and is given by

$$J = n_b v_i \tag{2.3.2}$$

Where n_b is the number density of particles in the beam and v_i their velocity in the rest frame of the target. Hence the rate W_r at which a specific reaction r occurs in a particular experiment can be written in the form

$$W_r = JN\sigma_r \tag{2.3.3}$$

Where σ_r, is the constant of proportionality, is called the cross-section for reaction r.

if the beam has a cross-sectional area S, its intensity is $I = JS$ and so an alternative expression for the rate is

$$W_r = (N\sigma_r I)/S = I\sigma_r n_t t \tag{2.3.4}$$

Where n_t is the number of target particles per unit volume and t is the thickness of the target. It can be seen from the above equations that the cross-section has the dimensions of an area; the rate per target particle $J\sigma_r$ at which the reaction occurs is equal to the rate at which beam particles would hit a surface of area σ_r, placed in the beam at rest with respect to the target and perpendicular to the beam direction. The quantity σ_r is better named the partial cross-section, because it is the cross-section for a particular reaction r. The total cross-section σ is defined by

$$\sigma \equiv \sum_r \sigma_r \tag{2.3.5}$$

2.4 Differential cross-section

Another useful quantity is the differential cross-section, $d\sigma_r(\theta, \phi)/d\Omega$, which is defined by

$$dW_r = JN_r \frac{d\sigma_r(\theta, \phi)}{d\Omega} d\Omega \tag{2.4.1}$$

Where dW_r is the measured rate for the particles to be emitted in to an element of solid angle $dW = dcos\theta d\phi$ in the direction (θ, ϕ), as shown in the figure The total

cross-section is obtained by integrating the partial cross-section over all angle, i.e.

$$\sigma_r = \int_0^{2\pi} d\phi \int_{-1}^{1} dcos\theta \frac{d\sigma_r(\theta,\phi)}{d\Omega} \tag{2.4.2}$$

The final step is to write these formulae in terms of the scattering amplitude $|f(q^2)|$ appropriate fore describing the scattering of a non-relativistic spineless particle from a potential [14]. To do this it is convenient to consider a single beam particle interacting with a single target particle and to confine the whole system in an arbitrary volume V (which cancels in the final result). The incident flux is then given by

$$J = n_b v_i = \frac{v_i}{V} \tag{2.4.3}$$

And since the number of target particles is $N = 1$, the differential rate is

$$dW_r = \frac{v_i}{V} \frac{d\sigma_r(\theta,\phi)}{d\Omega} d\Omega \tag{2.4.4}$$

In quantum mechanics, provided the interaction is too strong, the transition rate for any process is given in perturbation theory by the born approximation

$$dW_r = \frac{2\pi}{\hbar} | \int d^3X \Psi_f^* V(X) \Psi_i |^2 \rho(E_f) \tag{2.4.5}$$

The term $\rho(E_f)$ is the density-of-states factor and we take the initial and final state wave functions to be plane waves:

$$\Psi_i = \frac{1}{\sqrt{V}} exp[iq_i.\frac{X}{\hbar}], \Psi_f = \frac{1}{\sqrt{V}} exp[iq_f.\frac{X}{\hbar}] \tag{2.4.6}$$

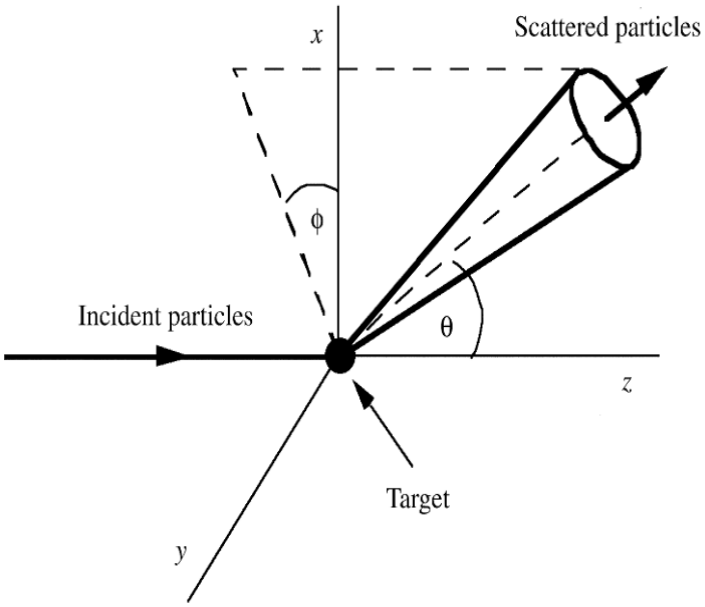

Figure 2.2: *Geometry of the differential cross-section [14]*

Where the final momentum q_f lies within a small solid angle $d\Omega$ located in the direction (θ, ϕ). Then by direct integration

$$dW_r = \frac{2\pi}{\hbar V^2}|f(q)^2|^2\rho(E_f) \tag{2.4.7}$$

Where $f(q^2)$ is the scattering amplitude defined by equation

$$f(q^2) = \int d^3X V(X) exp[iq_i.\frac{X}{\hbar}] \tag{2.4.8}$$

i.e the Fourier transform of the potential, where $q = q_i - q_f$ is the moment transfer. The integration may be done using polar co-ordinate. Taking q in the x-direction gives

$$q.X = |q|rcos\theta \tag{2.4.9}$$

and

$$d^3X = r^2 sin\theta d\theta dr d\phi \tag{2.4.10}$$

Where $r = |X|$. For the Yukawa potential the integral in equ. $f(q^2) = \int d^3X V(X)$ $exp[iq_i.\frac{X}{\hbar}]$ gives

$$f(q^2) = \frac{-g^2\hbar^2}{q^2 + M_X^2c^2} \tag{2.4.11}$$

The density of states $\rho(E_f)$that appears in equ.$dW_r = \frac{2\pi}{\hbar}|\int d^3X\Psi_f^* V(X)\Psi_i|^2\rho(E_f)$ is the number of possible final states with energy lying between E_f and $E_f + dE_f$ and is given by

$$\rho(E_f) = \frac{V}{2\pi\hbar^3}\frac{q_f^2}{V_f}d\Omega \tag{2.4.12}$$

If we use this and equ. $dW_r = \frac{2\pi}{\hbar V^2}|f(q)^2|^2\rho(E_f)$ in equ.$dW_r = \frac{v_i}{V}\frac{d\sigma_r(\theta,\phi)}{d\Omega}d\Omega$ we have

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi^2\hbar^4}\frac{q_f^2}{v_i V_f}|f(q)^2|^2 \tag{2.4.13}$$

Although this result has been derived in the laboratory system, because we have taken a massive target it is also valid in the Centre-of-mass system [14].

2.5 Classical estimation of cross-sections

In this the total cross-section is separated in to two parts: an elastic scattering cross-section and a non-elastic or reaction cross-section. Thus, $\sigma_t = \sigma_s c + \sigma_r$. Further consider that a nuclear reaction leading to σ_r can only take place if the colliding nuclei come within range of nuclear force, which is short ranged. If the distance between their centers $r \leq R$, a nuclear reaction can take place and if $r > R$, no reaction occur [15]. The interaction radius depends on the interacting nuclei and can be represented as a sum $R_1 + R_2$ of effective radii of the two nuclei. The interaction radius and the effective radii are related to the geometric sizes of the nuclei, but do not have definite values of the range of the nuclear force because the distribution of

nuclear matter in a nucleus has a diffuse surface so that an estimate of R can be made from experimental measurement.

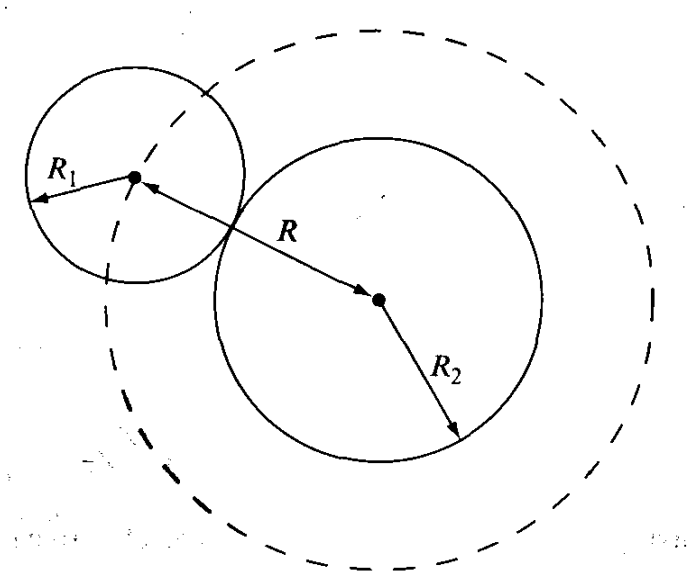

Figure 2.3: *Diagram showing two nuclei with effective interaction radii R_1 and R_2. [15]*

For uncharged particles, the geometric cross-section for the nuclei to collide is $\sigma = \pi R^2$, given by cross-sectional area determined by the interaction radius [15]. However, in general, the colliding nuclei will be charged and the collision cross-section will be modified because the nuclei experience an energy barrier due to the repulsive Coulomb force acting between them. The collision cross-section is given by πb^2, where b is the impact parameter for a distance of closest approach equal to R. Assuming the nuclei have sharp edges, the Coulomb energy at the distance of closest approach is given by the familiar formula

$$B = Z_1 Z_2 e^2/(4\pi\varepsilon_o)R \tag{2.5.1}$$

Where Z_1 and Z_2 are the atomic numbers of the two nuclei. The value of impact parameter b is obtained by applying conservation laws [14]. At the distance of closest approach, the initial kinetic energy E appears partly as reduced kinetic energy E' and partly as Coulomb potential energy B. Hence,

$$E = E' + B \tag{2.5.2}$$

Applying conservation of angular momentum gives

$$L = pb = p'R \tag{2.5.3}$$

Where p and p' are the projectile momenta initially and at the distance of closest approach, respectively. We know that $E'/E = (p'/p)^2 = (b/R)^2$, from which it follows that

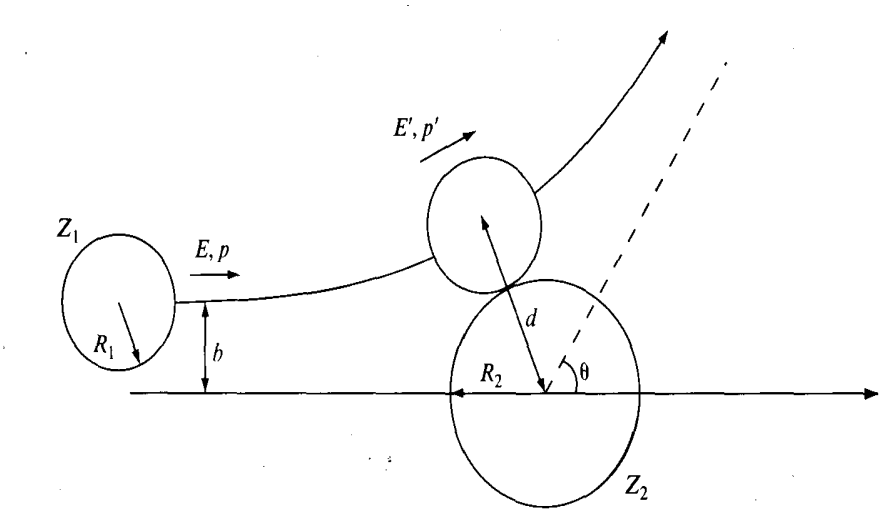

Figure 2.4: *Classical grazing trajectory of a charged particle [15]*

$$\sigma = \pi R^2 \frac{E\prime}{E} = \pi R^2 (1 - \frac{B}{E}) for E \geq B \tag{2.5.4}$$

For the general situation, which takes target recoil in to account, E is replased by the centre-of-mass energy $E_{cm} = EM/(M + m)$, where E is the energy of projectile (mass m) in the laboratory system and M is the mass of the target, initially at rest. Note that we obtain the value [15]

of πR^2 for uncharged particles when $B = 0$. Also equation $\sigma = \pi R^2 \frac{E\prime}{E} = \pi R^2(1 - \frac{B}{E}) for E \geq B$. Approaches this limit at high energy when the effect of the Coulomb force is small. The cross-section $\sigma = \pi b^2$ can be written in terms of the wave number $k(= p/\hbar)$ of the projectile and the angular momentum quantum number l as

$$\sigma = \pi(L/p)^2 = \frac{\pi\ell(\ell + 1)\hbar^2}{(\hbar k)^2} \approx \frac{\pi\ell^2}{k^2} \tag{2.5.5}$$

Where we assumed that $\ell \gg 1$ in the classical limit we are considering here. It must be remembered that these equations represent an upper limit to the total reaction cross-section, since it is assumed that there is a 100 chance of reaction occurring if $r \leq R$.

According to equation $\sigma = \pi R^2 \frac{E\prime}{E} = \pi R^2(1 - \frac{B}{E}) for E \geq B$, the cross-section falls to zero when $E = B$ and it remains there at lower energies because the nuclei are always out of contact with each other, even in a head-on collision . In reality, however, the cross-section remains finite when $E < B$ because, even though classically the particles remain energetically out of range, there is a probability of the Coulomb barrier being penetrated and a reaction taking place. It is an example of the effects of the wave nature of matter, which we explore a little further below [15].

2.6 Quantum mechanical considerations of cross-sections

Classical formulae are generally only useful when the de Broglie wave length λ is small compared with the nuclear size (or interaction radius). When λ is comparable with or greater than R, quantum effects become important; a proper trajectory cannot be defined and the simple relationship between the geometric cross section, impact parameter and angular momentum break down [15].

The interaction region by approaching projectile is divided into a set of ring-shaped zones concentric with the head-on collision point. The zones are labeled by the orbital angular momentum quantum number ℓ. The inner most ($\ell = 0$) zone correspond to particles with impact parameters less than the reduced wavelength $\bar{\lambda}$ of the beam particles, the next includes impact parameters between $\bar{\lambda}$ and $2\bar{\lambda}$ and so on. Impact parameters for the ℓ^{th} zone range from $\ell\bar{\lambda}$ to $(\ell+1)\bar{\lambda}$ and correspond, classically, to particles with momentum p having angular momenta between $p\ell\bar{\lambda}$, i. e. between $p\ell\bar{\lambda}$ and $p(\ell+1)\bar{\lambda}$. In quantum mechanics, only integral value of ℓ are allowed and, although the concept of impact parameter is imprecise, we interpret this picture to say that particles with angular momentum ℓ correspond to the ℓth zone. In this way, a plane wave, representing a parallel beam, can be split in to a set of partial waves, or ℓ waves, each associated with a particular zone and partial- wave cross-section σ_ℓ.. The cross-sectional area of the ℓ^{th} zone is

$$\sigma_\ell = (2\ell+1)\pi\bar{\lambda}^2 \tag{2.6.1}$$

It represents an upper limit to the total reaction cross section since no more particles can be removed than are contained within the zone. Hence, the reaction

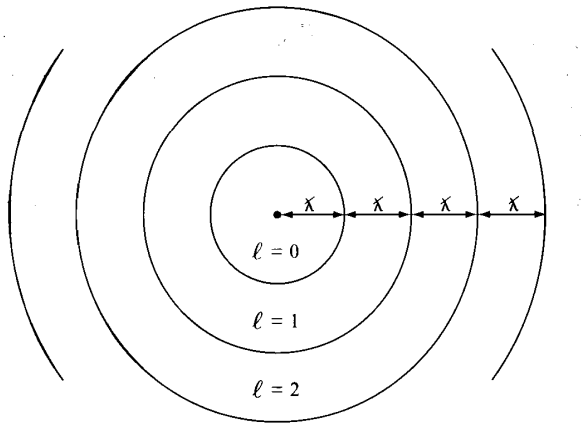

Figure 2.5: *: Angular momentum zones for an incident beam directed perpendicular to the plane of the figure. Particles with a given angular momentum quantum number l, relative to the center, are mainly confined to the ring-shaped zone corresponding to that value of l.*

cross section for the ℓth partial wave is [15]

$$\sigma_{r,\ell} \leq (2\ell + 1)\pi\bar{\lambda}^2 \tag{2.6.2}$$

It does not apply to the elastic scattering cross section.

2.7 General s-wave ($\ell = 0$) elastic scattering and absorption

Fluxes: The $\ell = 0$ part of the plane wave

$$\phi(r) = e^{ikz} \tag{2.7.1}$$

Is the sum of spherical incoming and outgoing s-waves:

$$\phi_o(r) = \frac{sinkr}{kr} = (-e^{-ikr} + e^{ikr})\frac{1}{2ikr} \tag{2.7.2}$$

The effect of a scattering centre only changes the outgoing part ($\propto e^{ikr}$). This still propagates as a free wave when $r > R$, but its amplitude and phase may be altered by the interaction. Thus, the modified s-wave can be written:

$$\psi_o(r) = \frac{1}{2ikr}(-e^{-ikr} + \eta e^{ikr}) = \phi_o(r) + \frac{(\eta - 1)e^{ikr}}{2ikr} \tag{2.7.3}$$

Where we have written $\psi_o(r)$ as the sum of the incident wave and a scattered wave:

$$\psi_{sc}(r) = \frac{(\eta - 1)}{2ikr}e^{ikr} \tag{2.7.4}$$

The integrated outgoing s-wave flux, R_{out}, is equal to the rate at which s-wave particles pass outwardly through a sphere (of radius $r \geq R$), i.e.

$$R_{out} = |\frac{\eta e^{ikr}}{2ikr}|^2 4\pi r^2 v = \frac{|\eta|^2 \pi v}{k^2} \tag{2.7.5}$$

Similarly, we can write the integrated incoming s-wave flux as

$$R_{in} = \frac{\pi v}{k^2} \tag{2.7.6}$$

And the integrated flux of scattered s-wave particles as

$$R_{sc} = \frac{|\eta - 1|^2 \pi v}{k^2} \tag{2.7.7}$$

If we have only elastic scattering and no reaction (i.e. no loss of elastic flux), $R_{out} = R_{in}$ and $|\eta| = 1$. The incoming and outcoming amplitudes have the same magnitude and differ only in phase. If other reactions occur (which include inelastic scattering), then the outgoing integrated flux is deplated: $R_{out} < R_{in}$ and $|\eta| < 1$ [15].

2.7.1 Matching the wave function at the nuclear surface

So far, we have considered the behaviour of the waves in the out side region ($r \geq R$). Solving the schrodinger equation for a force field gives the wave function everywhere. However, in the inside region ($r < R$), the particles no longer propagate as free waves. At the surface ($r = R$), the interior and exterior wave function, $\psi_i(r)$ and $\psi_0(r)$, must join smoothly, which means that the wave function and its derivation must be continuous at $r = R$. It is simpler algebraically to consider $u(r) = r\psi(r)$ and apply the condition that u and du/dr are continuous at the boundary, i.e.

$$f \equiv R[\frac{du_o(r)/dr}{u_o(r)}]_{r=R} = R[\frac{du_i(r)/dr}{u_i(r)}[_{r=R} \tag{2.7.8}$$

We can evaluate f from $u_o(r)$, which we know from equ. $\psi_0(r) = \frac{1}{2ikr}(-e^{-ikr}+\eta e^{ikr}) = \phi_0(r) + \frac{(\eta-1)e^{ikr}}{2ikr}$. Also, we know some thing about η from observed cross sections. Therefore, equ. $f \equiv R[\frac{du_o(r)/dr}{u_o(r)}]_{r=R} = R[\frac{du_i(r)/dr}{u_i(r)}[_{r=R}$ tells us some thing about the wave function inside the nucleus and, in this way, we see that outside measurement provide information about the interior region. Using the expression for $u_o(r)$, we obtain

$$f \equiv R[\frac{du_o(r)/dr}{u_o(r)}]_{r=R} = ikR(\frac{\eta e^{ikR} + e^{-ikR}}{\eta e^{ikR} - e^{-ikR}}) \tag{2.7.9}$$

And solving this for η in terms of f gives

$$\eta = \frac{f + ikR}{f - ikR} exp(-2ikR) \tag{2.7.10}$$

Which by substitution in to Equ. $\sigma_{sc,0} = \frac{R_{sc}}{F_{inc}} = \frac{\pi|\eta-1|^2}{k^2} = \pi\bar{\lambda}^2(1 - |\eta|^2)$ and $\sigma_{r,0} = \frac{R_{in}-R_{out}}{F_{inc}} = \pi\bar{\lambda}^2(1-|\eta|^2)$ Gives expressions for the scattering and reaction cross sections in terms of f. Equ. $f \equiv R[\frac{du_o(r)/dr}{u_o(r)}]_{r=R} = ikR(\frac{\eta e^{ikR}+e^{-ikR}}{\eta e^{ikR}-e^{-ikR}})$ and $\eta = \frac{f+ikR}{f-ikR}exp(-2ikR)$ are general A particular nuclear model allows 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. An example of such a model is the optical model for calculating the elastic scattering and total reaction cross sections [15]. Another simple model is the compound-nucleus model, which assumes that particles reaching the inside region fuse with the target nucleus and do not reappear. We can drive a useful general result by using this model. Again, we shall consider the case of low-energy (s-wave) scattering of neutrons [15].

2.8 Scattering via a compound nucleus

In this treatment we make use of the approximation that the nuclear potential energy experienced by an incoming particle can be represented by a mean field due to the attractive force of the nucleons in the target nucleus. For a neutron, this potential is the same as the shell-model potential and has a depth V of about $50MeV$. We further assume that the nucleus has a well-defined surface and represent the edge of the nucleus by a potential step of height V at the interaction radius R. Part of the incident wave will be reflected at the discontinuity and part will be transmitted. The transmitted wave represents particles entering the nucleus, and the compound-nucleus hypothesis is that these particles rapidly exchange energy by colliding with nucleons in the target and are lost from the entrance (elastic) channel. Thus, inside the nucleus, the wave function is an ingoing wave only and we have

$$u_i(r) \propto e^{ikr}, (r \leq R) \tag{2.8.1}$$

Where k is the wave number of the neutron inside the nucleus. A low-energy neutron will gain about $50MeV$ of kinetic energy after it crosses the surface, leading to a value

of k of about $1.6fm^{-1}$ [15]. Using the above expression for $u_i(r)$, we obtain from equ. $f = R[\frac{du_o(r)/dr}{u_o(r)}]_{r=R} = R[\frac{du_i(r)/dr}{u_i(r)}]_{r=R}$ gives:

$$f = -ikR \tag{2.8.2}$$

Substituting this in to equ. $\eta = (\frac{f+ikR}{f-ikR})exp{-2ikR}$ gives

$$\eta = (\frac{K-k}{K+k})exp^{-2ikR} \tag{2.8.3}$$

Hence, from equation $\sigma_{r,o} = \frac{R_{in}-R_{out}}{R_{inc}} = \pi\bar{\lambda}^2(1-|\eta|^2)$, we have

$$\sigma_{r,o} = \pi\bar{\lambda}^2\frac{4Kk}{(K+k)^2} \tag{2.8.4}$$

Now $k \propto \sqrt{E}$ and $K \propto \sqrt{E+V}$, where V is the nuclear potential energy (approximately $50MeV$ inside the nucleus) and E is the incoming nutron energy. Therefore, if $E \ll V$, as it will be for very slow nutrons, $k \ll K$ and K will vary little with E. Then since $\lambda/2\pi = 1/k$, we obtain directly

$$\sigma_{r,o} \approx 4\pi/kK \propto 1/v \tag{2.8.5}$$

This is the $'1/v'$ law.

Chapter 3

Materials and Methodology

3.1 Materials

The study is aimed at theoretical study and numerical analysis of Calculation of alpha induced reactions $[(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p)]$ cross section on iron Fe-54 in different energy regions.

To carry out this research work the following materials and softwares have been used.

- Computer
- Flash disc
- CD
- A nuclear reaction code COMPLET
- Stationary materials
- Printer
- journals and other sources of information.

3.2 Methodology

3.2.1 Analytical Method

Output data has been analyzed in sight of best available experimental data sources in existing libraries. 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.

3.3 Computational Method

The nuclear reaction cross-section data and projectile energy has been taken from EXFOR experimental data then by using FORTRAN-77 based computer code COMPLET data was generated.

3.4 Analysis with Computer code COMPLET

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

The code COMPLET [16] is a nuclear reactions code which was designed for versatility and ease of use in the bombarding energy range of few Mev to several hundred MeV. The code COMPLET is based on same philosophy as the former code INDEX. It applies the statistical model of compound nucleus decay developed by

WeisskopfEwing and the hybrid and geometric dependent hybrid model of Blann and the further simplification and improvement by Ernst [17]. 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.

The COMPLET code, originally, has been developed out of the code overlaid Alice by M.Blann. In this code, while some standard routines remained particularly unchanged (like FISROT, LYMASS, 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 COMPLET code includes damping of fission widths above a critical temperature, rotating liquid drop fission barriers and rotational energies due to Seirk included for $jcal = 0$. Still M and S or Exp. Masses are used as before.

Chapter 4

Result and Discussion

The excitation functions of alpha induced reactions on iron ^{54}Fe in different energy regions have been calculated using nuclear reaction code COMPLET.

The numerical values of the earlier report were taken from the original works, from the IAEA EXFOR database. During the data compiling theoretically data was saved in a computer. After completion of compiling the theoretical cross section data, for each of the three- α-induced reaction $^{54}_{26}Fe(\alpha,n)^{57}_{28}Ni$, $^{54}_{26}Fe(\alpha,2n)^{56}_{28}Ni$, and $^{54}_{26}Fe(\alpha,p)^{57}_{27}Co$ explained above, the data was presented in tables and graphs as shown below.

4.1 Reaction cross-section of $^{54}_{26}Fe(\alpha,n)^{57}_{28}Ni$.

In this reaction α projectile of energy range 7.3 MeV to 35.1 MeV have been used. Theoretically calculated cross-section data for $^{54}_{26}Fe(\alpha,n)^{57}_{28}Ni$ were displayed in table 4.1 together with experimentally given data in EXFOR per each energy.

The graph of energy versus cross-section (σ) is being plotted. The measured values are consistent with the given energy ranges.

The theoretically calculated values of nuclear reactions cross-section for excitation

Table 4.1: The table shows excitation function of ${}^{54}_{26}Fe(\alpha, n)^{57}_{28}Ni$

$Energy(MeV)$	7.3	10.2	12.5	14.6	16.4	23.2	25.8	28.1	30.7	32.9	35.1
$Exp.\sigma_t(mb)$	36	75	104	127	135	66	34	17.6	10.8	8.3	6.6
$Theo.\sigma_t(mb)$	22.9	78.3	116	137	140.4	67.32	36.15	18.14	11.43	10.69	8.26

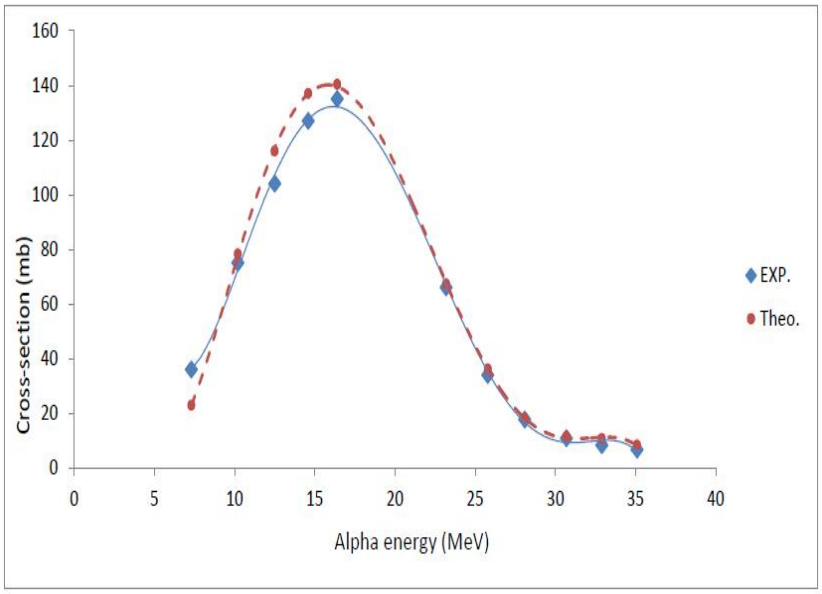

Figure 4.1: *Graph shows the excitation function of* ${}^{54}_{26}Fe(\alpha, n)^{57}_{28}Ni$

function of the reactions ${}^{54}_{26}Fe(\alpha, n)^{57}_{28}Ni$ starts from the energy of projectile at about minimum energy of 7.3 MeV with cross section of 22.9 mb and reaches its maximum peak at about 16.4 MeV with 140.4 mb and starts to fall down for increasing value of energy of projectile. Similarly the Experimental value indicates that the excitation function starts at about minimum energy 7.3 MeV with cross section of 36 mb and reaches its maximum peak at about 16.4 MeV with cross section of 135 mb.

It observed that a good agreement between the theoretical calculated value and experimental value in a given range of energy.

4.2 Reaction cross-section of $^{54}_{26}Fe(\alpha, 2n)^{56}_{28}Ni$

In this reaction α-projectile of energy range 17.3 MeV to 45.8 MeV have been used. Theoretically calculated cross-section data for $^{54}_{26}Fe(\alpha, 2n)^{56}_{28}Ni$ were displayed in table 4.2 together with experimentally given data in EXFOR per each energy. The graph of energy versus cross-section (σ) is being plotted.

Table 4.2: The table shows excitation function of $^{54}_{26}Fe(\alpha, 2n)^{56}_{28}Ni$

$Energy(MeV)$	17.3	21.8	25	27.5	29.9	32.3	34.5	37.5	41.4	45	45.8
$Exp.\sigma_t(mb)$	1.5	4	5.6	6.3	7.5	8.1	7.8	6.8	4	2.9	3.1
$Theo.\sigma_t(mb)$	1.8	4.2	6.238	7.36	7.83	8.191	7.89	6.952	4.807	2.812	3

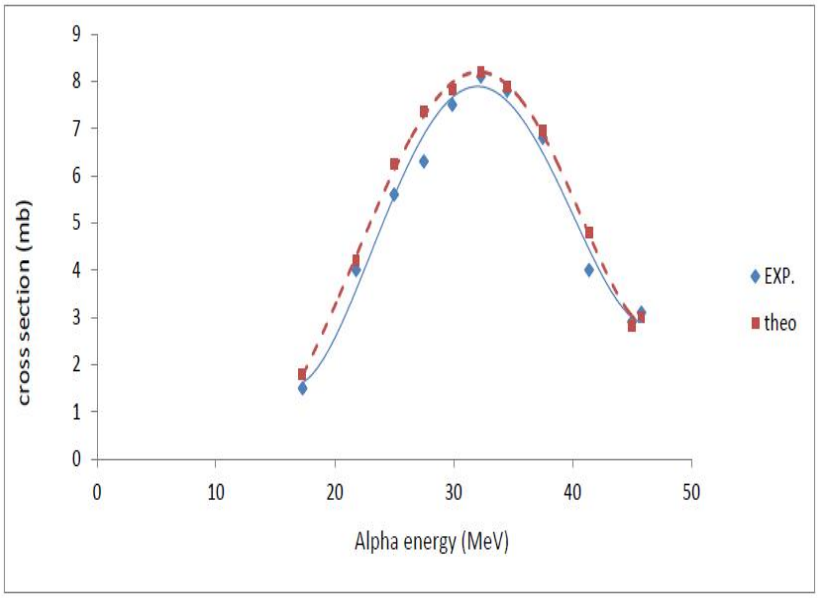

Figure 4.2: *Graph shows the excitation function of* $^{54}_{26}Fe(\alpha, 2n)^{56}_{28}Ni$

The theoretically calculated values of nuclear reactions cross-section for excitation functions of the reaction $^{54}_{26}Fe(\alpha, 2n)^{56}_{28}Ni$ starts from the energy of projectile at about

minimum energy of 17.3 MeV with cross section of 1.8 mb and reaches its maximum peak at about 32.3 MeV with 8.191 mb and starts to fall down for increasing value of energy of projectile up to 45.8 MeV with cross section of 3 mb. Similarly the Experimental value indicates that the excitation function starts at about minimum energy 17.3 MeV with cross section of 1.5 mb and reaches its maximum peak at about 32.3 MeV with cross section of 8.1 mb. It observed that a good agreement between the theoretical calculated value and experimental value in a given range of energy.

4.3 Reaction cross-section of ${}^{54}_{26}Fe(\alpha,p){}^{57}_{27}Co$

In this reaction α-projectile of energy range 7.3 MeV to 35.1 MeV have been used. Theoretically calculated cross-section data for ${}^{54}_{26}Fe(\alpha,p){}^{57}_{27}Co$ were displayed in table 4.3 together with experimentally given data in EXFOR per each energy. The graph of energy versus cross-section (σ) is being plotted.

Table 4.3: The table shows excitation function of ${}^{54}_{26}Fe(\alpha,p){}^{57}_{27}Co$

$Energy(MeV)$	7.3	10.2	12.5	16.4	18.2	20.1	23.2	25.8	28.1	30.7	32.9	35.1
$Exp.\sigma_t(mb)$	140	300	399	466	427	341	284	160	88	59	48	44
$Theo.\sigma_t(mb)$	102.89	293.7	381.6	443.9	425.2	329.1	211.7	151	91.7	60.74	55.08	49.78

The theoretically calculated values of nuclear reactions cross-section for excitation functions of the reaction ${}^{54}_{26}Fe(\alpha,p){}^{57}_{27}Co$ starts from the energy of projectile at about minimum energy of 7.3 MeV with cross section of 102.89 mb and reaches its maximum peak at about 16.4 MeV with cross section of 443.9 mb and starts to fall down for increasing value of energy of projectile up to 35.1 MeV with cross section of 49.78 mb. Similarly the Experimental value indicates that the excitation function starts at about minimum energy 7.3 MeV with cross section of 140 mb and reaches its

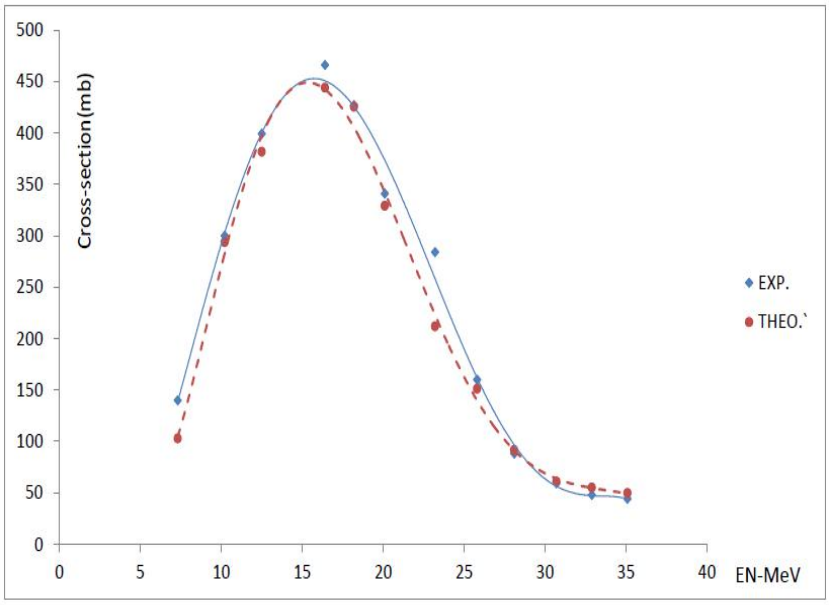

Figure 4.3: *Graph shows the excitation function of* ${}^{54}_{26}Fe(\alpha,p){}^{57}_{27}Co$

maximum peak at about 16.4 MeV with cross section of 466 mb and starts to fall down for increasing value of energy of projectile up to 35.1 MeV with cross section of 44 mb. It observed that a good agreement between the theoretical calculated value and experimental value in a given range of energy.

Chapter 5

Conclusion

In this study calculation of excitation function of alpha induced reactions ${}^{54}_{26}Fe(\alpha, n){}^{57}_{28}Ni$, ${}^{54}_{26}Fe(\alpha, 2n){}^{56}_{28}Ni$, and ${}^{54}_{26}Fe(\alpha, p){}^{57}_{27}Co$ on iron have been carried out. the theoretical calculation were done using code COMPLET and compared with experimental value taken from EXFOR data base. It observed that a good agreement between the theoretical calculated value and experimental value in a given range of energy. alpha-induced reaction cross-sections provide clues to understand the nuclear structure and offers a good testing ground for ideas about nuclear forces. In this study, alpha-induced reactions on iron ${}^{54}Fe$ in different energy regions have been calculated as part of a systematic investigation of excitation functions. The cross-sections were calculated for the production of ${}^{56,57}Ni$ and ${}^{57}Co$ in ${}^{54}Fe(\alpha, Xn)$ where $X = 1, 2$ and ${}^{54}Fe(\alpha, P)$ respectively.

Experimental data are not available for ${}^{54}Fe(\alpha, 3n){}^{55}Ni$. Studies of excitation functions of charged particle-induced reactions like protons and α-particles are of considerable significance for testing nuclear models as well as for practical applications.

Bibliography

[1] J. J. Griffin:*phys. Rev. Lett.*, **27** (1966), 478.

[2] Walter E.Meyerhof, *Elements of nuclear physics.*, McGraw-Hill,Inc. 1986.

[3] *WorldAutoSteel*, (2012).

[4] F.Tarkanyi et al.*Activation cross section of alpha inducednuclear reaction on iron up to* $40MeV$*. Nuclear Instruments andMethods in Physics Research B*, **207** (2003), 381-394.

[5] David Halliday *Introductory Nuclear Physics*, Modern Asianedition.Tokyo 1958.

[6] ,A.F. Wudu *Notes on Subharmonic FunctionsMaster thesis,Addis Ababa University, Addis Ababa, Ethiopia*,2013.

[7] P.E.Hodgson, E.Gadioli and E.GadioliErba *Introductory NuclearPhysics*,Oxford University Press,2003

[8] Unnati, M.K.Sharma, B.P.Singh, S.Gupta, H.D.Bhardwaj, A.K.Sinha,*International Journal of Modern Physics E*, 2005.

[9] P.E.Hodgson *G. Physics; Nuclear reaction structure*,Clarendonpress Oxford 1971

[10] ,K. Chen. G. Friedlander, G. D. Harp and J. M. Miller:*phys.Rev.*,**166** (1966), 949

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

[12] .J. J. Grin: *phys.Rev. Lett.* ,**27**(1966)478.

[13] R. Server: *phys. Rev.* **72**(1947)1114.

[14] B.R. Martin, *Nuclear and particle physics*, John Wiley and Sons,Ltd. England(2006)

[15] John Lilley *Nuclear physics principles andapplications.*Baffins Lane, Chichester, West Sussex PO19IUD.England2001

[16] J.Ernst, *Institute for Solid State and Nuclear Physics, TheComplet Code library: Complet.for*; **445**, Germany,1997

[17] K.F.Amanuel, *PHD thesis, Addis Ababa University,* AddisAbaba,Ethiopia, 2011.

APPENDIX A

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 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 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 piinduced 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-directsemi- direct capture gamma ray estimate :0: no emission0: 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[**?**]. The mean free path multiplier for intra nuclear transition rates are calculated from optical potential parameters.

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

Name of Student: **Amare Gebrewold** ID No. SMSc01916/05

Graduate Program: **Summer, MSc.**

1. Course Work Performance

Course Code	Course Title	Cr. hr	Number Grade	Rank **	Remark
Phys699	**MSc. Thesis**	**6**	**75.45**	**Very Good**	

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

Thesis Title

Calculation of alpha induced reactions [(a,n),(a,2n),(a,3n),(a,p)] cross section on iron Fe-54 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	Mr. Chali Yadeta	_____	_____
External Examiner	Prof. A.K Chaubey	_____	_____
Internal Examiner	Dr. Memberu Mengesha	_____	_____
Major Advisor	Dr. Teklemariam Tessema	_____	_____

_____ _____ _____

Department head 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 **Amare Gebrewold** have read and evaluated his/her thesis entitled "**Calculation of alpha induced reactions [(a,n),(a,2n),(a,3n),(a,p)] cross section on iron Fe-54 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: Amare Gebrewold

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