EXCITATION FUNCTION OF ALPHA INDUCED REACTIONS $\{(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p), (\alpha, 2p)\}$ ON COPPER (^{65}Cu) IN INTERMEDIATE ENERGY RANGE FROM 16 MeV TO 35 MeV

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

By Tolina Guta

JIMMA UNIVERSITY
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DEPARTMENT OF
PHYSICS

This is to certify that the thesis prepared by **Tolina Guta** Graduate Studies entitled "**EXCITATION FUNCTION OF ALPHA INDUCED REACTIONS** $\{(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p), (\alpha, 2p)\}$ **ON COPPER** (^{65}Cu) **IN INTERMEDIATE ENERGY RANGE FROM 16 MeV TO 35 MeV** " 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: September 2017

Supervisor: ____________________
Dr.Teklemariam Tessema

Readers: ____________________
Mr. Chali Yadeta

____

JIMMA UNIVERSITY

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Author: **Tolina Guta**

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Abstract

In this work, alpha (^4He) induced reactions on copper nucleus ($^{65}_{29}Cu$) in between the energy range 16 MeV up to 35 MeV were studied. The nuclear reaction cross sections for five reactions namely, $^{65}Cu(\alpha, n)^{68}Ga$, $^{65}Cu(\alpha, 2n)^{67}Ga$, $^{65}Cu(\alpha, 3n)^{66}Ga$, $^{65}Cu(\alpha, p)^{68}Zn$ and $^{65}Cu(\alpha, 2p)^{67}Cu$ were calculated theoretically. For the sake of comparison, the results of experimental cross sections were extracted from the EXFOR library. The main intent of the research was to fill the gap between the experimental and the theoretical excitation functions of nuclear reaction by generating data using computational CODE COMPLET. To this end, the excitation functions of the reactions were depicted for the energy ranges similar to that of the experimental results.

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Chapter 1

INTRODUCTION

1.1 Background of the Study

Nowadays, the study of nuclear reaction has trapped the interest of scientists and researchers for many reasons. Starting from cosmological studies to microscopic study of nature, the application of nuclear physics is of great importance. The eager of human being to live in new world and know the deep space, celestial bodies like stars, planets, asteroids, the sun and so forth has become increasingly enforcing them to tilt their attention towards the study of nuclear reaction. The medical laboratory treatments of tumors, nuclear weapons, nuclear power plant are a few of pivotal issues of the present time activities that use the applications nuclear reaction. For instance, the use of permanent radioactive seed implants for the treatment of early prostate cancer has gained renewed interest with the introduction of ^{125}I and ^{103}Pd seeds, which emit low energy (30 keV) photons [1].

Copper is a reddish-brown metallic element with high electrical and thermal conductivity with chemical symbol Cu and atomic number 29. It has two most abundant isotopes, ^{63}Cu and ^{65}Cu covering 69.17 % and 30.83 % percent respectively [2]. Both isotopes of copper, ^{63}Cu and ^{65}Cu, are used to study copper metabolism and gastrointestinal diseases in medical science and for production of other elements. Specifically, ^{65}Cu was used to manufacture semi-conductors such as gallium (Ga), zinc (Zn)-from which semi-conductor zinc oxide (ZnO) can be produced [3].

Nuclear reaction mechanisms can be seen based on the time taken for intra-nuclear collisions of nucleons before the statistical equilibrium is reached. These are direct reaction, compound reaction, and pre-equilibrium reaction. Direct nuclear reaction takes place within a short time of interaction to the order of $\sim 10^{-22}$ seconds [2]. The other reaction mechanism, compound nuclear reaction, is the interaction process that occurs within ten thousand times the time taken by direct reaction (i.e. $\sim 10^{-18}$ seconds) [4]. Pre-equilibrium reaction takes place in between the two extremes providing a sizeable part of the reaction cross section for incident energies between 10 - 200 MeV. Based on the projectile induced reaction in projectile energy per nucleon, nuclear reaction can be categorized as low energy ($= 10\ MeV/nucleon$), high energy ($= 400\ MeV/nucleon$), and perhaps not surprisingly the reactions induced by 20 - 250 MeV/nucleon projectiles are called intermediate energy reactions [5].

In this thesis, alpha particle is used as a projectile for the production of the intended residual nuclei. Alpha particle is a heavy charged particle containing two protons and two neutrons and is usually expressed as a helium nucleus. Most of heavy nuclei are unstable. Therefore, they undergo nuclear reaction called radioactivity. Radioactive nuclei emit alpha particles spontaneously when they decay in the form of alpha decay in order to reach a more stable state [6]. For example,

$$^{235}U \longrightarrow ^{231}Th + ^{4}He \tag{1.1.1}$$

The area of the target nucleus hit by the beam of particles at right angle, which is called nuclear cross section, is the most probable area to continue reaction with the nucleus. In this thesis, we focus attention to the calculation of reaction cross-section induced by alpha particle. The energy of alpha particles depends on half-life of the emission process [7]. To get alpha particle beam of energy range between 16 - 35 MeV, usually particle accelerators such as cyclotron, Van de Graaff accelerator, the Cockcroft-Walton machine, the electrostatic generator, the synchrotron etc. are used [6] in doing an experiment [8].

The motivation for this thesis stems firstly from theoretical study of the production of ^{68}Ga, ^{67}Ga, ^{66}Ga, ^{68}Zn and ^{67}Cu. In the second phase, to compare the theoretically calculated data with the experimentally obtained results and finally to study the reaction mechanism involved in the production of ^{68}Ga, ^{67}Ga, ^{66}Ga, ^{68}Zn and ^{67}Cu isotopes. In the case of this work, A FORTRAN 77 based computer code, COMPLET, was used to simulate virtual beam of alpha particle energy ranging between 16 - 35 MeV focussed onto a target copper (^{65}Cu).

1.2 Statement of the Problem

The stability of a given nucleus can be affected by the ratio of protons and neutrons embodied in the nucleus; that is to say it will emit the extra nucleon to be set to stable state. If alpha particle is induced into the copper nucleus particularly ^{65}Cu, the compound nucleus contain 31 protons and 38 neutrons and will be highly excited. Afterwards, the compound nucleus will emit some nucleons.

References have shown that the measurement of excitation function of ^{65}Cu bombarded by alpha particle in intermediate energy range 15 - 42 MeV were used to produce a set of outgoing particles n, 2n, 3n, nt, 4nA, 3nt, nA, n2A, 3n2A separately [3]. The residual nuclei of these results were $^{66,67,68}Ga,^{65}Zn,^{61}Cu,^{63}Zn,^{64}Cu,^{60}Co$ and ^{58}Co respectively. JANIS Book of alpha-induced cross-sections compares evaluated cross-sections below 200 MeV with corresponding experimental data from the EXFOR database for a number of evaluated libraries [9] focusing on the production of $^{66,67,68}Ga$ and $^{64,67}Cu$.

Being thankful to their work, in this work, it was needed to work theoretically on the production of $^{66,67,68}Ga$, ^{67}Cu and ^{68}Zn by changing the energy range of alpha-induced reaction on copper(^{65}Cu) from 16 - 35 MeV to compare the excitation function of the reactions with the experimental data from the EXFOR database with the corresponding energy range. With this regard, reactions {(α, n), (α, 2n), (α, 3n), (α, p), (α, 2p)} were studied and the cross sections for each reaction were calculated with the respective incident alpha energy range reacting with ^{65}Cu.

Generally, the thesis has necessitated to fill the gap between theoretical calculation and experimental calculation in the intermediate energy range.

1.3 Objectives of the Study

1.3.1 General Objectives

The general objective of this study is:

To calculate the excitation function for alpha induced reaction on copper (^{65}Cu) in intermediate incident energy between 16 to 35MeV for the reactions {(α, n), (α, 2n), (α, 3n), (α, p), (α, 2p)}.

1.3.2 Specific Objectives

The specific objectives were:

- To generate reaction cross section data for alpha induced reaction on copper (^{65}Cu) in intermediate incident energy between 16 - 35 MeV specifically for reactions {(α, n), (α, 2n), (α, 3n), (α, p), (α, 2p)}, by using FORTRAN 77 based computer code.

- To compare the excitation functions of the generated data with the experimental result obtained from the EXFOR data center in order to reproduce the experimental cross section.

1.4 Significance of the Study

This study was believed to help develop the basic understanding of theoretical calculation of equilibrium reaction cross section for alpha induced reaction on copper (^{65}Cu) for the intermediate energy region. The reaction helps as the mechanism for the production of $^{66,67,68}Ga$, ^{67}Cu and ^{68}Zn. The product of Zn, zinc oxide, is a semiconductor material. Growth of large area and high-quality ZnO crystals is important not just for basic investigations but also for many device applications. For instance, high-quality large ZnO single crystals would be beneficial for the UV and blue-UV light-emitting devices [10]. Gallium radioisotopes ($^{66,67,68}Ga$) are applicable for a positron emission tomography (PET) imaging. For instance, the gallium isotope ^{67}Ga has higher affinity for lactoferrin and easily attaches to siderophores of bacteria. That is why the nuclear physicians use it for leukopenic (i.e. disease caused due to low count of white blood cell) patients to detect sterile abscesses [1]. Another advantage of this research work is to theoretically verify experimental cross sections of some alpha induced reactions on copper (^{65}Cu).

1.5 Limitations of the Study

Because of the limitations in the time, we focussed only on cross-section calculation of alpha induced reactions. Due to lack of nuclear laboratory, we conducted the research only theoretically.

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Chapter 2

LITERATURE REVIEW

2.1 Nuclear Reaction

If two nuclei collide one other, then they will react. The reaction takes place either when the two nuclei are in motion or one of them is at rest and the other is in motion [5]. In the case where one of them is at rest, the nucleus projected towards the stationary nucleus is called projectile and the stationary nucleus is known as target nucleus. Now, lets focus our attention on the reaction in which the target nucleus is at rest and the projectile is in motion. Nuclear reaction might be categorized as compound reaction and direct reaction depending upon the time of interaction of projectile and target nucleus after collision [4].

2.1.1 Direct Nuclear Reaction

This occurs when two nuclei strike each other and separate at a glance, which is very short time of contact to the order of $\sim 10^{-22}$ sec [8]. During collision, the projectile may lose some of its energy or have one or more nucleons transferred from or to it [6]. Direct reaction takes place when the projectile reacts with the nucleus at the impact parameter comparable to the nuclear radius. Impact parameter is the distance between the original direction of the projectile and the nuclear diameter that is parallel to the beam direction. The projectile only interacts with only surface nucleons. The reaction can be summarized as

$P + T \rightarrow X + R$

Where P = projectile

T = target

X = ejected particle

R = residual nucleus

2.1.2 Pre-compound Reaction

This is an intermediate level of the reaction that takes the time in between the direct reaction and the compound reaction [6]. The particles have neither enough time to stay in the nucleus until the nucleons equally share the projectile's energy nor enough energy equal to that of the direct reaction to leave the nucleus. In this type of reaction, the ejecting particles leave the nucleus before the compound nucleus is formed. This is analogous to the evaporation of liquid molecules before the boiling point of the liquid [8]. If it is electrolyzed, then water molecules evaporate immediately- direct reaction. But if you heat it, then it will take some time to evaporate until the heat energy transmits throughout the water volume-compound reaction. Before reaching 100°C , some fast molecules evaporate off the outer surface [2]. Likewise,in pre-equilibrium or pre-compound nuclear reaction, before the nucleons of the target share the projectile's energy equally, some fast nuclear particles may be ejected. Equilibrium reaction or compound reaction is the statistical equilibrium in which the reaction is equally likely to proceed [11].

2.1.3 Compound Nuclear (CN) Reaction

Nuclei can also combine to form highly excited Compound Nucleus (C*) that lives for relatively long time sufficient for excitation energy to be shared by all nucleons. The compound nuclear reaction takes place at the end of very large number of internal collisions and therefore takes longer time comparatively than time taken by direct reaction [6]. If sufficient energy localized on one or more nucleons they can escape and CN decays.

In compound reaction, there is highly excited compound nucleus, C*.

$$P + T \rightarrow C^* \rightarrow X + R \tag{2.1.1}$$

The short hand notation of the above equation might be given as:

T(P,X)R

The compound nucleus may release an outgoing particle similar to the incident particle with the same center of mass energy. This type of compound nuclear decay is known as compound elastic scattering. Possibly, the outgoing particle differs from the incident particle in that it only delays slightly.

2.1.4 Disintegration Reaction

After the reaction of projectile and target nucleus, if prompt particles or projectile plus gamma will be emitted, then the reaction is called disintegration reaction [8].

In this type of reaction, the outgoing particle is different or more in number than projectile. Reactions of the following form are disintegration reaction.

$$
\begin{aligned}
x + X &\rightarrow Y + y \\
&\rightarrow Z + z \\
&\rightarrow W + 2x
\end{aligned}
$$

where the x is projectile and X is target while Y, Z, and W are residual nuclei and y, z, and $2x$ are the outgoing particles.

2.1.5 Nuclear Reaction Model

There were different types of model to describe nuclear reaction until the end of 1950s [6]. According to liquid drop model (Bohr 1936), nucleons in the nucleus quickly share the energy brought by projectile very fast so that a compound nucleus formation happens in any reaction. But Feshback in 1954 based on the shell model proposed that an incident particle would interact with the nucleus via shell model potential and that the probability of absorption into a compound nucleus would be relatively small [8].

Though they are contradicting models, both of them had also the same point of agreement. After its formation, the compound nucleus forgets its history of occurrence and the decay of the compound nucleus does not depend on how it was formed.

In the modern theory, a single theory mediating the two theories was given by Weiskopf in 1958 [7]. According to Weiskopf, any nuclear reaction proceeds through a series of stages indicated as in Figure 2.1

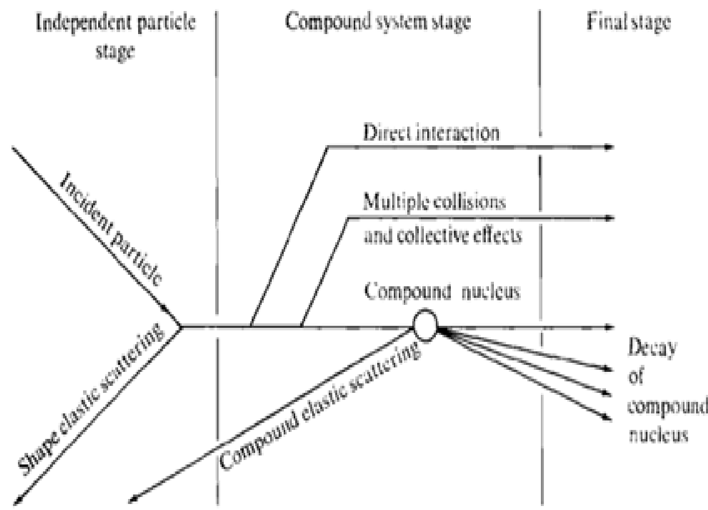

Figure 2.1: *Sequence of stages in a nuclear reaction according to Weiskopf [7]*

When the incident particles of alpha beam reach near the nuclear potential, some of them reflect off without interacting. This is shown by the shape elastic scattering. Moreover, particles in this case can excite the nucleus through the electric field pulse created at a nucleus when they pass close by without penetrating deep into the nuclear radius. This is known as Coulomb excitation [7].

If the nucleus interacts only with the surface nucleons and the nucleon leaves the nucleus, the direct reaction will be proceeded. Contrary to this, the ejection of nucleons might delay until all the nucleons share the projectile energy equally and lead the target to be excited at higher energy. It then will decay to its ground state by either gamma radiation or ejection of other nuclear particles. Such a nuclear reaction is called compound nuclear reaction. The compound nucleus is formed in such a complicated set of interaction that probably forgets its initial mode of formation [11]. This is to mean that its decay does not depend on how it was formed.

2.2 Energetics of Nuclear Reactions

Consider the reaction in the above notation, T(P, X)R, the values of the masses after may differ from the ground state masses [5]. The difference in the masses is known the mass deficit. Using the deficit and kinetic energies before and after collision, we can calculate the Q value of the reaction, which in turn can take part in letting the reaction go. In order to start the reaction, the particle projected- the projectile, which in our case is positively charged particle- α particle, must have enough energy to overcome the attractive force from the cloud of electrons around the nucleus and the repulsive force from the protons confined in the nucleus. The Einstein's special law of relativity states that a particle moving with the speed nearest to the speed of light has energy equal to, $E = mc^2$ where m is mass of the particle and c is the speed of light [11].

$$\sum T_i + \sum m_i c^2 = \sum T_f + \sum m_f c^2$$

[5]

Experimentally, the initial and final amount of mass differ. The law of conservation of mass or energy is best defined as the law of mass-energy conservation. It tells us that the amount of mass difference before the reaction and after the reaction must be equal to the amount mass converted into energy. In this case, we assume that the final sum of mass is less than the initial one. The binding energy, that is, the energy required to hold the nucleus together, which is known as the Q value of the reaction, is the difference in mass-energies of the reactants and the products [11] and is given as:

$$Q = (\sum m_i - \sum m_f)c^2 = \sum T_f - \sum T_i \tag{2.2.1}$$

Keeping the target nucleus at rest, one can calculate Q value by measuring the mass deficit or the kinetic energies. Thus, the Q value will be:

Q=$(m_T + m_P - (m_X + m_R))c^2 = T_X + T_R - T_P$

In order to start up the reaction, the sum of the Q value and the kinetic energy of the projectile must be greater than or equal to zero. Mathematically, [11]

$$Q + T_P \geq 0$$

Moreover, the kinetic energy of the projectile is not fully dissipated in the reaction. Instead, the kinetic energy of the center of mass, T_{cm}, must be carried away by the center of mass. Thus, the available energy transferred to other type of energy is:

$$T_P - T_{CM}{=}T_0$$

But T_{CM} can be calculated as,

$$M_{CM} = M_P + M_T$$

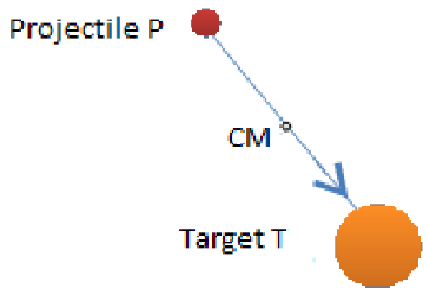

Figure 2.2: *The schematic diagram illustrating the relative motion of projectile with respect to the stationary target*

$$T_{CM} = \tfrac{1}{2} M_{CM} V_{CM}^2$$
$$V_{CM} = V_P \tfrac{M_P}{M_P + M_T}$$

$$T_{cm} = T_P \frac{M_T}{M_P + M_T} \qquad (2.2.2)$$

Purely to start up the reaction [5],

$$Q + T_{cm} \geq 0 \qquad (2.2.3)$$

By substituting for T_0, we can obtain the energy by which the projectile must be launched to break the potential barrier and get into the nucleus and proceed the reaction.

$$\Rightarrow T_P \geq -Q((M_P + M_T)/M_T) \qquad (2.2.4)$$

This is the minimum kinetic energy that the projectile must have to make the reaction go. It is called the threshold energy for the reaction.

Now, let's consider a beam of projectile nuclei of intensity I_0 particles/sec is incident up on a thin foil of target nuclei with the result that the beam is attenuated by reactions in the foil such that the transmitted intensity is I particles/sec.

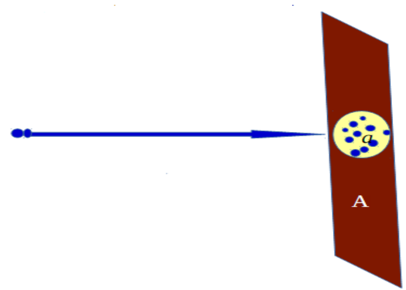

Figure 2.3: *The diagram showing a beam of particles attenuated by reaction of thin foil*

The fraction of area, A, covered by the beam is given by a/A. If the foil contains N (atoms/cm^2), then the area, a, blocked by the beam of projectile nuclei, is given by

$N(atoms/cm^2)A(cm^2)(the\ effective\ area\ subtended\ by\ one\ atom)\ (cm^2/atom)$.

2.3 Conservation Laws in Nuclear Reactions

The concept of mass deficit implies that there exists mass difference between initial and final product. From the mass-energy conversion in the reaction, the mass deficit is the amount of mass converted into energy [6]. The nucleon number before the reaction is the same as that after the reaction until the reaction energies are high enough to create nucleon antinucleon pairs [8]. This entails that the number of charge before the reaction balances the number of charge after the reaction as particles carry elementary charges [12]. The discovery of Stern and Gerlach in 1922 revealed that the angular momentum comprises spin angular momentum [13]. Therefore, the total angular momentum, $\mathbf{J}$ is the vector sum of spin angular momentum, $\boldsymbol{S}$ and orbital angular momentum, $\boldsymbol{l}$. The law of conservation of angular momentum states that the total angular momentum is conserved. The law of conservation of linear momentum also states that the vector sum of linear momenta before the reaction is the same as the vector sum of the linear momenta after the reaction. In the reaction and then, the symmetry of the reference frame and the system cannot alter- parity conservation cannot be violated [2].

2.4 The Decay Width (Γ)

The decay law of Rutherford and Soddy states that the disintegration of radioactive nuclei in small time interval, dt is proportional to the number of radioactive nuclei at time t [6].

$$\tfrac{dN}{dt} \propto N$$

If we introduce a constant into this relation, it simplifies to the following equation.

$$\frac{dN}{dt} = -\lambda N \qquad (2.4.1)$$

where the negative sign indicates the decrease in the number of the radioactive nuclei. The constant, λ, is known as the decay constant measured in per second. It is related to the mean lifetime of the nucleus by the equation,

$$\tau = \frac{1}{\lambda} \tag{2.4.2}$$

The uncertainty in the energy is given as $\Delta E \Delta t \geq \frac{\hbar}{2}$ [14] with the extremely short lifetime, Δt. When observables are made of the rest mass energy of unstable particle with the most precise instruments, the graph of outgoing particle yield versus the energy is given as Breit - Wigner line shape [2].

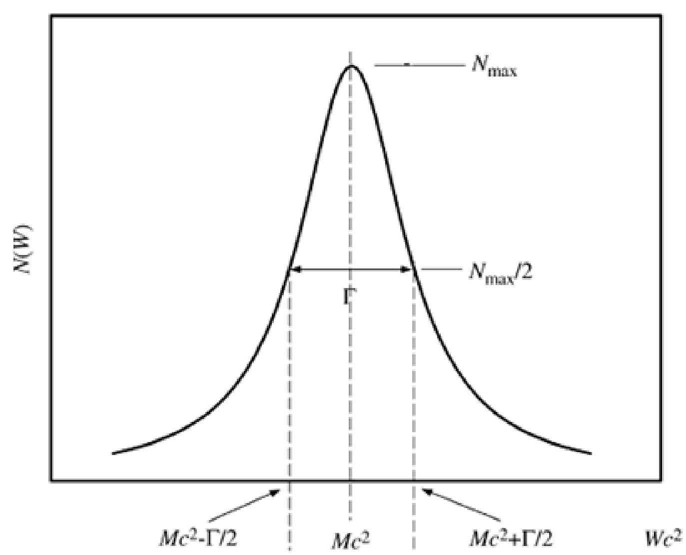

Figure 2.4: *Diagram showing the Breit Wigner formula [2] given by equation (2.4.4)*

The width of such energy distribution is known as the decay width, Γ, and is related the uncertainty in energy and thereby to the decay constant λ by the equation

$$\Gamma = 2\Delta E = \frac{\hbar}{\tau} \tag{2.4.3}$$

The energy distribution of an unstable state i to a final state f has the BreitWigner form

$$N_f(W) \propto \frac{\Gamma_f}{(W-M)^2C^4 + \frac{\Gamma^2}{4}} \tag{2.4.4}$$

where M is the mass of the decaying state and W is the invariant mass of the decay products. This proportionality is inserted to describe (Figure 2.4) leading to the equation (2.4.5) in the vicinity of a resonance of mass M, and width Γ , the cross-section (more in section 2.5.5) for the reaction $i \rightarrow f$ is given by [2]

$$\sigma_{if} = \frac{\pi\hbar^2}{{q_i}^2} \frac{2j+1}{(2s_1+1)(2s_2+1)} \frac{\Gamma_i\Gamma_f}{(E-MC^2)^2 + \frac{\Gamma^2}{4}} \tag{2.4.5}$$

where E is the total energy of the system, q_i is the initial momentum and if the resonance particle has spin j and the spins of the initial particles are s_1 and s_2 respectively.

2.5 Nuclear Reaction Cross Section

For the reaction under study, the effective area subtended by an atom is what we call the reaction cross section [5] (see Figure 2.3). Nuclear cross section is the number of reactions per target nucleus per unit time when the target is hit by a unit flux of projectile particles, which is by one particle per unit target area per unit time. Before all, now lets see the earliest Rutherford's strive to calculate cross section.

2.5.1 Rutherford Cross Section

In 1911 Ernest Rutherford with his two students bombarded a nucleus by alpha particle.

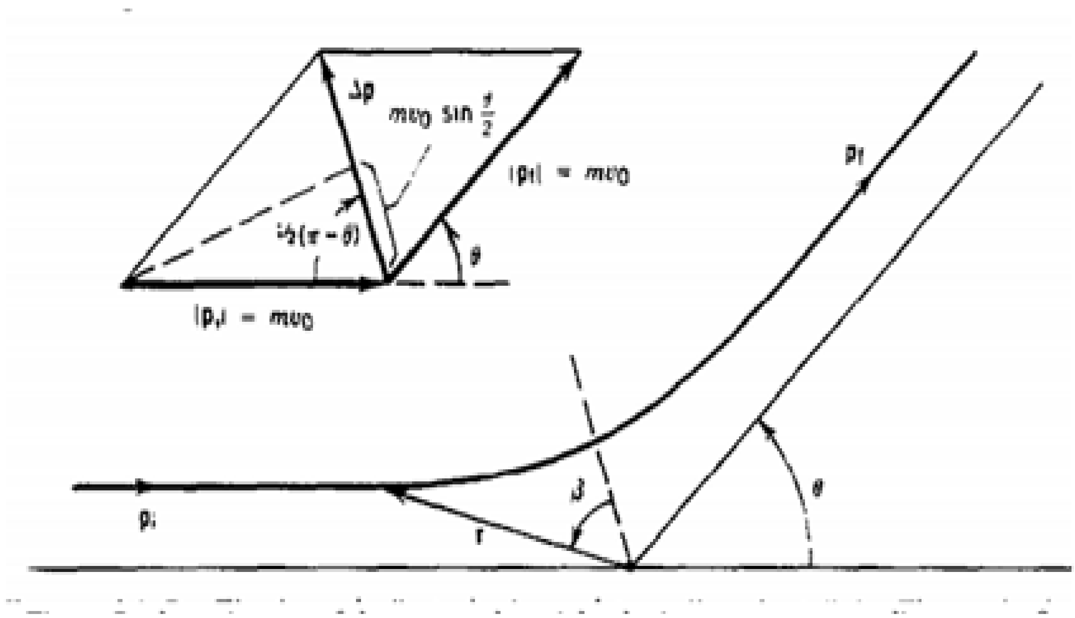

Figure 2.5: *The trajectory of the scattered particle, the instantaneous coordinate are r, the change in momentum is in the direction of dashed line that bisects the trajectory [8]*

Geiger and Marsden verified the aspects of the Rutherford formula, the dependence on z^2, T_a^{-2} and $sin^{-4}(\frac{\theta}{2})$. The Rutherford formula [8] is known as the Rutherford cross section.

$$\frac{d\sigma}{d\Omega} = (\frac{zZe^2}{4\pi\epsilon_0})^2(\frac{1}{4T_a})^2\frac{1}{sin^4(\frac{\theta}{2})} \tag{2.5.1}$$

where T_a is the kinetic energy of the incident particle, z is the number of nucleons in the incident particle, Z is the atomic number of the target nucleus and e is the elementary charge.

2.5.2 Total Cross Section

In a typical experiment, a beam of particles is allowed to hit a target and the rate of production of various particles is counted. The rate will be proportional to:

(a) The number N of particles in the target nucleus illuminated by the beam.

(b) The rate per unit area at which beam particles cross a small surface placed in the beam with respect to the target and perpendicular to the beam direction. The latter is called the flux and is given by:

$$J = n_b v_i \tag{2.5.2}$$

where n_b is the number density of particle beam v_i is their velocity in the rest frame of the target.

The rate at which a specific reaction r occurs is

$$W_r = JN\sigma_r \tag{2.5.3}$$

where σ_r is constant of proportionality is called the reaction cross section of 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=$N\sigma_r I/S$

$$W_r = I\sigma_r n_t t \tag{2.5.4}$$

where n_t is the number of target particles per unit volume and t = the thickness target. If the target has an isotopic mass M_A and density ρ, then

$$n_t = \rho N_A / M_A \tag{2.5.5}$$

Substituting (2.5.5) in (2.5.4), the rate of reaction r will be

$$W_r = I\sigma_r(\rho t) N_A / M_A \tag{2.5.6}$$

In equation (2.5.3) the product term, JN is the quantity known as luminosity, L given by $L = JN$. It contains all the dependencies on the densities and geometries of the beam and the target. The cross section does not depend on these factors [2]. 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 total cross section

$$\sigma = \sum_r \sigma_r \tag{2.5.7}$$

where the σ_r is the partial cross section for reaction r.

2.5.3 Differential Cross Section

Now let's turn our attention on the other important quantity of nuclear reaction known as the differential cross section (see Figure 2.6). Assume the detector is placed at angle (θ, ϕ) with respect to the original direction of the beam. The detector does not observe all the outgoing particles. Therefore, it defines a small solid angle $d\Omega$ off the target nucleus for which a partial reaction cross section $d\sigma_r(\theta, \phi)$ can be described.

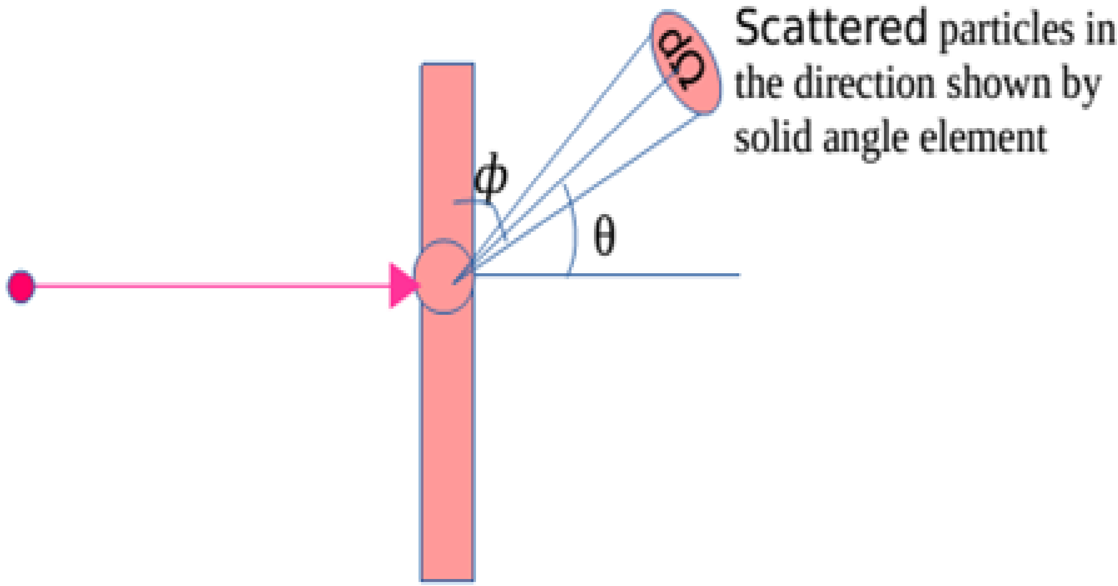

Figure 2.6: *The schematic diagram showing the bombardment of copper nucleus by alpha incident, and outgoing beam into solid angle at* $d\Omega$

The differential cross-section, $d\sigma_r(\theta, \phi)/d\Omega$ is defined by

$$dW_r = JN\frac{d\sigma_r(\theta, \phi)}{d\Omega}d\Omega \tag{2.5.8}$$

where dW_r is the measured rate for the particles to be emitted into an element of solid angle $d\Omega = d(\cos\theta)d\phi$ in the direction (θ, ϕ). The total cross-section is obtained by integrating the partial cross-section over all angles, i.e.

$$\sigma_r = \int_0^{2\pi} d\phi \int_{-1}^{1} d(\cos\theta)\frac{d\sigma_r(\theta, \phi)}{d\Omega} \tag{2.5.9}$$

Now, let's write these formulae in terms of the scattering amplitude $f(\mathbf{q}^2)$ appropriate for describing the scattering of a non-relativistic spin-less particle from a potential.

Consider a single beam interacting with a single target particle and to confine the whole system in an arbitrary volume V. The incident flux is

$J = n_b v_i$

$$dW_r = \frac{v_i}{V}\frac{d}{d\Omega}\sigma_r(\theta,\phi)d\Omega \tag{2.5.10}$$

In quantum mechanics, provided that the interaction is not too strong,the transition rate for any process is given in perturbation theory by the Born approximation

$$dW_r = \frac{2\pi}{\hbar}|\int d^3\vec{x}\psi_f^* V(\vec{x})\psi_i|^2\rho(E_f) \tag{2.5.11}$$

where $\rho(E_f)$ is the density of states factor. Taking the initial and final state wave functions to be plane wave, ψ_i and ψ_f we can solve for the differential wave.

$\psi_i = \frac{1}{\sqrt{V}}e^{(i\mathbf{q}_i\cdot\frac{\mathbf{x}}{\hbar})}$, $\psi_f = \frac{1}{\sqrt{V}}e^{(i\vec{q}_f\cdot\frac{\vec{x}}{\hbar})}$ where the final momentum $\mathbf{q}_f$ lies within a small solid angle $d\Omega$ located in the direction (θ,ϕ). Then by disintegration,

$$dW_r = \frac{2\pi}{\hbar V^2}|f(\mathbf{q}^2)|^2\rho(E_f) \tag{2.5.12}$$

where $f(\mathbf{q}^2)$ is the scattering amplitude.

The density of state is the number of possible final states with energy lying between E_f and $E_f + dE_f$ is given by [11].

$$\rho(E_f) = \frac{V}{(2\pi\hbar)^3}\frac{q_f^2}{v_f}d\Omega \tag{2.5.13}$$

where $q_f = |\mathbf{q}|$. Putting (2.5.13) in (2.5.12) and comparing with equation (2.5.10),

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi^2\hbar^4}\frac{q_f^2}{v_i v_f}|f(\mathbf{q}^2)|^2 \tag{2.5.14}$$

When we discuss a specific reaction, the exact meaning of the term cross section will depend on the exactly what we measure. For example, in the reaction X(x, γ)Y, if we observe the excitation energy of Y by subsequent energy of γ emission, the differential cross section [2] will be

$$\frac{d\sigma}{d\Omega}$$

2.5.4 Semi-classical Cross Section

The treatment of Rutherford cross section has been based on the classical concept, no quantum effects are included. The Rutherford cross section does not have effect for the impact parameter less than the nuclear radius. Therefore, it fails at that point to account for the cross section. Rutherford cross section, because it depends on coulomb interaction only, fails to account for nuclear cross section [2].

Let the direction of incident particle be in the z direction. Assuming that it can be represented by a plane wave, the corresponding momentum $\mathbf{p} = \hbar\mathbf{k}$. The outgoing particles will be represented by spherical waves and so the manipulations become easier if we express the incident plane wave as a superposition of spherical waves.

ψ_{inci}=Ae^{ikz}

$$\psi_{inci} = A\sum_{l=0}^{\infty} i^l(2l+1)j_l(kr)P_l Cos\theta \tag{2.5.15}$$

where approximately chosen normalization constant, $j_l(kr)$ is the spherical Bessel functions which are solutions of the radial part of Schrodinger equation $j_l(kr)$=$(\frac{-r}{k})$ $(\frac{1}{r}\frac{d}{dr})$ $j_0(kr)$ for $j_0(kr)$ in a region far from the target where the nuclear potential vanishes, and the term $P_l(cos\theta)$ is the Legendre polynomial [8].

This expansion of the incident wave is called partial wave corresponding to the specific angular momentum $\boldsymbol{l}$. Such procedure is valid if the nuclear potential is assumed to be central. If the particles of momentum of magnitude p interact with impact parameter, b, then the semi-classical relative angular momentum will be:

$l\hbar{=}pb$

$b = l\frac{\hbar}{p}{=}l\frac{\lambda}{2\pi}{=}l\bar{\lambda}$

where $\bar{\lambda} = \frac{\lambda}{2\pi}$ is reduced de Broglei wavelength.

$\bar{\lambda}{=}\ k^{-1}$ In quantum mechanics, for $l = 0$, $l = 1$, the interaction through the impact parameter between 0 or and thus effectively over a cross section of at most $\pi\bar{\lambda}^2$. With $\hbar \leq l \leq \hbar$, the cross section is a ring of inner $\bar{\lambda}$ radius and outer radius $2\bar{\lambda}$ and thus area is $3\pi\bar{\lambda}^2$. If we divide the interaction area into a number of zones, each corresponding a specific angular momentum l and area A,

$A_{\texttt{total}} = \pi\bar{\lambda}^2(l+1)^2 - \pi(l\bar{\lambda})^2$

$$A_{\texttt{total}} = (2l+1)\pi\bar{\lambda}^2 \tag{2.5.16}$$

For the radii of projectile and the target, we can estimate the maximum impact parameter will be $R = R_1 + R_2$ where R_1 and R_2 are the radii of the projectile and target respectively.

$l_{\texttt{max}} = R/\bar{\lambda}$ and correspondingly.

$\sigma_{\texttt{total}} = \sum_{l=0}^{R/\bar{\lambda}} (2l+1)\pi\bar{\lambda}^2$

$$\sigma_{\texttt{total}} = \pi(R+\bar{\lambda})^2 \tag{2.5.17}$$

where $(R+\bar{\lambda})$ is the effective interaction radius. When the wave is far from the nucleus, $j_l(kr)$ expands conveniently as

$$j_l(kr) = \frac{sin(kr-\frac{1}{2}l\pi)}{kr}, \text{ for } kr \gg l$$
$$j_l(kr) = i\frac{e^{-i(kr-\frac{\pi l}{2})}-e^{i(kr-\frac{l\pi}{2})}}{2kr}$$

Equation (2.5.15) will be

$$\psi_{inci} = \frac{A}{2kr}\sum_{l=0}^{\infty}(2l+1)[e^{-i(kr-\frac{\pi l}{2})} - e^{i(kr-\frac{l\pi}{2})}]P_l(cos\theta) \tag{2.5.18}$$

$(2l+1)$ and e^{-ikr} represent incoming spherical wave and e^{ikr}represents an outgoing spherical wave emerging from the target nucleus. The superposition of these two waves gives the plane wave. The scattering can affect only the outgoing wave it in through a change in phase shift or through a change in amplitude. There may be fewer particles in the e^{ikr}term following the inelastic scattering.

Let's introduce a complex coefficient η_l into the outgoing (e^{ikr}) to account for changes in l^{th} outgoing partial wave.

$$\psi_{sc} = \frac{A}{2kr}\sum_{l=0}^{\infty} i^{l+1}\ (2l+1)\ (1-\eta_l)\ e^{(kr-\frac{l\pi}{2})}\ P_l(cos\theta)$$

$$\psi_{sc} = \frac{A}{2kr}\frac{e^{ikr}}{r}\sum_{l=0}^{\infty}(2l+1)i(1-\eta_l)P_l(cos\theta) \tag{2.5.19}$$

The superposition of incident and scattered waves is:

$$\psi = \psi_{inci} + \psi_{sc}$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{4k^2}|\sum_{l=0}^{\infty}(2l+1)i(1-\eta_l)P_l(cos\theta)|^2 \tag{2.5.20}$$

Thus,

$\sigma_{sc} = \sum_{l=0}^{\infty}\pi\lambda^2(2l+1)|1-\eta_l|^2$ simplifies to

$$\sigma_{sc} = \pi(R+\lambda)^2 \tag{2.5.21}$$

for non-elastic reactions. However, we group all these processes together under the term reaction cross section, σ_r.

$$\sigma_r = \sum_{l=0}^{l}\pi\lambda^2(2l+1)|1-\eta_l|^2$$

$$\sigma_r = \pi(R+\lambda)^2 \tag{2.5.22}$$

$$\sigma_t = \sigma_{sc} + \sigma_r = 2\pi(R+\lambda)^2 \tag{2.5.23}$$

The transmission probability for a rectangular potential well can be calculated [2] as in equation (2.5.24). The mathematical aspects of non-relativistic quantum mechanics are determined by solutions to the Schrodinger equation. In one-dimension, the time-independent Schrodinger equation for a particle of mass m with a potential operator V(x) is:

$$\frac{-\hbar^2}{2m}\frac{d^2}{dx^2}\psi_x + V(x)\psi_x = E\psi_x$$

Solution of this equation and equation (2.5.23) lead to the result

$$\sigma = \pi(R+\lambda)^2 \frac{4kK}{(k+K)^2} \tag{2.5.24}$$

where $K = \sqrt{2m(E+V_0)/\hbar^2}$ for a barrier of depth V_0 and $k = \sqrt{2mE/\hbar^2}$

2.5.5 Resonance Energy and Cross Section

The binding energy of the alpha particle in the compound nucleus becomes available as excitation becomes available as excitation energy which can be added to resonance energies to obtain the excitation energies. The resonance energy is defined by bombarding Al by alpha particles of different energies and recording the emission of proton for the respective energies [7]. In the reaction $^{27}Al\ (\alpha, p)\ ^{30}Si$, the yield of protons had peaks at α-energies of different energies and markedly there was lower energy in range between any two successive peaks (Figure 2.7). The occurrence of the maxima in the reaction rate at which the maxima occur are called resonance and the energies at which the maxima occur are called resonance energies. The total cross section presented by the target nucleus can be calculated as a function of incident energy, E using Breit-Wigner formula [6], and is given as

$$\sigma(E) = \frac{\pi}{k^2}\frac{g\Gamma_i\Gamma}{(E-E_0)^2 + \frac{\Gamma^2}{4}} \tag{2.5.25}$$

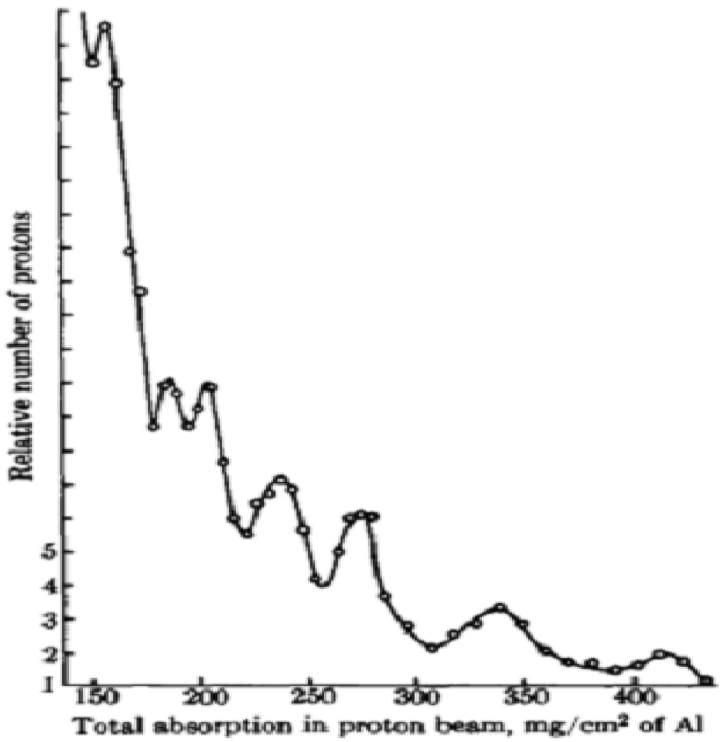

Figure 2.7: *Proton groups from the reaction of* $^{27}Al(\alpha, p)^{30}Si$ [8]

where $k = |\mathbf{k}|$ and $\mathbf{k}$ is the wave vector of the incoming particle in CM frame

Γ_i= the partial width for decay into the incident channel (see equation 2.4.3).

g = the statistical factor

E = the kinetic energy in the center of mass system

E_0 = the resonance energy

The effect of Coulomb repulsion between the particles in the initial and final channels of the reaction leads to differences in the reaction cross sections [7].

$$\sigma(E) = \frac{1}{E} S(E) e^{-G(E} \tag{2.5.26}$$

where $G(E) = \frac{\pi}{\hbar c}(\frac{2Z_d e^2}{4\pi\epsilon_0})$

The function $g(\frac{r_s}{r_c}) = \frac{2}{\pi}[cos^{-1}(\frac{r_s}{r_c}) - \sqrt{\frac{r_s}{r_c}(1-\frac{r_s}{r_c})}]$

Z_d = atomic number of daughter nucleus

r_c= the classical distance of closest approach to the nucleus of an α-particle and is given by

$r_c = (\frac{1}{4\pi\epsilon_0})\frac{qQ}{E_\alpha}$ where $E_\alpha = qV_E$ kinetic energy of α-particle.

r_s= the distance at which the strong interaction with the nucleus takes over and is given by

$$r_s = 1.1[A^{1/3} + 4^{1/3}] \text{ fm}$$

S(E)=Statistical factor of the reaction

The reaction cross section can be expressed in terms of the interaction barrier as [5]

$$\sigma(E) = \pi R_{int}^2 (1 - \frac{V(R_{int})}{E_{cm}}) \tag{2.5.27}$$

Where R_{int} is the interaction radius given as $R_{int} = R_1 + R_2 + 3.2$ fm and is 9.64 fm for the interaction of copper and alpha particle.

$R_I = 1.12A_i^{1/3} - 0.94A^{-1/3}\ fm$

$R_1 = 1.19\ fm$ for alpha particle and $R_2 = 4.021\ fm$ for the copper isotope of A= 65 amu and the interaction barrier is given as

$V(R_{int}) = 1.44\frac{Z_1 Z_2}{R_{int}} - b\frac{R_1 R_2}{R_1+R_2}$

where b is the impact parameter. In this case, $V(R_{int})$ is measured in MeV.

Chapter 3

Research Methodology

3.1 Materials Used

The study was intended to find the theoretical calculation of reaction cross-section and compare with experimental values for the excitation functions of alpha induced reaction on copper ^{65}Cu. During the research work, the following materials and resources were used.

- computer, flash disc
- stationary materials
- printer and accessaries
- references like journals, books, websites, thesis and dissertation.
- nuclear reaction code, COMPLET, Microsoft Office EXCEL 2007
- EXFOR database

3.2 TECHNIQUES OF DATA GATHERING

In this thesis, FORTRAN 77 based computer code, code COMPLET [15] (given in **Annexed** of this thesis), was used to generate data. In COMPLET code a pre-equilibrium process in two stages is assumed. The particles in the initial configuration (TD =EX1+ EX2+ EX3) can be neutron, proton or alpha particle, represented by the exciton numbers EX1, EX2 and EX3 respectively. Where TD is the sum of excited particle(s) and hole. In the input parameters TD, EX1, EX2, M3, threshold energy, alpha energies in the nuclear database and approximate probable energies in the range between two neighbor energies of the nuclear data were used in the generation of theoretical data.

3.2.1 Analytical

In this thesis one of the method or approach used to solve the problem was analytical method. That is the Schrödinger equation of an alpha particle with energy E and nuclear potential V_0 was used to derive nuclear reaction cross section analytically.

3.2.2 Computational

With the aid of Microsoft Office EXCEL 2007, the generated nuclear data were analyzed graphically. The graphs were interpreted verbally in a brief way as given in chapter 4.

Chapter 4

Results and Discussion

4.1 Introduction

In this work, the reaction cross section of of five nuclear reactions namely, $^{65}Cu(\alpha, n)$ ^{68}Ga, $^{65}Cu(\alpha, 2n)^{67}Ga,^{65}Cu(\alpha, 3n)^{66}Ga, ^{65}Cu(\alpha, p)^{68}Zn$ and $^{65}Cu(\alpha, 2p)^{67}Cu$ were studied theoretically. These were accomplished by the theoretical calculation of the reaction cross section of copper ^{65}Cu bombarded by alpha particle with intermediate energy range between 16 MeV to 35 MeV.

The excitation functions of the reactions were depicted after the generation of data with the help of Microsoft Excel. The results of experimental cross sections were extracted from the EXFOR library. The experimental data for the reaction $^{65}Cu(\alpha, n)^{68}Ga$, $^{65}Cu(\alpha, 2n)^{67}Ga$, $^{65}Cu(\alpha, 3n)^{66}Ga$, $^{65}Cu(\alpha, p)^{68}Zn$ and $^{65}Cu(\alpha, 2p)^{67}Cu$ was taken from the authors A.Navin, V.Tripathi, Y.Blumenfeld, V.Nanal, C.Simenel, J.M.Casandjian, G.DeFrance, R.Raabe, D.Bazin, A.Chatterjee, M.Dasgupta, S.Kailas, R.C.Lemmon, K.Mahata, R.G.Pillay, E.C.Pollacco, K.Ramachandran, M.Rejmund, A.Shrivastava, J.L.Sida, E.Tryggestad, [16].

All the energies given as the projectile energy in the laboratory system were also used in the theoretical calculations. During the data compiling theoretically, data were saved in a computer. After completion of compiling the theoretical cross section data for each of the five alpha induced reaction explained above, the data were presented in tables and graphs as shown.

4.2 Reaction Cross Section of $^{65}Cu(\alpha, n)^{68}Ga$

In this reaction, α-projectile of energy range between 16.3 to 33.6 MeV has been used. The theoretically calculated cross section data for the reaction were as displayed in Table 4.1 together with experimentally given data in EXFOR for each energy.

Table 4.1: Theoretical and measured cross section for the reaction $^{65}Cu(\alpha, n)^{68}Ga$

E_α (MeV)	$\sigma - Experimental$ (mb)	$\sigma - Theoretical$ (mb)
16.3	804	809.495
19.0	587	595.152
19.6	551	555.328
21.2	373	453.143
22.9	267	370.501
25.4	127	224.367
26	109	215.588
26.4	116	194.988
27.1	78	152.71
28.6	65	90.912
30.6	51	70.503
31.4	49	60.037
31.5	42	47.83
32.4	35	35.401
33.6	3	3.168

Radionuclide ^{68}Ga is produced when alpha particle of energy between 16.3 to 33.6 MeV strikes copper ^{65}Cu [16]. It has half-life (67.71 min) [8] and used in the medical treatment of tumors [3].

The excitation function of the reaction shows that the graph declines almost exponentially showing close approach with the excitation function of the experimental results in the energy range. The graphs of the experimental results and theoretical calculation are exhibited (Figure 4.1) as the excitation functions of $^{65}Cu(\alpha, n)^{68}Ga$ and were compared to diminish the incongruity between them.

Intuitively, it can be understood from the graph that the excitation function of the theoretical data (solid blue line on Figure 4.1) is very close to the excitation function of the neutron evaporation from the compound nucleus, ^{69}Ga. The maximum cross section was obtained at 16.3 MeV leading to the conclusion that the maximum probability of formation of the compound nucleus equals 809.495 mb in this energy range. The data generated between 21.2 - 30.6 MeV were slightly far from the experimental result.

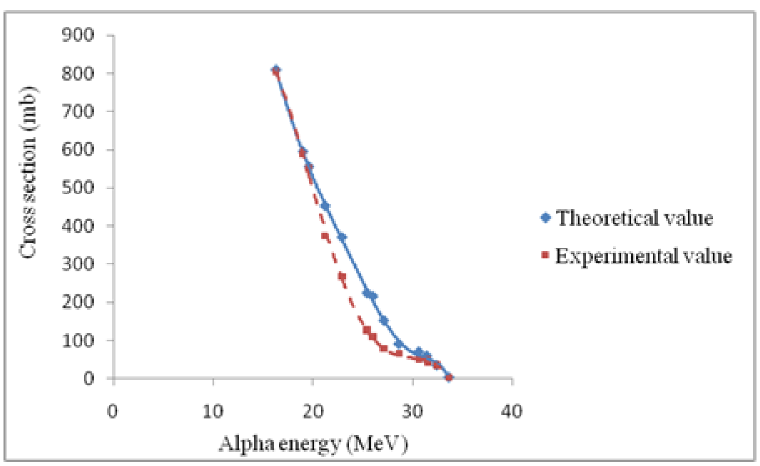

Figure 4.1: *Experimental and theoretical excitation function for the reaction* $^{65}Cu(\alpha, n)^{68}Ga$

4.3 Reaction Cross Section of $^{65}Cu(\alpha, 2n)^{67}Ga$

In this section, the nuclear cross section of the reaction $^{65}Cu(\alpha, 2n)^{67}Ga$, was calculated theoretically for each energy of alpha particle given in Table 4.2. As can be seen from the table, the projectile energy of 32.191 MeV is best closest to the experimental result.

^{67}Ga is produced from alpha induced reactions on copper (^{65}Cu) by the releasing of two protons [17] from the compound nucleus. Gallium (^{67}Ga) is a radionuclide of half-life $t_{1/2} = 3.2617d$ [8] and decays to the stable ^{67}Zn through EC(100%) process with the emission of few γ-lines [17].

The graph of the excitation function of the the reaction was also plotted showing very close relationship to the experimental results [16]. The excitation functions of the compound reaction plotted for the theoretically calculated data(the graph marked by broken blue line on Figure 4.2) behaves like that of the experimentally plotted graphs (the graph shown by solid red line on Figure 4.2) within the energy range from 16-35 MeV in that both firstly increase and then decline with the increasing projectile energy showing graphs of similar character.

Table 4.2: Measured and Theoretical cross sections for the reaction $^{65}Cu(\alpha, 2n)^{67}Ga$

E_{lab}	$\sigma - Theoretical$ (mb)	$\sigma - Experimental$ (mb)
15.577	25.586	25.318
17.102	125.887	145.43
17.967	194.997	219.29
18.976	249.071	290.69
22.645	568.727	594.85
25.446	623.677	624.09
28.389	528.268	560.98
32.191	369.674	389.41

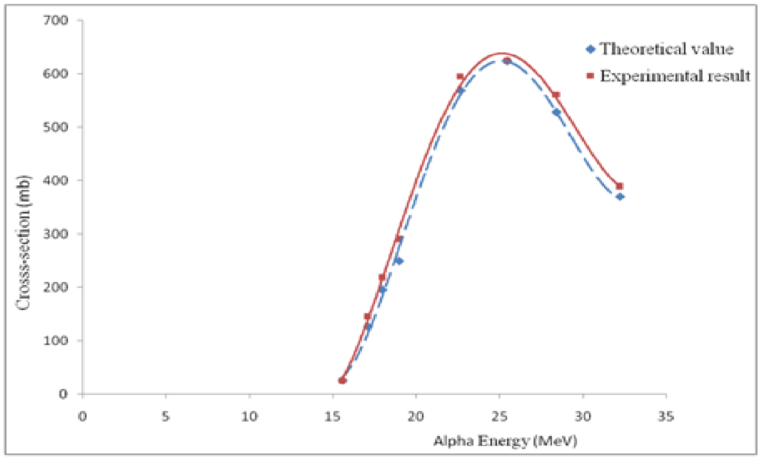

Figure 4.2: *Experimental and theoretical excitation function for the reaction* $^{65}Cu(\alpha,2n)^{67}Ga$

4.4 Reaction Cross Section of $^{65}Cu(\alpha,3n)^{66}Ga$

Nuclear cross sections of the reaction $^{65}Cu(\alpha,3n)^{66}Ga$ were calculated theoretically by using the alpha energy ranging from 28 - 33 MeV for the sake of comparison (Table 4.3). Within the range, the maximum cross section approaching the experimental result was the cross section calculated with the alpha energy of 28.342 MeV leading to the solution 43.325 mb.

The radionuclide ^{66}Ga is produced from the compound reaction with the projectile energy in the laboratory system [18]. The excitation function of reaction, $^{65}Cu(\alpha,3n)^{66}Ga$ [19], [20] were calculated theoretically showing the maximum production probability of the nuclide. The graph of reaction given by (Figure 4.3) was plotted after the theoretical calculation of the reaction in the energy range 28 - 33 MeV. At the start of the graph, the edge of the graph shows the point marked theoretically by the coordinate (28.342, 43.325) and the experimental value (28.342, 42.82) and at the end of the graph, the point marked by the blue diamond shows the graph plotted after the experimental result while the tip of the graph shows theoretical value matching Table 4.3. Eventhough the experimental and the theoretical values were slightly far away, the table shows that the maximum probability of the reaction was at the alpha energy equal to 32.087 MeV both theoretically and experimentally.

Table 4.3: Theoretical and Measured cross section for the reaction $^{65}Cu(\alpha, 3n)^{66}Ga$

E_{lab} (MeV)	$\sigma - Theoretical$ (mb)	$\sigma - Experimental$ (mb)
28.342	43.325	42.82
29.342	58.79	—
30.342	101.7	—
31.342	131.31	—
32.087	144.096	148.23

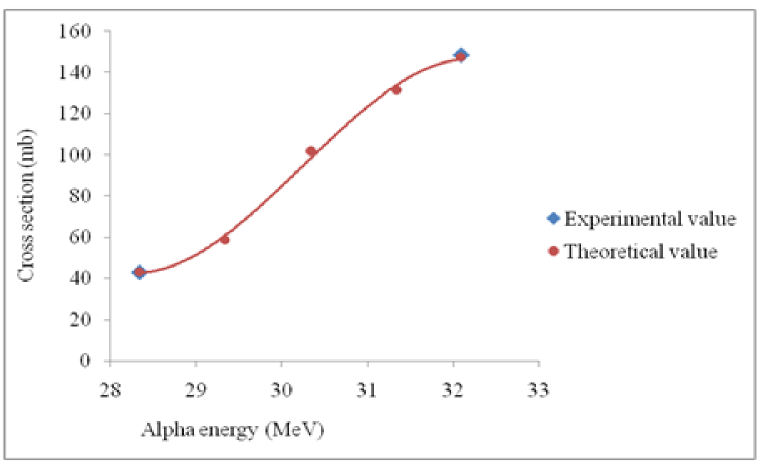

Figure 4.3: *Experimental and theoretical excitation function for the reaction* $^{65}Cu(\alpha, 3n)^{66}Ga$

4.5 Reaction Cross Section of $^{65}Cu(\alpha, p)^{68}Zn$

In this reaction, alpha of energy 16.897 to 19.704 MeV was used to calculate the reaction cross section of $^{65}Cu(\alpha, p)^{68}Zn$ [16]. The cross sections of the reaction were very close to the experimental result as given in Table 4.4. In the table, it can be seen that the energy in the first two rows best fit with experimental result.

Furthermore, the production of ^{68}Zn, which is a non-radioactive isotope of zinc covering 18.5% [21], by the compound nucleus releasing of a proton when alpha particle inters copper nucleus with energy 16.897 MeV-19.704 MeV in accordance with the experimental results of the reaction was studied. As ^{68}Zn is one of the five stable isotopes of Zn, the product of this reaction can be used by semiconductor engineers to produce ZnO [10].
The excitation function of the reaction $^{65}Cu(\alpha,p)^{68}Zn$ was plotted for the reaction cross section as in Figure 4.4 showing that the compound reaction best approaches the experimental values. It has been arrived at the conclusion that the two graphs have shown similar characteristics. Both the figure and the table have shown that the maximum cross section would be around 45 mb. Therefore, it has been verified theoretically that alpha energy of around 16 MeV was most probable to proceed the reaction.

Table 4.4: Theoretical and measured cross section for the reaction $^{65}Cu(\alpha,p)^{68}Zn$

E_{lab} (MeV)	$\sigma - theoretical$ (mb)	$\sigma - Experimental$ (mb)
16.897	45.096	45.179
17.833	43.163	44.018
18.768	35.071	37.681
19.704	30.61	34.861

4.6 Reaction Cross Section of $^{65}Cu(\alpha,2p)^{67}Cu$

At last, the reaction cross sections of $^{65}Cu(\alpha,2p)^{67}Cu$ were calculated theoretically by generating data using the code. From Table 4.5, it can be seen that alpha energy ranging between 21 and 34 MeV were used to calculate the reaction cross sections and plot the graph. Theoretically generated data given in Table 4.5 have shown that alpha energy 34 MeV was most probable to produce ^{67}Cu. The energy to produce the best fit for experimental and theoretical cross sections, 0.67 mb and 0.6728 mb

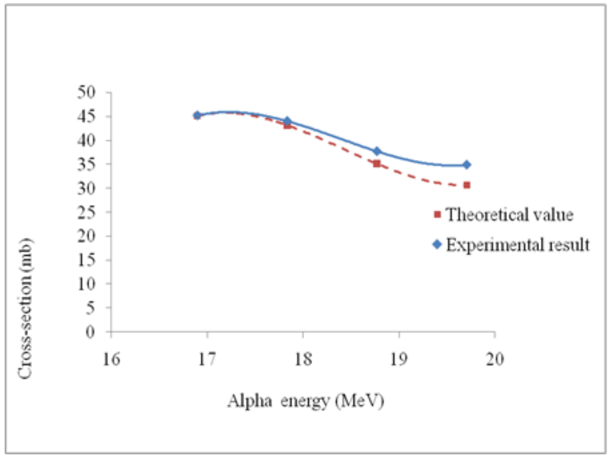

Figure 4.4: *Experimental and theoretical excitation function for the reaction* $^{65}Cu(\alpha, p)^{68}Zn$

respectively was 29.6 MeV.

The isotope ^{67}Cu is considered as one of the most perspective for application in radio-immunotherapy [22]. The production of ^{67}Cu from alpha induced reaction on copper (^{65}Cu) [1] is identifiable for the excitation function of the reaction conforming the excitation function of the evaporation of two protons from the compound nucleus.

The graph of both the experimental and theoretical cross sections in the case of $^{65}Cu(\alpha, 2p)^{67}Cu$ exit channel was compared as in Figure 4.5. The figure illustrates that the theoretically plotted graphs had characteristics similar to slightly the first half of Breit-Wigner shape given in Figure 2.4.

Table 4.5: Theoretical and Measured cross section for the reaction $^{65}Cu(\alpha, 2p)^{67}Cu$

$E_{lab}(MeV)$	$\sigma - Theoretical$(mb)	$\sigma - Experimental(mb)$
21	0.04635	0.021
23.6	0.1023	0.072
25.6	0.1548	0.15
28.1	0.5743	0.47
29.6	0.6728	0.67
31.2	1.327	1
34	2.0544	1.9

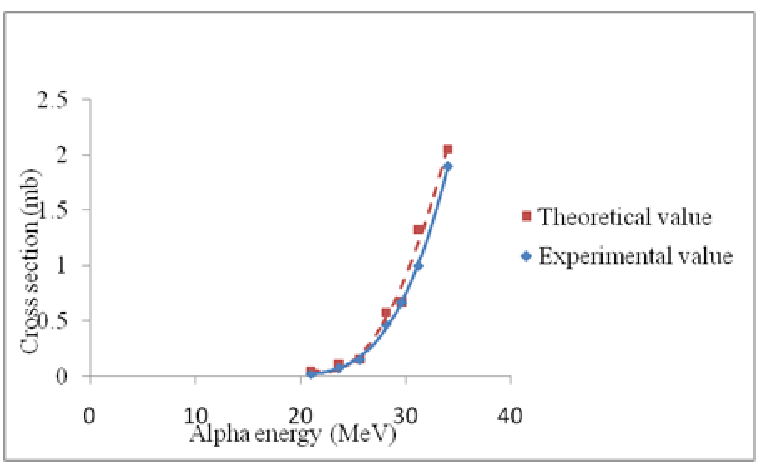

Figure 4.5: *Experimental and theoretical excitation function for the reaction* $^{65}Cu(\alpha, 2p)^{67}Cu$

Chapter 5

Conclusion

In this work, the reaction cross section of five nuclear reactions namely, $^{65}Cu(\alpha,n)^{68}Ga$, $^{65}Cu(\alpha,2n)^{67}Ga,^{65}Cu(\alpha,3n)^{66}Ga$, $^{65}Cu(\alpha,p)^{68}Zn$ and $^{65}Cu(\alpha,2p)^{67}Cu$ were studied which were accomplished by the theoretical calculation of the reaction cross section of copper (^{65}Cu) bombarded by alpha particle in the intermediate energy range between 16 MeV to 35 MeV. The excitation functions of the reactions were depicted by Microsoft Excel after the generation of data with the help of code COMPLET. The results of experimental cross sections were extracted from the EXFOR library. The production of radionuclide ^{68}Ga, which has half-life (67.71 min) and could be used in the medical treatment of tumors, was studied when alpha particle of energy between 16.3 to 33.6 MeV strikes the nucleus of copper (^{65}Cu). The theoretical calculation of the reaction cross section has shown that the production probability of ^{67}Ga that best fit the experimental result was alpha particle of energy 32.191 MeV induced reaction on copper(^{65}Cu) by releasing two protons. It was also studied that the probability of formation of radionuclide ^{66}Ga has shown as the energy gets closer to the 28.342 to 32.087 MeV energy alpha in the laboratory system. ^{68}Zn, which is mostly used in the production of semiconductor instruments, could be produced by the compound nucleus releasing of a proton when alpha particle inters copper nucleus with energy 16.897 MeV-19.704 MeV in accordance with the experimental results of the reaction Theoretically generated data have shown that alpha energy 34 MeV was most probable to produce ^{67}Cu showing the cross section of 2.0544 mb and closer cross section to the experimental result of value 1.9 mb. The energy to produce the best fit for experimental and theoretical cross sections, 0.67 mb and 0.6728 mb respectively was 29.6 MeV. This was identifiable for the excitation function of the reaction conforming the excitation function of reaction cross section in the evaporation of two protons in the reaction.

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Annexed

CODE COMPLET

The Code COMPLET is a FORTRAN 77 based computer code and is a nuclear reaction code used to simulate virtual beam by generating energy from a few MeV to a number of MeV. The computational code was commanded in the following manner in the ForTran Compiler.

CARD 1 General Input Data

AP Projectile Mass Number

AT Target Mass Number

ZP Projectile Charge

ZT Target Charge

QVAL Reaction Q Value = AP+AT-ACN. =0: Calc. From M and S Mass Formula.

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

PLD Level density parameter 'a', a=ACN/PLD. =0: a=ACN/8.

CLD ratio of single particle level densities $\frac{af}{an} = 0$: $\frac{af}{an}$=1.0

BARFAC multiplies the rotating drop fission barrier by this value.

=0: BARFAC = 1.

ROTFAC multiplies the rotational energy by this value.

=0: ROTFAC=1.

RO critical temperature above onset of retarded fission

GI nuclear friction parameter from EQ. deformation to saddle

G0 nuclear friction parameter from saddle to scission point

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

NZ number of Z 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 (17.7.91)

MC shell correction option for masses subroutine.

MC=0,shell corr.

MC=1, no shell corr.

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. =0:no correction;

=1:pairing term

=2: masses are from nuclear wallet cards;

=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

If 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, =5: n, p, alpha, deuteron and triton; =6: n, p, alpha, deuteron, triton and helion (3He); =7: as before incl. Gammas. calculations until gamma emission is finished, important for isomeric ratio calculations.

INVER inverse cross section param.

=0: user will supply;

=1: results by O.M. subroutines as in ALICE/85/300, + PEREY'S t,3He O.M., d,t,3He O.M.,

=2: O.M. for n,p as in old ALICE, a as in PRC49,2136 + PEREY'S d,t,3He O.M.,

=3: sharp cut off values for inverse cross-sections.

IKE If =1: no particle spectra will be printed;

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

If =3: only PE- spectra will be printed;

If = 5: PE plus summed equilibrium spectra will be (separately) printed; if = 4: as 2+3 !!!

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

If IKE <= 0 or IKE >= 6 most reduced output

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 Card - 80 Columns

If MC = 2 on card1, read user supplied n, p, alpha, deuteron triton and helion binding energies here, format(4F10.5) for IA=1 to NA, IZ=1 to NZ if INVER = 0 on card1, read n, p, alpha, deuteron, triton, helion and gamma inverse cross sections here. format is (7E10.5) in ascending channel energy, first value = 0.1 MeV, incremented by 1 MeV, 48 values per particle type in sequence n, p, a, d, t, ^3He and gamma depending on value of M3.

CARD 3 Energy and CN and PE Options

EKIN 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 not 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 CARD1.

RCSS =0: reaction cross section is calculated from subroutine (for pi-induced reactions: if RCSS(input)=0., RCSS = 100 mb) > 0: number of T(l) values to be read from the next card if < 0: calculated rcss is multiplied by this value times -0.01

JCAL type of calculation option. =1: Weisskopf,

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

=3: s-wave with rigid body,

=0: calc for all partial wave including fission and full angular momentum coupling up to delta l=12 (for gammas delta l=0,1). (previous option JCAL = -1 is no more existing).

JFRAC direct-semidirect capture gamma ray estimate: < 0 no emission, > 0 approach of KALKA, $= 0$ simple approach with initial exciton-number =1 for p,n.

JUPPER JUPPER LT 0, Blann-Reffo type PE-gamma-emission using s.p. state densities instead of 1P1H two-partcile densities.

Normalization factor = 1/GIANT with GIANT=ABS(JUPPER)/100.

For JUPPER GE 0 photo absorption yield normalized to 1P1H state normalization factor = GIANT with GIANT=ABS(JUPPER)/100.

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 additional parameters on this card are for pre-compound options. Put TD-value to zero if no PE calculation is wanted

IJ if = 1 (or 3): GP=GN=3/4*A/POT

if = 0 (or 2): GP=3/2*Z/POT,GN=3/2*(A-Z)/POT

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 calculated from nucl. Matter value = 37.8 MeV

AV if = 0.: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 1st stage exciton gets an alpha particle in the second stage. (1-ALF): complementary probability if ALF > 1 calculation for two initial exciton 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 EXC. Numbers.

CMFP mean free paths are multiplied by CMFP. If CMFP=0.: multiplier is 1.0

GDO critical angular momentum. GDO > 0: partial waves with $l >$ GDO are not taken into account in the 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.

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

Name of Student: **Tolina Guta** ID No. **SMSc 00915/06**

Graduate Program: **Summer, MSc.**

1. Course Work Performance

Course Code	Course Title	Cr. hr	Score (%)	Rank **	Remark
Phys 699	**MSc. Thesis**	**6**	**87.25**	**Excellent**	

** Excellent, Very Good, Good, Satisfactory, Fail.

Thesis Title

EXCITATION FUNCTION OF ALPHA INDUCED REACTIONS $\{(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p), (\alpha, 2p)\}$ ON COPPER (Cu-65) IN INTERMEDIATE ENERGY RANGE FROM 16MeV TO 35MeV.

2. Board of Examiners decision Mark × in one of the boxes. Promoted [×] Failed [ ]
   If failed, give reasons and indicate plans for re-examination.

   ____

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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	__________	__________	__________

____________________ ____________ ____________

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 **Tolina Guta**, have read and evaluated his thesis entitled "**EXCITATION FUNCTION OF ALPHA INDUCED REACTIONS** $\{(\alpha, n), (\alpha, 2n), (\alpha, 3n), (\alpha, p), (\alpha, 2p)\}$ **ON COPPER (Cu-65) IN INTERMEDIATE ENERGY RANGE FROM 16MeV TO 35MeV**" and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfilment of the requirements for the degree of 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 thesis 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 thesis have been duly acknowledged.

Name: Tolina Guta

Signature: _________________
email: gutatolina@gmail.com

This Msc thesis 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