EXCITATION FUNCTION OF ALPHA INDUCED REACTION ON ISOTOPES OF ZINC (^{64}Zn, ^{68}Zn, ^{70}Zn) WITH ALPHA ENERGY BELOW 50 MeV

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A Thesis Submitted to the Department of Physics Jimma University Presented in Partial Fulfillment of the Requirements for the Degree of Masters of science(Msc) in Physics (Nuclear Physics)

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February, 2022

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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.

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This Thesis has been submitted for examination with my approval as university advisor.

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Acknowledgment

First of all, I am indebted to my ALMIGHTY GOD who gave me long life and helped me to pass through different ups and downs to reach this time. Next, I would like to express my deepest gratitude to my advisor **Teklemariam Tessemma (PhD)** for his guidance, intelligent comments, and helpful suggestions to prepare this thesis. I also convey thanks to my co-advisor **Chali Yadeta (MSc)** for his consulting, encouragement, and well-mannered support to carry out this thesis. Also I would like to forward my special thanks to Jimma University, Department of Physics for providing me favorable conditions to accomplish the required courses. Honestly, I would like to disclose my greetings to Addis Ababa Education Bureau for giving me such an opportunity to attend post graduate studies. Lastly, I would like to thank my colleague Daniel Alayu (Msc) for his constant encouragement ,support and tangible comments I received during the time I spent on this thesis.

Abstract

In this thesis alpha induced reactions on stable isotopes of Zinc for energies of alpha below 50MeV were studied. Experimentally measured excitation function obtained from EXFOR data source IAEA, for the isotopes ${}^{64}_{30}Zn(\alpha,p){}^{67}_{31}Ga$, ${}^{68}_{30}Zn(\alpha,n){}^{71}_{32}Ge$, ${}^{64}_{30}Zn(\alpha,n+p){}^{66}_{31}Ga$, ${}^{70}_{30}Zn(\alpha,p){}^{73}_{31}Ga$ *and* ${}^{68}_{30}Zn(\alpha,3n){}^{69}_{32}Ge$ *were used to compare with the theoretical calculation for understanding how well the calculation able to admit the experiment providing a theoretical explanation of the excitation functions based on the COMPLET code calculation was the major objective of the thesis. For the theoretical calculation the COMPLET code has been employed. The level density parameter(k) was varied to get good agreement between the theoretical and measured data. The COMPLET code for both compound nuclear reactions and pre-equilibrium reactions. The relation-ships of alpha-energy and reaction cross-section have been plotted as excitation functions and the correlation was explained. The result shows relatively higher energy parts of excitation functions are dominated by pre-equilibrium reaction mechanism, whereas the low energy parts are dominated by compound nucleus reaction mechanism. When the incident alpha energy increases the pre-equilibrium reaction is more significant. The experimental excitation function agrees well with the theoretical calculations in most of the energy region. The thesis may raise interest and could be a resource for further study on excitation function of alpha induced reaction on Zinc stable isotopes.*

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Chapter 1

Introduction

1.1 General Background

Studies on nuclear reaction cross sections are important in a number of areas such as accelerator-driven systems, fission, fusion, dosimetery, radiation therapy, medical radionuclide production. In particular, data on the cross sections of fast alpha -induced nuclear reactions are essential for understanding nuclear phenomena [1].
Many nuclear physicists are interested in the study of nuclear reactions generated by heavy ions because it provides understanding of the nature of nuclear forces, nuclear structure, and many other nucleochemical phenomena. Nuclear physicists have made numerous contributions over the last decade. In recent years, there has been a lot of research put into understanding the process behind the heavy ion(HI) induced reaction [2].

The development of nuclear technology was one of the significant achievements of the 20th century and this technology and its derivatives are currently used in almost every field of human endeavor. Radioisotopes which are the main products of this technology were first practically used by G. de Hevesy in 1911. Radioisotopes or radionuclides are artificially

produced unstable atoms of a chemical element, which have a different number of neutrons in the nucleus, but the same number of protons and the same chemical properties [2].

Alpha induced reaction on zinc stable isotopes is used to produce isotopes of Germanium ^{66}Ge,^{68}Ge,^{69}Ge and other isotopes of zinc decay to produce ^{69}Ga,^{71}Ga,^{72}Ga,^{73}Ga, some isotopes of Cu and isotopes of Ni. The production cross sections of ^{66}Ge,^{68}Ge,^{69}Ge and ^{69}Ga,^{71}Ga,^{72}Ga,^{73}Ga by alpha -induced reactions on ^{nat}Zn is measured using the stacked-foil activation method and gamma ray spectrometry from their threshold energies to 50 MeV. The medium-Z positron emitter radio-nuclei are: ^{68}Ge (270.93 days), ^{68}Ga (67.71 min) the radionuclide ^{68}Ga has a suitable half-life and can be used as the substitute of ^{18}F and ^{11}C. The PET radio-isotope ^{68}Ga is a decay product of long-lived ^{68}Ge. The zinc alloy is important for the nuclear science and reactor technology. The zinc target used for this reaction is a silver-gray, brittle and lustrous metal, which has five stable isotopes such as ^{64}Zn, ^{66}Zn, ^{67}Zn, ^{68}Zn and ^{70}Zn with isotopic abundances of 49.17%, 27.73%, 4.1%, 18.45% and 0.61%, respectively [3]. Theoretical calculation may provide more detail explanation of nuclear reactions beside the experimentally provided data. For the purpose of studying theoretical excitation function of alpha induced reaction in the intermediate mass region excitation function of alpha induced reaction of zinc stable isotopes energy below 50 MeV was calculated in this thesis. The work focused only on the use of zinc Particles as a target material and alpha particles of different kinetic energy as projectile. In the process the alpha projectile was induced to make reaction with zinc stable isotopes. The result of this process is the formation of a new element. As far as, this reaction is concerned the behavior of reaction cross section with the projectiles of alpha on different stable isotopes of zinc in different reaction channels (α , x) of reaction where $'\alpha'$ is the projectile alpha particle and 'x' is the outgoing particle that was studied theoretically.

1.2 Statement of the Problem

There is experimental literature on nuclear reactions available. However, there is not such much theoretically calculated nuclear reaction data, as widely as experimental data in studying the cross-section of alpha-induced reaction on Zinc. Therefore, this research is intended for providing theoretical reaction data about alpha-induced reactions on some isotopes of Zinc. The results of the theoretical excitation function were compared to experimental data from the EXFOR database.

1. How the COMPLET code based excitation functions of alpha induced nuclear reactions for energy below 50MeV on isotopes of Zn with mass 64, 68 and 70 described?
2. What is the characteristics of the crocross-section a function of alpha energy for each of the alpha induced reactions, (α, p) and (α, n) on ${}^{64}_{30}Zn$, ${}^{68}_{30}Zn$ and${}^{70}_{30}Zn$ isotopes?
3. How well the COMPLET code calculation cross section does agree with the expexperimental values obtained from the EXFOR data library?

1.3 Objectives

1.3.1 General Objective

The general objective of this study is to investigate the behavior of excitation function of alpha induced reaction on ${}^{64}Zn$,${}^{68}Zn$, and ${}^{70}Zn$ stable isotopes energy below 50 MeV

1.3.2 Specific Objectives

1. To describe the results of excitation function of alpha induced reaction on three stable isotopes of Zinc of ${}^{64}Zn$,${}^{68}Zn$, and ${}^{70}Zn$.

2. To differentiate the features of the graph of the reaction cross section versus alpha energy below 50 MeV.for the alpha induced reactions on the Zinc isotopes.

3. To prove the theoretical data in the calculation, comparing it with experimental data obtained from EXFOR data library.

1.4 Scope of the Study

The scope of this thesis is to investigate the theoretical excitation function of alpha induced reaction on three stable isotopes of zinc using the nuclear reaction code called COMPLET. The calculation is limited to only (alpha, proton) and (alpha, neutron) compound nucleus and pre-equilibrium reactions and it does not include other channels and direct reactions because of the limitations in time, and other resources including the limitation in the code that it cannot be used for direct reaction calculations.

1.5 Significance of the Study

This thesis explored the theoretical excitation function of alpha induced reaction on Zinc isotopes which is significant in the way including but not limited to follow, providing theoretical data on (alpha, proton) and (alpha, neutron) reactions induced by alpha of energy below 50MeV, give theoretical explanation on the excitation function of the reactions so that it can be used as a reference for other researchers, and used as a final work for completion of Msc in Science.

Chapter 2

Literature Review

2.1 Nuclear Reaction

The interaction of mono energetic light nuclear particles (p, n, d) or nuclei on a target material (nuclei) is called nuclear reaction. A nuclear reaction is represented as:

$$a + X \rightarrow b + Y \tag{2.1}$$

where a is projectile; X is target nucleus; Y is the product nucleus after interaction and b is the outgoing particle or Y-radiation etc. In brief the above reaction is denoted as X (a,b) Y [5].

A nuclear reaction is a process that occurs when a nuclear particle i.e. nucleon or nucleus gets into close contact with another. Most of the known nuclear reactions are produced by exposing different materials to a beam of accelerated nuclear particles. It is considered to be the process in which two nuclear particles (two nuclei or a nucleus and a nucleon) interact to produce two or more nuclear particles or γ rays. Thus, a nuclear reaction must cause a transformation of at least one nuclide to another [5].

In order a nuclear reaction to occur, the nucleons in the incident particle, or projectile, must interact with the nucleons in the target. Thus the energy must be high enough to overcome the natural electromagnetic repulsion between the protons. This energy barrier is called the Coulomb barrier. If the energy is below the barrier, the nuclei will bounce of each other. Early experiments by Rutherford used low-energy alpha particles from naturally radioactive material to bounce of target atoms and measure the size of the target nuclei. A particle accelerator, which produces a beam of high-velocity charged particles (electrons, protons, alpha particles, or heavy ions), creates these reactions when they strike a target nucleus [6]. Sometimes if a nucleus interacts with another nucleus or particle without changing the nature of any nuclide, the process is referred to a nuclear scattering, rather than a nuclear reaction [7]. Reactions that exchange energy or nucleons can be used to measure the energies of binding and excitation, quantum numbers of energy levels, and transition rates between levels. 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. A nuclear reaction is described by identifying the incident particle, target nucleus, and reaction products [6]. For example, when a neutron strikes a nitrogen nucleus,^{14}N, to produce a proton, $^{1}_{1}H$, and an isotope of carbon,^{14}C, the reaction is written as:

$$^{1}_{0}n +^{14}_{7} N \rightarrow^{14}_{6} C +^{1}_{1} H \tag{2.2}$$

A number of conservation conditions apply and holds true to any reaction equation. 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. Beams of photons, mesons, and neutrinos can also

produce nuclear reactions [8]. Reaction mechanisms in nuclear reaction can be three types, direct nuclear reaction, com pound nuclear reaction and pre-equilibrium nuclear reaction. The contribution of these three processes depends on the given reaction and the energy of the incident particle. These three stages can be distinguished by their angular distributions and time scales [9].

2.1.1 Direct Nuclear Reaction

For projectile energies above 50 MeV and for light target nuclei ($A < 30$) a direct transition from the entrance to the exit channel occurs within a very short time scale of about 10^{-22} seconds, which is roughly the time it takes to traverse the nuclear field. There is no creation and subsequent decay of a highly excited intermediate state, which results in an isotropic and forward-peaked angular distribution. Typical examples of direct reactions are elastic and inelastic scattering, charge transfer, stripping, pick-up, and knock-on processes [10]. Direct reactions become more probable as one increases the energy of the incident particle the wavelength associated to the particle decreases and localized areas of the nucleus can be probed by the projectile. In this context, peripheral reactions, where only a few nucleons of the surface participate become important. Direct reaction happens during a time of the order of 10^{-22} sec. reactions with formation compound nuclei can be up to six orders of magnitude slower. A reaction type at a given energy is not necessarily exclusive; the same final products can be obtained, part of the events in a direct way, other parts through the formation and decay of a compound nucleus [10].

There are two characteristic types of direct reactions. In the first the incident particle scatters in-elastically and the transferred energy is used to excite a collective mode of the nucleus. Rotational and vibrational bands can be studied in this way. The second type involves a modification in the nuclear composition. Examples are transfer of nucleons, as pick-up and stripping reactions. An important reaction of the latter kind is a knock-out reaction where

the incident particle knocks out a particle of the target nucleus and continues in its path, resulting in three reaction products. Reactions with nucleon exchange can also be used to excite collective states. An example is a pick-up reaction where a projectile captures a neutron from a deformed target and the product nucleus is in an excited state belonging to a rotational band. Direct reactions exhibit a peculiar form of angular distribution, which allows us to extract information on the reaction mechanism with the employment of simple models [9].

2.1.2 Compound Nuclear Reaction

Compound nucleus formation is a reaction in which two nuclei combine into a single excited nucleus; the excited nucleus lives for a relatively long time and forgets how it was formed. The decay from this state of excitation is by evaporation of nucleons from the heated liquid drop of the compound nucleus, by gamma decay, or by fission of the compound nucleus. The statistical nature of this process teaches us about the average properties of excited states of complex nuclei [11]. A compound nucleus reaction is given by:

$$a + A \rightarrow C^* \rightarrow b + B \tag{2.3}$$

The projectile is captured by the target and the two systems joined to form a highly excited state (the compound nucleus) C^*. The excitation energy is shared uniformly among the constituent nucleons. A nucleon or group of nucleons can be given enough energy to escape (random process) i.e, decay of C^*. If B (the product nucleus) has enough energy, more emissions can occur, otherwise it will de-excite by β decay or γ decay. The compound nucleus is a relatively long-lived intermediate state of particle-target composite system. It involves many nucleon-nucleon interactions. The large number of collisions between the nucleons leads to a thermal equilibrium inside the compound nucleus. The time scale of

compound nucleus reactions is of the order of $10^{-18}s$ - $10^{-16}s$. It is usually created if the projectile has low energy [12].

Incident particles interact in the volume of a target nucleus. Products of the compound nucleus reactions are distributed near isotropically in angle (the nucleus loses memory of how it was created the Bohr's hypothesis of independence). The mode of decay of compound nucleus does not depend on the way the compound nucleus is formed. Resonances in the cross- section are typical for the compound nucleus reaction [12].

At low energies, the largest probability is the continuation of the process so that the initial energy is distributed among all nucleons, with no emitted particle. The final nucleus with (A+1) nucleons has an excitation energy equal to the kinetic energy of the incident neutron plus the binding energy the neutron has in the new, highly unstable, nucleus. It can, among other processes, emit a neutron with the same or smaller energy to the one absorbed. The de-excitation process is not necessarily immediate and the excited nucleus can live a relatively long time [13]. We say that there is, in this situation, the formation of a compound nucleus as intermediary stage of the reaction. In the final stage the compound nucleus can evaporate one or more particles, fission, etc. In our notation, for the most common situation in which two final products are formed (the evaporated particle plus the residual nucleus or two fission fragments, etc.) [14].

2.1.3 Pre-Equilibrium Reactions

In the compound nucleus reaction the projectile is captured and initiates numerous collisions and the energy is distributed over the entire nucleus so that a thermal equilibrium is reached in a relatively long time ($\sim$ 10^{-14}–$10^{-16}s$). The hot liquid drop cools off by emitting one or more particles. We can expect some events to occur after the first stage of direct reaction is over but in relatively few collisions the compound nucleus evaporates long before the thermal equilibrium is reached. Such reactions are called pre-equilibrium

reactions or pre-compound reactions. Their time scale is intermediate between the very fast direct reactions and the relatively slow compound nucleus reactions. Direct evidence for pre-equilibrium reactions is provided by the energy spectra of particles at relatively high energy particles. They show conspicuous deviation from the Maxwellian distribution expected from compound nucleus reactions and by the presence of peak from the excitation of low lying energy level due to direct reactions [10].

On a time scale this process lays between the direct and the compound nucleus reactions. The particle is emitted before the energy is evenly distributed over all nucleons, thus giving a smooth forward-peaked angular distribution. Another characteristic is a pronounced high-energy tail in the excitation function [10].

When a low energy neutron ($< 50MeV$) enters the range of nuclear forces it can be scattered or begin a series of collisions with the nucleons. The products of these collisions, including the incident particle, will continue in their course, leading to new collisions and new changes of energy. During this process one or more particles can be emitted and they form with the residual nucleus the products of a reaction that is known as pre-equilibrium [5].

2.2 Nuclear Cross Sections

The nuclear cross section of a nucleus is used to describe the probability that a nuclear reaction will occur. The concept of a nuclear cross section can be quantified physically in terms of "characteristic area" where a larger area means a larger probability of interaction. The standard unit for measuring a nuclear cross section is denoted as (b) is the barn, which is equal to $10^{-28}m^2$, $10^{-24}cm^2 or 100fm^2$. Cross sections can be measured for all possible interaction processes together, in which case they are called total cross sections, or for specific processes, distinguishing elastic scattering and inelastic scattering; of the latter, amongst neutron cross sections the absorption cross sections are of particular interest. It is

a measure of probability that a specific process will take place in a collision of two particles. For example, the Rutherford cross-section is a measure of probability that an alpha particle will be deflected by a given angle during a collision with an atomic nucleus.

Cross section is typically denoted by "σ" and is expressed in terms of the transverse area that the incident particle must hit in order for the given process to Occur. When two particles interact, their mutual cross section is the area transverse to their relative motion within which they must meet in order to scatter from each other. In order to measure the probability quantitatively that a given nuclear reaction will take place we introduce the concept of cross-section. Consider a reaction of the type x(a,b)y . If I_o is the flux of particles 'a' incident per unit area on a target consisting N nuclei of type x, then the number of particles b emitted per unit time (I) will be proportional to both I_o and N. The constant of proportionality σ is called the cross-section which has the dimensions of area [10].

Thus $I \sim I_o N$

$$\sigma = \frac{I}{N I_o} \tag{2.4}$$

If the particles are hard inelastic spheres that interact only upon contact, their scattering cross section is related to their geometric size. If the particles interact through some action-at-a-distance force, such as electromagnetism or gravity, their scattering cross section is generally larger than their geometric size. When a cross section is specified as a function of some final-state variable, such as particle, angle or energy, it is called a differential cross section. When a cross section is integrated over all scattering angles (and possibly other variables), it is called a total cross section. Scattering cross sections may be defined in nuclear, atomic, and particle physics for collisions of accelerated beams of one type of particle with targets (either stationary or moving) of a second type of particle. The probability for any given reaction to occur is in proportion to its cross section. Thus, specifying the cross section for a given reaction is a proxy for stating the probability that a given scattering

process will occur. The measured reaction rate of a given process depends strongly on experimental variables such as the density of the target material, the intensity of the beam, the detection efficiency of the apparatus, or the angle setting of the detection apparatus. However, these quantities can be factored away, allowing measurement of the underlying two-particle collision cross section.

2.2.1 Scattering Cross Section

A scattering cross-section (σ), is a quantity proportional to the rate at which a particular radiation target interaction occurs. Once the double-differential cross-section is derived or measured, $(\frac{d\sigma}{d\omega})$ and σ can be calculated by integrating over the energy of the scattered radiation and solid angle. Thus, σ_s may denote the cross section for scattering of a given kind of particle, and may consist of two parts, σ_e the cross section for elastic scattering, and σ_{in} the cross section for inelastic scattering. There are also cross sections for individual reactions, such as $\sigma(\alpha, p)$, $\sigma(\alpha, n)$, and $\sigma(p, \alpha)$. Let's notice something about the overall behavior of the scattering event. There is a region of space, with cross-sectional area σ, that projectiles cannot pass through. If the incoming path of a projectile passes through this cross sectional area, it will be deflected off at some angle. For this reason, we define σ to be the scattering cross section for this potential. The scattering cross section gives us an intuitive sense of how much area is blocked out by the target during a scattering event.

2.2.2 Reaction Cross Section

Roughly speaking the cross section is a measure of the relative probability for the reaction to occur. If we have a detector placed to record particle b emitted in a direction (ϕ) with respect to the beam direction, the detector defines a small solid angle ($d\omega$) at the target nucleus. Let the current of incident particles be I_a particles per unit time, and let the target

show to the beam N target nuclei per unit area. If the outgoing particles appear at a rate R_b then the reaction cross section is [9]:

$$\sigma = \frac{R_b}{NI_a} \tag{2.5}$$

It is usually given in barns ($1b = 10^{-28}m^2$)

The term "cross section" has already been met in connection with the attenuation of a ray beam, when it was used as a measure of the probability that a photon is removed from the beam; the cross section was regarded there as a form of absorption coefficient. In the discussion of nuclear reactions, a more detailed consideration of the idea of cross sections will prove useful. The concept of a nuclear cross section can be most easily visualized as the cross sectional area, or target area, presented by a nucleus to an incident particle [14]. If the nuclei are considered as spheres of radius R cm and the incident particles as point projectiles, then the target area, or cross section *sigma*, of each nucleus is given by:

$$\sigma = \pi R^2 cm^2 \tag{2.6}$$

2.2.3 Total Cross Section

There is still another cross section that may be of interest, the total cross section at σ_t here, for a specific incident particle a, we add the reaction cross sections σ for all possible different outgoing particles b, no matter what their direction or energy. Such a determination would tell us the probability for an incident particle to have any reaction at all with the target and thus be removed from the beam of incident particles. This can be deduced directly by measuring the loss in intensity of a collimated beam in passing through a certain thickness of the target material. For the same entrance channel a number of exit channels will be open corresponding to different reaction products at a given energy. As the exit channels are

independent, there will not be any quantum interference and the cross-section of different reaction channels may be added. The sum of all these non-elastic channels cross-section is called the reaction or absorption cross-sections and is denoted by σ_r When the elastic cross-section is also added we speak of the total cross-section [15].

$$\sigma_t = \sigma_r + \sigma_{el} \tag{2.7}$$

For a given bombarding particle and target can react in a variety of ways producing a variety of light reaction products n_1, n_2, n_3 per unit time. Then the total cross section is:

$$\sigma_{tot} = \frac{n_1 + n_2 + n_3}{\frac{I}{A}\rho A d} \tag{2.8}$$

It is convenient to define also a partial cross section for the i^{th} process by:

$$\sigma_{tot} = \frac{n}{\frac{I}{A}\rho A d} \tag{2.9}$$

Where σ_{tot} is total area, $\frac{I}{A}$ is intensity per unit area, ρ is density of emitted particle and d is thickness of material.

2.3 Alpha Induced Reactions

Studies on charged particle induced reaction cross sections as a function of projectile energy, which is also called as the excitation function has various practical applications. Those applications are thin layer activation for testing reaction theory and for the studies of behavior of materials by particle irradiation. It is also important from the point of accelerator technology, medical radioisotope production etc. Most of the isotopes produced from charged particle induced reactions are positron emitter and thus useful in positron emission

tomography (PET). In PET a positron emitting radionuclide or tracer able to track a specific biologic process at molecular level is injected into the patient. As these radioactive tracers decay, they emit positrons, which are then detected using a PET scanner. The resulting images will help to distinguish between normal and abnormal biological tissue sites [16].

Excitation function is a term used in nuclear physics to describe a graphical plot of the yield of a radionuclide or reaction channel as a function of the bombarding projectile energy or the calculated excitation energy of the compound nucleus. The distribution of the cross-section as a function of the beam energy is called the 'excitation function. The excitation function typically resembles a Gaussian bell curve. Mathematically, it is described as a Breit-Wigner function, owing to the resonant nature of the production of the compound nucleus. Alpha particles, also called alpha rays or alpha radiation, consist of two protons and two neutrons bound together into a particle identical to a helium-4 nucleus. They are generally produced in the process of alpha decay, but may also be produced in other ways.

During the process of nuclear decay, the liberated energy (decay energy) is shared between the daughter nucleus and the alpha particle. The two neutrons of an alpha particle give it additional mass that further facilitates ionization by columbic interaction or even direct collision of the alpha particle with atomic electrons. Alpha particles as well as other types of charged particles dissipate their energy during these collisions mainly by two mechanisms: ionization and electron excitation. The high mass and charge of an alpha particle, relative to other forms of nuclear radiation, give it greater ionization power but a weak ability to penetrate matter. However, electron excitation occurs when the alpha particle fails to impart sufficient energy to an atomic electron for it to be ejected from the atom. Rather, the atoms or molecules of a given material absorb a portion of the alpha-particle energy and become elevated to a higher energy state [17].

Alpha particles exhibit three important characteristics: scattering, ionization and activation. Among others, alpha particles are used in elemental analysis, investigation and improvement

of materials properties, nuclear reaction studies and medical radionuclide production. Alpha induced reaction on zinc isotopes is a process used to produce isotopes of Germanium ^{66}Ge,^{68}Ge,^{69}Ge and isotopes of Gallium ^{66}Ga,^{67}Ga,^{69}Ga,^{71}Ga,^{72}Ga,^{73}Ga.

The production cross sections of ^{68}Ge, ^{69}Ge and ^{66}Ga, ^{67}Ga by α-induced reactions on ^{nat}Zn will be measured using the stacked-foil activation method and off-line γ-ray spectrometry from their threshold energies to 50 MeV.

2.4 The Zinc Element and Its Isotopes

Zinc is a chemical element with the symbol Zn and atomic number 30. Zinc is a slightly brittle metal at room temperature and has a silvery-grayish appearance when oxidation is removed. It is the first element in group 12 (IIB) of the periodic table. Most zinc is used to galvanize other metals, such as iron, to prevent rusting.

- Zinc melts at 787 $^0F(420^0C)$, and boils at 1,665 $^0F(907^0C)$.
- Zinc comprises an estimated 0.004% of the Earth's crust.
- Zinc ranks 24^{th} in order of material abundance in the Earth

Zinc is a mineral that is essential to the body and is a constituent of many enzymes that permit chemical reactions to proceed at normal rates. Zinc is involved in the manufacture of protein (protein synthesis) and in cell division. Zinc is also a constituent of insulin, and it is involved with the sense of smell [23].

There are two types of decay chains, single step and many steps decay chain. If the decay is a one step process, it means that a stable atom is formed, like in case of ^{60}Co in to ^{60}Ni. On the other hand, nucleus of the decay product, which is called its daughter, might be unstable and this result in other decay till the daughter nuclei is stable. This multiple step is called a decay series.The thorium (4n) series, the uranium (4n+2) series, the actinium (4n+3) series are the three naturally occurring unstable radioactive elements. The fourth

set, the neptunium (4n+1) series, produced artificially by a nuclear reaction and do not occur naturally. The decay of ^{238}U to ^{208}Pb is an example of decay series [17].

Naturally occurring zinc ($_{30}Zn$) is composed of 5 stable isotopes ^{64}Zn, ^{66}Zn, ^{67}Zn, ^{68}Zn, and ^{70}Zn with ^{64}Zn being the most abundant (48.6% natural abundance). Twenty-five radioisotopes have been characterized with the most abundant and stable being ^{65}Zn with a half-life of 244.26 days, and ^{72}Zn with a half-life of 46.5 hours. All of the remaining radioactive isotopes have half-lives that are less than 14 hours and the majority of these have half-lives that are less than 1 second. This element also has 10 Meta states. Zinc has been proposed as a "salting" material for nuclear weapons. A jacket of isotopic ally enriched ^{64}Zn, irradiated by the intense high-energy neutron flux from an exploding thermonuclear weapon, would transmute into the radioactive isotope ^{65}Zn with a half-life of 244 days and produce approximately 1.115 MeV of gamma radiation, significantly increasing the radioactivity of the weapon's fallout for several years. Such a weapon is not known to have ever been built, tested, or used [14].

Zinc isotopes are used extensively in both industrial and medical applications. Depleted ^{64}Zn is added to the cooling water of nuclear reactors in the form of oxide or acetate to prevent stress corrosion cracking [3].

It also reduces the release of (stable) ^{59}Co into the cooling water by forming a thin spinel layer on the Co containing steel surfaces. Neutron irradiation of ^{59}Co will result in the formation of ^{60}Co a radioisotope which emits high energy gamma radiation and is a major contributor to the dose rate of personnel working in the reactor [24].

Enriched ^{67}Zn can also be used for the production of radioactive ^{67}Ga in smaller cyclotrons. However, by far most Ga-67 is made from ^{68}Zn, ^{67}Zn, and ^{70}Zn can all be used for the production of the therapeutic isotope ^{67}Cu. ^{66}Zn has been proposed as an alternative target for the production of ^{64}Cu and ^{67}Ga. Finally ^{70}Zn is also used in biological research and in research into super-heavy elements [4].

Chapter 3

Methodology

3.1 Materials

The research used standard literatures, books, websites, EXFOR data library of IAEA for the experimental excitation function and the COMPLET code for the theoretical excitation function.

3.2 Method of Data Presentation and Analysis

The experimental cross section data has been explored from EXFOR data Library, IAEA. Then the data has been plotted as a function of projectile energy called experimental excitation function. The COMPLET code is used to calculate the reaction cross section for the selected channels. This code calculates the excitation function of light and heavy-ion induced reactions.

When calculation is performed the Exciton numbers to non-zero or zero for pre equilibrium or compound nucleus were used. Based on the excitation number, the compound nucleus and pre-equilibrium reaction calculations were selected. The other necessary inputs to use

for the code are the channel energy, atomic and mass numbers of the projectile and the target, and the level density parameter (K).

The result of the COMPLET code calculation of the cross sections has been displayed in tables and graphs together with data obtained from EXFOR library, of IAEA data source. Both results are used in plotting graph of excitation function (graph of cross section vs. energy). Thus, the discussion was followed based on displayed data in tables and plotted graphs. Finally, conclusions on the dependency of nuclear reaction cross section vs alpha energy for given range energy below 50MeV for the two channels have been presented.

The COMPLET code gives the results of both equilibrium (CN) reaction and preequilibrium (PEQ) reaction. Level densities of the residual nuclei play an important role In deciding the shapes and absolute value of the excitation functions. In COMPLET code the level density parameter 'a', which largely affects the equilibrium components of the cross-section is calculated from the expression $a = \frac{A}{k}$ MeV where A is the nucleon number of a compound system and k is an adjustable constant, which may be varied to match the experimental data. Also in this code, the pre-equilibrium components of the cross-section are sensitive to initial exciton configuration, number, and mean free path multiplier, MFM. The sensitivity of the initial exciton number on Pre-equilibrium cross-section was done by varying the initial exciton configuration, no (n+p+h) which is described by the number of neutrons (n) and by the number of a proton (p) in excited states, and the the number of holes (h) following the first interaction of a projectile with a target. The total exciton no is equal to the sum of n, p and h. The code COMPLET provides yields and spectra for all reactions populated by all combinations of n, p, d, alpha and can provide all input parameters internally. The running time of the code is very short. This code includes damping of fission widths above a critical temperature R0. The used code is a further simplification of the formulae due to Paul and Thoennessen in Ann.Rev.Nucl and particle science 44(1944). The code COMPLET includes pre-equilibrium neutron, proton and alpha emission up to two particle, as well as evaporation

of neutrons, protons, alphas, deuterons, tritons and hellions. Originally, this code has been developed out of the code OVERLAID ALICE by M.Blann, while some standard routines remained practically 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 underlying PE-MODEL is described in Z.Phys.A328 (1989).It is contained in subroutine INDEX. The INPUT is described below. The notion card from the old FORTRAN input is still kept but now corresponds to lines. Free formats, the input values should be separated by, or CR.

CARD 1 - GENERAL INPUT DATA AP Projectile mass number

AT Target mass number

ZP Projectile charge

ZT Target charge

QVAL Reaction Qvalue = 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 $\leq$ 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 $\leq$ 0 or IKE $\geq$ 6 most reduced output:

emitting nuclides and all partial waves) of pre-compound plus equilibrium spectra. To print gamma spectra, increase the IKE value selected by 5.

If IPCH =1 or =2, fission barriers are to be read in after this first record IPCH = - 1: inverse cross sections will be readout for possible future use in separate output file.

= 0: or NE from 1.no printout

KPLT - number of decades to be plotted as excitation function on line printer. If

KPLT = 0: no plotting

Card 2 Title - 80 columns

If MC = 2 on CARD 1, read user supplied n, p,alpha, deuteron triton and helion binding energies here, Format for IA = 1 to NA, IZ = 1 to NZ.

If INVER = 0 on CARD1, read the n, p, alpha, deuteron triton, helion and gamma inverse cross sections here.

In ascending channel energy, first value = 0.1 Mev, incremented by 1Mev, 48 values per particle type in sequence N,P,A,D,T,3HE, and gamma depending on value of M3.

CARD 3 energy, compound nucleus and pre-equilibrium option

Symbol Description

IKEN - projectile kinetic energy in the laboratory system.

If = 0: A new problem will begin at CARD1.

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

If EKIN = 0 on two successive cards, a normal exit will occur for negative target mass on card 1.

RCSS = 0: reaction cross section is calculated from subroutine (for pi-induced reactions: if RCSS (input) =0, RCSS=100 mb) >: number of T(l) values to be read from the next card

JCAL

= 1, weisskopf-ewing evaporation calculation

= 2, S - wave approximation, liquid drop moment of inertia

= 3, S - wave approximation, rigid body moment of inertia (only if entrance channel cross sections calculated by parabolic approximation, i.e.. ZP >1 and RCSS= 0.)

=0, evaporation-fission competition, partial wave by partial wave.

JFRAC - direct - semi-direct capture gamma ray estimate :<0: no emission >0: approach of kalka

JANG - JANG + 1 = maximum number of contributing incoming partial waves.

Usually use the maximum: JANG = 99. Otherwise, JANG can be used for cutoff on L- values provided by subroutines OVER1 and 2

All other parameters on this card are for the pre-compound calculation options. Put TD-values to zero, if no pre-compound calculation is wanted.

TD - Initial exciton number =p+h

EX1 - Initial excited neutron number

EX2 - Initial excited proton number

EX3 - Initial alpha particle exciton number

POT - Fermi energy in Mev

If = 0: POT is calculate from nucl.matter value= 37.8 Mev;

AV - if AV = 0: = 1 OPTICAL MODEL mean free paths are used in routine MFP.

Not to be used above 55 Mev

If AV = 1: Nucleon - Nucleon mean free paths are used in NUCMFP.

ALF - probability that newly created exciton particle from first stage exciton gets an alpha particle in the second stage.

(1-ALF): complementary probability

If ALF >1 calculation for two initial exiton numbers

A)ATD=TD-3 (min.1.5) AEX1=AEX2=0. AEX3=2;ATD=TD-6 for T D¿9 with weight

ULF=INT (ALF)100

B)Weight = (1-ULF), with initial exciton numbers.

CMFP - mean free paths are multiplied by CMFP.if CMFP =0:multiplier is 1

GDO - critical angular momentum. GDO>0: partial waves with L>GDO are not taken in to account in line of isotone cross sections while cross sections for partial waves with L>GDO are accounted for in the line below

N.B For GDO $\leq +0.5 Nocut - off$.

In this thesis, different initial exciton numbers have been used for each reaction channel based on the closeness of the calculated values and the experimental values. The other important parameter is a level density parameter and also its value has been chosen as the calculated values fit the experimental values. When calculation was performed the Exciton numbers to non-zero or zero for pre equilibrium or compound nucleus respectively has been used. The other necessary inputs used for the code are the channel energy, atomic and mass numbers of the projectile and the target, and the level density parameter. The other

important parameter that plays a great role in calculating reaction cross section is exciton numbers ($n_o = E_{X1} + E_{X2} + E_{X3}$). This was set to which the calculated values best fit with experimental values in each reaction [25].

The compound nucleus formed by bombarding particle (alpha) is de-excited by evaporating one or more neutrons. If the excitation energy is sufficient, then the evaporation of one particle may leave enough energy to enable the second particle to leave, and so on. The probability of decay through a large number of the particle increases with greater excitation. When little excitation is left, particle emission ceases and only gamma emission is possible [25].

Exciton Number

The exciton number is found to play an important role in the calculated predictions for pre-equilibrium reactions. But it hasn't affected on compound nucleus reaction. So in this thesis, the exciton number which is used in the selected reaction channels of pre equilibrium reactions are given in table 4.1 below.

Table 3.1: Exciton number of selected pre-equilibrium reaction channels in this study

S.No	Reactions channels	Total exciton number	Configuration
1	${}^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$	6	(4He+1n+1h)
2	${}^{108}_{48}Cd(\alpha,n)^{111}_{50}Sn$	6	(4He+1n+1h)
3	${}^{114}_{48}Cd(\alpha,2n)^{116}_{50}Sn$	8	(4He+2n+2h)
4	${}^{114}_{48}Cd(\alpha,3n)^{115}_{50}Sn$	10	(4He+3n+3h)

Level Density Parameter

Level density parameter also plays an important role in calculating the nuclear reaction model statistically, such as in calculating the evaporation model of nuclear reaction and in the studies of different energy ranges of nuclear reaction. The level density parameter obtained by the experiment shows a linear dependence with the mass number of the compound nucleus [**?**]. In general, it is given by an expression:

$$a = \frac{ACN}{K} \tag{3.1}$$

where ACN is the mass of the compound nucleus and K is the free constant.

In this thesis, the level density parameter was employed for respective reactions, which gives the best fit to experimental results. The cause for the variation of the value of K here is seeking the best fit to the experimentally measured excitation function. However, the effort had been made to use the same K value for analogous reaction channels of the isotopes for reasonable comparison [**?**].

The nuclear level density $\rho(E)$ is a characteristic property of every nucleus and it is defined as the number of levels per unit of energy at certain excitation energy [**?**].

The calculated cross sections were displayed in tables and graphs together with data obtained from the IAEA data source, EXFOR library. Both results were used in plotting the graph of excitation function (graph of cross section Vs energy).

Then the discussion was followed based on displayed data in tables and plotted graphs. Finally, conclusions on the dependence of nuclear reaction cross section on alpha energy of given range for (α, n) reaction channels were drawn.

Chapter 4

Result and Discussion

4.1 Result and Discussion

In this chapter, the result of the calculations on the excitation functions of five reactions were presented. Those reaction are: ${}^{64}_{30}Zn(\alpha,p){}^{67}_{31}Ga$, ${}^{68}_{30}Zn(\alpha,n){}^{71}_{32}Ge$, ${}^{64}_{30}Zn(\alpha,n+p){}^{66}_{31}Ga$, ${}^{70}_{30}Zn(\alpha,p){}^{73}_{31}Ga$, and ${}^{68}_{30}Zn(\alpha,3n){}^{69}_{32}Ge$ in the alpha energy range below 50MeV. The experimental reaction cross section is obtained from IAEA data source, EXFOR library [21].

The theoretical calculation is performed for two reaction mechanisms. These are for pre-equilibrium and for compound nucleus mechanisms. Excitation function produced by the reaction of alpha particle with the target of some stable isotopes of Zinc with different reaction channels have been compared with experimental data. The energy range selected from the experimental data EXFOR is same with calculated data of compound nucleus and pre-equilibrium reaction. Various parameters used for calculations of excitation functions, however, exciton number is found to be play a crucial role in performing calculated values. For the pre-equilibrium stage of the reactions and shifting slightly the value of the level density parameter was used to recalculate the data to get better fit of the experimental data.

In this thesis, different exciton numbers have been used for each reaction channels. The other

important parameter is a level density parameter (K) and also its value has been chosen as the calculated values fit the experimental values. The experimental reaction cross sections and the calculated reaction cross sections are plotted against alpha energy as shown in Figure 4.1 to 4.5. Both calculated excitation functions and experimental excitation functions are shown by colored line. The compound nucleus formed by bombarding particle (alpha) is de-excited by evaporating one neutron and proton. If the excitation energy is sufficient, then the evaporation of one particle may leave enough energy to enable the second particle to leave and so on. The probability of decay through a large number of particle increases with greater excitation. When little excitation is left, particle emission ceases and only gamma emission is possible.

4.1.1 Calculation of the Cross section for $^{64}_{30}Zn(\alpha,p)^{67}_{31}Ga$

For this reaction channel the total experimental reaction cross section data obtained from EXFOR Library [18]. In the reaction, alpha flux of energy in the range 12.8 to 35.3 MeV as shown in Table 4.1 were incident on to a Zinc target $^{64}_{30}Zn$ nucleus to give one proton and a residue of $^{67}_{31}Ga$. The theoretical reaction was calculated using COMPLET computer code, for compound nucleus and pre-equilibrium stages of reaction. The data obtained has been displayed in the table 4.1.

Table 4.1: Experimental and Theoretical Cross section for $^{64}_{30}Zn(\alpha,p)^{67}_{31}Ga$

Alpha energy(MeV)	σ (Exp)	σ(Compound)	σ (pre-equilibrium)
12.8	259	256.8	236.0
15	396	347.3	250.1
16.7	455	394.1	307.1
18.4	506	430.8	450.0
20.2	420	273.1	398.5
21.8	422	395.7	400.8
23.2	330	260.1	272.1
24.6	241	171.2	197.7
26.0	217	161.3	167.0
27.2	161	118.7	132.3
28.3	154	106.2	109.1
29.5	94	123.0	100.2
30.7	115	75.1	81.7
32.0	60	81.8	63.2
33.1	80	67.2	73.8
34.1	50	78.1	47.8
35.3	60	70.0	53.7

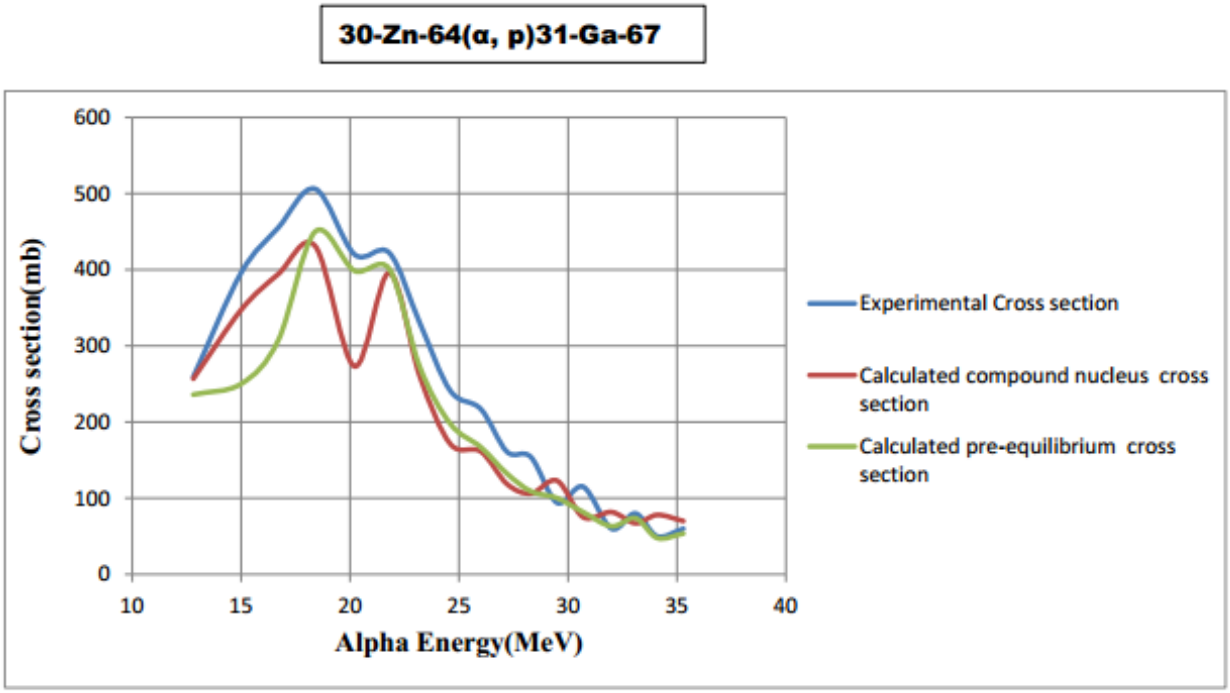

Figure 4.1: Experimental and Theoretical excitation function for the reaction ${}^{64}_{30}Zn(\alpha,p){}^{67}_{31}Ga$

Table 4.1 and Fig. 4.1 show that the probability of the reactions depend on the energy of the projectile. As shown in the Fig. 4.1. If we gradually increase the energy beyond 12.8MeV the cross section of compound nucleus reaction approaches the experimental curve with less error than the pre-equilibrium reaction cross section. In the region of the curve below the 16.7MeV projectile energy we expect that a compound nucleus is formed from the reaction ${}^{64}_{30}Zn(\alpha,p){}^{67}_{31}Ga$. Then the compound nucleus decays (evaporates) by an emission of one proton with a certain decay probability. The cross section values in both the COMPLET code calculation and experiment agree well and increases with increasing energy to the maximum at energy 18.4MeV, that could be the resonance peak for the pre-equilibrium stage of the nuclear reaction.

At higher energies beyond 28.3MeV, the pre-equilibrium reaction cross section reaction better approximates the experiment but the error between the compound nucleus and the pre-

equilibrium reaction cross section reactions is not high as shown from the graph the energies from 21.8MeV to 28.3MeV both curves tend to follow approximately similar passion. The reason for the compound nucleus cross section calculation approximates the experimental reaction better at lower energy regions of the reaction, because from its properties that at lower energies the compound nucleus dominates the reaction and the pre-equilibrium calculated cross section approaches better the experimental reaction at higher energy regions. For energies beyond 28.3MeV the experimental and both theoretical reaction cross sections overlap. This is due to personal errors and choice of variables in the code.

4.1.2 Calculation of the Cross section for $^{68}_{30}Zn(\alpha, n)^{71}_{32}Ge$

For this reaction channel the total experimental reaction cross section data obtained from EXFOR Library [19]. In this reaction, a alpha flux of energy in the range 14.56 to 20.32 MeV as shown in Table 4.2 were assumed incident on to a Zinc target $^{68}_{30}Zn$ nucleus to give one neutron and a residue of $^{71}_{32}Ge$. The reaction was calculated using COMPLET computer code, for compound nucleus and pre-equilibrium stages of reaction. The data obtained has been displayed in the table 4.2.

Table 4.2: Experimental and Theoretical Cross section for $^{68}_{30}Zn(\alpha, n)^{71}_{32}Ge$

Alpha energy(MeV)	σ (Exp)	σ(Compound)	σ (pre-equilibrium)
14.56	440	490.2	495.2
14.83	430	450.0	450.5
16.33	700	715.5	720.5
17.97	730	710.0	715.0
18.82	550	288.7	410.1
20.32	330	261.3	327.1

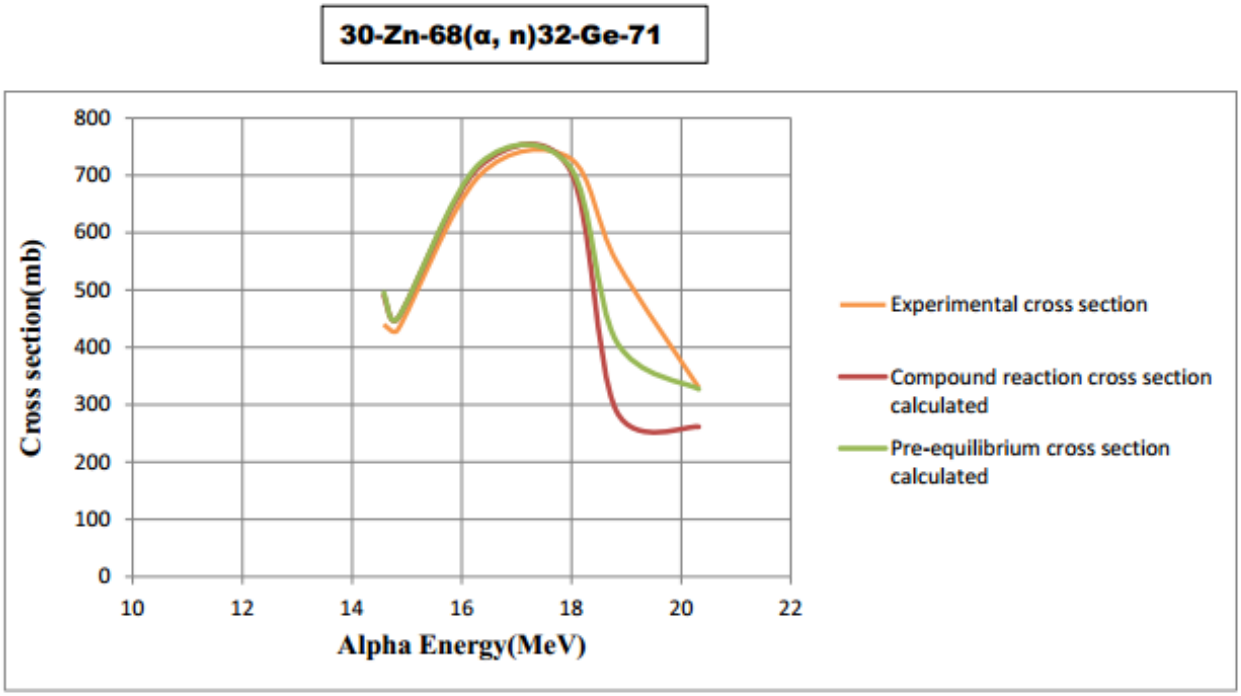

Figure 4.2: Experimental and Theoretical excitation function for the reaction ${}^{68}_{30}Zn(\alpha, n)^{71}_{32}Ge$

Table 4.2 and Fig, 4.2 show that the nature of the reactions depend on the energy of the projectile. As shown in the Fig. 4.2., the result of the cross sections in this calculation agree well with experiment in literature, i.e., both attains their minimum and maximum at equal energy points. If we gradually increase the energy beyond 15MeV, the dominant reaction is expected to be the compound nucleus reaction, since compound nucleus reaction cross section curve assumes less error from the experiment than the pre-equilibrium curve. In the region of the curve about below the 16.33MeV projectile energy we expect that a compound nucleus is formed from the reaction ${}^{68}_{30}Zn(\alpha, n)^{71}_{32}Ge$. Then the compound nucleus decays by an emission of one neutron with a certain decay probability given by the cross section in the Fig.4.2 for the compound nucleus reaction. After 16.33MeV of the projectile energy as seen from the graph, the pre-equilibrium stage of the reaction happens to dominate, because the pre-equilibrium stage starts at energy above the energy of the formation of the compound

nucleus by its property and from the Fig.4.2 the curve of the pre- equilibrium reaction approaches the experiment curve with less error than the compound nucleus. Thus the cross section values in both the COMPLET CODE calculation and the experiment agree well and decreases with increasing energy to the maximum at energy 17.97MeV, that could be the resonance peak for the pre-equilibrium stage of the nuclear reaction. For all energy both the experimental and the theoretical calculated pre-equilibrium reaction and compound nuclear reactions seem undeviating, except for energy range between 18.82MeV to 20.32MeV. A higher deviation seen for higher energy. The reason for this deviation may be related to choice of variable in the code.

4.1.3 Calculation of the Cross section for $^{64}_{30}Zn(\alpha, n+p)^{66}_{31}Ga$

For this reaction channel the total experimental reaction cross section data obtained from EXFOR Library [20]. In this reaction, a alpha flux of energy in the range 18.9MeV to 31.4MeV as shown in table 4.3 were assumed incident on to a Zinc target $^{64}_{30}Zn$ nucleus to give one proton and one neutron, and a residue of $^{66}_{31}Ga$. The reaction was calculated using COMPLET computer code, for compound nucleus and pre-equilibrium stages of reaction. The data obtained has been displayed in the table 4.3.

Table 4.3: Experimental and Theoretical Cross section for$^{64}_{30}Zn(\alpha, n+p)^{66}_{31}Ga$

Alpha energy(MeV)	σ (Exp)	σ(Compound)	σ (pre-equilibrium)
18.9	1	2.6	2.7
20.7	19	16.3	17.4
23.3	223	152.9	173.7
28.3	577	161.5	297.2
30.3	724	269.5	302.9
31.4	753	206.7	227.6

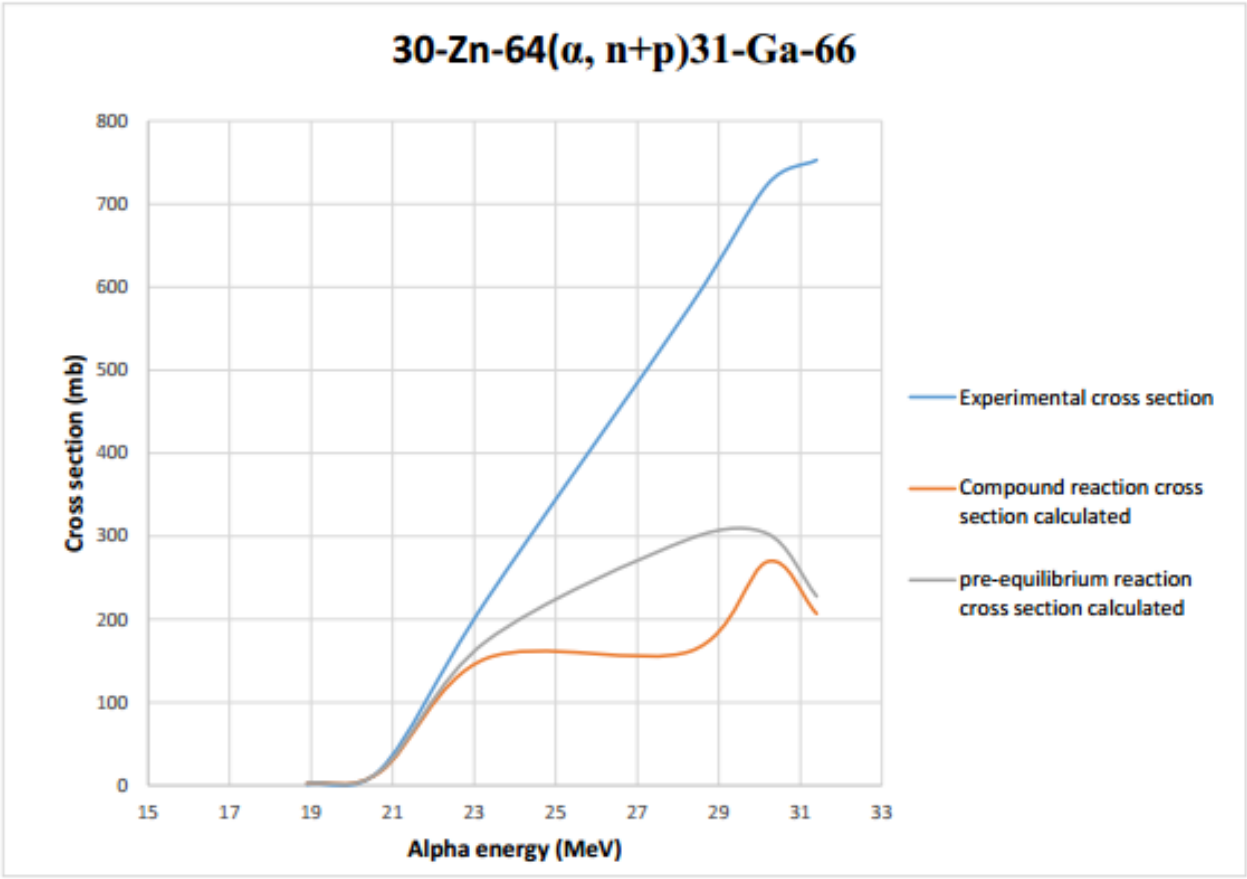

Figure 4.3: Experimental and Theoretical excitation function for the reaction ${}^{64}_{30}Zn(\alpha, n + p){}^{66}_{31}Ga$

Table 4.3 and Fig. 4.3 show that the characteristics of the reactions depend on the energy of the Projectile. At the low energy region of the curve near 18.9MeV the compound nucleus reaction is seen to dominate over the pre-equilibrium reaction i.e. compound nucleus is formed from the reaction ${}^{64}_{30}Zn(\alpha, n + p){}^{66}_{31}Ga$. Then the compound nucleus decomposes by an emission of one neutron and one proton with a certain decay probability. As of the projectile energy increases from 20.7MeV as seen from the graph, the pre-equilibrium stage dominates the reaction than the compound nucleus reaction. Staring from energy 23.3MeV, a higher deviation is seen between experimental cross section and both calculated reactions

cross sections. From the graph at energy 30.3MeV the resonance peak for the pre-equilibrium stage of the nuclear reaction is as certained.

This can be explained by the curve of the pre-equilibrium reaction is relatively approaches the experimental cross section curve with less error. In the region of energy above 28.3MeV both the equilibrium and pre-equilibrium reaction cross section curves deviate very far from the experimental cross section curve. The error is mainly due to the high energy region is dominated by other stage of reaction like direct reaction. Of course the calculation was not error free so that there is some contribution from errors and choice of variables in the code.

4.1.4 Calculation of the Cross section for $^{70}_{30}Zn(\alpha,p)^{73}_{31}Ga$

For this reaction channel the total experimental reaction cross section data obtained from EXFOR Library [21]. In this reaction, a alpha flux of energy in the range 14.8 to 24.4 MeV as shown in Table 4.4 were assumed incident on to a Zinc target $^{70}_{30}Zn$ nucleus to give a proton and a residue of $^{73}_{31}Ga$.The reaction was calculated using COMPLET computer code, for compound nucleus and pre-equilibrium stages of reaction. The data obtained has been displayed in the table 4.4.

Table 4.4: Experimental and Theoretical Cross section for $^{70}_{30}Zn(\alpha,p)^{73}_{31}Ga$

Alpha energy(MeV)	σ (Exp)	σ(Compound)	σ (pre-equilibrium)
14.8	3	3.74	3.73
16.4	7	8.10	8.01
18.2	12	10.32	8.66
19.1	14	11.02	10.20
20.0	16	13.87	12.54
20.6	17	15.02	14.26
22.4	16	6.12	13.10
23.4	11	4.81	10.30
24.4	6	4.32	5.60

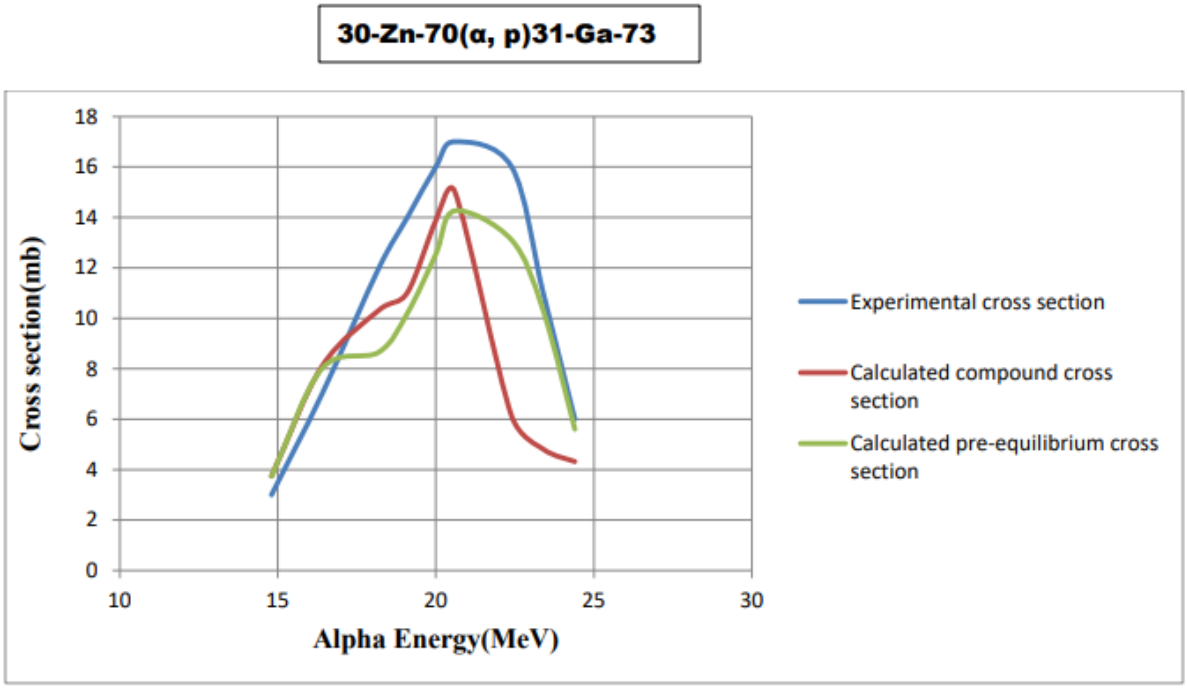

Figure 4.4: Experimental and Theoretical excitation function for the reaction ${}^{70}_{30}Zn(\alpha,p){}^{73}_{31}Ga$

Table 4.4 and Fig. 4.4 showed that the features of the reactions depend on the energy of the projectile. Near the low energies between 14.8MeV to 16.4MeV region of the curve in the Fig 4.4, the compound and pre-equilibrium cross sections are very close to experimental cross section. Higher deviation between the experiment and the calculated cross sections is observed between energies 18.2MeV to 22.4MeV. If we gradually increase the energy beyond 18.2MeV, the dominant reaction is predicted to be the compound nucleus reaction. In the region of the curve below 20.6MeV projectile energy we expect that a compound nucleus is formed from the reaction ${}^{70}_{30}Zn(\alpha,p){}^{73}_{31}Ga$.Then the compound nucleus decays (evaporates) by an emission of one proton with a certain decay probability.

The compound nucleus cross section calculation approximates the experimental reaction better at lower energy regions of the reaction. The pre-equilibrium calculated cross section approaches better the experimental reaction at higher energy regions of the graph shown

in the fig.4.4, because the pre-equilibrium reaction dominates relatively at higher energies than the compound nucleus reaction. If we gradually increase the energy beyond 20.6MeV, of the projectile energy as seen from the graph, the pre-equilibrium stage of the reaction happens to begin, because the pre-equilibrium stage starts at energy above the energy of the formation of the compound nucleus. Thus the cross section values in both the COMPLET code calculations and experiment agrees well and increases with increasing energy to the maximum at energy 20.6MeV, that could be the resonance peak for the pre-equilibrium stage of the nuclear reaction. After 20.6MeV both theoretical and experimental reaction cross sections values are seen with similar pattern.

4.1.5 Calculation of the Cross section for $^{68}_{30}Zn(\alpha, 3n)^{69}_{32}Ge$

For this reaction channel the total experimental reaction cross section data obtained from EXFOR Library [26]. In this reaction, a alpha flux of energy in the range 31.4 to 38.6 MeV as shown in Table 4.5 were assumed incident on to a Zinc target $^{68}_{30}Zn$ nucleus to give three neutron and a residue of $^{69}_{32}Ge$.The reaction was calculated using COMPLET computer code, for compound nucleus and pre-equilibrium stages of reaction. The data obtained has been displayed in the table 4.5.

Table 4.5: Experimental and Theoretical Cross section for $^{68}_{30}Zn(\alpha, 3n)^{69}_{32}Ge$

Alpha energy(MeV)	σ (Exp)	σ(Compound)	σ (pre-equilibrium)
31.4	95	59.17	65.31
32.0	110	105.0	115.5
32.5	137	174.1	294.4
33.1	187	293.7	307.4
33.6	191	312.2	314.4
34.1	243	322.1	342.2
34.7	292	352.4	354.6
35.7	353	314.5	316.9
36.7	427	325.3	335.1
37.7	455	432.6	436.2
38.6	502	468.6	395.2

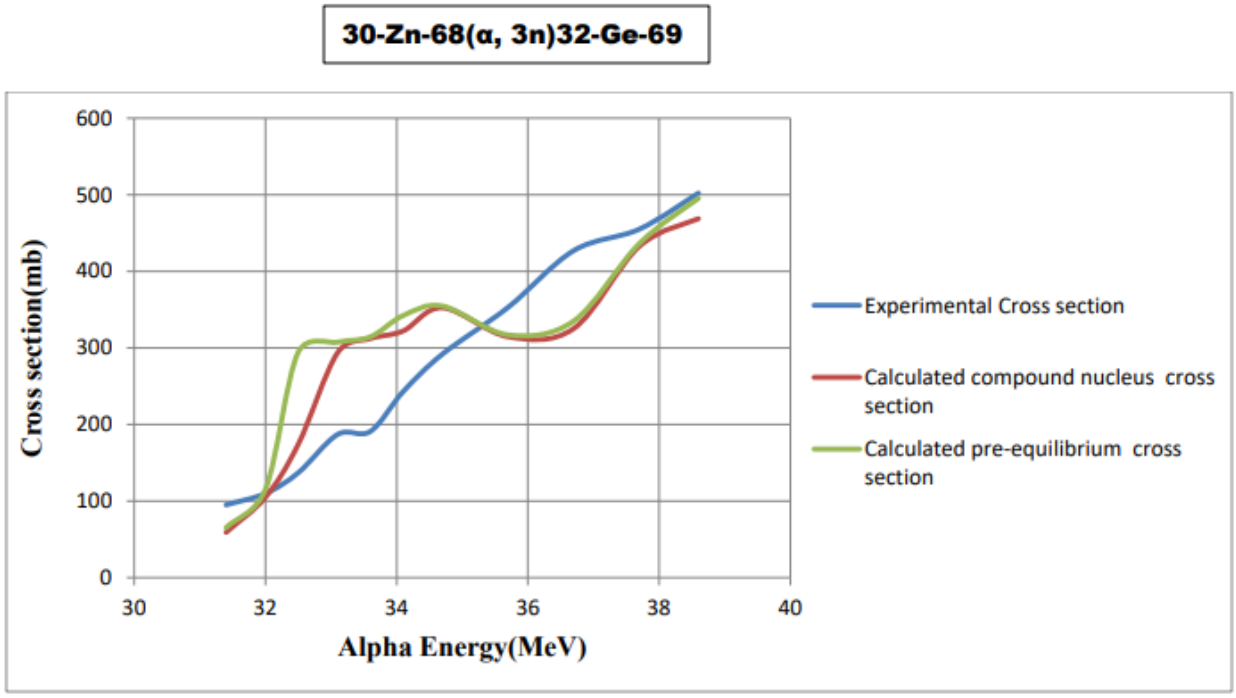

Figure 4.5: Experimental and Theoretical excitation function for the reaction ${}^{68}_{30}Zn(\alpha, 3n){}^{69}_{32}Ge$

Table 4.5 and Fig. 4.5 showed that the features of the reactions depend on the energy of the projectile. Near the low energies between 31.4MeV to 32.5MeV region of the curve in the Fig 4.5, the compound and pre-equilibrium cross sections are very close to experimental cross section. Higher deviation between the experiment and the calculated cross sections is observed between energies 31.1MeV to 34.7MeV. The reason for this deviation may be related to choice of variable in the code. If we gradually increase the energy beyond 32.5MeV, the dominant reaction is predicted to be the compound nucleus reaction. In the region of the curve below 34.5MeV projectile energy we expect that a compound nucleus is formed from the reaction ${}^{68}_{30}Zn(\alpha, 3n){}^{69}_{32}Ge$.Then the compound nucleus decays (evaporates) by an emission of three neutron with a certain decay probability.

The compound nucleus cross section calculation approximates the experimental reaction

better at lower energy regions of the reaction. The pre-equilibrium calculated cross section approaches better the experimental reaction at higher energy regions of the graph shown in the fig.4.5, because the pre-equilibrium reaction dominates relatively at higher energies than the compound nucleus reaction. If we gradually increase the energy beyond 35.5MeV, of the projectile energy as seen from the graph, the pre-equilibrium stage of the reaction happens to begin, because the pre-equilibrium stage starts at energy above the energy of the formation of the compound nucleus. Thus from 31.4MeV to 34.7Mev, the cross section values in both the COMPLET code calculations and experiment agrees well and increases with increasing energy to the maximum at energy 34.7MeV, that could be the resonance peak for the pre-equilibrium stage of the nuclear reaction. Beyond energy of 36MeV both theoretical and experimental reaction cross sections values are seen ascending.

Chapter 5

Conclusion

In the present work, a study of the excitation function in the interaction of alpha on Zinc isotopes for the energy range of below 50MeV was studied by using an excitation model with a computer COMPLET code software. As a result of this, the compound nucleus was occurred through the de-excitation of selected nuclei by emitting one neutron(n), one neutron and one proton (n+p), one proton(p) and three neutron(3n) using the fitting level density parameter. In alpha-induced reaction with Gallium isotopes ^{67}Ga,^{66}Ga,^{71}Ge,^{73}Ga, and ^{69}Ge were produced. During the study of the reaction compound and pre-equilibrium reaction were occurred but direct reaction was almost not expected. Direct reaction is required a very large amount of energy. The level density parameter and initial excitation configuration were targeted quantities for the pre-equilibrium reaction. It should be further pointed out that a set of level density (k=8), exciton number (no = 4) with mean free path (MFM = 1.0) is found to give a satisfactory reproduction of the theoretical calculation.

The pre-compound reaction was depended on the projectile energy and target mass. Thus, the reaction was occurred at high energy but not significant at low energy range. Even though projectile energy very low compound nucleus might have occurred but experimental data was not available in the EXFOR data center for such low energies. The projectile is

captured by the target nucleus in compound nucleus reactions, and its energy is shared and re-shared among the target nucleons until statistical equilibrium is reached. A nucleon or a group of nucleons at the surface get enough energy to escape after a time far longer than the nuclear transit time, just as a molecule evaporates from a hot liquid drop.

When a composite nucleus achieves statistical equilibrium, compound nuclear emissions occur as a result of statistical variations from the equilibrium configuration. While the composite nucleus is approaching statistical equilibrium, particle emission (pre-equilibrium emission) is also possible. At one extreme of the nuclear reaction time range are pre-equilibrium processes. Nuclear physics requires models such as the exciton model to describe these reactions. In this thesis, calculation of excitation function of alpha induced reaction on some stable isotopes of Zinc (Zn) were studied. The reaction cross section values for ${}^{64}_{30}Zn(\alpha,p){}^{67}_{31}Ga$, ${}^{68}_{30}Zn(\alpha,n){}^{71}_{32}Ge$, ${}^{64}_{30}Zn(\alpha,n+p){}^{66}_{31}Ga$, ${}^{70}_{30}Zn(\alpha,p){}^{73}_{31}Ga$, and ${}^{68}_{30}Zn(\alpha,3n){}^{69}_{32}Ge$ reaction channels have been calculated for incident alpha energy ranges below 50Mev.The results of the excitation functions for the reaction processes are given in Figure 4.1 to 4.5.

The experimental cross sections are obtained from the IAEA data source, EXFOR library. The calculated and experimental cross sections for the reaction channels stated above were tabulated as in Table 4.1 to 4.5 and plotted against alpha energy range considered together as in Figures 4.1 to 4.5. As it can be seen from the Table 4.1 to 4.5 and Figure 4.1 to 4.5. Both the calculated and experimental cross section display the same pattern i.e. both attain their minima and maxima at equal values of alpha energy in each reaction channels.

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