Theoretical Calculation of Reaction Cross-section Induced by Alpha Particle on Zinc Isotopes(^{64}Zn, ^{66}Zn) Below 46MeV

By Muluken Gebre Mechalo

Supervisor Dr. Teklemariam Tessema

A Thesis Submitted to

The Department of Physics

PRESENTED IN FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN PHYSICS
(NUCLEAR PHYSICS)
JIMMA UNIVERSITY
JIMMA, ETHIOPIA
JUNE 2018

JIMMA UNIVERSITY
DEPARTMENT OF
PHYSICS

This is to certify that the thesis prepared by **Muluken Gebre Mechalo** Graduate Studies entitled "**Theoretical Calculation of Reaction Cross-section Induced by Alpha Particle on Zinc Isotopes(^{64}Zn, ^{66}Zn) Below 46MeV**" in fulfillment of the requirements for the degree of **Master of Science in Physics(Nuclear Physics)** complies with the regulations of the University and meets the accepted standards with respect to originality and quality. .

Dated: June 2018

Supervisor: ______________________
Dr. Teklemariam Tessema

External Examiner: ______________________
Proff. A.K Chaubey

Internal Examiner ______________________
Proff. Vijay Kumar Mittal

JIMMA UNIVERSITY

Date: **June 2018**

Author: **Muluken Gebre Mechalo**

Title: **Theoretical Calculation of Reaction Cross-section Induced by Alpha Particle on Zinc Isotopes(^{64}Zn, ^{66}Zn) Below 46MeV**

Department: **Physics**

Degree: **M.Sc.** Convocation: **June** Year: **2018**

Signature of Author

To my family and all my friends

Table of Contents

Abstract

In this work, calculations of the excitation function of alpha particle induced reaction on zinc isotopes ^{64}Zn and ^{66}Zn below 46 MeV have been studied. The theoretical cross-section induced by alpha-particle on zinc isotopes ^{64}Zn and ^{66}Zn for the reaction ($^{64}Zn(\alpha, n)^{67}Ge$, $^{64}Zn(\alpha, 2n)^{66}Ge$, $^{64}Zn(\alpha, p)^{67}Ga$, $^{66}Zn(\alpha, n)^{69}Ge$, $^{66}Zn(\alpha, 2n)^{68}Ge$) below 46 MeV energy has been calculated using COMPLET code. Excitation function for the reactions were compared with the experimental data on the cross-section of the same reactions have been done. The experimentally measured excitation functions obtained from EXFOR data source, IAEA, have been compared with the theoretical calculations made by COMPLET code. Level density parameter, kinetic energy and exciton number were varied to get good agreement between the calculated and measured data. In the study different dependence of reaction cross-section on projectile energies were observed between zinc isotopes ^{64}Zn and ^{66}Zn while being bombarded by the projectile of alpha particle for the energy below 46 MeV. The graph of energy versus cross-section (σ), the excitation function was plotted. It was observed that theoretical cross-sections were in good agreement with experimental data taken from EXFOR data center. Generally calculation using a COMPLET code gives good result for the reaction cross-section of alpha induced reaction on two isotopes of zinc (^{64}Zn and ^{66}Zn) below 46 MeV projectile energy.

Acknowledgements

Completion of a study cannot be anticipated without contribution of many individuals and institutions. It would be thus fair to mention people and institutions that have lend a hand for the successful completion of the research project. I would like to thank God! for his help in all my way. First and foremost, my advisor, Dr. Teklemariam Tessema , for providing a positive and intellectually stimulating research environment that has enabled me to mature both scientifically and personally. I am grateful for his continuous guidance and encouragement through many challenges I have encountered. In addition to all of the opportunities and support that he has provided in research writing skill.

I would like to thank my instructors and all staff members in physics department for their support during my study. I am thankful to my father and my mother, and also for all my families for their economical and psychological support. Finally, I would like to express my deepest gratitude to my dearest Sister W/ro Asegedech Gebre her husband Habtamu Haile, for their support throughout my study.

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background of the study

Since the 1940s, nuclear physics has seen important developments, but most practical applications and their simple theoretical explanations were in place by the mid 1950s[1]. In a nuclear reaction an atomic nucleus (or atomic particles) interacts with the nuclear projectile, emitting nuclear particles and or radiations leaving behind the residual nucleus. Study of nuclear reaction mechanism is a fundamental tool to study the properties of nucleus as well as the behavior of nuclear force between the nucleus and hence to understand the nuclear structure. Macroscopically we know the system before and after the reaction but what exactly happens during the reaction process is not known. Since it is not possible to look into the reaction process directly, models for reaction mechanism is proposed to explain the yield and angular and energy distributions of the reaction products. The first attempt to model a reaction was made by Neils Bohr in 1936[2]. According to this model the incident particle strikes the target and fuses with it to form the compound nucleus; the kinetic energy of the projectile is shared among all the constituents.

In order for a nuclear reaction to occur, the nucleons in the incident particle, or projectile, must interact with the nucleons in the target. Thus the energy must be high enough to overcome the natural electromagnetic repulsion between the protons. When a collision occurs between the incident particle and a target nucleus, either the beam particle scatters elastically leaving the target nucleus in its ground state or the target nucleus is internally excited and subsequently decays by emitting radiation or nucleons[3].

The Exciton model was proposed by Griffin [5] for explaining various experimental nuclear reaction data. In this model the equilibration between target and projectile is achieved by the succession of two body interactions and the composite nucleus states are characterized by the number of excited particles and holes (the exciton) at any stage of the nucleon-nucleon cascade. The exciton number (n), $n = p + h$ where, p is number of particles and h is the number of holes[5]. Reactions that exchange energy or nucleons can be used to measure the energies of binding and excitation. The initial configuration is fixed by the nature of the projectile.

The element Zinc has an atomic number of 30, an atomic mass of 65, one main oxidation state (+2) and five naturally occurring isotopes (64-Zn, 66-Zn, 67-Zn, 68-Zn and 70-Zn), of which 64-Zn, 66-Zn and 68-Zn are the most abundant at 48.6 %, 27.9 % and 18.8 % respectively of the total mass.

An alpha particle is a helium nucleus, i.e., it is a bound entity of two protons and two neutrons. The strong binding of an alpha particle makes it behave more like a nucleon rather than a complex particle, except that it has double the charge of a proton, which leads to a much stronger Coulomb interaction than in the case of a proton[7]. It consists of two protons and two neutrons; it therefore has charge

$+2e$. It is the same as the nucleus of a helium atom, ${}_{2}^{4}He$. The energy of alpha particle obtained from natural radioactive nuclei distributes to all parts and discrete in nature and appreciably smaller than the coulomb barrier and they are not suitable to have nuclear reactions effectively. The interaction of an alpha-particle with another nucleus may cause Coulomb excitation or may induce a nuclear reaction.[7].

However, the alpha particles from the accelerator machine have continues and higher energy and they are frequently used for the study of the nuclear reaction mechanisms of different isotopes. At much lower energies the transit time of a nucleon through a nucleus is sufficiently long that multiple scattering may take place frequently enough to complicate the reaction. At much higher energies, good resolution is difficult to achieve and the increased production rates of pions and other secondary particles make the condition unfavorable for studying nucleon-nucleus interaction [4].

In this thesis, we intended to calculate the excitation function of α-induced reactions on zinc isotopes, alpha-particle is the projectile or the bombarding particle and zinc isotopes (${}^{64}Zn$, ${}^{66}Zn$) are the targets. The different reaction channels studied were: (${}^{64}Zn(\alpha,n){}^{67}Ge$, ${}^{64}Zn(\alpha,2n){}^{66}Ge$, ${}^{64}Zn(\alpha,p){}^{67}Ga$, ${}^{66}Zn(\alpha,n){}^{69}Ge$, ${}^{66}Zn(\alpha,2n){}^{68}Ge$).

The products of this reaction were Ge-67 with a half-life of ($t_{\frac{1}{2}}$=18.7 min), Ge-66 ($t_{\frac{1}{2}}$= 2.3 days), Ga-67 ($t_{\frac{1}{2}}$= 78.3 hours), Ge-69 ($t_{\frac{1}{2}}$= 39.05 hours) and Ge-68 ($t_{\frac{1}{2}}$= 271 days). The two gallium radionuclides 67-Ga and 68-Ga are widely used in nuclear medicine. Gallium (administered mostly as gallium citrate) is a tumor seeking isotope for soft tissue tumors as well as bone seeking and dynamic studies. Radiopharmaceutical 67-Ga with a half-life of ($t_{\frac{1}{2}}$=78.3 hours) is a gamma-emitting isotope used in scintigraphy for medical imaging. The investigational studies have shown that Gallium Ga-67 accumulates in lysosomes and is bound to a soluble intracellular proton and allows scintigraphic localization.

Germanium Ge-66 with its half-life ($t_{\frac{1}{2}}$= 2.3 days) of the interest in nuclear medicine for its therapeutic properties. The parent isotope, 68-Ge, has a half-life of ($t_{\frac{1}{2}}$ =270.95 d) and can be used as the source of 68Ga, which has a half-life of only 68 minutes. Germanium (Ge-68) is used to produce calibration sources for radiometric equipment, PET scanners. Positron emission tomography (PET), which noninvasively provides information regarding blood flow and metabolism in patients, is a common procedure in clinical nuclear medicine.

1.2 Statement of the problem

Helium-nucleus energy plays an essential role for the calculation of α-induced reaction cross-sections nuclear reaction. The present work has been studied the pre-equilibrium cross-section induced by alpha particles on zinc isotopes (^{64}Zn, ^{66}Zn) for the reactions ($^{64}Zn(\alpha,n)^{67}Ge$, $^{64}Zn(\alpha,2n)^{66}Ge$, $^{64}Zn(\alpha,p)^{67}Ga$, $^{66}Zn(\alpha,n)^{69}Ge$, $^{66}Zn(\alpha,2n)^{68}Ge$) below 46MeV. Nuclear reaction takes place whenever energetic projectiles (α-particles in this case) fall up on isotopes(^{64}Zn, ^{66}Zn) to produce the isotopes of Germanium and Gallium.

The study has been made depending on the following questions:

- What is the values of theoretically calculated reaction cross-section induced by α-particle on zinc isotopes (^{64}Zn, ^{66}Zn)for reactions ($^{64}Zn(\alpha,n)^{67}Ge$, $^{64}Zn(\alpha,2n)^{66}Ge$, $^{64}Zn(\alpha,p)^{67}Ga$, $^{66}Zn(\alpha,n)^{69}Ge$, $^{66}Zn(\alpha,2n)^{68}Ge$) below 46 MeV?

- How is the calculated result compared with the experimental reaction cross-section induced by α-particle on zinc isotopes for the same reaction and energy range?
- How do the calculated reaction cross-section vary as a function of α-incident energies?

1.3 Objectives

1.3.1 General Objectives

The general objective of this work is is to calculate

- To calculate theoretical values of the nuclear reaction cross-section induced by alpha particles on zinc isotopes (^{64}Zn, ^{66}Zn) below 46 MeV energy and plot the excitation function curves.

1.3.2 Specific Objectives

The specific objectives of the study were:

- To calculate reaction cross-section induced by alpha particles on zinc isotopes for the reactions ($^{64}Zn(\alpha,n)^{67}Ge$, $^{64}Zn(\alpha,2n)^{66}Ge$, $^{64}Zn(\alpha,p)^{67}Ga$, $^{66}Zn(\alpha,n)^{69}Ge$, $^{66}Zn(\alpha,2n)^{68}Ge$) in the energy below 46 MeV.
- To validate the calculated theoretical reaction cross-section induced by alpha particles on zinc isotopes (^{64}Zn, ^{66}Zn) with the available experimental data.
- to check the behavior of the reaction cross-section induced by α-particle on zinc isotopes (^{64}Zn, ^{66}Zn) as a function of α energy below 46 MeV.

1.4 Significance of the study

The study would be used to generate values of the theoretical reaction cross-section induced by alpha particles on zinc isotopes (^{64}Zn, ^{66}Zn)for the reactions ($^{64}Zn(\alpha,n)^{67}Ge$, $^{64}Zn(\alpha,2n)^{66}Ge$, $^{64}Zn(\alpha,p)^{67}Ga$, $^{66}Zn(\alpha,n)^{69}Ge$, $^{66}Zn(\alpha,2n)^{68}Ge$) in the energy below 46 MeV. It would also be used to develop the basic understanding of theoretical calculation of excitation function of alpha induced reaction on zinc isotopes, to gain better insight about nuclear reaction and the exciton model. The research work could be used as a reference for further studies.

1.5 Limitation of the study

The main shortcoming of this research work is lack of senior nuclear laboratory to conduct an experiment for the experimental values on alpha induced reaction, due to this reason we have been used the experimental data from the EXFOR data center. The other limitations were lack of sufficient time, absence of reference materials in the library and less internet access.

1.6 scope of the study

In this research work we were absolutely focussed on the theoretical calculation of the cross-section induced by alpha particle on Zinc isotopes, downloading recent experimentally available data from EXFOR data center, and compare the calculated results with experimental data to validate the result. For the purpose of calculating reaction cross-section exciton model based program called COMPLET have been used.

.

Chapter 2

Literature Review

2.1 Theory of Nuclear Reaction

Since the 1940s, nuclear physics has seen important developments, but most practical applications and their simple theoretical explanations were in place by the mid 1950s[1]. Nuclear reaction is the process in which the incident particle is absorbed or scattered, same particles or some other particle(s) are emitted in different directions[4]. It is the process in which the target nucleus is bombarded by a particle and results in another nucleus (Residual) with emitted (outgoing) particle. When a nuclear particle(s) are in closer contact with another nucleon or nucleus, the interaction takes place in which energy momentum transfer may take place. In order for a nuclear reaction to occur, the nucleon(s) in the incident particle, or projectile, must interact with the nucleon(s) in the target. Thus the energy must be high enough to overcome the natural electromagnetic repulsion between the protons. When a collision occurs between the incident particle and a target nucleus, either the beam particle scatters elastically leaving the target nucleus in its ground state or the target nucleus is internally excited and subsequently decays by emitting radiation or nucleons.[9]

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

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

Where, a -is a projectile (incident particle)

X-is target nucleus

Y-is the residual nucleus (recoil nucleus) and

b -is an emitted particle (outgoing particle).[10]

We can characterize the energetics of the reaction with a reaction energy Q, defined as the energy released in the reaction or the difference between the final and initial kinetic energies[8]. Q value is an important quantity in nuclear reaction. The Q is positive if the total mass of the products is less than that of the projectile and target, indicating that the total nuclear binding energy has increased [8].

The Q-value can be written in equation form as

$$Q = T_b + T_Y - T_a \tag{2.1.2}$$

Where, T_a-is the kinetic energy of the projectile

T_Y-is the kinetic energy of the residual nucleus and

T_b-is the kinetic energy of the emitted particle.

$$Q = (m_X + m_a - m_Y - m_b)c^2 \tag{2.1.3}$$

Where, m_X-is the mass of target nucleus

m_a-is the mass of the projectile

m_Y-is the mass of the residual nucleus and

m_b-is the mass of the emitted particle.

A reaction can not takes place unless particle b and Y emerges with positive kinetic energies that is $T_b + T_Y \geq 0$ or $Q + T_a \geq 0$. We classify reactions in many ways. If the incident and outgoing particles are the same (and correspondingly X and Y are the same nucleus), it is a scattering process, elastic if Y and b are in their ground states and inelastic if Y or b is in an excited state (from which it will generally decay quickly by γ emission)[3, 8]. Meaning, if the internal states of the two colliding systems do not change, we have elastic scattering and if one or both systems are excited in the exit channel, it is inelastic scattering. As regards nuclear reaction studies using alpha-particles, some online measurements on the spectra of emitted neutrons and charged particles have been performed with a view to investigating angular and energy distributions of the emitted particles[7]. The data lead to very useful information on the mechanism of emission of those particles.

2.2 Mechanism of Nuclear Reaction

There are different reaction mechanisms which are called direct reaction, compound nuclear reaction and pre-equilibrium nuclear reactions. These reaction mechanisms are described by different models which depend on the energy of the projectiles. The most investigated range of energies are 0 to 200MeV. In this energy range one can determine different reaction mechanisms which are called, direct reaction, compound nuclear reaction and pre-equilibrium nuclear reactions.

2.2.1 Direct Reaction

The reaction which takes place without the formation of compound nucleus is called direct reaction. These are fast reactions which roughly take to about $(10^{-22} -$

10^{-20})sec, these interactions takes place with only few nucleon(s) inside the nucleus and the projectile [4, 6]. In this reaction the projectile interacts with a nucleon, a group of nucleons or the whole nucleus and emission takes place immediately. The direct reaction which includes the 'stripping' and 'pick-up' reactions are characterized by certain angular distributions of the scattered or the outgoing particles and forward peaking. Those particles can be understood by regarding the reactions as having involved only the interaction between the incident particle and the outer nucleons of the target nucleus.

2.2.2 Compound Nucleus Reaction

This stage of nuclear reaction (compound nucleus) is historically proposed by Neils Bohr[2]. These are slow reaction process ($10^{-18} - 10^{-16}$)sec, these interactions takes place with all of the nucleon(s) inside the nucleus and projectile[4, 6]. In compound nucleus reactions the energy of the projectile shared among the nucleons of the compound nucleus until it reaches the state of statistical equilibrium. The initiation to develop the compound nucleus theory is the problem for resonance peak of nuclear reactions. According to this theory the sharp peak of the reaction cross section is due to the existence of the quasi-stable nuclear state for particular value of resonance energy. When particle a, with this resonance energy approaches the target nucleus X, within the range of nuclear forces, a compound nucleus is formed. This compound nucleus will then disintegrate into two or more products Y and b[4].

Thus this type of nuclear reaction is regarded as consisting of two successive steps, the formation and the decay stages. In compound nucleus reactions the projectile is captured by the target nucleus and its energy is shared and re-shared among the nucleons of the compound nucleus until it reaches a state of statistical equilibrium.

The term compound nucleus reaction is commonly used for two different processes:

(i) capture of the projectile in the target nucleus to form a compound nucleus, which subsequently emits a particle or gamma,

(ii) multiple emissions from the chain of excited residual nuclide following the binary reaction.[8, 18]. Compound processes involves predominantly at low energies (below 10 MeV).

2.2.3 Pre-equilibrium Reaction

Pre-equilibrium reaction mechanism is the reaction processes between direct and compound nucleus reaction. To explain this theory different pre-equilibrium nuclear reaction models have been developed. The first model developed by J.J Griffin was the exciton model [5]. It can happen that a particle is emitted neither immediately after the interaction of the projectile with a nucleon(s) of the target nucleus, as in direct reaction, nor after a long time by the statistical decay of the compound nucleus. The projectile may share its energy among a small number of nucleons which may further interact with other nucleons, and during this cascade of nucleon-nucleon interactions through which the energy of the incident particle is progressively shared among the target nucleons, a particle may be emitted long before the attainment of statistical equilibrium. These processes are the pre-compound or pre-equilibrium reaction process[18].

Hence the Pre-equilibrium reaction mechanism constitute the bridge between the fast, direct processes and slow, compound processes and provides an explanation for the observed high-energy tails in spectra and the smoothly forward peaked angular distributions. Nuclear reactions induced by a particles at intermediate energy are characterized by pre-equilibrium (PE) particle emission followed by equilibrium (EQ) decay. As the projectile energy increases, the PE particle emission becomes more and more pronounced.

To calculate the cross-section in model of compound nucleus and in pre-equilibrium models, the most important ingredients are the exciton number and the level density parameter. The theoretical results are compared with the experimental data obtained from EXFOR data source, IAEA[14]. It is now well-known that the separation of nuclear reaction mechanisms into direct and compound is too simplistic. As Figure 2.1 shows, the cross section as predicted by the pure compound process is too small with respect to measured continuum spectra, and the direct processes. Apparently, as an intermediate between the two extremes, there exists a reaction type that embodies both direct- and compound-like features. These reactions are referred to as pre-equilibrium or pre-compound processes. Pre-equilibrium emission takes place after the first stage of the reaction but long before statistical equilibrium of the compound nucleus is attained. It is imagined that the incident particle step-by-step creates more complex states in the compound system and gradually loses its memory of the initial energy and direction. Pre-equilibrium processes which has an important mechanism, takes place between the direct process ($10^{-22}s - 10^{-20}s$) and compound process ($10^{-18}s - 10^{-16}s$) cover a sizable part of the reaction cross section for incident energies between 10 and (at least) 200 MeV.

The energy regions to which direct(D), pre-equilibrium(P) and compound(C) mechanisms contribute are indicated in Figure 2.1. The dashed curve in Figure 2.1 distinguishes the compound contribution from the rest in transitional energy region.

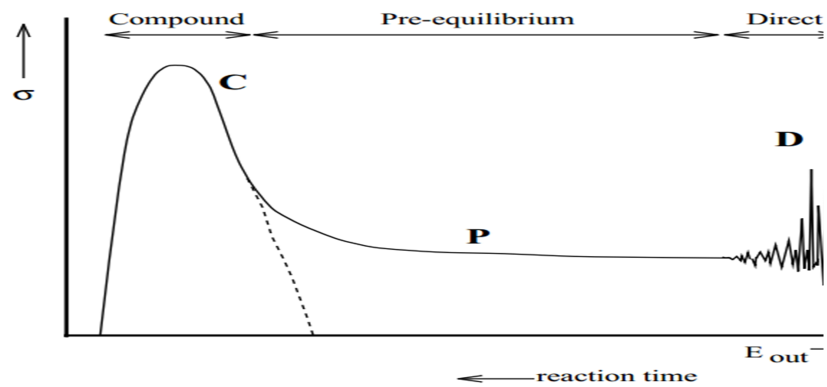

Figure 2.1: Schematically drawing of an outgoing particle spectrum.

Exciton Model

The Exciton model proposed by J.J Griffin[5] for the formation and decay of the average compound nuclear state and explaining various experimental nuclear reaction data. The model was further modified and developed by M. Blann [11] et al. In the pre-equilibrium theories of nuclear reaction it is assumed that interaction is due to successive nucleon-nucleon interaction in a series of stages. Each interaction produces a particle-hole (p-h) pair and the particle-hole pair is called an exciton. The nuclear state is characterized by the excitation energy of the composite nucleus and the exciton number, which is the total number of particles(p) above and holes(h) below the fermi surface[5, 12].

In this model the equilibration between target and projectile is achieved by the succession of two body interactions and the composite nucleus states are characterized by the number of excited particles and holes (the exciton) at any stage of the nucleon-nucleon cascade. The exciton number (n), $n = p + h$ where, p is number of particles and h is the number of holes.

Initial configuration of the compound system defined by its exciton number $n_0 = n_p + n_h$ is an important parameter of pre-equilibrium formalism. It is, therefore, of particular interest to look for the initial number and the assumed divisions of the excitons into particles and holes required to reproduce the data. In literature values of $n_0 = 3$ are used for proton induced reactions and $n_0 = 6$ are used for alpha induced reactions. These values may be justified, since the first projectile-target interaction may give rise to the excitation of one particle above the Fermi energy, leaving behind a hole in excited state, i.e., in all $3(2p + 1h)$ and $6(5p + 1h)$ initial exciton states for proton- and alpha induced reactions, respectively.[6]

If however, particle emission does not take place, and then there will be a further two body interaction either between one of the excited particle and a nucleon below Fermi Sea or between the two excited particles themselves. The first process leads to the formation of $n = 5(3p2h)$ state while the second would produced a new state $n = 3(2p1h)$ state having different energy configuration of the hole and particles, or back to the original $n = 1$ exciton state. Restrictions to two-body interactions lead to the following selections rules concerning the possible variation of the number of particles p, holes h, and exciton $n = p+h$, in the course of the cascade of interactions: $\Delta p = 0, 1$, $\Delta h = 0, 1$, $\Delta n = 0, 2$[12]. The states which are excited in the course of this interaction cascade are very unstable.

2.3 Nuclear Reaction Cross-section

The nuclear reaction cross-section is a quantitative measure of the probability with which nuclear reactions and other collision processes occur [13]. Cross-section data of charged particle induced nuclear reactions are needed in a number of applications and basic sciences fields. However, the status of the charged particle reaction data is in many cases are not satisfactory. The evaluated and recommended data are available only for a few reactions. To calculate the cross-section in model of compound nucleus and in pre-equilibrium models, the most important ingredients are the exciton number and the level density parameter. The theoretical results are compared with the experimental data obtained from EXFOR data source, IAEA [14]. These are plotted together for comparison. The cross-section can be measured experimentally and calculated in such a way that the theoretical and experimental values can be compared readily.

The development of nuclear reaction theory strongly depends on the understanding of nucleon-induced reactions. The reactions can produce accurate nuclear reaction data of common cross-section and energy differential cross-sections and especially the data of proton and neutron energy angle correlated spectra of secondary light particles such as neutron, proton, deuteron, triton, hellion and alpha particles. Reaction cross-sections are required to bench mark the nuclear reaction codes in the incident energy region where many reaction mechanisms compete [16].

The cross-section is the measure of relative probability for the reaction to occur. If a detector placed to record particle b emitted in a direction (θ, ϕ) with respect to the beam direction as seen in the Figure 2.2; the detector defines a small solid angle $d\Omega$ at the target nucleus[8].

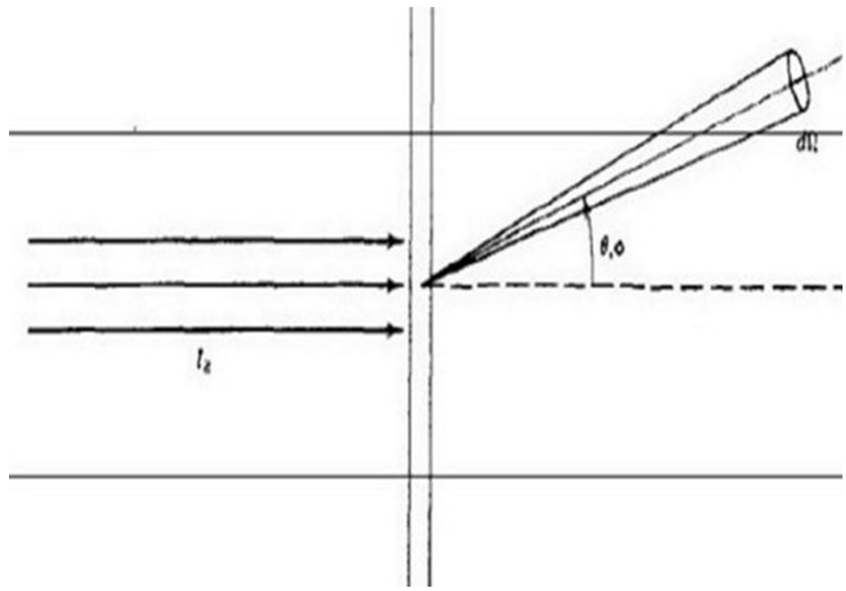

Figure 2.2: Reaction geometry showing incident beam, target and outgoing beam going in to solid angle $d\Omega$ at (θ, ϕ)

Let the current of incident particles be I_a particles per unit time and let target shown to a beam N target per unit area.

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

Where R_b is the number of events of given type per unit time, I_a is the incident particles per unit time and N is the target nucleus per unit area

The cross-section (σ), has a dimension of area and it may be very much larger or smaller than the geometrical area of the disc of the target nucleus seen by incoming beam. If we let the angular distribution function be arbitrarily represented by $r(\theta, \phi)$ then $dR_b = r(\theta, \phi)\frac{d\Omega}{4\pi}$ (The 4π is introduced to make $\frac{d\Omega}{4\pi}$ a pure fraction.) Then

$$\frac{d\sigma}{d\Omega} = \frac{r(\theta, \phi)}{4\pi I_a N} \tag{2.3.2}$$

$\frac{d\sigma}{d\Omega}$ is called the differential cross-section and its measurement gives us important information on the angular distribution of the reaction products. The reaction cross-section (σ) can be found by integrating $\frac{d\sigma}{d\Omega}$ over all angles with $d\Omega = sin\theta d\theta d\phi$ we have

$$\sigma = \int \frac{d\sigma}{d\Omega} d\Omega = \int_0^{\pi} sin\theta d\theta \int_0^{2\pi} d\phi \frac{d\sigma}{d\Omega} \tag{2.3.3}$$

Notice that if $\frac{d\sigma}{d\Omega}$ is constant (independent of angle), the integral gives

$$\sigma = 4\phi(\frac{d\sigma}{d\Omega}) \tag{2.3.4}$$

Dependence of reaction cross-section on energy

The cross-section for various nuclear reactions depend on bombarding energy in highly individualistic manner. The detailed dependence of cross-section on bombarding energy is often called "Excitation function" for the particular reaction[17].

2.4 Scattering and Reaction Cross-section

We take the z-axis to be the direction of the incident beam and assume it can be represented by the plane wave e^{ikz} corresponding to momentum $p = \hbar k$. 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 the spherical waves[8]:

$$\psi_{inc} = Ae^{ikz} = A\sum_{l=0}^{\infty} i^l(2l+1)j_l(kr)P_l(\cos\theta) \tag{2.4.1}$$

Where A is normalization constant.

The radial functions $j_l(kr)$ are spherical Bessel functions which are the solutions to radial part of Schrodinger equation.

The angular functions $P_l(\cos\theta)$ are Legendre polynomials which is obtained from spherical harmonics

$$Y_{l,m(\theta,\varphi)} = (-1)^m \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}} P_l^m(cos\theta)e^{im\varphi} \tag{2.4.2}$$

Then the Legendre polynomial $P_l(\cos\theta)$ for m=0 is given by

$$P_l(\cos\theta) = \sqrt{\frac{4\pi}{2l+1}} Y_{l,0}(\theta) \tag{2.4.3}$$

The spherical harmonics for m=0 becomes

For $l = 0$, $Y_{0,0} = \frac{1}{\sqrt{4\pi}}$
For $l = 1$, $Y_{1,0} = \sqrt{\frac{3}{4\pi}} cos\theta$
For $l = 2$, $Y_{2,0} = \sqrt{\frac{5}{16\pi}} (3cos^2\theta - 1)$

The analogous angular functions $P_l(\cos\theta)$ (Legendre polynomials) to the above spherical harmonics are

$P_0(\cos\theta) = 1$

$P_l(\cos\theta) = \cos\theta$

$$P_l(\cos\theta) = \frac{1}{2}(3\cos^2\theta - 1) \tag{2.4.4}$$

The expansions of the incident wave are called the partial wave expansion, with each partial wave corresponding to a specific angular momentum l. If the particles of momentum p interact with impact parameter b, then the (semi-classical) relative angular momentum will be $l\hbar = pb$

$$b = \frac{l\hbar}{p} = l\frac{\lambda}{2\pi} = l\bar{\lambda} \tag{2.4.5}$$

where $\bar{\lambda} = \frac{\lambda}{2\pi}$ is reduced de Brogile wavelength incidently $\bar{\lambda} = k^{-1}$.

Particle with (semi-classical) angular momenta between $0\hbar$ and $1\hbar$ will interact through impact parameters between 0 and $\bar{\lambda}$ and thus effectively over an area (cross section) of atmost $\pi(\bar{\lambda})^2$. With $\hbar \leq l \leq 2\hbar$ the cross section is a ring of inner radius $\bar{\lambda}$ and outer radius $2\bar{\lambda}$ and thus the area $3\pi\bar{\lambda}^2$. We can thus divide the interaction area in to number of zones each corresponding to a specific angular momentum l and each having area $l\hbar = pb$

$$\pi[(l+1)\bar{\lambda}]^2 - \pi(l\bar{\lambda})^2 = (2l+1)\pi(\bar{\lambda})^2 \tag{2.4.6}$$

We can estimate the maximum impact parameter for nuclear scattering is to be about $R = R_1 + R_2$ (sum of radii of incident and target nuclei), and thus the maximum l value likely to occur is $R/\bar{\lambda}$ and the total cross section is correspondingly

$$\sigma = \sum_{l=0}^{R/\bar{\lambda}} (2l+1)\pi(\bar{\lambda})^2 = \pi(R+\bar{\lambda})^2 \tag{2.4.7}$$

This is reasonable estimate, for it includes not only an interaction distance R, but it allows the incident particles wave nature to spread over distance of the order of $\bar{\lambda}$, making the interaction radius $(R+\bar{\lambda})$. When the wave is far from the nucleus (i.e., $r \to \infty$) the $j_l(kr)$ have the following convenient expansion

$$j_l(kr) = \frac{\sin(kr - \frac{l\pi}{2})}{kr}, for kr \gg l \tag{2.4.8}$$

$$j_l(kr) = i\frac{e^{-i(kr-\frac{l\pi}{2})} - e^{+i(kr-\frac{l\pi}{2})}}{2kr} \tag{2.4.9}$$

So that

$$\psi_{inc} = Ae^{ikz} = \frac{A}{2kr}\sum_{l=0}^{\infty} i^{l+1}(2l+1)[e^{-i(kr-\frac{l\pi}{2})} - e^{+i(kr-\frac{l\pi}{2})}]P_l(\cos\theta) \tag{2.4.10}$$

The first term in the brackets, involving e^{-ikr}, represents an incoming spherical wave converging on the target e^{+ikr} represents an outgoing spherical wave emerging from the target nucleus. The superposition of these two spherical waves, gives the plane wave. The scattering can affect only the outgoing waves, and can affect in either of the two ways: through a change in phase and through change in amplitude. The change in amplitude suggests that there may be fewer particles coming out than there were going in, which may appear to be a loss in the number of particles. We account for the change in the l^{th} outgoing partial wave by introducing the complex coefficient η_l in to the outgoing (e^{ikr}) term in the above Eqn.(2.4.10)

$$\psi = \frac{A}{2kr}\sum_{l=0}^{\infty} i^{l+1}(2l+1)[e^{-i(kr-\frac{l\pi}{2})} - \eta_l e^{+i(kr-\frac{l\pi}{2})}]P_l(\cos\theta) \tag{2.4.11}$$

This wave represents a superposition of the incident wave and scattered wave $\psi = \psi_{inc} + \psi_{sc}$. To find the scattered wave subtract Eqn.(2.4.11) from Eqn.(2.4.10)

$$\psi_{sc} = \frac{A}{2kr}\sum_{l=0}^{\infty} i^{l+1}(2l+1)i(1-\eta_l)e^{i(kr-\frac{l\pi}{2})}P_l(\cos\theta) \tag{2.4.12}$$

$$\psi_{sc} = \frac{A}{2k}\frac{e^{ikr}}{r}\sum_{l=0}^{\infty}(2l+1)i(1-\eta_l)P_l(\cos\theta) \tag{2.4.13}$$

Then

$$j_{sc} = \frac{\hbar}{2mi}(\psi_{sc}^{*}\frac{\partial\psi_{sc}}{\partial r} - \frac{\partial\psi_{sc}^{*}}{\partial r}\psi_{sc}) \tag{2.4.14}$$

$$j_{sc} = |A|^2\frac{\hbar}{2mkr^2}|\sum_{l=0}^{\infty}(2l+1)i(1-\eta_l)P_l(\cos\theta)|^2 \tag{2.4.15}$$

$$j_{inc} = \frac{\hbar}{4mk}|A|^2 \tag{2.4.16}$$

Then the differential cross section is

$$\frac{d\sigma}{d\Omega} = \frac{\hbar}{4k^2} | \sum_{l=0}^{\infty} (2l+1) i (1-\eta_l) P_l(\cos\theta)|^2 \tag{2.4.17}$$

To find the total cross-section we require the integral Legendre polynomials

$$\int P_l(\cos\theta) P_{l'}(\cos\theta) \sin\theta d\theta d\phi = \frac{4\pi}{2l+1}, forl = l^{'} \tag{2.4.18}$$

$$\int P_l(\cos\theta) P_{l'}(\cos\theta) \sin\theta d\theta d\phi = 0, forl \neq l^{'} \tag{2.4.19}$$

thus

$$\sigma_{sc} = \sum_{l=0}^{\infty} \pi(\bar{\lambda})^2 (2l+1) |1-\eta_l|^2 \tag{2.4.20}$$

If elastic scattering were the only process that could occur , then $|\eta_l| = 1$ and it is conventional to write $\eta_l = e^{2i\delta_l}$ where δ_l is the phase shift of l^{th} partial wave. For this case,$|1-\eta_l|^2 = 4\sin^2\delta_l$ and

$$\sigma_{sc} = \sum_{l=0}^{\infty} 4\pi(\bar{\lambda})^2 (2l+1) \sin^2\delta_l \tag{2.4.21}$$

The reaction cross-section becomes

$$\sigma_r = \sum_{l=0}^{\infty} \pi(\bar{\lambda})^2 (2l+1)(1-|\eta_l|^2 \tag{2.4.22}$$

The total cross-section including all processes is

$$\sigma_t = \sigma_{sc} + \sigma_r = \sum_{l=0}^{\infty} 2\pi(\bar{\lambda})^2 (2l+1)(1-R_e\eta_l) \tag{2.4.23}$$

2.5 Classical estimation of cross-sections

In this the total cross-section is separated in to two parts: an elastic scattering cross-section and a non-elastic or reaction cross-section[3]. Thus,

$$\sigma_t = \sigma_{sc} + \sigma_r \tag{2.5.1}$$

Further consider that a nuclear reaction leading to σ_r can only take place if the colliding nuclei come within range of nuclear force, which is short ranged. If the distance between their centers $r < R$, a nuclear reaction can take place and if $r > R$, no reaction occurs. The interaction radius depends on the interacting nuclei and can be represented as a sum $R_1 + R_2$ of effective radii of the two nuclei as shown in the Figure 2.3. The interaction radius and the effective radii are related to the geometric sizes of the nuclei, but do not have definite values of the range of the nuclear force because the distribution of nuclear matter in a nucleus has a diffuse surface so that an estimate of R can be made from experimental measurement.

The dotted circle in the Figure 2.3 denotes the region representing the nuclear collision cross-section. If the nuclei approach each other within the distance $R = R_1 + R_2$, they undergo a nuclear collision [3]. For uncharged particles, the geometric cross-section for the nuclei to collide is $\sigma = \pi R^2$, given by cross-sectional area determined by the interaction radius. However, in general, the colliding nuclei will be charged and the collision cross-section will be modified because the nuclei experience an energy barrier due to the repulsive Coulomb force acting between them. The collision cross-section is given by πb^2, where b is the impact parameter for a distance of closest approach equal to R.

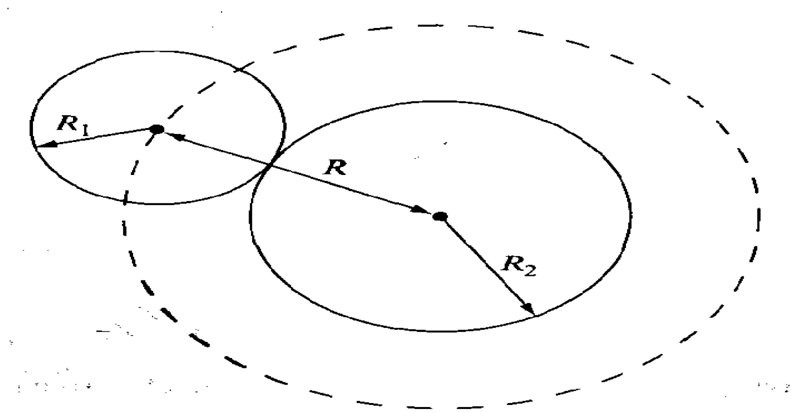

Figure 2.3: Diagram showing two nuclei with effective interaction radii $R_1$and R_2.

Assuming the nuclei have sharp edges, the Coulomb energy at the distance of closest approach is given by the familiar formula

$$B = z_1 z_2 e^2/(4\pi\varepsilon_0)R \tag{2.5.2}$$

Where z_1 and z_2 are the atomic numbers of the two nuclei. The value of impact parameter b is obtained by applying conservation laws. At the distance of closest approach, the initial kinetic energy E appears partly as reduced kinetic energy E' and partly as Coulomb potential energy B. Hence,

$$E = E' + B \tag{2.5.3}$$

Applying conservation of angular momentum gives

$$L = pb = p'R \tag{2.5.4}$$

Where p and p' are the projectile momenta initially and at the distance of closest approach, respectively.

We know that $E/E^{'} = (p/p^{'})^2 = (b/R)^2$, from which it follows that

$$\sigma = \pi R^2 \frac{E^{'}}{E} = \pi R^2 (1 - \frac{B}{E}), for E \geq B \tag{2.5.5}$$

For the general situation, which takes target recoil in to account, E is replaced by the center-of-mass energy $E_{cm} = \frac{EM}{(M+m)}$, where E is the energy of projectile (mass m) in the laboratory system and M is the mass of the target, initially at rest. Note that we obtain the value of πR^2 for uncharged particles when B=0 and also equation

$$\sigma = \pi R^2 \frac{E^{'}}{E} = \pi R^2 (1 - \frac{B}{E}), for E \geq B \tag{2.5.6}$$

Approaches this limit at high energy when the effect of the Coulomb force is small. The cross-section $\sigma = \pi R^2$ can be written in terms of the wave number $k(= p/h)$ of the projectile and the angular momentum quantum number l as

$$\sigma = \pi (\frac{L}{p})^2 = \frac{\pi l(l+1)\hbar^2}{(\hbar k)^2} \approx \frac{\pi l^2}{k^2} \tag{2.5.7}$$

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

$$\sigma = \pi R^2 \frac{E^{'}}{E} = \pi R^2 (1 - \frac{B}{E}) for E \geq B \tag{2.5.8}$$

The cross-section falls to zero when $E = B$ and it remains there at lower energies because the nuclei are always out of contact with each other, even in a head-on collision[3].

Chapter 3

Materials and Methodology

3.1 Materials

The materials that have been used to carry out this research were the following:

- computer, Flashes and CD
- Software's
- journals, research papers, articles etc.
- stationery materials (like papers, photocopy and print etc.)

3.2 Methodology

3.2.1 Data Computation

In this thesis one of the method or approach used to solve the problem is analytical method. The equation of reaction cross-section used by the FORTRAN-77 code called COMPLET have been discussed. This is analytically to calculate the theoretical reaction cross-section induced by alpha particles on zinc isotopes, ^{64}Zn and ^{66}Zn below 46 MeV energy. The program was run and the input and output directory was defined.

The alpha particle was chosen as incident particle followed by selecting the target nucleus and excitation function in the general option section for this calculation. The number of incident energy was specified followed by the first incident energy, and then the incident energy step is also specified based on the available experimental data obtained. The cross-section correspond to each particular energy was obtained. Data from EXFOR cite were[14] downloaded for experiments. The detail of using the fortran based computer code called COMPLET can be viewed from appendix.

3.2.2 Method of Data Presentation

All the output data of the cross-section were presented in tables and graphs per each energy in a manner to compare the data with the experimental data. Both experimental and theoretically calculated data were discussed after each table and graph.

Chapter 4

Results And Discussion

This chapter presents sample description and characterization of data obtained during the calculation using tables and plots in comparison with the experimental data. The excitation functions of alpha induced reactions on zinc isotopes (^{64}Zn, ^{66}Zn)for the reactions ($^{64}Zn(\alpha,n)^{67}Ge$, $^{64}Zn(\alpha,2n)^{66}Ge$, $^{64}Zn(\alpha,p)^{67}Ga$, $^{66}Zn(\alpha,n)^{69}Ge$, $^{66}Zn(\alpha,2n)^{68}Ge$) below 46 MeV energy have been theoretically calculated using COMPLET code. The numerical values of the earlier experimental cross-section data report were taken from the original works, from the IAEA, EXFOR data center. The results were compared with the experimental values taken from EXFOR data library[14]. The EXFOR (EXchange FORmat) database is a large collection of experimental nuclear reaction data for incident neutrons, charged particles and photons.[14] The various parameters are used for calculations of excitation functions. However, the initial exciton number is found to play an important role in the theoretical predictions for pre-equilibrium reactions. In this thesis the initial exciton number ($n_0 = 6$) has been mainly taken for alpha projectile, which interact independently with particles below the Fermi level creating either new particle-hole configuration in the second stage or getting emitted in to the continuum. Partial 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 studies of the energy below 46 MeV.

4.1 Reaction cross-section for $^{64}Zn(\alpha,n)^{67}Ge$

4.1.1 Experimental reaction cross-section for $^{64}Zn(\alpha,n)^{67}Ge$

In this reaction the experimental data obtained from EXFOR per each of the projectile energies were done by Gy. Gyurky et al. in 2012. These experimental cross-section values ranges from minimum projectile energy 9.605 MeV to maximum energy 13.1431 MeV as shown in Table 4.1. The graph of energy versus cross-section (σ) called the excitation function were plotted as seen in Graph 4.1, then the experimental data used in the solid line.

E_{proj}(MeV)	9.605	10.285	10.9438	11.7831	12.325	12.9838	13.1431
σ_{exp}(mb)	10.6	41.7	70.4	106	120	165	179

Table 4.1: Experimental Cross-section for the reaction $^{64}Zn(\alpha,n)^{67}Ge$

4.1.2 Theoretical reaction cross-section for $^{64}Zn(\alpha,n)^{67}Ge$

The theoretical reaction cross-section for the reaction $^{64}Zn(\alpha,n)^{67}Ge$ were calculated using COMPLET code and the value were saved in the Table 4.2. The theoretically calculated cross-section for the reaction $^{64}Zn(\alpha,n)^{67}Ge$ have been carried out at the same as the experimental energies. The theoretical reaction cross-section versus the energy graph called excitation function for the calculated data was plotted as in Graph 4.1 using broken line.

E_{proj}(MeV)	9.605	10.285	10.94	11.7831	12.325	12.9838	13.1431
σ_{theo}(mb)	12.94	29.56	57.83	94.41	116.6	145.9	154

Table 4.2: Theoretical Cross-section for the reaction $^{64}Zn(\alpha,n)^{67}Ge$

4.1.3 The excitation function for the reaction $^{64}Zn(\alpha,n)^{67}Ge$

The experimental reaction cross-sections obtained from EXFOR data center and theoretically calculated cross-section using COMPLET code were listed in the Tables 4.1 and 4.2. Using this data the excitation function graph were plotted for each individual energy with their respective theoretically calculated and experimental reaction cross-section for the reaction $^{64}Zn(\alpha,n)^{67}Ge$ as in the Graph 4.1. The solid line shows the experimental excitation function and the broken line shows the theoretical excitation function.

The theoretically calculated cross-section for the reaction $^{64}Zn(\alpha,n)^{67}Ge$ starts from the minimum projectile energy 9.605 MeV with cross section of 12.94 mb and reaches its maximum energy at about 13.1431 MeV with 154 mb. The theoretical cross-section value increases with increasing projectile energy as seen in Graph 4.1. Similarly in Table4.2 the experimental value indicates that the excitation function starts at about minimum energy 9.605 MeV with cross section of 10.4 mb and reaches its maximum peak at about 13.1431 MeV with 179mb. Then the reaction cross-section for those theoretical and experimental cross-section against projectile energy were plotted in the Graph 4.1. The theoretically calculated cross-section value increases with the increase in the experimental cross-section value in a given range of energy.

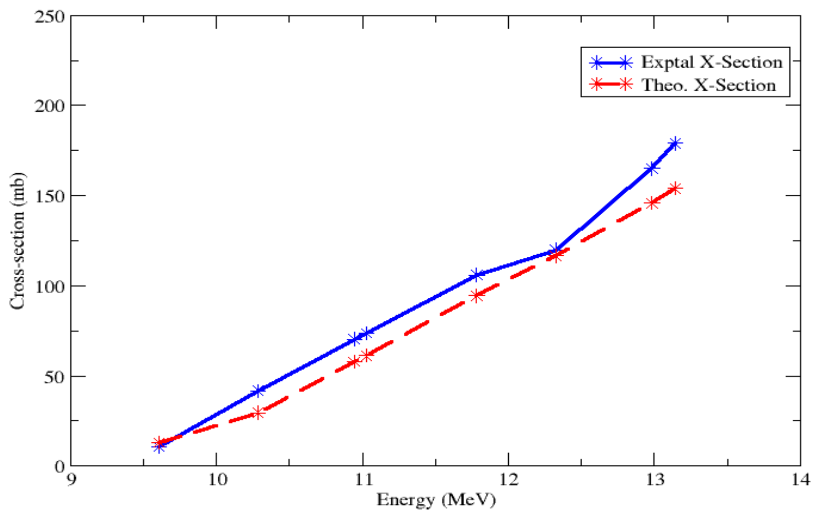

Figure 4.1: The theoretical and experimental excitation function for the reaction $^{64}Zn(\alpha, n)^{67}Ge$

Both the theoretical and experimental cross-sections attain their minima and maxima at the energies 9.605 MeV and 13.1431 MeV respectively. This shows that both follows the same pattern with projectile energy. Thus, the excitation function curve shows both theoretical and experimental cross-sections were nearer to each other. It was observed that the theoretical calculated value best agrees the experimental cross-section value for the projectile energy 9.605 MeV and 12.325 MeV as seen in Graph4.1. Generally, the theoretically calculated and experimental reaction cross-section are in a good agreement for reaction $^{64}Zn(\alpha, n)^{67}Ge$. This shows that COMPLET code calculation give good result for the reaction in energies at 9.605 MeV and 12.325 MeV.

4.2 Reaction cross-section for $^{64}Zn(\alpha, 2n)^{66}Ge$

4.2.1 Experimental reaction cross-section for $^{64}Zn(\alpha, 2n)^{66}Ge$

In this reaction the experimental data for the reaction $^{64}Zn(\alpha, 2n)^{66}Ge$ obtained from EXFOR data library per each of the projectile energies were done by V.N. Levkovski in 1991, Moscow. These experimental value ranges in the projectile energy from minimum of 32.5 MeV to the maximum energy value 37.7 MeV. The experimental cross-section against the projectile energy called excitation function were plotted as in Graph 4.2 shown with a solid line.

E_{proj}(MeV)	32.5	33.6	34.7	35.7	36.7	37.7
σ_{exp}(mb)	69	70	72	63	59	57

Table 4.3: Experimental Cross-section for the reaction $^{64}Zn(\alpha, 2n)^{66}Ge$

4.2.2 Theoretical Reaction cross-section for $^{64}Zn(\alpha, 2n)^{66}Ge$

The theoretical cross-section for the reaction $^{64}Zn(\alpha, 2n)^{66}Ge$ were calculated using COMPLET code for each projectile energy. The theoretically calculated values of nuclear reactions cross-section for the reactions $^{64}Zn(\alpha, 2n)^{66}Ge$ starts from the energy of projectile at about minimum energy of 32.5 MeV and reaches its maximum energy at about 37.7 MeV. The theoretical reaction cross-section versus the energy graph called excitation function for the calculated data was plotted as in Graph 4.2 shown by the broken line.

E_{proj}(MeV)	32.5	33.6	34.7	35.7	36.7	37.7
σ_{theo}(mb)	75.05	75.97	78.76	70.2	60	58.3

Table 4.4: Theoretical Cross-section for the reaction $^{64}Zn(\alpha, 2n)^{66}Ge$

4.2.3 The Excitation function for the reaction $^{64}Zn(\alpha, 2n)^{66}Ge$

The data in the Table 4.3 and 4.4 were used to plot the excitation function for each individual energy with their respective theoretically calculated and experimental cross-section value for the reaction $^{64}Zn(\alpha, 2n)^{66}Ge$.

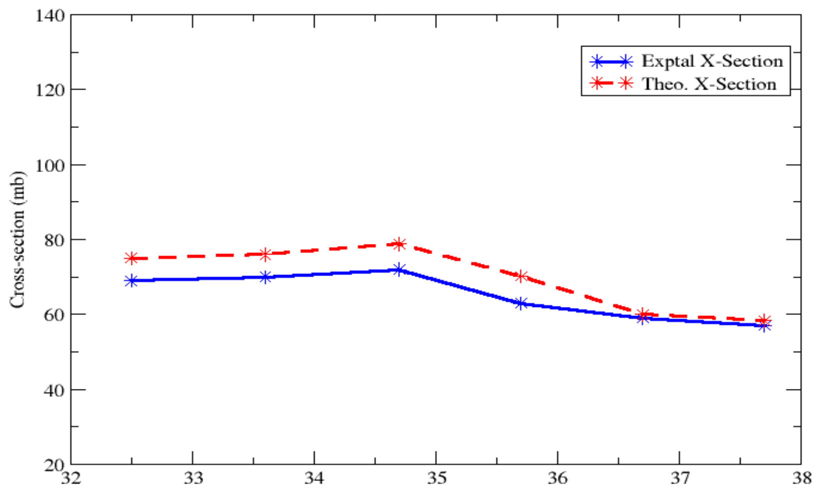

Figure 4.2: The theoretical and experimental excitation function for the reaction $^{64}Zn(\alpha, 2n)^{66}Ge$

The excitation function for the reaction has been plotted as in the Graph 4.2. The experimental excitation function were shown by solid line and the theoretical excitation functions by broken line. The theoretically calculated cross-section for the reaction $^{64}Zn(\alpha, 2n)^{66}Ge$ starts from minimum energy of 32.5 MeV with cross section of 75.05 mb and reaches its maximum energy at about 37.7 MeV with 58.3 mb. The theoretical cross-section starts to fall down at energy 34.7 MeV with cross-section of

78.76 mb for increasing projectile energy.

Similarly the experimental value indicates that the excitation function starts at about minimum energy 32.5 MeV with cross section of 69 mb and reaches its maximum peak at about 37.7 MeV with cross section of 57 mb and starts to fall at energy of 34.7 MeV with cross-section 72 mb. At the minimum energy (32.5 MeV) the theoretical cross-section is 75.05 mb and the experimental value is 69 mb, the difference is 6.5 mb. At the energy of 36.7 Mev the two cross-section comes very closer to each other with 1 mb difference. Thus, both the theoretical and experimental cross-sections were nearer to each other. From the Graph 4.2 it shows that the theoretically calculated cross-section comes very nearer to the experimental cross-section value as the projectile energy increases. It was observed that the theoretically calculated values fit to the experimental cross-section value best for the projectile energies 36.7 MeV and 37.7 MeV. In general there is a good agreement between the theoretical and experimental excitation function as seen in the Graph 4.2. It implies that the COMPLET code gives a better result for the reaction in the projectile energies from 36.7 MeV and 37.7 MeV.

4.3 Reaction cross-section for $^{64}Zn(\alpha,p)^{67}Ga$

4.3.1 Experimental reaction cross-section for $^{64}Zn(\alpha,p)^{67}Ga$

The experimental data obtained from EXFOR data center was done by Gy.Gyurky, et.al in 2012. The experimental data was shown in Table 4.5 that corresponds to the reaction $^{64}Zn(\alpha,p)^{67}Ga$ in energy range between 6.545 MeV to 11.0288 MeV. The experimental excitation function for the cross-section data obtained from EXFOR data library against the energies were plotted in the Graph 4.3 and shown by a solid line.

E_{proj}(MeV)	6.545	7.225	7.97938	8.99938	9.33938	9.605	10.285	10.9438	11.0288
σ_{exp}(mb)	0.0373	0.438	5.95	36.6	49.8	72.3	123	172	177

Table 4.5: Experimental cross-section for reaction $^{64}Zn(\alpha,p)^{67}Ga$

4.3.2 Theoretical Reaction cross-section for $^{64}Zn(\alpha,p)^{67}Ga$

The theoretically calculated reaction cross-section for the reaction $^{64}Zn(\alpha,p)^{67}Ga$ ranges in the energy from 6.545 MeV to 11.0288 MeV. The calculation were made using COMPLET code. Theoretically calculated cross-section data for $^{64}Zn(\alpha,p)^{67}Ga$ were displayed in the Table 4.6. The theoretical excitation function for the calculated cross-section data against the energies were plotted as in the Graph 4.3 using broken line.

E_{proj}(MeV)	6.545	7.225	7.97938	8.99938	9.33938	9.605	10.285	10.9438	11.0288
σ_{theo}(mb)	0.4514	2.615	13.21	66.77	108	125.5	212.1	284.8	295.4

Table 4.6: Theoretical Cross-section for the reaction $^{64}Zn(\alpha,p)^{67}Ga$

4.3.3 The Excitation function for the reaction $^{64}Zn(\alpha,p)^{67}Ga$

The theoretically calculated cross-section using COMPLET code and the experimental reaction cross-sections obtained from EXFOR data center for reaction $^{64}Zn(\alpha,p)^{67}Ga$ were listed in the above Table 4.5 and 4.6. Using this data the excitation function for each individual energy with their respective theoretically calculated and experimentally measured reaction cross-section for the reaction $^{64}Zn(\alpha,p)^{67}Ga$ were plotted as shown in Graph 4.3.

Both the theoretical and experimental cross-sections attain their minima and maxima at the energies 6.545 MeV and 11.0288 MeV respectively.

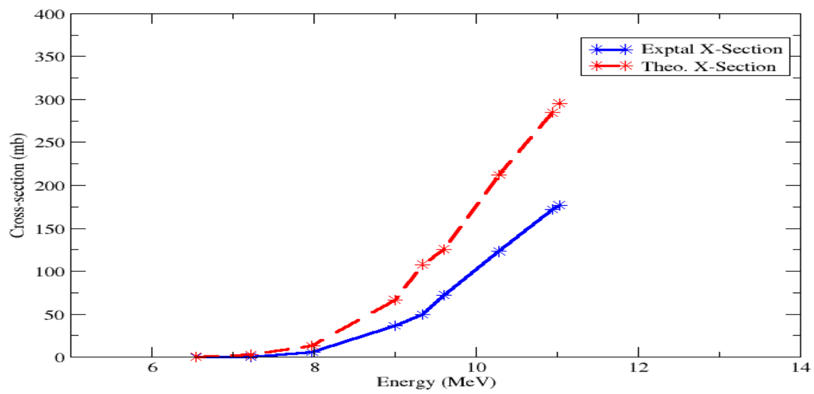

Figure 4.3: The excitation function for the reaction $^{64}Zn(\alpha, p)^{67}Ga$

The nature of the reaction depends on the energy of the projectile.

Both theoretically calculated and experimental reaction cross-section values increases for the same increasing energies. The theoretically calculated data using the COMPLET code is a little bit higher than the experimental data. The error of deviation from experimental data increase when projectile energy gets higher. The experimental cross-section values are nearer to the theoretically calculated value for a given energy ranges as in the Graph 4.3. Here the solid line stands for the experimental excitation function and the broken line for the theoretical excitation function. Even if there was a gap between the experimental and the theoretical excitation function at some energies, both follows the same pattern through out the increase in the projectile energy. It was observed that the theoretically calculated values are nearer to the experimental value best for the energy from 6.545 MeV to 7.97938 MeV as in Graph 4.3.

The excitation function plotted for theoretically calculated cross-section values are too much closer to experimental cross-section value obtained from EXFOR data library with the given energy ranges and have the same pattern as shown in Graph 4.3. In general the theoretical reaction cross-section were in a good agreement with the experimental value obtained from EXFOR data library. This implies the COMPLET code gives best fitting result for the reaction energy range from 6.545 MeV to 7.97938 MeV.

4.4 Reaction cross-section for $^{66}Zn(\alpha, n)^{69}Ge$

4.4.1 Experimental reaction cross-section for $^{66}Zn(\alpha, n)^{69}Ge$

In this reaction a projectile energy ranges from 10.4 MeV to 37 MeV have been used. The experimental reaction cross-section data per each projectile energy from EXFOR data library for the reaction $^{66}Zn(\alpha, n)^{69}Ge$ were displayed in the Table 4.7. These experimental data obtained from EXFOR data center was done by V.N.Levkovski, in 1991, Moscow. The experimental reaction cross-section versus the projectile energy called the excitation function were plotted as in Graph 4.3 using solid line.

E_{proj}(MeV)	10.4	20.2	23.2	25.1	28.9	30.7	32.5	34.7	37
σ_{exp}(mb)	257	600	388	212	98	74	56	43	36

Table 4.7: Experimental Cross-section for the reaction $^{66}Zn(\alpha, n)^{69}Ge$

4.4.2 Theoretical reaction cross-section for $^{66}Zn(\alpha, n)^{69}Ge$

The theoretical reaction cross-section for the reaction $^{66}Zn(\alpha, n)^{69}Ge$ in the energy range between 10.4 MeV to 37 MeV were calculated using COMPLET code as shown in the Table 4.8. The theoretically calculated values of nuclear reactions cross-section for excitation function has been carried out as the same energy as the experimental cross-section. The theoretically calculated value were used to plot the theoretical excitation function as seen in the Graph 4.4 using broken line.

E_{proj}(MeV)	10.4	20.2	23.2	25.1	28.9	30.7	32.5	34.7	37
σ_{theo}(mb)	215	471.6	74.9	22.5	25.35	1.18	1.08	0.83	0.579

Table 4.8: Theoretical Cross-section for the reaction $^{66}Zn(\alpha, n)^{69}Ge$

4.4.3 Excitation function for the reaction $^{66}Zn(\alpha, n)^{69}Ge$

Both the theoretically calculated cross-section using COMPLET code and the experimental reaction cross-sections were listed in the above Table 4.7 and 4.8. Using this data the energy versus theoretically calculated and experimental reaction cross-section (σ) called the excitation function for the reaction $^{66}Zn(\alpha, n)^{69}Ge$ were plotted as shown in the Graph 4.4. However, the experimental cross-section value obtained from EXFOR data center exceeds at the the theoretically calculated value at the same energy.

From this Graph 4.4 the theoretically calculated cross-section value seemingly approaches to the experimental cross-section values for the given energy ranges. The theoretically calculated values of nuclear reactions cross-section for the reaction $^{66}Zn(\alpha, n)^{69}Ge$ reaches its maximum peak at about 20.2 MeV with 471.6 mb and very rapidly starts to fall down for increasing value of projectile energy. Similarly the experimental value reaches its maximum peak at the same energy with cross section of 600 mb and this also slightly falls at the same energy with the theoretical cross-section value. At the minimum energy (10.4 MeV) and from 28.9 MeV to 37 MeV energy both the theoretical cross-section and the experimental cross-section value best fit

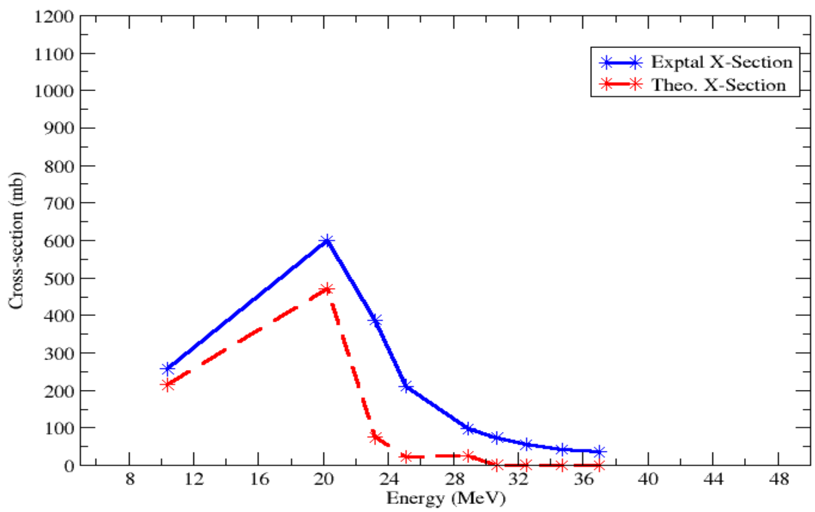

Figure 4.4: The theoretical and experimental excitation function for the reaction $^{66}Zn(\alpha, n)^{69}Ge$

as in the Graph 4.4. Here in this graph the solid line represents the experimental excitation function and the broken line for the theoretical excitation function. It was observed that on other energy regions there was a gap in numerical value between the theoretically calculated cross-section and experimental cross-section. Here the experimental value exceeds the theoretically calculated value. As seen from Graph 4.4 of excitation function for the reaction $^{66}Zn(\alpha, n)^{69}Ge$, the pattern of the graph were the same. Thus there is a good agreement in the theoretical and experimental reaction cross-section with small error in the cross-section. This finally shows that the COMPLET code gives a good result for the reaction in the range from 28.9 MeV to 37 MeV as seen in Graph 4.4.

4.5 Reaction cross-section of $^{66}Zn(\alpha, 2n)^{68}Ge$

4.5.1 Experimental reaction cross-section for $^{66}Zn(\alpha, 2n)^{68}Ge$

In the reaction $^{66}Zn(\alpha, 2n)^{68}Ge$, the experimental reaction cross-section value obtained from EXFOR data center ranges from the energy 23.8 MeV to 46 MeV as shown in Table 4.9. These experimental data obtained from EXFOR data center was done by V.N.Levkovski in 1991, Moscow. The graph of experimental reaction cross-section versus the projectile energy called the excitation function were plotted as in Graph 4.3 using a solid line.

E_{proj}(MeV)	23.8	25.1	28.9	31.4	34.7	37.7	40.5	43.4	46
σ_{exp}(mb)	374	415	529	565	526	448	306	151	129

Table 4.9: Experimental Cross-section for the reaction $^{66}Zn(\alpha, 2n)^{68}Ge$

4.5.2 Theoretical reaction cross-section of $^{66}Zn(\alpha, 2n)^{68}Ge$

The theoretical reaction cross-section were calculated using COMPLET computer code and the result was saved in Table 4.10. The theoretically calculated nuclear reaction cross-section values for the reaction $^{66}Zn(\alpha, 2n)^{68}Ge$ starts from the projectile energy at about minimum energy of 23.8 MeV to maximum energy 46 MeV as in the Table 4.10. The graph was plotted for theoretical reaction cross-section calculated from the code against the respective energy called excitation function as shown in the Graph 4.5 using the broken line.

E_{proj}(MeV)	23.8	25.1	28.9	31.4	34.7	37.7	40.5	43.4	46
σ_{theo}(mb)	288.6	337.8	452.1	404.4	284.3	181.9	122.3	105.8	84.8

Table 4.10: Theoretical Cross-section for the reaction $^{66}Zn(\alpha, 2n)^{68}Ge$

4.5.3 The Excitation function of $^{66}Zn(\alpha, 2n)^{68}Ge$

The theoretically calculated cross-section using COMPLET code and the experimental reaction cross-sections were listed in the Table 4.9 and 4.10. The excitation function for each individual energy with their respective theoretically calculated and experimentally measured reaction cross-section value for the reaction $^{66}Zn(\alpha, p)^{68}Ge$ were plotted as in the Graph 4.5. The solid line in the graph shows the experimental excitation function and the broken line shows the theoretical excitation function.

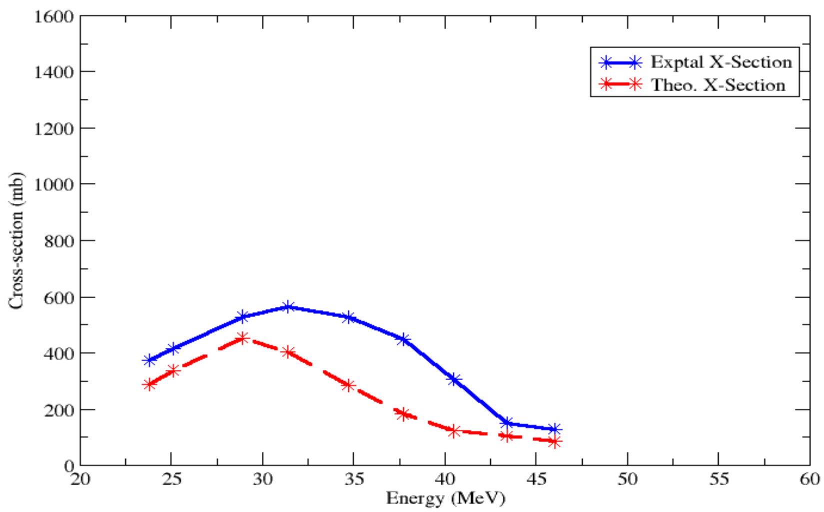

Figure 4.5: The theoretical and experimental excitation function for the reaction $^{66}Zn(\alpha, 2n)^{68}Ge$

The theoretically calculated cross-section values for the reaction $^{66}Zn(\alpha, 2n)^{68}Ge$ starts from the minimum energy of 23.8 MeV with cross section of 288.8 mb and reaches its maximum peak at about 28.9 MeV with 452.1 mb and starts to fall down for increasing value of energy. Similarly the experimental reaction cross-section starts to fall down at about the projectile energy of 31.4 MeV reaching its maximum cross-section 565 mb. The theoretically calculated and experimental reaction cross-section values in a given energy range are different at some energies but they both increases and decreases at the same time with the same projectile energy as in the Graph 4.5. This shows that both the theoretical and experimental excitation functions follows the same pattern at the same projectile energy. It was observed that there was a gap in the energy between 28.9 MeV to 40.5 MeV, in the theoretically calculated and experimental reaction cross-section. Whereas, the theoretically calculated cross-section approaches the experimental cross-section value best for the energy from 23.8 -28.9 MeV and 43.4- 46 MeV as in the Graph 4.5. In general both the theoretical and experimental reaction cross-section are in a good agreement for the reaction $^{66}Zn(\alpha, 2n)^{68}Ge$. This shows that COMPLET code calculation give good result for energy from 23.8 MeV to 28.9 MeV and 43.4 MeV to 46 MeV compared to other energy regions.

Chapter 5

Conclusion

In this study calculation of excitation function of alpha induced reaction on zinc isotopes (^{64}Zn, ^{66}Zn) for the reactions ($^{64}Zn(\alpha,n)^{67}Ge$, $^{64}Zn(\alpha,2n)^{66}Ge$, $^{64}Zn(\alpha,p)^{67}Ga$, $^{66}Zn(\alpha,n)^{69}Ge$, $^{66}Zn(\alpha,2n)^{68}Ge$) below 46 MeV have been carried out. The theoretical calculation were done using COMPLET nuclear reaction computer code and compared with experimental value taken from EXFOR data center. Alpha-induced reaction cross-sections provide clues to understand the nuclear structure and offers a production of residual nucleus. In this study, alpha-induced reactions on zinc isotopes (^{64}Zn, ^{66}Zn) for energy below 46 MeV have been calculated as part of a systematic investigation of excitation functions. The cross-sections were calculated for the production of ^{67}Ge, ^{66}Ge, ^{67}Ga, ^{69}Ge and ^{68}Ge in ($^{64}Zn(\alpha,xn)$, $^{66}Zn(\alpha,xn)$) where x = 1, 2 and $^{64}Zn(\alpha,P)$.

The following conclusions have been drawn depending on comparison between the calculated data and the experimental data.

- COMPLET code gives good result for the reaction $^{64}Zn(\alpha,n)^{67}Ge$ for energies at 9.605 and 12.325 MeV.

- Reaction cross-section using a COMPLET code calculation agrees where with an experimental cross-section of the reaction $^{64}Zn(\alpha, 2n)^{66}Ge$ at energies 36.7 MeV and 37.7 MeV.

- COMPLET code give good result for the reaction $^{64}Zn(\alpha, p)^{67}Ga$ energy from 6.545 MeV to 7.97938 MeV

- A better result were found for the reaction $^{66}Zn(\alpha, n)^{69}Ge$ for energy from 28.9 MeV to 37 MeV from COMPLET code calculation compared to other energy energy regions.

- COMPLET code gives best fitting result for the reaction $^{66}Zn(\alpha, 2n)^{68}Ge$ for energy from 23.8 MeV - 28.9 MeV and 43.4 MeV to 46 MeV.

The Studies of excitation functions of charged particle-induced reactions like protons and alpha-particles are of considerable significance for testing nuclear models as well as for practical applications.

Bibliography

[1] Fundamentals in Nuclear Physics, Jean-Louis Basdevant, James Rich, Michel Spiro Palaiseau, France,April, 2005]

[2] N. Bohr, Nature, 137(1936)344.

[3] John Lilley; Nuclear physics principles and applications. Baffins Lane, Chichester, The University of Manchester (2001)

[4] Samuel S.M. Wong, Introductory Nuclear Physics University of Toronto Second Edition (2004:303)

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

[6] E.Betak, Recomendations For Pre-Equilibrium Calculations Institute of Physics, Slov. Acad. Sci., 84228 Bratislava,

[7] SyedM.Qaim*, "Usesofalphaparticles", IngoSpahn,Bernhard Scholten,and Bernd Neumaier,Radiochim. Acta 2016; 104(9): 601624

[8] Kenneth S. Krane; Introductory Nuclear Physics Oregon State University NewYork, Chichester, 2nd edition.(1955)

[9] Walter E. Meyerhof, Elements of nuclear physics. McGraw-Hill, Inc. (1967)

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

[11] M. Blann, (1975) Annu. Rev. Nucl. Sci. 25 123.

[12] A.J. Koning and J.M. Akkermans, Pre-equilibrium nuclear reactions Netherlands Energy Research Foundation ECV,

[13] David Halliday, Introductory Nuclear Physics, Modern Asian edition, Tokyo, 1958.

[14] IAEA, EXFOR Nuclear Data Library, https://www-nds.iaea.org/exfor/exfor.htm

[15] Kaplan, Nuclear physics, 2nd edition

[16] E. Raeymackers, et al., "Light charged particles emission in fast neutron (25-65 MeV) induced reactions",Nucl. Phys. A 726 210-250 (2003).

[17] PhD Thesis, Ibrahim A/Rahim Shaddad Khartoum, 1995

[18] Introductory Nuclear Physics, P.E. Hodgson, E. Gadioli andE.GadioliErba: Oxford University press, 2003.

Appendix

Nuclear reaction cross-section data is being collected using nuclear reaction code per a given projectile energy. Due to lack of senior laboratory to experimentally determine the nuclear reaction cross-sections, experimental data has been taken from nuclear reaction data center, EXFOR. The nuclear reaction code used in this thesis is a fortran-77 based computational computer code called complet. The code COMPLET is a nuclear reactions code which was designed for validity and ease use in the bombarding energy range of a few Mev to several hundred Mev.

The COMPLET CODE INPUT is described below. The notion card from the old FORTRAN input is still kept but now corresponds to lines. Free formats, the input values should be separated by , or CR.

CARD 1 General input data Symbol description

AP - Projectile mass number

AT - Target mass number

ZP - Projectile charge

ZT - Target charge

QVAL - Reaction Q value = AP+AT-ACN. = 0: calculated from M and S mass formula. = 1: calculated from mass excesses of 1990 nuclear wallet cards

PLD - Level density parameters "A", A= ACN/PLD=0: A = ACN/8

CLD- ratio of single particle level densities AF/AN = 0: AF/AN = 1. If parameter ISOT is nonzero, CLD is isotopic abundance input default value =1.0 If =0, use rotating finite range fission barriers due to A.J.sierk

BARFAC- multiplies the rotating drop fission barrier by this value. BARFAC = 0: BARFAC=1

ROFFAC - multiplies the rotational energy by this value. = 0:ROTFAC=1.

RO- critical temperature above onset of retarded fission

GI- nuclear friction parameter from equilibrium deformation to saddle

GO - nuclear friction parameter from saddle to scission point

NA- the number of nuclide of each z to be included in the calculation. Up to 21 neutrons may be emitted (maximum NA=22)

NZ -the number of Z- values to be calculated in the emission process. Up to 8 protons may be emitted (maximum NZ=9). For correct PE calculations binding energies are calculated for all nuclei with IZ, IA 5 5 (17.7.91)

MC- Shell correction option for masses subroutine. MC = 0, masses incl. Shell correction. MC = 1, masses without shell correction term MC = 2, BE values will be supplied as input. MC > 2, BE values are calculated from 1990 nuclear wallet cards.

MP- pairing correction to masses. MP = 0: no pairing term in masses. MP = 1: pairing term in masses, ldgs calculated from msl formula and applied back 30 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.

IPCH - = 1: inverse cross sections will be readout for possible future use in separate output file. = 0: or NE from 1.no printout

KPLT - number of decades to be plotted as excitation function on line printer. If KPLT = 0: no plotting Card 2 Title -80 columns If MC = 2 on CARD 1, read user supplied n, p,alpha, deuteron triton and helion binding energies here, Format for IA =1 to NA, IZ=1 to NZ. If INVER =0 on CARD1, read the n, p, alpha, deuteron triton, helion and gamma inverse cross sections here. In ascending channel energy, first value = 0.1 Mev, incremented by 1Mev, 48 values per particle type in sequence N,P,A,D,T,3HE, and gamma depending on value of M3.

CARD 3 ENERGY and COMPOUND NUCLEUS and PRE-EQUILIBRIUM OPTION Symbol Description

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 KPLT=0, EKIN values were run in ascending order they are plotted). If

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

RCSS = 0: reaction cross section is calculated from subroutine ¡for pi-induced reactions: if RCSS $< input > = 0$,RCSS = 100mb>: > 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-ewing evaporation, = 2: S-wave approximation with liquid drop moment of inertia, = 3: S- wave approximation with rigid body =0; calculated for all partial wave including fission and full angular omentum coupling <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<Z.Phys .H and N A341 <92> 289> =0; simple approach with initial exciton number = 1 for P, N

JUPPER- JUPPER LT 0, Blann- Retto type PE-gamma emission using S.P. state densities instead of 1P1H two particle densities Normalization factor =1/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 other parameters on this card are for the pre-compound calculation options. Put TD- values to zero, if no pre-compound calculation is wanted.

IJ- IF=1 $< or3 >$ GP = GN =3/4*A/ POT IF= 0 $< or2 >$ 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 calculate from nucl.matter value= 37.8 Mev;

AV - if AV = 0: =1 OPTICAL MODEL mean free paths are used in routine CMFP. Not to be used above 55 Mev. If AV = 1: Nucleon-Nucleon mean free paths are used in NUCMFP.

ALF - probability that newly created exciton particle from first stage exciton gets an alpha particle in the second stage. <1-ALF>: complementary probability If ALF > 1 calculation for two initial exiton numbers A)ATD=TD-3 <min.1.5> AEX1=AEX2=0. AEX3=2; ATD= TD-6 for TD > 9 with weight ULF= INT <ALF>/100 B > Weight = <1-ULF>, with initial exciton numbers.

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

GDO - critical angular momentum. $GDO > 0$: partial waves with L > GDO are not taken in to account in line of isotone cross sections while cross sections for partial waves with $L > GDO$ are accounted for in the line below N.B For $GDO = +0.5$ No cut-off.

CARD 4 ENERGY AND REACTION CROSS SECTION

EKIN Projectile kinetic energy in the laboratory system. This card is repeated for each energy wanted in calculating excitation function with parameters specified in card 1 and card 3.

RCSS As on card 3

CARD 5 ISOBARIC YIELD CALCULATIONS IN EXCITATION FUNCTIONS < Card 5 is read after negative energy on card 4 or 3> ISOBA 28 numbers are expected since maximum 28 isobaric chains exist starting from CAN-1. The 28 ISOBA inputs may vary from 0 to 9 according to the number of ISOBARS to be added.

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

Name of Student: **Muluken Gebre** ID No. **RM 1198/09**

Graduate Program: **Regular, MSc.**

1. Course Work Performance

Course Code	Course Title	Cr. hr	Number Grade	Rank **	Remark
Phys799	**MSc. Thesis**	**6**	**80.55**	**Very Good**	

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

Thesis Title

Theoretical Calculation of Reaction Cross-section Induced by Alpha Particle on Zinc Isotopes(^{64}Zn, ^{66}Zn) Below 46MeV

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

   ____

   ____

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

Committee member	Name	Signature	Date
Chairman	Mr. Chali Yadeta		
External Examiner	Proff. A.K Chaubey		
Internal Examiner	Proff. Vijay Kumar Mittal		
Major Advisor	Dr. T/Mariam Tessema		
Department Head	Mr. Solomon H/Mariam		

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 **Muluken Gebre** have read and evaluated his/her thesis entitled "**Theoretical Calculation of Reaction Cross-section Induced by Alpha Particle on Zinc Isotopes(^{64}Zn, ^{66}Zn) Below 46MeV**" and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfilment of the requirements for the degree Master of Science in **Physics (Nuclear Physics)**.

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

SCHOOL OF GRADUATE STUDIES