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DEPARTMENT OF PHYSICS

INVESTIGATION OF COMPLETE FUSION DYNAMICS ON ^{7}LI + ^{24}MG, ^{12}C + ^{208}PB AND ^{4}HE + ^{69}GA SYSTEM AT A PROJECTILE ENERGY FROM 9 TO 93 MEV

By: Belisti Molla

Advisor: Awoke Taddese (PhD)

Debre Berhan University

Debre Berhan, Ethiopia

June, 2023

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The undersigned hereby certify that they have read and recommend to the Faculty of Post Graduate Studies for acceptance a thesis entitled **"Investigation Of Complete Fusion dynamics on ^{7}Li + ^{24}Mg, ^{12}C + ^{208}Pb and ^{4}He+^{69}Ga System at a Projectile Energy from 9 MeV to 93 MeV"** by **Belisti Molla Ayele** in partial fulfillment of the requirements for the degree of **Master of science in physics**.

Dated: June, 2023

External Examiner: __________________________ **Sign**____________________

Research Supervisor: **Awoke Taddese (PHD)** **Sign**____________________

Examing Committee: _________________________ **Sign**____________________

_________________________ **Sign** ____________________

DEBRE BERHAN UNIVERSITY

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Department**: Physics**

Degree**: Msc.** Convocation**: June** Year**: 2023**

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Abstract

In the present work, the dynamics of complete fusion reactions are involved in the interactions of ^{7}Li + ^{24}Mg, ^{12}C + ^{208}Pb and ^{4}He + ^{69}Ga targets have been investigated at projectiles energy from 9MeV to 93MeV. The excitation functions of experimental cross sections are obtained from EXFOR, IAEA, data center/library/ and theoretical calculations are obtained from LISE++ 9.7.1 version of PACE4 code. Level density parameter is one of the typical parameters used to evaluate the theoretical cross section at different values of the free constants. The results of the evaluated cross sections are compared graphically with the experimental cross section. The evaporation residual nucleuses produced in the channels are none alpha particle emitted channels due to the direct fusions of its projectile and targets.

Key words: Excitation Functions, LISE ++, EXFOR, IAEA, PACE4, Channels, alpha particles, residual nucleus, cross section

Acknowledgements

First and above all I would to thank the almighty of God for assisting and keeping me through all my life. The beginning and finishing of this work have been through his endless support.

I would also like to express my deepest gratitude to the Amhara regional state education bureau, East Gojjam branches, Basoliben education office for its government sponsor ship.

Next, I would like to express my greatest appreciation to my advisor Dr. Awoke Tadesse for his valuable constructive comments and suggestions during the development of this work. His willingness to give me his generous time experience helped me through this study. The completion of this work has been through his kindness adjurations.

I also thank Debre Berhan University, Department of physics for its academic and material support. Lastly, I would like to thank my families and my friends for helping and encouraging me by Supportive ideas to accomplish my work.

Belisti Molla Ayele

Debre Berhan, Ethiopia

June 20, 2015 E.C

Lists of Abbreviations

CF	Complete Fusion
HI	Heavy Ion
EFs	Excitation Functions
ERs	Excitation Residues
PACE4	Projection Angular momentum Coupled Evaporation code
EXFOR	EXchange FORmat
IAEA	International Atomic Energy Agency
MSC	Multi Step Compound
MSD	Multi Step Direct
CN	Compound Nucleus
PE	Pre Equilibrium
PLD	Partial Level Density
Mb	Milli barn
MeV	Mega electron Volt

Chapter One

Introduction

1.1 Back ground of the study

The investigation of the characteristics of atomic nuclei and the fundamental relationship governing their interaction between fast moving particles like α, β and γ or accelerating particle proton, neutron, deuteron, heavy ion and the target material is the basic for all nuclear technologies. The process of yielding new residue nuclei and elementary particles in the interaction of particles and the nuclei is known as nuclear reaction [1]. The complete fusion reaction is a vital for the formation of compound nucleus which is the dominant process at low energies. In compound nucleus formation 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 static equilibrium. After a time much longer than the time required by the projectile to cross the nucleus, a nucleon or a group of nucleon near the surface by statistical fluctuation, receive enough energy to escape, just as a molecule may evaporate from a heated drop of liquid. At moderate excitation energies, however, there are indications those pre- equilibrium emissions (where there is emission of a particle long before the attention stastical equilibrium) also contribute the reaction process. In the interaction of two heavy ions a number of reaction channels open and transfer of clusters of nucleons and angular momentum takes place.. In CF process, the projectile completely fuses with the target and formed highly excited compound nucleus decays by emitting evaporating nucleons and particles like element at equilibrium stage [2].

The study of complete fusion dynamics involving heavy ions induced reaction is an important concept because it shows several characteristic features that make them amenable to simple method of analysis and sensitive to particular aspects of nuclear structure, if the incident projectile, on overcoming, the coulomb barrier, is able to transfer the total incident momentum to the target nucleus is known as complete fusion (CF) [3].

Weakly bounded projectile is the interest for probing the influence low lying state in the continuum, the extended shape of nuclei, and quantum tunneling at the energies near the coulomb barrier. In this case, fusion reactions with radioactive ion beams are a key for their possible applications in the productions of super heavy nuclei. It is expected that the extended structure of loosely bound nuclei could be in principle induces a large enhancement of fusion which may aid to the synthesis of super heavy nuclei in fusion reactions. On the other hand, for weakly bounded nuclei, fusion reaction may be affected by their low lying energies, which can cause them to breakup while approaching to the fusion barrier. This may effectively reduce the complete fusion cross section, making it difficult to form super heavy nuclei [4].

In this work, heavy ion (A ≥ 4) induced reaction in various projectiles target combination produces the EFs of the evaporation residues that have an indicated importance of complete fusion dynamical processes above the coulomb barrier. This gives more emphasis on the EFs of the ERs produced in the ^{7}**Li** + ^{24}**Mg**; ^{12}**C** + ^{208}**Pb**, and ^{4}**He** +^{69}**Ga** systems have been studied. The theoretical calculations obtained using PACE4 Computer program compared with the experimental prediction from EXFOR data, IAEA, which evaluates the complete fusion cross section of heavy ion reactions [5].

1.2 Statement of the problem

Many nuclear physics researchers conduct a research on heavy ion induced nuclear reactions that are essentail to the formation of compound nucleus which are used for in different area of science such as midical science, astronomy, millitary and energy generation. This work gives more emphasis on the calculation of complete fusion cross-section reaction between ^{7}Li + ^{24}Mg, ^{12}C + ^{208}Pb, and ^{4}He + ^{69}Ga which oppens the following seven channels of the evaporation residues in the projectile enrgy range 9 to 93 MeV; ^{24}Mg(^{7}Li, 2p3n)^{26}Al, ^{24}Mg(^{7}Li, pn)^{29}Si, ^{208}Pb(^{12}C, 4n)^{216}Ra, ^{208}Pb(^{12}C, 3n)^{217}Ra, ^{69}Ga(^{4}He, 3n)^{70}As, ^{69}Ga(^{4}He, n)^{72}As, ^{69}Ga(^{4}He, 2n)^{71}As. Many studies on ^{7}Li, ^{12}C, and ^{4}He induces on ^{24}Mg, ^{208}Pb, and ^{69}Ga respectivelly are done experimentally for various projectile energy range. To the best of our knowledge, the theoretical investigation of complete fusion dynamics on ^{7}Li + ^{24}Mg, ^{12}C + ^{208}Pb, and ^{4}He + ^{69}Ga system by using PACE4 computer program.are not yet studied and reported theoretically. This is the main concern of the study as a research gap.

1.3 Objectives of the Study

1.3.1 General Objective

The general objective of this study is to investigate the complete fusion dynamics for ^{7}Li + ^{24}Mg, ^{12}C + ^{208}Pb, and ^{4}He + ^{69}Ga systems of heavy ion reactions.

1.3.2. Specific Objective

The study of the investigation of complete fusion dynamics on ^{7}Li + ^{24}Mg, ^{12}C + ^{208}Pb, and ^{4}He + ^{69}Ga reactions have the following specific objectives.

- Explain mechanism of complete fusion reactions for ^{7}Li + ^{24}Mg, ^{12}C + ^{208}Pb, and ^{4}He + ^{69}Ga systems.
- Determine the complete fusion cross section of ^{7}Li + ^{24}Mg, ^{12}C + ^{208}Pb, and ^{4}He + ^{69}Ga systems.
- To compare the theoretical data obtained from PACE4 computer programs with the experimental data obtained from EXFOR, IAEA data library.

1.4 Significance of the study

The result of the study will have the following significance.

- Developing the experience of using computer programs PACE4 and obtains relevant theoretical data.
- It provides a brief knowledge about complete fusion reactions.
- It may serve as a reference for other researcher in the future.

1.5 The scope of the study

This research was confined with how to investigate complete fusion dynamics of ^{7}Li + ^{24}Mg, ^{12}C + ^{208}Pb, and ^{4}He + ^{69}Ga systems at projectile energies 9 – 93 MeV. This has been done by using LISE ++ version of PACE4 computer code.

Chapter two

Theories of Nuclear reaction

2.1 Basics Concepts of Nuclear Reaction

Nuclear reaction is the change in identity of an atomic nucleus, induced by bombarding it with an energetic particle. The bombarding particles may be an alpha particle, a gamma ray, photon, a proton, a neutron, or a heavy ion. In many case, the bombarding particle must have enough energy to approach the positively charged nucleus to within the range of nuclear force. A typical nuclear reaction involves two reacting particles, that is a heavy target nucleus and a light bombarding particle, and produce two new particles (a heavier product nucleus and a lighter ejected particle). In the first observed nuclear reaction (1919), Ernest Ruther ford bombarded Nitrogen with alpha particle and identified the ejected lighter particle as hydrogen nuclei or protons (p)and the product nuclei as rare oxygen isotopes. In the first nuclear reaction produced by artificially accelerated particles (1932), the English physicist J.D Cock croft and E.T.S Walton bombarded Lithium with accelerated protons and thereby produced two Helium nuclei, or alpha particles. As it has become possible to accelerate charged particles to increasingly greater energy, many higher energy nuclear reactions have been observed that produces a variety of sub atomic particles are called mesons, baryons, protons, neutrons, and resonance particles [6].

A nuclear reaction is a process that occurs when nuclear particles (nucleon & nucleus) get in to close contact with one another. Most of the known nuclear reaction is produced by exposing different materials to a beam of accelerated nuclear particle. Usually a strong energy and momentum exchange takes place and the final product of the reactions are one, two, or more nuclear particles leaving the point of close contact in various direction. The products are mostly of a species different from the particle in the original pair.

Nuclear reaction is commonly represented by:

$$a + X \longrightarrow Y + b \tag{2.1.1}$$

or in more compact form or notation X (a, b) Y. The notation means that particle ***a*** strikes nucleus X to produce nucleus Y and outgoing particle ***b***, particle **a** & **b** may be elementary particles, but they can also themselves be a nuclei (e.g. deuteron, alpha particle, nucleus) [7].

2.1.1 Conservation laws in nuclear reaction

Conservation laws are the most fundamental concepts in nuclear reaction if the incident particles/projectiles/ are make a collision with the target nuclei; any nuclear reaction are a subject of conservation laws. Then, conservation laws are always applied in analyzing any nuclear reaction, and always applied before and after a nuclear reaction, because the quantity that must be conserved in nuclear reaction are mass, energy, momentum, angular momentum, charge and number of nucleon. There is an exception for high energy reaction involving the production of mesons. The number of proton and neutron must be conserved in nuclear reaction. In any nuclear reaction, the following conservation laws exist before & after a nuclear reaction.

- **Conservation of charge** (z): Charges can be transferred from one body to another body, but the total charge before the reaction must be equals to the total charge after the reaction.
- **Conservation of momentum (p);** the total linear momentum of the residual nuclei and emitting particle are the same as the total momentum of the target and the projectile (the target nucleus is ordinary taken to be at rest).
- **Conservation of angular momentum (J);** The total angular momentum involves the sum of intrinsic spin angular momentum S and relative orbital angular momentum L of the product must be the same as the angular momentum of initial particle.
- **Conservation of energy (Q);** The total energy of product, including both mass energy and kinetic energy of product nuclei and emitting particles are equals to the mass energy and kinetic energy of projectile & target nucleus
- **Conservation of number of nucleon (A);** Nucleon numbers are neither created nor destroyed, so that the number of nucleon minus anti nucleon in the universe remains constant. At higher energy, we still conserve the total nucleon number, but at low energy we conserve separately proton and neutron number [8].

2.1.2 Energetics of nuclear reaction

In nuclear physics, the Q- value of a nuclear reaction is defined as the measure of energy gain/lost/ due to the difference between the sum of reactant masses(projectile & target) and product (residual nuclei & emitting) particles mass. The Q- value is sometimes called the energy balance of the reaction and its can be mathematically given by the equation

$$Q = (M_{\text{initial}} - M_{\text{final}})\, C^2 = (M_a + M_X - M_y - M_b)\, C^2 \qquad (2.1.2)$$

This is the same as the excess kinetic energy of the final product given by

$$Q = E_{\text{Final}} - E_{\text{initial}} = E_y + E_b - E_x - E_a \tag{2.1.3}$$

Based on the basic nuclear reaction, the conservation of total relativistic energy is

$$M_aC^2 + E_a + M_xC^2 + E_x = M_yC^2 + E_y + M_bC^2 + E_b \tag{2.1.4}$$

In this case, $E_x = 0$, because the target nuclei must at rest, $V_x = 0$, andE_a, E_y&E_b are the kinetic energy of the projectile, target nucleus & emitting particle respectively, where as M_x, M_a, M_y & M_b are rest mass of the projectile, target nuclei, residual nuclei, and emitting particle respectively.

$$Q = E_y + E_b - E_a \tag{2.1.5}$$

The Q-value of a nuclear reaction positive, negative or zero value probabilities

- If $Q > 0$ ($M_{\text{initial}} > M_{\text{final}}$) or ($E_{\text{final}} > E_{\text{initial}}$), the reaction is said to be **exoergic or exothermic**, the Q – value becomes positive indicating that the mass is converted to energy, so that heat energy released during nuclear reaction.
- If $Q < 0$ ($M_{\text{initial}} < M_{\text{final}}$) or ($E_{\text{final}} < E_{\text{initial}}$), the Q – vale becomes negative, the reaction is said to be **endoergic or endothermic**; so that energy is converted to mass. The change in mass and energy must be related by the expression of special relativity, $\Delta E = \Delta MC^2$ any change in the kinetic energy of reacting particles must be balanced by equal change in its rest mass, in such case, no lose of energy/ energy must be conserved [9].

2.2 Reaction Cross Section

In nuclear physics, reaction cross section is one of the most important quantities in nuclear reaction study. The reaction cross section is the measure of the probability of a particular reaction to occur. Since interactions in a nuclear reaction takes place with individual target nuclei independently of each other, it is useful to refer the probability of a nuclear reaction in one target nucleus. To define the reaction cross section, assume that in a given experiment has a thin slabs of target material is struck by mono energetic beam consists of I particles per unit time distributed uniformly over an area A. if a nuclear reaction produces N particles per unit time, we can pretend that with each target nucleus there is associated an area σ, which is perpendicular to the incident beam such that if the center of a bombarding particle sticks inside of σ, there is a hit and a reaction is produced; and if the center of bombarding particle misses σ, no reaction is produced. So the quantity σ is defined as cross section and it gives a measure of reaction probability per target nucleus. It is a fictitious area, which need not be related to cross sectional area (πR^2) of the struck nucleus.

It is also possible to describe the reaction probability by the ratio $\frac{\mathbf{N}}{\mathbf{I}}$ but this quantity depend on the target density as well as its thickness $\Delta\mathbf{x}$, where σ is associated with an individual target nucleus. The probability that any one bombarding particle has a hit equals to $\frac{\mathbf{N}}{\mathbf{I}}$ and is also equal to the projected total cross section of all target nuclei lying with the area A, as seen along the beam direction divided by A. if there are n target nuclei per unit volume in the target material, **n A Δx ,** such nuclei are within reach of any bombarding particle in the beam. Each target nucleus has an associated cross section **σ** so that $\frac{N}{I} = \frac{\mathbf{nA\,\Delta x\,\sigma}}{A}$. Using this relation we can define cross section by writing;

$$\boldsymbol{\sigma} = \frac{N}{(I/A)\mathbf{n\,A\,\Delta x}} \qquad (2.2.1)$$

Where, **N** = Number of reaction particles to be emitted, $(\mathbf{I}/\mathbf{A})$ = Number of beam particles per unit area, **n A Δx =** Number target nuclei within the beam. The cross section has the dimension of area and measured in barn or cm^2, where, 1barn= 10^{-24}cm^2 [10].

2.2.1 Fusion cross sections

In the one-dimensional potential, the relative motion of the colliding nuclei is the only variable. In the case where the atomic numbers Z of the nuclei are high, a greater overlap of the densities of the colliding nuclei is required to overcome the barrier which is directly proportional to the product of the charges of colliding nuclei. When there is a significant overlap, the nucleon – nucleon interaction becomes dominant and leads to a substantial loss of kinetic energy and angular momentum of the relative motion. As a result, fusion of two nuclei that cannot escape the potential pocket, takes place. The transmission coefficient T_l(E) describes the probability that the system with angular momentum l at energy E will cross the barrier overcoming the total potential. In one – dimensional model, the interaction is closely linked to the transmission coefficient. The fusion cross - section of a partial wave with angular momentum l is expressed as

$$\sigma^{fus}(\mathrm{E}) = \pi\lambda^2(2l+1)\ T_l(\mathrm{E}) \qquad (2.2.2)$$

Where, λ is the reduced De Broglie wave length of the relative motion. The total cross-section is obtained by the sum of all partial waves. However, as discussed before, not all the partial wave takes part in the fusion process. Only values of angular momentum up to l_{crit} contribute to the fusion cross-section. Considering that, classically, the probability of partial wave to overcome the coulomb barrier and leads to fusion is 'one' for $1 \leq l_{crit}$, the fusion cross section can be expressed as

$$\sigma^{fus}(\mathrm{E}) = \sum_{l=0}^{l_{crit}} \pi\lambda^2(2l + 1)\, T_l(\mathrm{E}) \qquad (2.2.3)$$

The transmission coefficient can be calculated in different ways. One is to derive from the solution of the Schrödinger equation. Another way is to use the Hill-Wheeler approximation, where the coulomb barrier is approximated by a parabola;

$$V_l(\mathrm{r}) \sim V_{bl} - \frac{1}{2}\mu\Omega_l(r - R)^2 \qquad (2.2.4)$$

Where V_{bl} the barrier is potential, Ω_l is the curvature and R_{bl} is the position of the barrier relative to l^{th} wave. The corresponding Transmission coefficient with in this approximation is an analytically calculated as;

$$T_l\,(\mathrm{E}) = \frac{1}{1+exp\left(\left[\frac{2\pi}{\hbar\,\Omega_l}(V_b - E)\right]\right)} \qquad (2.2.5)$$

The curvature Ω_l is defined as $\Omega_l = \sqrt{-\frac{1}{\mu}\frac{d^2V_l(r)}{d^2(r)}}\,|_{r=R_{bl}}$. The transmission coefficient is replaced. The fusion cross – section can now be expressed as

$$\sigma^{fus}(\mathrm{E}) = \sum_{l=0}^{l_{crit}} \pi\lambda^2 \frac{2l + 1}{1+exp\left(\left[\frac{2\pi}{\hbar\Omega_l}(V_b - E)\right]\right)} \qquad (2.2.6)$$

If it is assumed that both the curvature and the position of the coulomb barrier are independent angular momentum l, then the simple expression, where the values approximate to the ones for s – wave ($l = 0$) is obtained. i.e. $R_{bl} \sim R_o\Omega_l$. The height of the barrier relative to the l^{th} wave can be expressed as;

$$V_{bl} = V_0 + \frac{\hbar^2}{\mu}\frac{l(l+1)}{R^2{}_{b0}} \qquad (2.2.7)$$

The dependence of the transmission coefficient on angular momentum approximated by shifting the incident energy by centrifugal term;

$$T_l\,(\mathrm{E}) = \mathrm{T}\left(E - \frac{\hbar^2}{\mu}\,\frac{l(l+1)}{R^2{}_{bo}}\right) \tag{2.2.8}$$

Considering that any partial wave contributes to the fusion cross- section can be expressed in the form of integrals as;

$$\sigma^{\,fus}\,(\mathrm{E}) = \pi\lambda^2 \int_0^{crit} \;(2l\;+\;1)\,T_l\,(\mathrm{E})\,\mathrm{d}\,l \tag{2.2.9}$$

If the variables are changed from l to $l(l$ + 1), the integral can be explicitly calculated. This leads to the Wong's formula;

$$\sigma^{\,fus}\;(\mathrm{E}) = \frac{\hbar\,\omega_o\,R_{bo}}{2E}\;\ln 1 + exp\;\left(\left[\frac{2\,\pi}{\hbar\,\Omega_0}\,(\,E - V_b)\right]\right) \tag{2.2.10}$$

For energies higher than the coulomb barrier (E $>>$ V_{bo}, the cross section can approximates that as;

$$\sigma^{\,fus}\;(\mathrm{E}) = \pi\,R^2{}_{bo}\left(1 - \frac{V_{bo}}{E}\right) \tag{2.2.11}$$

Considering equation, for higher energies, and assuming T_l = 0 for 1 $> l_{\;crit}$ and T_l = 1 for 1 $< l_{\;crit}$, the fusion cross section can be expressed as

$$\sigma^{\,fus}\;(\mathrm{E}) = \sum_{l=0}^{l_{crit}}\;\;\pi\lambda^2\,(2l\;+\;1)\;\;= \pi\,\lambda^2\;\;l^2{}_{\,crit} \tag{2.2.12}$$

By replacing the value of l_{crit} from the above expression, the cross- section can be approximated as;

$$\sigma^{\,fus}\;(\mathrm{E}) = \frac{\hbar\;\omega_o\;R_{bo}}{2E}\;\;exp\;\;\left(\left[\;\frac{2\,\pi}{\hbar\,\Omega_0}\,(\,E - V_{bo})\right]\right) \tag{2.2.13}$$

So for the energies bellow the coulomb barrier, the cross- section depends experimentally on the difference $(\,E - V_{bo})$ [11].

2.3 Nuclear Reaction Mechanism

Nuclear reactions, like chemical reaction, can occur via different reaction mechanism. Weiss kop has presented a simple conceptual model for illustrating the relationship between various nuclear reaction mechanisms. Let us consider the general nuclear reaction of the type X (a, b) Y bearing in mind that for some case, the nuclei b& Y may be identical to a & X. The particle a may move near the target nucleus X, and has a certain probability interacting with the nucleon force field of X causing it's to change, but not lose of any energy(Q=0). This reaction mechanism is called shape elastic. If shape elastic scattering does not occur, then the projectile may interacts with X via two- body collision between the projectile and some nucleon of X, raising the nucleon of X to unfilled level [12].

If the struck nucleon leaves the nucleus, a direct reaction is said to have occur, where as the struck nucleon does not leave the nucleus, further two body collision may occur and eventually, the entire kinetic energy of the projectile nucleus may be distributed between the nucleon of the **a + X** combination leading to the formation of compound nucleus. Because of the complicated set of interaction leading to the formation of compound nucleus, we can say that it forgets its mode of formation and its subsequent break up only depends on the excitation energy, angular momentum of compound nucleus, etc., but not the nature of the projectile and the target nuclei. Sometimes compound nucleus may emits a particle of the same kind as the projectile or even the projectile itself with the same energy as the projectile if this happens, compound elastic scattering has occurred as shown **in Figure 2.1**.

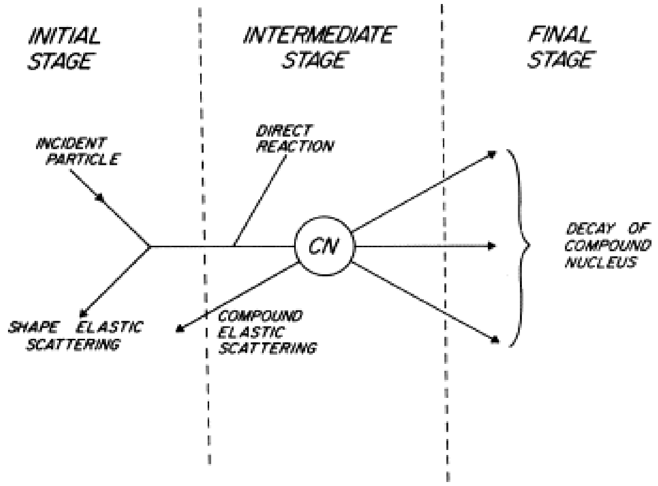


Figure 2. 1: The schematic view of the various types of reaction mechanism..

The cross section of many nuclear reactions for the projectile energy exceeding about 40 MeV is usually larger than the predicted cross section by compound nucleus theory. In many case, the cross section is forward peaked and attributes one step direct interaction. Multi step process can also occur after the first collisions, but longer before stastical equilibrium reaches. These pre – equilibrium process are divided in to two types known as multistep compound (MSC) and multi step direct (MSD) reactions. In multi- step compound (MSC) reaction, all particles are bounded to at least one stage of the process. On the other hand, in multi step direct (MSD) reaction at least one particle is in continuum. The probability reaction mechanism and there relation to energy is shown in **Figure 2.2**

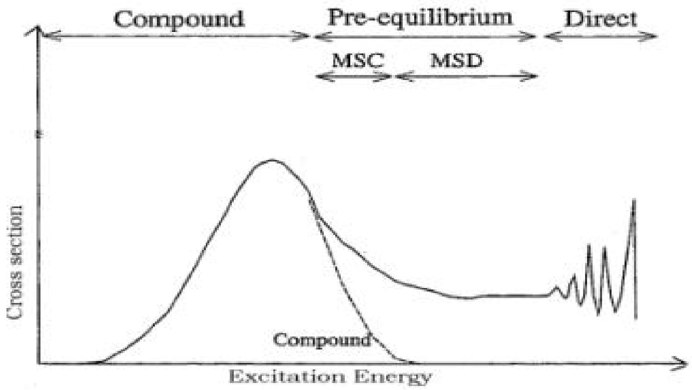


Figure 2.2: Schematic drawing of an outgoing particle spectrum

2.3.1 Direct reaction

Direct reaction occurs when a projectile interacts primarily with the nucleon in the surface of the target nucleus. The interaction is between one or two nucleons. Energy and momentum transfer is very small and the transfer is only too few nucleons, and emission of the particle most probably is in the direction of motion of the projectile. The main characteristics of direct reactions are, **firs**t, the emission of much larger number of high energy particles than expected on the basis of evaporation model. **Second**, the angular distribution of emitted particle shows a forward peaking. This may be because the direct reaction takes place with the surface of the nucleon. The **third** main characteristic of direct reaction is monotonic charge of cross- section with energy, no resonances are observed.

There are a number of categories under direct reaction. The simplest direct reaction is elastic scattering, which leaves the target nucleus in its ground state. Inelastic scattering occurs when the projectile interacts with the target nucleus and gives it some of its energy, raising it to an excited state. Measurement of the lost of energy gives the energy of an exited state. At low energy incident energy, the target nucleus can be excited purely by the coulomb excitation and it is appreciable only for highly charged particle- heavy ions. At higher energies, the excitation is due to nuclear interaction between the projectile and the target modified the presence of coulomb field. By inelastic scattering, mainly, it is collectively states that strongly excited. This shows that the projectile interacts with the target nucleus as a whole not just with one of it's constitute nucleon. This is a collective excitation and may be described as a coherent sum of many individual particle - hole interaction.

Charge-exchange reaction is other types of direct reaction. In this reaction both energy and charge are transferred between the projectile and the target nucleus. Charge exchange reaction shows the importance of isospine in nuclear reaction. These reactions are particularly interesting because only the charge exchange isospine-dependant term in the effective interaction contributes to the cross section. If the reaction goes to the isobaric analogue state of the target nucleus, the reaction is particularly simple as only the isospine vectors are flipped, such reactions are very similar to elastic scattering, and sometimes referred to as quasi elastic scattering.

The other reaction under direct reaction is transfer reaction. In this reaction one or more nucleons are transferred from the projectile to the target - stripping or from the target to the projectile- pick up reaction. As the energy of the projectile increases, it becomes likely that more than one particle is emitted. The simplest examples are the break - up of composite projectile in to it's constitute and the knock – out of the nucleon, or a group of nucleon from the target. At low projectile energy, the break-up due to the coulomb fields of the target nucleus, and as energy increases the nuclear fields are also contributes. Coulomb break-up is more pronounced for heavy charged nuclei. Break-up reaction can have the target in its ground state, or raise it's to an excited state. These process are refers to elastic and inelastic break-up. In knock-out reaction, the incident particle is small compared with the inter nucleon separation in the nucleus, and the projectile energy is much higher than the binding energy of the struck nucleon [14].

2.3.2 Compound Nucleus Reaction

The formation of compound nucleus is a slow process (10^{-16} s) as compared to nuclear time (10^{-21} to 10^{-22} sec.). During the formation of compound nucleus interactions taking with incoming projectile and nucleon present in the target, a lot of energy and momentum is transfer and this is shared by almost all nucleons in this much large time. If the projectile happens to be a nucleon, it will be not possible to distinguish its from the other nucleon. After large number of collision between the nucleon statistical thermodynamics equilibrium is established. And we can say that the compound nucleus forgets the way in which it was formed.

A further characteristic of compound nucleus is angular distribution of products. Because of random interactions among, we expect that the outgoing particle to be emitted with nearly isotropic angular momentum. If heavy ion is the incident particle, large amount of angular momentum can be transferred to the compound nucleus and to extract that angular momentum the emitted particle tends to be emitted at right angle angular momentum and thus preferentially at 0 degree and 180 degree, with light projectile this effect is negligible. If the idea of compound nucleus is valid and if one choose the energy of the proton and α- particle to produce the same excitation energy, then the cross section for each one of the three excited channels should be independent of the way of compound nucleus is formed. That is, the properties of compound nucleus don't have any relationship with the nuclei that formed it, where one can see clearly that the cross section depends practically only on the excited channel [15].

2.3.3 Pre-equilibrium reaction

Pre- equilibrium reaction is neither direct nor compound nucleus reactions. In these types of reaction, particles are emitted after the first stage of nuclear interaction (direct reaction) but longer before the attainment of statistical equilibrium (compound nucleus formation). Their time scale is intermediate between the very fast direct reactions and the relatively slow compound nucleus formation. In pre-equilibrium reactions, the emissions of particles from the excited target nucleus is neither by statistical decay of a compound nucleus nor by the prompt emission after collisions. In this reaction, the projectile shares its energy among a small number of nucleons in the target, the struck nucleons initiate a cascade of reactions with the target, at the source which a particle can be emitted before the compound nucleus was reached at a state of statistical equilibrium.

The energy of a projectile is shared among the nucleon of the target by a cascade of nucleon-nucleon interactions that excites particle-hole state of increasing complexity. A pre-equilibrium reaction corresponds to emissions of unbounded particles from one of these particle-hole stats when the composite nucleus is not yet equilibrated. Most of pre-equilibrium reaction takes place at energies high enough for it's to be no longer possible to resolve the individual final states. The cross-section is that reaction to a continuum of final states, and the absence of fluctuations in these continuum spectra shows that to a high degree of accuracy one may assumes that there are no interference effect so that pre- equilibrium cross section can be evaluated by adding incoherently the contribution for each stage of the nucleon-nucleon interaction cascade. The total cross- section for pre-equilibrium emission is then the sum of the cross-section for the emission from each stage of the cascade [16].

2.4 Heavy ion Reaction

The study of heavy ion reaction is one of the most important concerns in nuclear physics. Because of the heavy mass of the incident heavy ion, angular momentum, and plenty of energy can be conveyed to the target nucleus and give rise to a new observable facts as fusion, fission, and e.t.c. All nucleotides sometimes known as projectile which is heavier than α-

particle are considered as heavy particles (ions). The span of the projectile studied is large, ranging from light ions, C, O, Ne to medium mass ion such as S, Ar, Ca, Kr to heavy projectile Xe, Au, and even U. In the light nucleus region, we have assumed that the neutron and protons are "isotropically" similar; in heavy nucleus region, in which an important role is played by Coulomb force, this assumption is no longer valid. The properties of light nuclei depends on the total number of nucleon in a shell where as the properties of heavy nuclei depends on the number of neutron, N and the number of protons, Z individually. Accelerator devoted to the study of heavy ion induced reactions can produce a beam of ions up to ^{238}U; at the typical energy of the order 1-10 MeV per nucleon through much higher energies are also possible [17].

Heavy ion reactions can be divided into three main classes. The first class is due to their huge mass, two heavy nuclei feel a strong mutual coulomb repulsion barrier for an ever so heavy target, it is necessary about 5 MeV per nucleons. Subsequently, the wave length of the projectile is small compared to the dimension of the nuclei; so classical and semi- classical methods became useful in the description of the reaction. Secondly, the projectile carries large amount of angular momentum and rotational bends with several dozens of unit of angular momentum can be treated. Thirdly, direct reactions and the formation of compound nucleus are also common process in reaction with heavy ions. One of these processes can be understood as intermediate between a direct reaction and formation of compound nucleus. Fusion does not occur but projectile and target passes relatively long time under the mutual action of the nuclear force. Nuclear matter is exchanged between both and there is a strong heating of two nuclei, with large transfer of kinetic energy in the internal degree of freedom. These are deep inelastic collision, this process depends on the distance between the projectile and the target is

$$d = \frac{a}{2} + \left[\left(\frac{a}{2}\right)^2 + b^2\right]^{1/2} \tag{2.4.1}$$

Where **a** is given as $a = \frac{z_1 z_2 e^2}{4\pi\varepsilon_0 E}$ is the distance of closest approach in a head-on collision, and **b** is an impact parameters. If two ion energies in the center of mass system, E_{cm} can be surrounds the coulomb barrier, nuclear reaction can be happens and associated wave length which is less than the nuclear distribution is equals to

$$\lambda = \frac{h}{\sqrt{2\,ME_{cm}}} \tag{2.4.2}$$

The minimum distance between two interacting heavy ion in relation to nuclear potential $V(r_{min})$ between two ions.

$$r_{min} = \frac{b}{\sqrt{1-\frac{V(r_{min})}{E_{cm}}}} \tag{2.4.3}$$

- If $0 \leq r_{min} \leq R_F$, we are in the fusion region, where R_F is radius of fusion.
- If $R_F \leq r_{min} \leq R_{DIC}$, we are in deep inelastic in compound fusion
- If $R_{DIC} \leq r_{min} \leq R_N$, we are in peripheral region.
- If$r_{min} \leq R_N$where $R_N$is the distance above which nuclear interaction is negligible, we are in the coulomb region.

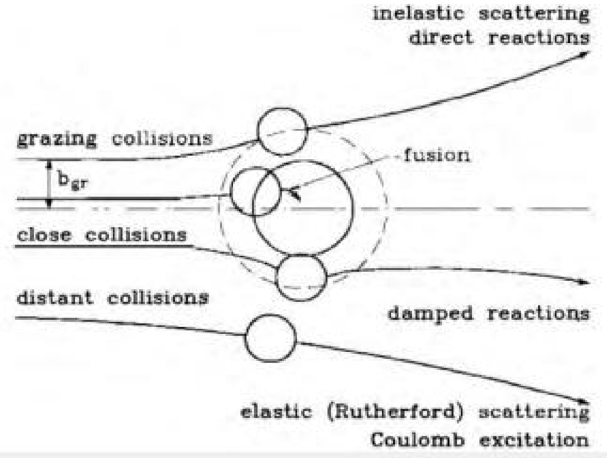


Figure 2.3: The Diagram representation of heavy ion reactions

The ion corresponds to these region are schematically shown in Figure above in fusion region , the two ion interaction leads predominantly to the formation of composite nucleus, which is initially quit far from statistical equilibrium since large parts of its excitation energy is in the form of an orderly collective translational motion of nucleons of the projectile and the target. This orderly motion is transformed in the chaotic thermal motion by means of a cascade of nucleon- nucleon interaction. This thermalization eventually leads to a compound nucleus in statistical equilibrium, but before reaching this, a considerable fraction of the excitation energy may be carried off fast particle or cluster of particle with energy considerable greater than the average thermal energy. Nuclear reaction induced by heavy ions bellow but near the coulomb barrier is useful for exciting collective model of the excitation of the target nuclei. Because, coulomb barrier is comparatively high in a heavy ion induced reactions and the projectile energies generally available are of the same order as the coulomb barrier. The coulomb barrier energy becomes very good reference energy to describe the reactions [18].

2.4.1 Complete Fusion of HI

Heavy ion complete fusion reaction is a reaction where there is an entire momentum transfer from the projectile to the target nucleus takes place. In this reaction, a fully equilibrated excited compound nucleus of pre- determined charge, mass, and angular momentum is formed. Heavy ion fusion reactions have been extensively studied because they offer possibility producing nuclei with high excitation energy and high spin thus allowing study of nuclear matter in a condition which are not easily formed in other reactions. Heavy ion reactions have also been used to produce supper heavy nuclei and to produce proton rich nuclei very far from the stable line [19]. There are important features of fusion reactions. For light projectile and low incident energies, the fusion cross-section may be a considerable fraction of reaction cross-section. The second important feature is, with increasing charges of interacting ions the fusion probability falls abruptly. The other features of fusion reaction is the fusion cross section at first increases linearly with $1/_{E_{cm}}$, reaches a maximum and there after decreasing linearly with$1/_{E_{cm}}$. The detailed energy dependence of fusion cross section may defer quit considerable for different interacting ions forming compound nucleus. In general, the fusion cross section varies quit smoothly with the energy, but in case of light system it may shows a quit large oscillations.

When heavy ions fuse, they form a compound nucleus which is far from statistical equilibrium, since a large fraction of its energy in the form of an orderly collective translational motion of the nucleons of projectiles and the target. This orderly motion transforms to chaotic thermal motion through a cascade of nucleon – nucleon interactions during the thermalization of compound nucleus. This takes sometimes and before reaching the thermal equilibrium, nucleon or clusters of which still have energy considerably higher than their equilibrium thermal energy may be emitted in to the continuum. These pre – equilibrium emissions must be taken in to account to reproduce the multiplicity and the spectra of the ejectile measured in heavy ion fusion reactions. The excitation functions of several heavy ion fusion reactions depart from what is expected for purely evaporative contributions. Starting from bombarding energies only slightly above the coulomb barrier acting between the two interacting ions and seems to be satisfactory reproduced only if emissions of pre – equilibrium nucleons is taking in to account. Some calculation suggested that with increasing bombarding energy an increasing freedom of excitation energy is dissipated by emitting pre – equilibrium particles (about 50% at energies about 30 MeV/nucleon), greatly reducing the probability of forming very excited equilibrated nuclei [20].

Chapter Three

Computer Code and Formalism

3.1 Computer Code

Computer codes are programs designed to calculate numerically the statistical value of nuclear interaction (reaction) and the interaction product which are the result of a certain nuclear reactions. The computer codes are used to simplify the complicated numerical value analysis of nuclear reaction at different stages of interaction and decay process. It is both practically and economically impossible to measure the necessary fusion cross section for all the isotopes in the periodic table for a wide range of energies. Nuclear reaction models are always needed to get the estimates of particle induced reaction cross sections. This reaction model is very important when the experimental data are not available or unable to measure the cross section due to the experimental difficulty. There for, nuclear reaction calculations by computer code play an important role in the nuclear data evaluation [21].

3.1.1 The LISE + + program

This program intended to calculate the transmission and yields of the produced fragments. Allows one to fully simulate the production of radioactive ion beam (RIB) from the parameters of reaction mechanism to the detection of nuclei selected by the fragment separator. among the goals of this program is a highly supper friendly environment, designed not only to forecast intensities and purities for planning experiment, but also as a tuning tool during experiments were its result can be quickly compared to the online data.

The program LISE++ offers the possibility to compare the LisFus model with the program PACE4 ported to windows from FORTRAN to C++, and incorporated in the LISE++ package under the name PACE4 [22].

3.1.2 PACE 4; Fusion - evaporation code

The PACE which stands for Projection Angular-momentum Coupled Evaporation is statistical model evaporation code which is used to simulate the main evaporation channels in fusion reactions at different laboratory beam energies. It uses Monte-Carlo simulation for de-excitation of compound nucleus. The major advantage of Monte-Carlo simulation is that it will provide correlation between various quantities. The code calculates probabilities and decay widths for all the nuclei which are present in the decay chain. It happens till the residual nuclei will no longer decay. Energy spectra and angular distribution of emitted particles can be obtained from this code. The code also gives the evaporation residue cross section as well as fission cross-section. It is possible to calculate up to 1000000 cascades at excitation energy of 2000 MeV.

It may be screen out that the code PACE 4 works only the statistical equilibrium model that is the formation of compound nucleus calculations and it does not concern that pre - equilibrium (PE) and incomplete fusion processes in to consideration [23].

3.1.3 Description of Input parameters

The descriptions of some symbols and abbreviations are taken as input parameters in the theoretical calculations of PACE 4computers are listed below.

CARD 1; Indicates the general input data, cross – section calculation, and definition

NCASC = Number of cascades, which means events to be used in Monte Carlo calculation < 1000000. (In this data calculation I used, NCASC = 1000)

INPUT = 1 projectile + target input. AGRAZ parameter determines the diffuseness of partial wave distribution. INPUT =2 Compound nucleus input for single spin. INPUT = 3 Compound Nucleus input, spin distribution read in. INPUT = 4 Compound nucleus input. Spin distribution calculated taking spin- cutoff parameters at Ex. INPUT =5 Triangular cross section (SIGMA = 2l + 1) between LMINN & maximum spin. (In this part I Selected, INPUT = 1, because my task is projectile + target input of complete fusion dynamics)

FYRAST = 0 Parameters determining yrast line to be used FYRAST < 0 provides the G – C Yrast line & provides Gilbert Cameroon spin Cut – off parameters. EROT = (SPIN) **2/2.*SIGSQ) EROT = rotating liquid drop rotational energy, multiplying by a factor of FYRAST. If the value changed to FRAST = 1, in both case, level density is calculated as Ate = EX – EROT.

BARFAC = 0, the program assumes the A.J Sierk modified rotating liquid barrier if this equals to Zero. If BarFac is positive, it will be taken as the desired Zero input fusion barrier. If BarFac is negative, its absolute value will be taken as a factor to multiply the Sierk barrier.

ARATIO = 1, Ratio of Fermi gas level density parameters “LITTLE- A” at the saddle point to the ground state value. The saddle point level density is determined by g.s.’LITTLE- A’ *ARATIO

FACLA = Level density parameter = MASS/FACLA if not Zero. If ==0 Gilbert Cameroon values are used. In this thesis FACLA runs between k=4 and k=12.

CARD 2; Lists of input parameters and its abbreviations in this card were used

AP = Projectile Mass Number

AT = Target Mass Number

ZP = Projectile Atomic Number (charge)

ZT = Target Mass Number

ACN = mass Number of Compound nucleus

ZCN = compound Nucleus atomic Number (charge)

Q VAL = Reaction Q Value = AP + AT – CAN

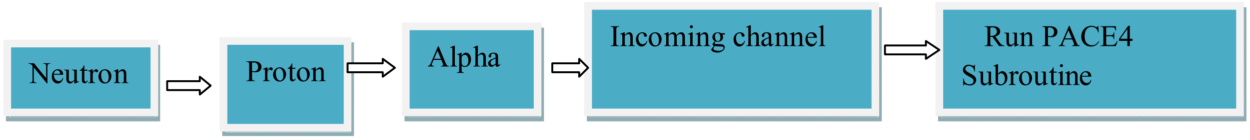
E - Lab = the beam energy/projectile energy inserted in MeV that taken from the EXFOR data.

EXPSIG = Experimental fusion cross- section. If = = 0 Bass (PRL- 1977) fusion barrier being used. (For all reaction channels, I used EXPSIG=0)

ELOSS = the energy loss beam through full target width (total dE) energies will be distributed from between E beam & E beam loss. This used to APRROXIMATE the theoretical cross-section to the experimental ones by inserting ELOSS = 0 to ELoss =10.

LIMNN = Lowest partial wave L in the calculation partial waves from L = 0 to LMINN. Excludes, enabling low L non fusion windows in reaction calculation.

CARD 3; In this part, there is a series of pathways to obtain/calculate the theoretical prediction of cross- sections [24].



3.1.4 The EXFOR data Center

The EXFOR data base is the exchange format for the formation of experimental reaction data between national and international nuclear reaction data center. The EXFOR (Exchange format) was designed for the collection, exchange, and dissemination of microscopic neutron induced reaction data based on a combination of key words, coded information's and frees texts. The EXFOR format was further developed to cover charged particle induced and photo nuclear data in addition to neutron induced reaction data. The format is flexible in order to record all necessary information. It is used for the benefits of researchers, scholars, and nuclear users in all countries. It is the library and the formats for collection, storage, exchange and retrieval of experimental nuclear reaction data. Although, the EXFOR formats can be used for both the compilation and dissemination centers may have their own formats for data service. EXFOR is derived from exchange formats of experimental nuclear reaction data complied regularly through the network of nuclear reaction data center [25].

3.2 General Formalism for Level Density

The experimental set up for this study is not found in our country, Ethiopia due to the lack of Level densities are very important ingredients for both statistical and pre- equilibrium models of nuclear reactions.

For the simplest system that contains **"A"** number of constitutes with an excitation energy **E**, the most general expressions for level densities is

$$\rho\ (A, E) = \frac{dN(A,E)}{dE} \qquad (3.2.1)$$

Which is the derivative with respect to energy of the total number of levels N (A, E) of a nucleus with A con that may have a excitation energy lower than E.

The level density of the nuclide involved in the evaporation chain may be calculated from the Fermi density distributions is

$$\rho\ (A, E) = \frac{1}{\sqrt{2\pi a}} \frac{\sqrt{\pi}}{12} \frac{e^{2\sqrt{aE}}}{a^{1/4}\ E^{5/4}} \qquad (3.2.2)$$

Where, **E** is the excitation energy and **a** is the level density parameter. The level density obtained by an experiment shows that a linear dependant with the mass number of compound nucleus.

In general, it is given by the expression;

$$A = \frac{A_{CN}}{K} \qquad (3.2.3)$$

Where, A_{CN} is the mass of compound nucleus, and k is a free constant. The value of free constant, k is adjusted to different numbers from 4 to 12 in the calculation of this work.

3.3 Error Estimation

The deviations between experimental cross section and the theoretical cross section should be minimized. The Chi (χ^2) minimization techniques of best fitted data is given by;

$$\chi^2 = \frac{1}{N} \sum_{i=1}^{N} \frac{(\sigma_{\text{Exp}} - \sigma_{\text{Theor}})^2}{\sigma_{\text{Exp}}} \qquad (3.3.1)$$

Where, N - is the total number of observations in the data, σ_{Exp} - is the experimental cross section. σ_{Theo} - is the theoretical cross section. In this thesis, I have three theoretical cross sections obtained from PACE4 code by adjusting different level density parameters for each reaction channels. Among these, the chi ($\chi2$) error estimation technique is performed by selecting the most appropriate or closest theoretical cross sections to the experimental cross section [26].

Chapter four

Data analysis and Interpretations

This chapter deals with the present works of the excitation function for the residue produced in the complete fusion dynamics of ^{12}C + ^{208}Pb, ^{7}Li + ^{24}Mg, and ^{4}He +^{69}Ga system were studied at a projectile energy from 9 MeV to 93 MeV. These energy ranges of projectiles are directly taken from the EXFOR, data center, IAEA in order to compare the cross- section obtained from PACE4 computer Code. The theoretical cross sections are obtained are evaluated by the computer code LISE++ (PACE4). Various input parameters have used in this work. These parameters are based on the PACE4 calculations to yield the most approximate values of theoretical cross sections to the values of experimental cross sections. Among these parameters, the level density parameters are the most important and approximate parameters to determine accurate values of the cross section of residual nucleus. The most important parameters which are randomized and selected to approximate for the values of experimental cross sections varies from 4 to 12 for all reaction channels. Even through the values of constants k is taken from 4 to 12, the values 4, 6, 8, 10, and 12 were the most in put parameters for best fit to the experimental data [27].

The experimental cross section for the reaction channels have been taken from different authors in the base of EXFOR, IAEA data center. The experimental cross section for the channels ^{24}Mg (^{7}Li, 2p3n) ^{26}Al and ^{24}Mg (^{7}Li, pn) ^{29}Si are taken from the authors (M.Ray, A.Mukheherejee, M.K. Pardon) [28]. The reaction cross section for the channels ^{69}Ga (^{4}He, 3n) ^{70}As, ^{69}Ga (^{4}He, 2n) ^{71}As and ^{69}Ga (^{4}He, n) ^{72}As are taken from the author V.N Levkovski [29]. The last two reaction cross section for the channels ^{208}Pb (^{12}C, 4n) ^{216}Ra and ^{208}Pb (^{12}C, 3n) ^{217}Ra are taken from the authors k.kalita [30]. The theoretical and experimental data are given together for each reaction channels in the table from 4.1 to 4.7 and the analysis of these result are given based on the Figure 4.1 to 4.7 which is plotted by cross section (mb) versus the energy (MeV) of the incident particles.

4.1. The production of ^{26} Al

Table 4.1: The Experimental and theoretical cross section for the reaction ^{24}Mg (^{7}Li, 2p3n) ^{26}Al.

Energy(MeV)	Exp. Cross section(mb)	Theoretical cross section (mb)			Chi (χ^2) value
		PACE4 (K=4)	PACE4 (K= 6)	PACE 4(K=8)	
10	92.34	75.8	82.3	69.9	5.58
11	112.61	98	105	84.7	6.5
12	148.68	120	129	115.3	19.4
13	167.48	123.6	140.3	132	26
14	181.32	125.12	145.3	129	27
15	196.29	132	152.4	135.1	27.1
16	204.24	155	162	165	26.1
17	212.5	169	175	159	26.5
19	204.21	171	179	174	10.3
21	188.61	165.	173	169	2.74
23	167.42	139	142	150	0.48
25	148.61	121	126	129	0.01
27	131.92	108	119	126	0.06
29	112	84.5	70.2	108	0.32
				χ^2_{av}	10.4

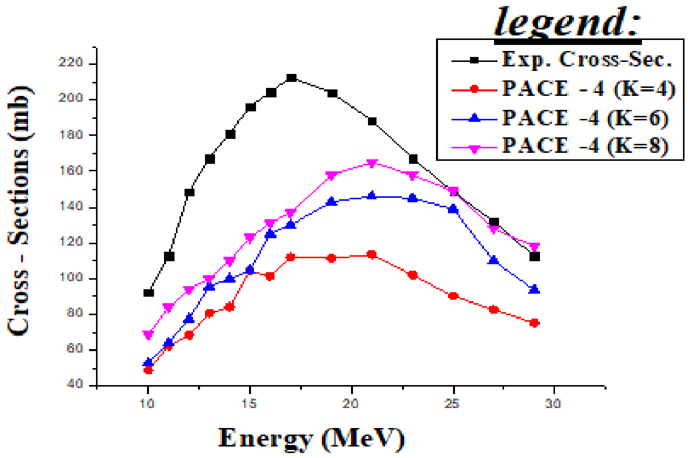


Figure 4.4: The theoretical and the experimental cross-section for the ^{24}Mg (^{7}Li, 2p3n) ^{26}Al reaction.

For the reaction ^{24}Mg(^{7}Li, 2p3n)^{26}Al as shown in **Figure 4.4** , the theoretical cross section obtained from PACE4 donot agree well from the the experimental resuls at lower enrgy from 10 MeV 19 MeV. This may be due to the openning of other channels during the break up ^{7} Li projectile, where as at higher energy from 21 MeV to 29MeV, theoretical cross sections paricularly at k=8 and k=6 are fairly agree with the experimental data obtained from EXFOR, IAEA library. This may assumes that their is complete fusion between ^{7}Li and ^{24}Mg produce a compound nucleus ^{31}P*, where this evaporates two protons and three neutrons , the residual nucleus ^{26}Al is producing in the reaction.

4.2 The production of ^{29}Si

Table 4.2: The theoretical and experimental Cross section for the reaction ^{24}Mg (^{7}Li, pn) ^{29}Si

Energy(MeV)	Exp. Cross section(mb)	Theoretical cross- Section(mb)			Chi (χ^2) value
		PACE 4(K=4)	PACE 4(K =6)	PACE 4(K =8)	
9	181.29	209	194	191	2.23
10	221.09	285	272	268	8.47
11	174.22	203	195	186	2.75
12	204.18	268	266	263	9.9
13	196.22	246	263	260	2.68
14	181.23	214	261	262	3.01
15	174.16	190	239	255	0.47
16	167.37	174	168	174	0.24
17	137.23	161	148	162	0.11
19	112.5	119	122	142	0.37
21	48.86	56.8	88.6	64.2	0.2
				χ^2_{av}	2.72

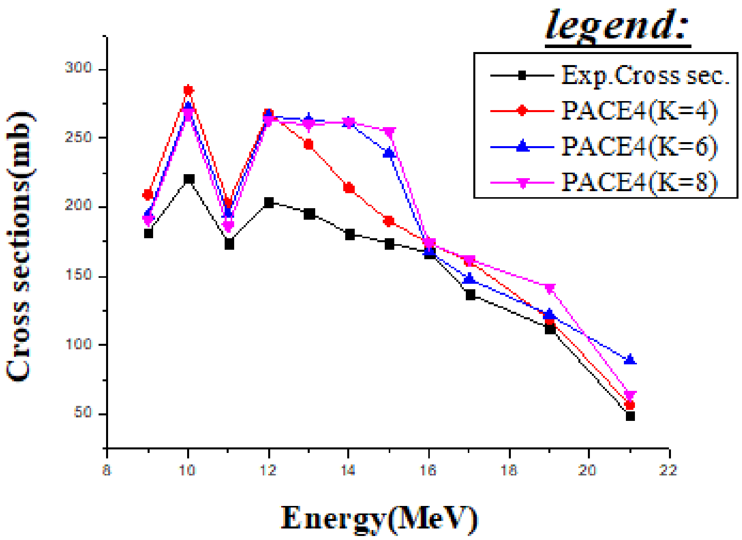


Figure 4.5: The theoretical and experimental Cross section for the reaction ^{24}Mg (^{7}Li, pn) ^{29}Si

For the reaction ^{24}Mg (^{7}Li, pn) ^{29}Si as shown in **Figure 4.5,** the theoretical calculations of cross sections is not in good agreement with the experimental cross section obtained from EXFOR, IAEA data center at lower energies from 9Mev to 15MeV due to the projectile up while approaching to the fusion barrier, whereas from 16 MeV to 21 MeV the theoretical cross section is approaches to the experimental ones particularly at the free constant level density parameters at k = 4. In this case, the projectile fuses with the target to formed excited compound nucleus state ^{31}P*, where this excited compound nucleus emits one proton (P) and neutron (n) produced a residual nucleus ^{29} Si of an element. Here is again as it can be seen from this figure, the highest theoretical cross section is found for the level density free constants particularly at k = 4 and k = 6 other than k = 8 with the projectile energy at 10 MeV, where as the minimum cross section is found at a projectile energy of 21MeV. In general, this shows that the increasing projectile energy indicates the decreasing cross section for both theoretical and experimental case.

4.3 The production of ^{70}As

Table 4.3: The theoretical and experimental Cross section for the reaction ^{69}Ga (^{4}He, 3n) ^{70}As

Energy(MeV)	Exp. Cross section(mb)	Theoretica cross section (mb)			Chi (χ^2) value
		PACE 4(K=6)	PACE 4(K=8)	PACE 4(K=10)	
34	101	68.8	35.1	26.2	10.2
35	120	96.7	67.1	41.3	4.52
36	179	128	106	60.2	14.5
37	203	172	144	98.1	4.7
38	257	186	161	138	19.6
39	277	190	183	164	27.3
40	286	219	222	171	15.6
41	281	215	197	177	15.5
42	274	225	204	190	8.76
43	261	221	208	204	6.13
44	248	197	203	187	10.4
45	254	206	192	200	0.07
46	250	196	205	200	11.6
				χ^2_{av}	9.82

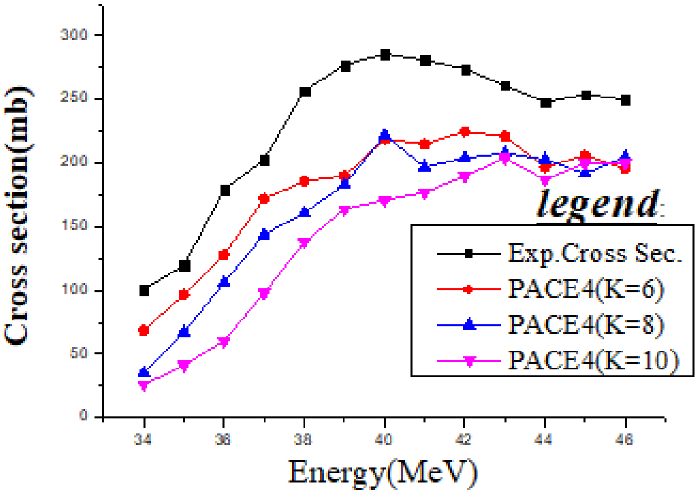


Figure 4.6: The theoretical and experimental Cross section for the reaction ^{69}Ga (^{4}He, 3n) ^{70}As

For the reaction ^{69}Ga(^{4}He, 3n)^{70}As as shown in the **Figure 4.6**, the theoretical cross sections obtained by using PACE4 is slightly closest with the experimental cross section particularly a free constant level density parameters at k= 6 in the energy range between 34 MeV and 39 MeV. But, for the energy above the 39 MeV the theoretical cross sections are overlapped and approached to each other. The cross sections obtained by PACE4 at k=6 is slightly fitted with the experimental cross section other than the other free constant level density parameters at k=8 & k=10. This may be assumes that the fusion reaction between the projectile ^{4}He and the target ^{69}Ga to formed an excited state of ^{73}As*, where as this excited state emits 3n behind the thermalization in order to produced ^{70}As residual nuclei.

4.4 The production of ^{72}As

Table 4.4: The theoretical and experimental Cross section for the reaction ^{69}Ga (^{4}He, n) ^{72}As

Energy(MeV)	Exp.Cross section(mb)	Theoretica cross section (mb)			Chi (χ^2) value
		PACE 4(K=6)	PACE 4(K=8)	PACE 4(K=10)	
10	225.6	133	137	137	34
11	291.8	268	288	304	0.03
12	388.9	397	410	433	1.14
13	476.6	490	502	523	1.41
14	548.3	591	581	592	1.98
15	592.9	608	580	575	0.24
16	626	666	664	637	2.30
17	600.7	607	585	555	0.37
18	548	589	577	531	1.53
				χ^2_{av}	4.78

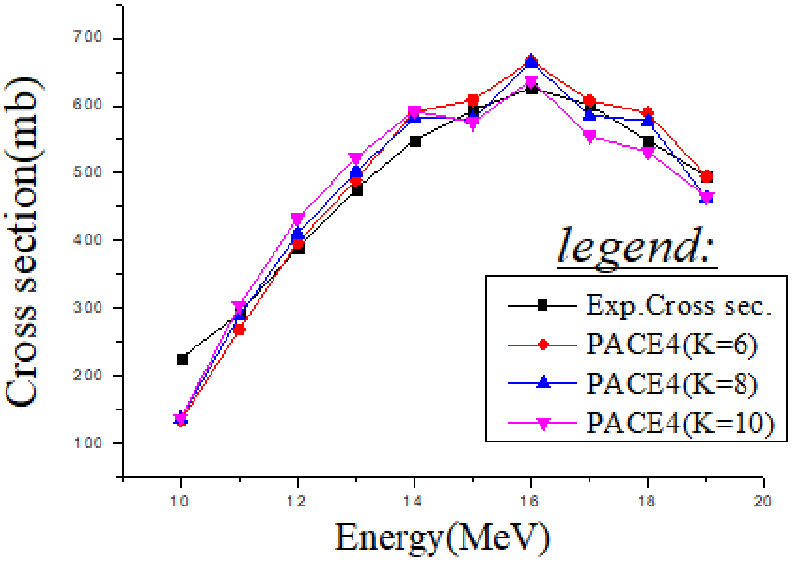


Figure 4. 7: The theoretical and experimental Cross section for the reaction ^{69}Ga (^{4}He, n) ^{72}As

For the ^{69}Ga (^{4}He, n) ^{72}As shown in the **Figure 4.7**, all theoretical calculation curves using PACE4 have the same starting point at a projectile energy of 10 MeV and they have small variations with the experimental curve due to the penetration of coulomb barrier for less energy of incident projectiles. From 11 MeV to 14 MeV, k=6 curve is more approaches to the experimental curve. At higher energies from 15 MeV to 19 MeV, all theoretical cross section curves are over lapped and approximates with the experimental curve. This approximately curves between the theoretical and experimental results may indicates the projectile(^{4}He) is highly fused with the target nuclei (^{69}Ga) to form the compound nucleus ^{73}As*, where as this compound nucleus emits a single neutron(n), for producing ^{72}As residual nucleus behind the thermalization effect.

4.5 The production of ^{71}As

Table 4.5: The theoretical and experimental Cross section for the reaction ^{69}Ga (^{4}He, 2n) ^{71}As

Energy(MeV)	Exp. cross section (mb)	Theore. Cross Section(mb)			Chi (χ^2) value
		PACE4(K=6)	PACE4(k =8)	PACE4(k=10)	
21	270.3	326	195	92.6	11.6
24	661.2	735	654	588	8.26
26	864	717	701	633	25.01
29	743	704	693	642	2.04
39	111.3	115	198	242	0.14
44	67.5	14.8	40.6	70.2	41.4
48	57.8	7.39	14.5	13.3	43.9
				χ^2_{av}	18.9

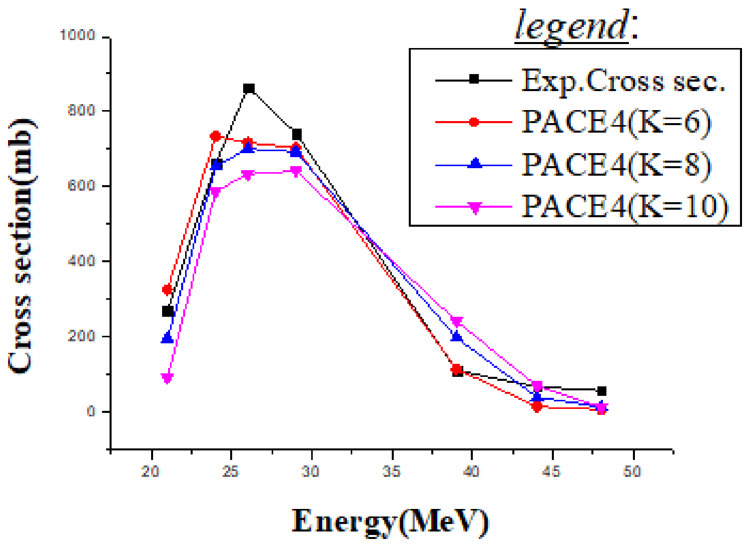


Figure 4.8: The theoretical and experimental Cross section for the reaction ^{69}Ga (^{4}He, 2n) ^{71}As

For the reaction ^{69}Ga (^{4}He, 2n) ^{71}As as shown in **Figure 4.8**, the theoretical cross section is obtained from PACE4 code by adjusting free constant level densities (k =6, 8, and 10) increases at low energies from 21MeV to 26MeV. For medium energy at 26 MeV the PACE 4 gives a higher theoretical cross section around 717 mb for k = 6, 701mb for k = 8 & 633 mb for k = 10. This higher cross section indicates the reaction reaches at state statistical equilibrium (maximum peaks). Above 26 MeV, the cross sections are strictly decreasing. This may indicates the projectile crosses the surface of target nucleus by statistical fluctuation/receives enough energy to escape/ like molecule evaporates from a heated drop of liquids. As it can be seen from the figure, the theoretical calculation is approaches to the experimental results particularly at k = 8 for all projectile energy range except 44 MeV and 48 MeV. In this case, it may be assumed that the projectile ^{4}He struck directly with the target ^{69}Ga to form the compound nucleus^{73}As*, where, this compound nuclear state emits two neutron (2n) for produced ^{71}As residual nuclei.

4.6 The production of ^{217}Ra

Table 4.6: The theoretical and experimental Cross section for the reaction ^{208}Pb (^{12}C, 3n) ^{217}Ra

Energy(MeV)	Exp. Cross section(mb)	Theoretical Cross- Sections (mb)			Chi (χ^2) value
		PACE 4(k = 8)	PACE 4(k =10)	PACE 4(k=12)	
64	150.21	94.8	94.4	87.1	20.5
65	216.05	143	145	138	23.3
67	228.43	236	234	231	0.13
69	200.2	200	222	235	2.42
71	121.53	102	139	149	2.66
75	32.03	20.09	30.3	39	0.12

81	6.73	0.897	2.69	2.69	2.42
				$\chi^2{}_{av}$	7.36

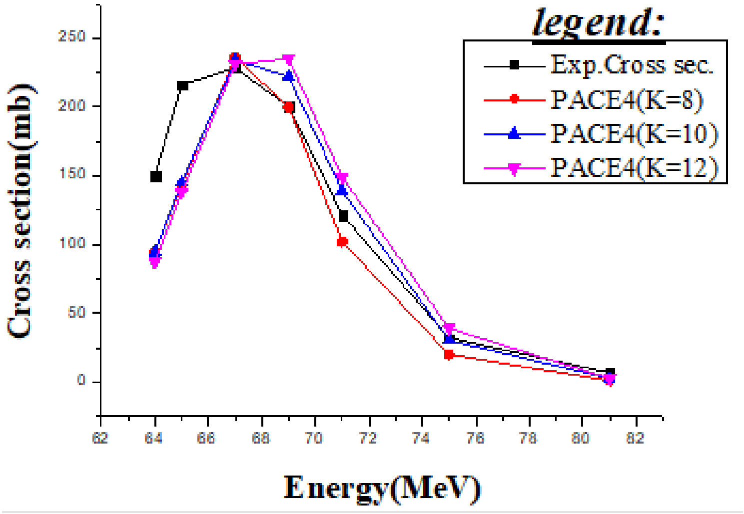


Figure 4.9: The theoretical and experimental Cross section for the reaction ^{208}Pb (^{12}C, 3n) ^{217}As

In the reaction ^{208}Pb (^{12}C, 3n) ^{217}Ra as shown in the **Figure 4.9**, the theoretical calculations obtained from PACE4 code have the same starting point and they have a little deviations/poor agreement / with the experimental values at lower energy(~64 MeV). For this case, at lower energy the fusion cross section between the projectile and the target is small due to the repulsive force between them This may be effectively reduce complete fusion reaction, whereas at higher energy/around 81 MeV/ particularly for a free constant level density parameters at k = 10 and k = 12 the theoretical prediction is almost comparable with the experimental data. This condition opens a good chance for a projectile to be completely fused with the target. The reaction forms an excited state of ^{220}Ra*, where this excited state evaporates three neutrons (3n) for producing ^{217}Ra nucleus.

4.7 The production of ^{216}Ra

Table 4 7: The theoretical and experimental Cross section for the reaction ^{208}Pb (^{12}C, 4n) ^{216}Ra

Energy(MeV)	Exp. Cross-section(mb)	PACE4 (k =8)	PACE4 (K = 10)	PACE4 (k=12)	χ^2 Value
67	54.43	10.4	2.88	0.897	2.62
69	230.32	133	75.8	52.1	40
71	354.13	313	252	210	4.74
75	456.52	427	460	393	1.88
81	184.68	121	183	190	21.49
87	39.32	39.2	20.6	21.6	0.12
93	22.7	1.24	2.47	1.24	2.28

	χ^2_{av}	7.35

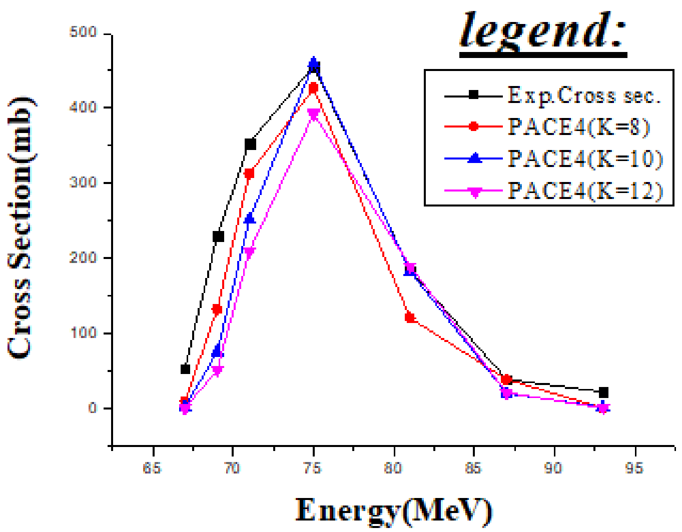


Figure 4.10The theoretical and experimental Cross section for the reaction ^{208}Pb (^{12}C, 4n) ^{216}Ra

For a given reaction ^{208}Pb (^{12}C, 4n) ^{216}Ra as shown in **Figure 4.10**, here is again the theoretical predictions have the same initial points and they have variations with the experimental data at lower energy of 67 MeV. This may indicates complete fusion reaction is a dominant proces at lower enrgy range, it is difficult to form supper heavy nuclei. For the medium projectile around 75MeV, both theoretical and experimental cros sections have a maximum value (i.e.reaches in statistically equilibrium/peaks/). Above 75 MeV, the theoretical calculations obtained using PACE4 especially for a free level density parameters at k = 10 & k=12 are fairly in good agreement with the experimental data. From this observation, it is possible to explain this reaction as a complete fusion of the projectile and the target. The reaction forms an excited state of ^{220}Ra*, where this excited state emits four neutrons leaving behind the rresidue ^{216} Ra nucleus.

Chapter five

Conclusion and Recommendation

5.1 Conclusion

In the present work, the excitation functions of complete fusion dynamics in heavy ion induced reactions on the types ^{7}Li + ^{24}Mg, ^{12}C+^{208}Pb, and ^{4}He + ^{69} Ga system have been studied in the energy range between 9MeV to 93MeV. These reaction opens the seven (7) excitation functions of the form ^{24}Mg (^{7}Li,2p3n) ^{26}Al, ^{24}Mg (^{7}Li, pn) ^{29}Si, ^{208}Pb (^{12}C, 3n) ^{217}Ra, ^{208}Pb (^{12}C, 4n) ^{216}Ra, Ga (4He, 3n) ^{70}As, ^{69}Ga (^{4}He, 2n) ^{71}As, and ^{69}Ga (^{4}He, n) ^{72}As were studied in this energy range . For this study, the experimental cross – section is obtained from EXFOR, IAEA library and their theoretical values are obtained by the help of LISE++(PACE 4:Fusion evaporation code). In theoretical calculation, free consatant level density parametr or FACLA in PACE4 plays an important role which varies from one reaction type to another reaction type and runs between k=4 and k=12 in this work.

In the ^{7}Li + ^{24}Mg reaction system, the residue ^{26}Al and ^{29}Si were formed by the complete fusion excitation functions of ^{24}Mg(^{7}Li,2p3n)^{26}Al and ^{24}Mg(^{7}Li, pn) ^{29}Si respectivelly. In this reaction , the theoretical cross section are approches to the experimental results especially at higher energies. So, the projectile completly fused with the target nucleus to form an excited state ^{31}P*

For complete fusion of ^{12}C + ^{208} Pb, the Radium family residues(i.e.^{217}Ra & ^{216} Ra) were formed by the excitation functions of ^{208}Pb(^{12}C, 3n) ^{217}Ra & of ^{208}Pb(^{12}C, 4n) ^{216}Ra respectivelly. In this reaction, at lower energy (~ 64 MeV) ther is a little deviations between theoretical and experimental cross sections where as at higher energies especially for free constant level density parameters at k = 10 & k=12 theoretical predictions and experimental results are almost comparable. This a good indicator of complete fusion between the projectile and the target to form an excited state ^{220}Ra*.

For ^{4}He + ^{69}Ga system, Arsenic family residues(i.e. ^{70}As, ^{71}As. &^{72}As) were formed in the excitaion functions of ^{69}Ga(^{4}He, 3n)^{70}As, ^{69}Ga(^{4}He, 2n)^{71}As, ^{69}Ga(^{4}He, n)^{72}As respecvtivelly. In this part, most curve fitting is exists at higher eneries (low cross – section) where as at low energy the theoretical cross section is not agree with the experimenta resuls. because of ^{4}He projectile requires higher enrgy to be completely fused with ^{69}Ga target. In general, at low projectile enrgy theoretical cross section is far from the experimental predictions because the projectilr requres high energy to over came the coulomb barrier(or to facillitate the nuclear reactions) where as at medium projectile energy the theoretical cross section becames maximum or reaches at statistical equilibrium(creating peaks in a graph), in this part compound nucleus is formed(i.e the projectile is completely fused with the targets). At higher enrgies, the theoretical cross sections becomes strictly decline for producing residual nucleus behind the thermalization effect.

5.2 Recommendation

The study of this thesis could bring valuable information that provides to have a well understandings on the complete fusion dynamics of some ion system at the energy range. The following further investigations are recommended.

- The study theoretically calculated results of complete fusion dynamics on some heavy ion systems are performed by changing different isotopes of the projectile with different targets.
- proper training relevant to computer soft Wares during searching and analyzing a well scientific writing like Latex, WinEdt, PACE4, Organ 8.5 plotting Soft wares etc.

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Declaration

This thesis is my original work, has not been presented for a degree in any other University and that all the sources of material used for the thesis have been dully acknowledged.

Name: Belisti Molla Ayele

Signature: ______________

Date: ___________________

Place and time of submission: Debre Berhan University, June 2015 E.C

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

Name: Awoke Taddese (PHD)

Signature:______________

Date:_________________