Calculation of total cross section for different channels of alpha induced reaction on Cadmium(^{106}Cd, ^{108}Cd, ^{114}Cd) in the energy range between 10MeV and 60MeV

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A Thesis Submitted to Department of Physics

Jimma University

Presented in Partial Fulfillment of the Requirements for the Degree of Masters(Msc) in Physics (Nuclear Physics)

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January, 2022

Jimma, Ethiopia

Declaration

I hereby declare that this Msc dissertation is my original work and has not been presented for a degree in any other University and that all sources of materials used for the dissertation have been duly acknowledged.

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Date...............................

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

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Place and date of submission:

Jimma University
Department of Physics
January, 2022

Acknowledgment

First of all, I am indebted to my ALMIGHTY GOD who gave me long life and helped me to pass through different ups and downs to reach this time. Next, I would like to express my deepest gratitude to my advisor **Teklemariam Tesemma (PhD)** and my co-advisor **Chali Yadeta (MSc)** for their excellent guidance, care, patience, motivation, encouraging and providing me with an excellent atmosphere for doing this thesis. Also, I would like to thank, Jimma University, Department of Physics for giving me such an opportunity. Lastly, I would like to thank my parents for their unconditional love and support; they taught me how to succeed, and I attribute all of my accomplishments to their assistance and encouragement.

Yadesa Dabala

Abstract

In this thesis, alpha-induced reactions on Cadmium for various energy of alpha have been studied. Excitation function for four reactions of the type ${}^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$, ${}^{108}_{48}Cd(\alpha,n)^{111}_{50}Sn$, ${}^{114}_{48}Cd(\alpha,2n)^{116}_{50}Sn$, *and* ${}^{114}_{48}Cd(\alpha,3n)^{115}_{50}Sn$ *in the incident alpha energy range from 10MeV up to 60MeV were studied. Theoretical calculations have been carried out by using COMPLET code including both compound nucleus as well as pre-compound. The theoretical results are compared with the experimental excitation functions obtained from the EXFOR data source, IAEA. The study shows that high energy parts of excitation functions are dominated by the pre-equilibrium reaction mechanism whereas the low energy parts are dominated by the compound nucleus reaction mechanism.*

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Acronomys/Nomenclature

MeV	Megaelectron Volt.
1D	One dimensional.
IAEA	International Atomic Energy Agency.

Chapter 1

Introduction

1.1 Background of the study

Nuclear physics is the study of atomic nuclei. From deuteron to uranium, there are almost 1700 species that occur naturally on earth. In addition, large numbers of others are created in the laboratory and in the interior of stars. The main force responsible for nuclear properties comes from strong interaction. However, both weak and electromagnetic interactions also play important roles. For these reasons, nuclear physics serves as an important platform where basic properties of subatomic matter can be examined and fundamental laws of physics can be studied [32].

When a particle or a nucleus collides with another nucleon or nucleus, a nuclear reaction occurs. In other terms, a nuclear reaction occurs when a nuclear particle comes into close contact with another nucleus, resulting in an energy and momentum exchange. Nuclear reactions involve the emission of one nucleus and the formation of a product nucleus in the ground state or in an excited state that returns to the ground state with the emission of one or more γ-rays. Many nuclear physicists are interested in the study of nuclear reactions generated by heavy ions because it provides understanding of the nature of nuclear forces, and nuclear structure. Nuclear physicists have made numerous contributions over the last decade. In recent years, there has been a lot of research put into understanding the process behind the heavy ion(HI) induced reaction [2].

Nuclear reactions are used to investigate the structure of nuclei and how they generate energy. Nuclear reactions also provide information on nuclei's interactions, which is used to calculate the total cross section for different alpha induced reaction channels. Nuclear reaction is the process in which two nuclei, or else a nucleus of an atom and a subatomic particle (such as a neutron, or high energy electron) from outside the atom, collide to produce products different from the initial particles. It is the process in which the incident particle is absorbed or scattered ,same particles or some other particles or particle are emitted in different directions. It is the process in which the target nucleus is bombarded by a particle and results in another nucleus with emitted particle. When a nuclear particle or particles is in closer contact with another nucleon or nucleus, the interaction takes place in which energy momentum transfer may take place.If an incident projectile hits the target nucleus, a nuclear reaction takes place as a result there is a new nucleus and an outgoing particle [3].

A typical nuclear reaction is written:

$$a + X \rightarrow Y + b$$

where a is the accelerated projectile, X is the target, and Y and b are the reaction products. Usually, Y will be a heavy product that stops in the target and is not directly observed, while b is a light particle that can be detected and measured.

An alternative and compact way of indicating the same reaction is

$$\text{X(a,b)Y}$$

which is convenient because it gives us a natural way to refer to a general class of reactions with common properties, for example (a, n) or (n, γ) reactions. 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). Sometimes a and b are the same particle, but the reaction causes yet another nucleon to be ejected separately (so that there are three particles in the final state); this is called a knockout reaction. In a transfer reaction, one or two nucleons are transferred between projectile and target, such as an incoming deuteron turning into an outgoing proton or neutron, thereby adding one nucleon to the target X to form Y. Reactions can also be classified by the mechanism that governs the process. In direct reactions (of which transfer reactions are an important subgroup), only very few nucleons take part in the reaction, with the remaining nucleons of the target serving as passive spectators. Such reactions might insert or remove a single nucleon from a shell-model state and might therefore serve as ways to explore the shell structure of nuclei. Many excited states of Y can be reached in these reactions. The other extreme is the compound nucleus mechanism, in which the incoming and target nuclei merge briefly for a complete sharing of energy before the outgoing nucleon is ejected [10].

Cadmium is a metal used in industry as an alloying element in many construction materials and as a corrosion-resistant plating element. Its natural occurrence consists of 7 stable isotopes with the composition of ^{106}Cd: 0.0125, ^{108}Cd: 0.0089, ^{110}Cd: 0.1251, ^{111}Cd: 0.1281, ^{112}Cd: 0.2413, ^{113}Cd: 0.1222, and ^{114}Cd: 0.2872, [4].

The employment of cadmium as a target material in the production of medically and industrially relevant radioisotopes attracted our interest. Among these radioisotopes the most important is the so called theranostic (therapeutic + diagnostic) radioisotope ^{117}Sn [5].

Cadmium, in its purest form, is a delicate silver-white metal. It is most usually found as complex oxides, sulphides, and carbonates in zinc, lead, and copper ores, rather than as a pure metal. Cadmium (Cd) is a silver-white soft, ductile metal that, like zinc and mercury, belongs to Group IIb of the Periodic table. It has a high vapour pressure and low melting and boiling temperatures (320.9 °C and 765 °C, respectively) [17].

Cadmium is easily oxidized in the air to cadmium oxide. Cadmium vapour, on the other hand, forms cadmium carbonate, hydroxide, sulfite, sulfate, or chloride when it reacts with reactive gases or vapours such carbon dioxide, water vapour, sulfur dioxide, sulfur trioxide, or hydrogen chloride [17].

This study was motivated to calculate the theoretical calculation of the total cross section of alpha induced reactions on Cadium for the energy level between 10MeV and 60MeV. In this thesis the the alpha particle is the projectile or the bombarding particle and Cadmium is the target. The different reaction channels studied are ${}^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$, ${}^{108}_{48}Cd(\alpha,n)^{111}_{50}Sn$, ${}^{114}_{48}Cd(\alpha,2n)^{116}_{50}Sn$, and ${}^{114}_{48}Cd(\alpha,3n)^{115}_{50}Sn$.

1.2 Statement of the Problem

There is experimental literature on nuclear reactions available. However, there is not such much theoretically calculated nuclear reaction data, as widely as experimental data in studying the cross-section of alpha-induced reaction on Cadmium. Therefore, this research is intended for providing theoretical reaction data about alpha-induced reactions on some isotopes of Cadmium [32, 33, 34]. The results of the theoretical excitation function were compared to experimental data from the EXFOR database. In the present research work the following questions have been answered.

1. What are the reaction cross section for ${}^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$, ${}^{108}_{48}Cd(\alpha,n)^{111}_{50}Sn$, ${}^{114}_{48}Cd(\alpha,2n)^{116}_{50}Sn$, and ${}^{114}_{48}Cd(\alpha,3n)^{115}_{50}Sn$?

2. How the compound nucleus and pre-equilibrium reactions dominate the ${}^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$, ${}^{108}_{48}Cd(\alpha,n)^{111}_{50}Sn$, ${}^{114}_{48}Cd(\alpha,2n)^{116}_{50}Sn$, and ${}^{114}_{48}Cd(\alpha,3n)^{115}_{50}Sn$?

3. How the total cross section varies with alpha-energy?

4. How the theoretical result agrees with experimental values?

1.3 Objectives

1.3.1 General Objective

The general objective of this study is to investigate total cross section for different channels of alpha induced reaction on Cadmium(${}^{106}Cd$, ${}^{108}Cd$, and ${}^{114}Cd$) in the energy range between 10MeV and 60MeV

1.3.2 Specific Objectives

1. To calculate the reaction cross section for ${}^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$, ${}^{108}_{48}Cd(\alpha,n)^{111}_{50}Sn$, ${}^{114}_{48}Cd(\alpha,2n)^{116}_{50}Sn$, and ${}^{114}_{48}Cd(\alpha,3n)^{115}_{50}Sn$.

2. To identify the way of compound nucleus and pre-equilibrium reactions dominate the $^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$, $^{108}_{48}Cd(\alpha,n)^{111}_{50}Sn$, $^{114}_{48}Cd(\alpha,2n)^{116}_{50}Sn$, and $^{114}_{48}Cd(\alpha,3n)^{115}_{50}Sn$.

3. To determine the cross section varies with alpha-energy.

4. To validate theoretical calculation with the experimental value obtained from EXFOR data source.

1.4 Significance of the Study

This study was based on calculation excitation function of alpha induced reaction on the Cadmium (^{106}Cd, ^{108}Cd, and ^{114}Cd and (α,n) reaction channels. This study is used to improve the understanding of reaction cross section of Cadmium isotopes in the alpha energy range of 10MeV to 60MeV for the reaction $^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$, $^{108}_{48}Cd(\alpha,n)^{111}_{50}Sn$, $^{114}_{48}Cd(\alpha,2n)^{116}_{50}Sn$, and $^{114}_{48}Cd(\alpha,3n)^{115}_{50}Sn$. It used as a reference material for the reader.

1.5 Scope of the Study

The scope of this study was a calculation of the theoretical value of the total cross section for different channels of alpha induced reaction on Cadmium(^{106}Cd, ^{108}Cd, and ^{114}Cd) in the energy range between 10MeV and 60MeV.

1.6 Limitation of the Study

The main limitation faced to carry out this research was a lack of expriences to conduct such research.

Chapter 2

Literature Review

2.1 Nuclear reaction

Nuclear reactions induced by medium energy α-particles are interesting in view of the associated pre-equilibrium and equilibrium de-excitation processes. For the last several years it has been a point of interest to get a better understanding of the reaction mechanism that actually takes place in the medium energy region. The high-energy tail of measured excitation functions contains important information about the reaction mechanism. Enough evidence is now available to believe that the highly excited nuclear system produced by the α-particle bombardment decays first by emitting a number of fast nucleons or a cluster of nucleons at the pre-equilibrium (PE) stage, and later by evaporating low energy nucleons at the equilibrium (EQ) stage [28]. When energetic particles from a reactor or accelerator (or even from a radioactive source) are allowed to fall up on bulk matter, there is the possibility of a nuclear reaction taking place. The first such nuclear reactions were done in Rutherfords laboratory, using a particles from a radioactive source. In some of these early experiments, the (gamma particles merely rebounded elastically from the target nuclei; this phenomenon, known ever since as Rutherford scattering, gave us the first evidence for the existence of atomic nuclei. In other experiments, Rutherford was able to observe a change or transmutation of nuclear species, as in this reaction done in 1919 [10].

2.1.1 Introduction to total cross section

Nuclear reaction cross section is one of the most important quantities which we encounter easily in nuclear reactions. It can be defined as the probability of interaction. Thus given a reaction of a given type, the cross section for that reaction is the probability that, the reaction will take place or simply the probability of occurrence of the said reaction. Nuclear reaction cross section is the measurement of probability of the reaction [29].

The sum of the inelastic and reaction cross sections is the total cross section. It is given by

$$\sigma_{tot} = \sigma_{sc} + \sigma_r \tag{2.1}$$

Thus we have for the total cross section

$$\sigma_t = \sigma_r + \sigma_e = \pi(R+\lambda)^2 + \pi(R+\lambda)^2 = 2\pi(R+\lambda)^2 \tag{2.2}$$

For high energy R >> λ

$$\sigma_t = 2\pi R^2 \tag{2.3}$$

The total cross section is twice of the geometrical cross section of the nucleus. In the case of this study we haven't scattered cross-section. The total cross-section can be reduced to: For high energy R >> λ

$$\sigma_t = \pi R^2 \tag{2.4}$$

2.1.2 Stages of nuclear reaction

The stage of nuclear reactions are direct, compound nucleus and pre-equilibrium stage. These three processes depends on the given reaction and the energy of the incident particle. They are distinguished by their angular distributions and time scales [13, 14].

1. **Direct Reaction**

A "direct reaction" involves a projectile that is energetic enough to have a reduced wavelength, of the order of 1 fm (a 20 MeV nucleon, for example), that interacts in the periphery of the nucleus (where the nuclear density starts to fall off), and interacts with single valence nucleon. Elastic and inelastic scattering are examples of so-called direct reactions. These are defined as ones where the incident particle interacts in a time comparable to the time taken to transit the nucleus. They are more likely when the incident particle has an energy corresponding to a de Broglie wavelength closer to the size of a nucleon rather than that of the nucleus. The collisions are largely peripheral, with only a relatively small fraction of the available energy transferred to the target. The direct reaction $^{16}O(p,d)^{15}O$ is an example of a pickup reaction, because one or more nucleons (in this case a neutron) is stripped off the target nucleus and carried away by the projectile. The 'inverse' of this reaction is $^{16}O(d,p)^{17}O$. This is an example of a stripping reaction, because one or more nucleons (in this case again a neutron) is stripped off the projectile and transferred to the target nucleus [26].

A direct transition from the entrance to the exit channel occurs for projectile energies above 50 MeV and for light target nuclei ($A < 30$) within a relatively short time scale of around 10^{-22} seconds, which is roughly the time it takes to traverse the nuclear field [9, 14].

Direct reactions become more probable as the energy of the incident particle increases: the wavelength associated with the particle decreases, and the localized areas of the nucleus can be probed by the projectile. Peripheral reactions, in which only a few surface nucleons participate, become essential in this context. Direct reactions take on the order of 10^{-22} seconds to occur. Compound nuclei formation reactions can take up to six orders of magnitude slower. At a given energy, a reaction type is not necessarily exclusive; It is possible to obtain the same final results, part of the events in a direct way, other parts through the formation and decay of a compound nucleus [6, 11].

Direct reactions can be divided into two categories. The first one is incident particle scatters in-elastically and the transferred energy is used to excite a collective mode of the nucleus.This method can be used to investigate rotational and vibrational bands. The second one involves a modification in the nuclear composition. Transfer of nucleons, such as pick-up and stripping reactions, are examples. Another important reaction is a knock-out reaction is a type of reaction in which an incident particle knocks out a particle from the target nucleus and continues on its way, resulting in three reaction products. Reactions with nucleon exchange can also be used to excite collective states. An example is a pick-up reaction where a projectile captures a neutron from a deformed target and the product nucleus is in an excited state belonging to a rotational band [9, 10].

2. **Compound Nucleus**

A reaction in which two nuclei combine to generate a single excited nucleus is known as compound nucleus formation. The excited nucleus has a long life span and ”forgets” how it was formed. The “evaporation” of nucleons from the heated liquid drop of the compound nucleus, gamma decay, or fission of the compound nucleus are the methods of decay from this state of excitement. We can learn about the average properties of excited states of complex nuclei due to the statistical nature of this process [11, 16].

Compound nucleus reactions can be written as the following

$$a + X \to Z^* \to b + Y^* \tag{2.5}$$

The target ‘captures’ the projectile, and the two systems come together to form a highly excited state (the ‘compound nucleus’). The constituent nucleons share the excitation energy in an uniform way. It is possible to provide a nucleon or a group of nucleons enough energy to escape. More emissions may occur if Y has enough energy, otherwise it will de-excite by

β-decay or γ-decay.

The compound nucleus is a relatively long-lived intermediate state of particle-target composite system. Many nucleon-nucleon interactions are involved. The large number of collisions between the nucleons leads to a thermal equilibrium inside the compound nucleus. The time scale of compound nucleus reactions is of the order of $10^{-18}s$ - $10^{-16}s$. It is usually created if the projectile has low energy[11]. The mode of decay of compound nucleus do not depend on the way the compound nucleus is formed. Resonances in the cross-section are typical for the compound nucleus reaction [14, 16].

At low energies, the largest probability is the continuation of the process so that the initial energy is distributed among all nucleons, with no emitted particle. The de-excitation process is not necessarily immediate and the excited nucleus can live a relatively long time [15].

We say that there is, in this situation, the formation of a compound nucleus as intermediary stage of the reaction. In the final stage the compound nucleus can evaporate one or more particles, fission, etc. In our notation, for the most common situation in which two final products are formed (the evaporated particle plus the residual nucleus or two fission fragments, etc.) [12, 14].

3. **Pre-compound or Pre-equilibrium Reactions**

Pre-equilibrium particles tend to be emitted forwards, and are generally more energetic than those from the compound nucleus. To calculate the cross-section for pre-equilibrium emission, the interaction process is considered to take place in several stages. The first stage can lead to the emission of direct particles, or to the excitation of a particle-hole pair. In the second stage further interactions can occur, which can lead to the excitation of further particle-hole pairs, and so on until finally the compound nucleus is formed. At each stage in the excitation process it is possible for pre-equilibrium particles to be emitted.

When high energy alpha particle enters the region of nuclear forces, it can be scattered or start a chain reaction of nucleon collisions. The products of these collisions, including the incident particle, will continue in their course, leading to new collisions and new changes of energy. During this process one or more particles can be emitted and they form with the residual nucleus the products of a reaction that is known as pre-equilibrium [13].

2.1.3 Channels of reaction

We shall be interested in the whole set of reactions

$$x + X = \begin{cases} X + x \\ X^* + x \\ Y^* + y \\ Z + z \end{cases} \tag{2.6}$$

The first two reactions (2.6) are distinguished by the fact that the projectile x re-emerges after the reaction. The first of these represents elastic scattering: the projectile x leaves with the same energy (in the center-of-gravity system), and the target nucleus X is left in its initial state. The second reaction represents inelastic scattering: the target nucleus X is forced into an excited state X*, and the projectile x re-emerges, but with an energy lower than its initial one by the amount of the excitation energy given to the target nucleus.

It will prove useful to consider as elastic scattering only those events in which the initial and final states of the target nucleus are completely identical (e.g., there should not be any change of the spin direction of X, even if no excitation energy is involved). We shall therefore include in the inelastic scattering those events in which X changes its internal state in such a way that its energy stays constant, i.e., there is no energy transfer between X and x.

All the reactions (2.6), except the elastic scattering, can be subdivided again according to the quantum state of the residual nucleus and the emerging particle. We denote the states of the nuclei by α', β', γ', ... , and the states of the incident or emerging particles by α'', β'', γ'', ... , If particles x, y, etc., are elementary, states α'', β'', etc., refer to their spin orientation. We get the reactions

$$\mathrm{x}_{\alpha''} + X_{\alpha'} = \begin{cases} \mathrm{X}_{\alpha'} + x_{\alpha''} \\ \mathrm{X}_{\beta'} + x_{\beta''} \\ \mathrm{Y}_{\gamma'} + y_{\gamma''} \end{cases}$$

Here $\alpha^{'}$ and $\alpha^{''}$ are states of the target nucleus and the incident particle, $\beta^{'}$ and $\beta^{''}$, or γ' and γ'', can denote any quantum state of X and x. or Y and y, respectively, which can be created in this reaction. Of course, the conservation laws of energy, angular momentum, and parity restrict the possible pairs of $\beta^{'}$ and $\beta^{''}$, or γ' and γ'', etc. Any such possible pair of residual nucleus and emerging particle, each in a definite quantum state, is called a **reaction channel**. We shall denote channels by single Greek letters, α, β, ... , which comprise both indices $\alpha^{'}$ and $\alpha^{''}$, or $\beta^{'}$ and $\beta^{''}$. Channel $X_{\alpha'} + a_{\alpha''}$ is called the **entrance channel or initiating channel of reaction**.

2.1.4 Channel Energy

Let us now consider the energy relations occurring in the nuclear reaction. If the incident particle a and the target nucleus X are still very far apart, there is no interaction energy between them, and the total energy E can be expressed as the sum of the kinetic energy ϵ_α of the relative motion of the two partners a and X in channel α, and their internal energies $E_{\alpha'}$ of X and $\mathrm{E}_{\alpha''}$ of x:

$E = \epsilon_\alpha + E_{\alpha'} + E_{\alpha''}$

Since we always consider the center of gravity at rest, the main part of ϵ_α comes from the lighter partner x. Therefore ϵ_α is essentially the kinetic energy of the incoming projectile x. Consider, for example, channel β, which leads to a residual nucleus Y in state $\beta^{'}$ and an emitted particle y in state $\beta^{''}$.

The total energy must be equal to the total energy E in the entrance channel if the partners

Y and y are far apart. we can express E in terms of the sum of the kinetic energy ϵ_α and the internal energies $E_{\beta'}$ and $E_{\beta''}$ of the two partners:

$E = \epsilon_\beta + E_{\beta'} + E_{\beta''}$

ϵ_β is again called **the channel energy** and is the sum of the kinetic energies of the outgoing particle y and of the residual nucleus Y in the center-of-gravity system.

The channel energy ϵ_β is related to the entrance channel energy ϵ_α by:

$\epsilon_\beta = \epsilon_\alpha + Q_{\alpha\beta}$

where

$Q_{\alpha\beta} = E_{\alpha'} + E_{\alpha''} - E_{\beta'} - E_{\beta''}$

is the **"Q value"** from channel α to channel β.It is the difference in energy in the outgoing and entrance channels.

$Q_{\alpha\beta} = - Q_{\beta\alpha}$ is characteristic of channels α and β and is independent of the channel energies.

2.1.5 Threshold Energy

In practice the target nucleus, as well as the bombarding particle, is in its ground state. We are often interested in knowing the minimum kinetic energy of a necessary to make the X(x,y)Y reaction occur, without inquiring into the precise channel through which the outgoing particles emerge.

The minimum energy corresponds to the channel in which the outgoing particle y and the residual nucleus Y are both in their ground states; we shall call this channel the β_o channel.

The "Q value of the X (x,y) Y reaction" is defined by

$Q_{xy} = E_{\alpha o'} + E_{\alpha o''} - E_{\beta o'} - E_{\beta o''}$

where $E_{\alpha o'}$, etc., are the energies of the ground states of the particles X, x, Y, and y, respectively.

If Q_{xy} is positive, the X(x,y)Y reaction is "exoergic"; it proceeds even with zero kinetic energy in the entrance channel. The kinetic energy in the exit channel β_o is the maximum kinetic energy which the outgoing particle y and the residual nucleus Y can have.

This energy is often used, and we shall call it ϵ_{yY}. It is given by:

$\epsilon_{\beta o} = \epsilon_{yY} = \epsilon + Q_{xy}$

where $\epsilon = \epsilon_{\alpha o}$ is the kinetic energy in the entrance channel (both x and X in their ground states).

If the Q value, Q_{xy}, of the X(x,y)Y reaction is negative, the reaction is "endoergic" and does not proceed unless the channel energy ϵ in the entrance channel exceeds a certain amount.

$\epsilon_{\beta o} = \epsilon_{yY} = \epsilon + Q_{xy}$ implies that ϵ must exceed $-Q_{xy}$ in order that the channel β_o be "open" (i.e., that ϵ_{yY} be positive).

This minimum energy $-Q_{xy}$ for an endoergic reaction is also called the **threshold energy** of the X(x,y)Y reaction.

2.1.6 Elastic Scatering and Reaction cross section

Elastic scattering occur when the ejected particle and projectile are same. The projectile after striking the target nucleus leaves it without loss of energy (same energy) either in the same direction.

The nuclear cross section of a nucleus is used to characterize the probability that a nuclear reaction will occur. The standard unit for measuring a nuclear cross section is the barn, which is equal to $10^{-28} m^2$. Cross section can be measured for all possible interaction processes together, in which case they are called total cross section [25].

Consider a beam of particles directed at a layer of matter. In most nuclear reactions the effect of this layer is composed additively of the effects of individual units (scattering centers) in the layer; the individual nuclei in the material act as independent scattering centers. The cross section of a reaction is then defined by a measure of the relative probability for the reaction to occur (number of events of given type per unit time per nucleus divided by number of incident particles per unit area per unit time) [11, 12].

Let us consider a plane wave of particles a incident upon the nucleus X, representing an entrance channel . Particle can be re-emitted into the same channel, or it can initiate a nuclear reaction which leads into another channel. We shall separate the elastic scattering events from all the other reactions, so that the total cross section $\sigma_t(\alpha)$ for all events which may take place is given by [23].

$\sigma_t(\alpha) = \sigma_{sc}(\alpha) + \sigma_r(\alpha)$

Here $\sigma_{sc}(\alpha)$ denotes the elastic scattering cross section, and $\sigma_t(\alpha)$ denotes the combined cross section for all events. We include the various inelastic scattering cross sections in σ_r. We shall refer to σ_r as the reaction cross section. We assume for the sake of simplicity that target nucleus X, as well as projectile a, has zero spin. This assumption is correct only if we use alpha-particles as projectiles, and nuclei with even A as targets. It is certainly incorrect for neutron or proton reactions. Most of the results, however, are not affected by this assumption, which greatly simplifies the treatment [23].

The occurrence of a nuclear reaction through a given reaction channel leads to a modification of the outgoing part of the wave function not only by a phase factor, but also by changing its magnitude, indicating that there is a loss of particles in the elastic channel. For a projectile with momentum $p = \hbar k$, this can be expressed by:

$$\psi \sim \frac{1}{2i}\sum_{l=0}^{\infty} i^l(2l+1)\eta_l[\frac{e^{i(kr-\frac{l\pi}{2})} - e^{-i(kr-\frac{l\pi}{2})}}{kr}]p_l(cos\theta) \tag{2.7}$$

If $\eta = 1$, the sum in equation above can be done analytically leading to $\psi \sim e^{ikr}$, i.e. a plane wave. But if $\eta_l = e^{[i\delta_l]}$ with δ_l the incoming and outgoing waves have the same magnitude, i.e. the scattering is elastic. We take the z axis to be the direction of the incident beam and assume it can be represented by a plane wave e^{ikz} corresponding to momentum $p = \hbar k$.

$$\psi_{inc} = Ae^{ikz} \tag{2.8}$$

The outgoing particles will be represented by spherical waves, and so the manipulations become easier if we express the incident plane wave as a superposition of spherical waves:

$$\psi_{inc} = Ae^{ikz} = A\sum_{l=0}^{\infty} i^l (2l+1) j_l(kr) p_l(cos\theta) \tag{2.9}$$

where A is an appropriately chosen normalization constant. The radial functions $j_l(kr)$ are spherical Bessel functions.They are solutions to the radial part of the Schrodinger equation in a region far from the target where the nuclear potential vanishes.

The angular functions $P_l cos\theta)$ are Legendre polynomials:

$P_0(cos\theta) = 0$

$P_1(cos\theta) = cos\theta$

$P_2(cos\theta) = \frac{1}{2}(3cos^2\theta - 1)$

The solution to the Schrödinger equation in a region of space where there is no potential (or a constant potential).

Since no potential is also a central potential (in the sense that it does not depend on orientation), we should be able to recast the solution in spherical-polar coordinates, and identify the angular momentum components of the incident wave.

The j_l's are the "spherical Bessel functions, and the P_l's are the regular Legendre polynomials, that we have encountered before.

The properties of the j_l's are:

$j_0(z) = \frac{sinz}{z}$

$j_1(z) = \frac{sinz}{z^2} - \frac{cosz}{z}$

$j_2(z) = \frac{3sinz}{z^3} - \frac{3cosz}{z^2} - \frac{sinz}{z}$

$j_l(z) = (-z^l)(\frac{1}{z}\frac{d}{dz})^l j_0(z)$
$\lim_{z\to 0} j_l(z) = \frac{z^l}{(2l+1)!!} + \vartheta(z^{l+1})$
$\lim_{z\to\infty} j_l(z) = \frac{sin(z-\frac{l\pi}{2}}{z}) + \vartheta(z^{-2})$

(2.10)

Equation (2.10) is called the "partial wave expansion", and exploiting it to extract physical results is called **"partial wave analysis"**.

Thus, we have identified the angular momentum components of the incoming wave, with angular momentum components $l\hbar$.

Semi-classical introduction

We know, from classical scattering analysis, that the impact parameter(b) is associated with the angular momentum of the projectile about the target, centered at the origin. Equating the quantum mechanical angular momentum of the wave component with its classical counterpart, we get:

$$pb = l\hbar \tag{2.11}$$

or

$$b = \frac{l\hbar}{p} = \frac{l}{2\pi}\frac{h}{p} = l\frac{\lambda}{2\pi} = l\lambda \tag{2.12}$$

in terms of the reduced wavelength λ.

So, continuing with this semiclassical train of thought:

$l = 0 \to 1$ covers the area $\pi\lambda^2$

$l = 1 \to 2$ covers the area $(4-1)\pi\lambda^2$

$l \to l+1$ covers the area $[(l+1)^2 - l^2]\pi\lambda^2$=$(2l+1)\pi\lambda^2$

Summing up all these contributions:

$$\sigma = \sum_{l=0}^{[\frac{R}{\lambda}]} (2l+1)\pi\lambda^2 = \pi(R+\lambda)^2 \tag{2.13}$$

where R is the nuclear radius. Thus, we see that λ factors into the computation of the cross section as an effective size of the projectile.

The quantum approach

We start by recognizing that we wish to consider the mathematic representation of the wave at locations far from the scattering center.

Thus, for kr >>1, we use the asymptotic result of equation (2.9)

$$\lim_{kr\to\infty} j_l(kr) = \frac{sin(kr - \frac{l\pi}{2})}{kr} = i\frac{[e^{-i(kr-\frac{l\pi}{2})} - e^{i(kr-\frac{l\pi}{2})}]}{2kr} \tag{2.14}$$

Combining (2.13) with (2.9) gives,

$$\psi_{inc} = Ae^{ikz} = \frac{A}{2kr}\sum_{l=0}^{\infty} i^{l+1}(2l+1)[e^{-i(kr-\frac{l\pi}{2})} - e^{i(kr-\frac{l\pi}{2})}]p_l(cos\theta) \tag{2.15}$$

This is an interesting result! The $\frac{e^{-ikr}}{kr}$ part represents a spherical wave converging on the nucleus, while the $\frac{e^{ikr}}{kr}$ part represents a spherical wave moving away from the nucleus. The nucleus can only modify the outgoing part. One way of representing this is via a modification of the outgoing part. Thus, the total solution, with incoming and scattered parts, is written:

$$\psi_{inc} = Ae^{ikz} = \frac{A}{2kr}\sum_{l=0}^{\infty} i^{l+1}(2l+1)[e^{-i(kr-\frac{l\pi}{2})} - \eta_l e^{i(kr-\frac{l\pi}{2})}]p_l(cos\theta) \tag{2.16}$$

where η_l is a complex coefficient that represents the mixing the two parts of the outgoing wave, part of which is associated with the initial plane wave, as well as the scattered part. Thus, the total wave is a combination of both,

$$\psi = \psi_{inc} + \psi_{sc} \tag{2.17}$$

allowing us to express the scattered part by itself,

$$\psi_{sc} = \frac{Aie^{i(kr}}{2kr}\sum_{l=0}^{\infty}(2l+1)(1-\eta_l)p_l(cos\theta) \tag{2.18}$$

Reaction cross sections

$$\frac{d\sigma_r}{d\Omega} = \frac{j_{in} - j_{out}}{j_{inc}}r^2 \tag{2.19}$$

as the reaction cross section, involving the difference between the currents of the incoming and outgoing spherical waves.

From (2.15) we see that:

$$\psi_{in} = \frac{A}{2kr}\sum_{l=0}^{\infty} i^{2l+1}(2l+1)[e^{-i(kr-\frac{l\pi}{2})}]p_l(cos\theta) \tag{2.20}$$

$$\psi_{in} = \frac{Aie^{-ikr}}{2kr}\sum_{l=0}^{\infty} i^{2l}(2l+1)P_l(cos\theta) \tag{2.21}$$

$$\psi_{out} = -\frac{A}{2kr}\sum_{l=0}^{\infty} i^{2l}(2l+1)\eta_l[e^{-i(kr-\frac{l\pi}{2})}]p_l(cos\theta) \tag{2.22}$$

$$\psi_{out} = -\frac{Aie^{-ikr}}{2kr}\sum_{l=0}^{\infty}(2l+1)\eta_l P_l(cos\theta) \tag{2.23}$$

As in 1D, we use the probability current density to evaluate the effectiveness of the scatterer. The scattered probability current is:

$$j_{sc} = \frac{\hbar}{2im}[\psi_{sc}^*(\frac{\partial\psi_{sc}}{\partial r}) - (\frac{\partial\psi_{sc}^*}{\partial r})\psi_{sc}] \tag{2.24}$$

Putting (2.18) into (2.24) results in:

$$j_{sc} = |A|^2(\frac{\hbar}{4kr^2})|[\sum_{l=0}^{\infty}(2l+1)(1-\eta_l)p_l(cos\theta)]|^2 \tag{2.25}$$

Since the incoming wave has probability current

$$j_{inc} = \frac{\hbar k}{m} \tag{2.26}$$

the differential cross section is expressed as follows:

$$\frac{d\sigma}{d\Omega} = \frac{j_{sc}}{j_{inc}} r^2 \tag{2.27}$$

in analogy with the 1D transmission and reflection coefficients.

Then, we can show that

$$\frac{d\sigma_{sc}}{d\Omega} = \frac{1}{4k^2} | \sum_{l=0}^{\infty} (2l+1)(1-\eta_l) p_l(cos\theta)|^2 \tag{2.28}$$

and

$$\sigma_{sc} = \frac{\pi}{k^2} \sum_{l=0}^{\infty} (2l+1)|1-\eta_l|^2 \tag{2.29}$$

Since both the incident and outgoing waves have wavenumber k, the cross sections discussed above model elastic scattering. Elastic scattering is characterized by no loss of probability of the incoming particle. Mathematically, this expressed by,

$|\eta_l| = 1$ for all l.

Thus, the only thing that the target does is to redirect the wave and shift its phase. Hence we define a phase shift (σ_l) for each l component, using the following convention,

$\eta_l = e^{2i\sigma_l}$ from which we can derive:

$$\sigma_{sc}^{elas} = 4\pi\lambda^2 \sum_{l=0}^{\infty} (2l+1) \sin^2 \sigma_l \tag{2.30}$$

From now on, we'll reserve the name,σ_{sc} for elastic scattering only.

Note that

$\frac{1}{k} = \frac{\lambda}{2\pi} = \lambda$

Generally, $|\eta_l| < 1$, as the incoming beam can be absorbed, and part of it unabsorbed. We will identify

$$\frac{d\sigma_r}{d\Omega} = \frac{j_{in} - j_{out}}{j_{inc}} r^2 \tag{2.31}$$

as the reaction cross section, involving the difference between the currents of the incoming and outgoing spherical waves.

Adapting (2.23) we obtain the incoming and outgoing probability currents:

$$j_{in} = |A|^2 (\frac{\hbar}{4kr^2}) |[\sum_{l=0}^{\infty} i^{2l}(2l+1)P_l(cos\theta)]|^2 \tag{2.32}$$

$$j_{out} = |A|^2 (\frac{\hbar}{4kr^2}) |[\sum_{l=0}^{\infty} (2l+1)\eta_l P_l(cos\theta)]|^2 \tag{2.33}$$

Combining (2.31) with (2.26), (2.32) and (2.33), and then integrating over all angles,results in:

$$\sigma_r = \pi\lambda^2 \sum_{i}^{\infty} (2l+1)(1-|\eta_l|^2) \tag{2.34}$$

Note that for elastic scattering, $\sigma_r = 0$.

when $|\eta_l| = 1$ the reaction cross section is zero and we have pure scattering.

In general there is a region of allowed values of η_l for which the two cross sections can coexist.

The maximum of σ_r happens for $|\eta_l| = 0$ that corresponds to total absorption.

For $|\eta_l| = 0$ the scattering and reaction cross sections are identical, yielding the total cross section

$$\sigma_t = \sigma_r + \sigma_e = \pi(R+\lambda)^2 + \pi(R+\lambda)^2 = 2\pi(R+\lambda)^2 \tag{2.35}$$

For high energy R >> λ

$$\sigma_t = 2\pi R^2 cm^2 \tag{2.36}$$

Total cross-section is twice of the geometrical cross-section of the nucleus.

In the case of this thesis since we haven't scattered cross-section total cross-section can be reduced to:

$$\sigma_t = \pi R^2 \tag{2.37}$$

Chapter 3

Methodology

3.1 Method of Data Presentation and analysis

The experimental cross section data has been downloaded from EXFOR data Library, IAEA. Then the data has been plotted as a function of projectile energy called excitation function. **COMPLET code** has been employed. This code calculates the excitation function of light and heavy-ion induced reactions. Computer code was used to calculate the total reaction cross section for all selected channels. Various parameters are used for the calculations of excitation functions. However, the initial exciton number is found to play a crucial role in performing calculated values.

The code COMPLET provides yields and spectra for all reactions populated by all combinations of n, p, d, alpha and can provide all input parameters internally. The running time of the code is very short. This code includes damping of fission widths above a critical temperature R0. The used code is a further simplification of the formulae due to Paul and Thoennessen in Ann.Rev.Nucl and particle science 44(1944). The code COMPLET includes pre-equilibrium neutron, proton and alpha emission up to two particle, as well as evaporation of neutrons, protons, alphas, deuterons, tritons and hellions. Originally, this code has been developed out of the code OVERLAID ALICE by M.Blann, while some standard routines remained practically unchanged (like FISROT, LYMASS, PUNCH, PLT, PARAP, OVER1, OVER2 and TLJ) others have been substantially modified (like MAIN, SHAFT, NUCMFP, etc) or are completely new (like, INDEX, PARDEN, TRAPRO, ANGULAR, etc) the underlying PE-MODEL is described in Z.Phys.A328 (1989).It is contained in subroutine INDEX. The INPUT is described below. The notion card from the old FORTRAN input is still kept but now corresponds to lines. Free formats, the input values should be separated by, or CR.

CARD 1 - GENERAL INPUT DATA AP Projectile mass number

AT Target mass number

ZP Projectile charge

ZT Target charge

QVAL Reaction Qvalue = AP + AT - ACN

= 0: calculated from M and S mass formula.

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

CLD - ratio of single particle level densities $\frac{af}{an}$ = 0: $\frac{af}{an}$ = 1 [27].

If parameter ISOT is nonzero, CLD is isotopic abundance input default value =1.0

If =0, use rotating finite range fission barriers due to A.J.sierk

BARFAC - multiplies the rotating drop fission barrier by this value.

BARFAC = 0: BARFAC = 1

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

RO - critical temperature above onset of retarded fission

GI - nuclear friction parameter from equilibrium deformation to saddle

GO - nuclear friction parameter from saddle to scission point

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

NZ - the number of Z - values to be calculated in the emission process. up to 8 protons may be emitted (maximum NZ=9).

For correct PE calculations binding energies are calculated for all nuclei with IZ, IA $\leqq$ 5

(17.7.91)

MC - Shell correction option for masses subroutine.

MC = 0, masses incl. Shell correction.

MC = 1, masses without shell correction term

MC = 2, BE values will be supplied as input.

MC>2, BE values are calculated from 1990 nuclear wallet cards.

MP - pairing correction to masses.

MP = 0: no pairing term in masses.

MP = 1: pairing term in masses, ldgs calculated from msl formula and applied back shifted

MP = 2: masses are from nuclear wallet cards;

MP = 3: pairing correction in masses, NOTE: changes are not corrections in only level densities

IPA - pairing corrections in level densities

IP = -1, no corrections

IP = 0, standard correction i.e multiplier =12

IPA>0 multiplier is IPA

M3 - number and type of particles to be emitted from each nuclide

If = 1: N only;= 2:N and p;=3 or =0:N,p and Alpha;=4:N,p,alpha and Deuteron.

If = 5: N, p, Alpha, Deuteron and Triton;=6: N,P, Alpha, Deuteron, Triton and hellion (3HE)

IF = 7: as before incl. Gammas. Calculations until gamma emission is finished important for isomeric ratio calculations.

INVER inverse cross section parameters.

If = 0: user supplied:

If = 1: results by O.M subroutines as ALICE/85/300,

If = 2: O.M for N, p as in old ALICE

If = 3: sharp cutoff values for inverse cross sections

Option Inver = 2 greatly reduces total cpu time

IKE if = 1 no particle spectra will be printed:

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

If = 3 pre-compound spectra will be printed:

If = 5 PE and summed equilibrium spectra will be (separately) printed:

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

If IKE $\leqq$ 0 or IKE $\geqq$ 6 most reduced output:

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

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

= 0: or NE from 1.no printout

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

KPLT = 0: no plotting

Card 2 Title - 80 columns

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

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

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

CARD 3 energy, compound nucleus and pre-equilibrium option

Symbol Description

IKEN - projectile kinetic energy in the laboratory system.

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

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

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

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

JCAL

= 1, weisskopf-ewing evaporation calculation

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

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

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

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

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

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

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

TD - Initial exciton number =p+h

EX1 - Initial excited neutron number

EX2 - Initial excited proton number

EX3 - Initial alpha particle exciton number

POT - Fermi energy in Mev

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

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

Not to be used above 55 Mev

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

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

(1-ALF): complementary probability

If ALF >1 calculation for two initial exiton numbers

A)ATD=TD-3 (min.1.5) AEX1=AEX2=0. AEX3=2;ATD=TD-6 for T D¿9 with weight ULF=INT (ALF)100

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

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

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

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

In this thesis, different initial exciton numbers have been used for each reaction channel based on the closeness of the calculated values and the experimental values. The other important parameter is a level density parameter and also its value has been chosen as the calculated values fit the experimental values. When calculation was performed the Exciton numbers to non-zero or zero for pre equilibrium or compound nucleus respectively has been used. The other necessary inputs used for the code are the channel energy, atomic and mass numbers of the projectile and the target, and the level density parameter. The other important parameter that plays a great role in calculating reaction cross section is exciton numbers ($n_o = E_{X1} + E_{X2} + E_{X3}$). This was set to which the calculated values best fit with experimental values in each reaction [21].

The compound nucleus formed by bombarding particle (alpha) is de-excited by evaporating one or more neutrons. If the excitation energy is sufficient, then the evaporation of one particle may leave enough energy to enable the second particle to leave, and so on. The probability of decay through a large number of the particle increases with greater excitation. When little excitation is left, particle emission ceases and only gamma emission is possible [21].

Exciton Number

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

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

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

Level Density Parameter

Level density parameter also plays an important role in calculating the nuclear reaction model statistically, such as in calculating the evaporation model of nuclear reaction and in the studies of different energy ranges of nuclear reaction. The level density parameter obtained by the experiment shows a linear dependence with the mass number of the compound nucleus [22]. In general, it is given by an expression:

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

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

In this thesis, the level density parameter was employed for respective reactions, which gives the best fit to experimental results. The cause for the variation of the value of K here is seeking the best fit to the experimentally measured excitation function. However, the effort had been made to use the same K value for analogous reaction channels of the isotopes for reasonable comparison [22].

The nuclear level density $\rho(E)$ is a characteristic property of every nucleus and it is defined as the number of levels per unit of energy at certain excitation energy [22].

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

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

Percentage Error Calculation

In this study error calculation is performed in order to check the quality of the calculated result and to compare with experimental data that obtained from EXFOR Library. In general the percentage error of the calculated data from the experimental data assumes different values. In energy region where a per-equilibrium calculation or compound nucleus calculation has a percentage error more than 20% , we say the specific stage of reaction is dominated. If the percentage error is less than (10 - 15)% , we calculated that the particular stage of reaction is dominating in that energy region.

Thus having larger error is not mean that the calculation must be wrong. It indicate that the dominance of one nuclear reaction stage over the other. Percentage error is given by:

$$Perc.error = \frac{|Exp.value - Meas.value|}{Exp.valve} \tag{3.2}$$

Chapter 4

Result and Discussion

4.1 Result

In this chapter, the result of the calculations on the excitation functions of four reactions was presented. Those reaction are: ${}^{106}_{48}Cd(\alpha, n)^{109}_{50}Sn$, ${}^{108}_{48}Cd(\alpha, n)^{111}_{50}Sn$, ${}^{114}_{48}Cd(\alpha, 2n)^{116}_{50}Sn$, and ${}^{114}_{48}Cd(\alpha, 3n)^{115}_{50}Sn$ in the alpha energy range 10MeV to 60MeV. The experimental reaction cross section is obtained from the IAEA data source, EXFOR library[19].

The theoretical calculation is performed for two reaction mechanisms. These are for pre-equilibrium decay excitation function and for compound nucleus decay excitation function. The excitation function produced by the target of different stable isotopes of Cadmium with different reaction channels was compared with experimental data and explained. The energy range selected from the experimental data from EXFOR is the same with calculated data of compound nucleus and pre-equilibrium reaction. The experimental reaction cross sections and the calculated reaction cross sections are plotted against helium energy as shown in Figures 4.1 to 4.6. The calculated excitation function is shown by dotted line whereas, the experimental excitation function is shown by the line in each figure.

4.1.1 Calculation of the Cross section for ${}^{114}_{48}Cd(\alpha, 2n)^{116}_{50}Sn$

For this reaction channel, the total experimental reaction cross section data were obtained from EXFOR Library [8]. In this reaction, alpha energy in the range 35 to 55 MeV as shown in table 4.1 were assumed to the incident onto a Cadmium target (${}^{114}_{48}Cd$) nucleus to give two neutrons and a residue of ${}^{116}_{50}Sn$.

Alpha energy(MeV)	σ (Exp)	σ(Compound)	% error	σ(pre-equilibrium)	% error
35	324	386.2	19.19	369	13.9
40	161	162.9	1.18	153.7	4.53
45	85	66.51	21.75	64.27	24.38
50	48.5	25.74	46.92	27.17	43.97
55	26.1	61.5	10.05	12.33	52.8

Table 4.1: Experimental and Theoretical Cross section for ${}^{114}_{48}Cd(\alpha, 2n)^{116}_{50}Sn$

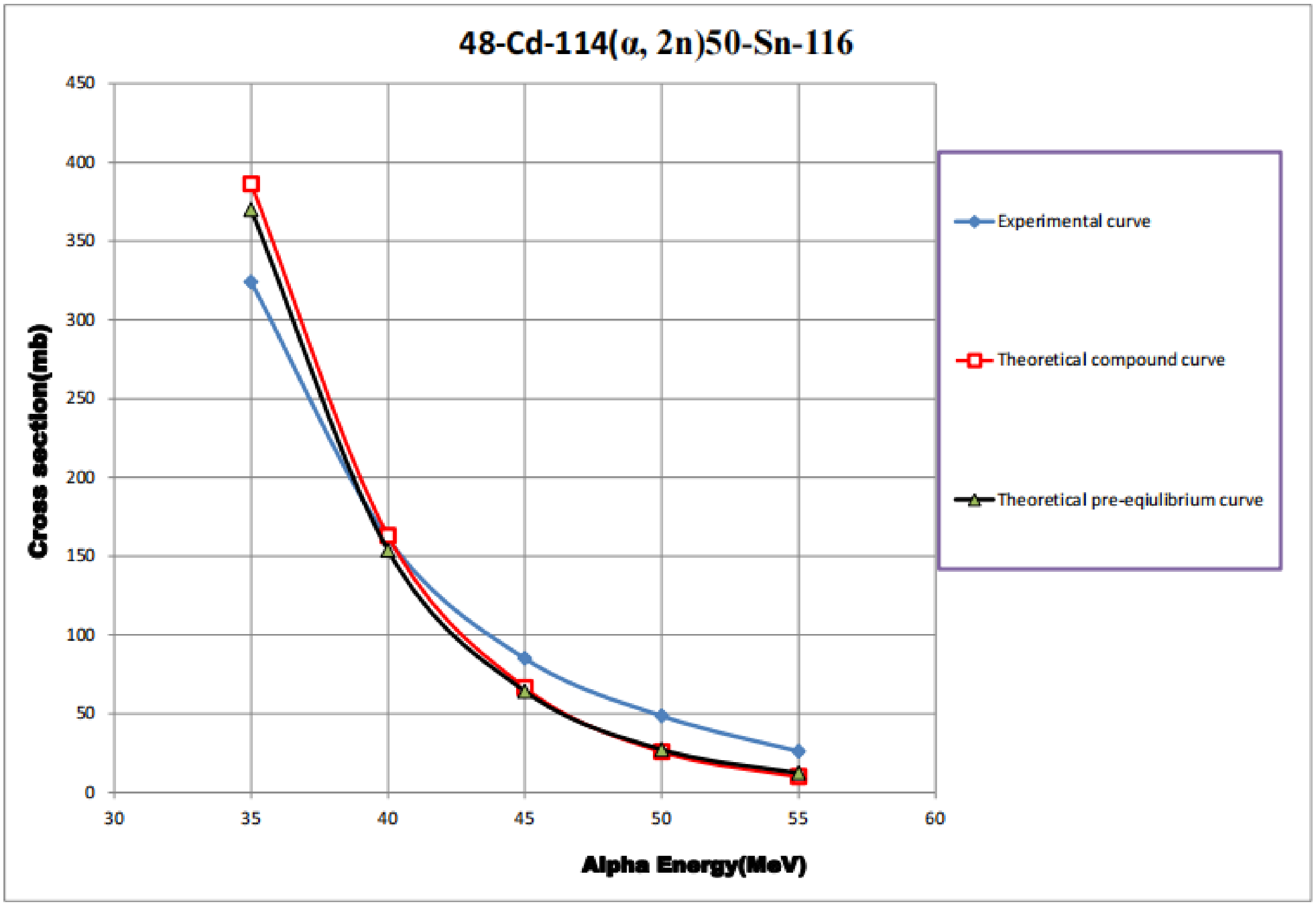

Figure 4.1: Experimental and Theoretical excitation function for the reaction $^{114}_{48}Cd(\alpha,2n)^{116}_{50}Sn$

Table (4.1) and Fig. (4.1) showed that the nature of the reaction depends on the energy of the projectile. As shown in Fig. 4.1. the result of the cross section in this calculation agrees well with an experiment in literature. From the graph we can see at the energy around 30MeV, there is no cross section because may be due to the energy nearer to the threshold energy of the reaction, no possibility for the reaction to happen. If the energy gradually increases beyond 40MeV, the dominant reaction is expected to be the pre-equilibrium reaction, since the compound nucleus reaction is at low energies, in its properties. In the region of the curve below the 40MeV projectile energy the expected compound nucleus $^{118}_{50}Sn^{*}$ is formed from the

reaction $^{114}_{48}Cd(\alpha, 2n)^{116}_{50}Sn$ represented by the graph in Fig. 4.1. Then the compound nucleus decays (evaporates) by emission of two neutrons with a certain decay probability. The cross section in Fig 4.1 the energy below 40MeV gives the probability for the formation and decay of the compound nucleus. After 40MeV of the projectile energy as seen from the graph, the pre-equilibrium stage of the reaction happens to begin, because the pre-equilibrium stage starts at an energy above the energy of the formation of the compound nucleus. Thus the cross section values in both the COMPLET CODE calculation and experiment agree well and decrease with increasing energy to the maximum at energy 55MeV, which could be the resonance peak for the pre-equilibrium stage of the nuclear reaction. The curve in Fig 4.1 shows no information about the direct stage of the nuclear reaction considered because the computational code used in this thesis was not designed to calculate the cross section for the high energy cases, Direct reaction. For all energy both the experimentally and theoretically calculated pre-equilibrium reaction and compound nuclear reactions seems to overlap.
The % Error for reaction channel of all enregy range is calclated below for Compound nucleus and Pre-equilibrium reaction stages.

4.1.2 Calculation of the Cross section for ${}^{114}_{48}Cd(\alpha, 3n)^{115}_{50}Sn$

For this reaction channel, the total experimental reaction cross section data was obtained from EXFOR Library [8]. In this reaction, a alpha energy in the range 35 to 55 MeV as shown in table 4.2 were assumed to the incident onto a Cadmium target (${}^{114}_{48}Cd$) nucleus to give three neutrons and a residue of ${}^{115}_{50}Sn$.

Alpha energy(MeV)	σ (Exp)	σ(Compound)	% error	σ(pre-equilibrium)	% error
35	1166	1166	0	1171	0.42
40	1042	1034	0.77	1032	0.96
45	539	597.4	10.83	593.2	10.05
50	223	265.4	19	266.5	19.5
55	112	105.7	5.62	109.9	1.87

Table 4.2: Experimental and Theoretical Cross section for ${}^{114}_{48}Cd(\alpha, 3n)^{115}_{50}Sn$

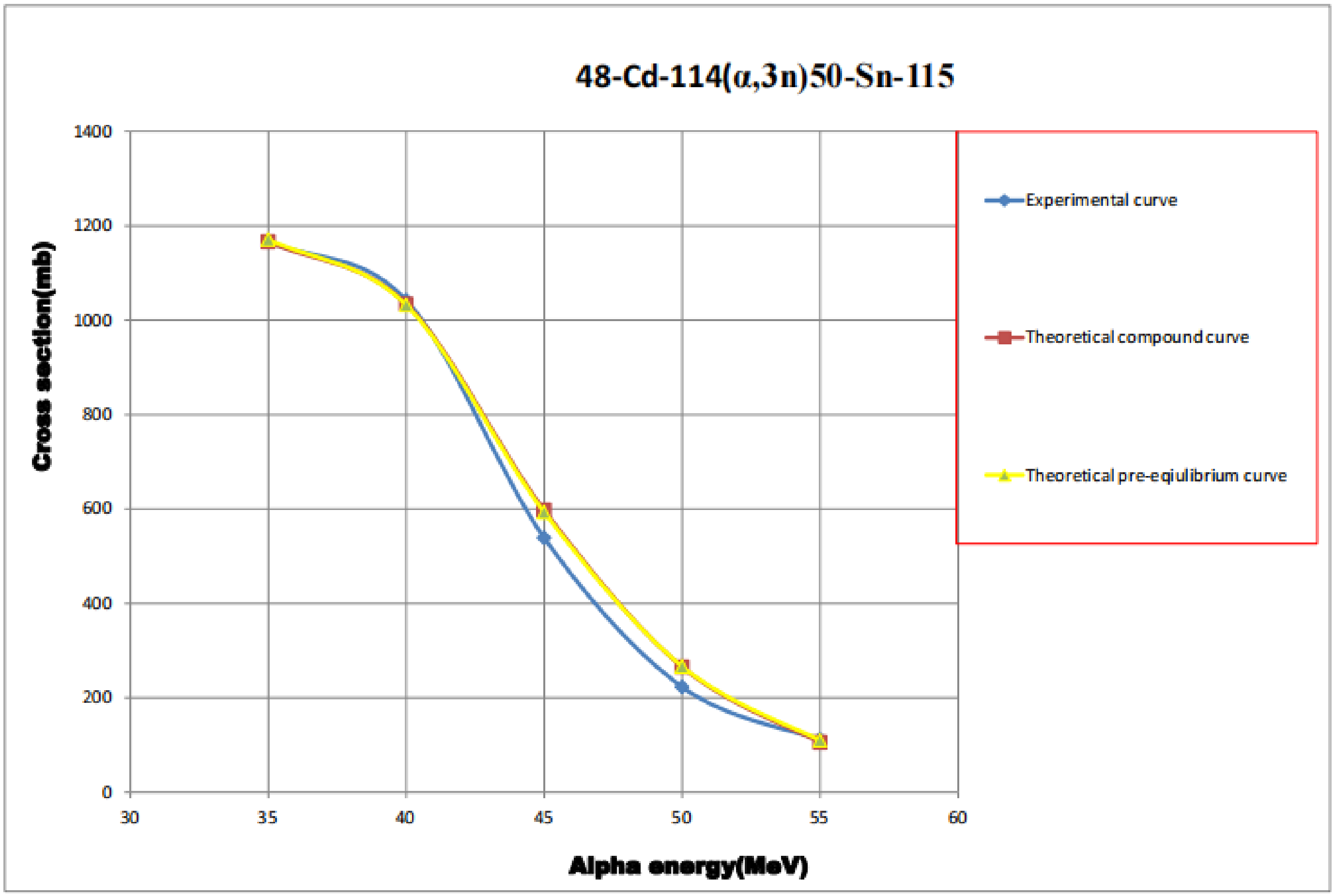

Figure 4.2: Experimental and Theoretical excitation function for the reaction ${}^{114}_{48}Cd(\alpha, 3n)^{115}_{50}Sn$

Table (4.2) and Fig. (4.2) showed that the nature of the reaction depends on the energy of the projectile. As shown in Fig. 4.2. the result of the cross section in this calculation agrees well with the experiment in literature. From the graph we can see at the energy around 30MeV, there is no cross section because may be due to the energy nearer to the threshold energy of the reaction, no possibility for the reaction to happen. For energy 35MeV the experimentally and theoretically calculated compound nucleus reactions overlapped. If the energy gradually increases beyond 40MeV, the dominant reaction is expected to be the pre-equilibrium reaction. In the region of the curve below the 40MeV projectile energy the expected compound nucleus ${}^{118}_{50}Sn^{*}$ is formed from the reaction ${}^{114}_{48}Cd(\alpha, 3n)^{115}_{50}Sn$ represented by the graph in Fig. 4.2. Then the compound nucleus decays (evaporates) by emission of three neutrons with a certain decay probability. The cross section in Fig 4.2 the energy below 40MeV gives the probability for the formation and decay of the compound nucleus. After 40MeV of the projectile energy as seen from the graph, the pre-equilibrium stage of the reaction happens to begin, because the pre-equilibrium stage starts at an energy above the energy of the formation of the compound nucleus. Thus the cross section values in both the COMPLET CODE calculation and experiment agree well and decrease with increasing energy to the maximum at energy 55MeV, that could be the resonance peak for the pre-equilibrium stage of the nuclear reaction. The curve in Fig 4.2 shows no information about the direct stage of the nuclear reaction considered because the computational code used in this thesis was not designed to calculate the cross section for the high energy cases, direct reaction. For all energy both the experimentally and theoretically calculated pre-equilibrium reaction and compound nuclear reactions seems to overlap.

4.1.3 Calculation of the Cross section for ${}^{108}_{48}Cd(\alpha, n)^{111}_{50}Sn$

For this reaction channel, the total experimental reaction cross section data were obtained from EXFOR Library [18]. In this reaction, alpha energy in the range 10.5529 to 13.4582MeV as shown in table 4.3 were assumed to incident onto a Cadmium target (${}^{108}_{48}Cd$) nucleus to give neutron and a residue of ${}^{111}_{50}Sn$.

Alpha energy(MeV)	σ (Exp)	σ(Compound)	% error	σ(pre-equilibrium)	% error
10.5529	0.14	0.3309	136.35	0.3309	136.35
10.864	0.31	0.9571	208.74	0.9764	214.96
11.1751	0.53	1.864	251.69	1.867	252.26
11.4873	1.18	3.323	181.61	3.327	181.94
11.7984	1.93	5.074	162.9	5.221	170.51
12.1095	3.8	9.268	143.9	9.307	144.92
12.4216	6.57	15.14	130.44	15.2	131.35
12.4216	6.42	20.44	218.38	21.35	232.56
12.9401	12.63	20.44	61.84	21.35	69.04
13.4597	34.7	44.54	28.35	45.23	30.34
13.4597	33.45	67.42	101.55	71.63	114.14
13.4597	39.99	67.42	68.59	71.63	79.11
13.4597	38.45	67.42	75.34	71.63	86.29
13.4582	59.59	67.42	13.13	71.63	20.2
13.4582	57.3	67.3	17.45	71.5	24.78

Table 4.3: Experimental and Theoretical Cross section for ${}^{108}_{48}Cd(\alpha, n)^{111}_{50}Sn$

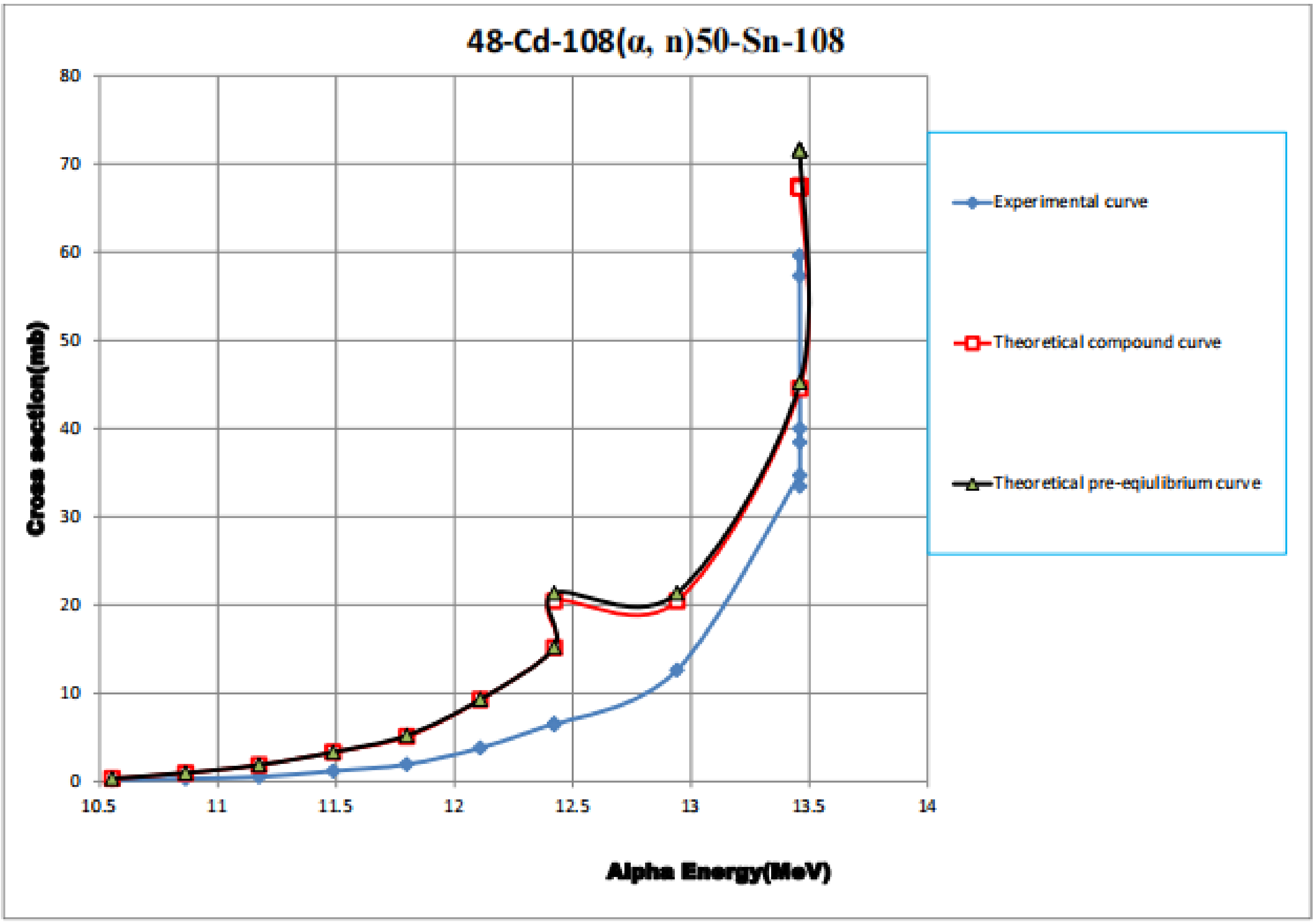

Figure 4.3: Experimental and Theoretical excitation function for the reaction $^{108}_{48}Cd(\alpha,n)^{111}_{50}Sn$

Table (4.3) and Fig. (4.3) showed that the nature of the reaction depends on the energy of the projectile. As shown in Fig. 4.3. the result of the cross section in this calculation agrees well with an experiment in literature. Near the low energy region of the curve in Fig 4.3, the cross section is low nearer to zero. Higher deviate of the cross section between the experiment and the calculation is seen at energy 11.7984MeV to 13.4597MeV with the experimental value of cross section 1.93mb and 38.45mb respectively, but both the theoretically calculated cross section for compound nucleus and pre-equilibrium reaction seems to overlap. Except for this energy, the present calculation agrees well with the experiment. The reason for this deviation might be related to the choice of the variables in the code. In the region of the curve below the 11.5MeV projectile energy, we expect that a compound nucleus $^{112}_{50}Sn^*$ is formed from the reaction $^{108}_{48}Cd(\alpha, n)^{111}_{50}Sn$ represented by the graph in Fig. 4.3. Then the compound nucleus decays (evaporates) by emission of one neutron with a certain decay probability. The cross section in Fig 4.3 the energy below 11.5MeV gives the probability for the formation and decay of the compound nucleus. After 11.5MeV of the projectile energy as seen from the graph, the pre-equilibrium stage of the reaction happens to begin, because the pre-equilibrium stage starts at an energy above the energy of the formation of the compound nucleus. Thus the cross section values in both the COMPLET CODE calculation and experiment agree well and increase with increasing energy to the maximum at energy 13.4582MeV, which could be the resonance peak for the pre-equilibrium stage of the nuclear reaction. For the energy between 12.4216MeV and 12.9401MeV, both the theoretically calculated pre-equilibrium reaction have the same value which is equal to 21.35mb and the theoretically calculated compound nuclear reactions has the same value which is equal to 20.44mb.

4.1.4 Calculation of the Cross section for ${}^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$

For this reaction channel, the total experimental reaction cross section data were obtained from EXFOR Library [20]. In this reaction, alpha energy in the range 10.7624 to 12.512 MeV as shown in table 4.4 were assumed to incident onto a Cadmium target (${}^{106}_{48}Cd$) nucleus to give neutron and a residue of ${}^{109}_{50}Sn$.

Alpha energy(MeV)	σ (Exp)	σ(Compound)	% error	σ(pre-equilibrium)	% error
10.7624	0.42	0.2984	28.95	0.2978	29.09
11.1816	1.42	1.203	15.28	1.216	14.36
11.5884	2.47	2.479	0.36	2.52	2.02
11.5884	2.6	4.955	90.57	5.076	95.23
11.9796	4.79	4.955	3.44	5.076	5.97
12.512	14.4	11.05	23.26	11	23.61

Table 4.4: Theoretical and Experimental cross-section for the reaction ${}^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$

^{109}Sn is produced when a projectile (alpha particle) strikes a target element Cadmium (^{106}Cd) and emits a single neutron(n). The theoretically calculated excitation functions of $^{106}_{48}Cd(\alpha, n)^{109}_{50}Sn$ reaction are compared with the experimental result.

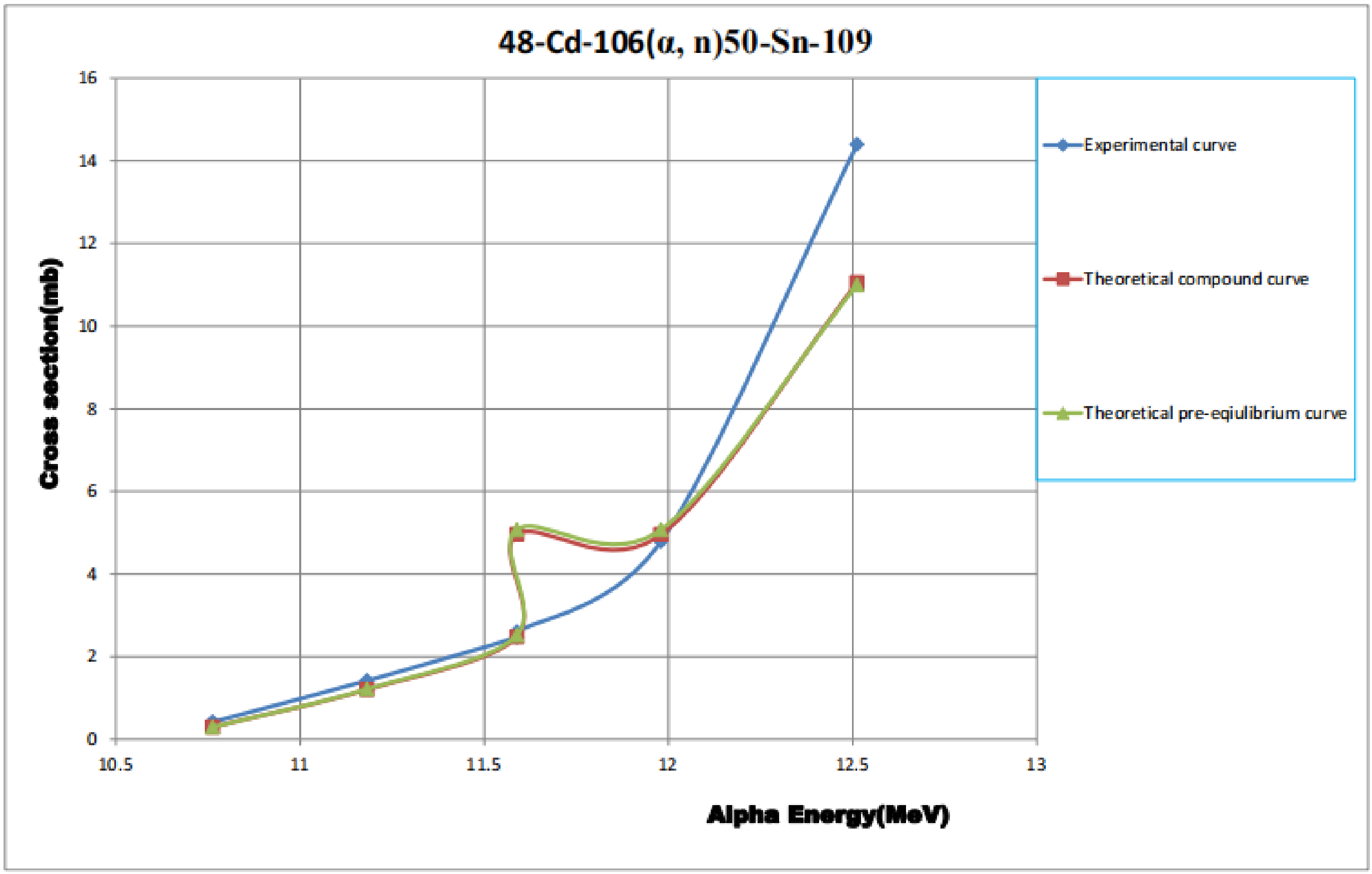

Figure 4.4: Experimental and theoretical excitation function for the reaction $^{106}_{48}Cd(\alpha, n)^{109}_{50}Sn$

Table (4.4) and Fig. (4.4) showed that the nature of the reaction depends on the energy of the projectile. As shown in Fig. 4.4. the result of the cross section in this calculation agrees well with an experiment in the literature. From the graph, we can see that for lower energy 10.7624MeV to 11.5884MeV with the experimental value of cross section 2.47mb both the experimentally and theoretically calculated pre-equilibrium reaction and compound nuclear reactions seems to overlap. For the higher energy 11.5884MeV with the experimental value of cross section 2.6mb to 12.512MeV both the theoretically calculated pre-equilibrium reaction and compound nucleus reactions seems to overlap.

A higher deviate of the cross section between the experiment and the calculation is seen at energy 11.5884MeV with the experimental value of cross section 2.6mb, but both the theoretically calculated cross section for compound nucleus and pre-equilibrium reaction seems to overlap. Except at this energy the present calculation agrees well with the experiment. The reason for this deviation might be related to the choice of the variables in the code.

Near the low energy region of the curve in Fig 4.4, the cross section is low nearer to zero. At energy around 10.5MeV, there is no cross section because may be due to the energy nearer to the threshold energy of the reaction, no possibility for the reaction to happen.

If we gradually increase the energy beyond 10.5 MeV, the dominant reaction is expected to be the compound nucleus reaction, since the compound nucleus reaction is at low energies, in its properties. Since there is no peak below 12Mev, there is no resonance peak for the compound nucleus for this reaction. In the region of the curve below the 12MeV projectile energy, we expect that a compound nucleus ${}^{110}_{50}Sn^*$ is formed from the reaction ${}^{106}_{48}Cd(\alpha, n){}^{109}_{50}Sn$ represented by the graph in Fig. 4.4. Then the compound nucleus decays (evaporates) by emission of one neutron with a certain decay probability.

The cross section in Fig 4.4 the energy below 12MeV gives the probability for the formation and decay of the compound nucleus. After 12MeV of the projectile energy as seen from the graph, the pre-equilibrium stage of the reaction happens to begin, because the pre-equilibrium stage starts at an energy above the energy of the formation of the compound nucleus. Thus the cross section values in both the COMPLET CODE calculation and experiment agree well and increase with increasing energy to the maximum at energy 12.512MeV, which could be the resonance peak for the pre-equilibrium stage of the nuclear reaction. The curve in Fig 4.4 shows no information about the direct stage of the nuclear reaction considered because the computational code used in this thesis was not designed to calculate the cross section for the high energy cases, direct reaction.

Chapter 5

Conclusion

In this study, the contribution from the direct reaction process is not expected. In the compound nucleus reactions, the projectile is captured by the target nucleus, and its energy is shared and re-shared among the nucleons of the target until it reaches a state of statistical equilibrium. A compound nucleus is formed when the composite nucleus attains statistical equilibrium and emissions taking place through statistical fluctuations from the equilibrium configuration are called compound nuclear emissions.

Particle emission is also possible while the composite nucleus is proceeding towards statistical equilibrium. This is called pre-equilibrium emission. The pre-equilibrium reactions are at one end of the nuclear reaction time scale.

For explaining these reactions nuclear physics needs models like the exciton model. In this thesis, the calculation of the excitation function of induced alpha on some stable isotopes of Cadmium(Cd) was studied. The reaction cross section values for $^{106}_{48}Cd(\alpha,n)^{109}_{50}Sn$, $^{108}_{48}Cd(\alpha,n)^{111}_{50}Sn$, $^{114}_{48}Cd(\alpha,2n)^{116}_{50}Sn$, and $^{114}_{48}Cd(\alpha,3n)^{115}_{50}Sn$ reaction channels has been calculated for 10Mev to 60Mev incident alpha energy ranges. The calculation results on the excitation functions and the energy ranges for the reaction process are given in figures 4.1 to 4.4. In the thesis, for the study of alpha induced reaction on Cadmium, the reaction is studied using both the exciton model with computer code COMPLET. Using this code, the calculated excitation functions were computed by supplying standard input parameters of the problem and also the adjustable free parameters.

The experimental cross sections are obtained from the IAEA data source, EXFOR library. The calculated and experimental cross sections for the reaction channels stated above were tabulated as in table 4.1 to 4.4 and plotted against the alpha energy range considered together as in figures 4.1 to 4.4. As it can be seen from table 4.1 to 4.4, and figure 4.1 to 4.4, both the calculated and experimental cross section displays the same pattern i.e. both attain their minima and maxima at equal values of alpha energy for each reaction channel. The compound nucleus reaction was dominate this reaction in the lower energy region, and pre-equilibrium reaction was dominate in the higher energy region. From the agreement of calculated and experimental data, in all energies considered, it can be concluded that the calculation reproduces the experimental data with the acceptable range of errors. Therefore, the calculation of the cross section for each reaction channel listed above is in good agreement with experimental data.

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