THE BEHAVIOR OF REACTION CROSS SECTION WITH PROTON PROJECTILES ON DIFFERENT ISOTOPES OF MOLYBDENUM TO PRODUCE TECHNETIUM

by

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

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DECLARATION

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

Lijalem Tezera

Signature.....

Date.....

This is to certify that this thesis entitled **"The Behavior of Reaction Cross section With Proton Projectile on Different Molybdenum Isotopes to Produce Technetium "** accepted in Partial Fulfillment of the requirements for the award of the Degree of Master of Science in Nuclear Physics by the School of Graduate Studies, Jimma University through the College of Natural Science, done by **Lijalem Tezera** is a genuine work carried out by him under my guidance. The matter embodied in this thesis work has not been submitted earlier for the award of any Degree or Diploma.The assistance and help received during the course of this investigation have been duly acknowledged. Therefore, We recommend that it can be accepted as fulfilling the research thesis requirements.

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Abstract

In the present study the behaviour of reaction cross section of Technetium production with protons as projectile on different stable isotopes of Molybdenum with its importance had been studied. The theoretical reaction cross-section calculation had been done by using COMPLET computer code based on the compound nucleus and pre-equilibrium nuclear reaction stages. The result have been compared with experimental data to check its quality. The evaluation has been done for some selected reaction channels of ${}^{95}_{42}Mo$(p,n)${}^{95}_{43}Tc$, ${}^{96}_{42}Mo$(p,n)${}^{96}_{43}Tc$, ${}^{97}_{42}Mo$(p,2n)${}^{96}_{43}Tc$, ${}^{98}_{42}Mo$(p,3n)${}^{96}_{43}Tc$ and ${}^{100}_{42}Mo$(p,2n)${}^{99}_{43}Tc$ in the incident proton energy range from 10 MeV up to 30 MeV by using ${}^{95}_{42}Mo$, ${}^{96}_{42}Mo$, ${}^{97}_{42}Mo$, ${}^{98}_{42}Mo$ and ${}^{100}_{42}Mo$ Molybdenum isotopes as a target nucleus. As a result calculated reaction cross sections is higher in case of ${}^{100}_{42}Mo$ and reaction channel ${}^{100}_{42}Mo$(p,2n)${}^{99}_{43}Tc$ comparatively. This indicates, production of Technetium is better in these isotope and reaction channel. The probability of production of Technetium is dependent of the incident proton energy and comparatively at lower energy region the dominance of compound nucleus reaction stage has been seen. But at higher energy region it is dominated by pre-equilibrium reaction stage. Also the result of calculated reaction cross section by COMPLET code is closer to experimental data that is obtained from EXFOR Library with variation of less than 10% in most reaction channels. All the above results obtained from the study had been analyzed and presented in tabular and graphical form in relation to proton kinetic energy.

Keywords: Reaction cross sections, COMPLET code, Technetium, proton projectile, Molybdenum.

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Chapter One

1 Introduction

1.1 General Background

The development of nuclear technology was one of the significant achievements of the twentieth century. This technology and its derivatives are currently used in almost every field of human endeavor. Radioisotopes, which are the main products of this technology were practically used by G. de Hevesy in 1911 for the first time. Radioisotopes or radionuclides are artificially produced, unstable atoms of a chemical element, which have a different number of neutrons but the same number of protons in the nucleus. Radioisotopes have the same chemical properties [1].

1.1.1 Radioisotope Production Methods

There are broadly two methods of radioisotope production on the world today. These methods are via rector and via accelerator.

I. Production Via Reactor

Radioisotopes can be produced in reactors by exposing suitable target materials to the intense reactor neutron flux for an appropriate time. A wide range of isotopes are made at reactors, from as light as Carbon-14 to as heavy as Mercury-203, with irradiations lasting minutes to weeks. For example, Mo-99 (the parent to the widely used medical diagnostic radioisotope Tc-99m) is usually produced via neutron-induced fission of targets with U-235 using a four to eight day irradiation time [1, 5].

II. Production Via Accelerators

Particle accelerators, in particular, cyclotrons were very important in the preparation of radioisotopes during the years from 1935 to 1941. After World War II, reactors were used to produce radioactive elements. The use of accelerators for this purpose became less common. As the techniques for using radio-tracers became more sophisticated, it became clear that reactor produced radionuclides could not completely satisfy the growing demand and therefore, accelerators were needed to produce new radioisotopes that could be used in new ways in both industry and medicine [1, 5, 23].

These two methods of preparation of a radioisotopes require vary expensive use of materials and research facilities. It is difficult to produce these radioisotopes using

these methods in our country. Therefore, it is better to use simple method of nuclear reaction for production of these radioisotopes for different purposes [1, 4, 22].

1.1.2 Molybdenum(Mo)

It is the transition metal placed in the center of the periodic table. It is group 6 and row 5 element with atomic number of 42 and atomic mass 95.94. It is a hard, silvery-white metal with a very high melting point about 26100^0C and boiling point 48000^0C to 55600^0C. Its density is $10.28g/cm^3$ [13].

There are seven naturally occurring isotopes of molybdenum exist:
$[^{92}Mo,^{94}Mo,^{95}Mo,^{96}Mo,^{97}Mo,^{98}Mo,^{100}Mo]$. None of the seven naturally occurring molybdenum isotopes are radioactive (all are stable). However, about a dozen artificial radioactive isotopes have been produced. i.e.$[^{83}Mo,^{84}Mo,^{85}Mo$ to $^{115}Mo]$ except the above [2, 4, 5].

1.1.3 Technetium(Tc)

It is a chemical element with the symbol Tc and atomic number 43. It is the lightest element that its isotopes are all radioactive. None of them are stable, excluding the fully ionized state of ^{97}Tc. Nearly all technetium were produced as a synthetic element, and only about 18,000 tons can be found at any given time in the Earth's crust [2]. Naturally occurring technetium is a spontaneous fission product in uranium ore and thorium ore, the most common source, or the product of neutron capture in molybdenum ores. This silvery gray, crystalline transition metal lies between manganese and rhenium in group 7 of the periodic table, and its chemical properties are intermediate between these two adjacent elements. From these two metals, technetium is more closely resembles to rhenium. Particularly in its chemical inertness and tendency to form covalent bonds [2, 4, 22].

Isotopes of Technetium are $[^{85}Tc$ to $^{118}Tc]$. But the most common naturally occurring isotope is ^{99}Tc. The most stable radioactive isotopes are technetium-97 with a half-life of 4.21 million years, technetium-98 with 4.2 million years, and technetium-99 with 211,100 years. Thirty other radioisotopes have been characterized with mass numbers ranging from 85 to 118. Most of these have half-lives that are less than an hour, the exceptions being technetium-93 (2.73 hours), technetium-94 (4.88 hours), technetium-95 (20 hours), technetium-96 (4.3 days) and technetium-99m (6 hours) [5, 6, 23].

The primary decay mode for isotopes lighter than technetium-98 (^{98}Tc) is electron capture, producing molybdenum (Z = 42). For technetium-98 and heavier isotopes, the primary mode is beta emission (the emission of an electron or positron), producing ruthenium (Z = 44), with the exception that technetium-100 can decay both by beta emission and electron capture [4, 5]. Technetium also has numerous nuclear isomer, which are isotopes with one or more exited nucleons. Technetium-97m (^{97m}Tc; "m" stands for meta-stability) is the most stable, with a half-life of 91 days and excitation energy 0.0965 MeV. This is followed by technetium-95m (61 days, 0.03 MeV), and technetium-99m (6.01 hours, 0.142 MeV) [5, 6].

Technetium-99m emits only gamma rays and decays to technetium-99.Technetium-99 (^{99}Tc) is a major product of the fission of uranium-235 (^{235}U), making it the most common and most readily available isotope of technetium. One gram of technetium-99 produces 6.2Ã108 disintegrations per second (in other words, the specific activity of ^{99}Tc is 0.62 GBq/g). Since Uranium is a very expensive and required more moderate technology in reaction and cyclotrons the Technetium radioisotopes scarce and expensive [4, 5, 6].

Technetium-99m is the radioisotope commonly used in nuclear medicine. It offers many advantages as compared to many other radionuclides, due to its very good physical and chemical characteristics. The gamma radiation emitted has the appropriate energy, 140KeV to provide a good image whilst keeping low radiation dose to the patient (also because ^{99m}Tc is a nearly pure gamma emitter: 89 percent). Technetium-99m accounts for nearly 85 percent of all nuclear medicine imaging studies [2, 4]. The clinical uses of this important radioisotope enables diagnostic imaging to be carried out in many areas in the human body such as respiratory and renal systems, musculoskeletal, the central nervous systems and other body systems [6].

1.2 Statement of Problem

As described in the background of this study, Technetium production requires very expensive technique and apparatus but it is very useful in medical diagnosis.
Despite the above importance of Tc, Ethiopia do not able to produce this radionuclide locally to feed its medical facilities. As a result there is always frequent shortage of this radionuclide in our medical facilities causing unnecessary delays in medical examinations and treatment.
Therefore, in this study theoretical calculation of production of Technetium using nuclear reaction has been done. To the best of my knowledge there is no such calculation in literature. The study had been focused only on the use of Molybdenum isotopes as a target material and using proton of different kinetic energy as projectile particle to produce Technetium in better way. In the absence of the local capacities for Tc production, it is necessary to undertake a theoretical study to investigate the possible production locally in the near future using nuclear reaction.

Basic Research Question
The research has been guided by the following leading questions:

1. Which isotopes of Molybdenum is preferable for production of sufficient Technetium ?
2. Which reaction channel is produce technetium with higher probability?
3. What was the probability of production of Technetium as a function of proton energy?
4. Which stage of nuclear reaction was dominant on reaction cross section calculation to produce Technetium in energy range 10 MeV to 30 Mev?
5. How the theoretical results agree with experimental values?

1.3 Objective

1.3.1 General Objective

The general objective of this study is to investigate the behavior of reaction cross section with proton as projectile on different isotopes of Molybdenum to produce Technetium.

1.3.2 Specific Objectives

1. To identify isotope of Molybdenum which is produce sufficient Technetium.
2. To identify reaction channel which is produce Technetium with higher probability.
3. To determine the probability of production of Technetium as the function of proton energy.
4. To identify the dominant stage of nuclear reaction on reaction cross section calculation to produce Technetium.
5. To validate how the theoretical result agrees with the experimental value.

1.4 Scope of the Study

The scope of this study had been aimed to calculate theoretically the cross section of reaction using nuclear models in reaction channel of Mo(p,x)Tc (where x is any outgoing particle) based on compound nucleus and pre-equilibrium stage of nuclear reaction. And the result had been compared with experimental value and it explored information regarding the reaction cross section in the literature (experimental value).

1.5 Significance of the Study

This study has significant impact in understanding of the behavior of reaction cross section with proton projectile on isotopes of Molybdenum in reaction channels of (p,x). As a result, the study might be used:

1. To justify theoretically the probability of production of Technetium using proton induced reaction on Molybdenum isotopes.
2. As reference material for anyone who works on this area.
3. To improve the understanding of reaction cross section of stable Molybdenum isotopes in the proton energy in the production of Technetium.

Chapter Two

2 Literature Review

2.1 Nuclear Reaction

2.1.1 Introduction to Nuclear Reaction

A nuclear reaction is the process that occurs when a nuclear particle i.e nucleon/nucleus/ gets into close contact with another. Most of the known nuclear reactions are produced by exposing different materials to a beam of accelerated nuclear particles [4, 5].

A nuclear reaction is considered to be the process in which two nuclear particles (two nuclei or a nucleus and a nucleon) interact to produce two or more nuclear particles or γ-rays. Thus, a nuclear reaction must cause a transformation of at least one nuclide to another. Sometimes if a nucleus interacts with another nucleus or particle without changing the nature of any nuclide, the process is referred to a nuclear scattering, rather than a nuclear reaction [5, 6]

Nuclear reactions and nuclear scattering are used to measure the properties of nuclei. Reactions that exchange energy or nucleons can be used to measure the energies of binding and excitation, quantum numbers of energy levels, and transition rates between levels. A particle accelerator, which produces a beam of high-velocity charged particles (electrons, protons, alpha, or heavy ions), creates these reactions when they strike a target nucleus [3, 7].

Nuclear reactions can also be produced in nature by high-velocity particles from cosmic rays, for instance in the upper atmosphere or in space. Beams of neutrons can be obtained from nuclear reactors or as secondary products when a charged particle beam knocks out weakly bound neutrons from a target nucleus. Beams of photons, mesons, and neutrinos can also produce nuclear reactions [8, 22].

In order for a nuclear reaction to occur, the nucleons in the incident particle, or projectile, must interact with the nucleons in the target. Thus the energy must be high enough to overcome the natural electromagnetic repulsion between the protons. This energy barrier is called the Coulomb barrier [9]. If the energy is below the barrier, the

nuclei will bounce off each other. Early experiments by Rutherford used low-energy alpha particles from naturally radioactive material to bounce off target atoms and measure the size of the target nuclei [9, 14].

$$a + X \rightarrow Y + b \quad \text{.....(2.1)}$$

When a collision occurs between the incident particle and a target nucleus, either the beam particle scatters elastically leaving the target nucleus in its ground state or the target nucleus is internally excited and subsequently decays by emitting radiation or nucleons. A nuclear reaction is described by identifying the incident particle, target nucleus, and reaction products [7, 8]. For example, when a neutron strikes a nitrogen nucleus,^{14}N, to produce a proton, 1H, and an isotope of carbon,^{14}C, the reaction is written as:

$$^1_0n + ^{14}_7 N \rightarrow ^{14}_6 C + ^1_1 H \quad \text{.....(2.2)}$$

Sometimes the reaction is abbreviated as $^{14}N(n,p)^{14}C$.
A number of conservation conditions apply to any reaction equation.

2.1.2 Reaction Mechanisms/Stages of Nuclear Reactions/

Nuclear reactions may entail three types of reaction mechanisms direct, compound nucleus and pre-equilibrium effects. The contribution of three processes depends and the given reaction and the energy of the incident particle. These three stages can be distinguished by their angular distributions and time scales [11, 12].

I. **Direct Reaction**

For projectile energies above 50 MeV and for light target nuclei($A < 30$) a direct transition from the entrance to the exit channel occurs within a very short time scale of about 10^{-22} seconds, which is roughly the time it takes to traverse the nuclear field. There is no creation and subsequent decay of a highly excited intermediate state, which results in an isotropic and forward-peaked angular distribution. Typical examples of direct reactions are elastic and inelastic scattering, charge transfer, stripping, pick-up, and knock-on processes [8, 14].

Direct reactions becomes more probable as one increases the energy of the incident particle: the wavelength associated to the particle decreases and localized areas of the nucleus can be probed by the projectile [3, 6]. In this context, peripheral reactions, where only a few nucleons of the surface participate become important. Direct reactions happen during a time of the order of 10^{-22}seconds.

Reactions with formation of compound nuclei can be up to six orders of magnitude slower. A reaction type at a given energy is not necessarily exclusive; the same final products can be obtained, part of the events in a direct way, other parts through the formation and decay of a compound nucleus [3, 6].

There are two characteristic types of direct reactions. In the first the incident particle scatters in-elastically and the transferred energy is used to excite a collective mode of the nucleus. Rotational and vibrational bands can be studied in this way. The second type involves a modification in the nuclear composition. Examples are transfer of nucleons, as pick-up and stripping reactions. An important reaction of the latter kind is a knock-out reaction where the incident particle knocks out a particle of the target nucleus and continues in its path, resulting in three reaction products. Reactions with nucleon exchange can also be used to excite collective states. An example is a pick-up reaction where a projectile captures a neutron from a deformed target and the product nucleus is in an excited state belonging to a rotational band [7, 8].

Direct reactions exhibit a peculiar form of angular distribution, which allows us to extract information on the reaction mechanism with the employment of simple models [11, 23]. Typical examples are the stripping reactions (d, n) and (d, p), where the angular distribution of the remaining nucleon presents a forward prominent peak and smaller peaks at larger angles, with the characteristic aspect of a diffraction figure.

II. **Compound Nucleus**

Compound nucleus formation is a reaction in which two nuclei combine into a single excited nucleus; the excited nucleus lives for a relatively long time and forgets how it was formed. The decay from this state of excitation is by evaporation of nucleons from the heated liquid drop of the compound nucleus, by gamma decay, or by fission of the compound nucleus. The statistical nature of this process teaches us about the average properties of excited states of complex nuclei [9, 14].
Compound nucleus reactions is given by:

$$a + A \rightarrow C^* \rightarrow b + B^* \quad \text{.....(2.3)}$$

The projectile is captured by the target and the two systems coalesce to form a highly excited state (the compound nucleus).

The excitation energy is shared uniformly among the constituent nucleons.

A nucleon or group of nucleons can be given enough energy to escape (random process): decay of C^*.

If B has enough energy, more emissions can occur, otherwise it will de-excite by β-decay or γ-decay.

The compound nucleus is a relatively long-lived intermediate state of particle-target composite system. It involves many nucleon-nucleon interactions. The large number of collisions between the nucleons leads to a thermal equilibrium inside the compound nucleus. The time scale of compound nucleus reactions is of the order of $10^{-18}s$ - $10^{-16}s$. It is usually created if the projectile has low energy [10].

Incident particles interact in the volume of a target nucleus. Products of the compound nucleus reactions are distributed near isotropically in angle (the nucleus loses memory of how it was created the Bohr's hypothesis of independence). The mode of decay of compound nucleus do not depend on the way the compound nucleus is formed. Resonances in the cross-section are typical for the compound nucleus reaction [12, 14].

At low energies, the largest probability is the continuation of the process so that the initial energy is distributed among all nucleons, with no emitted particle. The final nucleus with A+1 nucleons has an excitation energy equal to the kinetic energy of the incident neutron plus the binding energy the neutron has in the new, highly unstable, nucleus. It can, among other processes, emit a neutron with the same or smaller energy to the one absorbed. The de-excitation process is not necessarily immediate and the excited nucleus can live a relatively long time [13].

We say that there is, in this situation, the formation of a compound nucleus as intermediary stage of the reaction. In the final stage the compound nucleus can evaporate one or more particles, fission, etc. In our notation, for the most common situation in which two final products are formed (the evaporated particle plus the residual nucleus or two fission fragments, etc.) [10, 12].

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

On a time scale this process lies between the direct and the compound nucleus reactions. The particle is emitted before the energy is evenly distributed over all nucleons, thus giving a smooth forward-peaked angular distribution. Another characteristic is a pronounced high-energy tail in the excitation function [12].

When a low energy neutron ($< 50MeV$) enters the range of nuclear forces it can be scattered or begin a series of collisions with the nucleons. The products of these collisions, including the incident particle, will continue in their course, leading to new

collisions and new changes of energy. During this process one or more particles can be emitted and they form with the residual nucleus the products of a reaction that is known as pre-equilibrium [9, 11].

2.1.3 Reaction Models

I. Compound Nucleus Model

Hauser-Feshbach theory describes reaction cross section that involve a large number of compound nuclear states. The Bohr independence hypothesis allows the cross section to be written as the product of two factors, the cross section σ for formation of the compound nucleus and the probability P_b will be decay in to the channel b [3, 8]:

$$\sigma_b b = \sigma_a P_b \quad \text{.....(2.4)}$$

The compound nucleus formation cross section at a particular orbital angular momentum l is given by

$$\sigma_a = \pi\lambda_a^2(2l+1)T_a \quad \text{.....(2.5)}$$

Where λ is the reduced wavelength in the incident channel (inverse of the wave number k) and the transmission coefficient Ta for the entrance channel a is given by
$Ta = l - [S_{aa}]^2$ where S_{aa} is average S-matrix. The reciprocity theorem relates a cross section to its inverse [6]

$$\lambda_a^2\sigma_{ab} = \lambda_a^2\sigma_{\hat{a}\hat{b}} \quad \text{.....(2.6)}$$

Where $\hat{a}$ and $\hat{b}$ refer to time-reversed states. Combining these equations imply that

$$T_a P_b = T_{\hat{b}} P_{\hat{a}} \quad \text{.....(2.7)}$$

Since this is true for all channels a and b,

$$\frac{P_a}{T_a} = \frac{P_b}{T_b} = k \quad \text{.....(2.8)}$$

Where k is constant and P's are probabilities.

$$\sum_a p_a = k\sum_a T_a = 1 \quad \text{.....(2.9)}$$

Therfore

$$P_b = kT_b = \frac{T_b}{\sum_a T_a} \quad \text{.....(2.10)}$$

Thus we get

$$\sigma_{ab} = \pi\lambda_a^2(2l+1)\frac{T_b T_b}{\sum_a T_c} \quad \text{.....(2.11)}$$

The transmission coefficients Ta can be calculated from the appropriate optical model potentials. This Hauser - Fesbach formula provides the cross section of a compound nuclear reaction from a single incident channel a to a single outgoing channel b, in a particular angular momentum state l in the absence of spin. If the interacting particles have spin, the expressions for the cross section must be include in the appropriate spin weighting factors [13].

II. **The Excitation Model**

Still modified and logically simple model is presented by Griffin. In this model it is assumed that the incoming projectile, by interacting with the target nucleus, gives rise to a simple initial configuration characterized by a small number of excited particles and holes called exciton. $(n = p + h)$ Successive two-body residual interactions give rise to an intranuclear cascade through which a sequence of states characterized by an increasing exciton number, eventually leads to a fully equilibrated residual nucleus [14]. Restriction to two-body residual interactions leads to the following selection rules concerning the possible variation of the number n of exciton, of particles p and hole h: $\Delta n = 0, \pm 2; \Delta p = 0, \pm 1; \Delta h = 0, \pm 1$

III. **The WeissKopf's Ewing Model**

Weiss Kopf and Ewing developed theoretical calculations of reaction cross-sections according to the Bohr model using partial wave analysis. In this model the conservation of angular momentum and parity for each partial wave is not taken into account. Nevertheless, it provides a good estimate for the magnitude of the cross - section. On the other hand Hauser and Feshbach treated the problem in a more detailed way and have explicitly taken into account the conservation of angular momentum and parity [10].

2.2 Reaction Channel

All the reactions in equation (2.12) below, 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 a, b, etc. are elementary, states
α", β", etc., refer to their spin orientation [20]. We get the reactions

$$a_{\alpha''} + X_{\alpha'} = \begin{cases} X_{\alpha'} + a_{\alpha''} \\ X_{\beta'} + a_{\beta''} \\ Y_{\gamma'} + b_{\gamma''} \\ etc. \end{cases} \quad \text{.....(2.12)}$$

Here α' and α" are states of the target nucleus and the incident particle, β' and β" or γ' and γ", can denote any quantum state of X and a or Y and b, respectively, which can be created in this reaction. Of course, the conservation laws of energy, angular momentum, and parity restrict the possible pairs of β' and β", γ' and γ" etc [20].

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 induces α' and α", or β' and β". Channel $X_{\alpha'} + a_{\alpha''}$ is called the entrance channel or initiating channel of reaction in equation (2.12) and the channels shown by $X_{\alpha'} + a_{\alpha''}, X_{\beta'} + a_{\beta''}, Y_{\gamma'} + b_{\gamma''}$ are called exit channels.

The special position accorded to particle a and nucleus X in equation (2.12) corresponds to the experimental setup, in which a uniform beam of particles a bombard nucleus X. Nucleus X is initially at rest (or moving very slowly in comparison to the projectiles a),and all projectiles are moving with the same velocity [20].

2.3 Reaction Cross Section

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. Or number of events of given type per unit time per nucleus divided by number of incident particles per unit area per unit time [10, 11] .

The concept of a cross section cannot be used if large numbers of nuclei act coherently. This occurs in only one type of nuclear reaction: the scattering (but not the absorption) of a beam of very slow neutrons by crystalline material. In all other cases the cross section has a well-defined above. Let us consider a plane wave of particles a incident upon the nucleus X, representing an entrance channel α. Particle α 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 [20]

$$\sigma_t(\alpha) = \sigma_{sct}(\alpha) + \sigma_r(\alpha) \quad \text{.....(2.13)}$$

Here $\sigma_{sct}(\alpha)$ denotes the elastic scattering cross section, and $\sigma_r(\alpha)$ denotes the combined cross section for all events other than elastic scattering. (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 [20].
This quantity "σ" which has the dimension of area, is measured by the experimental ratio

$$\sigma = \frac{N_{rpe}}{(N_{bp}/A)(N_{tnb})} \quad \text{.....(2.14)}$$

Where: $\sigma-$ is cross section
$N_{rpe}-$ is number of reaction particles emitted
$N_{bp}/A-$ is number of beam particles per unit area
$N_{tnb}-$ is number of target nuclei within the beam
The term "cross section " has already been met in connection with the attenuation of a ray beam, when it was used as a measure of the probability that a photon is removed from the beam; the cross section was regarded: there as a form of absorption coefficient. In the discussion of nuclear reactions, a more detailed consideration of the idea of cross sections will prove useful [11, 12].

The concept of a nuclear cross section can be most easily visualized as the cross-sectional area, or target area, presented by a nucleus to an incident particle [10, 11, 12]. If the nuclei are considered as spheres of radius R cm and the incident particles as point projectiles, then the target area, or cross section σ, of each nucleus is given by

$$\sigma = \pi R^2 cm^2 \quad (2.15)$$

If we have a detector placed to record particle b emitted in a direction(θ, ϕ) with respect to the beam direction, the detector defines a small solid angle $(d\Omega)$ at the target nucleus [10, 11]. Let the current of incident particles be I_a particles per unit time, and let the target show to the beam N target nuclei per unit area. If the outgoing particles appear at a rateR_b, then the reaction cross section is

$$\sigma = \frac{R_b}{I_a N} \quad (2.16)$$

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

2.3.1 Total Cross Section

The total cross section σ_t for a specific incident particle a, we add the reaction cross sections for all possible different outgoing particles b, no matter what their direction or energy. Such a determination would tell us the probability for an incident particle to have any reaction at all with the target and thus be removed from the beam of incident particles. This can be deduced directly by measuring the loss in intensity of a collimated beam in passing through a certain thickness of the target material [10, 12]. It is given by

$$\sigma_{tot} = \sigma_{sc} + \sigma_{abs} \quad (2.17)$$

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

$$\sigma_{tot} = \frac{n_1 + n_2 + n_3}{\frac{I}{A}\rho A d} \quad (2.18)$$

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

$$\sigma_{tot} = \frac{n}{\frac{I}{A}\rho A d} \quad (2.19)$$

Where σ_{tot} is total area, I/A is Intensity per unit area, ρ is density of emitted particle and d is thickness of material. So that

$$\sigma_t = \sum_i \sigma_t \quad (2.20)$$

2.4 Conservation Laws in Nuclear Reaction

In analyzing nuclear reactions, we apply many conservation laws. Nuclear reactions are subject to classical conservation laws for charge, nucleon number, spin, parity, linear momentum, angular momentum, and energy (including rest energies). Additional conservation laws, not anticipated by classical physics, are electric charge lepton number and baryon number. Certain of these laws are obeyed under all circumstances, others are not [10, 11].

We have accepted conservation of energy and momentum. In all the examples given we assume that the number of protons and the number of neutrons is separately conserved. We shall find circumstances and conditions in which this rule is not true. Where we are considering non- relativistic nuclear reactions, it is essentially true. However, where we are considering relativistic nuclear energies or those involving the weak interactions, we shall find that these principles must be extended [12].

Some conservation principles have arisen from theoretical considerations, others are just empirical relationships. Notwithstanding, any reaction not expressly forbidden by the conservation laws will generally occur, if perhaps at a slow rate. This expectation is based on quantum mechanics. Unless the barrier between the initial and final states is infinitely high, there is always a non-zero probability that a system will make the transition between them [11, 12].

2.4.1 Conservation of Energy

The total energy before the reaction must equal the total energy after the reaction. The total energy includes the particle kinetic energies plus the energy equivalent of the particle rest masses, $E = mc^2$.

Particle and radiation detectors designed for the expected charge and energy of each product are arranged around the target. The conservation of the total energy (rest + kinetic energy) plays an important role in the dynamics and in the kinematics of nuclear reactions [10, 12]. Here only the kinematics will be discussed. The Q value of nuclear reactions is given by the mass differences between exit and entrance-channel particles. It is given by:

$$Q = [(m_1 + m_2) - \sum_{n_{out}} m_i]c^2 \quad (2.21)$$

Because of the constancy of the total energy Q can also be expressed by the difference between the kinetic energies. The Q value determines the quite different behavior of

endothermal ($Q < 0$), elastic (Q= 0), or exothermal ($Q > 0$) reactions, especially at low energies [7, 12]. The endothermic reactions start at a threshold energy, at which the energy of the relative motion (energy ion the center-of-mass system "E_{cm}") is just equal to Q.

2.4.2 Conservation of Linear Momentum Conservation

Linear momentum before and after the reaction must be equal. For two-particle final state and initial state of reaction are determined. This means a measurement of one particle's momentum determines the other particle's momentum. Quantum rules govern the balancing of the angular momentum, parity, and isospin of the nuclear levels. A specific reaction is studied by measuring the angles and kinetic energies of the reaction products (the kinematic variables) [11, 12].

The conservation of momentum is quantum-mechanically equally important as in classical collision processes. Together with energy conservation it determines the kinematics of all decays and nuclear reactions. Certain processes like pair creation are possible only if a heavier collision partner takes care of the momentum conservation [8, 9].

2.4.3 Conservation of Angular Momentum

Angular-momentum conservation is connected with continuous transformations, namely with rotations in 3D space. J_Z is conserved ($[J_Z, H] = 0$) if the potential does not explicitly depend on ϕ. Similarly, J or J^2 are conserved if the potential depends explicitly only on r but not on θ and ϕ i.e. like in classical physics for central forces, because the operator of J acts only on angular variables [7, 9].

The usual description of nuclear reactions takes care of the conservation of angular momentum by describing the observable in the angular-momentum representation. The solution of the *Schrödinger* equation is normally done in spherical polar coordinates. The angular-momentum eigen functions $Y_\ell^m(\theta, \phi)$ are the angle-dependent parts of the wave function and are separable from the spatial wave-function part. For particles with spin the description is much more complicated because the orbital angular momentum and the channel spins of the incoming and the outgoing channels must each be coupled to the total angular momentum J, which is the only conserved angular-momentum quantity [9, 10].

Depending on the observable Racah algebra, i.e. 3j- 6j-9j symbols may be used. The most general formalism (for neutral particles) was published by Walton giving general

(polarization) observable of the exit channel as functions of those of the entrance channel in a partial-wave expansion and showing the clear separation between the dynamics (transition matrix elements), angular-momentum algebra, and the geometry (rotation functions $D^L_{mm'}(\theta, \phi, \beta)$. For spin less particles and central forces the orbital angular momentum is a conserved quantity, for reactions with particles, whose spin is, $\neq 0$ only the total angular momentum J is conserved [9, 10].

Chapter Three

3 Materials and Methodology

3.1 Materials

The following materials had used for the purpose of this study.

Different standard literature,

Published and unpublished Journals,

Published and unpublished articles,

Books, Web sites, Laptops, flash card, CDRW and stationary materials (paper and pens)

3.2 Methodology

3.2.1 Analytic Method

In this study analytically the equation of probability of different channels of the reaction Mo(p, x) which yield Technetium had been derived based on compound nucleus and pre-equilibrium mechanisms of nuclear reactions.

3.2.2 Computational Method

The reaction cross sections had been calculated and arranged according to the energy range from 10 MeV to 30 MeV using computational method. In this method, ALICC-91 based nuclear reaction computer code (COMPLET code) had been employed.

COMPLET CODE

The code COMPLET is a nuclear reactions code which was designed for versatility and ease of use in the bombarding energy range of a few MeV to several hundred MeV. It is based on same philosophy as the former code COMPLEX and an extension of code INDEX. COMPLET code is an extension of the code ALICE-91 and INDEX. These two codes employ the Weisskopf-Ewing model for the statistical part and geometry dependent hybrid model of M.Blann for the pre-equilibrium emission [16].

The code COMPLET gives the result of compound reaction and compound nucleus plus pre-equilibrium reaction. The projectile energy is measured in Mega Electronvolt (MeV) and the cross-section are measured in millibarn (mb) [16].

In COMPLET code a pre-equilibrium process in two stages is assumed. The particles in the initial configuration (n_0 = EX1 + EX2 + EX3) can be neutron, proton or alpha particle, represented by the exciton numbers EX1, EX2 and EX3 respectively. It is customary to use the initial exciton number n_0 separated in to proton and neutron above and holes below the Fermi level as a fit parameter to match theoretical prediction with experimental excitation function. The requirement of detailed input parameters was sacrificed to achieve this goal [16].

The code COMPLET provides yields and spectra for all reactions populated by all combinations of n; p; d; α 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 R_0. The used code is a further simplification of the formulae due to Paul and Thoennessen in Ann.Rev.Nucl and particle science 44(1944) [16].

The code COMPLET includes pre-equilibrium neutron, proton and alpha emission up to two particle, as well as evaporation of neutrons, protons, alpha, deuterons, tritones and hellions [16].
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 [16].

3.2.3 Method of Data Presentation and Analysis

a. The reaction cross sections data obtained from EXFOR had been arranged according to the given energy intervals in MeV for 10 MeV to 30 MeV energy range.

b. The theoretical calculation of reaction cross sections as a function of kinetic energy has been done using nuclear reaction computer code (COMPLET code).

c. The resulting reaction cross sections had been arranged according to the given proton energy interval and compared with the experimental value.

d. Finally the E_P Vs σ (Proton Energy Vs Reaction cross section)graph has been plotted in graphs in comparison with literature values to check the validity of the data.

Chapter Four

4 Result and Discussion

This chapter presents description and analysis of the main results, which are discussions of graph trends, patterns and connections using tables and plots. The behaviour of reaction cross section with proton projectile on different Molybdenum isotopes to produce Technetium are thus explained using the reaction channels of ${}^{95}_{42}Mo$(p,n) ${}^{95}_{43}Tc$, ${}^{96}_{42}Mo$(p,n) ${}^{96}_{43}Tc$, ${}^{97}_{42}Mo$(p,2n)${}^{96}_{43}Tc$, ${}^{98}_{42}Mo$(p,3n)${}^{96}_{43}Tc$ and ${}^{100}_{42}Mo$(p,2n)${}^{99}_{43}Tc$.

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 molybdenum with different reaction channels were compared with experimental data and explained. The energy range selected from the experimental data from EXFOR is same with calculated data of compound nucleus and pre-equilibrium reaction.

The reaction cross-section of calculated and experimental data with the selected energy range (10MeV to 30MeV) are given in tables.(from table 2 up to table 6 below.)
The various parameters are used for calculations of excitation functions in the present study. Some major parameters were discussed below.

Exciton Number

The exciton number is found to play an important role in the calculated predictions for pre-equilibrium reactions. But it hasn't effect on compound nucleus reaction. So in this thesis the exciton number which are used in the selected reaction channels of pre equilibrium reactions are given in the table 1 below.

Table 1: Exciton number of selected pre-equilibrium reaction channels in this study

S.No	Reactions channels	Total exciton number	Configuration
1	${}^{95}_{42}Mo$ (p,n) ${}^{95}_{43}Tc$	3	(1p+1n+1h)
2	${}^{96}_{42}Mo$ (p,n) ${}^{96}_{43}Tc$	3	(1p+1n+1h)
3	${}^{97}_{42}Mo$ (p,2n)${}^{96}_{43}Tc$	5	(1p+2n+2h)
4	${}^{98}_{42}Mo$ (p,3n)${}^{96}_{43}Tc$	7	(1p+3n+3h)
5	${}^{100}_{42}Mo$(p,2n)${}^{99}_{43}Tc$	5	(1p+2n+2h)

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 range of nuclear reaction. The level density parameter obtained by experiment shows a linear dependent with the mass number of the compound nucleus [16]. In general it is given by an expression:

$$a = \frac{ACN}{K} \quad \text{.....(4.1)}$$

where ACN is the mass of the compound nucleus and K is the free constant. In this thesis the level density parameter were employed for respective reactions, which gives the best fit to experimental results. The cause for the variation of the value of K here is that seeking for the best fit to the experimentally measured excitation function. However, effort had been made to use the same K value for analogous reaction channels of the isotopes for reasonable comparison [16].

The nuclear level density $\rho(E)$ is a characteristic property of every nucleus and it is defined as the number of levels per unit energy at a certain excitation energy [16]. Average level density:

$$\rho(E) = \frac{dN}{dE} \quad \text{.....(4.2)}$$

In other words it is the number of different ways in which individual nucleons can be placed in the various single particle orbital such that the excitation energy lies in

the range E to E+dE. It increases rapidly with excitation energy. In the simplest approach, the nucleus can be considered as a system of fermions which can occupy levels equidistant in energy. The density of excited states is given as [16]

$$\rho(E) = \frac{exp(2\sqrt{aE})}{4\sqrt{3E}} \quad \text{.....(4.3)}$$

Where the parameter a is known as the level density parameter. A more realistic extension of this model considers the fact that fermions have the tendency to form pairs, and that it takes an extra amount of energy to separate them. This can be taken into account by introducing a shift E in the excitation energy (E is considered as an adjustable parameter), which leads to the Back - Shifted Fermi Gas model (BSFG) [16]

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:

$$Perc.Error = \frac{Exp.value - meas.value}{Exp.Value} \times 100\% \quad \text{.....(4.4)}$$

As a sample %Error for the frist reaction channel of 1^{st} and 3^{rd} enregy renge is calclated below for CN and PRE reaction stages.

%Error = $\frac{489-490.3}{489} \times 100\% = 0.27\%$ CN and % Error = $\frac{489-476.2}{489} \times 100\% = 2.6\%$ PRE

%Error = $\frac{511-492.4}{511} \times 100\% = 3.6\%$ CN and %Error = $\frac{511-451}{511} \times 100\% = 11.7\%$ PRE.

NB: In the same way for reaction channels the percentage error had been calculated and presented in Table 2 up to Table 6

4.1 Reaction Channel of $^{95}_{42}Mo$ (p,n)$^{95}_{43}Tc$

For this reaction channel the total experimental reaction cross section data obtained from EXFOR Library [17] and calculated / evaluated/ by using the COMPLET computer code for compound nucleus and pre-equilibrium reactions with their corresponding error are given in the table 2 below and plotted on Figure 1 to compare with experimental data in order to check the quality of calculated reaction cross sections of reaction channel.

Table 2: Experimental and calculated reaction cross section of $^{95}_{42}Mo$ (p,n) $^{95}_{43}Tc$ reaction channel

Energy (MeV)	EXP .σ (mb)	CN .σ (mb)	Error (%)	PRE .σ (mb)	Error (%)
10.48	489	490.3	0.27	476.2	2.6
11.79	511	492.4	3.6	451	11.7
13.04	517	448.8	13	321.2	37.8
14.05	358	292.5	9	237.7	33.6
14.73	292	263.3	9.8	247.1	15.4
15.1	257	241.7	5.9	185.1	27.9
16.08	178	179.6	0.9	144.1	19
16.31	107	137.9	28.8	113.9	6.45
17.9	55.3	137.3	148	60.36	9.1
20.6	24.4	77.34	216	30.03	23
23.29	18.6	50.5	171	22.4	20
25.82	17.3	25.5	47	16.4	5.2
28.19	16	14.41	12	16.35	0.2

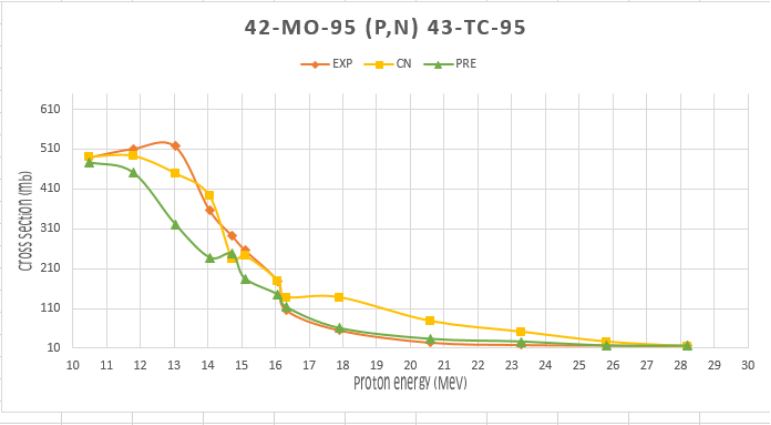

Figure 1: Proton Energy Vs reaction cross section of experimental data and calculated value for reaction channel of $^{95}_{42}Mo$ (p,n) $^{95}_{43}Tc$.

As one can observe from the graph as proton kinetic energy increase the experimental reaction cross section as well as calculated reaction cross section decreased. Comparatively at lower energy range i.e below 16.08 MeV reaction cross section calculated for compound nucleus stage of reaction is dominating with error less than 10% in this channel of reaction and pre-equilibrium reactions stage has relatively large error. But at the higher energy region i.e above 16.08 MeV comparatively reaction cross section calculated for compound nucleus reaction stage is dominated by pre-equilibrium nuclear reaction stage.

Generally in the lower energy region compound nucleus is dominant and at higher energy region pre-equilibrium nuclear reaction stage is dominant. As a whole the prediction by COMPLET code is acceptable when compared to the experimental with less error i.e up to 20%.

4.2 Reaction Channel of $^{96}_{42}Mo$ (p,n)$^{96}_{43}Tc$

The experimental total cross section data was obtained from EXFOR Library [21]. But the compound nucleus reaction cross-section and pre-equilibrium reaction cross-section were calculated / evaluated/ by using the COMPLET computer code. Therefore all experimental and calculated data are given in the Table 3 below with their corresponding error. And also plotted on Figure 2 to compare these data with experimental one in order to check the quality of calculated reaction cross sections.

Table 3: Experimental and calculated reaction cross section of $^{96}_{42}Mo$ (p,n)$^{96}_{43}Tc$ reaction channel

Energy (MeV)	EXP .σ (mb)	CN .σ (mb)	Error (%)	PRE .σ (mb)	Error (%)
10	498	574.6	15	574.7	15.4
15	522	373.3	28	371	28.9
20	235	166.9	28.9	172.1	26.7
25	78	76.8	1.5	84.43	8
30	50	34.31	31	43.13	13

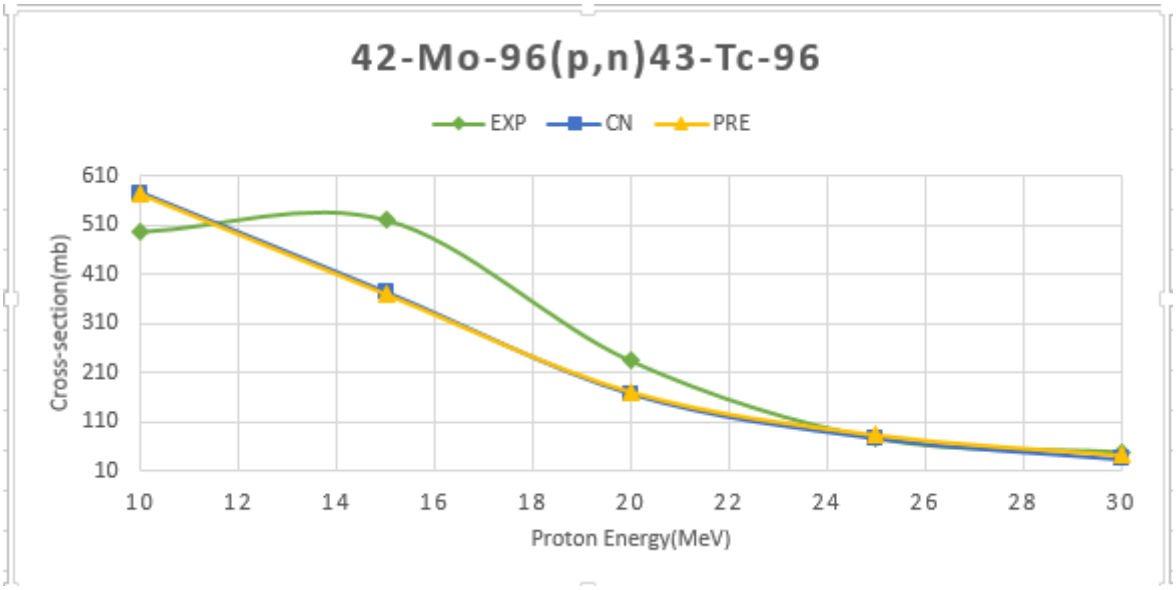

Figure 2: Proton Energy Vs reaction cross section of experimental data and calculated value for reaction channel of $^{96}_{42}Mo$ (p,n)$^{96}_{43}Tc$.

This graph indicated that at the lower energy around 10 MeV both compound nucleus and pre-equilibrium reactions are close to the experimental value i.e there is a probability of occurrence for both reaction stages. But starting from 15 MeV to 20 MeV these

results far from the experimental value. This implies, there is very less probability of occurrence of reaction cross section for both reaction stages. Finally at projectile energy of 25 MeV there is high probability for both stages. But at 30 MeV compound nucleus reaction stage is dominated by pre-equilibrium reaction.

In generally the result obtained in this reaction channel is not as expected as from theoretical calculation. The error occurs might be due to the choice of input parameters but the effort made to re-calculated the data by changing the parameter (LDP) with the available time was appreciable. But I couldn't get data more than this.

4.3 Reaction Channel of $^{97}_{42}Mo$ (p,2n)$^{96}_{43}Tc$

For this reaction channel the total experimental reaction cross section data obtained from EXFOR Library [18]. The calculated data was obtained using a computational computer code COMPLET. Both data with their corresponding error had been presented in the Table 4 and plotted as in Figure 3

Table 4: Experimental and calculated reaction cross section of $^{97}_{42}Mo$ (p,2n)$^{96}_{43}Tc$ reaction channel

Energy (MeV)	EXP .σ (mb)	CN .σ (mb)	Error (%)	PRE .σ (mb)	Error (%)
12.8	758	712.6	5.9	696.3	8
13.8	977	832.2	14.8	812.2	16.8
14.8	1070	913.6	14.6	891.8	16.6
15.8	1140	961.6	15.6	938	17.7
16.7	1150	992.5	13.7	968.4	15.6
17.5	1200	989.9	17.5	960.3	20
18.3	1200	1012	15.6	982.2	18
19.3	1230	976.8	20	953.5	22
20.3	1122	875.9	21.9	868.6	22.5
21.4	978	740.2	24	758.1	22.4
22.2	871	587.2	32.6	631.3	27.5
23.1	692	446.9	35	514.1	25
24	549	328.9	39	414.1	24
24.8	457	227.6	50	324.9	28
25.7	380	157.1	58	258	32
26.6	316	106.8	66	206.6	34
27.6	257	73.1	71	172.2	33
28.5	186	49.37	73	144.8	22
29.5	126	56.67	55	165.4	30

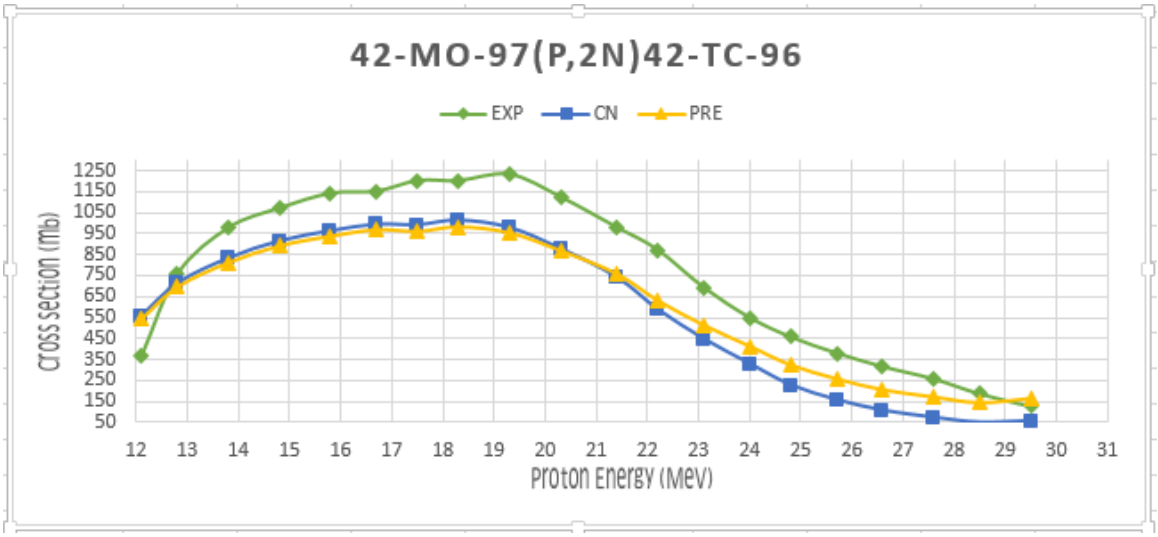

Figure 3: Proton Energy Vs reaction cross section of experimental data and calculated value for reaction channel of ${}^{97}_{42}Mo$ (p,2n)${}^{96}_{43}Tc$.

In this reaction channel at lower energy region i.e from 12.8 MeV to 18.3 MeV calculated reaction cross section for both compound nucleus and pre-equilibrium reaction stages are closer to experimentally obtained data with error less than 20%. But at higher energy region i.e above 19.3 MeV region both reaction stages are far from experimental value with the percentage error of greater than 20%. This indicates at lower energy region both reaction stages are dominating the probability. This means there is a probability of occurrence for both compound nucleus and pre-equilibrium reaction stages. But at higher energy range both compound nucleus and pre-equilibrium reaction stages are dominated by other reaction stage. It is may be direct reaction stage.

Therefore the theoretical (calculated) result obtained using COMPLET code by assignment of exciton number and zero exciton number for this reaction channel gives almost similar result at both the lower and the higher energy region.

4.4 Reaction Channel of $^{98}_{42}Mo$ (p,3n)$^{96}_{43}Tc$

The experimental total cross section data were obtained from EXFOR Library [18] and the compound nucleus and pre-equilibrium reactions were calculated / evaluated/ by using the COMPLET computer code. Therefore all experimental and calculated data with their corresponding error are given in the Table 5 below. And also plotted on Figure 4 to compare these data with experimental one in order to check the quality of calculated reaction cross sections.

Table 5: Experimental and calculated reaction cross section of $^{98}_{42}Mo$ (p,3n)$^{96}_{43}Tc$ reaction channel

Energy (MeV)	EXP .σ (mb)	CN .σ (mb)	Error (%)	PRE .σ (mb)	Error (%)
20.3	43	106	146	106.5	146
21.4	132	301.1	128	355.8	168
22.2	245	321	31	338.8	37.9
23.1	389	467.5	20	464.3	19.2
24	589	582.5	1.2	578.4	1.8
24.8	631	681.8	7.9	676.8	7.1
25.7	732	757.2	3.4	751.7	2.6
26.6	724	814.9	12.5	808.7	11.6
27.6	813	849	4.4	842.4	3.5
28.5	891	867.1	2.7	880.6	1.2
29.5	955	860	9.9	893.8	6.4

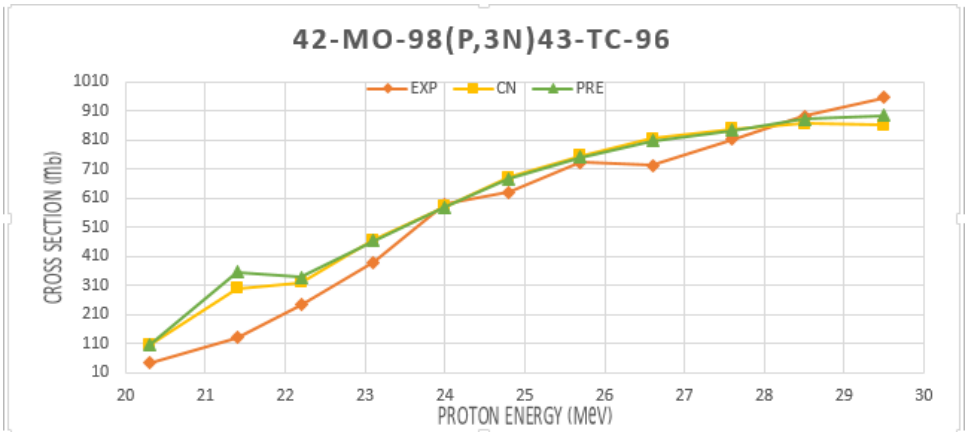

Figure 4: Proton Energy Vs reaction cross section of experimental data and calculated value for reaction channel of $^{98}_{42}Mo$ (p,3n)$^{96}_{43}Tc$.

In this reaction excitation functions calculation for compound nucleus and pre-equilibrium reaction have large error from experimental data at lower energy region i.e from 20.3

MeV to 23.1 MeV. This show in this range there is less probability of both reaction stage to occur and may be other reaction stage occurs in this energy region. But at region above 24 MeV (at higher energy region) both compound nucleus and pre-equilibrium reaction cross sections are more approach to experimental data with percentage error less than 10%. This indicate there is high probability of occurrence of both compound nucleus and pre-equilibrium reaction stages.

In general both reaction stages are dominating at higher energy region and dominated at lower energy region. During the calculation many trial inputs has been tried, but I unable to get data better than displayed.

4.5 Reaction Channel of $^{100}_{42}Mo$(p,2n)$^{99}_{43}Tc$

For this reaction channel the total experimental reaction cross section data obtained from EXFOR Library [17] and calculated / evaluated/ by using the COMPLET computer code for compound nucleus and pre-equilibrium reactions with their corresponding error are given in the table 6 below and plotted on the Figure 5 to compare with experimental data in order to check the quality of calculated reaction cross sections of reaction channel .

Table 6: Experimental and calculated reaction cross section of $^{100}_{42}Mo$(p,2n) $^{99}_{43}Tc$ reaction channel

Energy (MeV)	EXP .σ (mb)	CN .σ (mb)	Error (%)	PRE .σ (mb)	Error (%)
10	317	318.9	0.59	192.9	39
11.3	536	490.4	8.5	316	41
12.5	680	740.3	8.8	535.7	21
13.5	630	850.6	35	639.3	1.4
14.6	689	936.2	35	723.7	4.9
15.6	749	993.4	32	784.7	4.6
16.6	807	1030	27.6	827.9	2.4
17.5	812	1020	25	815.1	0.4

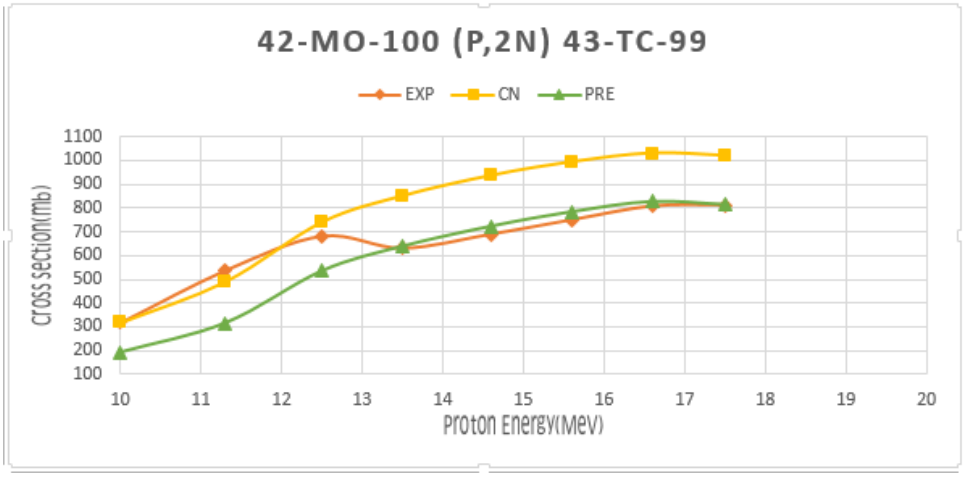

Figure 5: Proton Energy Vs reaction cross section of experimental data and calculated value for reaction channel of $^{100}_{42}Mo$(p,2n)$^{99}_{43}Tc$.

From the graph one can see at lower energy region i.e from 10 MeV up to 12.5 MeV compound nucleus reaction stage cross section is nearer to the experimental value with

percentage error less than 10%. This implies that compound nucleus stage is dominating. But from 13.5 MeV to the last energy range i.e 17.5 MeV the cross section of pre-equilibrium reaction stage is nearer to experimental data with less than 10% error. i.e Dominance of pre-equilibrium stage reaction cross section had been observed. Generally as energy increase the reaction cross section of pre-equilibrium reaction stage is more approach to the experimental data than compound nucleus. This implies that the probability of pre-equilibrium reaction is more than compound nucleus reaction in higher energy range.

Therefore in this reaction channel the pre-equilibrium reaction stage is dominant at higher energy region and compound nucleus reaction stage is dominant at lower energy region. This indicate that the excitation function curves predicted exactly what is expected from theoretical calculation.

Chapter Five

5 Summary and Conclusion

As mentioned earlier, the objective of this study is to investigate the behavior of reaction cross section with proton projectile on the different isotopes of Molybdenum to produce Technetium. So the experimental and calculated best fit of excitation function of ${}^{95}_{42}Mo$(p,n)${}^{95}_{43}Tc$, ${}^{96}_{42}Mo$(p,n)${}^{96}_{43}Tc$, ${}^{97}_{42}Mo$(p,2n)${}^{96}_{43}Tc$, ${}^{98}_{42}Mo$(p,3n)${}^{96}_{43}Tc$, and ${}^{100}_{42}Mo$(p,2n)${}^{99}_{43}Tc$ had been done and concluded as follow.

1. In the study Molybdenum-100 (${}^{100}_{42}Mo$) is preferable to produce sufficient Technetium.
2. Reaction channel ${}^{100}_{42}Mo$(p,2n)${}^{99}_{43}Tc$ is best to produce sufficient Technetium.
3. The probability of production of technetium is depending on the value of projectile proton energy in both nuclear reaction stages.
4. At lower energy region the compound nucleus reaction stage is the dominant. But at the higher energy region dominance of the pre-equilibrium reaction stage had been observed.
5. The calculated results of compound nucleus and pre-equilibrium reaction stage reaction cross sections are comparatively closer to the experimental value which was obtained from EXFOR Library with variation less than 10%

Generally in this study the reaction cross section of compound nucleus and pre-equilibrium reaction stages that had been computed by using COMPLET code were good results when compared to the experimental value since the error is less than 10% in most reactions.

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