Calculation of Neutron and Proton Induced Reaction Cross Sections on Scandium Isotope(^{45}Sc)

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DECLARATION

I hereby declare that this MSc thesis is my original work and has not been presented for a degree in any other university and that all sources of material used for the thesis have been duly acknowledged.

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Contents

List of Figures

List of Tables

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Abstract

The objective of the work was to find the cross section values for the reactions ${}^{45}_{21}Sc(n,2n)^{44}_{21}Sc$, ${}^{45}_{21}Sc(n,p)^{45}_{21}Ca$, ${}^{45}_{21}Sc(p,n)^{45}_{22}Ti$ and ${}^{45}_{21}Sc(p,2n)^{44}_{22}Ti$ using a computational nuclear reaction code called COMPLET. The results were compared with the experimental data obtained from different literature s published in EXFOR data base. The calculated were done using COMPLET computer code, which is based on Geometry Dependent Hybrid(GDH) model. Various parameters were changed to see the effect on the excitation functions. The comparison gives the best fit parameters viz pld, exciton number etc. The results in this work agree will with experimental in most of the reactions.

1

Introduction

1.1 Background of the Study

The Lord-Rutherford in 1919, carried out the first nuclear reaction in laboratory he bombarding α-particles on a nitrogen nucleus and showed that protons are produced in the nuclear reaction[1]. The Rutherford cross-section is a measure of probability that an alpha-particle will be deflected by a given angle during a collision with an atomic nucleus. When two discrete particle interact in classical physics, their mutual cross-section is the area transverse to their relative motion with in which they must meet in order to scatter from each other. If the particle interact through some action-at a distance force, such as electromagnetism or gravity, their scattering cross-section is generally larger than their geometric size[2].

The first systematic studies of nuclear reaction mechanisms, were carried out in 1932 to 1933 by fermi. In 1933 fermi's activity entered a new stage, when after Joliot-Gurie's discovery of the production of artificial radioactivity by particle bombardment he took up neutron research as an experimenter or theoretician as the situation required. Fermi learnt to construct Geiger counters and was able to use the radon from the 1gram of radium belonging to the Bureau of public health to build a radome-beryllium neutron source. With this he began a systematic search through the elements for artificial radioactivity, starting with hydrogen[3,4].

The term "nuclear reaction" is quite generic, It refer to interaction of nuclei with nuclei, nucleon with nuclei, nucleons with one another and even the interactions of protons. Nuclear reactions are the fundamental means by which we probe the nature of nuclear force, the structure of complex nuclei and the means by which we produce radioactive

nuclei for study application[4,5].

In basic nuclear physics, cross section for the productions of nuclide in nuclear reactions induced by medium energy protons and neutrons are increasing importance for a wide variety of applications. These applications range from astro- physics and cosmophysics over space and environmental sciences, medicine (radionuclide production, dosimetry in mixed nucleon fields, radiation protection, therapy), accelerator technology activation of detectors, radiation protection on-line mass separation, space and aviation technology to accelerator-based nuclear waste transmutation and energy amplification[3,5].

The nature of experimental observation are the following, abeam of particle such as protons, deuterons, alpha particles, or heavy ion(heavier nuclei), are accelerated to a desired energy and then deflected so as to strike a target known isotopic composition[3]. The energy and scattering angle of some of the products of collision are measured. A reaction initiated by protons, so proton itself will sometimes deflected angle and having some energy in the center of mass system. This elastic measurement of cross-section because its analysis of the parameters of the optical potential. Sometimes the proton will excite the target nucleus from its ground to some higher-energy state, thus losing some energy & sometime being deflected angle. This is an inelastic scattering. The cross section for such an event yields information on the spin and party of the nuclear transition[4,6].

The nuclear cross-section is one of the fundamental observable of cross sectional area. It is used to characterized the probability that a nuclear reaction will occur. It can be quantized physically in terms of characteristic area where a large area means a large probability interaction. Nuclear reactions can be measured for all possible interaction processes together, in which case they are called total cross-sections, or for specific processes, a distinguishing elastic and inelastic scattering and the sum of the cross sections for all events other than the elastic scattering.

1.2 Statement of the Problem

The theoretical excitation function of function of ^{45}Sc(n,p)^{45}Ca reaction have been calculated by Tarik Siddik in Salahaddin University using the computer code TALYS 1.0. The experimental points points between 6-15MeV. The equilibrium spectra calculations of emitted proton particles are approximately maxewellian. In this article the pre-equilibrium calculations shows the best agreement with the experimental data 13-15MeV[7]. The results of nuclear model calculations for the ^{45}Sc(p,n)^{45}Ti and ^{45}Sc(p,2n)^{44}Ti processes together with the available experimental data within the studied proton energy range. The formation cross section the ^{45}Sc(p,n)^{45}Ti shows a wide peaks in the energy range 6-18MeV[8]. The nuclear reaction ^{45}Sc(p,2n)^{44}Ti presented has much lower cross section values around 23MeV. This reaction have been calculated by using TALYS and EMPIRE data are higher than the experimental values of the reaction ^{45}Sc(p,n)^{44}Ti at lower energy region 12-25MeV[9,10]. presently studies have been made to compare the excitation functions on scandium isotope of compound nucleus reactions cross section values of ^{45}Sc(n,2n)^{44}Sc in the neutron incident energy range between 15-24MeV, ^{45}Sc(n,p)^{45}Ca in the neutron energy range between 6-12MeV, ^{45}Sc(p,n)^{45}Ti in the proton energy range between 7-16MeV and ^{45}Sc(p,2n)^{44}Ti in the proton energy range between 25-55MeV by using the computer code COMPLET. In doing so, the following questions were answered.

- What are the reactions cross section values of the reaction (n,2n),(n,p),(p,n) and (p,2n) on scandium ^{45}Sc isotope ?
- What are the behavior of the reactions cross section values of the reaction (p,n) and (p,2n) on scandium ^{45}Sc isotope ?
- How the theoretical calculated values were compared with the experimental reactions cross section from EXFOR values of reaction (n,2n),(n,p), (p,n) and (p,2n)?

1.3 Objectives of the Study

1.3.1 General Objective

The main objective of this study is to calculate the neutron and proton induced reactions cross section on Scandium ^{45}Sc isotope for the formation of compound nucleus.

1.3.2 Specific Objectives

The specific objectives of this study are:

- To calculate compound nucleus reactions cross section values of reaction (n,2n),(n,p),(p,n) and (p,2n) on scandium ^{45}Sc isotope.
- To study the behavior of the reactions cross section value of the reaction (p,n)and (p,2n) on scandium ^{45}Sc isotope.
- To compare and contrast the experimental reactions cross section values of the reaction(n,2n), (n,p), (p,n) and (p,2n) with theoretically calculated values.

1.4 Significance of the Study

The significance of the research work is mainly to full fill the theoretical data gap on the compound nucleus reaction cross section for some neutron and proton induced reactions on the scandium isotope.

1.5 Limitation of the Study

The following are some of limitations faced during the work

- Lack of internet access around work area(fofa).
- Lack of time.

2

Review of Literature

2.1 Nuclear Reaction

A nuclear reaction is a process in which two nuclei, or a nucleus and an external subatomic particle, collide to produce one or more new nuclides. The bombarding particle may be α, β, or γ-rays obtained from natural radio active substance or may be accelerated protons and neutrons. Lord-Rutherford in 1919, carried out the first nuclear reaction in laboratory, he bombarding α-particles on a nitrogen nucleus & showed that protons are produced in the nuclear reaction[12,13]. The equation in Rutherford's transmutation reaction was given by:

$$^{14}_{7}N +^{4}_{2} He(\alpha) \longrightarrow^{17}_{8} O +^{1}_{1} H \tag{2.1}$$

The Reaction theory provides the necessary frame work to extract meaningful structure information from measured cross-sections and also permits the understanding of the dynamics of nuclear collisions. The interaction of nuclear particle such as (n, p, d, α, T, $^{4}_{2}He$) on a target material (nuclei) is called nuclear reaction. When the mass number or atomic number of the target nuclei change after the bombardment of projectile particle, is say that a nuclear reaction[13,14].

In general a nuclear reaction can be represent as

$$a + X \longrightarrow Y + b \tag{2.2}$$

Where, a=projectile particle, X= Target nucleus, Y=product nucleus, b =out going particle

2.2 Nuclear Cross-Section

The nuclear cross section of a nucleus is used to describe the probability that a nuclear reaction will occur. It is necessary to have a quantitative measure of the probability of a given nuclear reaction. The term "Cross Section" has already been met in connection with the attenuation of a γ-ray beam, when it was used as a measure of the probability that a photon is removed from the beam[13,15].

Cross section can be defined as the probability that an event may occur when a single nucleus is exposed to abeam of particle is shot perpendicularly at a target having one nucleus per unit area. Suppose that N number of each event is produced by incident particle of flux I. The probability of nuclear interaction, P is

$$P = \frac{N}{I} \tag{2.3}$$

This can also be expressed by the effective area as seen by the projectile to the total area of the target

$$p = \frac{\sigma n A dx}{A} \tag{2.4}$$

Equating expressions for P yields

$$\sigma = \frac{N}{I n dx} \tag{2.5}$$

where n=$\rho \frac{Na}{A}$ is the nuclear density, Na, Avogadro's number of nuclei. A- atomic weight and ρ is the density of the target.

If I_0 is the incident flux of say proton beam as it penetrate a distance x is in the target, the flux decreases by dI in passing through the element of distance dx given by

$$dI = -I_0 \sigma n dx \tag{2.6}$$

Which follows

$$I = I_0 exp(-\sigma n dx) \tag{2.7}$$

Thus the cross section can be measured experimentally by the attention of the incident beam. The concept of nuclear cross section can be most easily visualized as the cross

sectional area, seen by projectile to under go nuclear reactions. If the nuclei are considered as a sphere of radius R, in cm and the incident particle as point projectiles, then the target area, or cross section σ, of each nucleus is given by

$$\sigma = \pi R^2 cm^2 \tag{2.8}$$

In the discussion of the theory of α-decay, it was found that the radii of α-emitting nuclei may be represented by the formula.

$$R = r_0 A^{\frac{1}{3}} \tag{2.9}$$

If it is assumed that nuclear radii are 1-2 x $10^{-13}cm$ and nuclear have a spherical shape, this formula may be applied to all nuclei

$$\sigma = \pi R^2 = \pi(1.5)^2 A^{\frac{2}{3}} \times 10^{-26} cm^2 \tag{2.10}$$

Cross section for nuclear reactions are often expressed in terms of the unit $10^{-24}cm^2(10^{-28}m^2)$ this unit is called barn[15,16].

$$1b = 10^{-24}cm^2 = 10^{-28}m^2 \tag{2.11}$$

2.2.1 Partial Wave Analysis of Cross-Section

In the nuclear reaction there is collision between the incident particle (nuclei) and target nuclei. If we take u(r) as the potential energy of the projectile 'a' at a distance 'r' from the target 'X' such that when r$\rightarrow\infty$(very far) then u(r) =0 the Schrodinger equation, for a projectile 'a' [16,17].

$$\frac{-\hbar^2}{2m}\nabla^2\psi + u(r)\psi = T\psi \tag{2.12}$$

Where T is the kinetic energy of projectile. Now use K^2=$\frac{2mT}{\hbar^2}$=$\frac{p^2}{\hbar^2}$ and v(r)=$\frac{2m}{\hbar^2}$ u(r) from eqn 2.12

$$\nabla^2\psi + K^2\psi = \text{v(r)}\psi \tag{2.13}$$

This equation has many solution of v(r), in nuclear reaction, if ψ represents the total wave function. i.e

$$\psi = \psi_i + \psi_s \tag{2.14}$$

where ψ_i and ψ_s are incident and scattered wave functions. The incident wave function represents a beam of particle momentum $\hbar$k travailing in the Z- direction is given by

$$\psi_i = C_1 e^{ikz} \tag{2.15}$$

where $C_1$is the normalization constant. If there is a one particle per unit volume we have

$$\psi_i \psi_i^\star = |\psi_i|^2 = 1 \tag{2.16}$$

The function e^{ikz} can be expanded in a series of the wave functions to all angular momenta can written as

$$\psi_i = e^{ikz} = e^{ikrcos\theta} = \sum_{l=0}^{\infty}(2l+1)i^l.j_l(kr)p_l(cos\theta) = \frac{1}{kr}\sum_{0}^{\infty}(2l+1)i^l p_l(cos\theta).sin(kr - \frac{l\pi}{2})$$

Then

$$\psi_i = \frac{1}{kr}\sum_{0}^{\infty}(2l+1)i^l p_l(cos\theta).\frac{e^i(kr-\frac{l\pi}{2}) - e^{-i(kr-\frac{l\pi}{2})}}{2i} \tag{2.17}$$

from equation (2.17) is seen that the incident plane wave may be considered as a coherent superposition of the following wave: There is spherical wave converging on the center which represented as $e^{-i(kr-\frac{l\pi}{2})}$. The diverging out wave as represented by $e^{i(kr-\frac{l\pi}{2})}$ The nuclear interaction potential either may effect the out going wave in phase with out amplitude (intensity) change which is called "elastic scattering" or it may affect the amplitude and phase is called "inelastic scattering". Thus we have total cross section giving the "number of all events per unit time per nucleus" as a given as

$$\sigma_t = \sigma_{sc} + \sigma_r \tag{2.18}$$

where σ_{sc} denote the elastic scattering cross-section & σ_r denote the sum of the cross sections for all events other than the elastic scattering[12,13].

2.3 Energetic of Nuclear Reactions

2.3.1 Q- value of Nuclear Reaction

The nuclear reaction energy(Q) of a given nuclear reaction defined by the equation of :-

X(a,b)Y

projectile + Target $\rightarrow$ product nucleus + out going particle[12].

Rest mass are m_a, M_X, M_Y and m_b while their kinetic energies are $T_a, T_X = 0, T_Y$ and T_b respectively. After the reaction of ejected light particle 'b' goes out at angle 'θ' and the product—residual nucleus 'Y' recoils at an angle 'ϕ' with respect to the incident direction as shown in the figure below.

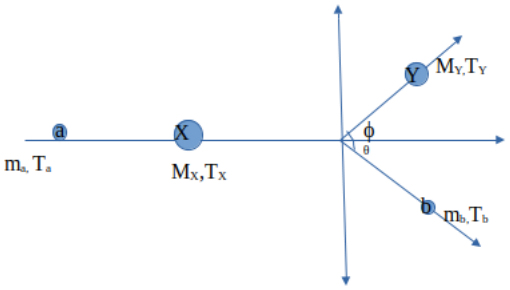

Figure 2.1: Representation of nuclear reaction

The relation of the mass and energy conservation law written as:

$$T_a + m_a C^2 + M_X C^2 = T_Y + M_Y C^2 + T_b + m_b C^2 \tag{2.19}$$

where T_a is the kinetic energy of the projectile, $m_a C^2$ is the rest mass energy of the projectile, T_X is the kinetic energy of the target, $M_X C^2$ is the rest mass energy of the target, T_Y is the kinetic energy of the resultant, $M_Y C^2$ is the rest mass energy of the resultant, T_b is the kinetic energy of the out going particle, $m_b C^2$ is the rest mass energy of the out going particle. The target nucleus X is at rest $(V_x = 0, T_x = 0)$. Then the Q- value is the kinetic energy released in the nuclear reaction which is equal to the rest-mass energy difference between the reactants and the resultants.Thus we have the 'Q' value written as:

$$Q = T_Y + T_b - T_a = [(m_a + M_X) - (M_Y + m_b)]C^2 \tag{2.20}$$

The equation (2.20) re-write as:

$$Q = E_{01} - E_{02} = T_2 - T_1 \tag{2.21}$$

Where E_{01}=$(m_a+M_X)C^2$; Rest mass energy of the reactants(projectile and target), $E_{02} = (m_b + M_Y)C^2$; Rest mass energy of the resultants(residual & outgoing particle); $T_1 = T_a+T_X = T_a$; (K.E of projectile and target) and $T_2 = T_b+T_Y$; (K.E of the product nucleus and outgoing particles). The reaction energy Q is zero elastic scattering, Q is positive for exoergic reaction , Q is negative for endoergic reaction.

2.3.2 The Theshold energy

The minimum energy for a nuclear reaction to occur is called threshold energy. the threshold energy obtained by the relation

$$T_{thre} = |Q| \times \frac{(m_a + M_X)}{M_X} \tag{2.22}$$

The energy of the out going particle is given by:-

$$T_b = T_{thres} \times m_b \times \frac{m_a}{(m_a + M_X)^2} \tag{2.23}$$

General equation for 'Q' value: from the above figure, we resolve the conservation of energy and linear momentum in the direction of the incident beam and perpendicular to the direction of the beam to apply:

$$\text{parallel} \rightarrow \sqrt{2m_aT_a} = \sqrt{2M_YT_Y}.cos\phi + \sqrt{2m_bT_b}.cos\theta \tag{2.24}$$

$$\text{perpendicular} \rightarrow 0 = \sqrt{2M_YT_Y}.sin\phi - \sqrt{2m_bT_b}.sin\theta \tag{2.25}$$

In a nuclear reaction experiment the kinetic energy of the projectile 'T'_a is known while the kinetic energy of the outgoing particle 'T'_b is measured at an angle 'θ' to the direction of incident particle. But the kinetic energy of product nucleus 'T_Y' and its recoil energy 'ϕ' are not measured[14]. The equation (2.24) and (2.25) may be written as:

$$\sqrt{2M_YT_Y}.cos\phi = \sqrt{2m_aT_a} - \sqrt{2m_bT_b}.cos\theta \tag{2.26}$$

$$\sqrt{2M_YT_Y}.sin\phi = \sqrt{2m_bT_b}.sin\theta \tag{2.27}$$

Squaring equation (2.26) and (2.27)

$$2M_YT_Ycos^2\phi = 2m_aT_a + 2m_bT_b.cos^2\theta - 2\sqrt{4m_aT_am_bT_b}.cos\theta \tag{2.28}$$

$$2M_YT_Y.sin^2\phi = 2m_bT_b.sin^2\theta \tag{2.29}$$

Adding the above equation (2.28) and (2.29) we get

$$2M_YT_Y = 2m_aT_a + 2m_bT_b - 2\sqrt{4m_aT_am_bT_b}.cos\theta \tag{2.30}$$

Substitute T_Y from equation (2.20) in to equation (2.30)

$$2M_Y(Q + T_a - T_b) = 2m_aT_a + 2m_bT_b - 2\sqrt{4m_aT_am_bT_b}.cos\theta$$

Finally

$$Q = T_b(1 + \frac{m_b}{M_Y}) - T_a(1 - \frac{m_a}{M_Y}) - \frac{2\sqrt{m_am_b.T_aT_b}}{M_Y}.cos\theta \tag{2.31}$$

In this equation the masses m_a, m_b and M_Y are taken from the nuclear tables while the Q quantities T_a, T_b and θ are measured. Hence the value Q is determined from equation(2.31). The masses can be replaced by the mass numbers to sufficient degree of accuracy. The Q-equation is simplified for θ=90^0 when the cosine term vanishes. The equation (2.31) may be re-written as a quadratic equation in $\sqrt{T_b}$ is

$$(1 + \frac{m_b}{M_Y})(\sqrt{T_b})^2 - \frac{2\sqrt{m_am_bT_a}}{M_Y}.cos\theta.\sqrt{T_b} - [(1 - \frac{m_a}{M_Y})T_a - Q] = 0 \tag{2.32}$$

The solution of this equation gives the values of kinetic energy of the outgoing particle as:-

$$\sqrt{T_b} = \frac{\frac{2\sqrt{m_am_bT_a}.cos\theta}{M_Y} \pm \sqrt{\frac{4m_am_bT_acos^2\theta}{M_Y^2} - 4(1 + \frac{m_b}{M_Y})(1 - \frac{m_a}{M_Y})T_a - Q}}{2(1 + \frac{m_b}{M_Y})} \tag{2.33}$$

When $\sqrt{T_b}$ is real and positive then only the nuclear reaction are energetically possible. for exoergic reactions $Q > 0$ and $M_y > m_a$ i.e, the residual—product nucleus is much heavier than the projectile than $\sqrt{T_b}$ has a single value of the projectile energy and its value is given by:-

$$\sqrt{T_b} = \frac{\sqrt{m_am_bT_a}cos\theta}{m_b + M_Y} \pm \sqrt{\frac{m_am_bT_a.cos^2\theta}{(m_b + M_Y)^2} + \frac{M_Y.Q + T_a(M_Y - m_a)}{(m_b + M_Y)}} \tag{2.34}$$

It has smallest value for θ=π i.e, in back ward direction. for endoergic reaction $\theta < 0$ then there is the smallest value of T_a (K.E of incident particle) for which the reaction can take place. This energy is called "Threshold energy". i.e,$(T_a)_{thre}$ is the smallest value of T_a when reaction is possible, the value of T_a' as:

$$T_a' = |Q|[\frac{m_b + M_Y}{(m_b + M_Y) - m_a - (\frac{m_a m_b}{M_Y})sin^2\theta}] \tag{2.35}$$

The value T_a' is minimum for θ=0. Thus the threshold value for a nuclear reaction is given by

$$(T_a)_{thres} = |Q|[\frac{m_b + M_Y}{m_b + M_Y - m_a}] \tag{2.36}$$

2.4 Reaction Mechanism

2.4.1 Direct Nuclear Reaction

Direct nuclear reaction that occur in a time comparable to time of transit of an incident particle a cross the nucleus are ($\sim 10^{-22}s$). The very short interaction time allows for an interaction of a single nucleon. In order to understanding the nature of nuclear reactions, the classification according to the time scale of these reaction has to be introduced. Interaction time is critical for defining the reaction mechanism. There are two extreme scenarios for nuclear reactions (not only neutron nuclear reaction)[15].
A projectile and a target nucleus are within the range of nuclear forces for the very short time allowing for an interaction of a single nucleon only. These type of reactions are called Direct nuclear reaction. A projectile and a target nucleus are within the range of nuclear forces for the time allowing for a large number of interactions between nucleons. These type of reactions are called Compound nucleus reactions. Direct reaction have another property which is very important. Products of a direct reaction are not distributed isotopically in angle, but they are forward focused. The cross-sections for direct reactions vary smoothly and slowly with energy in contrast to the compound nucleus reactions and these cross-sections are comparable to the geometrical cross-sections of target nuclei [18].
Types of direct reactions: elastic, inelastic, transfers, break up and knock out reaction.

Elastic Scattering is the projectile remains intact, change angle but not energy. In which a passing particle and a target stay in their ground state. In this nuclear reaction, the projectile strikes the target nucleus and leaves with out any loss of energy but in general with changed direction of motion. ${}^{4}_{2}He + {}^{197}_{79}\ Au \longrightarrow {}^{197}_{79}\ Au + {}^{4}_{2}\ He$. Inelastic Scattering is the projectile remains intact, changes angle and energy. In this type nuclear reaction, kinetic energy of a projectile particle does not remain conserved. i.e, a part of kinetic energy of projectile particle is taken by the target nucleus which as a result is excuted to higher energy state. Then the excuted nucleus comes to ground state by radiating excess energy in form of γ-rays. In which a passing particle changes its energy state [17]. i.e, $(p, p^{'})$ reaction. ${}^{7}_{3}Li + {}^{1}_{1}\ H \longrightarrow {}^{7}_{3}\ Li^{*} + {}^{1}_{1}\ H$. Transfer Reactions is the nucleons are either donated to the target from the projectile, or donated to the projectile from the target. These reactions are further classified to as, Stripping Reaction is in which one or more nucleons are transferred to a target nucleus from passing particle. The incident projectile on colliding with target nucleus, immediately loses one of its nucleons to the target nucleus. i.e, the neutron stripping in the (d,p) reaction. ${}^{63}_{29}Cu + {}^{2}_{1}\ H \longrightarrow {}^{64}_{29}\ Cu + {}^{1}_{1}\ H$. Pick-up Reaction in which one or more nucleons are transferred from a target nucleus to a passing particle. The incident projectile on colliding with the target nucleus pull one of the nucleon out of it. i.e, the neutron pick-up in the (p,d) reaction. ${}^{1}_{1}H + {}^{40}_{19}\ K \longrightarrow {}^{39}_{19}\ K + {}^{2}_{1}\ H$. Break-up Reaction in which a break-up of a projectile in to two or more fragments occurs. Knock-out Reaction in which a single nucleon or a light cluster is removed from the projectile by a collision with the target[18,19].

2.4.2 Pre-equilibrium

In a series of two body collision of a projectile with the target nucleons, the configuration of a compound system becomes even more complex ultimately the system reaches equilibrium. The projectile may share its energy a mong a small number of nucleons which may further interaction with other nucleons and during this cascade of nucleon-nucleon interaction through which the projectile energy is progressively shared a mong the target nucleons a particle may be emitted long before the attainment of statistical

equilibrium, these processes are called Pre-equilibrium reaction. A very long interaction time of the order of $10^{-16}s$ permits the formation of very complex state from the initial simple state, these state are called "Compound nuclear state" & these reactions are called compound nucleus reactions [19].

When the interaction time is very short $\approx 10^{-22}s$, the time required for the incident projectile to traverse the nucleus, the states developed during this time do not differ markedly from the initial nuclear states. These reaction are called Direct reaction.

Between these two limiting situations when the interaction time is $\approx 10^{-20}s$. i.e intermediate time than these reactions are called "Pre-equilibrium" reactions. The pre-equilibrium reactions occurs when nucleons are emitted before the formation of compound nucleus [20].

a. Characteristics of Pre-equilibrium Reaction

- The interaction time of pre-equilibrium reaction is between the direct interaction and compound nucleus reaction. it is the bridge between these two processes.
- There is an emission of the charged particles before the establishment of the thermodynamic equilibrium.
- There is an emission of larger number of the high energy particle than the compound nucleus evaporation.
- The energy spectrum has slowly descending tiers in the excitation functions.

In the case of proton projectile, protons are repelled by electrostatic field of the nucleus and are scattered elastically with a cross section, given by Ruther-ford formula in a direct reaction at low energy. Compound elastic scattering on light nuclei occurs if the proton energy is sufficient to surmount the coulomb barrier and interaction with the nucleus. Nuclear cross-section can be explained by a very simple model called optical model. In the case of this model the interaction between the projectile and the nucleus by one body-complex potential that depends mainly on the nuclear dimension and nuclear shape [20,21].

After the first interaction the nucleon may leave the nucleus immediately by direct re-

action or it may interact with a nucleon in the nucleus and start the cascade of nucleon-nucleon interaction from which pre-equilibrium emission may occur. During this cascade the energy shared among an increasing number of nucleons until eventually compound nucleus is formed. The compound nucleus may decays in to elastic or any of the reaction channels that are allowed energetically. The shape elastic and compound elastic processes combine to give the measured elastic scattering cross-section. Similarly the direct reaction, pre equilibrium and compound nucleus processes combine to give the inelastic and all non-other reaction[19,20,21].

b. Pre-equilibrium Reaction Model, Exciton Model

One of the most important quantities or parameter in pre-equilibrium model is the initial exciton number. The cascade-exciton model (CEM) combine essential feature of the intranuclear cascade (INC) model with the exciton model. The CEM assumes that the reaction occur in three stages (INC), pre-equilibrium and equilibrium or compound nucleus . In the intranuclear cascade step, incident particle interacts with the target nucleus through successive nucleon-nucleon hard collisions leading to the emission of high energy nucleons. After the intranuclear cascade stage of the reaction the nucleus is left in an excited state. This is the starting point for the second or pre-equilibrium stage of the reaction. In the evaporation phase of the reaction, the remaining nucleus de-excites either by evaporation or by fission. The cascade stage of interaction is described by the Dubna version of the intranuclear cascade model and the subsequent interaction state are considered in terms of the exciton model of the pre-equilibrium decay which includes the description of the equilibrium evaporative third stage of the reaction. Generally, these three components may contribute to any experimentally measured quantity. In particle, for the inclusive particle spectrum[21,22,23].
we have

$$\sigma_{(p)}dp = \sigma_{in}[N^{cas}(p) + N^{prq}(p) + N^{eq}(p)]dp \tag{2.37}$$

where p is linear momentum, N^{cas}, N^{prq}, N^{eq} are respectively.
The cascade, the pre-equilibrium and the equilibrium components. The inelastic cross-section σ_{in} is not taken from the experimental data or independent optical model calcu-

lations, but it is calculated within the calculated in characteristics and does not require any additional data or special normalization of its results[21].

The exciton model of Griffin provided the first explanation of the spectral shape of the nucleons emitted with continuous spectra for energy in excess of those characteristics of equilibrium evaporation. Several years after the exciton model was proposed basic premise was extended to permit a prior prediction of the magnitude as well as the spectral shapes of these compound or pre-equilibrium particles. In this model the the composite state are characterized by the number of excited particles and holes called exciton at any stage of N-N cascade. In the case of nucleon induced reaction, it is two particles and one configuration due to the interaction of the incident nucleon and the nucleon of the target which is excited from the state below to a state above the Fermi energy[22].

$$\text{Exciton} = n = p + h$$

Selection rule on the course of cascade of interaction:- $\Delta p = 0, \pm 1$, $\Delta h = 0, \pm 1$ and $\Delta n = 0, \pm 2$

The two possible sequences of events in the exciton model are:- first the incident particle as well as the excited particle are all bound, second the incident particle and one struck nucleon which attained a high energy are in the continuum[23].

The exciton model assumes that: At each state of the cascade all the state with the same configurations and the same total energy are equiprobable. At each state of the cascade all the processes which may occur are equiprobable.

The first assumption gives immediately the energy distribution of excited states. The number dNp(p,h,E,ε) of exciton with energy between ε and ε+$d\varepsilon$ in a configuration of any p, particles and h holes with total energy E is given by the state between the number of state in which one particle has energy between ε and ε+$d\varepsilon$ and the remaining p-1 particles and h holes have energy E[21,22]. If the density of state is given by:-‘

$$\rho_{p,h}(E) = \frac{\rho(g^E)^{p+h-1}}{p!h!(p+h-1)!} \tag{2.38}$$

Then $\rho_{p-1,h}$(E-ε) is the density of state of a single particle states in which one usually assume the fermi model expression $g = \frac{3A}{2E_F}$, $dNp(p,h,E,\varepsilon)$ is given by

$$dNp(p,h,E,\varepsilon) = \frac{\rho_{p-1,h}(E-\varepsilon)gd\varepsilon}{\rho_{p,h}(E)} \tag{2.39}$$

The second assumption simplifies the evaluation of the cross section. The probability per unit time for the emission in to the continuum of an unbound particle V with energy ε called escape width and spread with for nucleon-nucleon interaction which spreads the excitation energy among an increasing number of exciton are decay rates for the corresponding processes are related by equation[23].

$$\Gamma = W\hbar \tag{2.40}$$

When the particle is emitted a residual nucleus with p-1 excited particles and h holes is created. If $\rho_{\ p,h}$(E) and $\rho_{\ p-1,h}$(v) are the composite and the residual nucleus states the escape width from detailed balance principle for emission of particle V with energy ε and ε+$d\varepsilon$[24] and any possible directions is :-

$$\Gamma_{(v,\varepsilon|E,p,h)d\varepsilon} = \hbar W(v,\varepsilon_v|E,p,h)d\varepsilon_v = \frac{\hbar}{\rho_{p,h(\mu)}}\frac{\mu\sigma_{inv}(\varepsilon_v)}{v}\rho_{p-1,h(\mu)}\rho_\varepsilon(\varepsilon)d\varepsilon_v \tag{2.41}$$

Where V is the emitted particle velocity the cross section with subscript in V is the inverse process cross section and

$$\rho_\varepsilon(\varepsilon_v) = \frac{1}{\pi^2\hbar^2}\frac{(2S_v+1)m_v\varepsilon_v V}{v_0} \tag{2.42}$$

ρ_ε ($\varepsilon_{\ v}$) is the density of translational continuum states of the emitted particle as predicted by the fermi gas model, V is the laboratory volume.

2.4.3 Compound Nuclear Reaction

When the incident particle strikes on the target nucleus, then form a nucleus which required as a compound nucleus which lines for a short period of time and decays. The life time of the compound nucleus is about 10^{-15} to 10^{-16} seconds. In 1936 Niels Bohr proposed this theory of compound nucleus, according to Bohr a nuclear reaction are a two stage process [26,27].

i, Formation of Compound Nucleons

In the formation of compound nucleus is the bombarding particle is absorbed by the target nucleus and both together form a compound nucleus which is in tightly excited state[23].

$$x + X \longrightarrow C^*$$

The kinetic energy of the incident particle together with binding energy of the particle in a compound nucleus represents the excitation energy of the compound nucleus.

$$E^* = \frac{E_{(x)} \times M}{(m + M) + E_{(B)}} \tag{2.43}$$

Where E_x -kinetic energy of incident particle, m-mass of incident particle, M - mass of the target nucleus, $E_{(B)}$ - binding energy of the compound nucleus.

The incident particle quickly dissipate its energy as it enters in to the nucleons X and merged with nucleons in it. After the incident particle has merged completely with target nucleons, its energy is no longer remains concentrated on the particle. As a result the general random motion of the nucleons in nucleus is disturbed and each nucleons gain some extra energy but none of them will have enough energy to enable them to come out of the nucleons[28,29].

ii, Disintegration of Compound Nucleons

After the time interval of 10^{-15} seconds when a large number of collision take place enough energy is gain by one of the nucleon enabling it in to escape form the nucleons and thus the compound nucleus breaks up in to product nucleons, one or more emitted particle[28].

$$C^* \longrightarrow Y + y$$

The mode of disintegration of compound nucleus is independent of the mode of formation and depends only on its energy, angular momentum and parity. If different processes lead to some compound nucleus decomposition is identical. A compound nucleus once formed can decay in number of different ways[30]. The cross-section of the nuclear reaction through formation of compound nucleons is given as

$$\sigma_{(x,y)} = \sigma_c(X) \times \eta_c(y) \tag{2.44}$$

where $\sigma_{(c)}(X)$ is cross-section for the formation of compound nucleus C by the incident x with the target nucleons, $\eta_c(y)$ is the relative probability that the compound nucleons c ones formed decay with the emission of the particle y.

2.4.3.1 Processes of Cross-Section for Compound Nucleus

In terms of the compound nucleus process a nuclear reaction is written as a two-stage process.

$$a + X \longrightarrow C^* \longrightarrow Y + b$$

While the single-stage process is

$$a + X \longrightarrow Y + b$$

The second stage of the nuclear reaction is considered as independent as per Bohr's suggestion, the break-up of the compound nucleus C^* in to different reaction channels. Therefore the cross-section for the process X(a,b)Y may be written as

$$\sigma_{ab} = \sigma.\frac{\Gamma_b}{\Gamma} \tag{2.45}$$

where σ is the cross-section for the formation of compound nucleus by projectile 'a' with target 'X', Γ_b is proportional to the probability of break-up in to channel 'b' and Γ is equal to sum of all partial width(total widths).
According to the widths'Γ' and the space 'D' of the energy levels of the compound nucleus we have two cases i.e, $\Gamma << D$(resonance region) and $\Gamma >> D$ (continuum region)

a, Cross-Section for Discrete Levels of Compound Nucleus($\Gamma << D$)

In this case the nuclear levels are discrete and each level is characterized by its excitation energy E_0 above ground state, angular momentum, spin, parity and partial widths of decay[31]. The excitation of compound nucleus is

$$E = \epsilon_a + S_a \tag{2.46}$$

where ϵ_a is the incident channel energy and S_a is the separation energy for the particle 'a' in the compound nucleus.

A nuclear level/states has a finite width 'Γ', the wave function for a decay state of mean energy E_0 is written as:-

$$\Psi_t = \Psi_0 e^{\frac{-iE_0 t}{\hbar}} . e^{\frac{-\Gamma t}{2\hbar}} \tag{2.47}$$

This corresponds to an exponential decrease of intensity of excitation $|\Psi_t|^2$ with time constant τ=$\frac{\hbar}{\Gamma}$. The wave function is a superposition of stationary states of slightly different energy as a Fourier integral

$$\Psi_t = \int_{-\infty}^{+\infty} A(E) e^{\frac{-iEt}{\hbar}} dE \tag{2.48}$$

where A(E) is the amplitude of the state of energy 'E' from equation (2.47) and (2.48) we obtain

$$|A(E)|^2 = \frac{|\Psi_0|}{4\pi^2} \times \frac{1}{(E-E_0)^2 + \frac{\Gamma^2}{4}} \tag{2.49}$$

Therefore the cross-section for the excitation of the level by the collision of projectile 'a' with target nucleus 'X' will be

$$\sigma_a = \frac{C}{(E-E_0)^2 + \frac{\Gamma^2}{4}} \tag{2.50}$$

where C is a constant which is obtained from the simple statistical arguments.

In equilibrium state this rate of formation would be balanced by the decay of the excited state back in to the system X+a which has the probability:

$$\frac{\Gamma_a}{\hbar} \tag{2.51}$$

Thus the cross-section for the formation of the compound nucleus level becomes

$$\sigma_a(E) = \pi\hbar^2 \frac{\Gamma_a \Gamma}{(E-E_0)^2 + \frac{\Gamma^2}{4}} \tag{2.52}$$

If compound nucleus level is formed by particles of orbital angular momentum $l > 0$, then the spin of the level I_e=l if intrinsic spins are assumed to be zero. Hence, the level has statistical weight of (2l+1). Each substance can decay with equal probability and Γ_a should be replaced by gΓ_a where g=(2l+1) for spinless particles. Therefore the cross-section formula becomes

$$\sigma_a(E) = \frac{\lambda^2 g}{4\pi} . \frac{\Gamma_a \Gamma}{(E-E_0)^2 + \frac{\Gamma^2}{4}} \tag{2.53}$$

Thus for reaction X(a,b)Y we have the cross-section as:-

$$\sigma_{ab}(E) = \frac{\lambda^2 g}{4\pi} \frac{\Gamma_a \Gamma_b}{(E - E_0)^2 + \frac{\Gamma^2}{4}} \tag{2.54}$$

This is called "Breit wigner" single level formula for the reaction cross-section. we have two cases

- Elastic scattering, Γ_a=Γ_b=Γ and at resonance E=E_0 we obtain

$$\sigma_{ela} = \sigma_{ab} = \frac{\lambda^2 g}{4\pi} = \frac{\lambda^2}{4\pi}(2l + 1) \tag{2.55}$$

- Total inelastic scattering, Γ_b=Γ-Γ_a and E=E_0 at resonance gives

$$\sigma_{niel} = \frac{\lambda^2}{4\pi}(2l + 1) \frac{\Gamma_a(\Gamma - \Gamma_a)}{\frac{\Gamma^2}{4}} \leq \frac{\lambda^2}{4\pi}(2l + 1) \tag{2.56}$$

  The variation of σ_{ab} with energy (excitation function) is described by equation(2.54).

b, $\Gamma >> D$ (Overlapping of Compound Nucleus Levels)

When the excitation energy of compound nucleus increases then total width of levels also increases due to availability of more channels. since the yield of a nuclear reaction follows the total width, the sharp resonances are not observed for $\Gamma >> D$. Therefore, there is a contribution from many overlapping levels at any energy. In this continuum region the assumptions of the Bohr theory of nuclear reaction may not hold. According to Ericson in this region the statical assumption of random motion in the compound nucleus state are applicable and the excitation function show marked fluctuations. These fluctuations disappear if any energy average over a range larger than Γ is taken. Then Bohr's independent hypothesis may be valid. these calculations are the "statistical theory of nuclear reactions". In statical theory we explain the excitation functions and evaporation spectra in brief[32].

i, Excitation Functions

In simplest form the fermi's gas model predicts as

$$\omega(E) = c \times e^{2\sqrt{aE}} \tag{2.57}$$

where 'c' is constant, 'a' is a parameter proportional to the single-particle level spacing near the fermi energy. A modified form of equation(2.57)

$$\omega(E) = c \times E^{-2}.e^{2\sqrt{aE}} \tag{2.58}$$

From this formula the probability of decay as a function of the energy of the outgoing particle 'b' can be calculated.

ii, Evaporation Spectrum

The probability of the emission of a particle 'b' with energy between ϵ and ϵ+$d\epsilon$ is determined jointly by energy ϵ and by the level density ω_y(E) in the nucleus 'y' to which it corresponds as:

$$I(\epsilon)d\epsilon \propto \epsilon\omega_y(E)dE \tag{2.59}$$

The particle spectrum falls off at both high and low energies ($E = \epsilon_{max} - \epsilon$). For nuclei with A$\geq$50 and for energy $\epsilon_{max} \approx$ 10MeV, the spectrum has a continuous appearance like that of the energy distribution of molecules of gas. The outgoing particles can be regarded as evaporation products of a highly excited nucleus. we define a nuclear temperature 'T' which is related to the level density of residual nucleus 'y' at its maximum excitation. The level density as a function of E distribution of evaporation particle is usually isotopic in the center of mass system.

3

Materials and Method

3.1 Materials

Materials used to accomplish the study were:

- Different data source like Journals, publish articles and books etc.
- Computer, printer and flush disc.
- Plotting software or experimental information of reaction cross-section from EXFOR.

3.2 Method

Different information have been organized in doing project. The experimental data had been taken from the EXFOR and the theoretical nuclear reactions cross section values have been generated by using complet code. Finally, the experimental and theoretical values of cross section have been discussed in the form of tables and graphs.

4

Results and Discussion

In this work the experimental values of the reactions cross sections for the studied reactions were taken from the EXFOR data. The theoretical values were generated using COMPLET code. Then in this chapter the theoretical and experimental values are compared using tables and figures.

4.1 Reaction Cross Section Values of ^{45}Sc(n,2n)^{44}Sc

4.1.1 Theoretical Cross Section Values of ^{45}Sc(n,2n)^{44}Sc

When a neutron strikes a piece of matter, it does not interact with the atomic electrons (this happens only with charged particle); instead, neutrons interact with the nuclei. Neutrons are uncharged particle and therefore they do not participate in the electromagnetic interaction. These neutron nucleus interactions can result in the transfer of energy from the neutron to the nucleus[33]. All the main processes of interaction are caused by nuclear forces, as a result of various manifestations of which energetic charged particles produced by neutrons that transmit their energy to matter[34,35]. When the projectile (neutron particle) strike with a target element of Scandium(^{45}Sc), ^{44}Sc and emits two neutrons are produced. The excitation function of the reaction ^{45}Sc(n,2n)^{44}Sc was calculated in the energy range between 15MeV to 24MeV with the computer code COMPLET.

4.1.2 Experimental Cross Section Values of ^{45}Sc(n,2n)^{44}Sc

The experimental cross section values of the ^{45}Sc(n,2n)^{44}Sc reaction have been measured at ten neutron energies between 15MeV to 24MeV. The cross section values for

(n,2n) reactions above 14MeV have been taken from the EXFOR data. The experimental cross section values start from the projectile energy at 15MeV with reaction cross section of 331mb and reaches its maximum peak at 19MeV with reaction cross section of 533mb[36].

4.1.3 Comparison of Experimental and Theoretical Cross Section Values of ^{45}Sc(n,2n)^{44}Sc

Table 4.1: Theoretical and Experimental cross section values of ^{45}Sc(n,2n) ^{44}Sc

Energy(MeV)	15	16	17	18	19	20	21	22	23	24
σ_{exp}(mb)	331	473	514	489	533	523	501	490	450	361
σ_{theo}(mb)	342	515.2	532.7	500	496.3	475.2	467.5	447.4	430.6	328.8

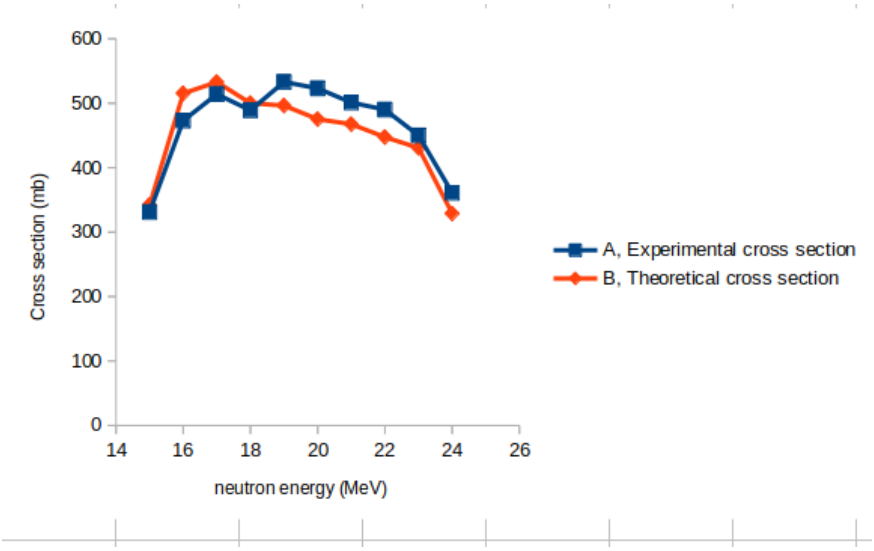

Figure 4.1: Cross section values of $^{45}_{21}Sc(n,2n)^{44}_{21}Sc$

The experimental reaction cross section values starts from the bottom of the assigned values of energy of the projectile at 15MeV with 331mb and reaches its maximum peak at about 19MeV with 533mb and starts to fall down for increasing value of energy of projectile. The calculated values of the reaction cross section and experimental measured value of the reaction cross sections nearly fit starting point and at the energy of the 18MeV. After 19MeV of the projectile energy both the experimental and theoretical

cross section values falls. The lower energy part is dominated by compound nucleus contribution.

4.2 Reaction Cross Section values of ^{45}Sc(n,p)^{45}Ca

4.2.1 Theoretical Cross Section Values of ^{45}Sc(n,p)^{45}Ca

When the projectile (neutron particle) strike with a target element of scandium (^{45}Sc), ^{45}Ca and emit a single proton are produced. The excitation function for (n,p) reactions from reaction threshold to 24MeV on some important target elements for astrophysical (n,p) reactions such as Si, Ca, Sc, Ti, Cr, Fe, Co and Ni were calculated using TALYS-1.0 nuclear model code[37]. This calculations include the excitation function of ^{45}Sc(n,p)^{45}Ca reaction have been carried out 6 to 12MeV incident neutron energy[37]. In this paper, the cross section values of the ^{45}Sc(n,p)^{45}Ca have been calculated for the neutron energy range between 6MeV to 12MeV by using the computer code COMPLET.

4.2.2 Experimental Cross Section Values of ^{45}Sc(n,p)^{45}Ca

The cross section values of the ^{45}Sc(n,p)^{45}Ca have been measured at seven neutron energies between 6MeV to 12MeV. The excitation function of the reaction on ^{45}Sc induced by 6MeV to 13MeV neutrons was taken from the experimental nuclear reaction data library (EXFOR). In this experiment the cross section values starts from the projectile energy at 6MeV with reaction cross section of 29mb and reaches its maximum projectile energy at 12MeV with the reaction cross section of 68mb[38].

4.2.3 Comparison of Theoretical and Experimental Cross Section Values of ^{45}Sc(n,p)^{45}Ca

Table 4.2: Theoretical and Experimental cross section values of ^{45}Sc(n,p) ^{45}Ca

Energy(MeV)	6	7	8	9	10	11	12
σ_{exp}(mb)	29	40	56	62.1	65.1	67.5	68
σ_{theo}(mb)	40	53.6	67.	71.4	79.9	84.9	92.1

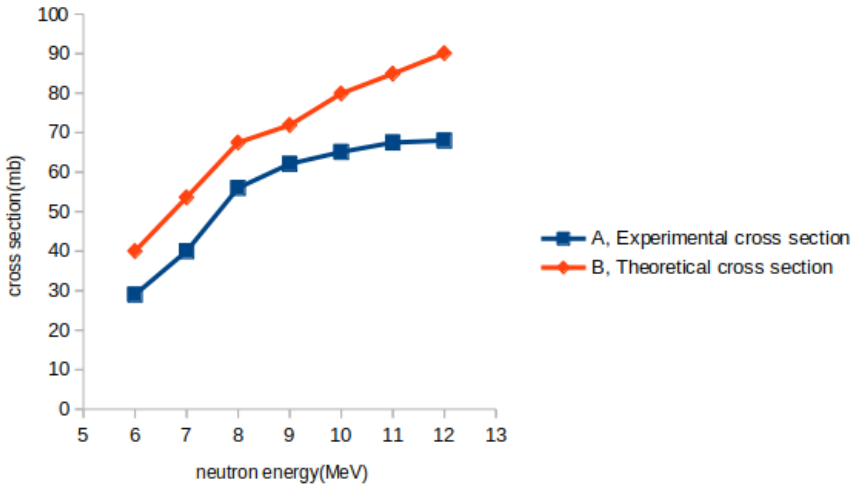

Figure 4.2: Cross section values of ${}^{45}_{21}Sc(n,p){}^{45}_{22}Ca$

From the theoretical calculations of the reaction cross section values starts at energy of the projectile about 6MeV with 40mb and reaches its maximum peak at energy of 12MeV with 92.1mb. In this reaction when the projectile energy range increase the cross section values sloping up. Both experimental and theoretical cross section values are increasing with the increase of projectile energy. Since the cross section values are resemble and near.

4.3 Reaction Cross Section Values of ^{45}Sc(p,n)^{45}Ti

4.3.1 Theoretical Cross Section Values of ^{45}Sc(p,n)^{45}Ti

When the projectile (proton particle) strike with a target element of scandium(^{45}Sc), ^{45}Ti and emit a single proton are produced. The excitation function of the reaction ^{45}Sc(p,n)^{45}Ti by Susan Shukur Noor, Iskender Akkurt, Nurdan Karpuz Demir for the injected positron emitter leads to 511KeV using the TALYS 1.6 code[39,40]. This paper deals with calculation of the cross section values of ^{45}Sc(p,n)^{45}Ti reaction by using the computer code COMPLET in the range of proton energy from 7MeV to 16MeV.

4.3.2 Experimental Cross Section Values of ^{45}Sc(p,n)^{45}Ti

The experimental cross section values of ^{45}Sc(p,n)^{45}Ti reaction have been measured at ten projectile energies between 7MeV to 16MeV. The experimental cross section values for (p,n) and (p,2n) interactions in Sc, proton energy between 8MeV and 14MeV was taken from the experimental nuclear reaction data library (EXFOR). In this experiment the cross section values starts from the projectile energy at 7MeV with the cross section of 305mb and reaches it maximum projectile energy of 16MeV with cross section of 394mb[41].

4.3.3 Comparison of Theoretical and Experimental Cross section of ^{45}Sc(p,n)^{45}Ti

Table 4.3: Theoretical and Experimental cross section values of ^{45}Sc(p,n) ^{45}Ti

Energy(MeV)	7	8	9	10	11	12	13	14	15	16
σ_{exp}(mb)	305	321	327	339	348	351	355	365	368	394
σ_{theo}(mb)	183.4	214.9	246.2	274.9	297.3	319.3	342.9	365.9	389.9	417.6

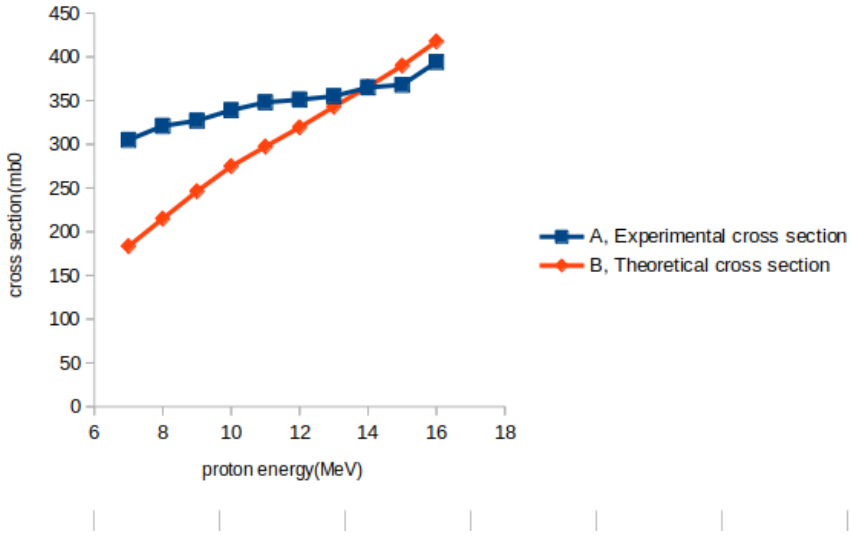

Figure 4.3: Cross section values of $^{45}Sc(p,n)^{45}Ti$

Theoretically calculated the nuclear reaction cross section values start at energy of

projectile about 7MeV with 183.4mb and its reaches maximum at energy of projectile about 16MeV with 417.6mb. The experimental measured values of the nuclear reaction cross section values starts at energy of projectile about 7MeV with 305mb and also its reaches maximum at energy of projectile about 16MeV with 394mb. The theoretical nuclear reaction excitation function fit with the experimental excitation function at 14MeV of the projectile energy. The projectile energy between 7MeV to 12MeV of the reaction cross section values of compound nucleus dominate than pre equilibrium reaction.

4.4 Reaction Cross Section Values of ^{45}Sc(p,2n)^{44}Ti

4.4.1 Theoretical Cross Section Values of ^{45}Sc(p,2n)^{44}Ti

The nuclear reaction cross section data can help to study the possibility of producing ^{45}Sc radioisotope via direct or indirect routes and evaluate the expected radioactive yield. The reported data for the nuclear reaction ^{44}Sc(p,2n)^{44}Ti and ^{44}Ca(p,n)^{44g}Sc have an indication that there is a high probability for the production of ^{44}Sc either in low or medium energy[42]. The study includes cross section calculations using TALYS and EMPIRE codes for nuclear processes that lead to producing the ^{44}Ti/^{44}Sc generator system on the cyclotron as indirect method for production[43]. In this paper cross section values have calculated for the reaction of ^{45}Sc(p,2n)^{44}Ti. The theoretical cross section values have been discussed and compared with the experimental values.

4.4.2 Experimental Cross Section Values of ^{45}Sc(p,2n)^{44}Ti

The excitation function of the ^{45}Sc(p,2n)^{44}Ti reaction have been measured at seven projectile energies between 25MeV to 55MeV. The title of cross section for ^{45}Sc(p,2n)^{44}Ti and related reactions were taken from the experimental nuclear reaction data library (EXFOR). In this experiment the cross section values starts from the projectile energy at 25MeV with the cross section of 19mb and reaches its projectile energy at 55MeV with the cross section of 3mb[44].

4.4.3 Comparison of Theoretical and Experimental Cross Section Values of ^{45}Sc(p,2n)^{44}Ti

Table 4.4: Theoretical and Experimental cross section values of ^{45}Sc(p,2n) ^{45}Ti

Energy(MeV)	25	30	35	40	45	50	55
σ_{exp}(mb)	19	14	6.7	3.5	3.7	2.7	3
σ_{theo}(mb)	18.57	15.10	8.67	5.72	4.13	3.4	2.9

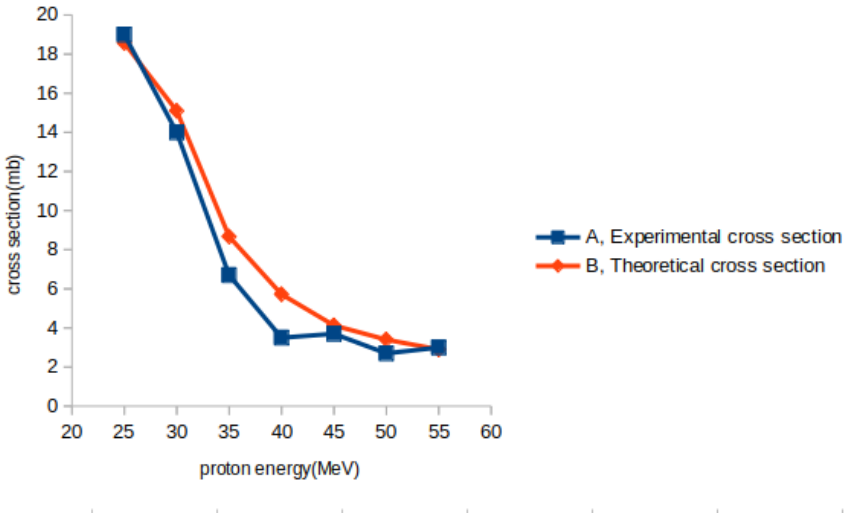

Figure 4.4: Cross section values of $^{45}_{21}Sc(p,2n)^{44}_{22}Ti$

When the projectile (proton) strike with a target element of Scandium(^{45}Sc), ^{44}Ti and emits two neutrons are produced. The theoretically calculated excitation function and experimental excitation function are the same form. This means both the reaction cross section values are fall downward with increasing of projectile energy. This condition that for increasing projectile energies the number of particle that can be captured in the target nucleus decrease. Therefore, the probability of compound nucleus reaction cross section decrease.

5

Conclusion

The results of the present work are summarized on the Figure (1-4), where experimental and theoretical best fit excitation function of ^{45}Sc(n,2n)^{44}Sc, ^{45}Sc(p,n)^{45}Ti, ^{45}Sc(n,p)^{45}Ca and ^{45}Sc(p,2n)^{44}Ti are plotted. The energy portion of the excitation functions can be satisfy with the theoretical components are included in the calculations. This shows that the compound nucleus theory does explain well cases of the incident energies of the projectile. The theoretical results have no appreciable change with the change of 'pld' values in equilibrium nuclear reaction cross-section. But the theoretical excitation function values changes with the change of exciton number. The initial exciton number n_o=3 is fit for the model of calculation. Thus for proton induced reaction experimental results fit the calculated theoretical values of reaction cross-section. Therefore the data obtained through the code of calculations are almost similar to those recorded in the EXFOR data.

Appendix

The COMPLET CODE and Description of Input Parameters Computer codes are programs used to calculate numerically the statistical weights of nuclear interactions and the interaction products which the results of reaction mechanisms using modified and improved models on times that verifies the predictions and fit the experimental data. The computer codes are thus designed to simplify the complicated numerical analyses of nuclear reactions at different stages of interaction and decay processes.

COMPLET CODE, ALICE-91, PACE-4, CASCADE,ACT etc, are some of the computer codes which are designed for the prediction and analyses of the excitation functions energy spectrum of reaction products of different type at different stages. In this paper complet code is used to obtain the prediction of excitation function for the compound nucleus neutron and proton induced reaction on scandium isotope, using the Weiss Kopf-Ewing model[23] while the pre-equilibrium components is simulated employing the geometric dependent hybrid model(GDH) of Blann[22].

At different stages of nuclear reaction the evaporation of particles (neutrons, protons, alpha particles, deuteron and their combination), depending up on the excitation energies, the binding energy of the composite system energy spectrum of the reaction products cross- section of different sorts and distribution of particles can be calculated. In complet code the level densities of nuclei evolved in the evaporation chains the mean free path multiplier and the initial exciton number are important parameters. The level density which affects the shape and the height of the excitation function is given by[23]

$$a = \frac{ACN}{k}$$

Where ACN is the mass number of the compound system and k is a constant which may be varied to match the excitation function.

The initial exciton configuration of the compound system is defined by its initial exciton number[2] n_0 as

$$n_o = p + h$$

where p is number of interacting particles and h- is the number of holes created and a value $n_0 = 3$ is taken for calculation because it is reasonable to assume that an incident proton in its first interaction with the target nucleus excites a particle above the fermi leaving a hole behind, i.e, in all two particles and one holes giving the initial exciton state.

Equilibrium and pre-equilibrium particle emissions during the decay process of a compound nucleus are very important for a better understanding of the nuclear reaction mechanism induced by medium energy particle. The primary pre-equilibrium differential cross section for the emission of a particle k with emission energy E_k can then be expressed in terms of τ, the composite-nucleus formation cross section σ^{CF} and an emission rate W_k,

$$\frac{d\sigma_k^{PE}}{dE_k} = \sigma^{CF} \sum_{p_\pi=p_\pi^o}^{p_\pi^{max}} \sum_{p_\upsilon=p_\upsilon^o}^{p_\upsilon^{max}} W_k(p_\pi, h_\pi, p_\upsilon, h_\upsilon, E_k) \times \tau(p_\pi, h_\pi, p_\upsilon, h_\upsilon) \times p(p_\pi, h_\pi, p_\upsilon, h_\upsilon)$$

where the factor p represents the part of the pre equilibrium population that has survived emission from the previous states and now passes through the (p_π,h_π,p_υ,h_υ) configurations, averaged over time. The initial proton and neutron particle numbers are p_π^o=ZP, and p_υ^o=NP, respectively with ZP(NP) the proton (neutron) number of the projectile. For any exciton state in the reaction process, h_π^o=h_υ^o=0 and h_υ=p_υ-p_υ^o, so that for primary pre-equilibrium emission the initial hole numbers are h_π^o=h_υ^o=0, particle emission only occurs from n=3(2p1h) and higher exciton states. We have a hardwired value of p_π^{max}=p_υ^{max}=6 as the upper limit of the summation. The maximum values p_π^{max} and p_υ^{max} thus entail an automatic separation of the pre-equilibrium population and the compound nucleus population.

The complet code of computer may be use to calculate for isotopically mixed target, e.g natural isotopic compositions. The following summarizes input requirements for the full operation of the program and find best calculated values in order that it fits to experimentally observed results of neutron and proton induced reactions.

Ap- projectile mass number

AT- Target mass number

Zp- projectile charge

ZT- Target charge

Qval- reaction Q value =Ap +AT-ACN=0, d=calculated Myer Swiateki lysek(msl) mass formula.

PLD-level density parameter 'A', $A = \frac{ACN}{PLD} = 0; A = \frac{ACN}{8}$

CLD- ratio of the single particle densities $\frac{AF}{AN} = 0, \frac{AF}{AN} = 1.0$

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

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

RO- critical temperature above onset of retarded fission.

GI- nuclear friction parameter from EQ. deformation to saddle.

Go- nuclear friction parameter from saddle to scission point

Na- number of nuclides of each z to be included calculation.

Nz- number of z to be calculated in the emission process.

MC- mass option, for separation energies and level density ground state shifts (level density ground state ldgs) together with mp.

MC=0, Myers Swiateck lysekil(msl) masses including shell correction.

MC=1, msl masses without shell correction term(with mp=0 only)

MC=2, msl masses including shell correction, but separation energies and /or ldgs at least partly provided by user.

Mc$>$ 2 BE value are calculated from 1990 nuclear wallet cards.

Mp- paring correction to masses.

Mp=0, no paring terms in masses.

Mp=1, paring terms in masses, ldgs calculated from msl, formula and applied back shifted.

Mp=2, as mp=1, but shell correction also included in ldgs.

Mp=3, normal paring shift, zero for odd-even nuclei, delta added to excitation for odd-odd nuclei.etc recommend values mc=10,mp=3

IPA- pairing corrections in level densities Ip=-1, no corrections Ip=0 standard correction.

M_3- number and particles to be emitted from each nuclide.

M_3=1, for neutrons only

M_3=2, for neutrons and protons

M_3=3, for neutrons, protons and alphas

M_3=4, for neutrons, protons alphas and deuterons

IVNER- inverse cross section parameter.

if=0, user supplies

if=1, results supplied by optical modal sub-routine

if=2, for N,P as old a lice

if=3, sharp cutoff values for inverse x-section

IKE- is energy bin mesh size in MeV

if=1, no particle spectra will be printed

if=2, equilibrium spectra for each nuclide will be printed

if=3, only pre-compound spectra printed

if=4, As 2+3

Ipch- if ipch=1 or 2 fission barriers may be read in after card number 1 as be exp. (ia,iz) one card for each barrier are independent of angular momentum for ipch=1, and are scaled as rldm barriers for ipch=2.

KPIt- if kpIt is 1 and the last energy line is followed by-1 in column 1-5, excitation functions will be plotted on standard output.

Card 2 title card 80 columns

1, If mc=2 on card 1, read user supplied n, p, alpha, deuteron, triton and helion binding energies

2, If inver=0 on card 1, read n, p, alpha, deuteron, inverse cross sections here, in ascending channel energy, first value 0,1MeV, incremented by 1MeV, steps 48 values per particle type, sequence n,p, alpha, deuteron.

Card 3 Energy and CN & PE options

EKIN- projectile kinetic energy in the laboratory system.

if=0, a new problem will begin at card 1

$if < 0$, previously calculated excitation functions will be printed,(if not Kplt=0.EKIN values were run in ascending order they are plotted).

if EKIN=0, on two successive cards, a normal excit will occur for negative Target mass on card 1.

RCSS- Reaction cross-section is calculated from subroutine.

if left blank, the reactions cross section will be internally generated by the optical model subroutine for incident n or p and by the parabolic model routine for all other projectiles.

JCAL- type of calculation option.

jcal=1, Weisskopf-ewing evaporation calculation.

jcal=2, s-wave approximation, liquid drop moment of inertia.

jcal=3, s-wave approximation, rigid body moment of inertia (only if entrance channel cross sections calculated by parap, i.e, zp.gtl and rcss.eq.0)

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

JFRAC- if a finite calculation is to be only in a specified angular momentum range, this is the lower limit.

JUPPER- is upper limit of angular momentum, if the range is to be restricted.

JANG- is option of emitted particles decreasing angular momentum. if=1 yes, if=0, no.

All additional parameters on this card are for pre-compound options. put TD-value to zero if no PE calculation is wanted.

IJ if=1 (or 3); Gp=GN=$\frac{3}{4} * \frac{A}{PoT}$

if =0 (or 2); GP =$\frac{3}{2} * \frac{z}{PoT}$, GN=$\frac{3}{2} * \frac{(A-Z)}{PoT}$

TD- initial Exciton number=p+h

E_{X1} -initial Exciton neutron number

E_{X2} - initial Exciton proton number

E_{X3} - initial alpha particle Exciton number

PoT - fermi energy in MeV

AV - if av=0, optical model transition rates; these value should not be used above 55MeV.

if av=1, nucleon-nucleon mean free paths are used.

ALF - probability that newly created Exciton particle from first stage Exciton gets on alpha particle in the second stage(1-ALF): complementary probability

if $ALF > 1$ calculation for two initial Exciton number

i, ATD = TD-3

ii, weight (1-ULF)

CMEP - mean free path are multiplied

GDO - critical angular momentum.

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