PHY4P01

PROJECT REPORT

RADIATIVE CAPTURE OF PROTON THROUGH THE $^{14}N(p,\gamma)^{15}O$ REACTION AT LOW ENERGY

A Dissertation Submitted in partial fulfilment of
the Requirements for the award of the degree of

Master of Science
in
Physics

Submitted by

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(SBAWMPH010)

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1.

2.

CALICUT UNIVERSITY

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This is certify that the project entitled "**Radiative capture of proton through the $^{14}N(p,\gamma)^{15}O$ reaction at low energy"** in partial fulfilment for the award of Degree of Master of Science in Physics, to the Calicut University is a bonafide record of the project work done by **ANUVIND VAS P (Reg. No SBAWMPH010)** during the academic year 2022-24. The results embodied in this project report have not been submitted to any other University or Institute for the award of degree or diploma.

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CALICUT UNIVERSITY

BONAFIDE CERTIFICATE

This is to certify that the Project entitled "**Radiative capture of proton through the $^{14}N(p,\gamma)^{15}O$ reaction at low energy"** submitted in fulfilment of the requirement for the fourth semester Project of Master of Science in Physics is result of the bonafide work carried out by **ANUVIND VAS P** during the academic year 2023-2024.

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DECLARATION

I ANUVIND VAS P, hereby declare that the project report entitled **"Radiative capture of proton through the $^{14}N(p,\gamma)^{15}O$ reaction at Low Energy"** under the guidance of Dr.Satheesh B submitted to Calicut University in the fulfilment of the requirements for the award of Master of Science. This is a bonafide work carried out by me and the results embodied in this project report have not been reproduced/copied from any source. The results embodied in this project report have not been submitted to any other university or institution for the award of any other degree or diploma.

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ABSTRACT

The CNO cycle is the main source of energy in stars more massive than our Sun. This process defines the energy production, the duration of which can be used to determine the lifetime of massive stars. The cycle is an important tool for determining the age of globular clusters.

Radiative proton capture via p + $^{14}N \rightarrow ^{15}O + \gamma$ at energies of astrophysical interest is an important process in the CNO cycle. The ^{14}N (p, γ radiative capture of photon through the 14N(p,γ)^{15}O reaction at low energy-pdf)^{15}O reaction regulates the rate of energy production for stars slightly more massive than the sun throughout stable hydrogen burning on the main sequence.

The $^{14}N(p, \gamma)^{15}O$ reaction rate also determines the luminosity for all stars after leaving the main sequence when their cores have exhausted hydrogen fuel and later when they become redgiant stars. The significant role that this reaction plays interstellar evolution has far reaching consequences for neutrino production in our sun, to age estimates of global clusters in our galaxy. The weak cross section and inherent coincidence summing in ^{15}O ray decay Scheme make a precision measurement gamma of the astrophysical S factor especially challenging particularly for the ground state transition in this project we apply TALYS 1.92 and Empire 3.2.3 Nuclear model calculation to obtain the low energy cross section for the above-mentioned reaction.

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Chapter 1

PROBLEM DEFINITION

1.1 Astrophysical Motivation

The mechanism by which stars generate energy is dependent upon their evolutionary stage and composition. The oldest stars observed, referred to as Population II stars, consist mostly of hydrogen, and thus their energy is produced primarily by the fusion of protons into helium. This process is known as the proton-proton chain [Bethe and Critchfield, 1938]. The stars observed today are at least second-generation Population I stars, formed from hydrogen and material ejected during the explosive deaths of Population II stars. In stars slightly more massive than the sun, higher density and temperature inside the core will favor a chain of nuclear reactions, known as the carbon nitrogen (CN) cycle [von Weizsäcker, 1938, Bethe, 1939], that still converts four protons into helium but involves heavier elements that act as catalysts. The rate of energy production in the CN cycle is governed by the slowest step, the $^{14}N(p,\gamma)^{15}O$ reaction, which acts as a "bottleneck" in the cycle. This work will examine the $^{14}N(p,\gamma)^{15}O$ reaction and its impact on the energy generation in our Sun and age estimates of some of the oldest clusters of stars in our Galaxy. Radiative capture reactions, i.e., those in which an atomic nucleus fuses with one or more nucleons or nuclei with the emission of electromagnetic radiation, play an important role in astrophysics. Their involvement in powering the stars via the pp chain (1) and CN cycle (2) was first described by Bethe in 1938. In addition, radiative capture reactions are prominent in the explosive conditions found in novae, x-ray bursts, and supernovae. Two features make them particularly influential in stellar astrophysics. For many nuclei, radiative captures are the only proton- or α-induced reactions possible with positive Q values, making knowledge of their rates essential for determining reaction pathways and energy release. Also, radiative capture reactions proceed slowly compared to strong interactions, rendering them rate-limiting steps in a number of reaction pathways and cycles. As such, they often control the reaction flow and rate of nucleosynthesis in a process.

Measuring the cross sections of radiative capture reactions at the relevant energies is the most reliable way to evaluate their rates, but due to the vanishingly small reaction probability this is not possible for every interesting case. When one of the reactants is radioactive, arranging for sufficient beam intensity or target thickness to enable a measurement at low energy is very challenging. The difficulties of direct measurements at astrophysical energies necessitate the use of indirect experimental techniques involving intermediate energy transfer and breakup reactions which have much higher yields. Theoretical insight is required at nearly every step. Extrapolation of measured radiative capture reaction cross sections downward from accessible to astrophysical energies can only be done reliably with the aid of nuclear theory. The inference of thermonuclear reaction rates from the analysis of related transfer and breakup reactions also relies on models of direct nuclear reactions.

In this work we cover radiative capture reactions in various astrophysical environments but specifically exclude big bang nucleosynthesis and the neutron captures of the s and r processes. The main aim of our work is to radiative capture of proton through the $^{14}N(p,\gamma)^{15}O$ reaction at low energy, energy range is from 0 - 120 MeV.

1.2 Low Energy

The $^{14}N(p,\gamma)^{15}O$ reaction regulates the rate of energy production for stars slightly more massive than the sun throughout stable hydrogen burning on the main sequence. The $^{14}N(p,\gamma)^{15}O$ reaction rate also determines the luminosity for all stars after leaving the main sequence when their cores have exhausted hydrogen fuel, and later when they become red giant stars. The significant role that this reaction plays in stellar evolution has far-reaching consequences, from neutrino production in our Sun, to age estimates of globular clusters in our Galaxy. The weak cross section and inherent coincidence summing in the ^{15}O γ-ray de cay scheme make a precision measurement of the astrophysical S-factor especially challenging, particularly for the ground-state transition. The present study, performed in the Laboratory for Experimental Nuclear Astrophysics (LENA), was aimed at measuring the ground-state transition at low energy by utilizing a new 24-element, position-sensitive, NaI(Tl) detector array. Because the array is highly segmented, the $^{14}N(p,\gamma)^{15}O$ S-factor was evaluated for transitions to the ground, 5.18, 6.18, and 6.79 MeV states without the need for coincidence summing corrections. Additionally, the position sensitivity of the detector was exploited to measure the angular correlation of the two-photon cascades. Software cuts were made to the data in order to identify single and coincident γ-ray events and a fraction fit analysis technique was used to extract the characteristic 15O peaks from the composite γ-ray spectrum. The results from the current work demonstrated a new approach to measuring weak nuclear cross sections near Astro physically relevant energies that, with refinements, has broader applications in γ-ray spectroscopy

1.3 Radiative Capture

Radiative capture reactions, i.e., those in which an atomic nucleus fuses with one or more nucleons or nuclei with the emission of electromagnetic radiation, play an important role in astrophysics. Their involvement in powering the stars via the pp chain (1) and CN cycle (2) was first described by Bethe in 1938. In addition radiative capture reactions are prominent in the explosive conditions found in novae, x-ray bursts, and supernovae. Two features make them particularly influential in stellar astrophysics. For many nuclei, radiative captures are the only proton- or-induced reactions possible with positive Q values, making knowledge of their rates essential for determining reaction pathways and energy release. Also radiative capture reactions proceed slowly compared to strong inter actions, rendering them rate-limiting steps in a number of reaction pathways and cycles. As such, they often control the reaction ow and rate of nucleosynthesis in a process.

Chapter 2

INTRODUCTION

Nuclear physics is the branch of physics that studies the constituents and interactions of atomic nuclei. It delves into the fundamental forces and particles within atomic nuclei, such as protons and neutrons, and explores their structure and behaviour under various conditions. Nuclear physics is crucial for understanding processes like nuclear reactions, radioactive decay, and nuclear fusion, which have profound implications for energy production, medicine, and our understanding of the universe.

Astro nuclear physics, on the other hand, extends these principles to astronomical scales and phenomena. It investigates nuclear processes occurring in stars, such as nuclear fusion that powers stars and produces elements through nucleosynthesis. Astro nuclear physics also explores extreme environments like supernovae and neutron stars, where conditions are ripe for exotic nuclear reactions and the formation of heavy elements beyond those formed in regular stellar fusion.

Together, nuclear and Astro nuclear physics provide a comprehensive framework for understanding the fundamental building blocks of matter, the energy sources of stars, and the evolution of elements throughout the cosmos. These fields are not only central to our understanding of the physical universe but also hold promise for future technologies and innovations in energy production and space exploration.

The Emergence of Nuclear and Astro Nuclear Physics

Nuclear physics emerged in the early 20th century with pivotal discoveries in radioactivity, initiated by Henry Becquerel in 1896, and further explored by Marie and Pierre Curie. The study of atomic nuclei advanced with Ernest Rutherford's gold foil experiment in 1909, revealing a dense, positively charged nucleus surrounded by electrons.

The development of quantum mechanics in the 1920s provided a theoretical foundation for nuclear physics, explaining phenomena such as nuclear energy levels, radioactive decay, and reactions. James Chadwick's discovery of the neutron in 1932 completed the picture of the atomic nucleus, revealing it as composed of protons and neutrons held together by the strong nuclear force.

Simultaneously, Astro nuclear physics evolved as scientists investigated the energy sources of stars. Building on nuclear physics principles, they proposed that stars derive their energy from nuclear fusion reactions, a concept solidified by Hans Bethe's work in the 1930s with the proton-proton chain and CNO cycle.

Since then, both fields have advanced significantly. Nuclear physics has expanded with high-energy particle accelerators probing atomic nuclei, while Astro nuclear physics has deepened our understanding of stellar evolution, supernovae, neutron stars, and the synthesis of elements in the universe. These disciplines not only explore fundamental forces but also have practical applications in energy production, medicine, and space exploration.

2.1 Nuclear Reaction

A nuclear reaction is a process in which two nuclei or nuclear particles collide to produce different products than the initial particles. Nuclear reaction mechanism is a key tool to study nuclear properties and structure. In a nuclear reaction an atomic nucleus, which is called as a target interacts with a nuclear projectile through some mechanism. After that it emits either a nuclear particle or radiations leaving a residual nucleus. Residual nucleus is known as evaporation residue. i.e., in a nuclear reaction nucleons are redistributed. After a nuclear reaction there is change in nuclear composition and the energy state of the interacting species. We can write a nuclear reaction as

X(a,b)Y

i.e., a nuclide 'X', when interacts with a nuclear particle 'a', forms a new nucleus 'Y' by emitting a nuclear particle of the type 'b'.

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

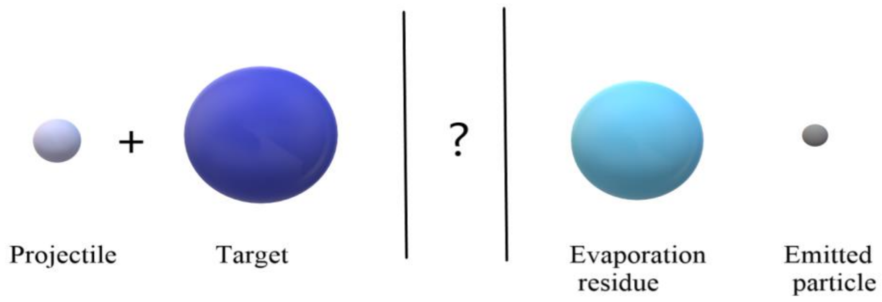

Figure 2.1: A typical nuclear reaction

2.1.1 Nuclear Fusion

Nuclear fusion, the process by which light atomic nuclei like hydrogen isotopes deuterium and tritium, combine to form heavier nuclei, releasing enormous amounts of energy. It represents a profound source of energy with implications ranging from astrophysics to sustainable power generation on Earth. This process powers stars, including our Sun. At its core, where hydrogen nuclei fuse to produce helium and release vast amounts of energy. Unlike nuclear fission, fusion produces minimal long-lived radioactive waste and utilizes fuel sources that are widely available, such as deuterium from water and lithium. It offers the potential for a nearly limitless energy supply. Achieving controlled fusion reactions involves technical challenges, such as sustaining the extreme temperatures (million ℃) and pressures required to initiate and maintain fusion reactions in a stable plasma (ionized gas) state, without losing too much energy.

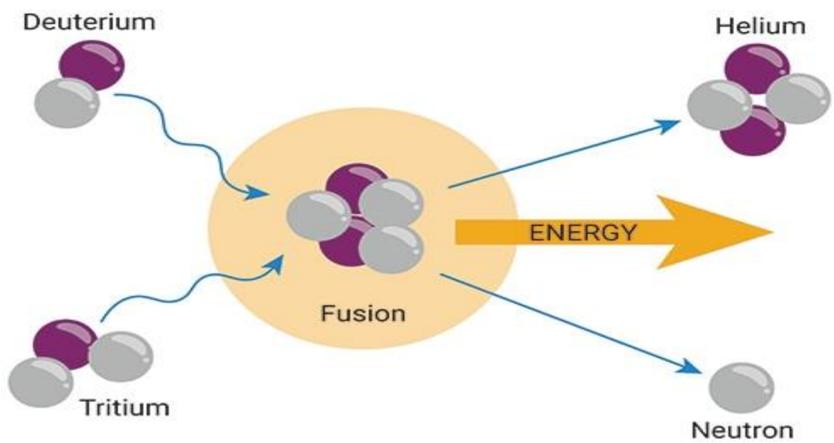

Figure 2.2: Nuclear Fusion

2.1.2 Nuclear Fission

Nuclear fission is the process where a heavy atomic nucleus, typically uranium-235 or plutonium-239, splits into smaller nuclei, releasing a large amount of energy in the form of heat and radiation. This phenomenon is the basis for nuclear reactors and atomic bombs. In a controlled nuclear reactor, fission reactions are harnessed to generate electricity by heating water to produce steam that drives turbines. However, fission also produces radioactive waste that requires careful handling and disposal due to its long-lived harmful effects. While nuclear fission provides a concentrated and reliable energy source, concerns about safety, waste management, and proliferation risks continue to shape its role in global energy strategies.

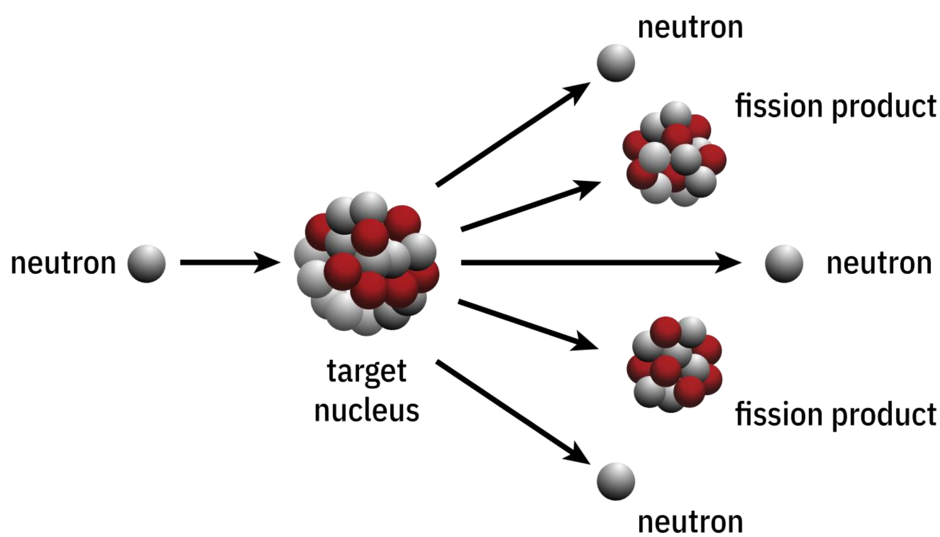

Figure 2.3 : Nuclear Fission

2.2 Nuclear Reaction Model

Macroscopically we know the system before and after reaction. But we don't know what exactly happens during the reaction dynamics. It is impossible to look in the reaction directly, models for reaction mechanism is used for that. We should know the interaction between nucleons to understand the reaction mechanism, nuclear force behaviour etc.,. For that a well idea of interaction potential between the nucleons is needed. The coulomb barrier gives idea about nucleus - nucleus interaction and also about fusion mechanism.

Fusion barriers for nuclear reactions

The total potential energy between two interacting nuclei is the sum of coulomb and nuclear potential energies. Coulomb potential energy is inversely proportional to distance and the nuclear potential energy is short range attractive between the two nuclei. Just outside the region of overlapping, magnitude of nuclear potential energy becomes equal to the coulomb potential energy. It produces a coulomb barrier or fusion barrier. There will be a potential well inside the barrier. When the incoming projectile overcome this coulomb barrier and enters in to the potential well the fusion between two nuclei occurs.

How to find fusion barrier:

The interaction potential between the target nucleus and the projectile can be written as the sum of Coulomb, Nuclear and Centrifugal potentials.

$V = V_c(r) + V_N(r) + \frac{\hbar^2 l(l+1)}{2\mu r^2}$ **(**Equation 2.1**)**

Where,

r is the distance between the centres of the target and projectile,

$\boldsymbol{\ell}$ is the angular momentum quantum number

μ is the reduced mass of the system

The coulomb potential can be written as

$\mathbf{V_c(r)} = \frac{Z_p Z_t e^2}{r}$ (Equation 2.2)

For $\boldsymbol{\ell}=0$ the maximum value of the potential V is called the Fusion barrier. Corresponding values of V and r are called the height (V_B) and position (R_B) of the fusion barrier.

Coulomb barrier energy in centre of mass frame is

$$\mathbf{E_{cm}} = \frac{1.44 Z_p Z_t}{1.2\left(A_p^{\frac{1}{3}} + A_t^{\frac{1}{3}}\right)} \qquad \text{(Equation 2.3)}$$

Coulomb barrier energy in lab frame is

$$\mathbf{E_{lab}} = \mathbf{E_{cm}}\left(\mathbf{1} + \frac{A_p}{A_t}\right) \qquad \text{(Equation 2.4)}$$

Where $Z_p$and $Z_t$are atomic number of projectile and target and $A_p$and $A_t$are mass number of projectile and target.

Classically, if the incident particle energy is sufficient to overcome the coulomb barrier then only nuclear reaction will occur. Whenever the incident particle overcome the coulomb barrier it can transfer all of its momentum to the target nucleus and entire projectile will be captured by the target, then it is known as complete fusion. In an incomplete fusion the projectile will break near the surface of target .It leads to partial transfer of momentum from projectile to target. Here some of the projectile fuse with the nucleus.

But we don't have the full quantum theory to approximate nucleon interaction to potential. So we need nuclear reaction models. The properties of various nuclear reaction can't be explained by a single model.The first model for nuclear reaction was proposed by Niels Bohr in 1936. The nuclear reaction models can be classified in to two according to nuclear potentials V_N

2.2.1 Independent particle model

The independent particle model assumes that there is no interaction between nucleons. That is nucleons are considered as free particle. A single nucleon moves inside a certain potential well independently from other nucleon. Some of the independent particle models are

a) Shell model:

The shell model assumes that energy level of a nucleus is similar to that of electron shell in atom. Shell model predicts the existence of magic number and by nuclear stability.

b) Optical model

Optical model is used to describe direct reaction. It used at higher energies and the potential is complex. It is a model developed on the basis of mathematical techniques used in optics. The optical potential used here consist of the real and imaginary potential. Optical model is useful only in describing average behaviour of reaction like scattering.

c) Bass model

The nuclear potential used here is bass potential. Bass model uses the idea of range of nuclear force and the surface energy parameters of liquid drop model. The potential is a quasi-elastic two body potential. Here angular momentum and energy dissipation due to friction at a point is taken in to account.

Nuclear potential in bass model

$$V_N(r) = \frac{-R_1R_2}{R_1+R_2}\,\Phi(r-R_1-R_2)\text{MeV} \qquad \text{(Equation 2.5)}$$

Where, R_i is given as

$$R_i = 1.16A_i^{\frac{1}{3}} - 1.39A_i^{\frac{1}{3}} fm \qquad \text{(Equation 2.6)}$$

Using the available data for fusion-cross section, Bass determined the experimental points for the function $\Phi(s=r-R_1-R_2)$. He found that the data can be fitted by an empirical function of the form

$$\Phi(s) = \left[A\ exp\left(\frac{s}{d_1}\right)+B exp\ \left(\frac{s}{d_2}\right)\right]^{-1} \qquad \text{(Equation 2.7)}$$

With

A= 0.03 MeV $^{-1}$, B = 0.0061 MeV $^{-1}$

$d_1 = 3.30fm$, $d_2 = 0.65fm$

2.2.2 Statistical model or compound nucleus model

This model assumes that there is a strong interaction between the nucleons. Here a compound nucleus is formed with high excitation energy. The incident energy is shared between the nucleons which equilibrates before the decay.

2.3 Light Ion induced nuclear reactions

Light ion induced nuclear reactions involve the interaction between a nucleus and a light ion, such as a proton (p), deuteron (d), triton (t), helion (3He), or alpha particle (α). These reactions are fundamental in both basic nuclear physics research and practical applications like nuclear energy production and medical isotope generation. Here's an explanation of the processes and mechanisms involved in these reactions:

Types of Light Ions

1. Protons (p): Hydrogen nuclei, consisting of a single proton.

2. Deuterons (d): Nuclei of deuterium, consisting of one proton and one neutron.

3. Tritons (t): Nuclei of tritium, consisting of one proton and two neutrons.

4. Helions (3He): Nuclei of helium-3, consisting of two protons and one neutron.

5. Alpha Particles (α): Helium-4 nuclei, consisting of two protons and two neutrons.

Reaction Mechanisms

1. Elastic Scattering

The light ion collides with the target nucleus and bounces off without any change in the internal structure of either particle. The energy and momentum are conserved, and the primary outcome is the deflection of the particles.

2. Inelastic Scattering

The light ion collides with the target nucleus, causing it to be excited to a higher energy state. The excited nucleus then releases energy by emitting gamma rays or other particles.

3. Direct Reactions

A quick interaction where one or more nucleons are transferred between the light ion and the target nucleus. Examples include stripping reactions (where a nucleon is removed from the light ion and added to the target) and pickup reactions (where a nucleon is removed from the target and added to the light ion).

4. Compound Nucleus Formation

The light ion is fully absorbed by the target nucleus, forming a compound nucleus in an excited state. This compound nucleus can then decay by emitting particles or gamma rays. The decay process can be complex and may involve multiple steps.

5. Fusion Reactions

In some cases, the light ion and the target nucleus fuse to form a heavier nucleus. This process releases a large amount of energy and is fundamental in stellar nucleosynthesis and fusion energy research.

2.4 Heavy ion induced nuclear reactions

Nuclear reactions, like chemical reaction can occur through different reaction mechanisms. On the basis of mechanism heavy ion reactions with mass number greater than 4 can be subdivided to four. They are:

- Direct reaction
- Compound nuclear reaction
- Pre-equilibrium reaction
- Quasi-fission reaction.

2.4.1 Direct reaction

In a direct reaction projectile and a target nucleus are within the range of nuclear forces. It remains in this state for very short time of the order of 10^{-22}sec. So that it allows only the interaction of a single nucleon. Direct reactions are most probable with high energy incident particle. The interaction time defines the reaction mechanism. The products of a direct reaction are not distributed isotropically. They are forward focused. Here the projectiles makes a very few, collisions with nucleons in the target and its forward momentum is not transferred to an entire compound state. The cross sections for direct reactions vary smoothly and slowly with energy in contrast to the compound nuclear reaction. It is a fast reaction. It has large impact parameter. This reaction is very important in determining the nuclear structure.

Direct reaction can be divided into:

a. Scattering

b. Transfer reactions

c. Break-up reaction

d. Knock-out reaction

a. Scattering

In a nuclear scattering, a nucleus interacts with a particle or another nucleus without changing the nature of nuclide. In a scattering process incident and outgoing particles are same.

- **Elastic scattering**: In an elastic scattering, energy is exchanged between the projectile and target nucleus but the Q value is zero. Here momentum and kinetic energy is conserved.
- **Inelastic scattering**: In an inelastic scattering a part of kinetic energy of the projectile is transferred to the target nucleus as excitation energy. Here the values of atomic and mass number of either projectile or target are not changed. Q value of this reaction is not zero.

b. Transfer reactions

In a transfer reaction the one or more nucleons are transferred to the target nucleus. Transfer reactions are of two types.

- **Stripping reaction:** In a stripping reaction the part of the incident projectile is "stripped away" .Then that particle enters the target nucleus. Here a neutron is taken in to the target nucleus and this reaction is similar to simple neutron capture reaction. Eg: (d,p) reaction.
- **Pickup reaction:** In a pickup reaction the emitted particle is a combination of the incident projectile and a few target nucleons. i.e., one or more nucleons are transferred from a target to projectile. Eg: $(\alpha, {}^{6}Li)$,(p,d).

c. Break-up reaction

Here the projectile is broken into one or more fragments.

d. Knock-out reaction

By the collision with the target, a single nucleon from the projectile is removed.

2.4.2. Compound nuclear reaction

Compound nucleus model was proposed by Bohr in1936.In the compound nuclear reaction the projectile and the target merge together for a short interval of time .There will be complete sharing of energy before the ejection of outgoing particle. Then the system will be in a complete thermal equilibrium. In this model compound nucleus is assumed like hot liquid. The binding energy of emitted particle corresponds to the heat of vaporization of the liquid molecule. The liquid drop will evaporate one or more nucleus, then it cools down. Similarly compound nucleus remain in an excited state until any nucleons gets enough excitation energy to leave the nucleus. The compound nucleus is excited by binding nuclear energy and projectile kinetic energy. Then we gets an evaporation residue and emitted particle. Since the projectile has lowest energy ,it interact with large number of nucleons in the target. A typical compound nuclear reaction can be written as

$$\mathbf{a + X \rightarrow C^* \rightarrow Y + b}$$

Where,

X - The target

a - The projectile

C* - The compound nucleus

Y - The evaporation residue

b - The emitted particle

The life time of a compound nucleus is of the order of 10^{-18} sec to 10^{-16} sec. The compound nucleus state is known as long lived intermediate state of particle-target composite system. It has small impact parameter.The angular distribution of the compound nuclear reaction is isotropic. For the compound nuclear reaction to be occur, the incident particle should have low energy and medium weight. If we give more energy to the compound nucleus, then the probability of ejection of particle will be more. For each reaction, cross section increases to a maximum and then decreases. Higher energy makes emission of more nucleon. If the incident particle is a heavy ion then large amount of angular momentum is transferred to the compound nucleus. The angular momentum of the compound nucleus favours the formation of high spin nuclides. According to Bohr, compound nuclear reaction has two steps.

1. Formation of compound nucleus.
2. Decay of compound nucleus in to products.

It is verified experimentally by S.N. Ghoshal in 1950

For the above reaction, cross section $\sigma(a,b)$can be written as

$$\sigma(a,b) = \sigma_c(T_i)P_b(E)$$

Where,$\sigma_c(T_i)$ is the cross section for the compound nucleus formation at kinetic energy T_i and $P_b(E)$ is the probability that the compound nucleus decay to an evaporation residue by the emission of particle b.

Bohr independent hypothesis

The mode of decay of compound nucleus does not depend on the way of its formation. Or the probabilities of the various exit channels are independent of the entrance channel.

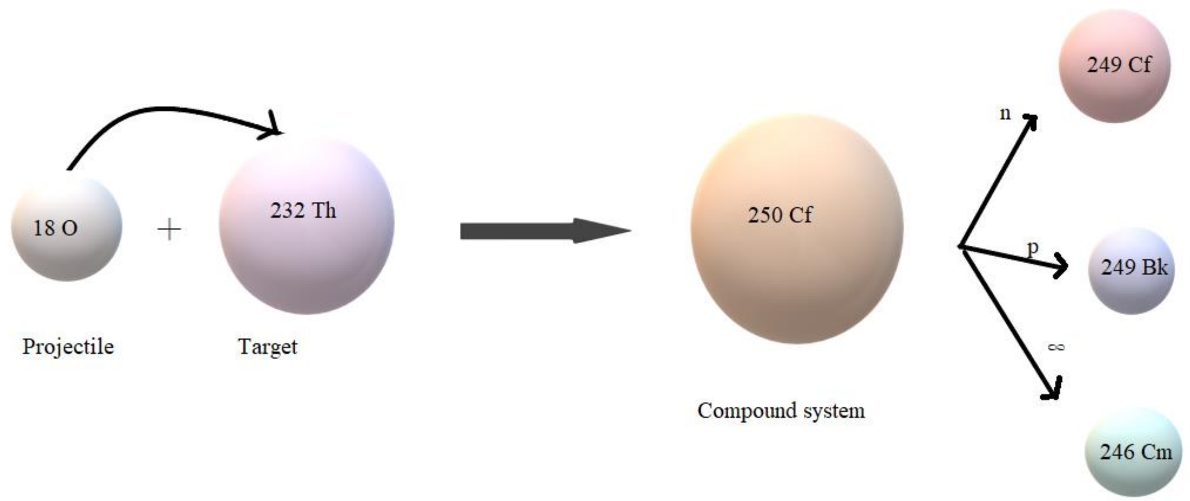

Figure 2.4: A typical compound nuclear reaction

2.4.3 Pre-equilibrium reaction

In pre-equilibrium nuclear reaction or pre-compound reaction the complex nuclei breaks before reaching the statistical equilibrium. Pre-equilibrium reaction has the properties intermediate between the compound and directreaction. It is also known as multistep process.The projectile shares its energy among a small number of nucleons in the target. The nucleons in the projectile initiate a series of reactions in the target. Before reaching the equilibrium it may emit particles. During the formation of the compound nucleus, composite system is not spherically symmetric. Initially it will be of the form of prolate or oblate spheroid. After a short interval of time it will rearrange to spherical nucleus. Intranuclear cascade model, the exciton and hybrid models are the most widely used pre-equilibrium models. Pre-equilibrium process does not hinder formation of super heavy elements.

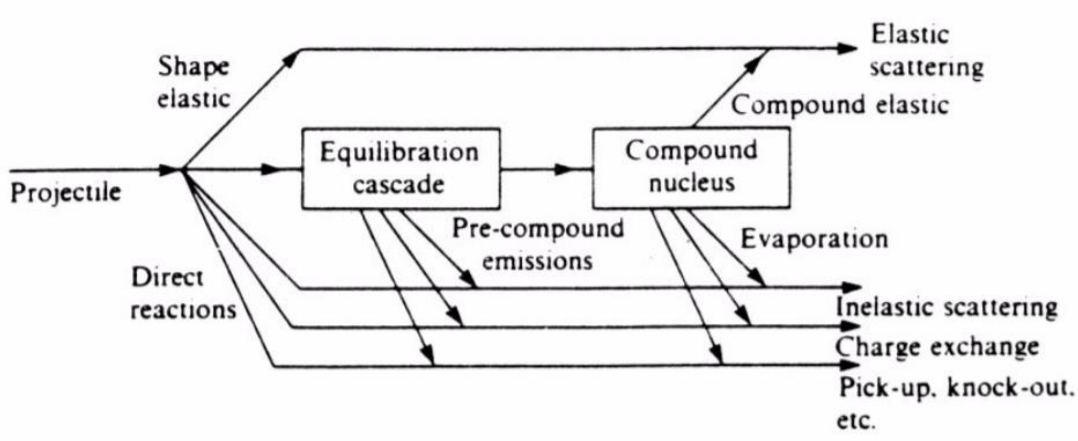

Figure 2.5: Overview of reaction mechanisms

2.4.4. Quasi- fission nuclear reaction

The heaviest nuclei are formed by fusion–evaporation mechanism. It is hindered by quasi-fission process. Quasi- fission occurs in the early stage of the collision. After the collision of projectile and target a di-nuclear composite system may turn to a compound nucleus or it may decay into fission like process called quasi-fission before the full equilibration. That is a neck is formed between two fragments. It re separates before reaching the equilibrium with more mass asymmetry than entrance channel. Quasi-fission is a multinucleon transfer process. It is also called as fusion followed by fission. Time scale of quasi-fission reaction is less than 10^{-20}sec (sticking time). The properties of quasi-fission is similar to fusion-fission i.e., compound nucleus decay (heavy system). Lighter systems may also exhibit quasi-Fission, but the probability is small. The quasi-fission reaction is characterized by full energy relaxation but incomplete mass and shape relaxation. Quasi-fission takes place at all values of orbital angular momentum. After full momentum transfer, the reacting system is not evolved inside the fission saddle point, but it re separates without significant mass exchange (asymmetric quasi-fission) or with significant mass transfer (symmetric quasi-fission). The fragment distribution is anisotropic.

Quasi-fission is responsible for the anomalous angular distribution. This event corresponds to the formation of di-nuclear system with small excitation energy. In these reactions, an additional energy above the Coulomb barrier, sometimes called “extra-push” energy, is needed for the system to fuse and form a CN. Quasi-fission reaction is competing process with fusion. The contact in quasi-fission is followed by rotation and mass exchange. It exhibits a characteristic distribution in Mass and Angle. The quasi–fission process is not a statistical process it is a dynamical mechanism which dependence on entrance channel. The quasi-fission and compound nucleus fission are two different processes. Compound nucleus fission is purely statistical and it is determined by temperature and angular momentum only.

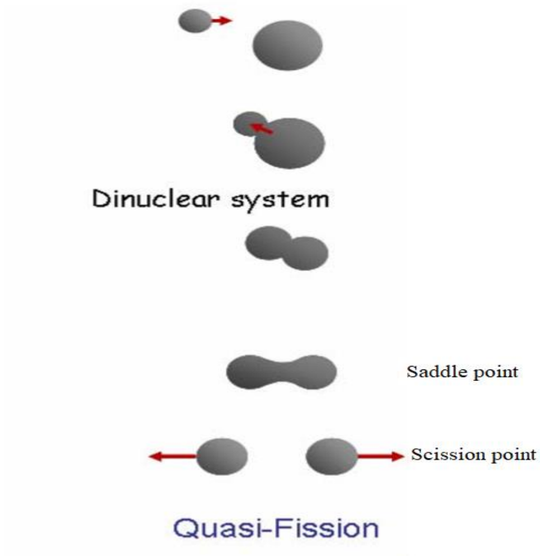

Figure 2.6: Quasi-fission nuclear reaction

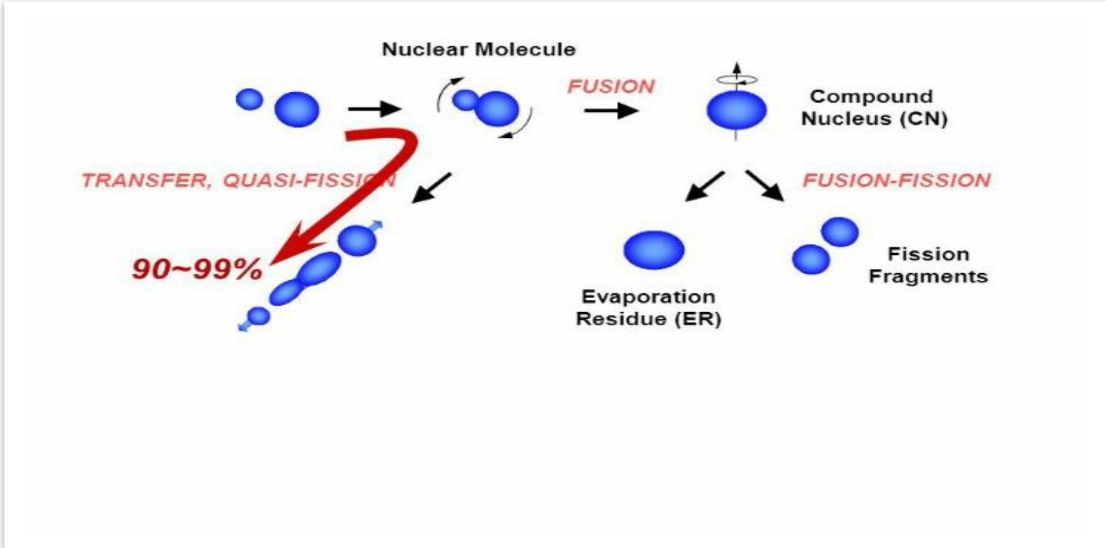

Fig2.7 : Typical quasi –fission nuclear reaction

2.5 Formation of super heavy elements and quasi-fission

The shell model of the nucleus assumes that the energy level of the nucleons is similar to that of an electronic energy level in an atom. The nuclei with magic number of protons and neutrons are more stable. (2,8,20,28,50,82,126) Nuclei with magic N and Z have zero quadrupole moment and hence they are spherical. Elements with proton number, $Z \geq 104$ are called super heavy elements. Most of them are unstable. The “island of stability” is the region of super heavy elements with half-lives (in the order of minutes/hours/days) several times longer than that of other super heavy elements. They are characterized by spherical shape nuclei. The “sea of instability” is the region in periodic table with highly unstable nuclei.

Formation of the super heavy elements mainly has three steps.

1. Hitting of projectile to the target and penetration to the coulomb barrier.
2. Fusion of two heavy nuclei to form the compound nucleus.
3. Decay of compound nucleus to evaporation residue.

The formation of super heavy elements is delayed by many parameters. They are collision energy, isospin, shell structure, mass asymmetry, deformation and orientation. The formation of fully equilibrated compound nucleus will not occur just after crossing the coulomb barrier. It needs extra push energy to form a mononucleus. This mononucleus needs extra extra push to equilibration in all degrees of freedom to form a compound nucleus. The need of extra extra push is in the systems with coulomb factor ZpZt>1600. The lack of this extra push energy leads to the quasi-fission. Fission barrier vanishes at higher angular momenta. So quasi-fission occurs. For the production of super heavy elements certain entrance channel conditions should be taken to reduce the quasi-fission probability. The cross sections of super heavy element is so small, it is less than 1 pb.

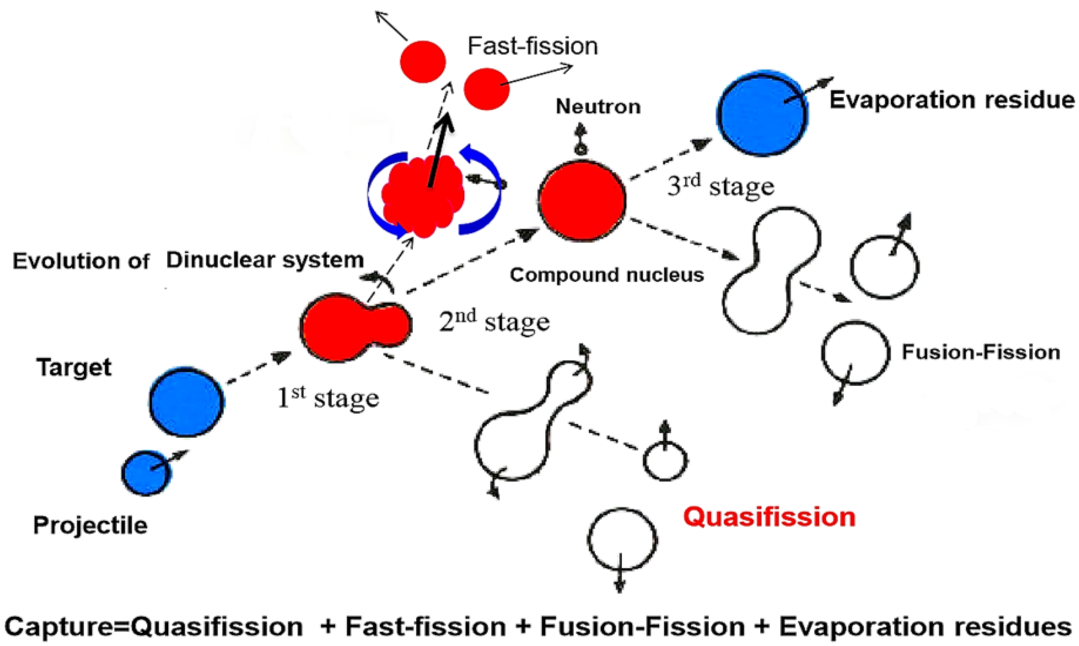

Figure 2.8: Super heavy element formation

2.5.1 Factors affecting the onset quasi-fission nuclear reaction

1. Excitation energy of the compound nucleus:

Excitation energy is the excess energy above the ground state of the compound nucleus. Every excited energy level has particular life time. After that the excitation energy is dissipated by emission of particles. Excitation function curve is the profile of cross section as a function of projectile energy.

2. Deformation and orientation of the colliding nuclei:

The fusion cross section depends strongly on relative orientation of the projectile and target. Fusion barrier height is also affected by relative orientation. The fusion probabilities with prolate target are higher than those with oblate target at lower incident energies. Target deformation favours onset quasi-fission. Static deformation alignment is as follows:

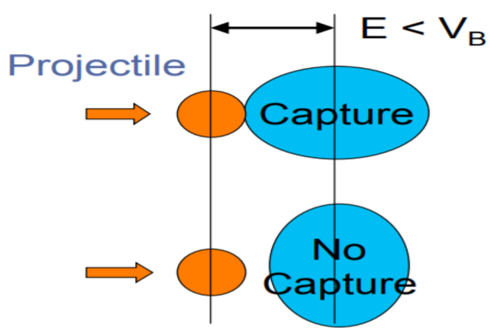

Fig 2.9: Deformation alignment

3. Mass asymmetry

Mass asymmetry $\alpha = \frac{A_p - A_t}{A_p + A_t}$

A_p and A_t are the atomic mass of projectile and target. The symmetric systems show large fusion hindrance.i.e; lesser mass asymmetry favours quasifission.

4. Charge asymmetry

$$\eta = \frac{Z_p - Z_t}{Z_p + Z_t}$$

Where Z_p and Z_t are atomic numbers of projectile and target respectively.

5. Nuclear charge product:

Quasi-fission occurs when coulomb factor Z_pZ_t>1600 .Where Z_p and Z_t are the charge number of projectile and target. Systems with coulomb factor less than 1600 have strong mass angle distribution. This indicates non equilibrium of the mass degree of freedom.

6. Closed shell nature:

The reactions involving nuclei having several magic numbers form a true compact compound nucleus with high probability. There will be reduced energy dissipation as the two nuclei is overlapping. Then compact shapes are formed. Since heavier doubly magic nuclei have different N/Z than lighter doubly magic nuclei, it is important to understand the effect of N/Z mismatch as well as the effect of shell closures. Theoretically entrance-channel spherical closed shells can enhance compound nucleus formation provided the N/Z asymmetry is small. Increase in the N/Z asymmetry is expected to destroy the effect of entrance-channel spherical closed shells, through nucleon transfer reactions.

7. Compound nucleus fissility:

Compound nucleus fissilty depends on entrance channel. The amount of quasi-fission decreases with decrease in fissilty parameter $\frac{Z^2}{A}$.

8. Angular momentum:

By studying angular momentum distribution of the dinuclear system the anisotropy in angular distribution can be studied.

2.5.2 Experimental signature of quasi-fission:

1. Suppression of fusion cross section:

Measurement of fusion cross section gives the probability of reaction to occur. The formation of super heavy element shows larger cross section. But it shows smaller cross section due to quasi-fission.

2. Mass ratio distribution:

The fission mass ratio is the ratio of one fragment mass to total mass.

$$\text{Mass ratio } M_R = \frac{M_P}{M_P + M_T}$$

Where M_P, M_T are projectile and target masses. M_R is the total mass. The plot between ranges of fragment masses to the total number of particles emitted represents mass ratio distribution. It is a Gaussian and peaked at 0.5. If there is any quasi-fission then the width of mass ratio distribution becomes broader.

Mass angle distribution:

Mass angle distribution is the plot of mass ratio against the angle at which the particles were emitted with respect to the centre of mass. The plot of binary mass split between projectile and target against the scattering angle during splitting gives a two dimensional matrix. This is known as mass angle distribution (MAD). MAD gives the characteristics of quasi-fission and thus the dynamics of super heavy element formation. There will be strong mass angle distribution if any quasi-fission occurs

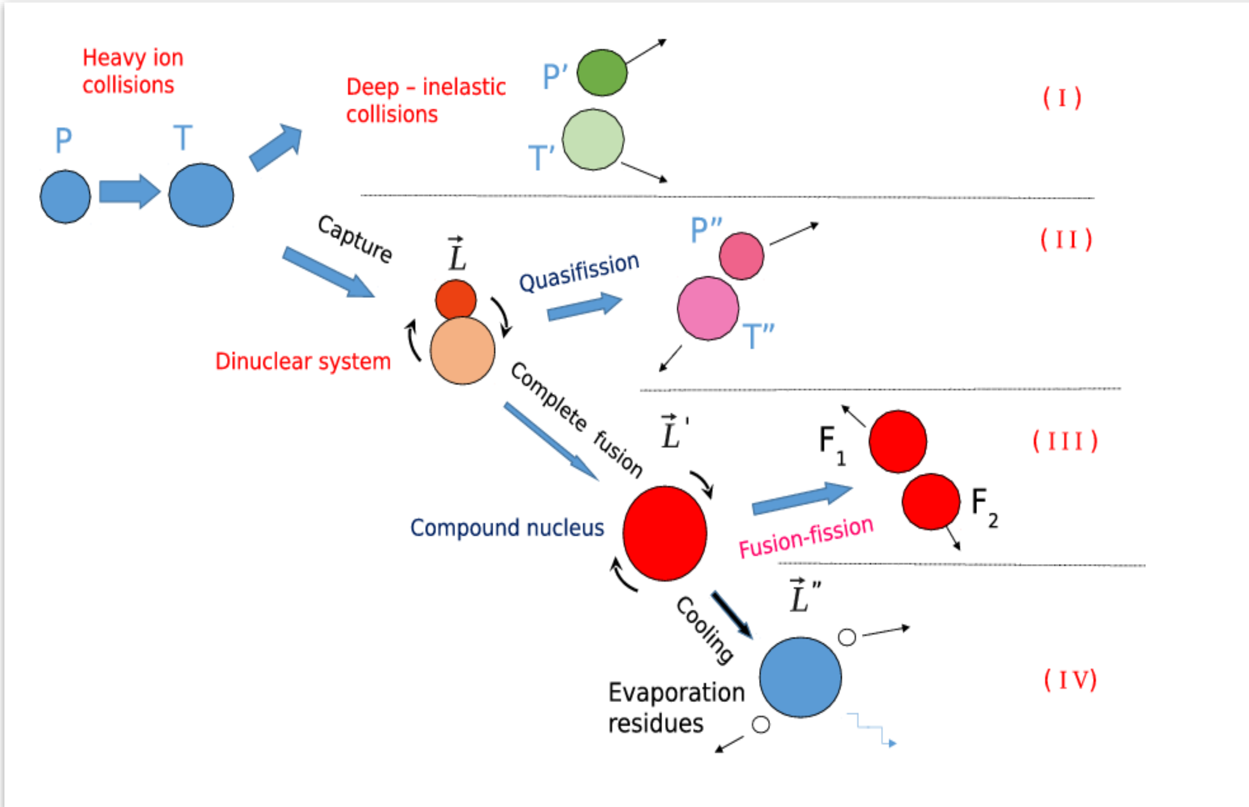

Fig 2.10 Nuclear reactions

2.6 Parameters in a nuclear reaction

The following parameters of nuclear reaction can be measured experimentally.

1. Excitation function: The distribution of the cross-section as a function of the beam energy is called the 'excitation function'.

2. Angular distribution: It is used to understand the dynamics of heavy ion collisions. The direction of fragments is given by the orientation of the nuclear symmetry axis.

3. Energy spectra: Energy spectra give the relation between energy of projectile and energy of emitted particle.

4. Emitted particles: Emitted particles can be identified and detected.

2.6.1 Measurement of reaction cross section

The reaction cross section is a key tool to study nuclear reaction. The reaction cross section represents the probability for a nuclear reaction to occur. Cross section has the dimension of area. Unit of cross section is barn, 1barn $=10^{-28}m^2$

1. Experimental Technique

It is possible to measure cross section experimentally. Cross section is something which tells the probability for the reaction to occur. The experimental data is available on the on the following data banks (EXFOR – IAEA), (JCPRG – JAPAN), (CINDA – CHINA) etc.,

2. Theoretical Method

In this method we use the nuclear reaction codes which are based on available nuclear reaction models. Also I used codes EMPIRE 3.2.3 Malta and Talys 1.92 , which are applicable for the light ion induced nuclear reaction calculation purpose.

Chapter 3

COMPUTER CODE

3.1 Nuclear reaction code Talys 1.92

a) What is TALYS 1.92

TALYS is a computer code system for the analysis and prediction of nuclear reactions. The main objective behind its development is the simulation of nuclear reactions which involve neutrons, photons, protons,deuterons,tritons,3He- and alpha-particles, in the 1KeV −200MeV energy range and for target must have the mass 12 or heavier , Many reaction models have been incorporated in this code which are used to calculate the reaction data.

b) Important features of TALYS 1.92

• In general, an exact implementation of many of the latest nu-clear models for direct, compound pre-equilibrium and fission reactions.

• A continuous, smooth description of reaction mechanisms over a wide energy range (0.001 − 200MeV) and mass number range ($12 < A < 339$).

• Completely integrated optical model and coupled-channels calculations by the ECIS − 06 code.

• Total and partial cross sections, energy spectra, angular distributions, double-differential spectra and recoils.

• Excitation functions for residual nuclide production, including isomeric cross sections.

• Automatic reference to nuclear structure parameters as masses, discrete levels, resonances, level density parameters, deformation parameters, fission barrier and gamma-ray parameters, generally from the IAEA Reference Input Parameter Library.

• Various fission models to predict cross sections and fission fragment and product yields, and neutron multiplicities.

• Models for pre-equilibrium reactions, and multiple pre-equilibriumreactions up to any order.

• Medical isotope production yields as a function of accelerator energy and beam current.

• Automatic generation of nuclear data in ENDF-6 format.

c) General Input Parameters in TALYS 1.92

With TALYS, a complete set of cross sections can be obtained with minimal a four-line input file of the type:

projectile n

element Fe

mass 56

energy 14.

These are the least four data we need to give as our input to Talys to be able to get the output. Eight different symbols can be given as projectile , namely n, p, d, t, h, a, g representing neutron, proton, deuteron, triton,3He, alpha and gamma, respectively, and 0, which is used if instead of a nuclear reaction (projectile +

target)we start with an initial population of an excited nucleus. Either the nuclear symbol or the charge number Z of the target nucleus can be

given. Possible values for element range from Li(3)to Ds(110).The incident energy in MeV. The user has four possibilities:

i. A single incident energy is specified in the input as a real number.

ii. A filename is specified, where the corresponding file contains a series of incident energies, with one incident energy per line.

If we want to be more specific regarding the calculation we have many other commands. In the following I will mention some of the input code with their outcome.

• target 1 → target in its first excited state

• ejectile → by default include all possible outgoing particles,

i.e. ejectiles g n p d t h a

• bins → The number of excitation energy bins in which the

continuum of the initial compound nucleus is divided for further decay

• maxN → The maximal number of neutrons away from the initial compound nucleus that is considered in a chain of nuclides

• angles → Number of emission angles for reactions to discrete states.

• anglescont → Number of emission angles for reactions to the continuum.

• relativistic → Flag for relativistic kinematics

3.2 Nuclear reaction code EMPIRE 3.2.3 MALTA

MALTA, has been designed to perform nuclear reaction calculations over a wide range of energies and incident particles. The covered energy range is from resonance region (~keV) to several hundreds of MeV, and the projectile could be any nucleon, ion (including heavy ion) or a photon. EMPIRE is equipped with a complex system of codes to describe all the important nuclear reaction mechanisms. The optical model and the direct reaction calculations were performed by the ECIS - 03 code. The optical model, discrete levels and deformation parameters were retrieved from the RIPL - 2 library. The direct channel calculations were performed by using the coupled channels model or the distorted wave Born approximation (DWBA) method. EMPIRE contains both the quantum mechanical (MSD/MSC) and classical models (DEGAS, PCROSS, HMS) to describe pre - equilibrium reactions. The following is the system that I studied.In the following system with their characterization are given. The graph shows theoretical and experimental predictions using EMPIRE 3.2.3 MALTA and TALYS 1.92. Here cross section versus lab frame energies are plotted.

Chapter 4

WORK DONE

The following is the system that I have studied. In the following system with their characterization are given. The graph shows theoretical and experimental predictions using EMPIRE 3.2.3 MALTA and TALYS 1.92. Here cross section versus lab frame energies are plotted.

Systems studied and their characteristics

Here ^{15}O is populated through ion induced reactions.ie, $^{14}N(p,\gamma)^{15}O$.
Here we have investigated the input parameters like effect of spin parity, the entrance channel effect, the effect of imparting energy (Incident energy in lab frame) etc.
Activation Cross section and Radiative Capture Cross section of proton through the $^{14}N(p,\gamma)^{15}O$ reaction at Low Energy from 20 – 110 MeV

$$^{14}N(p,\gamma)^{15}O$$

$$^{14}_{7}N + \,^{1}_{1}H \rightarrow \,^{15}_{8}O \rightarrow \,^{15}_{8}O + \gamma$$

 This fusion process typically releases energy, which can be seen as the production of gamma rays (γ) in the subsequent step.

(a) Coulomb energy at the centre of the mass ECM =2.27Mev

(b) Coulomb energy at the lab frame E_{Lab} = 2.4321Mev

(c) Spin-parity of ^{15}O $J\pi$ = -1/2

(d) Half-life of ^{15}O $T_{1/2}$ = 122.24 sec

(e) Spin-parity of ^{14}N $J\pi$ = +1

(f) Half-life of ^{14}N $T_{1/2}$ = stable

Chapter 5

RESULT AND DISCUSSION

Proton and α particle capture reactions play key roles across much of nuclear astrophysics, in both quiescent and explosive fusion scenarios. The rates of capture reactions strongly influence the generation of energy, neutrino production, and nucleosynthesis in stars, and also impact the nature of stellar explosions such as classical novae, Type-I x-ray bursts, and supernovae. As astrophysical models for these processes become more sophisticated, the impetus to determine accurate reaction rates grows more compelling.

The normalised experimental data compared with the results of nuclear model calculations using two codes, EMPIRE and TALYS. The nuclear reaction code system, EMPIRE 3.2.3 MALTA has been designed to perform nuclear reaction calculations over a wide range of energies and incident particles. The normalized experimental data were compared with the results of nuclear model calculations using codes, namely EMPIRE and TALYS. The model parameters were adjusted to get a better agreement between the experimental and calculated cross section values. The estimation of the best set of cross section data was obtained by multiplying the nuclear model calculations with the normalization factor, which was based on the ratio of measured to calculated cross section (*i.e.* measurement/calculation). An iterative approach was applied for the best approximation of the normalization factor.

The radiative capture process is a many-body nuclear physics problem. Although nuclear theory is making great strides towards heavy systems, experimental input is still required in all cases, except perhaps for the very lightest nuclei. For quiescent fusion, the major experimental challenge is that capture cross sections are extremely small and often unmeasurable in the astrophysical energy window. Such measurements are performed at the lowest energies feasible and theoretical models are used for the extrapolation to astrophysical energies. For explosive fusion, a new challenge emerges: the need to perform capture measurements on short-lived radioactive nuclei. Some of these measurements can now be performed using radioactive ion beams. For both scenarios, it is also productive to study the energies and spectroscopic properties of resonant or bound states using indirect techniques, as in many cases this information allows the reaction rate to estimate with good accuracy. The excitation function graph and the data tables are following.

Graph Plotting; The excitation function graphs

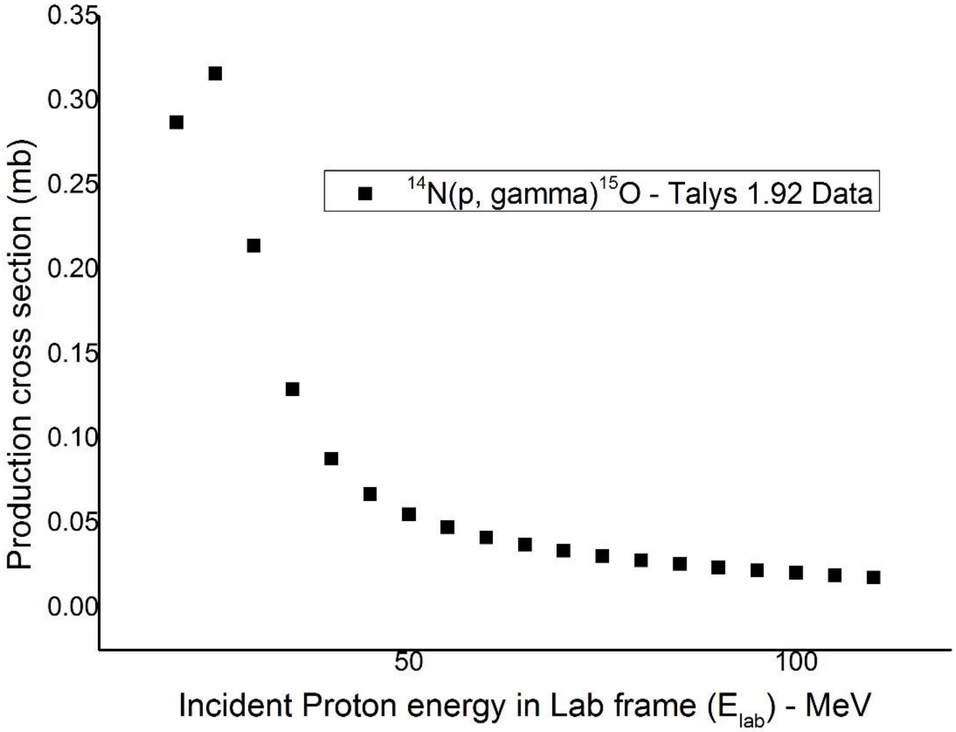

Fig 5.1. Excitation function graph 1. Theoretical excitation functions for protons induced reactions on ^{14}N. The data extracted from Talys 1.92 nuclear reaction model code

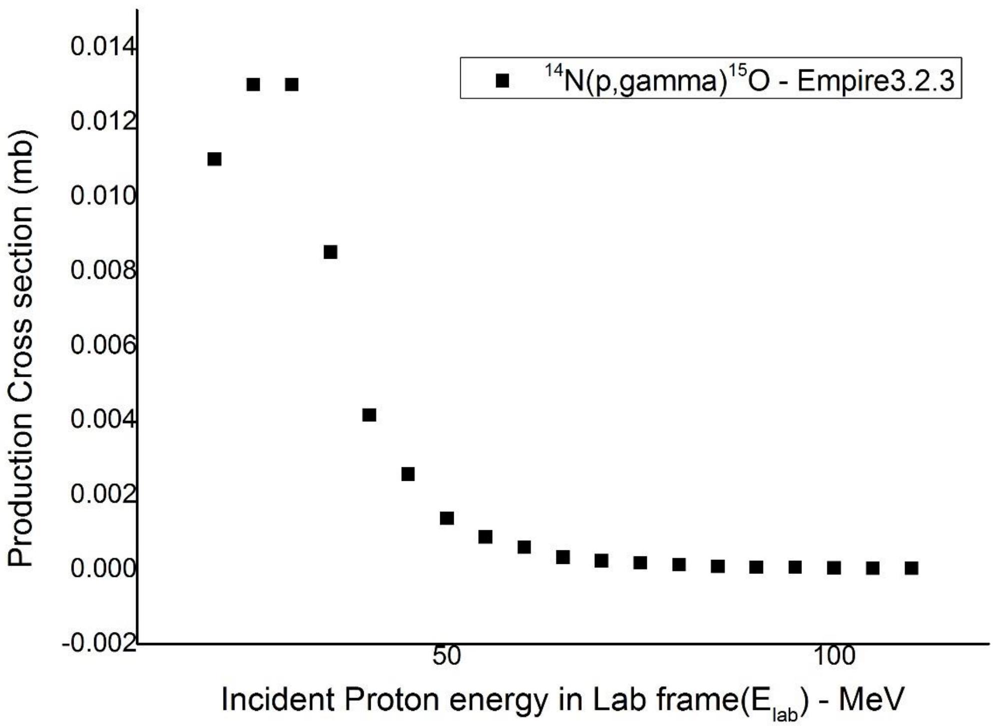

Fig 5.2. Excitation function graph 2. Theoretical excitation functions for protons induced reactions on ^{14}N. The data extracted from Empire 3.2.3 nuclear reaction model code

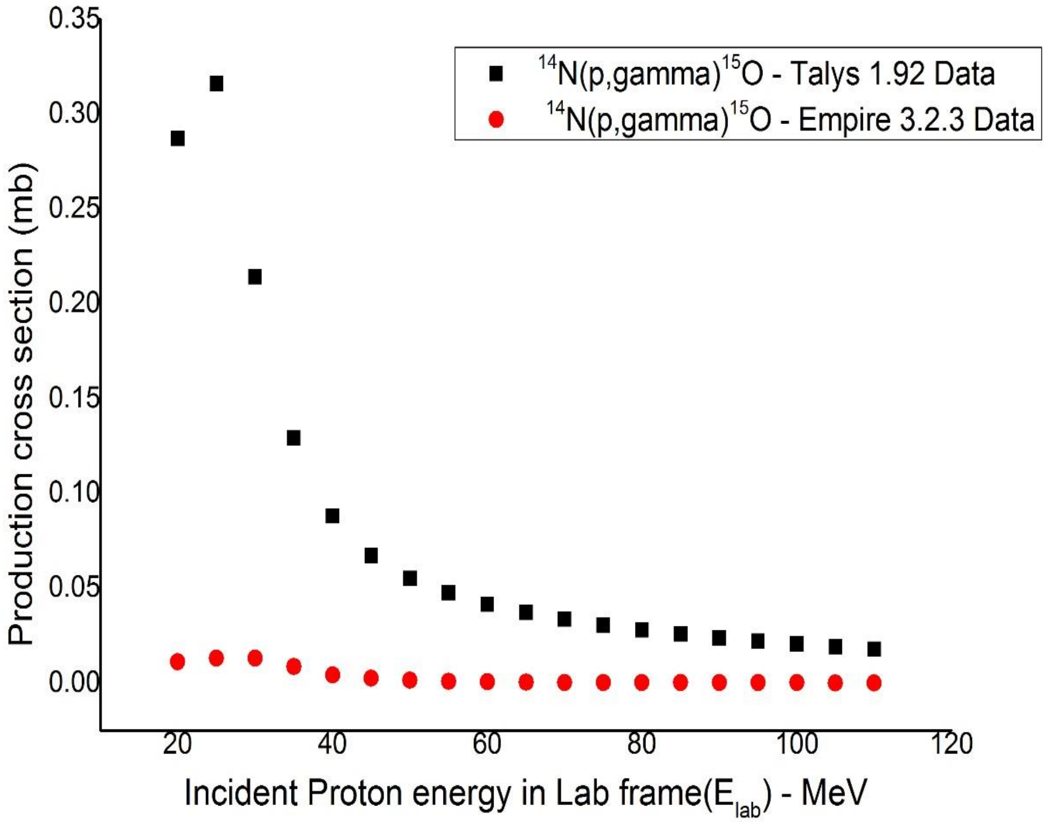

Fig 5.3. Excitation function graph 3. Theoretical excitation functions for protons induced reactions on ^{14}N. The data extracted from Empire 3.2.3 and Talys 1.92 nuclear reaction model code

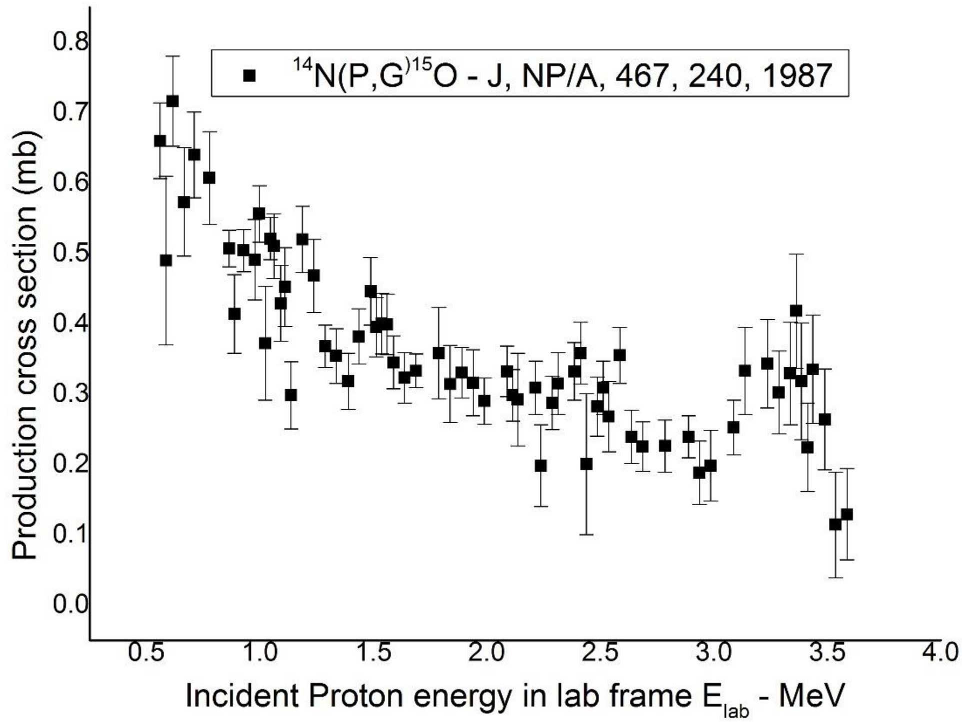

Fig 5.4. Experimental data Graph. Experimental data from J,NP/A,467,240,1987 using EXFOR

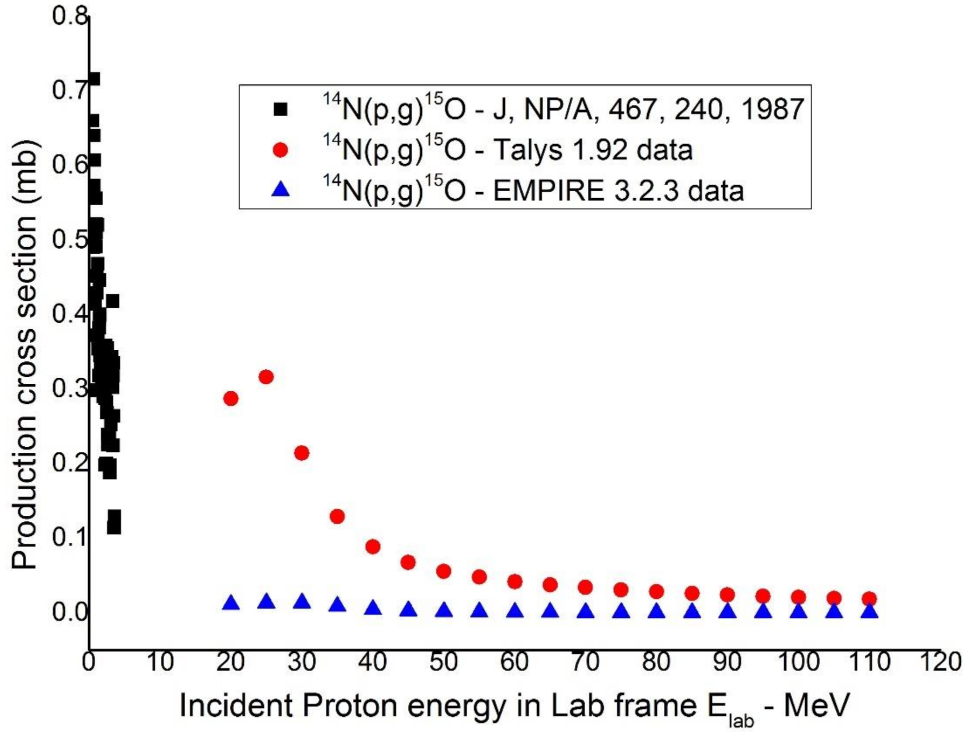

Fig 5.5. Combined Graph 5.Combination of selected experimental data (J,NP/A,467,240,1987) and theoretical data using nuclear codes Talys 1.92 and EMPIRE 3.2.3.

TABULATION: Data used for studying the reaction.

Energy (MeV)	Production cross section (mb) Talys 1.92 Data	Production cross section (mb) Empire 3.2.3 Data
20	0.287	0.011
25	0.316	0.013
30	0.214	0.013
35	0.129	0.0085
40	0.088	0.00413
45	0.067	0.00255
50	0.055	0.00136
55	0.0474	0.000863
60	0.0414	0.000591
65	0.0371	0.000323
70	0.0335	0.000221
75	0.0304	0.000163
80	0.0279	0.000122
85	0.0257	0.0000684
90	0.0237	0.0000530
95	0.0220	0.0000545
100	0.0204	0.0000318
105	0.0190	0.0000257
110	0.0178	0.0000209

Table 5.1: The data is obtained from Talys 1.92 and EMPIRE 3.2.3 nuclear reaction code.

Decay scheme of ^{15}O

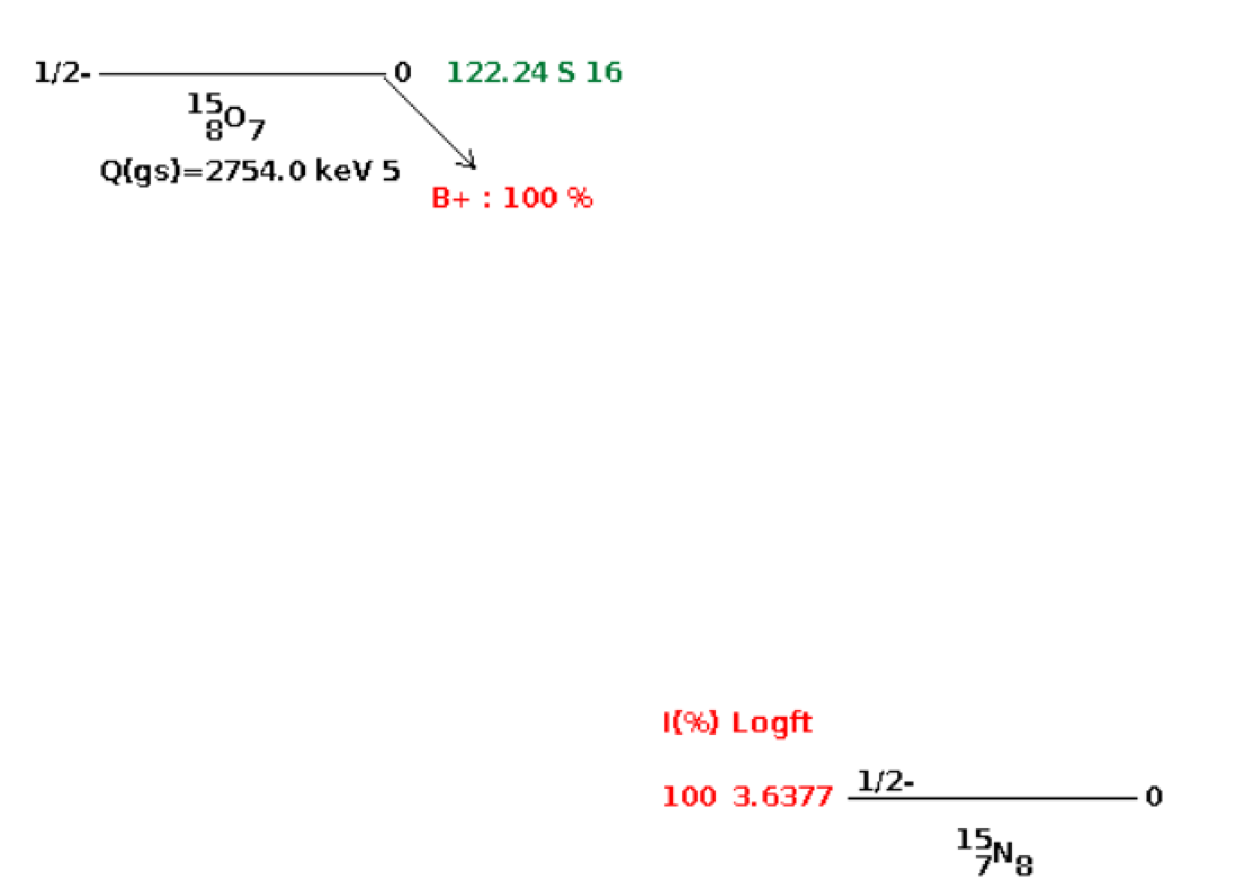

Fig 5.6 Typical decay scheme of ^{15}O

Chapter 6

CONCLUSION

To conclude, this thesis focuses on the $^{14}N(p,\gamma)^{15}O$ reaction, which determines the rate of the first CNO cycle and consequently influences the energy production and nucleosynthesis of a star. It is of particular importance for the understanding of the main astrophysical open issues, such as the Globular Clusters' age determination, which depends strongly on the rate of this reaction and gives an upper limit to the age of the Universe. The cross section of the $^{14}N(p,\gamma)^{15}O$ reaction has to be determined with high precision with two nuclear model code calculation Talys 1.92 and EMPIRE 3.2.3

6.1 REFERENCE

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