Chapter 1

Introduction

In this world with developing nations, the race to meet the increasing energy demand for everyday utilities is resulting with increased green house gases and pollutant into earth's atmosphere. There are ways to shift our dependence from conventional to non-conventional sources of energy like; reactors, windmill & solar power plants etc. Energy produced by a nuclear reactor is efficient and affordable. With the attractive features around, it also produces radio-toxic waste that is the main drawback of reactor generated energy. The problem of nuclear waste can be addressed by a high neutron flux accelerator, by converting it into stable nuclei. All these efforts can only be made if we have sufficient precise nuclear reaction data for different reactor based isotopes. Therefore, in the present work, nuclear reaction cross-section data have been measured for the isotopes vital for reactor based applications. The present chapter provides a clear insight into the present world energy scenario followed by the descriptions of advanced reactor systems like ADSs and ITER. The chapter puts light on the usefulness of reaction data in medical applications also. Then it summarizes different reaction mechanisms based on incident particle energy. Later, it provides motivation, objectives and the overview of the present thesis.

1.1 Preamble

The demand for energy in the form of electricity is ever increasing, which needs to be tackled by more advanced and efficient sources of the energy production. A nuclear reactor harness the energy from fissioning uranium atoms is the best source yet, which can meet the increasing demand for energy worldwide. There are a total number of 451 reactors [1] working across the different countries producing a combined electricity of around 400.3 Giga Watt energy (GW_e) [1]. In addition to this, 52 new reactors are under construction worldwide together with which the net installed output will be 527.04 GW_e [1]. A schematic diagram given in Figure 1.1 shows the number of active nuclear reactor installations for major countries. As the underdeveloped and small countries are developing the reactor and accelerator technologies, more nuclear reactor facilities are being installed, which will increase the total amount of radio-chemical waste. Figure 1.2 shows the nuclear energy share in different countries as compared to India. In India, there are 22 operational reactors and 7 are being constructed [2]. An output of 35388.68 Giga Watt hour (GW.h) is produced by nuclear reactors which is 3.13% of the total energy produced from all sources combined. This shows that India largely depends on the conventional sources of energy and it needs to be taken care by further advancement of reactor technology to reduce the green house emission. The produced short-lived nuclear waste from a running reactor takes hundreds of year to get stabilized, or in other words, the activity from waste material comes under safe limits. A few isotopes like, ^{237}Np and ^{241}Am have a half-life of 2.15 million years and 432.6 years [3], respectively. These isotopes can only be destroyed in a reactor with high neutron flux. Table 1.1 shows important minor actinides with their production per year, half-lives and dose rates. Another major problem with reactors is the production of the fission products. A large number isotopes get produced from the fission reaction, which are highly active for early 200 years. After 200 years, fission products get stabilized and minor actinides present the main problem. With 22 operational reactors, India has only 3 spent fuel storage facility and 1 spent fuel reprocessing and recycling facility [4]. More than 800 experimental reactors are being used in 67 different countries for the research, education and development of new technologies, which can tackle with the problems generated by conventional reactors [5]. The problem of nuclear waste might be solved by incineration of these long-lived isotopes and minor actinides by using a high energy accelerator capable of producing neutrons from spallation reaction of protons on a heavy metal. Such system was first introduced by C. Rubia [6] as an accelerator driven system (ADSs) which might be able to

work as nuclear waste incinerator and can produce energy from utilizing Th as fuel. Details about ADSs are provided in next section 1.2.

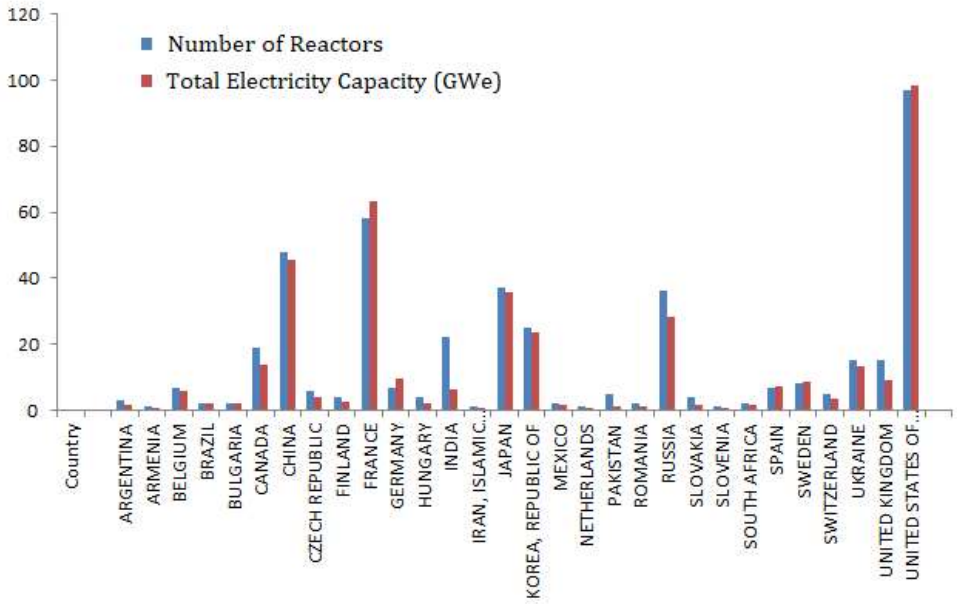

Figure 1.1: A plot showing a country wise data of total number of operational reactors with their net energy production capacity (GWe) [1]

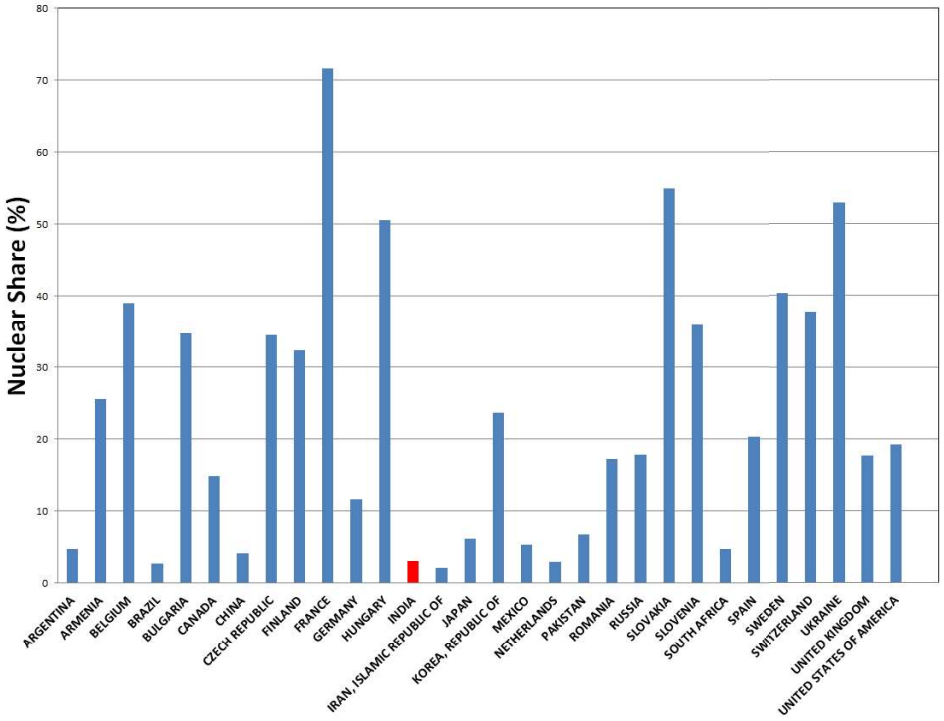

Figure 1.2: Country wise nuclear share to their total produced electricity combining all the resources [1].

Table 1.1: Quantities of minor actinides produced annually from a conventional pressurized water reactor with a standard burn-up of 33 gigawatt per day. These quantities are quoted for 1 ton and 23 tons of annual consumption of uranium.

Minor Actinides	kg Produced per Year		Half-life	Dose Factor
	1 ton U	Reactor	(Years)	Sv/Gbq
^{237}Np	0.43	10.1	2,140,000	110
^{241}Am	0.22	5.2	432.6	200
^{242}Am	0.0007	0.017	152	190
^{243}Am	0.101	3.30	7.380	200
^{242}Cm	0.00013	0.003	0.44	130
^{243}Cm	0.00032	0.007	28.5	200
^{244}Cm	0.024	0.56	18.1	160
Total Minor Actinides	0.582	17.5		

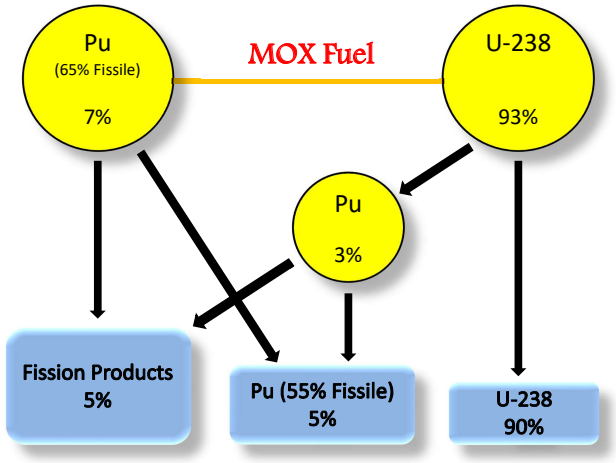

Figure 1.3: A schematic diagram showing the reactions and the products in a typical MOX fuel.

Major efforts are being made to harness the power of high energy fusion reaction, which normally occur within the Sun with the effect of intense heat and gravity, by developing a fusion reactor based reactor known as International Thermonuclear Experimental Reactor (ITER) or Tokamak [7]. Like any other source of generation of electricity which includes a source of power in the form of heat and a mechanical device which converts the heat coming from the source into electrical energy by using steam, a tokamak absorbs the heat coming from the fusion reaction through its inside walls

and convert the water into steam which later used to rotate turbines to produce electrical energy. The advantage of fusion based production is that, it does not produce any hazardous waste behind and is completely environment friendly. First developed by Soviets in 1960's, Tokamak has been adopted by world scientific community and an ITER (worlds largest configuration of magnetic fusion device) collaboration is formed aiming the first ITER plasma in December 2025 [7]. A detailed discussion on ITER and its operation is provided in section 1.3. Another way to minimize

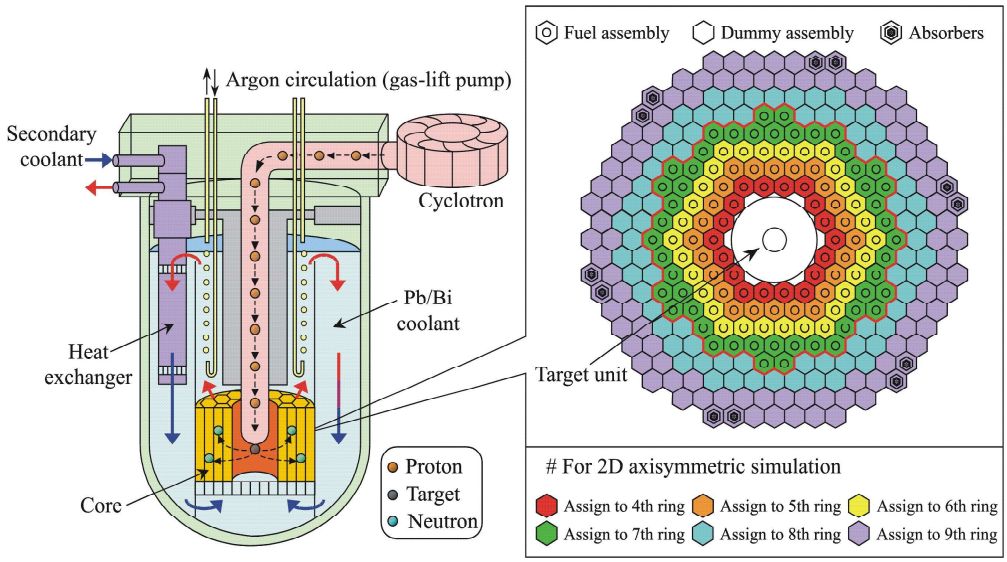

Figure 1.4: A schematic diagram of Accelerator Driven Sub-critical System (ADSs) [11]

the produced nuclear waste is to utilize it as metal oxide (MOX) fuel in ADSs and fast reactors. The current means of doing this is by separating the plutonium and recycling that, mixed with depleted uranium, as mixed oxide (MOX) fuel. In every nuclear reactor uranium-235 and uranium-238 form new heavier isotopes due to fission of ^{235}U and neutron capture by ^{238}U. Most of the fuel mass in a reactor is ^{238}U. This can become ^{239}Pu and ^{240}Pu, ^{241}Pu, ^{242}Pu as well as other transuranic isotopes by successive neutron capture. Among which, ^{239}Pu and ^{241}Pu are fissile isotopes, like ^{235}U. Normally, with the fuel being changed every three years or so, about half of the ^{239}Pu is 'burned' in the reactor, providing about one third of the total energy. It behaves like ^{235}U and its fission releases a similar amount of energy. The higher the burn-up, the less fissile plutonium remains in the used fuel. Typically about one percent of the used fuel discharged from a reactor is plutonium, and some two thirds of this is fissile. A schematics of a general MOX fuel is shown in Figure 1.3.

1.2 Accelerator Driven Sub-critical Systems (ADSs)

An accelerator driven system [6, 8, 9] is one which generates neutrons by bombarding high energy protons (usually > 500 MeV) on a heavy metal target like, tungsten, tantalum, depleted uranium, thorium, zirconium, lead-bismuth, mercury etc. A schematics of ADSs is shown in Figure 1.4 [11][1].

An ADSs with such power is capable of producing 20-30 spallation neutrons per 1000 MeV of the incident proton beam energy. If the spallation assembly is surrounded by fissile uranium, plutonium or ^{232}Th (which can be converted into fissile isotope ^{233}U) a sustainable fission reaction can be achieved. In such systems, the fission reaction is driven by the spallation neutrons (10% of the total neutron flux in the assembly) and the additional neutrons coming from the fission. The ADSs can only be operated by the spallation neutrons as the fuel used does not have sufficient fission-to-capture ratio to sustain the reaction. Therefore, the whole system can be shut down by only stopping the proton beam, which makes the whole system safe and functional. Though the reaction rate is less in ADSs as compared to a conventional reactor but still the reactor needs to be cooled down by a cooling agent. The controlling of the reaction by proton beam makes the reactor sub-critical.

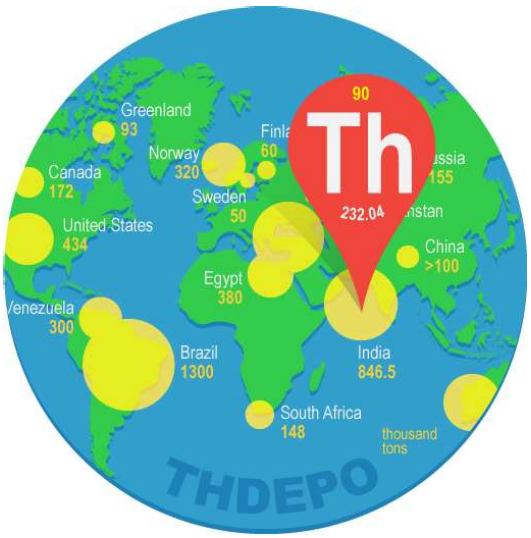

Figure 1.5: An illustration showing the thorium deposits (in thousand tonnes) around the world [10].

The abundances of Th all over the world makes the ADSs an attractive option for energy production. ^{232}Th can be converted to ^{233}Th in ADSs by capturing a neutron, which later decays to ^{233}U. Since, neutron flux inside ADSs is not sufficient to keep the reaction on, a driver fuel, either plutonium or enriched U, need to be mixed with Th. Among the fast developing countries, India has the largest Th deposit of around 846.5 thousand tons, which is shown in Figure 1.5 [10][2], therefore, India is actively researching on ADSs to assist the ongoing reactors for efficient power production. The core

[1] The image has been taken from the following webpage https://www.iket.kit.edu/221.php

[2] Image copyrights © 2012 International Atomic Energy Agency (IAEA)

of an ADSs is mostly thorium based, located at the bottom of a large tank filled with $\approx$ 8000 tonnes of molten lead or lead-bismuth acting as a coolant at high temperatures. The spallation assembly is kept isolated from the surroundings by an air gap which can also be used for providing additional cooling for the reactor. The proton beam is targeted on spallation material through a beam pipe causing breading of Th into ^{233}U. It is proposed that a 10 MW proton beam might produce $\approx$ 600 MW_e of electricity. The only hurdle in order to achieve such an operating system is the availability of an accelerator capable of producing a proton beam above 1 MW.

There are several research activities going on around the globe to develop an accelerator or cyclotron to deliver such power. India is running a small research reactor *Kamini*, which utilizes U-233 breded from ^{232}Th to be used in another reactor [12]. Another Power Reactor Thoria Reprocessing Facility (PRTRF) is planned at Bhabha Atomic Research Centre (BARC) for the research work related to the high γ levels of ^{232}U [13].

The advantages and disadvantages of an ADSs are summarized as follows:

Advantages:

- Much lesser long-lived actinides production
- Minimal or zero Probability for a runaway reaction
- Efficient burning of minor actinides
- Low pressure requirements

Disadvantages:

- More complex structure design and operation
- Less reliable power production due to accelerator assistance
- Large production of radioactive isotopes in spallation target
- Dangers related to the high energy proton beam

1.3 International Thermonuclear Experimental Reactor (ITER)

ITER, the most challenging project across the globe is designed to deliver power from the energy released from the fusion of two nuclei [7,14]. Fusion naturally occur in the cores of massive stellar bodies like our Sun and other distant stars. In fusion two hydrogen nuclei fuse to make heavier helium

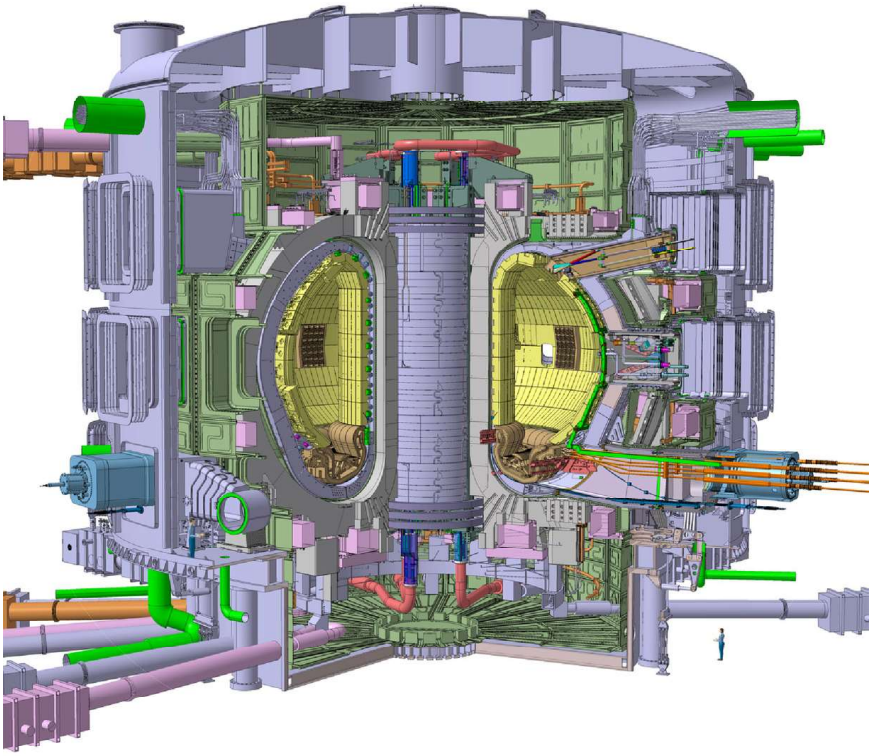

Figure 1.6: A schematic diagram of International Thermonuclear Experimental Reactor (ITER) [7]

nucleus, thus releases enormous amount of energy in the form of heat. The two isotopes of hydrogen, deuterium (D) and tritium (T) fuses together at much lower temperature than hydrogen and releases energy greater than the fusion of hydrogen following the conditions:

- Very high temperature of the order of 1.5×10^8 Celsius.
- Sufficient plasma particle density to ensure collision do occur.
- Sufficient plasma confinement time to increase the effective volume.

Since, the amount of energy produced by any reactor is proportional to the number of energy releasing events happening inside the reactor, therefore, larger plasma volume and greater confinement times are required to maintain proper energy gain. The maximum energy gain yet achieved by a tokamak is $Q = 0.67$, by European tokamak JET (1997) producing 16 MW O/P power from an 24 MW I/P heating power. The ITER is designed to deliver ten fold power output with $Q = 10.0$. A schematic diagram of proposed ITER (tokamak) is shown in Figure 1.6 [7][3]. As can be seen

[3]Image copyright © 2019, ITER ORGANIZATION

from the figure, it consists of a doughnut-shaped central vacuum chamber designed to hold the plasma by surrounding super-magnetic toroidal coils. The magnetic coils placed all around the central chamber are used to confine the plasma away from the walls. The conditions given above help producing a sustainable energy from the fusing D-T reaction.

1.4 Nuclear Medicine: *An application of fission products and relative nuclear data*

As discussed above, an operational nuclear reactor produces a considerable amount of waste containing, long-lived isotopes, minor actinides and fission products. Some of these products can only be made within a reactor core having such high neutron flux. Many of these isotopes are important in medicine and often used for different treatments. The production routes of these isotopes using a reactor, subsequent separation techniques to achieve a certain enrichment level, and transportation effect the cost of these isotopes, thus, benefits a very small percentage of population as per the need. Nuclear reactions using high flux accelerators may enable us to produce large volumes of these rare isotopes by using simplified reaction channels. Also, the nuclear reaction data for such isotopes is demanded by medical groups for dose estimation, finding cure to different deceases and to study the effects of radiation for cancer treatments. In the present work, excitation functions have been studied for a number of isotopes of prime interest in nuclear medicine by using proton and neutron reaction channels. A list of these isotopes with their applications is provided in Table 1.2.

From the discussion provided above, it is clear that the nuclear reaction cross-section is a primary input to make new developments in reactor/accelerator technology. A general description about the different reaction mechanisms depending upon the incident projectile energy are discussed in the following section.

1.5 Nuclear Reactions: General Approach

A nuclear reaction is said to be taken place when a target nucleus is bombarded with a projectile nucleus with sufficient energy to overcome the fusion barrier (V_{fus}), which is zero in case of neutron as projectile, between the two interacting nuclei. As a result, a variety of reactions can take place depending upon the energy and nature of the projectile. In general, a compound system may form which then de-excites with the emission of γ, n, p or α-particles. A general nuclear reaction can be written as,

Table 1.2: List of medical isotopes used for cross-section measurements in the present work

Isotope	Production Channel	Medical Application
^{99}Tc	$^{100}Mo(n,2n)^{99}Mo$ Decay	Imaging of skeleton and heart muscle in particular, but also used for brain, thyroid, lungs etc. organs
^{58}Co	$^{58}Ni(n,p)$	trace element for the absorption of vitamin B12 in the human body
^{89g}Zr	$^{93}Nb(p,\alpha)^{89}Zr$	PET Diagnostics
^{47}Sc	$^{48}Ti(p,2p)$ $^{49}Ti(p,^{3}He)$ $^{50}Ti(p,\alpha)$	Radio-Immunotherapy
^{46}Sc	$^{47}Ti(p,2p)$ $^{48}Ti(p,^{3}He)$ $^{49}Ti(p,\alpha)$ $^{50}Ti(p,n\alpha)$	A labeled micro-sphere for the investigation of an increased number of myocardial blood flow
^{44m}Sc	$^{48}Ti(p,n\alpha)$ $^{47}Ti(p,\alpha)$	Used for nuclear imaging using $\beta^{+}-\gamma$ coincidences

$$^{n}x_{z} +^{N} X_{Z} \rightarrow^{N+a} Y_{Z+b} +^{n-a} y_{z-b} + Q$$

where, $^{n}x_{z}$ and NX_{Z} are the projectile and target nucleus in the incoming channel, $^{N+a}Y_{Z+b}$ is the residual nucleus with $^{n-a}y_{z-b}$ as the ejectile in the outgoing channel. Q is known as the "Q-value" of the reaction, which may be refer as the algebraic difference of the masses of incoming and the outgoing channels. The sign of the Q-value signifies whether the reaction would be an exoergic ($Q > 0$; energy is evolved) or an endoergic ($Q < 0$; energy is absorbed) reaction. Since there is a net deficit of the energy in the endoergic processes, therefore, there is a definite amount of energy required to start these reactions, known as the threshold (E_{th}) energy, can be given

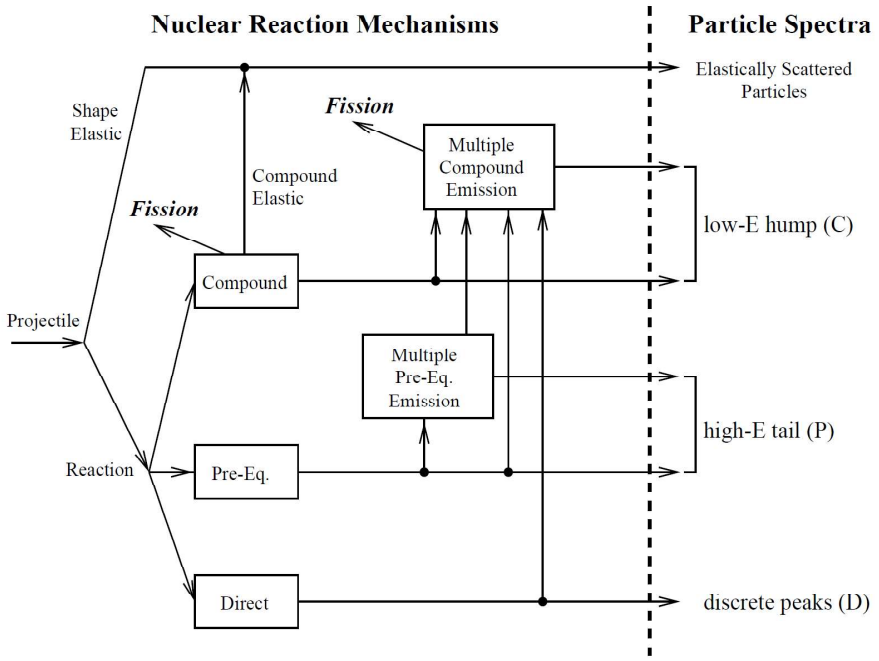

Figure 1.7: A chart showing different nuclear reactions and their outgoing particle spectra. The labels, C, P and D corresponds to the labels given in Figure 1.8

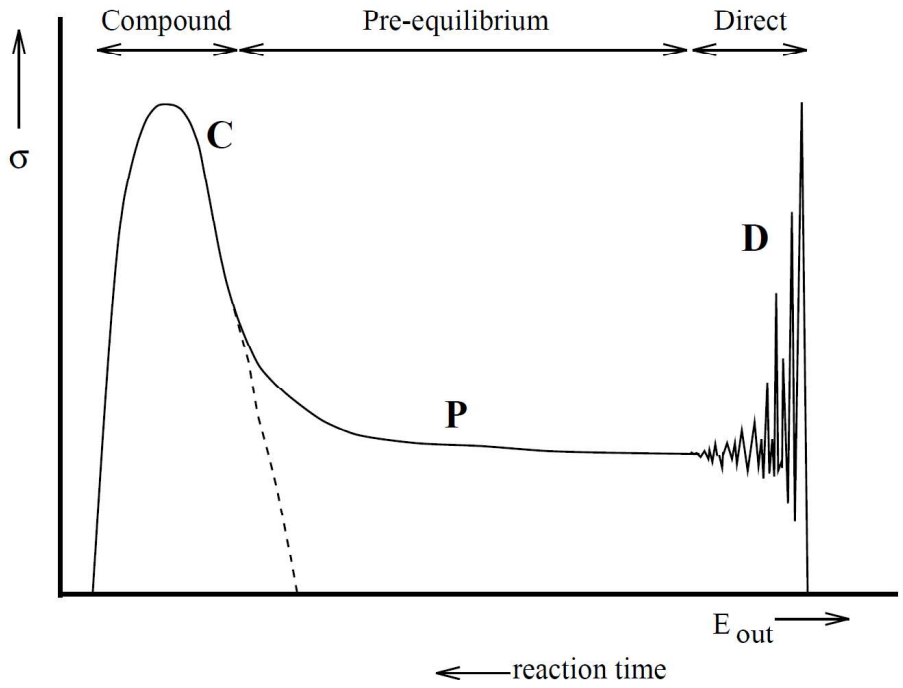

Figure 1.8: Schematic diagram of an outgoing particle spectra contributing from direct (D), compound nucleus (C) and pre-equilibrium (P) reactions. The dashed line separates the compound nucleus contribution from rest of the spectrum.

as,

$$E_{th} = 1 + \frac{M_x}{M_X}|-Q| \tag{1.1}$$

where, M_x and M_X are the masses of projectile and target nucleus. Since, an energy greater than E_{th} must be supplied to the projectile, in the form of kinetic energy, therefore, the nuclear reactions can be classified depending upon the energy of the projectile E_p as,

- $E_p < 0.2$ MeV →Elastic scattering and capture (compound nucleus reaction)
- $0.2 < E_p < 4$ MeV →Inelastic scattering to discrete states (compound and direct reactions)
- $E_p > 4$ MeV →Pre-equilibrium reactions
- $E_p > 8$ MeV →Multiple compound emissions
- $E_p > 40$ MeV →Multiple pre-equilibrium emissions

The different reactions mentioned above are also summarized in the Figure 1.7. The nuclear reactions mentioned above the compound nucleus, direct and pre-equilibrium processes are important from the perspective of the current work. The energy region where

1.6 Neutron Activation Analysis (NAA)

Neutron activation analysis is a technique commonly used for on-line and off-line γ-ray spectrometry. The target gets irradiated with neutrons or an ion having incident energy greater than the coulomb barrier of the target nucleus. A diagram showing the formation and de-excitation of a composite system is presented in Figure 1.9. The projectile and target together may form a composite system known as compound nucleus or direct reactions may take place depending upon the incident energy. The compound nucleus thus formed equilibrated via emission of either prompt γ-rays or by emitting single particle as n, p, α-particles or by emitting cluster of particles. After the equilibrium is achieved the compound nucleus decays to form a radionuclide which then subsequently decays following its half-life. The γ-lines coming from the de-excitation of the isotope formed, may be recorded by a suitable detector to extract the desired information. The detectors may be used during the target irradiation which is referred as on-line measurement on the other hand if the γ-detection is done after

the target is being irradiated, the technique is commonly known as off-line γ-ray measurement. A general formula has been developed for the measurement of cross-section at different incident particle energies using the decay properties and counting statistics of the γ-ray coming from the de-excitation of desired nuclei is provided in Chapter 3.

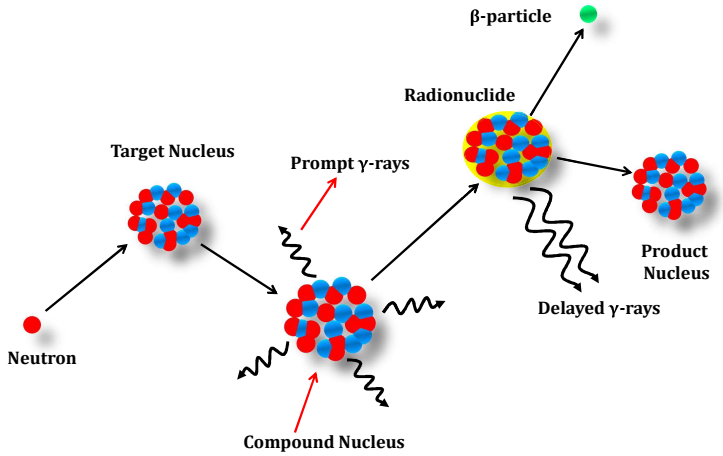

Figure 1.9: A general representation of nuclear reaction on a target nucleus with neutron being the incident particle.

1.7 Literature Survey

The detailed literature survey shows that exhaustive experimental work has been carried out in the low energy neutron induced reactions of structural as well as fuel materials. However, the data are usually scarce above the incident neutron energies of 10 MeV. In addition, there are discrepancies in the available data from different authors in the measured as well as evaluated data. Effects of neutron generator and monitor reactions[4] can be observed easily from the minor disagreement of the data from different authors. The EXFOR compilation on the neutron induced data also indicates that there could be an involvement of pre-equilibrium (PE) process in the formation of the reaction residues at these energies, which should be investigated by using different nuclear model codes. It has also been noticed that most of the authors have reported the uncertainties without considering the error from the monitor reaction data. Since, the monitor reaction data also contain significant uncertainties, thus it becomes important to use a proper error

[4]Check Tables 2.3 and 2.4 for details.

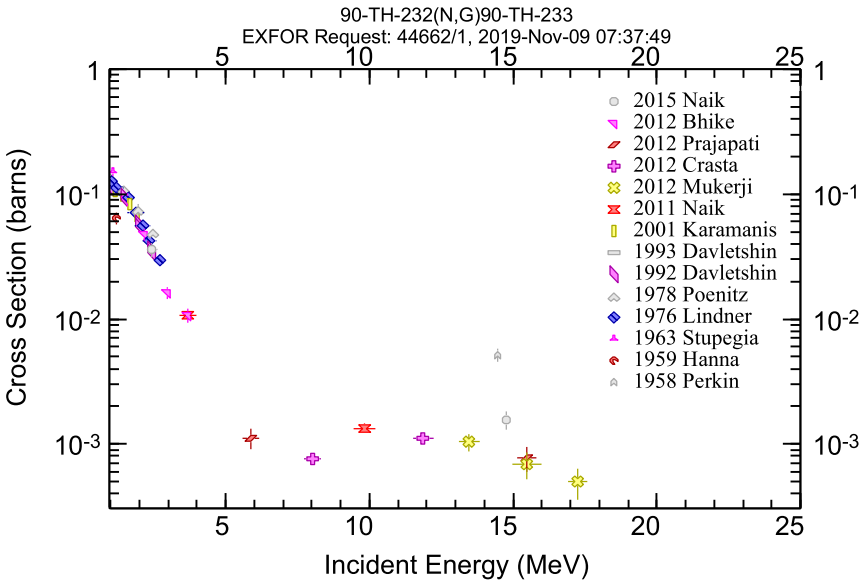

Figure 1.10: Excitation function of the $^{232}Th(n,\gamma)^{233}Th$ reaction cross-sections within the energy range of 1-25 MeV. The plot has been taken directly from the EXFOR website [15].

propagation method to involve the errors coming from each parameter used in the calculations.

For the representation[5], an EXFOR [15] generated plot for $^{232}Th(n,\gamma)^{233}Th$ reaction is shown in Figure 1.10. Among the reported data, the measurements were performed using D-T, D-D and $^{7}Li(p,n)$ generated neutrons. An insight into the neutron generator reaction and the technique is vital as the cross-sections above 6-7 MeV are very sensitive to low energy neutron contributions. It can be observed from the figure that, in general, more data points are required to study a proper trend of the cross-sections. The reported data are limited up to 18 MeV and further measurements at higher energies are required to understand the effect of (n, 2n), (n, 3n) etc. channels on (n,γ) cross-sections. Minor discrepancies can also be noticed in the reported data. The results from authors Naik et al., Bhike et al., Prajapati et al., Mukherji et al., and Crasta et al., were measured by using neutrons produced by $^{7}Li(p,n)$ generator reaction, are found to be consistent, whereas, the datum in the similar energy region reported by Perkin et al., shows

[5]A general discussion is provided here for the sake of completeness of this chapter, however, it is not possible to provide detailed literature survey for all the reactions studied in the present work, and hence, it is provided in separate chapters as the part of Introduction section.

enhanced cross-section which was measured by using D-T reaction. A Similar type of trend has been noticed among the $^{100}Mo(n,2n)$ and $^{58}Ni(n,x)$ reaction cross-section data, measured by using different neutron generator reactions from the compilation of the EXFOR library [15].

The literature survey of proton induced reaction data for the selected materials show that sufficient work has been done in order to understand the reaction mechanism up to 20 MeV incident particle energies. The reported data contain minor discrepancies and errors which may come from the use of different monitor reactions. Since, the irradiation is carried out by using proton which is a charged particle, therefore, the flux estimation can be done by monitoring the beam directly from a Faraday cup. The use of a Faraday cup reduces the errors due to beam fluctuations and also the cross-sections can be measured directly, unlike relative measurement in case of the use of monitor reaction. Also, the PE process dominates over the compound nucleus process at higher energies. To investigate the fact, PE contribution was measured with the help of theoretical nuclear codes and is plotted with different systematics formulas.

1.8 Motivation / Objectives

Tremendous amount of work has been done to study the nuclear reactions in low to moderate energy regime by using n, γ, and light-ions like, p, d, t and α-particle. Precise nuclear data are required for the prediction of the sustainability and suitability of different metal alloys to withstand the high radiation conditions around the fusion/fission reactor core. The cross-section data of different reaction channels with neutron and proton as incident particles help researchers find new routs to tackle with the problem of radioactive waste. Nuclear data plays an important key role in order to find the experimental parameters which may be used for the incineration of the long-lived radioisotopes in an ADSs or fast reactor. Neutron and proton induced reaction data, hence, have prime importance for the advancement of the current reactor and accelerator technologies. The literature survey on the neutron capture reaction cross-sections for thorium, structural/cladding material like molybdenum and nickel, using EXFOR library [15] shows that very limited data points are available at higher neutron energies, also, the reported data contains large discrepancies. Most of the are concentrated around 14 MeV using mono-energetic neutron sources. Other than 14 MeV [15], the data were measured using quasi mono-energetic sources relative to monitor reaction cross-sections. The data thus contains errors should include the uncertainties from the monitor reaction, which can easily be calculated by using covariance analysis. Therefore, the neutron-induced

reaction cross-sections were studied for the specific isotopes useful for the reactor based cladding and shielding materials at energies above 1 MeV with the uncertainties and correlation coefficients calculated from covariance analysis.

The charged particle induced reaction data are important for the dose estimation for the medical isotopes, charged particle beam monitoring purposes, hydrogen production etc. in the surrounding materials of a reactor. The proton-induced reaction data from EXFOR show that the PE equilibrium process may play an important role in the production of the reaction residues. To investigate this, nuclear model codes were used to calculate the PE contribution involved in the formation of residues. The present work also aim to check the feasibility of different nuclear models codes like; TALYS, ALICE and EMPIRE to reproduce the nuclear data at energies above 1 MeV. TALYS has been used extensively for reaction data at low energies and was found exceptionally well in order to compare the data, therefore, it also gives a comparison for the other two codes to evaluate their results.

Objectives

The following objectives have been fulfilled in the present work,

- To measure the (n, γ) reaction cross sections from medium to fast neutron induced reaction of ^{232}Th related to fast reactor and ADSs. We have also planned to measure the (n, p) and (n, 2n) reaction cross sections of few of the structural and cladding materials such as Mo, Ni, and Sn induced by fast neutrons. The mono-energetic fast neutrons can be produced using $^{7}Li(p, n)$ reaction at BARC-TIFR Pelletron and at FOTIA facilities.

- To measure the (p, x) reaction cross-sections for the structural materials like Nb, Ag, and Ti. The proton beams were taken for irradiation purposes from BARC-TIFR Pelletron accelerator.

- The experimental work consists of the irradiation of Th, structural materials (Mo and Ni) with quasi mono-energetic neutrons within 2-20 MeV energies and of Nb, Ag, Ti with proton beam at 10- 22 MeV energy range. This was followed by their γ-ray spectrometric analysis. The off-line γ-ray counting of the irradiated samples was carried out by using HPGe detectors.

- The covariance analysis was also carried out for the neutron induced

reaction cross-sections to calculate the uncertainties and correlations among the different data.

- A theoretical work consists of comparison of results of TALYS and EMPIRE model codes were made with the experimental data for (n, x) reactions of tin (Sn) isotopes related to the ITER applications. Different systematic formulas were also tested in order to reproduce the experimental results.

1.9 Overview of the Present Work

In order to investigate the behavior of production cross-sections of different radioisotopes at energies up to 20 MeV for both the proton and neutron-induced reactions, a series of experiments have been performed at Bhabha Atomic Research Centre - Tata institute of Fundamental Research Pelletron and FOTIA accelerators, Mumbai, INDIA. The neutrons were produced by using $^{7}Li(p,n)$ reaction. Suitable monitor reactions were used depending upon the target reaction threshold. In case of proton-induced reactions flux was monitored/measured directly by using a Faraday cup. The uncertainties in the measured cross-sections were calculated using covariance analysis. A common experimental setup and method used for the measurements is described in Chapter 2. The formulation for the cross-sections and the relative uncertainty and correlation technique is discussed in Chapter 3. Chapter 4 presents the insight into the different nuclear model codes which are used for the theoretical predictions and comparison of the present and literature data. Neutron-induced reaction cross-section measurements are presented in chapter 5, on the other hand, a detailed discussion for the experimental work for the proton-induced reaction cross-sections is provided in Chapter 6. Summary and the conclusions drawn from the present work are given in Chapter 7. The matrix calculations regarding the cross-section data presented in chapter 5 are given in Appendix A. For the clarity and ease of the reader, the references used are listed at the end of each chapter.

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