THE MAHARAJA SAYAJIRAO UNIVERSITY OF BARODA

SYNOPSIS

Study of neutron and charged particle induced nuclear reactions for reactor and astrophysical applications

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in

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1 Introduction

Nuclear reactions play an important role in nuclear power generation, radiation therapy, medicine, space exploration etc. The nuclear reactions are not only important for the nuclear physics perspective but also important to understand the energy generation in stars and the production of the elements, called nucleosynthesis. The nuclear reactions are considered as engines of the stars; they determine the structure, evolution and composition of large variety of the cosmic objects including the solar system. The current study is focused on nuclear reactions which are induced by neutron and charged particle and the study of astrophysics from nuclear physics perspective called Nuclear Astrophysics.

In developing countries, there is a growing demand for clean and efficient electricity, leading to an increased interest in nuclear reactors as a viable option. While nuclear reactors can produce affordable clean energy, they also generate radioactive waste, which poses a significant drawback. This issue can potentially be addressed by employing a high neutron flux accelerator to convert the waste into stable nuclei. However, to expand the usage of reactors, a comprehensive understanding of safety aspects is essential. This includes rigorous safety protocols, thorough risk assessments, and continuous monitoring and maintenance.

Structural materials play a pivotal role in the reactor's safety and performance. Structural materials play a crucial role in the functioning of nuclear reactors, as they need to possess radiation resistance and long-term durability. Given their usage in the reactor structure, these materials are exposed to neutron irradiation resulting from fission or fusion processes. Unfortunately, there are instances where data concerning the structural materials used in reactor applications remain insufficient and exhibit significant discrepancies. Hence, a comprehensive and accurate cross-section data library is imperative. This data is of utmost importance for the development of ITER (International Thermonuclear Experimental Reactor) [1] and the advancement of Accelerator-Driven Systems (ADSs) [2].

In conjunction with the selection of appropriate structural materials, the control rods play a critical role in maintaining reactor stability and safety. Control rods are inserted or withdrawn into the reactor core to control the rate of nuclear reactions and manage the power output. Absorbing neutrons, control rods effectively manage the chain reaction and prevent the reactor from reaching excessive temperatures or becoming unstable. Consequently, having precise knowledge of the control rod's composition and its interaction probability with neutrons is of significant importance [3].

The fusion reaction of deuterium and tritium (D-T) results in the production of high-energy (14 MeV) neutrons. These energetic neutrons transfer their energy to the breeding blanket and first wall of the reactor. Therefore, there is a significant demand for precise neutron data around 14 MeV, specifically for reactions such as (n, p), (n, α), and (n, 2n) [4]. To obtain such data with high precision, extensive measurements, calculations, and evaluations of these reaction cross-sections have been undertaken. However, there is a significant discrepancy between the measured experimental data of fusion reactor structural materials and the evaluated data from different databases at the same incident neutron energy. Therefore, obtaining accurate activation cross-section data at 14-15 MeV neutron energies becomes essential for the design, construction, and evaluation of fusion reactors. However, in some cases, direct measurements of the data are not feasible or discrepancies arise among experimental results due to relative measurements and a lack of mono-energetic neutron sources. To overcome these challenges and achieve more accurate neutron-induced reaction cross-section data, a systematic approach or theoretical predictions are employed. These methods help to bridge the gaps in the data and provide reliable information for various scientific and practical applications.

Consequently, the current study focuses on obtaining precise nuclear reaction cross-section data for the structural materials used in reactors. This data will play a crucial role in advancing nuclear technology and ensuring safer and more sustainable energy production.

Nuclear reaction also play a vital role in nuclear astrophysics. As these reactions act as a driving force for stars, affect how star develope, cause dramatic starbursts, and are the reason behind the creation of various elements. By simulating these reactions, we gain insights into how stars produce energy and form elements. The mystery surrounding the origin of chemical elements persisted until 1957, when E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle [5], along with A. G. W. Cameron [6], separately proposed the concept of nucleosynthesis as the explanation. Their research led to the creation of a new field called nuclear astrophysics, where techniques from nuclear physics are applied to solve problems in astrophysics [7]. All the stable and long-lived unstable isotopes are synthesized with the help of different astrophysical processes like stages of burning starting from hydrogen and helium and going through different steps like triple-alpha process, neutron capture processes like s-process, r-process etc.

The elements beyond iron cannot be formed through nuclear fusion reactions and require different methods for their production. The elements heavier than iron are believed to be created through astrophysical processes known as s-process, r-process, and p-process. There are around 35 proton-rich stable isotopes between ^{74}Se and ^{196}Hg which are bypassed by the s- and r- processes [8]. These are commonly referred as p-nuclei whose origin is still not completely understood. The origin of these nuclei can be explained by several processes summarized as p-process [9].

2 Motivation

Significant research has been conducted to investigate the nuclear reactions within the range of low to moderate energy regime though the utilization of neutrons. Accurate nuclear data is essential for predicting the sustainability and suitability of different metal alloys under the extreme radiation conditions near the core of fusion/fission reactors. Hence, neutron-induced reaction cross-sections were analyzed for the specific isotopes pertinent to reactor cladding and shielding materials at energies exceeding 1 MeV with the uncertainties and correlation coefficients derived through covariance analysis. There is strong need to measure reaction cross-sections of reactor cladding and shielding materials to the medium energy region (upto 20 MeV) with mono-energetic neutrons. Hence, measuring various reaction cross-section within the stated energy range is vital for gaining a detailed understanding of their energy-dependency. This endeavor will culminate in a comprehensive database, ultimately advancing our grasp of nuclear reaction mechanisms and contributing to future advancements in reactor technology. Table 1 below provides a concise summary of the neutron-induced reactions explored in this study specifically in the context of their application in reactor systems.

Exploring the uncertainty associated with the activation cross-section is crucial in determining the reasonable margin that ensures both economy and safety in nuclear reactor applications [10]. If multiple data points of the activation cross-sections are involved in evaluating quantity of interest, the correlation (covariance) among the data points must also be examined to prevent overestimating or underestimating the uncertainty. Therefore, the aim of modern evaluation reports is not only to estimate the most accurate cross-section but also to identify the uncertainty and covariance describing the correlation among the cross-sections. However, in most previous data, details regarding error propagation and correlations among the different attributes are not reported. Considering the above facts, new experimental cross-sections with covariance analysis are needed to enhance the accuracy and reliability of these evaluated nuclear data and theoretical models.

When direct measurements are not possible or discrepancies arise in experimental data due to relative measurements and the absence of mono-energetic neutron sources, there's a need for systematic approaches or theoretical predictions. This motivates the development of new semi-empirical formulas to improve the accuracy of neutron-induced reaction cross-section estimations. In the present work, new semi-empirical formulas around 14.5 MeV incident neutron energy have been developed to calculate and to predict (n, p), (n, α), and (n, 2n) reaction cross-sections within the target mass regions $24 \leq A \leq 238$ (including both $Z \leq 45$; >45), $26 \leq A \leq 181$, and $45 \leq A \leq 238$ (including both even and odd nuclei), respectively.

The motivation behind studying the astrophysical p-process lies in its pivotal role in shaping the universe's elemental composition, offering profound insights into the origins and evolution of celestial bodies. The "p-process," or proton capture process, gives rise to a range of naturally occurring neutron-deficient isotopes, known as p-nuclei, spanning elements from selenium to mercury. The origins of these nuclides remain a mystery, as the currently accepted p-process models cannot fully replicate the observed p-isotope abundances in the solar system. This discrepancy may arise from uncertainties related to the astrophysical conditions under which the process occurs. Alternatively, it could be attributed to limitations in our understanding of nuclear physics models. The p-process occurs in extreme astrophysical environments such as supernovae and X-ray bursts. During these events, protons are involved in nuclear reactions with heavy isotopes, leading to the formation of heavier elements. Accurate cross-section data are crucial for modeling these high-energy, high-temperature environments accurately. In light of these challenges, it is necessary to acquire low-energy proton capture cross-section data for heavy isotopes to enhance our understanding of the astrophysical p-process. Cross-section data are a fundamental input for nuclear reaction network simulations used in astrophysics. These simulations are crucial for modeling nucleosynthesis in various astrophysical environments and making predictions about the composition of stellar ejecta. Table 2 summarises theoretically studied nuclear reactions in this study specifically in the context of their astrophysical applications using the TALYS nuclear modular code [11].

Table 1: Nuclear spectroscopic data for ^{58}Ni(n, p)^{58}Co and ^{115}In(n, n′)^{115m}In reaction cross-section measured experimentally with significance for reactor applications [12].

Reaction	$T_{1/2}$	Decay Mode (%)	E_γ (keV)	I_γ (%)	Spin state J^π
^{58}Ni(n, p)^{58}Co	70.86 ± 0.06 d	ε(100 %)	810.759 ± 0.002	99.45 ± 0.01	2^+
^{115}In(n, n′)^{115m}In	4.486 ± 0.004 h	IT(95.00 %) β^-(5.00 %)	336.241 ± 0.025	45.9 ± 0.1	$1/2^-$

d → day, h → hour

Table 2: Nuclear spectroscopic data for reactions having astrophysical applications investigated theoretically [12].

Reaction	Product isotope	$T_{1/2}$	Decay Mode (%)	Spin state J^{π}
^{92}Mo(p, γ)	^{93,g}Tc	2.75 ± 0.05 h	ε(100 %)	$9/2^{+}$
^{92}Mo(p, γ)	^{93,m}Tc	0.725 ± 0.017 h	IT(77.40 %)	$1/2^{-}$
			ε(22.60 %)	
^{94}Mo(p, γ)	^{95,g}Tc	20.0 ± 0.1 h	ε(100 %)	$9/2^{+}$
^{74}Se(p, γ)	^{75}Br	96.7 ± 0.13 min	ε(100 %)	$3/2^{-}$
^{76}Se(p, γ)	^{77}Br	57.036 ± 0.006 h	ε(100 %)	$3/2^{-}$
^{82}Se(p, n)	^{82}Br	35.282 ± 0.007 h	β^{-}(100 %)	5^{-}

h $\rightarrow$ hour, min $\rightarrow$ minute

3 Objectives

The present work has achieved the following objectives:

- To measure the ^{58}Ni$(n, p)^{58}$Co and ^{115}In$(n, n')^{115m}$In reaction cross-sections with respect to their utilization in reactor applications. The production of mono-energetic fast neutrons is achieved through the ^{7}Li(p, n) reaction at BARC-TIFR Pelletron and FOTIA facilities.

- The experimental work consists of the irradiation of Ni and In samples with quasi-monoenergetic neutron within 1.6 to 2.7 MeV and 7 to 20 MeV respectively. The measurements were carried out through neutron activation analysis, followed by offline γ-ray spectrometry. The irradiated samples were counted by using HPGe detectors. The obtained results offer significant insights into nuclear reactions and their relevance in reactor studies.

- Covariance analysis was employed to estimate the uncertainty and correlation between the current experimental data for the neutron-induced reaction. This analysis takes into account the collective uncertainty arising from all attributes involved in the measurement process.

- To develop new semi-empirical mass formulae for the (n, p), (n, α) and $(n, 2n)$ reaction cross-sections at 14.5 MeV neutron energy. This provides an alternative approach to reproduce nuclear data at incident neutron energies of 14.5 MeV.

- To study proton capture reactions on Mo and Se isotopes at astrophysically relevant energies using TALYS code and calculating astrophysical S factors and reaction rates in a core-collapse supernova. Additionally the impact of different nuclear input parameter entering the reaction rate equation is also investigated. This research aims to enhance our understanding of low-energy proton capture cross-sections on heavy isotopes, particularly for the p-nuclei, and to unravel their origin and implications for astrophysical processes.

4 Outline of the Thesis

The thesis comprises six chapters, and their summarized details are as follows:

Chapter 1 emphasizes the importance of investigating neutron and charged particle induced nuclear reactions in both reactor and astrophysical domains. The chapter outlines the specific research objectives and underscores the practical implications of understanding these reactions, such as advancing reactor technology and enriching our knowledge of astrophysical phenomena.

Chapter 2 provides a thorough understanding of the nuclear codes used in the thesis for analyzing reactions in both reactor and astrophysical scenarios. It offers brief discussions about each code, aiding readers in grasping their specific details and applications.

Chapter 3 involves the measurement of $^{58}\mathrm{Ni(n,p)}^{58}\mathrm{Co}$ reaction cross-section in the neutron energy range of 1.6-2.7 MeV and the production of ^{115m}In using quasi-monoenergetic neutrons within the energy range of 7-20 MeV. The chapter presents the experimental procedure, data analysis, and cross-section measurements. Additionally, the ratio technique of co-variance analysis is introduced to estimate uncertainties and correlations between experimental data, encompassing the collective uncertainty from all measurement attributes.

Chapter 4 describes development of new systematic formulae for $\mathrm{(n,p)}$, (n,α) and $\mathrm{(n,2n)}$ reaction cross-section at 14.5 MeV neutron energy based on the statistical model considering Q-value dependence using the literature data available on EXFOR [13] data library.

Chapter 5 focuses on studying low-energy proton capture cross-sections on heavy isotopes to understand the astrophysical p-process. It involves investigating proton capture reactions on Mo and Se isotopes using the TALYS nuclear code and calculating astrophysical S factors and reaction rates in a core-collapse supernova. The impact of different nuclear input parameters on the stellar reaction rate is also explored.

Chapter 6 will be containing the summary, key findings and outcomes of the current study, alongside a concise depiction of its potential implications for the future.

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List of Publications

A. Publications in Peer-Reviewed Journals

Publications Related to Thesis

1. **Investigation of** $^{58}\mathrm{Ni(n,p)}^{58}\mathrm{Co}$ **reaction cross-section with covariance analysis**

   Akash Hingu, S. Mukherjee, Siddharth Parashari, Sangeeta, A. Gandhi, Mahima Upadhyay, Mahesh Choudhary, Sumit Bamal, Namrata Singh, G. Mishra, Sukanya De, Saurav Sood, Sajin Prasad, G. Saxena, Ajay Kumar, R.G. Thomas, B.K. Agrawal, A. Kumar
   Under Review in Chinese Physics C

2. **Astrophysical S factor and reaction rate of** $^{92,94}\mathrm{Mo}$ **(p,** γ**) relevant to the p-process**

   Akash Hingu, P. M. Prajapati, S. Mukherjee, R. G. Pizzone, and K. Katovsky
   *EPJ Web of Conferences, **275**, 02006, (2023)*

3. **Cross-sections for production of** $^{115m}\mathrm{In}$ **by quasi-monoenergetic neutrons within 7-20 MeV**

   Akash Hingu, Bhargav Soni, Siddharth Parashari, Rajnikant Makwana, P.M. Prajapati, Vibhuti Vashi, Mayur Mehta, R. Palit, S.V. Suryanarayana, B.K. Nayak, K. Katovsky, S. Mukherjee
   *Radiation Physics and Chemistry, **199**, 110270, (2022)*

4. **Semi-empirical systematics formulas for the (n, p), (n,** α**), and (n, 2n) reaction cross-sections at 14.5 MeV**

   Akash Hingu, Siddharth Parashari, Suraj K. Singh, Bhargav Soni and S. Mukherjee
   *Radiation Physics and Chemistry, **188**, 109634, (2021)*

Other Publications

5. **Measurement of neutron induced reaction cross-section of molybdenum with covariance analysis**

   Mahima Upadhyay, Mahesh Choudhary, Namrata Singh, A. Gandhi, Aman Sharma, Sumit Bamal, **Akash Hingu**, S. Mukherjee, G. Mishra, Sukanya De, L. S. Danu, Saurav Sood, Sajin Prasad, Ajay Kumar, R. G. Thomas, and A. Kumar
   Under Review in Journal of Physics G Nuclear and Particle Physics.

6. **A Comprehensive Analysis of Uncertainty Quantification for** $^{58}\mathrm{Ni(n,p)}^{58}\mathrm{Co}$ **Reaction**

   Mahesh Choudhary, Aman Sharma, Namrata Singh, Mahima Upadhyay, A. Kumar, G. Mishra, Sukanya De, L. S. Danu, Ajay Kumar, R. G. Thomas, Saurav Sood, Sajin Prasad, S. Mukherjee, K. Katovsky, A. Gandhi, and **Akash Hingu**
   Under Review in Journal of Physics G Nuclear and Particle Physics.

7. ^{13}C**(**α**,n)**^{16}O**: The Source of Neutrons for the s-process main component**

   P. M. Prajapati, Mahin Qureshi, **A. Hingu**, R. G. Pizzone, M. La Cognata, S. V. Suryanarayna, Sachin Shet, S. Mukherjee
   EPJ Web of Conferences, ***275***, *02014, (2023)*.

8. **Production and characterisation of** ^{20,22}Ne **targets**

   P. M. Prajapati, R. G. Pizzone, **Akash Hingu**, S. Mukherjee, and S. V. Suryanarayana
   Pramana, ***96***, *167, (2022)*.

B. Publications in Proceedings of the Conferences

1. **Measurements of neutron capture cross-sections on ^{109}Ag at 0.53, 1.05, 1.66 MeV**

   Mahima Upadhyay, A. Gandhi, Aman Sharma, Mahesh Choudhary, Namrata Singh, Sumit Bamal, **Akash Hingu**, S. Mukherjee, G. Mishra, Sukanya De, A. Mitra, L. S. Danu, Saurav Sood, Sajin Prasad, Ajay Kumar, R. G. Thomas, K. Katovsky and A. Kumar
   23rd International Scientific Conference on Electric Power Engineering (EPE), (2023).

2. **Measurement of ^{121}Sb(n, γ)^{122}Sb reaction cross-sections within 1.6-3.1 MeV neutron energy range**

   Namrata Singh, A. Gandhi, Mahesh Choudhary, Aman Sharma, Mahima Upadhyay, Punit Dubey, N. K. Dubey, Utakarsha Mishra, Sumit Bamal, **Akash Hingu**, R. K. Singh, G. Mishra, Sukanya De, A. Mitra, L. S. Danu, Saurav Sood, Sajin Prasad, Ajay Kumar, R. G. Thomas, and A. Kumar
   Proceedings of the DAE Symp. on Nucl. Phys. ***66*** *(2022).*

3. **Experimental and theoretical cross-sections of** ^{109}Ag(**n,**γ)^{110m}Ag **reaction in the incident neutron energy 0.5-1.6 MeV**

   Mahima Upadhyay, A. Gandhi, Aman Sharma, Mahesh Choudhary, Namrata Singh, Punit Dubey, N. K. Dubey, Utakarsha Mishra, Sumit Bamal, **Akash Hingu**, G. Mishra, Sukanya De, A. Mitra, L. S. Danu, Saurav Sood, Sajin Prasad, Ajay Kumar, R. G. Thomas, A. Kumar
   Proceedings of the DAE Symp. on Nucl. Phys. ***66*** *(2022).*

4. **Experimental and theoretical cross-sections of** ^{115}In(n, n$'$) **reaction at 19 and 16 MeV using quasi-monoenergetic neutrons**

   Akash Hingu, Bhargav Soni, S. Mukherjee, Rajnikant Makwana, Siddharth Parashari, Vibhuti Vashi, Mayur Mehta, R. Palit, and S. V. Suryanarayana
   Proceedings of the DAE Symp. on Nucl. Phys. ***65*** *(2021).*

5. **Measurement of isomeric cross-section at energy of astrophysical interest**

   Vibhuti Vashi, R. Makwana, B. Quintana, M. Mehta, S. Mukherjee, B. Soni, M. Abhangi, S. Vala, N. Singh, R. Singh, G. Patel, **A. Hingu**, S. Suryanarayana, B. Nayak, S. Sharma, and T. N. Nag
   Proceedings of the DAE Symp. on Nucl. Phys. ***65*** *(2021).*

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