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ABSTRACT

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

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$\mathbf{N}$uclear 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. This study focuses on neutron and charged particle induced reactions, which are crucial for both reactor and astrophysical applications. In the context of nuclear reactors, neutron-induced reactions are fundamental to maintaining controlled fission processes, influencing reactor efficiency, safety, and fuel cycle optimization. In astrophysical contexts, charged particle-induced reactions, such as proton and alpha captures, are vital for understanding stellar nucleosynthesis and energy generation in stars. By investigating these nuclear reactions, we gain valuable insights into both reactor design and operation, as well as the underlying processes that drive stellar evolution and element formation in the universe.

This thesis presents a comprehensive analysis of neutron-induced reaction cross-sections for reactor structural materials and proton capture reactions on p-nuclei at astrophysical energies using the Monte Carlo method, highlighting their significance for reactor physics and astrophysical processes.

The neutron-induced reaction cross-sections for the $^{58}\mathrm{Ni}(\mathrm{n},\mathrm{p})^{58}\mathrm{Co}$ reaction in the energy range of 1.6–2.7 MeV, and for the production of $^{115\mathrm{m}}\mathrm{In}$ in the range of 7–20 MeV, were measured using quasi-monoenergetic neutrons generated from the $^{7}\mathrm{Li}(\mathrm{p},\mathrm{n})$ reaction. The experiments were performed at the Folded Tandem Ion Accelerator (FOTIA) facility at Bhabha Atomic Research Centre (BARC) and the 14UD Pelletron accelerator at the BARC-Tata Institute of Fundamental Research (BARC-TIFR) facility, both located in Mumbai, India. The measurements were carried out using the neutron activation analysis technique followed by offline γ-ray spectroscopy. High-purity germanium (HPGe) detector was employed to determine the γ-activity of irradiated samples. The results were validated against previous experimental results in EXFOR data library, evaluated data libraries (ENDF/B-VIII.0, JEFF-3.3, JENDL-4.0, CENDL-3.2), and theoretical predictions from TALYS and EMPIRE codes. Covariance analysis was employed to estimate the uncertainty and correlation between the present experimental data for the neutron-induced reaction. This analysis takes into account the collective uncertainty arising from all attributes involved in the measurement process. The results hold significant importance for advanced reactor design, neutron flux determination, and nuclear medicine, while also contributing to the refinement of theoretical models and enhancing the reliability of data in

reactor safety and performance optimization.

While analyzing the neutron-induced reaction cross-section data for reactor structural materials, we found that there is 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. Therefore new Semi-empirical formulas are developed for the $(\mathrm{n,p})$, $(\mathrm{n,2n})$, and (n,α) reaction cross-section at 14.5 MeV incident neutron energy by using the literature data available at EXFOR library. The new formulas are derived based on the statistical model, taking into account the Q-value dependence. The results derived from this study were evaluated against other systematic formulas developed previously and compared with experimental data reported in the EXFOR library. The comparison has been done on the basis of statistical model as well as on the asymmetry parameter dependence. These formulas demonstrated consistency with existing literature data while offering enhanced predictive accuracy across specified mass ranges for various nuclear reactions, providing an alternative approach to reproducing nuclear data at 14.5 MeV incident neutron energies.

Cross-section data are also fundamental input for nuclear reaction network simulations used in astrophysics. The proton capture process, or "p-process", is responsible for producing a range of naturally occurring neutron-deficient isotopes, known as p-nuclei, spanning elements from selenium to mercury. However, the origins of these nuclides remain uncertain, as current p-process models fail to fully replicate the observed abundances of p-isotopes in the solar system. This discrepancy may arise from uncertainties in the astrophysical conditions under which the process occurs or from limitations in nuclear physics models. In this study, we aim to quantify the impact of uncertainties in nuclear model inputs on reaction cross-sections and reaction rates for proton capture on p-nuclei at astrophysically relevant energies. Utilizing Monte Carlo simulations, we integrate uncertainties related to optical model potential (OMP) and nuclear level density (NLD) parameters. Theoretical calculations are conducted using TALYS-1.96. Monte Carlo simulations

integrate uncertainties by varying input parameters to generate distributions of theoretical outcomes. This study underscores the importance of rigorous uncertainty quantification in proton capture reactions on p-nuclei, specifically within the astrophysically relevant energy range. The comparison between theoretical predictions and experimental data reveals both agreements and discrepancies, particularly at higher energies, emphasizing the necessity for additional experimental data to refine the theoretical models. Enhancing the accuracy of OMPs and NLDs remains crucial for reducing uncertainties in nuclear reaction rates. These advancements are essential for improving our understanding of nucleosynthesis in stellar environments, particularly within the p-process, and for achieving more precise predictions of elemental abundances in the universe.

The entire thesis is divided into six chapters as follows:
Chapter 1: Introduction
Chapter 2: Theoretical Framework
Chapter 3: Investigation of Neutron Induced Reaction Cross-sections
Chapter 4: Development of New Semi-empirical Formulas
Chapter 5: Charged Particle Induced Reactions & the Astrophysical p-Process
Chapter 6: Summary & Conclusions

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