Validating spin-parity conditions for neutron capture cross-sections using surrogate techniques

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Introduction

In reactor environments, structural materials are continuously exposed to high-intensity, high-energy neutron flux, which can induce a range of neutron-induced reactions and lead to the formation of long-lived radionuclides [1,2]. As the reactor operates continuously for a few months, these radionuclides are subjected to the continuous neutron flux, they may undergo further neutron-induced reactions, potentially producing charged particles. Such particles can inflict significant structural damage on reactor components. A key radionuclide generated in both fusion and fission reactors is ^{55}Fe. The rate at which this radioactive isotope transitions to its stable form ^{56}Fe, is governed by the cross-sections of the ^{55}Fe(n,γ)reaction.

Due to the inherent radioactivity of ^{55}Fe, measuring its cross-sections directly is challenging. Surrogate reactions are used instead to determine neutron cross-sections for unstable nuclei. While these reactions can match excitation energies, differences in spin-parity distributions may occur. The Surrogate Ratio Method (SRM) is proposed to address these uncertainties and improve accuracy. [3]. The Surrogate Ratio Method can yield accurate neutron cross-sections for capture channels if three conditions are satisfied. First, the spin distributions in the compound nuclei generated by the surrogate reactions must be comparable. Second, the spin values populated by the surrogate reaction should not exceed $10\hbar$, as spins higher than this are seldom observed in neutron-induced reactions. Third, the J^π-by-J^π convergence of branching ratios, often referred to as the weak Weisskopf-Ewing condition, must be met [4]. The present study focuses on evaluating the spin-parity matching for the surrogate reaction of ^{55}Fe(n,γ). We have selected ^{59}Co(p,α) as the surrogate channel for the desired ^{55}Fe(n,γ) reaction. To apply the Surrogate Ratio Method, we require a reference reaction. For this purpose, we have chosen ^{47}Ti(n,γ) as the reference reaction. Here ^{51}V(p,α) will serve as the surrogate channel for the reference reaction.

Theoretical Calculations

To evaluate the spin-parity matching between neutron-induced reactions and their corresponding surrogate channels, we calculated the spin-dependent decay probabilities for both the desired and reference nuclei using the statistical nuclear reaction code TALYS-1.96 [5]. In this study, gamma rays are the outgoing particles from both compound nuclei. Consequently, gamma decay probabilities for various spin (J) states of the compound nuclei ^{56}Fe and ^{48}Ti were calculated within the excitation energy range of 13 to 30 MeV. These compound nuclei are populated through the surrogate reactions ^{59}Co(p,α) and ^{51}V(p,α), respectively.

For the calculation of gamma decay probabilities, including states with $J=(12)^{\pm}$, the ‘populated initial nucleus’ option was employed. To achieve the desired spin-parity states of the compound nuclei within the specified energy range, the incident beam option was set to "Projectile 0" in the input file. This approach provided the initial compound nucleus population for specific spin-parity states. The decay probability was then determined as the ratio of the final residual nucleus population to the initial compound nucleus population. The theoretical calculations relied on the compound nucleus model, incorporating the phenomenological level density model,

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Generalised Superfluid model [6]. Since the calculated decay probabilities displayed similar trends across both positive and negative parity states, only the variation in decay probabilities with spin states is considered. The incident proton energy corresponding to the excitation energy range of 13 to 30 MeV was calculated, and decay probabilities for the surrogate channels were also computed using TALYS-1.96.

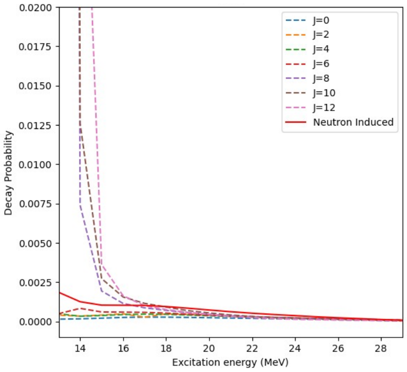

Fig. 1 The decay probabilities for different spin states(J) of ^{56}Fe* populated in the surrogate reaction ^{59}Co(p,α) along the same calculated for the desired reaction ^{55}Fe(n,γ)

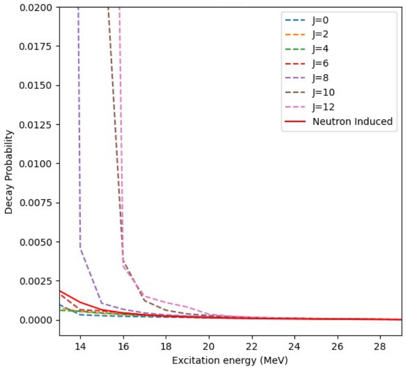

Fig. 2 The decay probabilities for different spin states(J) of ^{48}Ti* populated in the surrogate reaction ^{51}V(p,α) along the same calculated for the desired reaction ^{47}Ti(n,γ)

Results and Discussion

Figures 1 and 2 illustrate the decay probabilities for the compound nuclei 56Fe and 48Ti, as well as for the reactions 55Fe(n,γ) and 47Ti(n,γ). It can be seen from the figures that, in the lower energy range, the decay probabilities for neutron-induced reactions are influenced by angular momentum (J). However, at excitation energies exceeding 20 MeV, the decay probabilities for neutron-induced reactions and those corresponding to various spin states populated through surrogate reactions show a high degree of agreement. This consistency supports the validity of using the surrogate method for investigating 55Fe(n,γ). Additionally, employing the surrogate ratio method can reduce efficiency-related discrepancies, thereby enhancing the accuracy of cross-section measurements.

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