Surrogate reactions relevant for fusion and fission reactors

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Introduction

The increasing global energy demand, coupled with environmental concerns (such as CO_2 emissions and air pollution) and depleting fossil fuel reserves, necessitates a shift towards alternative energy sources. While renewable energy shows promise, its intermittent (weather and location dependence) nature makes it necessary to complement it with reliable, low-carbon energy options. Nuclear fission based powered reactors (currently offering ~10% to global electricity production) offers a clean and potent energy source with a minimal carbon footprint. However, the of management of high-level radioactive waste (HLW) remains a critical concern, inhibiting its broader utilization. Accelerator Driven Systems (ADS), utilizing high-intensity and high-energy neutron beams, are being considered as a global solution for nuclear waste incineration. Unlike fission reactors, fusion reactors produce no HLW. Deuterium-tritium (D-T) fusion, with its high energy release, holds immense potential as a waste-free energy source for future.

The precise nuclear data is essential for studying the reactor systems, as the accuracy of reactor simulations depends on the quality of nuclear data. While significant efforts have been dedicated to measuring nuclear data for traditional fission reactors (TFRs), future devices like fusion reactors and ADS operate with neutron energy exceeding the typical limits of TFRs. In these devices high-energy neutrons induce several threshold reactions (e.g., (*n,p*), (*n,d*), (*n,np*), (*n,t*) (*n,α*), and (*n,2n*) reactions) on reactor's structural material (SM) affecting their chemical composition and mechanical properties. Several radionuclides are produced through n-induced transmutation reactions on SM such as ^{53}Mn, ^{57}Co, ^{58}Co and ^{62}Cu with respective half-life of 3.74×10^6 yr, 271.79 d, 70.86 d, 9.67 min. Crucially, production of H-gas and He-gas via (*n,xp*) and (*n,xα*) reactions, leading to swelling and embrittlement of the reactor's SM can compromise reactor integrity. Therefore, the accurate nuclear data on n-induced (*n,xp*) and (*n,xα*) cross sections for the radionuclides produced within the SM (mentioned above), is crucial for complete assessment of structural integrity and safety in future devices [1-3].

^{53}Mn, ^{57}Co and ^{58}Co are among the dominant radionuclides produced via within the reactor's SM. However, till date there are no experimental measurements on (*n,xp*) cross sections for any of these isotopes due to unavailability of the target. Also, different evaluated nuclear data libraries show discrepancies for these reaction cross sections. To address the scarcity of direct measurements and to test the data libraries, this thesis employs the surrogate reaction ratio method (SRM) to determine the H-gas producing (*n,xp*) cross-sections for ^{53}Mn, ^{57}Co and ^{58}Co isotopes.

Though the surrogate technique has proven useful to measure (*n,f*) and (*n,γ*) cross sections provided certain conditions are met. But, the SRM has never been investigated to determine the (*n,xp*) cross sections for unstable nuclei in the mass region A ≈ 50–60. Therefore, before employing the SRM to determine the desired (*n,xp*) cross sections we have benchmarked the application of the SRM [4].

Experimental details and data analysis

In the SRM we take the cross-section ratio of two compound nuclear reactions (e.g., n+^{53}Mn $\rightarrow$ ^{54}Mn* $\rightarrow$ xp and n+^{60}Ni $\rightarrow$ ^{61}Ni* $\rightarrow$ xp) and direct measurements of one of the reaction cross sections (^{60}Ni(*n,xp*) cross sections) are used as reference to deduce the other (or desired) reaction cross sections using Eq. (1). Here (*n,xp*) channel is implying sum of all n-induced proton emissions such as (*n,p*), (*n,np*), (*n,2p*), reactions.

$$\frac{\sigma^{^{53}Mn(n,xp)}(E^*)}{\sigma^{^{60}Ni(n,xp)}(E^*)} = \frac{\sigma^{CN}_{n+^{53}Mn}(E^*)}{\sigma^{CN}_{n+^{60}Ni}(E^*)}\frac{P^{^{54}Mn}_{xp}(E^*)}{P^{^{61}Ni}_{xp}(E^*)} \quad (1)$$

The compound nucleus (CN) formation cross sections; $\sigma^{CN}_{n+^{53}Mn}(E^*)$ and $\sigma^{CN}_{n+^{60}Ni}(E^*)$ are calculated using optical model calculations. The

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p-decay probabilities; $P_{xp}^{^{54}Mn}(E^*)$ and $P_{xp}^{^{61}Ni}(E^*)$ are measured in surrogate experiments.

The ^{53}Mn(*n,xp*) cross section measurement is one of the motivations. The surrogate/transfer reactions ^{52}Cr(^{6}Li,α) and ^{59}Co(^{6}Li,α) were used to populate CN ^{54}Mn* (surrogate of n+^{53}Mn) and ^{61}Ni* (surrogate of n+^{60}Ni) by bombarding ^{6}Li beams on self-supporting targets of ^{52}Cr and ^{59}Co at BARC-TIFR Pelletron facility, Mumbai. The identification of projectile-like fragment (PLF) α in above transfer reactions that confirm the formation of CN ^{54}Mn* and ^{61}Ni*, was carried out by employing silicon surface barrier (SSB) ΔE -E detector telescope (T) mounted around the grazing angle. Two large area Si strip detector telescopes (S1 and S2) were mounted at backward angles, to detect evaporated particles (e.g., *p*, *d*, *t*, and α) from the CN ^{54}Mn* and ^{61}Ni*, in coincidence with the α-PLF.

We have employed a two body kinematics to extract the excitation energy ($E*$) spectra of CN ^{54}Mn* and ^{61}Ni*. The $P_{xp}^{CN}(E^*)$ for CN ^{54}Mn* and ^{61}Ni* are measured using the Eq. (2):

$$P_{xp}^{CN}(E^*) = \frac{N_{\alpha,p}(E^*)}{N_{\alpha}(E^*)}\ . \qquad (2)$$

Here N_α and $N_{\alpha,p}$ are α-singles (α detected in T) and α-p coincidences (α detected in T in coincidence with p detected in S1 or S2), respectively at E^*, for CN ^{54}Mn* and ^{61}Ni* populated in respective surrogate reactions. The measured P_{xp}^{CN} (using Eq. 2) and calculated CN formation cross sections together with known ^{60}Ni(n,xp) cross-section values, are used to determine the desired ^{53}Mn(*n,xp*) cross sections at each E^* bin. The E^* range was then converted to equivalent neutron energy (E_n) range.

Table 1: See text

E(^{6}Li) (MeV)	Surrogate Reaction	CN	Desired / Reference
33	^{52}Cr(^{6}Li,α)	^{54}Mn*	^{53}Mn(*n,xp*)
40.5	^{59}Co(^{6}Li,α)	^{61}Ni*	^{60}Ni(*n,xp*)
35.9	^{56}Fe(^{6}Li,α)	^{58}Co*	^{57}Co(*n,xp*)
40.5	^{59}Co(^{6}Li,α)	^{61}Ni*	^{60}Ni(*n,xp*)
37	^{57}Fe(^{6}Li,α)	^{58}Co*	^{58}Co(*n,xp*)
33	^{59}Co(^{6}Li,α)	^{61}Ni*	^{60}Ni(*n,xp*)

Two more experiments were performed to measure the ^{57}Co(*n,xp*) and ^{58}Co(*n,xp*) cross sections by employing the SRM and, using the ^{60}Ni(*n,xp*) cross section values as reference. For each of the three works under this thesis, the ^{6}Li beam energies, surrogate reactions used to populate the CN which are required to be formed in respective n-induced desired and reference reactions used under the SRM, are tabulated in Table 1. The (*n,xp*) cross sections were measured for ^{53}Mn, ^{57}Co and ^{58}Co isotopes in respective E_n ranges of 8.2-16.4, 8.6-18.8, 11.7-16.8 MeV.

Theoretical calculations and results

To understand the measured (*n,xp*) cross sections quantitatively we have performed the statistical model calculations using the TALYS code. The measured cross sections are compared with predictions of the TALYS code and of various evaluated nuclear data libraries such as ENDF, JEFF, JENDL, ROSFOND and TENDL.

The measured ^{53}Mn(*n,xp*) cross sections compare well with predictions of TALYS code and all the available evaluations within the experimental uncertainties. Whereas, for other two isotopes measured (*n,xp*) cross sections doesn't agree with any of the evaluations. The measured ^{57}Co(*n,xp*) cross sections agree with TALYS predictions with default OMP input parameters however, the measured ^{58}Co(*n,xp*) were well explained by TALYS after slight tuning of parameters. These studies indicate the need to revisit and improve the model parameters of the evaluations for (*n,xp*) reactions on ^{57}Co and ^{58}Co.

In summary first we have investigated the application of the SRM, then employed the same to measure ^{53}Mn(*n,xp*), ^{57}Co(*n,xp*) and ^{58}Co(*n,xp*) cross sections and, performed the statistical model calculations to quantify each of these. The research outcome of this thesis will refine the nuclear data and enhance the accuracy of reactor simulations assessing the structural integrity and design safety of advanced reactor systems.

References:

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