Measurement of $^{55}Fe(n,p)^{55}Mn$ reaction cross-section by Surrogate Reaction Method for Fusion Technology

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Introduction

Developing Fusion technology is a dream project for cheap, abundant and green energy source for future generations. Efforts are underway to build a International Thermonuclear Experimental Reactor (ITER project) using D-T fusion reaction releasing 14-MeV neutrons. It is needed to perform detailed neutronics study to qualify materials for component design for the fusion reactors, as presently done for fission reactors. Generally stainless steel (SS) is used as a structural material having Fe, Ni, Cr, Mn, Co, Nb as main constituents (in SS316 content of Fe~65%). Interaction of 14-MeV neutrons with structural material produces various long-lived radio nuclides. The assessment of the radiological hazard showed that the main contribution to activation comes from ^{54}Mn, ^{56}Mn, ^{55}Fe, ^{57}Co, ^{58}Co, ^{60}Co, ^{57}Ni, ^{51}Cr and ^{94}Nb that originate from transmutation reactions of neutrons with the elements in the initial SS composition **[1].** Fusion neutronics studies have been done during many years considering only the stable isotopes of Cr, Fe, Ni. But in the development of D-T fusion reactor, large amount radio nuclides will be produced during reactor operation as well as after shutdown of the reactor **[2].** ^{55}Fe is a primary dominant nuclide produced by neutron induced reaction on Fe,Co and Ni elements by $^{56}Fe(n,2n)$,$^{54}Fe(n,\gamma)$, $^{59}Co(n,\alpha)^{56}Mn(\beta^-)^{56}Fe(n,2n)$, and $^{58}Ni(n,\alpha)$ reactions .As of today, there is no experimental measurement of the $^{55}Fe(n,p)$ cross-section. Direct experimental determinations of cross-sections for unstable long lived radio nuclides are not possible as they do not exist in nature but at the same time they may contribute significantly in actual fusion reactor **[3].** The surrogate reaction method is such an indirect method which was first used in the 1970s for estimating neutron-induced fission cross-sections **[4].** First time surrogate technique has been used to measure the (n,p) cross-section in the mass region ~50-60.

Measurement and Analysis

Fresh self-supporting ^{nat}Cr (abundance ^{52}Cr~ 84%) and ^{45}Sc (abundance = 100%) target of thickness 500 µg/cm^2 were prepared with thermal evaporation technique and bombarded with a ^6Li beam of energy E_{lab}= 33.0 MeV and 35.75 MeV respectively, from a (14 MV) Pelletron-Linac Accelerator facility at BARC-TIFR, Mumbai. The $^{56}Fe^*$ and $^{47}Ti^*$ compound nuclei are formed in $^{52}Cr(^6Li,d)^{56}Fe^*$ and $^{45}Sc(^6Li,\alpha)^{47}Ti^*$ transfer reaction, which serve as a surrogate of $n + {}^{55}Fe \rightarrow {}^{56}Fe^* \rightarrow p + {}^{55}Mn$ and $n + {}^{46}Ti \rightarrow {}^{47}Ti^* \rightarrow p + {}^{46}Sc$ respectively. The two silicon surface barrier (SSB) ΔE-E detector telescope T1 and T2 with ΔE detector of thickness 150 and 100 µm. respectively, and with identical E detector of thickness of 1 mm were mounted at an angles of 25^0 and 35^0 with respect to beam direction around the transfer grazing angle to identify the projectile-like fragments (PLFs). The ground state (Q_{gg}) for $^{52}Cr(^6Li,d)^{56}Fe^*$ and $^{45}Sc(^6Li,\alpha)^{47}Ti^*$ transfer reactions are 6.139 MeV and 15.527 MeV respectively. The $^{56}Fe^*$ and $^{47}Ti^*$ compound systems are populated at overlapping excitation energies (19-30 MeV) in $^{6}Li + ^{52}Cr \rightarrow d + ^{56}Fe*$ transfer reaction (E_{lab}(^{6}Li)=33.0 MeV) and $^{6}Li + ^{45}Sc \rightarrow \alpha + ^{47}Ti*$ transfer reaction (E_{lab}(^{6}Li)=35.75 MeV) respectively.

The projectile like fragment (PLF) singles and coincidence between PLF and decay particles measurements were carried out to determine the proton decay probabilities of ^{56}Fe* and ^{47}Ti* compound nuclei produced in the transfer reactions, within the framework of the surrogate ratio method, by dividing the number of PLF (deuteron and alpha) - decay particle (proton) coincidence (N_{i-p}) by associated PLF-singles (N_i) data as follows:

$$\Gamma_p^{CN}(E_{ex}) = \frac{N_{i-p}}{N_i} \qquad (1)$$

The relative proton decay probabilities of the compound nuclei are multiplied with the relative neutron-induced compound nuclear formation cross-section $\sigma^{CN}_{n+^{55}Fe}$ and $\sigma^{CN}_{n+^{46}Ti}$ to obtain the ratio of the compound nuclear cross-section at the same excitation energies of $n + ^{55}Fe \rightarrow ^{56}Fe^{*} \rightarrow$ *proton decay* and $n + ^{46}Ti \rightarrow ^{47}Ti* \rightarrow$ *proton decay* as follows:

$$R(E_{ex}) = \frac{\sigma^{^{55}Fe(n,p)}(E_{ex})}{\sigma^{^{46}Ti(n,p)}(E_{ex})} = \frac{\sigma_{CN}^{n+^{55}Fe}(E_{ex})}{\sigma_{CN}^{n+^{46}Ti}(E_{ex})} \text{X} \frac{\Gamma_p^{^{56}Fe*}(E_{ex})}{\Gamma_p^{^{47}Ti*}(E_{ex})} \qquad (2)$$

The ^{46}Ti(n,p) cross-section section is well known measured has been used as reference monitor to determine ^{55}Fe(n,p) reaction cross-section from the R(E_{ex}) measurement.

Results and Discussion

The ratios of coincidence to singles counts i.e., proton decay probabilities were determined in steps of 1.0 MeV excitation energy bins over the excitation energy range 19.0 MeV-30.0 MeV for both ^{56}Fe* and ^{47}Ti* compound nuclear systems. The corresponding proton decay probabilities were then substituted in Eq.2 to determine ^{55}Fe(n,p) cross section for each excitation energy bins using ^{46}Ti(n,p) reaction cross section as reference. The ratio of neutron capture cross section values for ^{55}Fe and ^{46}Ti are taken as ratio of corresponding mass numbers in Eq.(2) The excitation energy was scaled down to the equivalent neutron energy by subtracting the neutron separation energy of ^{56}Fe* (11.197 MeV). The experimental ^{55}Fe(n,p)cross sections as a function of equivalent neutron energy, along with evaluated data libraries EAF-2010**,** TENDL-2014**,** ROSFOND-2010 **[5]** and EMPIRE-3.2.3 **[6]** predictions are shown in Fig 1. The measured ^{55}Fe(n,p) cross-sections are found to be reasonably consistent with the calculated cross-section and EAF-2010 data library but show deviation from ROSFOND-2010 and TENDL-2014 cross-sections at lower energies

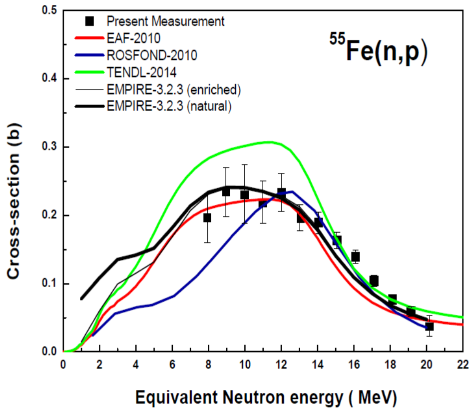

Fig 1. (Color online) The ^{55}Fe(n,p) cross-section as a function of equivalent neutron energy along with various evaluation results and EMPIRE-3.2.3 calculations.

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