Chapter 2

Measurement of $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ reaction cross-section at $E_n = 5.9, 9.85, 14.8$ and $15.5$ MeV.

The $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ reaction cross-section at neutron energies of $5.9\pm0.6$, $9.85\pm0.38$, $14.8\pm0.1$ and $15.5\pm0.7$ MeV from the $^7\text{Li}(p, n)$ as well as $^3\text{H}(d, n)$ reactions has been experimentally determined using activation and off-line $\gamma$-ray spectrometric technique. The experimentally determined $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ reaction cross-sections from the present work were compared with the latest available evaluated nuclear data libraries of ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1/A. The present data along with the literature data in a wide range of neutron energies were interpreted in terms of competition between different reaction channels. The cross-sections were also estimated theoretically using nuclear model based TALYS-1.4 and EMPIRE-2.19 computer codes over neutron energies from near reaction threshold to $20$ MeV to compare with the experimental data.
2.1: Introduction

The neutron induced reaction cross-sections such as \((n, \gamma)\), \((n, n')\), \((n, p)\) and \((n, \alpha)\) reactions of structural materials (e.g. Fe, Ni, Zr, Nb, etc.) are required for design calculations in nuclear reactors and other related technology. The need for fast neutron induced nuclear reaction cross-section data has been increasing in several applied fields such as production of radio-isotopes for biomedical applications (e.g. cancer therapy) and accelerator-driven sub-critical systems (ADSs) etc. The variation of cross-sections with neutron energy are important for studying the excitation of nuclei to different energy levels and subsequent decay to ground state, either directly or through different energy levels including meta-stable states [1]. One of the problem generally faced in the development of fusion reactor is the generation of charged particles through the fast neutron induced nuclear reactions such as \((n, p)\), \((n, \alpha)\), \((n, np)\) and \((n, n\alpha)\) reactions [2]. Such nuclear reactions are induced by fast neutrons on the elements of the first wall, structural and blanket components of the reactor [2]. The accurate determination of the \((n, \gamma)\), \((n, p)\) and \((n, \alpha)\) reaction cross-sections of structural materials (e.g. Fe) are important for the neutron economy in reactor. Further, these nuclear reactions lead to the formation of hydrogen and helium gases in the reactor wall at different locations. In addition, other processes such as atomic displacements and transmutations, etc. can produce micro-structural defect in the materials used in and around the reactor [2]. The work related to the development of radiation-resistant materials for their applications in nuclear industry have therefore gained importance in recent years [2]. The accurate \((n, p)\) reaction cross-section for the production of hydrogen in the reactor materials up to the neutron energy of 20 MeV are required. The fast neutron induced cross-sections are of prime interest for future fusion reactor, for the calculation of nuclear transmutation rate, nuclear heating, radiation damage effects, etc. [2]. The energy range up to the neutron energy of 20 MeV is relevant for ADSs, as most of the neutrons (~80–90%) leaving the spallation target have energies in this range [3].

Structural materials such as stainless steel, zirconium, niobium and aluminium are important from reactor point of view [4]. Among these zirconium and niobium (zircaloy) are used as cladding material of nuclear fuel in reactor, whereas stainless steel is used as the calandria vessel and pipe lines of secondary coolant circuit. In stainless steel, natural
Iron is a primary component with isotopic composition of $^{54}$Fe (5.85%), $^{56}$Fe (91.75%), $^{57}$Fe (2.12%) and $^{58}$Fe (0.28%) [5]. Generally, in reactor there is a broad neutron spectrum of energy ranging from 0 to 15 MeV [6]. Therefore, different nuclear reactions such as (n, $\gamma$), (n, n'), (n, p), (n, $\alpha$) reactions occur based on the energy of the neutron and isotopic composition of iron and hence neutron induced reactions on iron isotopes are of importance in wide range of applications. Neutron induced reaction cross-sections for structural materials are the basic data for evaluation of materials under irradiation in reactor. The $^{56}$Fe(n, p)$^{56}$Mn reaction cross-section is widely used as a monitor for the determination of the neutron induced reaction cross-sections as well as for the precision measurement of the neutron flux at the neutron energies ranging from 13 to 18 MeV [7].

Many reaction channels are opened in the neutron energy above 8 MeV, including complex and multiple particle emission reactions. The interplay between experiment and theory is essential for providing complete and accurate estimates of nuclear data. The predictive power of nuclear model codes can be validated and improved in comparison with good quality experimental data and in turn provides estimate, where no experimental data exist. A literature survey indicates that, neutron-induced reaction cross-sections for $^{56}$Fe(n, p)$^{56}$Mn reaction are widely studied and reported, and many of these are based on standard activation technique [8]. However, very few of those experiments cover the energy range below 8 MeV and above 15 MeV [8]. Different types of standard neutron sources and incident charged particle energies are used for the production of quasi-monoenergetic neutrons in the energy range up to 20 MeV, which is reflected in the available experimental data [9].

In the present work, we have measured the cross-section for the formation of $^{56}$Mn from the $^{56}$Fe(n, p) reaction at neutron energies of 5.9±0.6, 9.85±0.38, 14.8±0.1 and 15.5±0.7 MeV using activation and off-line $\gamma$-ray spectrometric technique. The theoretical values of cross-sections for this reaction were estimated from reaction threshold to 20 MeV by using the TALYS-1.4 [10] and EMPIRE-2.19 [11] computer codes. The cross-sections measured in the present work have been compared with the literature values from EXFOR database [8], and with the theoretical values from TALYS-1.4 [10], EMPIRE-2.19 [11] computer codes.
2.2: Experimental Details

2.2.1: Sample preparation and experimental arrangement

Two sets of experiment were carried out for the $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ reaction cross-sections measurement. The first experiment was performed at the 14 UD BARC-TIFR Pelletron accelerator facility at Mumbai, India for neutron energies of 5.9±0.6, 9.85±0.38 and 15.5±0.7 MeV [12]. The iron sample (with purity ~99.99%) in the form of thin metallic foil was used. For each energy run, separate samples were made by packing a known weight (60–170 mg) of the iron metal foil wrapped with 0.025 mm thick aluminium foil. Similarly, a known weight of metal foil of indium (141–156 mg) and uranium (570–990 mg) of same size were also wrapped separately with 0.025 mm thick aluminium foil. The iron foil sandwiched between the In and U metal foil was additionally wrapped with aluminium foil. In the second experiment of 14 MeV neutron irradiation, 1.69 g of iron metal foil wrapped with the super pure aluminium foil (744 mg) was sealed in a polyethylene bag.

In the first set of experiment, the fast neutrons were produced via the $^7\text{Li}(p, n)^7\text{Be}$ (Q = -1.64 MeV) reaction by bombarding a natural lithium target with a proton beam of energy 7.8, 12 and 18 MeV, respectively. These runs were carried out at 6 m height above the analysing magnet of the Pelletron facility to utilize the maximum proton current from the accelerator [12]. The current and energy of incident proton beam during the irradiations were 150 nA at 7.8 MeV, 400 nA at 12 MeV and 250 nA at 18 MeV, respectively. The emitted neutrons are not mono-energetic and have continuous energy distribution. However, the average energies of the emitted neutrons under the main peak were estimated to be 5.9±0.6, 9.85±0.38 and 15.5±0.7 MeV, which is discussed in detail in the next section. The energy spread for the proton beam at 6 m height was maximum 50–90 keV. At this port, the terminal voltage was regulated by GVM mode by using a terminal potential stabilizer. Further, we use a beam collimator of 6 mm diameter before the target. The energy error in the 10 MeV proton beam is about a few keV. The proton current is not constant during the irradiation time, which is monitored and shown by current integrator.

The lithium foil was made up of natural lithium with thickness 3.7 mg/cm$^2$, sandwiched between two tantalum foils of different thickness. The front tantalum foil
facing the proton beam is the thinnest one (~3.9 mg/cm$^2$), in which the degradation of proton energy is 50–85 keV. On the other hand, the back tantalum foil (beam stopper) is the thicker (0.025 mm), which is used to stop the proton beam. Behind the Ta–Li–Ta stack, the samples used for irradiation were the stack of natural indium, iron and uranium metal foils, which were wrapped separately with 0.025 mm thick aluminium foil to prevent contamination from one to the other. The In–Fe–U stack was mounted at zero degree angle with respect to the proton beam direction at a distance of 2 cm from the location of the Ta–Li–Ta stack. A schematic diagram of the Ta–Li–Ta stack and of the In–Fe–U stack is given in Fig. 2.1. Different sets of stacks were made for different irradiations at various neutron energies.

![Schematic Diagram](image)

**Figure 2.1:** A schematic view of the experimental set up used for the neutron irradiation from $^7$Li(p, n) reaction using Pelletron facility.

In the second set of experiment, the 14 MeV Neutron Generator facility of the Department of Physics, University of Pune was used [13]. The 14.8 MeV neutrons were produced through $^3$H(d, n)$^4$He reaction ($Q = 17.6$ MeV), in which an 8 curie (Ci) tritium target was bombarded by deuteron ions of energy ~175 keV at deuteron beam current of ~80 µA. Iron sample wrapped with 0.025 mm thick super pure aluminium foil was placed at an angle of $0^\circ$ to the axis of deuterium beam at distance of ~10 mm from the end of tritium target.
2.2.2: Neutron irradiation and measurement of gamma-ray activity

Each sample was irradiated with neutrons for a period decided by the neutron energy, its flux and half-life of the radioisotope produced through the neutron induced nuclear reaction. The irradiation times for the neutron energies of 5.9±0.6, 9.85±0.38 and 15.5±0.7 MeV were 15, 4 and 5 h respectively. In the case of neutron energy of 14.8±0.1 MeV, the irradiation was 30 min. After each irradiation, the irradiated samples were cooled for appropriate time depending upon the radiation dose. In case of neutron energy of 5.9±0.6, 9.85±0.38 and 15.5±0.7 MeV, the cooling time was 3–5 h, whereas in case of 14.8±0.1 MeV neutrons irradiation, the cooling time was 4-5 min. Then the irradiated samples were mounted on different Perspex plates and taken for γ-ray counting. The counting time was decided by the half-life and γ-ray activity of the radioisotope produced. The induced γ-ray activities of the irradiated samples were counted by a lead shielded 80 cm$^3$ HPGe detector coupled to a PC-based 4 K channel analyser. The detector efficiency was 20% at 1332.5 keV relative to 3” diameter × 3” length NaI(Tl) detector. The energy resolution of the detector system was 1.8 keV at 1332.5 keV γ-ray energy of $^{60}$Co. The photo peak efficiency of the detector system was determined by using standard γ-ray sources such as $^{152}$Eu and $^{133}$Ba. The γ-ray counting of the irradiated sample was done in live time mode and was followed as a function of time. The counting dead time was kept always less than 5% by placing the irradiated Fe, In, U and Al samples at a suitable distance from the detector to avoid the pile up effects. The γ-ray activity of the radioisotope of interest and that of flux monitor were counted for appropriate time to get a good counting statistics. A typical γ-ray spectrum of the irradiated Fe sample for a cooling period of 3 h 31 min is shown in Fig. 2.2.
Figure 2.2: Gamma-ray spectrum of $^{56}$Mn from $^{56}$Fe(n, p) nuclear reaction at $E_n = 9.85$ MeV.

2.3: Calculations

2.3.1: Calculation of neutron energy

The neutrons produced from $^7$Li(p, n) reaction are not mono-energetic at high proton energy. The incident proton energies in the present experiment were 5.6, 7.8, 12 and 18 MeV respectively. The degradation of proton energy on the front thin tantalum foil of 3.9 mg/cm$^2$ thickness is only 50–85 keV. The Q-value for the $^7$Li(p, n)$^7$Be reaction to the ground state is -1.644 MeV, whereas for the first excited state, it is 0.431 MeV above ground state leading to an average Q-value of -1.868 MeV. Thus, for the proton energy of 5.6, 7.8, 12 and 18 MeV, the resulting peak energy of first group of neutrons ($n_0$) would be 3.72, 6.12, 10.12 and 16.12 MeV to the ground state of $^7$Be having threshold energy of 1.881 MeV. Corresponding neutron energy of second group of neutrons ($n_1$), for the first excited state of $^7$Be will be 3.23, 5.63, 9.63 and 15.63 MeV, respectively. This is because above proton energy of 2.4 MeV, the $n_1$ group of neutrons is
also produced. Liskien and Paulsen [14] have given the branching ratio to the ground state and first excited state of $^7$Be up to the proton energy of 7 MeV. However, Poppe et al. [15] have given the branching ratio to ground state and first excited state of $^7$Be for the proton energy of 4.2 to 26 MeV. In addition to these, Meadows and Smith [16] have also given the branching ratio to the ground state and first excited state of $^7$Be up to to the proton energy of 7 MeV.

Based on their [14–16] prescription for the proton energy of 5.6 MeV, the contribution to $n_0$ and $n_1$ group of neutrons are 86.1–13.9% (86.1 and 13.9%) respectively. The proton energy of 5.6 MeV leads to an average neutron energy of $3.72\times0.861 + 3.23\times0.139 = 3.651$ MeV. Above proton energy of 4.5 MeV the fragmentations of the $^8$Be to $^4$He + $^3$He + n ($Q = -3.23$ MeV) occurs and other reaction channels are open to give continuous neutron energy distribution besides $n_0$ and $n_1$ groups of neutrons. Meadows and Smith [16] have given experimental neutron distributions from break up channels and also parameterized these distributions. For the proton energy of 5.6 MeV, we have used their parameterization for break up neutrons having a weight of 4% and two Gaussian distributions with weights of 84 and 12% for $n_0$ and $n_1$ groups of neutron, which is shown in Fig. 2.3. These Gaussians are centered at 3.7 and 3.2 MeV having a width of 0.3 MeV.

We obtained the continuous neutron spectra besides $n_0$ and $n_1$ groups of neutrons for the proton energies of 7.8, 12 and 18 MeV. We have generated neutron spectra for proton energies of 7.8 and 12 MeV by using the neutron energy distribution given by Poppe et al. [15] and given in Figs. 2.4 and 2.5, respectively. We have also generated neutron spectrum for proton energy of 18 MeV by using the neutron energy distribution given by Mashnik et al. [17] and shown in Fig. 2.6. The energy of the neutrons flux from $^7$Li(p, n) reaction does depend on the angle. However, as shown in Fig. 2.1, the maximum angle seen by the target for the sample size of 0.5 cm$^2$ area and 1 mm thickness is about 9.46$^\circ$. The angles for the energy distribution of neutrons shown in Figs. 2.3, 2.4 and 2.5 are at 0$^\circ$ (Mashnik et al.) and at 3.5$^\circ$ (Poppe et al.) for $E_p = 12$ MeV, respectively. Further, the proton is not of point size and beam is collimated to 6 mm diameter before the target. Therefore for high proton energies, these neutrons can be considered as forward peak and
neutron energy variation within this angle range for a given proton energy is expected to be very weak.

![Figure 2.3](image1.png)

**Figure 2.3:** Neutron spectrum from $^{7}$Li(p, n) reaction at $E_p = 5.6$ MeV calculated using the results of Meadows and Smith of Ref. [16].

![Figure 2.4](image2.png)

**Figure 2.4:** Neutron spectrum from $^{7}$Li(p, n) reaction at $E_p = 7.8$ MeV obtained from Ref. [15].
Figure 2.5: Neutron spectrum from $^7\text{Li}(p, n)$ reaction at $E_p = 12$ MeV obtained from Ref. [15].

![Figure 2.5](image1.png)

Figure 2.6: Neutron spectrum from $^7\text{Li}(p, n)$ reaction at $E_p = 18$ MeV obtained from Ref. [15].

![Figure 2.6](image2.png)

From Figs. 2.3, 2.4 and 2.5, the average neutron energies under the main peak region ($n_0$ and $n_1$ groups) were calculated as $5.9\pm0.6$, $9.85\pm0.38$ and $15.5\pm0.7$ MeV after
removing the tail part of distribution for the proton energies of 7.8, 12 and 18 MeV, respectively. The average neutron energy is calculated by using \( \int E_n \Phi(E) dE / \Phi(E) dE \), where \( \Phi(E) \) represents the neutron distributions under the quasi mono-energetic peak of the neutron energy spectra, shown in the Figs. 2.4, 2.5 and 2.6. The uncertainty in the neutron energy arises from the width of mono-energetic part of the spectra.

2.3.2: Calculation of neutron flux

For the calculation of neutron flux, the photo peak activity of 336.2 keV \( \gamma \)-line of \( ^{115m}\text{In} \) from \( ^{115}\text{In}(n, n') \) reaction was used for neutron energy of 5.9±0.6 MeV corresponding to the proton energy of 7.8 MeV. The observed photo peak activity \( (A_{\text{obs}}) \) for 336.2 keV \( \gamma \)-line of \( ^{115m}\text{In} \) is related to the neutron flux \( (\Phi) \) with the following relation [12]

\[
A_{\text{obs}} \left(\frac{CL}{LT}\right) = N \sigma \Phi a \varepsilon (1-e^{-\lambda t}) e^{-\lambda T} (1-e^{-\lambda CL}) / \lambda 
\]

(2.1)

where \( N \) is the number of target atoms and \( \sigma \) is the reaction cross-section of \( ^{115}\text{In}(n, n')^{115m}\text{In} \) reaction. ‘\( a \)’ is the branching intensity of the 336.2 keV \( \gamma \)-line of \( ^{115m}\text{In} \) and \( \varepsilon \) is its detection efficiency. ‘\( t \), T, CL and LT’ are the irradiation time, cooling time, clock time and counting (live) time respectively. In the above equation, the \( CL/LT \) term has been used for dead time correction.

The observed photo peak activity \( (A_{\text{obs}}) \) of 336.2 keV \( \gamma \)-line of \( ^{115m}\text{In} \) was obtained using PHAST peak fitting program [18]. Knowing the \( ^{115}\text{In}(n, n')^{115m}\text{In} \) reaction cross-section \( (\sigma) \) from literature [19], neutron flux at neutron energy of 5.9±0.6 MeV was calculated by using Eq. (2.1). The nuclear spectroscopic data such as half-life and branching intensity \( (\lambda) \) were taken from Ref. [4]. The neutron flux \( (\Phi) \) at the neutron energy of 5.9±0.6 MeV was obtained to be 3.03×10^6 n/cm^2 s. In order to examine this, the neutron flux was also calculated by using the yield \( (Y) \) of fission product \( (^{97}\text{Zr}) \), extracted from the experimental yields of Ref. [20] in the 5.9±0.6 MeV neutron induced fission of \( ^{238}\text{U} \). The equation used for such calculation is as follows [12]

\[
\Phi = \frac{A_{\text{obs}} \left(\frac{CL}{LT}\right) \lambda}{N \sigma_f Y a \varepsilon (1-e^{-\lambda t}) e^{-\lambda T} (1-e^{-\lambda CL})} 
\]

(2.2)
All terms in Eq. (2.2) have the same meaning as in Eq. (2.1) except the yield (Y) of the fission product [20] and fission cross-section (σf), which was taken from Ref. [8].

At neutron energy of 5.9±0.6 MeV, the neutron flux calculated by using Eq. (2.2) is $3.0 \times 10^6$ n/cm$^2$ s, which is in close agreement with the previous value of $3.03 \times 10^6$ n/cm$^2$ s as obtained from Eq. (1.1). In the cross-section calculations, we consider the neutron flux as $3.0 \times 10^6$ n/cm$^2$ s. Folding the neutron spectrum of Fig. 2.3 with the $^{238}$U(n, f) reaction cross-section [8] at different neutron energies gives the average fission cross-section. Using the average $^{238}$U(n, f) reaction cross-section also gives the similar neutron flux. This is due to the negligible tailing correction in the neutron spectrum for $E_n = 5.9$ MeV corresponding to the proton energy of 7.8 MeV (Fig. 2.4).

At higher neutron energy, the contribution from the second group and tailing due to break up reaction ($^8$Be $\rightarrow ^4$He $+ ^3$He $+ n$) is more important. It can be also seen from Figs. 2.5 and 2.6 that in the neutron spectrum from the 12 and 18 MeV proton beam, the tailing part of the low energy neutrons is quite significant. Within this range of neutron energy, the $^{115}$In(n, n')$^{115m}$In reaction cross-section changes drastically [19]. In view of this, the $^{115}$In(n, n')$^{115m}$In reaction is not used as a neutron flux monitor, but the $^{238}$U(n, f) reaction was used as the neutron flux monitor at $E_n = 9.85 \pm 0.38$ and 15.5±0.7 MeV. The fission cross-section of $^{238}$U(n, f) reaction at $E_n = 5.9$, 9.85 and 15.5 MeV was taken from Ref. [8]. The yield (Y) of the fission product $^{97}$Zr from $^{238}$U(n, f) reaction, was used for the calculation of neutron flux. This is justified because the yield of $^{97}$Zr in $^{238}$U(n, f) reaction vary marginally from 5.36% at 1.5 MeV to 5.62% at 14.8 MeV neutron energy [20]. Thus, it seems that in the neutron induced fission cross-section of $^{238}$U [8], yield of fission products [20] at the peak position of the mass yield curve do not change significantly. In view of this, the neutron flux at neutron energy of 9.85±0.38 MeV corresponding to the proton energy of 12 MeV was calculated using Eq. (2.2), which is $1.3 \times 10^7$ n/cm$^2$ s. Similarly, in the case of neutron energy of 15.5±0.7 MeV corresponding to the proton energy of 18 MeV, the neutron flux was $1.53 \times 10^7$ n/cm$^2$ s.

In case of 14.8 MeV neutron irradiation, the $^{27}$Al(n, p)$^{27}$Mg reaction (Q = -1.82 MeV) was used as a standard for neutron flux determination. The radioisotope $^{27}$Mg has a half-life of 9.45 min and emits γ-ray of energy 843.7 keV. The standard value of the $^{27}$Al(n, p)$^{27}$Mg reaction cross-section is 62.9±1.4 mb at neutron energy of 14.8 MeV [21].
The neutron flux during the irradiation was calculated and found to be $1.6 \times 10^7 \text{ n/cm}^2\text{s}$. Table 2.1 gives the details of the nuclear reactions and their related nuclear data used in the present work.

**Table 2.1:** The measured reaction and decay data [5] used in the present work.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Reaction product</th>
<th>Half-life</th>
<th>Gamma energy (keV)</th>
<th>Gamma intensity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{56}\text{Fe}(n, p)$</td>
<td>$^{56}\text{Mn}$</td>
<td>2.57 h</td>
<td>846.7</td>
<td>98.9</td>
</tr>
<tr>
<td>$^{27}\text{Al}(n, p)$</td>
<td>$^{27}\text{Mg}$</td>
<td>9.45 m</td>
<td>843.8</td>
<td>71.8</td>
</tr>
<tr>
<td>$^{115}\text{In}(n, n')$</td>
<td>$^{115m}\text{In}$</td>
<td>4.48 h</td>
<td>336.2</td>
<td>45.8</td>
</tr>
<tr>
<td>$^{238}\text{U}(n, f)$</td>
<td>$^{97}\text{Zr}$</td>
<td>16.74 h</td>
<td>743.4</td>
<td>93.1</td>
</tr>
</tbody>
</table>

**2.3.3: Determination of reaction cross-section**

The cross-section of a neutron induced nuclear reaction can be estimated using the following decay equation [12]

$$
\sigma = \frac{A_{\text{obs}} \left(\frac{CL}{LT}\right) \lambda}{N \cdot a \cdot \varepsilon \cdot \Phi \left(1-e^{-\lambda t}\right) \cdot \left(1-e^{-\lambda T}\right)}
$$ (2.3)

where $\Phi$ is the neutron flux, $N$ is the number of target atoms, $A_{\text{obs}}$ is the observed photo peak activity of the respective $\gamma$-ray peak, $\lambda$ is the decay constant of the product nucleus, $\varepsilon$ is the detection efficiency for the $\gamma$-line of interest and ‘a’ is the $\gamma$-ray intensity taken from Ref. [5]. ‘t’ is the irradiation time and $T$ is the cooling time, whereas CL and LT are clock time and live time of counting, respectively. In the above equation, the CL/LT term has been used for dead time correction.

Using the different terms in Eq. (2.3), the $^{56}\text{Fe}(n, p)$ reaction cross-section was calculated for the neutron energies of $5.9 \pm 0.6, 9.85 \pm 0.38, 14.8 \pm 0.1$ and $15.5 \pm 0.7$ MeV, which are given in Table 2.2.
Table 2.2: $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ reaction cross-sections at different neutron energies.

<table>
<thead>
<tr>
<th>Neutron energy (MeV)</th>
<th>Cross-section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>5.9±0.6</td>
<td>13.45±0.92</td>
</tr>
<tr>
<td>9.85±0.38</td>
<td>65.88±4.54</td>
</tr>
<tr>
<td>14.8±0.1</td>
<td>120.07±8.28</td>
</tr>
<tr>
<td>15.5±0.7</td>
<td>76.22±5.25</td>
</tr>
</tbody>
</table>

The uncertainty in the experimental cross-sections are mainly from the uncertainties in the (i) counting statistics (~4-8%), (ii) decay data, which constitute half-life and gamma ray abundance, which is ~2%, (iii) efficiency and energy calibration of the detector (~3%), (iv) monitor cross-section (~2%), (v) self-absorption of γ-rays in the sample (~2%), (vi) error due to neutron flux estimation (~4%). Thus, the total uncertainties were estimated in quadrature i.e. by taking the square root of the sum of the squares for the individual uncertainties.

2.3.4: Theoretical calculations of cross-sections

The nuclear model calculations for $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ were performed with two different reaction codes, TALYS-1.4 [10] and EMPIRE-2.19 [11]. TALYS-1.4 [10] and EMPIRE-2.19 [11] use the Hauser–Feshbach statistical model with width fluctuation corrections and estimates of the direct and pre-equilibrium contributions.

2.3.4.1: TALYS-1.4 calculations

In the present work, the cross-section for the formation of $^{56}\text{Mn}$ through the $^{56}\text{Fe}(n, p)$ reaction over the neutron energy range from 5 to 20 MeV has been calculated using the TALYS-1.4 [10] computer code.

In TALYS-1.4 [10] calculations, the optical model parameters for neutrons and protons were obtained by a local potential proposed by Koning and Delaroche [22].
Similarly, the simple folding approach of Watanabe [23] was used for alpha particles. The compound nucleus contribution was calculated by the Hauser–Feshbach model [24]. The two-compound exciton model developed by Kalbach [25] was used for calculating the pre-equilibrium contribution. For the level density calculation, the composite formula proposed by Gilbert and Cameron [26], consisting of a constant temperature law at low energies and a Fermi gas expression at high energies is applied. Energy-dependent shell effects are included.

2.3.4.2: EMPIRE-2.19 calculations

The reaction cross-section of \( ^{56}\text{Fe}(n, p)^{56}\text{Mn} \) from reaction threshold to 20 MeV was also studied theoretically using the computer code EMPIRE-2.19 [11].

In the present work, version 2.19 was used with the default input parameters (except nuclear level density model) concerning nuclear masses, ground-state deformations, discrete levels, decay schemes, level densities, moments of inertia (MOMFIT) and strength functions.

The direct contribution was determined via the coupled channel calculation using the built-in ECIS03 code [27]. The particle transmission coefficients were generated via the spherical optical model using the computer code ECIS03 [27], using the optical model parameters by Koning and Delaroche [22] for neutrons and protons and default parameters of [28] \( \alpha \) particles. The pre-equilibrium contribution was taken into account via the exciton model as implemented in the EMPIRE-2.19 code (DEGAS) [29]. These codes conserve the particle flux by dividing the absorption cross-section of the optical model between the different types of reaction mechanisms. In the present work, for the level densities calculation the Gilbert–Cameron [26] level density approach was used. This model has been parameterized by Ignatyuk et al. [30], Iljinov et al. [31], and Young et al. [32].

2.4: Results and Discussion

2.4.1: \( ^{56}\text{Fe}(n, p)^{56}\text{Mn} \) reaction

The experimental measured cross-sections data in the present work for \( ^{56}\text{Fe}(n, p)^{56}\text{Mn} \) reaction from Table 2.2 are plotted as a function of neutron energy in Fig. 2.7 together with the some literature values. The data points are the experimental cross-
sections obtained from the EXFOR database [8] and the cross-section measured at $E_n = 5.9 \pm 0.6$, $9.85 \pm 0.38$, $14.8 \pm 0.1$ and $15.5 \pm 0.7$ MeV in the present work. At a first glance, there appear to be large discrepancies in the data. However, a careful analysis clarifies the picture to some extent. The data can be divided into three groups: (a) the low energy region up to neutron energy of 8 MeV, where a systematic study has been done, (b) the neutron energy region around 14 MeV, where several measurements were performed using a neutron generator and discrepancies exist and (c) the neutron energy region above 15 MeV, where limited data exist. Good agreement was found with the measurement of Santry and Butler [33] and of Smith and Meadows [34] and agreement for the $^{56}$Fe(n, p) reaction with Ikeda et al. [35] and Mannhart and Schmidt [36] was reasonable. It can be seen from Fig. 2.7 that the $^{56}$Fe(n, p) reaction cross-section increases from reaction threshold of energy 2.96 to 13.5 MeV and thereafter decreases. This is due to the opening of other reaction channels above neutron energy of 13.5 MeV. The higher cross-section within neutron energy of 10–18 MeV is due to giant dipole resonance (GDR) effect. However, the $^{56}$Fe(n, p) reaction cross-section at neutron energy of 14.8 MeV from the present work is slightly higher than the earlier measured value. In order to examine this, the experimentally determined $^{56}$Fe(n, p) reaction cross-sections were also compared with latest available evaluated nuclear data from ENDF/B-VII.1 [37], JENDL-4.0 [38] and JEFF-3.1/A [39] library and also plotted in Fig. 2.7. These evaluated reaction cross-sections for $^{56}$Fe(n, p) reaction are quoted in Table 2.2 for the comparison of present experimental values. It can be seen from Table 2.2 that the experimentally measured $^{56}$Fe(n, p) reaction cross-section at neutron energy of 5.9±0.6 MeV is slightly lower than the JENDL-4.0 [38] and ENDF/B-VII.1 [37] data, but slightly higher than the JEFF-3.1/A [39] data, whereas it is slightly higher at neutron energy of 14.8±0.1 MeV than the evaluated data. However, at the neutron energy of 9.85±0.38 MeV, the $^{56}$Fe(n, p) reaction cross-section measured in the present work is good agreement with the evaluated data, but at the neutron energy of 15.5±0.7 MeV the measured cross-section is slightly lower than the evaluated data. Thus, Fig. 2.7 shows that the experimental $^{56}$Fe(n, p) reaction cross-section at neutron energies of 5.9±0.6, 9.85±0.38, 14.8±0.1 and 15.5±0.7 MeV are within the range of evaluated nuclear data. Further, the $^{56}$Fe(n, p) reaction cross-section
was also estimated theoretically using the nuclear model based computer codes TALYS-1.4 [10] and EMPIRE-2.19 [11].

![Figure 2.7](image)

**Figure 2.7:** Excitation function of the $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ reaction (i) measured at 5.9, 9.85, 14.8 and 15.5 MeV neutron energies and (ii) calculated over 5 to 20 MeV neutron energies using TALYS-1.4 [10] and EMPIRE-2.19 [11] codes in the present work. The data points are the experimental cross-section values obtained from EXFOR database [8].

The theoretical $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ reaction cross-section was calculated using TALYS 1.4 [10] and from EMPIRE-2.19 [11] codes and are plotted in Fig. 2.7. The fitted TALYS-1.4 [10] and EMPIRE-2.19 [11] calculations describe the measured data over the entire energy range of the experiment. It can be seen from Fig. 2.7 that within the uncertainties the experimentally measured cross-section values are close to the corresponding theoretical cross-sections estimated using the TALYS-1.4 [10] computer code at almost all the neutron energies. The theoretical study of $^{56}\text{Fe}(n, p)$ reaction using TALYS-1.4 code [10] indicates that the bell-like shape of the excitation curve is a typical characteristics of compound nucleus contribution which rises abruptly above the reaction
threshold and decrease due to opening of other reaction channels and increase of pre-equilibrium contribution with neutron energy. The lower part is dominated by compound nuclear contribution. On the other hand, the nuclear model calculation done using the code EMPIRE-2.19 [11] is in close agreement with the cross-section data in the low neutron energy region between 5 and 7 MeV and in the higher neutron energy region between 18 and 20 MeV. However, the EMPIRE-2.19 [11] calculation grossly overestimates the excitation function within neutron energy of 7–17 MeV. The agreement between the experimental cross-sections with the theoretical values in the present calculations obtained using TALYS-1.4 [10] code is better as compared to the cross-section obtained using EMPIRE-2.19 [11] code. The theoretical value from TALYS-1.4 [10] calculation shows good agreement with the evaluated data from ENDF/B-VII.1 [37], JENDL-4.0 [38] and JEFF-3.1/A [39] library. On the other hand, the theoretical value of the $^{56}$Fe(n, p) reaction cross-sections from EMPIRE-2.19 [11] code are in close agreement with the evaluated data from ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1/A library in the low neutron energy up to 7 MeV, but in the neutron energy range between 7 and 17 MeV shows higher values than the evaluated data.

2.5: Conclusions

i) The $^{56}$Fe(n, p) reaction cross-section at average neutron energies of $E_n = 5.9\pm0.6$, $9.85\pm0.38$, $14.8\pm0.1$ and $15.5\pm0.7$ MeV are determined in the present work using standard activation and off-line $\gamma$-ray spectrometric technique.

ii) The $^{56}$Fe(n, p) reaction cross-sections at neutron energies of $E_n = 5.9\pm0.6$, $9.85\pm0.38$, $14.8\pm0.1$ and $15.5\pm0.7$ MeV are in close agreement with the evaluated data from ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1/A library.

iii) The $^{56}$Fe(n, p) reaction cross-sections were calculated theoretically using TALYS-1.4 and EMPIRE-2.19 computer codes. The theoretical $^{56}$Fe(n, p) reaction cross-sections from TALYS-1.4 code are in close agreement with the experimental data almost all neutron energies. However, the $^{56}$Fe(n, p) reaction cross-sections from EMPIRE-2.19 code are in close agreement with the experimental data in the low neutron energy between 5 and 7 MeV and in the high energy between 18 and 20 MeV, but it overestimates within neutron energy of 7–17 MeV.
References:


[38] JENDL-4.0, available at


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