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Evaluation of neutron capture cross sections on ^{60}Fe

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The production of ^{60}Fe in the slow neutron capture process (s-process) has been discussed in this paper and the reaction cross sections have been evaluated using different nuclear reactions models and tabulated. The energy of proton energy of neutron energy spectrum code (EPEN) has been used to calculate the neutron energy spectrum and tabulated. Model code dependence of the prediction has also been discussed.

Keywords: Neutron capture cross section, Asymptotic giant branch (AGB) stars, Maxwellian averaged cross section (MACS), Energy of proton energy of neutron (EPEN)

1 Introduction

Knowledge of neutron physics quantities plays an important role in development of nuclear energy, national security and nuclear astrophysics applications. The usefulness of several recent evaluation works on cross section data as major sources of information is unquestionable. In this work, the reaction cross sections were evaluated using different nuclear reactions models and are tabulated. Also, the present status of experimental data for neutron capture cross sections is still inadequate both in quality and quantity. Therefore, it is important to perform precise measurements of capture cross-sections for this nuclide. The important motivations are neutron cross-section data are important for two purposes: first they provide insight into the nature of matter and increasing our understanding of fundamental physics. In astrophysical studies, nucleo synthesis, isotopic abundance and other quantities of interest demand the knowledge of cross sections for some nuclides in the stellar medium characteristic energy range. The production of ^{60}Fe in the slow neutron capture process (s - process) is hampered by the rather short-lived precursor $^{59}Fe(t_{1/2} = 44.495$ d), which acts as a branch point of the s-process path. Accordingly, high neutron densities are required to avoid that the reaction flow is by passes ^{60}Fe via the decay of ^{59}Fe. Once ^{60}Fe is reached, it can also be destroyed by neutron capture or on longer time scales by β^- decay. High neutron densities are generally accompanied by very high temperatures, but the synthesis of ^{60}Fe requires an upper limit of about 2×10^9 K, because photo-disintegration reactions such as $^{60}Fe(\gamma,n)$ and $^{59}Fe(\gamma,n)$ start to dominate otherwise. There are two different astrophysical scenarios where ^{60}Fe can be produced during the He–shell burning phase in low-mass thermally pulsing asymptotic giant branch (AGB) stars and during the convective C - shell burning in massive pre-supernova stars. In AGB stars neutron densities of 10^{10} cm^{-3}. According to detailed stellar model calculations by Limongi & Chieffi, about 65 % of the total yield of ^{60}Fe are in fact synthesized in the pre-supernova stage of massive stars and 18 % are contributed by the He burning shell of less massive stars. A third major component is eventually produced by explosive shell burning during the supernova itself. These contributions to the total ^{60}Fe yield are strongly affected by the respective masses and metallicities of the stars involved and may vary correspondingly. A crucial input for the production of ^{60}Fe in AGB stars and massive pre-supernova stars are the neutron capture cross sections at the respective stellar temperatures. So far, an activation measurement of the ^{60}Fe $(n,\gamma)^{61}Fe$ cross section at neutron energies corresponding to a thermal energy of kT=25 keV (typical for AGB stars) was performed at Forschungszentrum Karlsruhe, Germany[1]. The Maxwellian averaged cross section (MACS) at kT=30 keV was determined to (5.15±1.4) mb. The direct capture (DC) component of the cross section at this temperature constitutes an important information for the extrapolation towards the astro

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physically interesting temperatures in massive stars around kT=90 keV. The aim of this work is to evaluate the thermal neutron cross-sections for 2200 m/s neutrons and resonance integrals for $^{59}Fe(n,\gamma)^{60}Fe$ reaction by activation method with neutron source. The results of evaluation were obtained, using cadmium ratios, relative to the reference values of ^{197}Au with σ_0 = 98.659±0.09 barn and I_0 = 1550±28 barn [2].

2 Analysis and Results

The neutron flux will be monitored using $^{197}Au(n,\gamma)^{198}Au$ ($T_{1/2}$ = 2.6948 d, decay gamma energy = 411.802 KeV, with intensity 95.62%) and $^{59}Co(n,\gamma)^{60}Co$, standard cross section of $^{197}Au(n,\gamma)^{198}Au$ and $^{59}Co(n,\gamma)^{60}Co$ by the ENDF/B-7.1 will be used for normalization. ^{59}Co and ^{197}Au have different sensitivities to thermal and epithermal neutrons, these wires are appropriate to determine the thermal and the epithermal fractions of neutron flux. Parameters of the neutron flux monitor wires and nuclear data used for data evaluation is shown in Table 1-3. The effective cross section σ is defined by equating the reaction rate R to the product of σ and n_0, where n_0 is the neutron flux in the Westcott's[4] convention with the neutron density n, including thermal and epithermal neutrons, and with the velocity of neutron ν_0 = 2, 200 m/s,(thermal neutrons, 0.025 eV) so that, the reaction rate can be expressed as:

$$R = nv_0\sigma \quad \text{… (1)}$$

The relation between the effective cross section σ and σ_0 can be expressed as:

$$\sigma = \sigma_0 (g + rs) \quad \text{… (2)}$$

Where, σ_0 is the cross section for 2,200 m/s neutrons, g is a function of temperature, r is epithermal index in westcott's convention, s is a function of neutron temperature and resonance integral. s is defined by $s_0(T/T_0)^{1/2}$ then Eq. (2) can be expressed as:

$$\sigma = \sigma_0 [g\, G_{th} + r(T/T_0)^{1/2}\, s_0\, G_{epi}] \quad \text{… (3)}$$

Where, T is the neutron temperature and T_0 is 293.6 K. The quantity r $(T/T_0)^{1/2}$ gives the fraction of the epithermal neutron in the neutron spectrum. The parameters in the Eq. (3) are summarized in Table 1-3 together with the nuclear data. The value of g, G_{th} and G_{epi} are taken as unity in the following analysis in current target conditions. Then s_0 is defined by:

$$s_0 = \frac{2I_0'}{\sqrt{(\pi)\sigma_0}} \quad \text{… (4)}$$

Where, I_0' is the reduced resonance integral, G_{th} and G_{epi} is the self-shielding coefficients for thermal and epithermal neutrons. By substituting Eq. (3) in to (1), we get a simplified form:

$$(R/\sigma_0)_{monitor} = (\varphi_1 + \varphi_2 . s_0)_{monitor} \quad \text{... (5)}$$

For the irradiation without Cd capsule:

$$(R'/\sigma_0)_{monitor} = (\varphi_1' + \varphi_2' . s_0)_{monitor} \quad \text{… (6)}$$

The reaction rates R and R′ were obtained from peak counts of gamma rays from the monitors ^{60}Co and ^{198}Au. Here, φ_1 and φ'_1 are the neutron fluxes in thermal region, φ_2 and φ'_2 are neutron fluxes in epithermal region. The slope of R/σ_0 as a function of s_0 gives the values of φ_2 and φ'_2. The s_0 for the unknown element (present case Fe) can be measured by:

$$(s_0)unknown = -\frac{\varphi 1 - \varphi' 1\left(\frac{R}{R'}\right)}{\varphi 2 - \varphi' 2\left(\frac{R}{R'}\right)} \quad \text{… (7)}$$

Table 3 – Data evaluation.

Isotope	ϕ	t_{irr} (h)	Counts	Counts/sec
^{197}Au	10^{12} n/cm^2. sec	0.0167	37517550.93	694.76
^{59}Co	10^{12} n/cm^2. sec	2	4028165.20	111.89

Table 1 – Parameters of the neutron flux monitor wires and nuclear data used for data evaluation.

Monitors	Radioisotope	$T_{1/2}$	σ_0(barn)	g	s_0	G_{th}	G_{epi}
Co	^{60}Co	5.271 Y	37.18	1.00	1.738	1.00	1.00
Au	^{198}Au	2.695 D	98.65	1.00	17.22	1.00	1.00

Table 2 – Data evaluation.

Isotope	λ	$G\varepsilon$	$\theta(KeV)$	BR	$t_{co}(h)$	$t_{coo}(h)$	$\sigma(b)$
^{197}Au	2.97×10^{-6}	3%	411.802	95.6%	15	3	99
^{59}Co	4.2×10^{-9}	3%	1332.5	65%	10	3	347

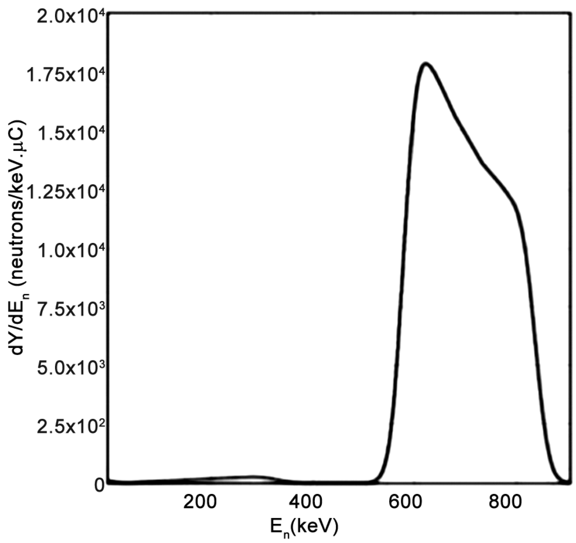

Fig. 1 – Neutron flux energy spectrum from the $^{7}Li(p, n_0)^{7}Be$ reaction at E_P=2.25±0.02 MeV obtained from the code EPEN[3].

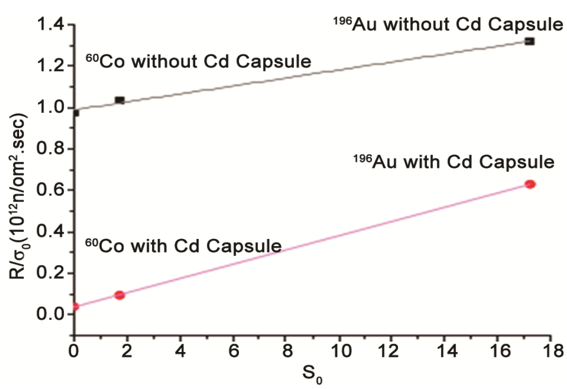

Fig. 2 – Experimental relations between R/σ_0 (or R'/σ_0) and s_0 obtained from gamma ray measurement of the flux monitor wires irradiated with and without the Cd capsule.

The resonance integral I_0 can be determined by:

$$I_0 = I_0' + 0.45\sigma_0 \qquad \dots (8)$$

Where, I'_0 is the reduced resonance integral it will obtained from Eq. (4).

The results are shown in Figs 1-3. Figure 1 shows neutron energy spectrum from the ^{7}Li (p, n_0)^{7}Be reaction at E_p = 2.25±0.02 MeV obtained from the code EPEN. Figure 2 shows experimental relation

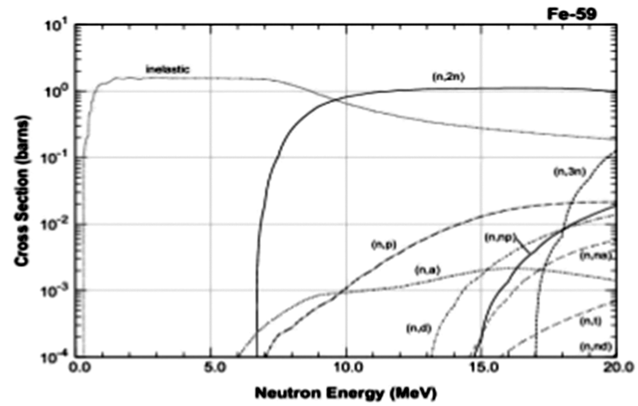

Fig. 3 – Cross section data ^{59}Fe.

Table 4 – Thermal neutron cross-section and resonance integral for $^{59}Fe(n,\gamma)^{60}Fe$.

This work	6.001 b	2.800 b
JENDL 4.0	6.002 b	2.809 b

between R/σ_0 and s_0. Figure 3 shows cross section data for ^{59}Fe. Present results and previous ones of thermal neutron cross-section and resonance integral for $^{59}Fe(n,\gamma)^{60}Fe$ are shown in Table 4.

3 Conclusions

The production of ^{60}Fe in the slow neutron capture process (s-process) was estimated in this paper and the reaction cross sections have been evaluated using different nuclear reactions models and are tabulated. The thermal neutron capture cross-section of ^{60}Fe was obtained as 6.001 b and the resonance integral measured was less than 2.800 b.

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