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Neutron Induced Reaction Cross Section Measurement for Silver with Detailed Uncertainty Quantification

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1. Introduction

Silver has antibacterial properties, used in water purification and medical field. ^{109}Ag is used for the production of ^{109}Cd, ^{110}In, ^{110m}Ag radioisotopes. Standardly, ^{59}Co,^{115}In, ^{197}Au are used as neutron flux monitors [1], but the product nuclide of ^{197}Au has a short half-life of 2.69 days. For long irradiations ^{197}Au is not preferred, whereas the product nuclide of ^{109}Ag has a half -life of 249.83 days and it can be preferred for long irradiations. ^{109}Ag can be used as flux monitor [2]. ^{110m}Ag is produced by the neutron capture reaction of ^{109}Ag which go through β-decay back to the valley of stability and make stable nuclei i.e., ^{110}Cd. ^{110}Cd is used for the production of ^{110}In, ^{113m}In radioisotopes which are well known for multipurpose imaging and scanning. Therefore, we need to execute cross section measurement of ^{109}Ag(n,γ)^{110m}Ag reaction.

2. Experimental Details

The experiment was carried out at the Folded Tandem Ion Accelerator (FOTIA) Facility, Bhabha Atomic Research Centre (BARC), Mumbai. For neutron production, ^{7}Li(p,n)^{7}Be reaction is used. The proton beam of energies 2.5, 3.0, 3.6 MeV with an energy spread of 0.02 MeV were bombarded on a 3 mg/cm^2 thick lithium target. The beam current was 30 nA. The silver (i.e. the activation sample) and natural indium foil (i.e. the monitor sample) were prepared in three different sets covered in aluminium foil. They were of area 10 x 10 mm^2. After irradiation of 24 hours, they were cooled and then counted using high-purity germanium (HPGe) detector. The nuclear decay data of characteristic γ–ray energy was acquired from NuDat 3.0 [3].

3. Data Analysis and Theoretical Framework

The efficiency of the HPGe detector was calibrated at various characteristic γ-ray energies using a standard ^{152}Eu point source. It was calculated using the equation (1) in Ref. [4]. The efficiency of the point source was transferred to the sample using EFFTRAN [5]. We interpolated the detector efficiency for the characteristic γ-ray energy of the product radionuclides with their uncertainties and used them in calculation of cross section. The cross section we have used is as follows,

$$<\sigma_s>=<\sigma_m>\eta\frac{C_s N_m I_m f_m}{C_m N_s I_s f_s}\times\frac{N_{low(s)}}{N_{low(m)}}\frac{C_{attn(s)}}{C_{attn(m)}}, \quad (1)$$

where counts, number of atoms in the foil, intensity of the characteristic γ-ray energy, timing factor are represented by *C, N, I, f* for sample (s) and monitor (m), respectively. The measurement was completed using standard monitor reaction cross section of ^{115}In(n,n'γ)^{115m}In from IRDFF-1.05, data library [6]. For the correction of low background neutrons (N_{low}), we have used EPEN [7] and for the correction of self γ-ray attenuation (C_{attn}) we have used XMuDat [8]. We divided the fluxes provided by EPEN and then calculated the reference monitor cross section and their uncertainties for our interested energies [9,10]. After calculation of cross section, we performed covariance analysis to calculate the uncertainties [11,12]. The fractional uncertainties in the various parameters associated in the measured cross section are given in Table 1.

TALYS-1.96 [13] has been employed for the theoretical calculations of the reaction ^{109}Ag(n,γ)^{110m}Ag at 0.1 to 2 MeV. In the present investigation, six different level density models available in the TALYS-1.96 are used to reproduce nuclear reaction cross sections.

Table 1. Fractional uncertainties in various parameters associated in the measured ^{109}Ag(n,γ)^{110m}Ag reaction cross section

Parameters	**Fractional Uncertainty (%)**		
	$<E_n>$ = 0.53 MeV	**$<E_n>$ = 1.05 MeV**	**$<E_n>$ = 1.66 MeV**
C_s	3.8069	4.3478	11.3961
C_m	2.8903	1.0086	0.7897
N_s	0.0681	0.0781	0.0887
N_m	0.1592	0.1215	0.1340
f_s	0.0158	0.0158	0.0159
f_m	0.0073	0.0087	0.0106
I_s	0.0941	0.0941	0.0941
I_m	0.2178	0.2178	0.2178
η	3.0469	3.0469	3.0469
σ_m	4.3700	3.0600	2.8100
Total Error (%)	7.16	6.21	12.15

4. Results and Discussions

The measured $^{109}Ag(n,\gamma)^{110m}Ag$ reaction cross sections at 0.53 ± 0.15, 1.05 ± 0.16, 1.66 ± 0.14 MeV neutron energies with their uncertainties, covariance, and correlation matrix are listed in Table 2. We plotted our experimental cross sections with the evaluated data from TENDL-2019, IRDFF-II, JENDL/AD, IRDF-2002G and data taken from EXFOR in Fig. 1. with theoretical results acquired from TALYS-1.96. The total uncertainty is 6-12% in the studied cross section. The evaluated data libraries are indicated as solid black for TENDL-2019 (dot-dash-dot-dash), IRDFF-II (dash-dash), JENDL/AD (dot-dot), IRDF-2002G (line). The different ldmodels are represented as ldmodel 1 (red), ldmodel 2 (green), ldmodel 3 (olive), ldmodel 4 (yellow), ldmodel 5 (light magneta) and ldmodel 6 (violet). The experimental data is in trend with the evaluated data libraries TENDL-2019, JENDL/AD except the data point at 0.53 MeV neutron energy. The computational results by using ldmodel-6 are best in agreement with the present experimental data.

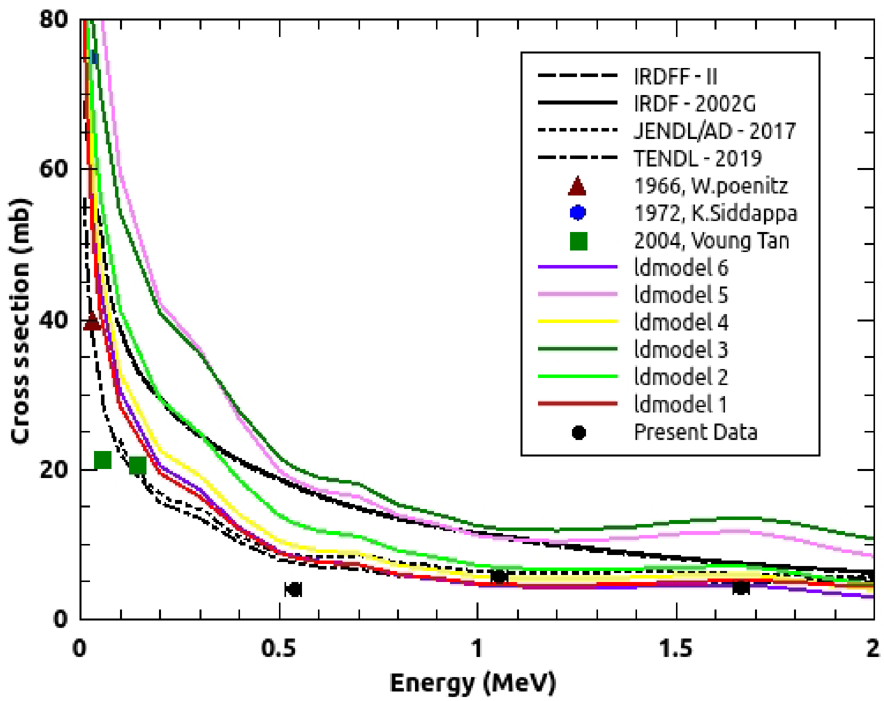

Fig.1. Cross sections measured in present work and its comparative studies.

Table 2. The $^{109}Ag(n,\gamma)^{110m}Ag$ cross sections measured in the present experiment with associated uncertainties and correlation coefficients

Energy (MeV)	**Cross-section (mb)**	**Correlation Matrix**		
0.53 ± 0.15	4.1063 ± 0.2941	1		
1.05 ± 0.16	5.7196 ± 0.3555	0.3018	1	
1.66 ± 0.14	4.2812 ± 0.5204	0.1387	0.1543	1

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