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Investigation of ^{164}Dy(n,γ)^{165}Dy reaction using an Am-Be neutron source facility

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The thermal neutron capture cross-section of ^{164}Dy(n,γ)^{165}Dy and half-life of ^{165}Dy was determined using Neutron Activation Analysis technique. The Dy target has been irradiated by neutron using Am-Be neutron source at MCNS, MAHE, Manipal, India. Using HPGe detector, the gamma ray spectrum of the irradiated sample has been measured. The half-life of ^{165}Dy was calculated to be 140 ± 1 min. The neutron flux distribution data from the most recent study in Ref. 12, based on the same Am-Be neutron source facility, have been used to calculate the thermal neutron cross-section of ^{165}Dy. The thermal neutron capture cross-section is determined to be 2008 ± 220 barns which is in good agreement with the recent measurement in Ref. 10 using neutron diffraction facility.

Keywords: Neutron activation analysis; thermal neutron cross-section; half-life; Am-Be source; neutron flux.

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1. Introduction

The cross-section data of a material play a vital role in understanding nuclear reactions and studying the behavior of different isotopes in different environments. To lower the uncertainty in the design and operation of future generation reactors, additional experimental, theoretical, or simulation-based research are needed to update the current understanding of nuclear data, particularly of neutron-induced processes. In contrast to the criterion (uncertainty $\leq 5\%$) for various applications, the sparseness in and dispersion across various cross-section measurements are still found to be substantial. Recent work[1] highlighted the necessity of thorough investigations to get nuclear data with lower uncertainty. One of the often used techniques for determining neutron cross-sections is neutron activation analysis (NAA).[2,3] In general, the nuclear reactors as well as D-D and D-T neutron sources are used for the neutron activation measurements. However, during the past few decades, it has become recognized that isotropic neutron sources like Am-Be can be used for neutron activation.

Theoretically, the heaviest stable isotope found in nature is ^{164}Dy with 28.1% natural abundance. Neutron capture cross-section of dysprosium (Dy) is very significant in the field of nuclear physics as well as in medical physics applications such as reactors and radiotherapy. Since dysprosium has large thermal neutron cross-section value, it is used in nuclear reactors as control rods to absorb thermal neutrons. Dysprosium is used as a cermet (dysprosium oxide-nickel) that cools nuclear reactor control rods, whereby it readily absorbs neutrons without contracting or swelling under prolonged neutron bombardment. Also, it is used in dosimeters in radiotherapy. It helps in monitoring and controlling the amount of radiation the patient receives during treatment. There are several measurements to derive thermal neutron cross-section and resonance integral values of ^{165}Dy.[4–10] In most of the experiments, nuclear reactor facilities had been used. Only in the study by Ref. 5, they had used an isotropic Am-Be neutron source facility moderated with paraffin wax to determine the thermal neutron cross-section using Cadmium (Cd)-cut method. But the reported thermal neutron cross-section is significantly higher compared to the most recent measurement by Belouadah *et al.*[10] Overall, the mean value of thermal neutron cross-section varies up to 600 barns. So, a fresh measurement is essential to reduce the uncertainty band in the cross-section value.

In this work, we have also used an Am-Be isotropic neutron source facility installed at Manipal Centre for Natural Sciences (MCNS). Comprehending the neutron flux distribution originating from an Am-Be neutron source is crucial as the energy-wise flux information is necessary for the capture cross-sections of different isotopes. Because of the scattering events caused by the structural materials around the source, the Am-Be spectra are different from the ISO[11] standard spectra. Our aim is to determine the thermal neutron capture cross-section of ^{164}Dy. To determine the thermal neutron cross-section, we need the information of the total flux in the thermal region. Recently, the neutron flux distribution was measured by Sachin *et al.*[12]

using the Au monitor foil by the Cd-cut technique. Using the flux distribution information, the thermal neutron cross-section of ^{164}Dy has been calculated. The result from the present measurement can be used further as a reference for the other cross-section measurements. The cross-section measurement will be followed by half-life ($T_{1/2}$) determination of ^{165}Dy. Accurate half-life measurement is crucial for controlling the radiation dose during radiotherapy. As the available half-life literature values[13] are several decades back, therefore with the advancement of detection systems and data acquisition systems, half-life measurement needs to be revisited. So, we have performed a fresh half-life measurement in this work.

2. Experimental Details

2.1. *Targets*

The natural dysprosium oxide (Dy_2O_3), which is in powder form, is used for conducting the experiment. We have weighed 0.2093 (10) g of the powdered sample and taken in a polyethylene zip lock bag. This sample has been irradiated for about twice the half-life of the Dy sample, that is for 5 h. The details of target with gamma lines of interest are given in Table 1.

2.2. *Irradiation setup*

The irradiation procedure employed a 16 Ci Am-Be neutron source facilitated by MCNS. Alpha emitting ^{241}Am oxide is combined with beryllium, the target material, in the Am-Be source, which has a half-life of 432.6 (6) years. Within the beryllium, the (α, n) process yields neutrons with an energy distribution. The energy of these neutrons ranges from around 4 MeV to about 11 MeV on average.

The neutron source is enclosed inside a stainless-steel casing with a dimension of 22 cm height and 5 cm diameter.[12] By employing a string that is fastened straight to the stainless steel casing, fail safe procedures are integrated for the source's security. A stainless steel tube is connected to a cage containing the source. The complete apparatus is encased within a $140 \times 140 \times 135$ cm concrete framework. A $40 \times 40 \times 70$ cm experimental hole is provided through the concrete shielding at a height of 45 cm above floor level. Employing a pulley and chain system, the source may be transported to the radiation site. Figure 1 illustrates the irradiation setup.

Table 1. Details of target material and gamma lines of interest.

Target	Weight (g)	Half-life ($T_{1/2}$)	γ-energy (keV)	I_γ (%)
Dy_2O_3	0.2093 (10)	2.334 (1) h	94.700 (3)	3.58 (18)
			361.68 (2)	0.84 (4)
			633.415 (20)	0.568 (12)

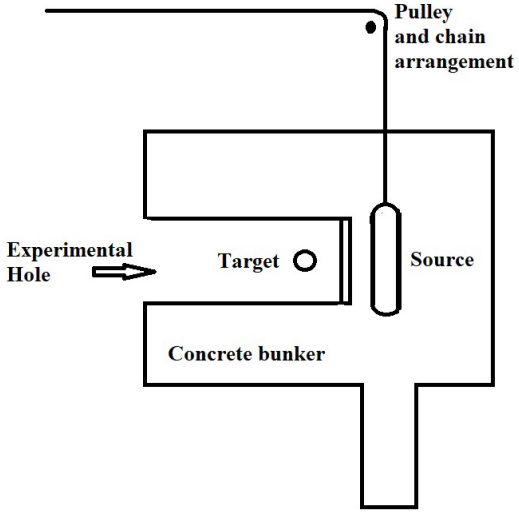

Fig. 1. Irradiation set up.

2.3. *Detection*

The HPGe detector was used to record gamma ray spectra of samples. The detector is well shielded using 10 cm thick lead and 1.0 cm of copper for reducing the background. The shield extends up to 10.5 cm above the detector with an opening of 20 cm at the top. A USB-based digital miniature multi-channel analyzer MCA-527 is connected to the detector. This is intended for amplification, high voltage, accumulation of pulse signals from the detection unit, spectra processing etc. The spectra are collected in the memory of the MCA-527 and periodically transferred via USB interface to computer. Gamma spectroscopy is performed using WINSPEC software.

The detector was calibrated using standard radioactive sources ^{152}Eu and ^{133}Ba. The relation between gamma energy and channel number was established using second order polynomial fit. The efficiency of the detector was also calibrated using the above-mentioned radioactive sources.

For half-life measurement, the gamma ray spectrum was collected 10 times for the time interval of 10 min each. For thermal neutron induced cross-section measurement, the gamma ray spectrum of Dy sample was collected for an interval of 2 h.

3. Data Analysis

3.1. *Half-life measurement*

The counts under the photopeaks are calculated using the gamma-ray spectra, which are obtained at different time intervals. Here, we have used the 94.7 keV gamma ray for the half-life determination. The photopeak areas have been determined with the help of OriginPro software.[14] The natural logarithm of the counts is then plotted against time which gives a linear relationship (shown in Fig. 2). After linear fitting

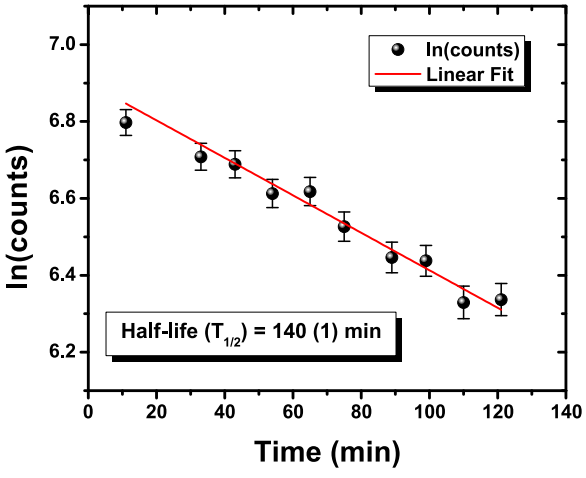

Fig. 2. Plot of natural logarithm of counts versus time.

with χ^2-minimization to this plot, a straight line is obtained, from which the slope was calculated. This slope represents the decay constant. Using decay constant value, the half-life was determined. Half-life is given by the following formula:

$$T_{1/2} = \frac{\ln 2}{\lambda}, \tag{1}$$

where λ is the decay constant.

3.2. *Efficiency measurement*

Absolute efficiency is basically the ratio of the total number of photons detected to the number of photons emitted by the source. The absolute efficiency of the detector is defined as

$$\epsilon = \frac{C}{At}, \tag{2}$$

where C is the area under the photopeak, A is the activity of source in Becquerel, t is the counting time.

The efficiency data have been taken with laboratory standard ^{152}Eu and ^{133}Ba sources. After that, the efficiency for ^{165}Dy gamma energy lines has been calculated.

3.3. *Neutron flux and cross-section measurement*

In this work, the thermal neutron capture cross-section for the $^{164}\mathrm{Dy}(\mathrm{n},\gamma)^{165}\mathrm{Dy}$ reaction is determined. The neutron flux is measured using the $^{197}\mathrm{Au}(\mathrm{n},\gamma)^{198}\mathrm{Au}$ monitor reaction from Ref. 12. The product of cross-section and flux is given by

$$\sigma(E)\phi(E) = \frac{C\lambda}{[1-e^{-\lambda t_{\mathrm{irr}}}][e^{-\lambda t_d}][1-e^{-\lambda t_c}]} \cdot \frac{M}{N_A \theta \epsilon \gamma m}, \tag{3}$$

where C is the area under photopeak, λ is the decay constant, M is the atomic mass of the sample, t_{irr} is the irradiation duration, t_d is the delay time, t_c is the counting time, N_A is the Avogadro number, θ is isotopic abundance, ϵ is the efficiency of the detector, γ is the branching and m is the weight of the sample.

4. Results and Discussions

The gamma ray spectra of ^{165}Dy and ^{198}Au are shown in Figs. 3 and 4, respectively. The photopeak area under prominent gamma peaks of energy 94.70, 361.68 and

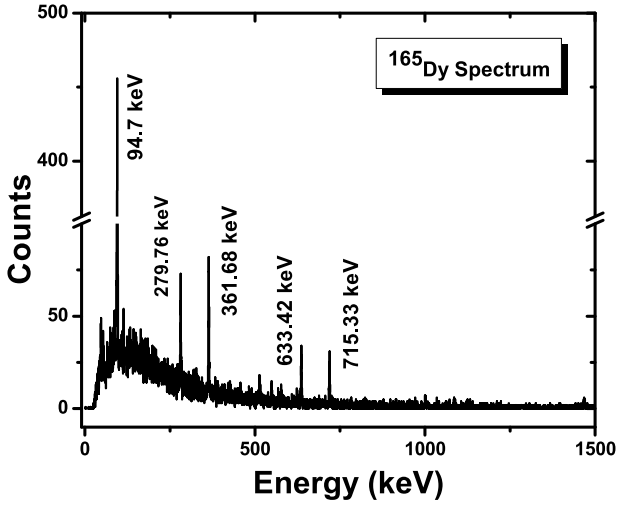

Fig. 3. Gamma ray spectrum of ^{165}Dy.

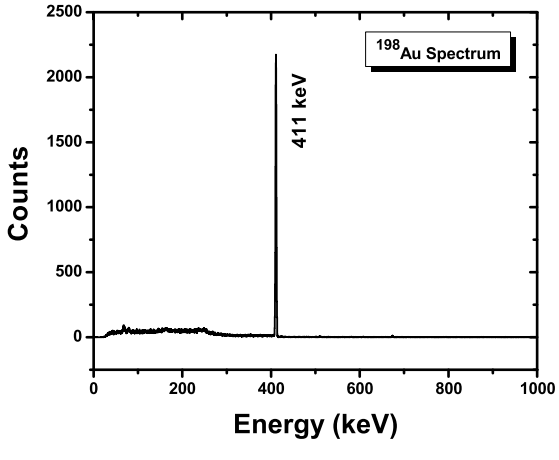

Fig. 4. Gamma ray spectrum of ^{198}Au.

Table 2. Comparison of half-life value from this study with the other literature values.

References	Half-life (min)
Haccoun *et al.*[13]	140.02 (36)
R. Sher *et al.*[15]	139.17 (14)
Present work	140 (1)

633.41 keV for ^{165}Dy is determined by fitting the peak using Gaussian distribution. We have used the OriginPro software[14] to correctly calculate the photopeak areas.

The half-life of ^{165}Dy was determined to be 140 (1) min. This number validates the robustness and reproducibility of the experimental methods used in this investigation and is consistent with the previous literature values. The plot of natural logarithm of counts versus time which was used for the calculation of half-life is shown in Fig. 2. Comparison of the half-life value found in this work with the previous literature works is shown in Table 2.

Using conventional radioactive sources ^{152}Eu and ^{133}Ba, the absolute efficiencies have been determined and fitted with a polynomial function with χ^2-minimization (shown in Fig. 5). After that, the efficiencies of the gamma lines of ^{165}Dy at 94.7, 361.68 and 633.41 keV have been determined from the fitting co-efficients. The efficiency values for gamma lines of interests are given in Table 3.

The neutron flux was measured using $^{197}\mathrm{Au}(\mathrm{n},\gamma)^{198}\mathrm{Au}$ reaction using Eq. (3). The neutron flux value and epi-cadmium to total flux ratio for Au has been taken from Ref. 12. The neutron flux in the used Am-Be facility was determined to be $2.33 \times 10^3 \pm 1.71 \times 10^2$ neutrons/cm^2/sec in the thermal region.[12] Using this value of flux and the measured epi-cadmium to total flux ratio, the thermal neutron capture

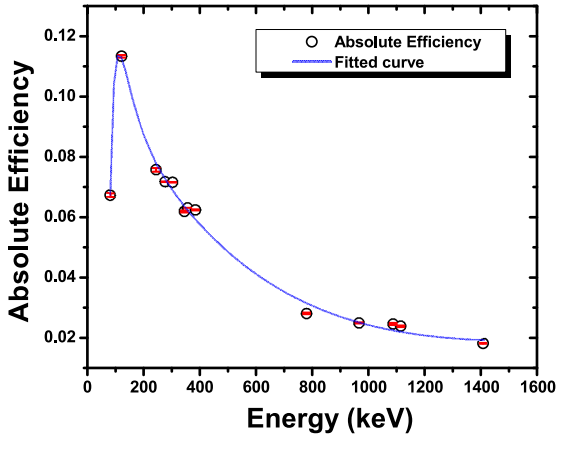

Fig. 5. (Color online) Absolute efficiency as a function of energy for the HPGe detector. The black opened circles denote the data points with red color error bars and the blue solid line is the fitted curve.

Table 3. Absolute efficiencies of the gamma lines of interest of ^{165}Dy.

Target	γ-energy (keV)	Absolute efficiency
Dy_2O_3	94.700 (3)	0.1045 (7)
	361.68 (2)	0.0617 (4)
	633.415 (20)	0.0391 (3)

Table 4. Comparison of thermal neutron capture cross-section value from present study with the other literature values.

References	Thermal neutron capture cross-section (b)
Cho *et al.*[4]	2656 (98)
Karadag *et al.*[5]	2672 (104)
Kim *et al.*[6]	2653
Farina Arobocco *et al.*[7]	2649
Sattar *et al.*[8]	2322 (140)
Block *et al.*[9]	2980 (10)
Belouadah *et al.*[10]	2198 (94)
Present work	2008 (220)

cross-section of ^{164}Dy was found to be 2008 (220) barns. The error quoted here includes the uncertainties in the measurement of weight of the sample, energy and efficiency calibration of the detector, counting statistics and nuclear data like half-life, branching, abundance and cross-section values. The value of cross-section is found to agree with the values in previous literature works. Comparison of the cross-section value found in this work with the previous literature works is shown in Table 4.

5. Summary and Future Outlook

Using Neutron Activation Analysis technique, the half-life of ^{165}Dy and thermal neutron capture cross-section of ^{164}Dy(n, γ)^{165}Dy reaction have been determined. The measured half-life is in good agreement with the previous literature values. The measured thermal neutron cross-section value is more closer to the recent measurement by Belouadah *et al.*[10] This reaction can be used as a monitor reaction for thermal neutron cross-section measurements. Also, this calculation can be used as one of the input in the SAND II,[16] GAMCD[17] theoretical codes to unfold the neutron energy spectra of the Am-Be facility to get the energy wise cross-section. Overall, this study will be helpful in ^{164}Dy's potential applications in a range of industries, including material science, nuclear reactors and medical imaging.

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References

1. S. Ganesan *et al.*, *Nucl. Data Sheets* **123** (2015) 21.
2. L. Hamidatou *et al.*, *Concepts, Instrumentation and Techniques of Neutron Activation Analysis* (2013), pp. 141–178. doi: 10.5772/5368.
3. R. R. Greenberg *et al.*, *Spectrochim. Acta B: At. Spectrosc.* **66** (2011) 193.
4. H. J. Cho *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **462** (2001) 442.
5. M. Karadag *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **550** (2005) 626.
6. H. I. Kim *et al.*, *Nucl. Instrum. Methods Phys. Res. B* **266** (2008) 3513.
7. F. Arbocco *et al.*, *J. Radioanal. Nucl. Chem.* **302** (2014) 655.
8. B. N. Sattar *et al.*, *J. Phys.: Conf. Ser.* **1718** (2021) 012010.
9. R. C. Block *et al.*, *Prog. Nucl. Energ.* **94** (2017) 126.
10. N. Belouadah *et al.*, *Radiochem. Acta.* **110** (2022) 947.
11. ISO Technical Committee ISO/TC 85, *Neutron Reference Radiations Fields Part 1: Characteristics and Methods of Production*, 2nd edn. (2021).
12. S. Shet *et al.*, *Nucl. Part. Phys. Proc.* **341** (2023) 53.
13. A. Haccoun *et al.*, *Nucl. Technol.* **17** (1973) 280.
14. A proprietary computer program for interactive scientific graphing and data analysis, *OriginPro*, Version 2024 (OriginLab Corporation, Northampton, MA, USA).
15. R. Sher *et al.*, *Phys. Rev.* **87** (1952) 523.
16. W. N. McElroy *et al.*, *A Computer-Automated Iterative Method for Neutron Flux Spectra Determination by Foil Activation* (1967).
17. B. Mukherjee *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **432** (1999) 305.