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# Determination of Thermal Neutron Cross Section and Resonance Integral for $^{64}Zn$ (n, γ) $^{65}Zn$ Reaction by Activation Method

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**Abstract:** *Despite the growing availability of resonance integral data for stable nuclides, several isotopes produced via (n,γ) reactions still lack precise or consistent experimental data. Accurate nuclear data are essential for reactor physics, neutron flux characterization, and analytical applications. This study reports the thermal neutron cross section and resonance integral of the $^{64}Zn(n,\gamma)^{65}Zn$ reaction, measured using the activation method at the Nigerian Research Reactor-1 (NIRR-1), Ahmadu Bello University, Zaria. High-purity powdered ZnO samples were irradiated under both bare and 1-mm cadmium-covered conditions to separate thermal and epithermal neutron contributions. A monitor with a well-known neutron cross section was used as a single comparator to minimize neutron self-shielding and to quantify zinc concentration. Irradiated samples were measured using a calibrated p-type high-purity germanium (HPGe) detector at a source-to-detector distance of 2.2 cm. The thermal neutron cross section of the $^{64}Zn(n,\gamma)^{65}Zn$ reaction was determined to be 0.726 ± 0.02 barn, while the resonance integral was found to be 1.47 ± 0.05 barn at a cadmium cut-off energy of 0.55 eV. The cadmium ratio (R_Cd) was measured as 7.01 ± 0.99, consistent with previous work in other NIRR-1 channels. These results agree well with evaluated nuclear data, such as 0.726 ± 0.02 barn (De Corte and Simonits, 2003), 0.76 ± 0.02 barn (Mughabghab, 2003), and 1.45–1.428 barn for the resonance integral from various libraries, while earlier experimental cross sections ranged from 0.72 ± 0.04 to 1.23 ± 0.12 barn and resonance integrals from 0.76 ± 0.08 to 3.10 ± 0.02 barn.The agreement of measured activities, cadmium ratio, and derived cross sections demonstrates the stability of the thermal neutron flux and the high analytical capability of the NIRR-1 LEU core. The results provide reliable nuclear data for $^{64}Zn$ and validate the use of powdered ZnO as a monitor in thermal neutron activation studies.*

**Keywords**: *Thermal neutron cross section, Resonance integrals, ZnO and $Al_2O_3$ monitor and Nigerian Research Reactor-1 (NIRR-1)*

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## 1.0 Introduction

Progress in experimental nuclear data and their applications in medicine, industry, agriculture, and energy has always depended on improvements in nuclear measurement techniques (De Corte & Simonits, 2003). Among these data, thermal neutron cross sections and resonance integrals are particularly important because they describe the probability of neutron interactions at thermal and epithermal energies. An accurate knowledge of thermal neutron cross sections ($\sigma_0$) is required in fundamental nuclear research as well as a wide range of applied nuclear fields such as dosimetry, shielding calculations, nuclear medicine, nuclear fuel circle analysis and waste management. Thermal neutron cross section ($\sigma_0$) and resonance integrals ($I_o$) are particularly required for reactor neutron flux and neutron activation analysis (De Corte, *et al.,* 2003, Rajput, *et al.,* 2003). Large discrepancies exist in the literature on neutron cross-section data (Rajput et al., 2003; Ahmad *et al*., 1983), especially for resonance integrals in the epithermal region of the reactor neutron spectrum. (Rajput, *et al.,* 2003; Ahmad *et al*, 1983), especially in the resonance integrals in the epithermal region of the reactor neutron spectrum. These discrepancies demand new state-of-the-art measurements to resolve the existing uncertainties. Enhanced accuracy in the measurements would ultimately contribute towards the improvement of the theoretical model frameworks and lead to more precise nuclear data which are crucial for application in astrophysics, and various other scientific and technological fields. Reported values for several isotopes differ significantly between experimental measurements and evaluated nuclear data libraries, highlighting the need for additional high-precision activation measurements.

Among the isotopes of practical interest, zinc isotopes play important roles in both applied and fundamental nuclear science. In particular, the $^{64}Zn(n,\gamma)^{65}Zn$ reaction is widely used in neutron activation analysis and flux monitoring because $^{65}Zn$ is a suitable gamma-emitting radionuclide with measurable half-life and gamma energies. In particular, neutron cross sections of zinc isotopes are needed for reactor material studies and radiation damage assessments in fission and fusion systems and the evaluation of radiation damage in the structural materials of reactors. $^{64}Zn(n,\gamma)$ $^{65}Zn$ can be considered particularly important because it can be used for a two-fold purpose: as a neutron flux monitor and for Zn concentration measurements. Previous studies revealed inconsistencies between experimentally measured $\sigma_0$ values and those recommended in evaluated nuclear data libraries such as the *Atlas of Neutron Resonances*, indicating unresolved uncertainties in both thermal cross sections and resonance integrals for $^{64}Zn$. Furthermore, limited activation measurements have been performed using well-characterized neutron spectra in research reactors within this region, creating a need for new experimental data with improved methodological control. (Mughabghab, 2003; Iwamato, 2012).

This forms the motivation for the present paper, which aims to experimentally determine the thermal neutron cross section ($\sigma_0$) and resonance integral ($I_0$) for the $^{64}Zn(n,\gamma)^{65}Zn$ reaction using the neutron activation method at the Nigerian Research Reactor-1 (NIRR-1).

The results will contribute to improved nuclear data libraries, enhance the reliability of zinc-based neutron activation analysis, and further validate the neutron spectrum characterization and analytical capability of NIRR-1 for high-quality nuclear measurements.

## 2.0 Theory

### *2.1 The Activation Equation*

By considering neutron capture (n,γ) activation followed by gamma-ray spectrometry, the relationship between the reaction rate and the number of counts (Np) collected under the full-energy peak can be

expressed according to equation 1, provided that the radionuclide of interest is produced directly through the (n,γ) reaction and the burn-up of both target and product nuclei is negligible (i.e. no burn up effects observed).

$$R = \frac{\frac{N_p / t_m}{wSDC}}{N_A \theta \varepsilon_p \gamma / M} - \quad (1)$$

where $N_p$ = number of counts in the full-energy peak, $t_m$ = measuring time (s),
S = Saturation factor ($1 - e^{-\lambda tirr}$) ; λ is the decay constant $\lambda ln2/t_{1/2}$ () related to the half ife (i.e $t_{1/2}$), $t_{irr}$ is the irradiation time, D = decay factor $e^{-\lambda t_d}$ ;td is decay time (s), C = measurement factor $\left(\left(1-e^{-\lambda t_m}\right)/\lambda t_m\right)$ correcting for decay during counting; tm is the counting (measurement) time, w = mass of irradiated element in (g), θ = Isotopic abundance (fraction), εp = full energy peak detection efficiency, γ = Absolute gamma intensity, M = Atomic weight
Let the specific count rate ($s^{-1}g^{-1}$) be denoted by equation 2

$$A_{sp} = \frac{N_p / t_m}{wSDC} \quad (2)$$

Then the activation equation can therefore be expressed in two equivalent forms, depending on whether bare or cadmium-covered irradiation is considered and can be expressed as equations 3 or 4

$$A_{sp} = \frac{N_A / \theta_\gamma}{M}\left[G_{th}\phi_s\sigma_0 + G_e\phi_e I_0(\alpha)\right]\varepsilon_p \quad (3)$$

$$\left(A_{sp}\right)_{cd} = \frac{N_A / \theta_\gamma}{M} G_e F_{cd}\phi_e I_0(\alpha)\varepsilon_p \quad (4)$$

The difference between the activities obtained from bare and cadmium-covered irradiations is known as the cadmium difference. Provided the same $\varepsilon_p$ – value is involved, the following equation applies,

$$\frac{A_{sp} - \left(A_{sp}\right)_{cd}}{F_{cd}} = \frac{N_A / \theta_\gamma}{M} G_{th}\phi_s\sigma_0\varepsilon_p \quad (5)$$

Based on equation 5,–the experimentally measured Cd – ratio, Rcd, can be expressed according to equation 6 as follows,

$$R_{cd} = \frac{A_{sp}}{\left(A_{sp}\right)_{cd}} \quad (6)$$

### *2.2 Determination of activity of $^{65}$Zn for $^{64}$Zn (n, γ) $^{65}$Zn reaction.*

The activity of $^{65}$Zn for $^{64}$Zn (n, γ) $^{65}$Zn reaction was calculated using the following equations (Simonits et al., 1984; De Corte et al., 1981, 1982, 1986):

$$A_{sp}^{-} = \left[\frac{N_p / t_c}{w.S.D.C}\right]_{bare} \;\&\; A_{sp}^{+} = \left[\frac{N_p / t_c}{w.S.D.C}\right]_{Cd} \quad (7)$$

where $A_{sp}^{-}$ and $A_{sp}^{+}$ are specific activities obtained after a bare and Cd covered isotope irradiation, Np is the net number of counts under the full-energy peak collected during the live counting time, $t_c$, w is the weight of the irradiated element, $S = 1 - e^{-\lambda t_{irr}}$ is the saturation factor with λ being the decay constant, and irradiation time, $t_{irr}$. $D = e^{-\lambda t_d}$ is the decay factor with being the decay time, $t_d$ and $C = \frac{1-e^{-\lambda t_r}}{\lambda t_r}$ is the measurement factor correcting for decay during measuring true (real) time, $t_r$, M is atomic weight, $\theta$ is the isotopic abundance, $N_A$ is Avogadro's number, $\gamma$ is the absolute gamma-ray emission probability, $\varepsilon_p$ is the full-energy peak detection efficiency measured at gamma-ray energy, E, and $F_g$, which is mostly ≤ 1 for all nuclides, is a correction factor for gamma ray attenuation.
-The gamma-ray attenuation correction factor ($F_g$) accounts for self-absorption of gamma rays within the sample and depends on sample composition, geometry, and gamma-ray energy. For the present work, $F_g$ ( $F_g = \frac{\mu t}{1-e^{-\mu t}}$ )was calculated for $^{65}$Zn and $^{28}$Al using a fixed cylindrical sample geometry (2.20 cm height) positioned coaxially with the detector (Berger et al., 1999; De Corte and Simonits, 2003). Typically, $F_g \leq 1$–It gives the accuracy of the analyzed result and

the non-ideality of the epithermal neutron spectrum.

### *2.3 Determination of Cd ratio of $^{65}$Zn isotope*

For convenience, the experimentally determined cadmium ratio of $^{65}$Zn was calculated using the following expression (equation 8):
(De Corte and Simonits, 1981; 1987).

$$R_{Cd} = \frac{A_{sp,bare}}{A_{sp,cd} / F_{cd}} \quad (8)$$

where $A_{sp,bare}$ *and* $A_{sp,Cd}$ are specific activities obtained after a bare and Cd covered monitor irradiation, respectively. The term $F_{Cd}$ which is mostly $\leq 1$ for elements, is the cadmium filter epithermal neutron transmission factor accounts for absorbed epithermal neutrons by the cadmium cover (Jovanovic, *et al*; 1989).

### *2.4 Thermal neutron cross section determination for $^{64}$Zn (n, γ)$^{65}$Zn, Isotope reaction.*

The thermal neutron cross section (σ₀) was calculated from the ratio of the specific activities of the zinc and monitor foils, followed by appropriate flux and spectral corrections, i,e, $I_0(\alpha)$ to $Q_0(\alpha)$ followed by the conversion of $I_0$ *to* $I_0(\alpha)$ and $Q_0$ *to* $Q_0(\alpha)$ value. The $Q_0(\alpha)$ values and the $I_0(\alpha)$ values used to determine the activation $\sigma_0$ *and* $I_0$ values respectively (De Corte and Simonits, 1981; 1987).
Therefore

$$Q_0(\alpha) = \frac{I_0(\alpha)}{\sigma_0} = \frac{fG_{th}}{(F_{cd}R_{cd} - 1)G_e} \quad (10)$$

$$I_0(\alpha) = \frac{fG_{th}}{(F_{cd}R_{cd} - 1)G_e}\sigma_0 \quad (11)$$

where f is the thermal-to-epithermal neutron flux ratio at the irradiation position.
Therefore,

$$\sigma_0 = \frac{I_0(\alpha)}{Q_0(\alpha)} \quad (12)$$

where $\sigma_0$ denotes the thermal neutron cross section. The effective cross section was determined elsewhere from equation (De Corte and Simonits, 1981; 1987).

$$\sigma_{eff} = \sigma_0\left(1 + \frac{Q_0(\alpha)}{f}\right) \quad (13)$$

### *2.5 Resonance Integral determination for $^{64}$Zn (n, γ)$^{65}$Zn reaction.*

For non-ideal conditions, the $\alpha$ – dependent term of the resonance integral $I_0(\alpha)$ is modified with resonance integral $I_0$, followed by the conversion of $I_0(\alpha)$ *to* $I_0$ (De Corte and Simonits, 1981; 1987). Therefore, equation 14 is obtained.

$$I_0(\alpha) = \left[\frac{I_0 - 0.429\sigma_0}{(\bar{E}_r)^{\alpha}} + \frac{0.429\sigma_0}{(E_{Cd} = 0.55eV)^{\alpha}(2\alpha + 1)}\right].1eV^{\alpha} \quad (14)$$

where $1eV^{\alpha} = E_0^{\alpha}$, $(E_r)^{\alpha}$ = effective resonance energy, $E_a^{\alpha}$ = 1 eV – arbitrary energy, $E_{cd}$ = 0.55 eV – effective cadmium cut-off energy, σ₀ is the standard thermal neutron cross section at a neutron velocity of 2200 m s$^{-1}$ and $\alpha$ =Epithermal neutron flux shaping factor, an experimentally determinable characteristics of the reactor channel (De Corte *et al.,* 1981; 1987).

$$I_0 = E_r^{\alpha}\left\{I_0(\alpha) - \frac{0.316\sigma_0}{\sqrt{E_{Cd}}}\left[\frac{1}{(2\alpha + 1)} - E_r^{\alpha}\right]\right\} \quad (15)$$

where; $I_o$ donates the resonance integral in the equation. $E_{Cd}$ is the cadmium cut-off energy taken as 0.55eV.

## 3.0 Materials and Methods

### *3.1 Materials*

The materials employed include the Nigerian Research Reactor–1 (NIRR-1) as the neutron source and a high-purity germanium (HPGe) coaxial gamma-ray spectrometer for activity measurement. Powdered zinc oxide ($ZnO_2$) was used as a neutron monitor, alongside the powdered zinc sample under investigation. Additional materials used during sample

preparation and handling include hand gloves, acetone, cotton wool, an analytical weighing balance, an agate mortar and pestle, a spatula, Whatman filter paper, polyethylene vials, and a 1 mm thick cadmium cover for epithermal neutron shielding.

### *3.2 Methodology*

In this work, about 3% of the ZnO sample was prepared along with 97% finely ground $Al_2O_3$ powder. Each ZnO sample was homogeneously mixed with $Al_2O_3$ powder to ensure uniform neutron flux distribution and minimize self-shielding effects. Six samples were irradiated in the B3 channel of NIRR-1. Three samples were irradiated inside a cylindrical cadmium cover (Cd-covered irradiation), while the remaining three were irradiated without cadmium shielding (bare irradiation). The irradiation times for the bare and cadmium-covered samples were 1 hour and 2 hours, respectively. These irradiation times were selected to produce measurable induced activity of $^{65}Zn$, considering its relatively long half-life. These irradiation times enable the Zn-64 isotope to have an appreciable activity to be measured due to its long half-life. After irradiation, the samples were allowed to cool for 1–7 days before counting to reduce detector dead-time losses and to allow short-lived interfering radionuclides to decay.

#### *3.2.1 Sample preparation*

Powdered ZnO and $Al_2O_3$ were used in this work to validate neutron activation analysis (NAA) protocols for the new LEU core configuration of NIRR-1. -The monitors used were obtained from NAA laboratory at the Centre for Energy Research and Training (CERT). Ahmadu Bello University, Zaria, and were manufactured by Merck.

i. Sample monitors were placed in a desiccator for drying using Silica gel to remove all source of moisture.
ii. Using disposable hand gloves and cotton wool, all apparatus *e.g* vials, spatula, agate and morta etc. were well cleaned using acetone to avoid contamination with $Na^+$ ions since $Na^+$ ion has high thermal cross-section and conductivity.
iii. iii. After zeroing the analytical balance, ZnO and $Al_2O_3$ powders were weighed in a ratio of 3% to 97% and thoroughly mixed. Sample masses ranged from 0.01 g to 0.05 g. iv. The weighed mixtures were wrapped in polyethylene, heat-sealed, and packed into clean polyethylene vials. For cadmium-covered irradiation, the vial was enclosed in a 1 mm thick cadmium shield.

#### *3.2.2 Flux Monitor Irradiation*

The flux monitors were cleaned with ethanol, before irradiation in the channel (B3) to eliminate possible surface contaminants that could become activated during irradiation, because sodium has a relatively high neutron activation cross section, which could introduce spectral interference. Then, weighed and packed in a stack inside a cleaned polyethylene capsule for "bare irradiation", while the second set was encapsulated inside a 1mm thick cadmium box for the "Cd-covered" irradiation. The two sets of irradiations were carried out in the inner irradiation channel (B3) at a thermal power level of 17 kW, which is equivalent to a preset neutron flux value of 5.0 x $10^{11}$ n/ $cm^2s$. Due to the proximity of B3 channel to the nuclear reactor core and higher neutron flux values in the inner channel, the bare and Cd-covered irradiations were performed for 1 hour and 2 hours, respectively.

#### *3.2.3 Sample Irradiation*

Two irradiation regimes were used. Bare samples were irradiated for 1 hour, while cadmium-covered samples were irradiated for 2 hours in the B3 inner irradiation channel of NIRR-1. The longer irradiation time for Cd-covered samples compensates for the reduction of thermal neutrons by the cadmium shield. All irradiations were conducted at a reactor power level of 17 kW, corresponding to an average neutron flux of approximately $5.0 \times 10^{11}$ $n \cdot cm^{-2} \cdot s^{-1}$ (Anas *et al.,* 2023). Similarly, samples going for long irradiation were packed in a single vial and

irradiated for two hours in the inner (B3) channel of NIRR-1 for maximum thermal neutron flux exposure.

In this work, two sets of detector monitors were prepared for the irradiation channel (B3-Inner channel). One set was arranged in a stack inside a vial for the 1-hour 'bare' irradiation, and the second set was arranged in a stack inside a 1mm thickness of Cd-shield box and kept inside the vial for the 2 hours Cd-cover irradiation, all irradiations were performed at a thermal power level of 17 kW, which corresponds to a preset neutron flux of $5.0\times10^{11} n/cm^2$ on the control console of the reactor, neutron spectrum.

### *3.4 Sample counting and analysis*

#### *3.4.1 Monitor counting/Gamma- ray spectrometry measurement*

After irradiation and an appropriate cooling time, the induced activity of the gamma ray spectra was measured using the p-type HPGe GEM30-76 coaxial detector coupled to a digital multi-channel analyzer (MCA), manufactured by ORTEC. The data was collected and analyzed with MAESTRO emulation software. The monitor activity was sufficiently high to ensure good counting statistics. Spectral acquisition and analysis were performed using MAESTRO software (Anas; *et al*., 2023).

#### *3.4.2 Counting of Zinc Monitor for 64Zn (n, γ)65Zn reaction*

The induced activity of $^{65}$Zn was measured after a cooling period of approximately 7 days, targeting the 1115.5 keV gamma-ray peak.

### *3.5 Experimental Analysi*

After the irradiation, the multi-purpose gamma ray analysis software was used for the peak identification and evaluation or analysis. For peak analysis of $^{65}$Zn radionuclide, Irradiated powdered samples from both bare and cadmium-covered irradiations were counted after cooling periods ranging from 1 to 7 days at a fixed source-to-detector distance of 2.20 cm.

## 4.0 Result and Discussion

### 4.1 Determination of activity of $^{65}$Zn for $^{64}$Zn (n, γ) $^{65}$Zn reaction.

The activity of $^{65}$Zn for $^{64}$Zn (n, γ)$^{65}$Zn reaction was determined to be 2.94E+06kBq and 4.19E+05kBq from the bare and cadmium-covered samples irradiations. The measured activities are consistent with expected values based on reported neutron capture cross sections for $^{64}$Zn in the literature, including 11.9 ±0.4 barns (Goyal *et al.* 2019), 12.1 ± 0.2 barns, 12.3 ±0.2 barns, 11.9±0.3 barns (Singh *et al.,* 2020; 2021; 2022), $7.18 \times 10^5$ barns and $8.74\times 10^3$ *barns* (Anas *et al.,* 2023) where they obtained respectively. The consistency of the measured activities indicates stable detector efficiency and steady neutron flux conditions at NIRR-1 during irradiation (i.e $5.010^{11}$ncm$^2$/s$^{-1}$). The specific activity values obtained were subsequently used in calculating the cadmium ratio, thermal neutron cross section, and resonance integral. Accurate activity determination is essential because uncertainties propagate directly into the derived nuclear parameters.

On the other hand, the specific activity was used to determine the neutron flux, which is essential for calculating the cadmium ratio and resonance integral. Knowing the specific activity helps optimize sample size for measurement. Higher specific activity can improve the detection limit for the measurement. Specific activity measurements validate the nuclear data used in the calculation. The consistency in specific activity measurement verifies the methodology used, and the accurate specific activity measurements ensure reliable results for the cadmium ratio and resonance integral.

### *4.2 Determination of Cd ratio of $^{65}$Zn isotope.*

The cadmium ratio of $^{65}$Zn was determined from the activity, of $^{65}$Zn for $^{64}$Zn (n, $\gamma$) $^{65}$Zn reaction of bare and cadmium-covered irradiation, the cadmium ratio was measured as 7.01±0.99 barns from B3 channel. This is in good agreement with the values 8.15±0.08

barns, by Jonah *et al*, (2005), from B2 and B4 channel 8.28±0.29 barns, calculated by Sadiq *et al*, (2010), from A1channel, and 8.22±0.23 barns, by Anas *et al*, (2023), from B3 channel respectively, for NIRR-1, ABU Zaria I The slight deviation from previously reported values may be attributed to differences in monitor form (powder versus high-purity foil) and
variations in irradiation geometry. This resulted from the use of foil monitors, which have much higher purities compared to the powdered monitor employed for this work. Nevertheless this underscores the analytical capability of NIRR-1. In the same vein, sodium ion contamination may also hinder the accuracy of the results, because Trace elemental impurities may also contribute to minor uncertainties in activity determination. Similarly, this 7.01 ± 0.99 barns cadmium ratio was used for the evaluation of thermal neutron cross section and resonance integral of Zn-65 isotope for $^{64}Zn(n,\gamma)^{65}Zn$ reaction, as shown in Table 1. This also confirms that the neutron flux of $5.010^{11}$ n/cm$^2$ s$^{-1}$ of NIRR – 1 is stable.

**Table 1 : Comparison of calculated values of $R_{Cd}$ for $^{65}Zn$ with previous works using NIRR-1**

| Site | Target nuclide | Product nuclide | Half-life (T1/2) | $R_{Cd}$ (barns) | Reference |
|---|---|---|---|---|---|
| | | | | **Inner Channels** | |
| Channels B2 and B4 | $^{64}Zn$ | $^{65}Zn$ | 244.0d | $8.15b \pm 0.08barns$ | Jonah *et al,* 2005 |
| Channel A1 | $^{64}Zn$ | $^{65}Zn$ | 244.0d | $8.28b \pm 0.29barns$ | Sadiq *et al,* 2010 |
| Channel B3 | $^{64}Zn$ | $^{65}Zn$ | 244.0d | $8.22b \pm 0.23barns$ | Anas *et al,* 2023 |
| Channels B3 | $^{64}Zn$ | $^{65}Zn$ | 244.0d | $7.01b \pm 0.99barns$ | This work |

The measured cadmium ratio confirms that the B3 irradiation channel provides a well-thermalised neutron spectrum suitable for activation-based cross-section measurements. The method increases the sensitivity of the activation technique, allowing for smaller sample sizes and lower neutron fluxes. It also enables a more accurate determination of the resonance integral, which is essential for understanding the neutron capture process. The results can be compared with theoretical values, providing insights into the accuracy of nuclear data and reaction mechanisms. The method used in this work validates the use of $Al_2O_3$ and ZnO powders as monitors for thermal neutron cross sections and resonance integral measurements. Although the slight deviation in the results in this work from other works was that powdered samples were used instead of foils that have a higher percentage purity of about 99.99% compared to powdered samples.

The cadmium ratio method can be applied to other neutron-induced reactions, expanding its utility in nuclear data measurements.

In this research, the cadmium ratio method was used to obtain more accurate and reliable thermal neutron cross-section and resonance integral values for $^{65}Zn$ for various nuclear applications.

### *4.3 Thermal neutron cross section and resonance integral for $^{64}Zn$ (n, γ)$^{65}Zn$ reaction*

The thermal neutron cross section and resonance integral for the $^{64}Zn(n,\gamma)^{65}Zn$ reaction were determined to be 0.726 ± 0.02 barns and 1.47 ± 0.05 barns, respectively. These results agreed well with the measurement of 0.76 ± 0.02 barns, 1.45 ± 0.06 barns (Mughabghab *et al.,* 2003), and 0.726 ± 0.02 barns and 1.43 ± 0.02 barns (De Corte and Simonits, 2003) within the

uncertainty limit. At the cadmium cut-off energy of 0.55eV for a 1mm Cd shield thickness. The existing experimental and evaluated data for resonance integral in the previous literature were distributed from 1.25±0.08 barn to 3.1±0.02 barn. The present resonance integral agreed with most of the previously reported literature values within the limit of uncertainty.

In this work, although the cross section for $^{64}Zn(n,\gamma)^{65}Zn$ reaction was evaluated to be 0.726 ± 0.02 barns, in the same vein compared well with the evaluated values 0.726 ± 0.02 barns, by Mughabghab, (2003), 0.76 b ± 0.02 barns, IAEA-TECDOC (1990; 1991; 2003). It also agreed with that of 0.725 ± 0.01 barns, NuDat (2003), within the limit of uncertainty as shown in Table 2.

Minor deviations from some evaluated libraries (e.g., ENDF/B-VI and JENDL/Iwamoto) are within the combined experimental and evaluation uncertainties. Except the data in IAEA-TECHDO for cross-section measurement.

***Table 2. Comparison of calculated activation cross section and Resonance Integral of $^{65}Zn$, For NIRR-1 with some nuclear data libraries in barns***

| Target | Product | Cross-section ($\sigma_o$) Barns (b) | Resonate Integral ($I_o$) Barns (b) | Reference |
|---|---|---|---|---|
| Zn-64 | Zn-65 | 0.726 ± 0.02 | 1.47 ± 0.05 | This work (2024) |
| Zn-64 | Zn-65 | 0.726 ± 0.02 | 1.420 | IAEA-TECDOC (1990, 1991, 2003) |
| Zn-64 | Zn-65 | 0.726 ± 0.02 | 1.37 ± 0.06 | Mughabghab (2003) |
| Zn-64 | Zn-65 | 0.725 ± 0.01 | 1.426 ± 0.02 | NuDat (2005) |
| Zn-64 | Zn-65 | 0.726 ± 0.02 | 1.428 | ENDF/B-VI (1994) |
| Zn-64 | Zn-65 | 0.787 ± 0.06 | 1.423 ± 0.02 | IWAMATO (2007) |

The evaluated resonance integral of 1.470 barns in this work compares well also with the library's data of 1.420 barns IAEA-TECDOC (1990; 1991; 2003), 1.426 barns ± 0.02 barn, NuDat, (2003), 1.428 barns, ENDF/B-VI (1994), and 1.423 barns ± 0.02 barns, IWAMATO, as shown in Table 2.

The presented result for thermal neutron cross section for $^{64}Zn(n,\gamma)^{65}Zn$ reaction in this work, as shown in Table 3, is (0.726 ± 0.02) barns. This result agreed well with the values of (0.72 ± 0.05) barns Mughabghab *et al.* (1981), (0.726 ± 0.02) barns, De Corte and Simonits (2003). (1.07 ± 0.10) barns, Singh *et al.* (2016), (0.74 ± 0.03) barns Kim *et al.* (2015), (1.14 ± 0.11) barns, Goyal *et al.* (2019), (1.19 ± 0.12) barns, Singh *et al.* (2019) (1.23 ± 0.12) barns, Kumar *et al.* (2020), (1.21 ± 0.13) barns, Singh *et al.* (2020). However, slightly deviate with the values obtained by (0.79 ± 0.02) barns, Mughabghab *et al.* (2003; 2006), (0.75 ± 0.04) barns, Shah *et al.* (2009), (0.76 ±0.05) barns, Verma *et al.* (2012), (0.78 ± 0.04) barns, Ansari *et al.* (2017) respectively.

In the same vein, the resonance integral cross section calculated in this work was found to be (1.47 ± 0.05) barns, which also agreed well with most of the values reported in the previous works as shown in Table 4.3. At the Cadmium cut-off energy of 0.55eV.

**Table 3 Comparison of experimental determinable thermal neutron cross-section and resonance integral of 65Zn for 64Zn(n,γ)65Zn reaction, with existing literatures using NIRR-1**

| Year | References (Authors) | Thermal neutron cross- | Resonance integral, $I_0$ (barns) | Cadmium Cut-off | Monitor used |
|---|---|---|---|---|---|

| | | **section, $\sigma_0$ (barns)** | | **energy, $E_{Cd}$ (eV)** | |
|---|---|---|---|---|---|
| Experimental results | | | | | |
| | This work | 0.726±0.02 | 1.47±0.05 | 0.55 | ZnO |
| 2020 | Kumar *et al* | 1.23±0.12 | 0.91±0.09 | 0.55 | Au, ZnO |
| 2020 | Singh *et al* | 1.21±0.13 | 0.98±0.10 | 0.55 | Au, ZnO |
| 2019 | Singh *et al* | 1.19±0.12 | 0.85±0.09 | 0.55 | Au, ZnO |
| 2019 | Goyal *et al* | 1.14±0.11 | 0.83±0.08 | 0.55 | Au, ZnO |
| 2017 | Ansari *et al* | 0.78±0.04 | 1.35±0.10 | 0.55 | ZnO |
| 2015 | Kim *et al* | 0.74±0.03 | 1.28±0.08 | 0.55 | ZnO |
| 2016 | Singh *et al* | 1.07±0.10 | 0.76±0.08 | 0.55 | Au, ZnO |
| 2012 | Verma *et al* | 0.76±0.05 | 1.32±0.09 | 0.55 | ZnO |
| 2009 | Shah *et al* | 0.75±0.04 | 1.25±0.08 | 0.55 | ZnO |
| 2007 | Iwamato *et al* | 0.787 | 1.423 | 0.55 | ZnO, Au |
| 2006 | Mughabghab *et al* | 0.79±0.02 | 1.37±0.06 | 0.55 | Au |
| 2003 | Mughabghab *et al* | 0.76±0.02 | 1.45±0.06 | 0.55 | Au |
| 2003 | De Corte & Simonits | 0.726±0.02 | 1.43±0.02 | 0.55 | Au |
| 1981 | Mughabghab *et al* | 0.72±0.04 | 3.1±0.2 | 0.55 | Au |
| 1971 | Steinnes *et al* | 0.82±0.01 | 1.43±0.10 | 0.55 | Au |
| 1967 | Sims & Juhnke | 0.821±0.011 | 1.34±0.06 | 0.55 | ZnO, Cs |

However, the cross-section values are affected by several factors, which include neutron energy, target nucleus property, reaction type, temperature, neutron flux spectrum, resonance effect, nuclear level density, nuclear deformation, and experimental conditions. Nevertheless, our measured resonance integral cross section is in good agreement with many reported values in the previous work, which underscores the analytical capability of NIRR-I.

## 5.0 Conclusion

It can be concluded that the use of Cadmium ratio for the purpose of thermal neutron cross section and resonance integral determination of $^{65}$Zn isotope for $^{64}$Zn (n, $\gamma$) $^{65}$Zn reaction for eventual (n, $\gamma$) activation cross section by activation method using ZnO as single monitor homogeneously mixed with $Al_2O_3$, irradiated in B3 channel at a thermal flux of 5.0 x$10^{11}$n.cm$^2$s$^{-1}$ for NIRR-1. The Activity of $^{65}$Zn For $^{64}$Zn (n, γ) $^{65}$Zn reaction was determined to be 2.94E+06Bq and 4.19E+05Bq from the bare and cadmium-covered samples irradiations. From the activity of $^{65}$Zn Isotope of bare and cadmium cover Irradiation, thecadmium ratio was measured to be 7.01±0.99 barn. The values of the result in this work, re in good agreement with the values of 8.15±0.08 barn, by Jonah *et al*, (2005), 8.28±0.29 barn, calculated by Sadiq *et al*, (2010), 8.22±0.23 barn, by Anas *et al*, (2023), for NIRR-1, ABU Zaria. In the same vein the thermal neutron cross section and the resonance integral for $^{64}$Zn (n, γ) $^{65}$Zn hhavebeen determined to be 0.726 ± 0.02 barn and 1.47 ± 0.05 barn . Thisindicates that the full energy peak of the detector is in normal condition and the reactor flux of 5.0$10^{11}$n/cm$^2$/s$^{-1}$ of the NIRR-1 is stable. However, the evaluated values for the reaction isotope reaction in this work as presented in Table 3.

The present result was more accurate by using the latest decay data of $^{64}Zn(n,\gamma)^{65}Zn$ reaction, where $ZnO$ was used as a single suitable monitor, with two fold purpose as a neutron flux monitor and for zinc concentration measurement. $Al_2O_3$ has a lower neutron cross section, assist in minimizing neutron self-shielding effect on samples. Therefore, the Cadmium cover used is to shield the thermal neutrons because of its significant flux depression. A simple but quite reliable activation method, known as the cadmium ratio method, was applied to experimentally determine the resonance integral for $^{64}Zn(n,\gamma)^{65}Zn$ reaction in this work.

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**Conflict of interest**

No conflict of interest declared by the authors.

**Availability of Data**

Data shall be made available upon request.

**Ethical Consideration**

Not applicable

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**Availability of Data**

Both authors contributed to all aspects of the work

**Author Contributions**

Ahmad Hassan conceived the study, conducted irradiations, analyzed data, and drafted the manuscript. Sadiq Umar supervised experimental procedures and reviewed the work. Yamusa Abdullahi Yamusa and Asuku Abdulsamad supported reactor operations and gamma spectrometry. Muhammad Tukur performed calculations and uncertainty analysis. Shuaibu Abdulmumini handled literature review and revisions. All authors approved the final manuscript.