

Experimental Determination of Thermal Neutron Capture Cross Sections of Zirconium and Zinc using Neutron Source at the HANARO Research Reactor

K. B. Dasari^{a,*}, S. P. Hong^b, H. Cho^c, J.H. Moon^b, H. Choi^b, J.H. Park^a, G. M. Sun^b

^aDepartment of Science Education, Chemistry Major, Jeonbuk National University, Jeonju

^bHanaro Utilization Division, Korea Atomic Energy Research Institute, Daejeon

^cDivision of Chemical and Material Metrology, Korea Research Institute of Standards and Science, Daejeon

(* Corresponding Author Email: dasari@jbnu.ac.kr)

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1. Introduction

Neutron-capture cross-section data are essential for neutron activation analysis (NAA), reactor physics, nuclear data evaluation, and various nuclear applications. Zirconium is one of the interesting study because frequently used as a flux minotr and also zirconium alloys are extensively used as fuel-cladding and structural materials in nuclear reactors. Zinc and Zirconium isotopes are important in NAA because of their different neutron-capture characteristics and sensitivities to thermal and epithermal neutrons, are also useful for neutron-flux characterization in combination with Au. Although evaluated nuclear-data libraries needs validating evaluated data and improving the reliability of nuclear calculations. Therefore, experimental determination of Zr and Zn neutron-capture cross sections is important for validating and improving nuclear data.

Neutron-capture cross sections are commonly investigated using accelerator-based neutron sources, particularly when energy-resolved measurements are required. However, research reactors offer a complementary and highly sensitive approach for activation-based measurements because of their intense thermal and epithermal neutron fields. Previous reactor-based activation studies by Krane at Oregon State University, as well as studies at the Dalat Nuclear Research Institute, demonstrated reliable approaches for determining thermal neutron-capture cross sections and resonance integrals using research reactors [1–3].

The HANARO research reactor provides a high-flux neutron irradiation environment with well-characterized neutron-spectrum parameters at different irradiation positions. With a maximum reactor power of 30 MW and thermal neutron fluxes reaching approximately $1 \times 10^{14} \text{ n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ at selected irradiation positions, HANARO offers favorable conditions for activation measurements with high counting statistics and relatively short irradiation times. The availability of irradiation positions with different thermal-to-epithermal neutron flux ratios also provides an opportunity to investigate the influence of neutron-spectrum characteristics on measured capture cross sections. In addition, previous work at the HANARO PGAA facility demonstrated the successful determination of prompt $k_{0,H}$ factors and partial γ -ray production cross sections using a hydrogen comparator [4].

The relative activation measurements with respect to $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction is used as a reference to reduce uncertainties associated with neutron-flux determination and irradiation conditions. In the present study, a gold-referenced relative neutron-capture cross sections methodology was developed at the HANARO research reactor. The methodology was initially evaluated using Zr and Zn isotopes with established literature data, and the measured values were compared with reported cross sections to assess the reliability of the approach.

2. Experimental

Natural-abundance Zr, Zn, and Al–0.1%Au alloy foils were used for the neutron-capture measurements. The sample masses were approximately 10–30 mg, with a thickness of about 0.1 mm. Irradiations were performed at three different irradiation positions (PTS#1, PTS#2, and PTS#3) of the HANARO research reactor. For each irradiation, two sets of samples were prepared, bare and cadmium covered. The bare and Cd-covered samples were irradiated simultaneously for 1 to 5 min. PTS#2 provides a highly thermalized neutron field, whereas PTS#3 has a relatively larger epithermal-neutron contribution. Following irradiation, the induced activities were measured using a high-resolution HPGe γ -ray spectrometer. The end-of-bombardment activities were determined from the net γ -ray peak areas after corrections for detector efficiency, γ -ray emission probability, decay during and after irradiation, and measurement geometry. The thermal neutron-capture cross section of the analyte isotope was obtained from the ratio of the thermal reaction rate of the analyte to that of ^{197}Au , taking into account the number of target atoms, the Westcott g-factor, and the corresponding corrections for the cadmium transmission and epithermal contribution [3]:

$$\sigma_{0,i} = \frac{\left[R_c - \frac{1}{F_{Cd}} R_{epi} \right]_i}{\left[R_c - \frac{1}{F_{Cd}} R_{epi} \right]_{Au}} \times \frac{(G_{th} \times g)_{Au}}{(G_{th} \times g)_i} \times \sigma_{0,Au} - (1)$$

$$I_0(\alpha)_i = I_0(\alpha)_{Au} \times \left(\frac{G_{epi}}{G_{th}} \right)_{Au} \times \left(\frac{G_{th}}{G_{epi}} \right)_i \times \frac{(g\sigma_0)_i}{(g\sigma_0)_{Au}} \times \frac{(F_{Cd}R_{Cd} - 1)_{Au}}{(F_{Cd}R_{Cd} - 1)_i} - (2)$$

where R_c , R_{epi} are the total reaction rate from bare and Cd wrapped samples of isotope, F_{cd} is Cd-transmission factor, R_{cd} Cd-ratio, G_{th} thermal neutron absorption coefficient, g-westcott g factor for thermal neutrons, σ_0 I_0 are thermal neutron cross section at neutron velocity of 2200 m s^{-1} and resonance integral, i and Au are analyte and comparator isotope gold.

Fig.1 shows representative γ -ray spectra obtained from the Zr foil with and without Cd covering. The spectra clearly demonstrate the different contributions of thermal and epithermal neutrons to the activation of Zr isotopes. In particular, the $^{94}\text{Zr}(n,\gamma)^{95}\text{Zr}$ reaction provides a useful response to the thermal neutron component, whereas the $^{96}\text{Zr}(n,\gamma)^{97m}\text{Nb}$ decay chain provides sensitivity to the neutron-spectrum-dependent activation component.

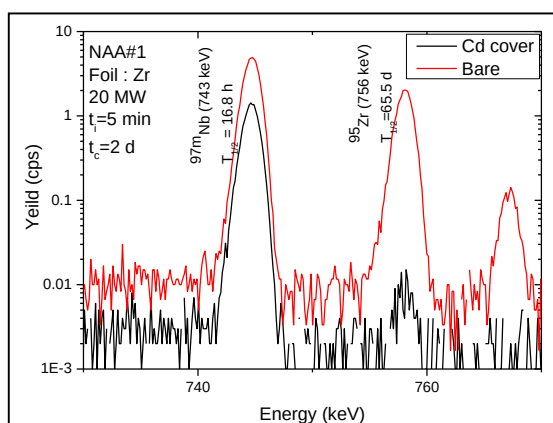


Fig. 1 Gamma-ray spectrum of Zr foil with and without Cd cover

3. Results and Discussion

The measured thermal neutron-capture cross sections and resonance integrals for the Zr and Zn isotopes are presented in Table 1, together with the corresponding literature values. In the present analysis, the cadmium cut-off energy was assumed to be $E_{Cd}=0.55 \text{ eV}$ for separation of the thermal and epithermal neutron contributions.

Table 1 Thermal neutron cross-section and resonance integral for Zr and Zn istopes.

Isotope	Thermal neutrons σ_0 , barns		Resonance intergral, I_0 , barns	
	Present	Literature[1]	Present	Literature [1]
^{94}Zr	0.0531(16)	0.0465(14)	0.301(21)	0.376(14)
^{96}Zr	0.025(18)	0.021(13)	5.02(35)	5.52(25)
^{64}Zn	0.72(4)	0.70(3)	1.55(12)	1.78(7)
^{69m}Zn	0.071(4)	0.069(3)	0.253(18)	0.294(12)

The total relative uncertainties of the present results were estimated from the quadratic sum of the individual uncertainty components. The main contributions included statistical uncertainty (0.3–1.1%), detector efficiency (0.5%), reference nuclear data for the thermal cross section and resonance integral (0.1% and 1.8%, respectively), thermal-neutron self-shielding correction (0.4%), and epithermal-neutron self-shielding correction (3%). Thus, the overall uncertainty budget was

predominantly influenced by the corrections associated with the epithermal neutron component.

The measured thermal neutron-capture cross sections show good agreement with the literature values. The deviations for ^{64}Zn and ^{69}Zn are approximately 3% and 2%, respectively, demonstrating the reliability of the Au-referenced activation approach. The ^{94}Zr and ^{96}Zr results show somewhat larger deviations, which may be related to their relatively low capture cross sections and the greater sensitivity of the measurements to epithermal-neutron corrections. The measured resonance integrals are lower than the corresponding literature values, with differences of approximately 9–24%. This difference emphasizes the importance of accurately characterizing the epithermal neutron spectrum and irradiation conditions. Further investigation of the neutron-spectrum parameters at the HANARO irradiation positions will therefore be important for improving the accuracy of resonance-integral determinations.

4. Conclusion

A reactor-based methodology for determining neutron-capture cross sections using the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction as a reference monitor was successfully demonstrated at HANARO. The methodology was applied to Zr and Zn isotopes with established literature data. The measured thermal neutron-capture cross sections showed good agreement with reported values. The developed methodology provides a basis for systematic neutron-capture cross-section measurements at HANARO and its future application to isotopes with limited or uncertain nuclear data.

Acknowledgments

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