Measurement Thermal Neutron Capture Cross Section and Resonance Integral of ^{94}Zr using Intense Resonance Neutron Source "IREN"

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Outline

I. INTRODUCTION
II. EXPERIMENT
III. RESULTS
IV. CONCLUSION

The Aim of the Research

Measurement nuclear data of ^{94}Zr isotope

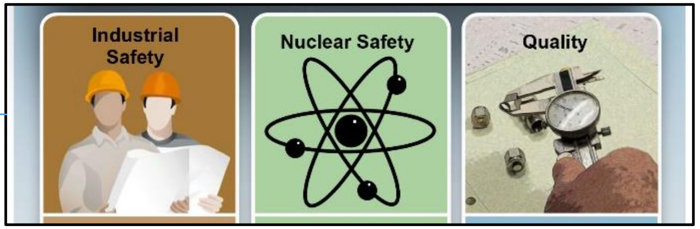
Thermal cross-section value (σ_o)

Resonance Integral quantity (I_o)

The importance of nuclear data

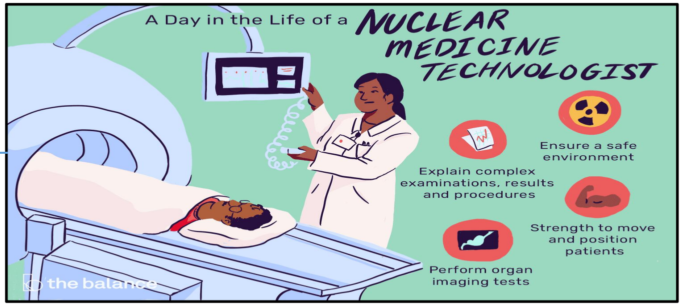
- **Nuclear data** provide an essential foundation for advances in a wide range of fields

nuclear safety



nuclear energy

nuclear medicine



Planetary, space exploration

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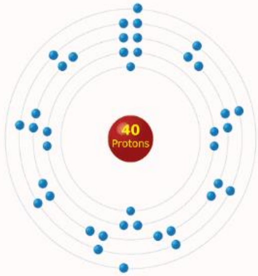
I. INTRODUCTION

I.1 Zirconium Isotopes

40
Zr
Zirconium
91.224

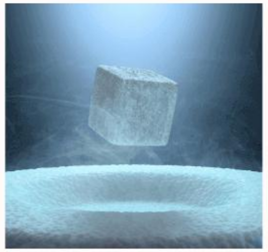
Zirconium Facts



Atomic Number: 40
Symbol: Zr
Atomic Weight: 91.224
Discovery: 1789 - Martin Klaproth (Germany)
Electron Configuration: [Kr] $4d^2\ 5s^2$
Appearance: Silver-colored Metal

zircon gemstone

dental implants



superconducting magnets

cubic zirconia

reactor fuel cladding

sciencenotes.org

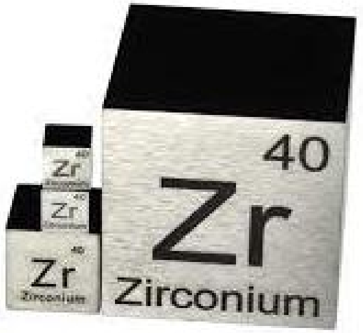
^{90}Zr-51.45%

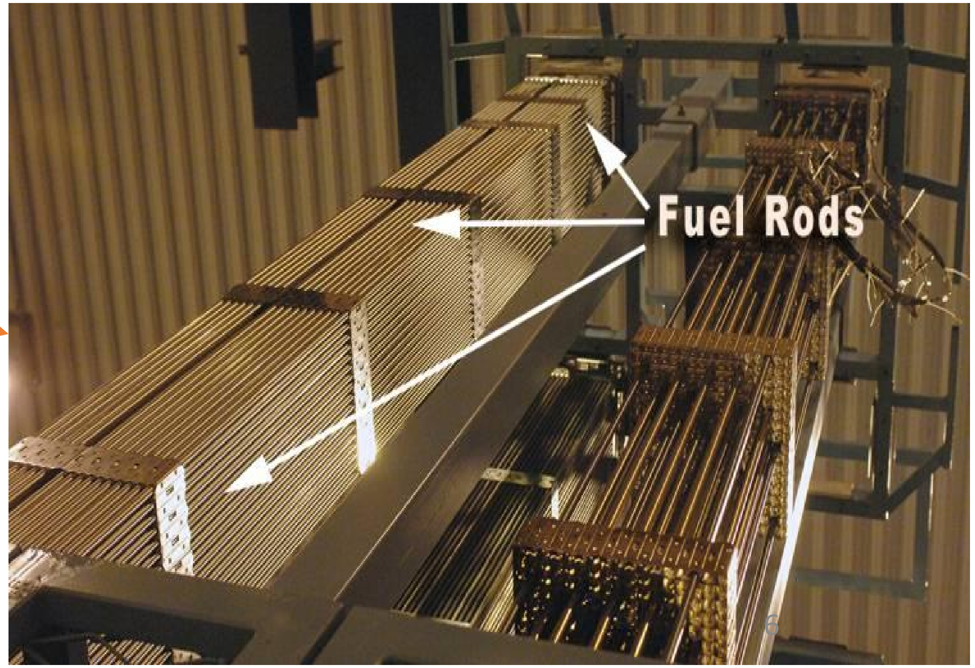
^{91}Zr-11.22%

^{92}Zr-17.15%

^{94}Zr-17.38%

^{96}Zr-2.8%

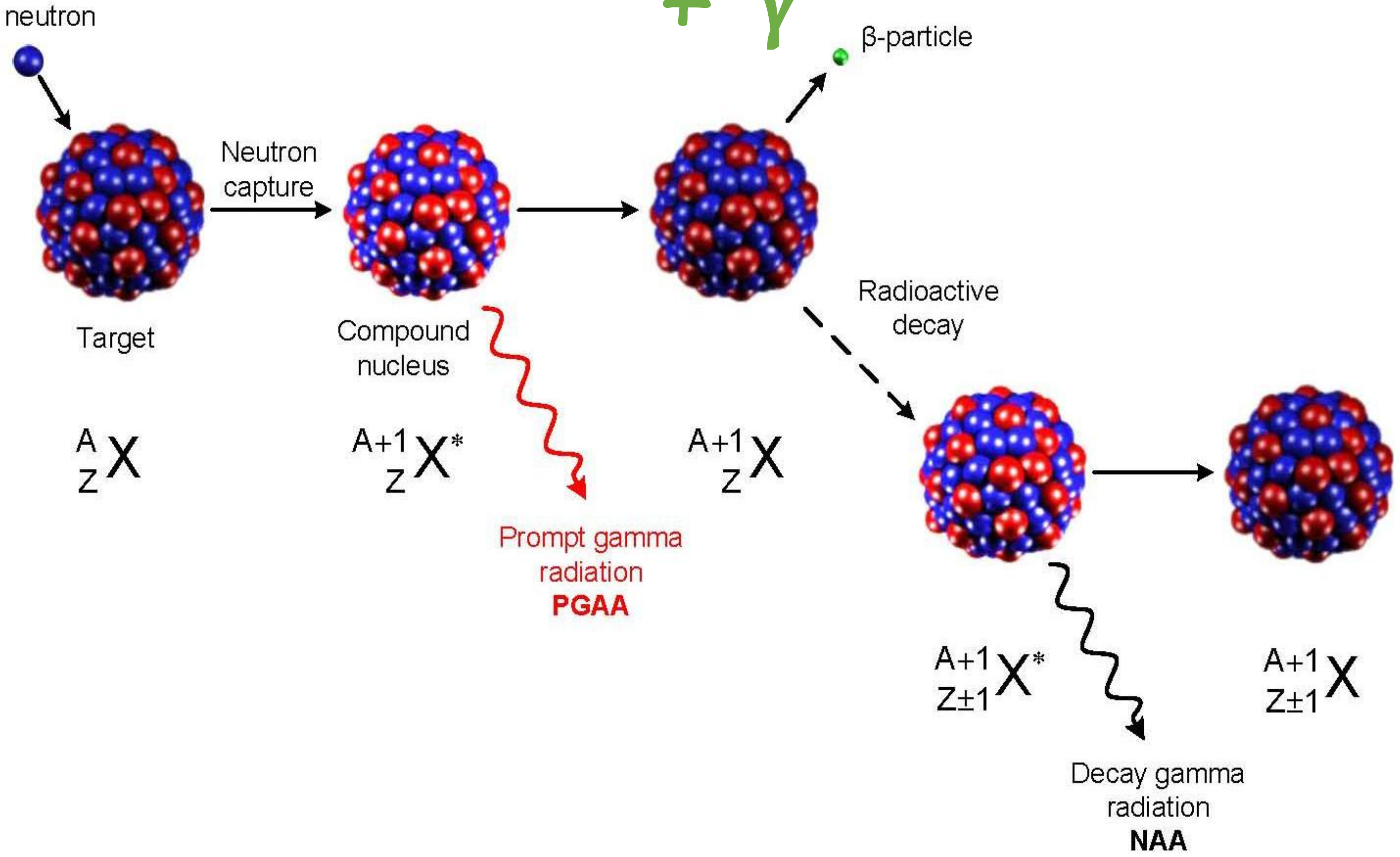


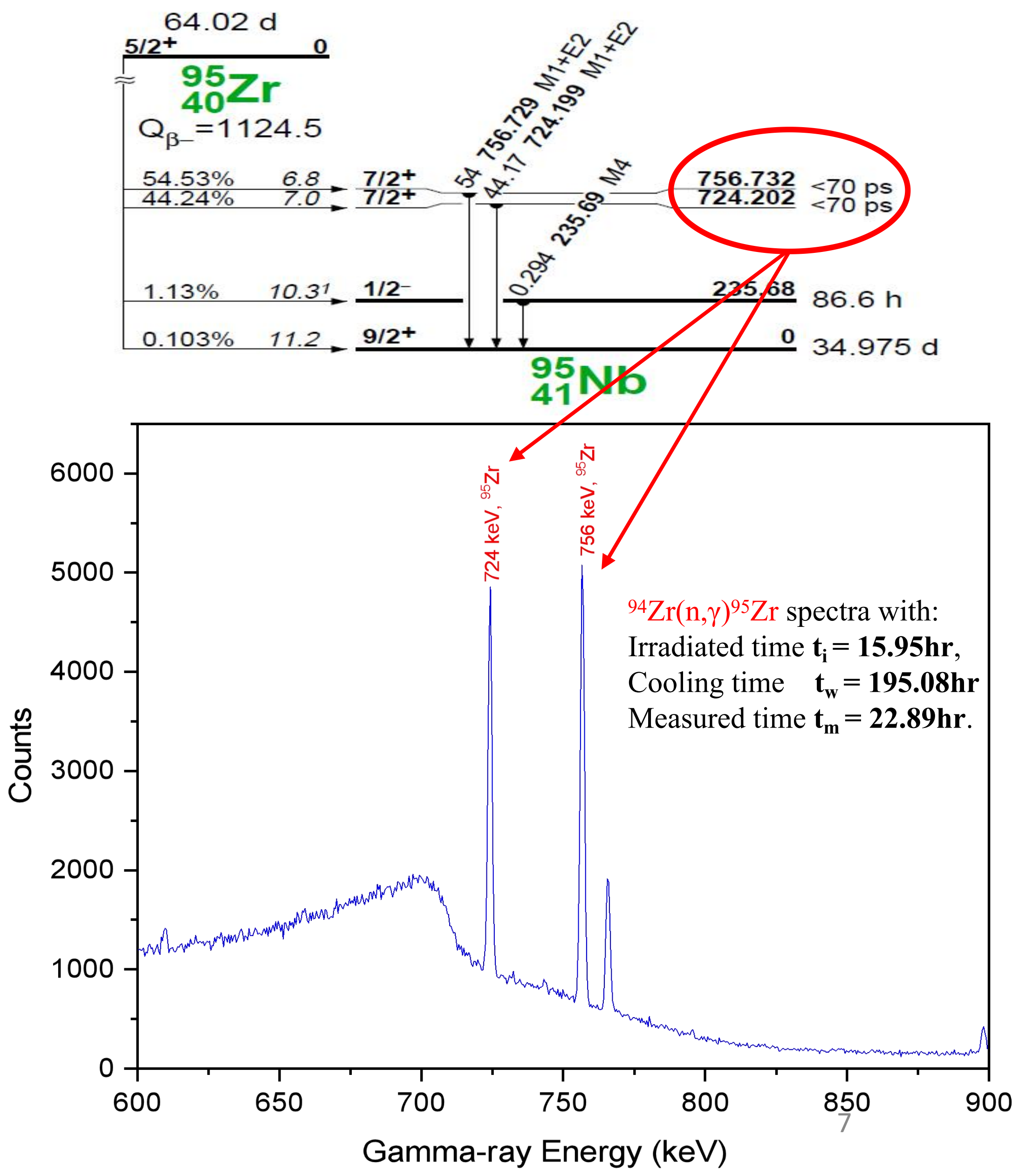


I. INTRODUCTION

I.2 Neutron Activation Analysis (NAA)

$$n + {}^{94}Zr \rightarrow {}^{95}Zr + \gamma$$





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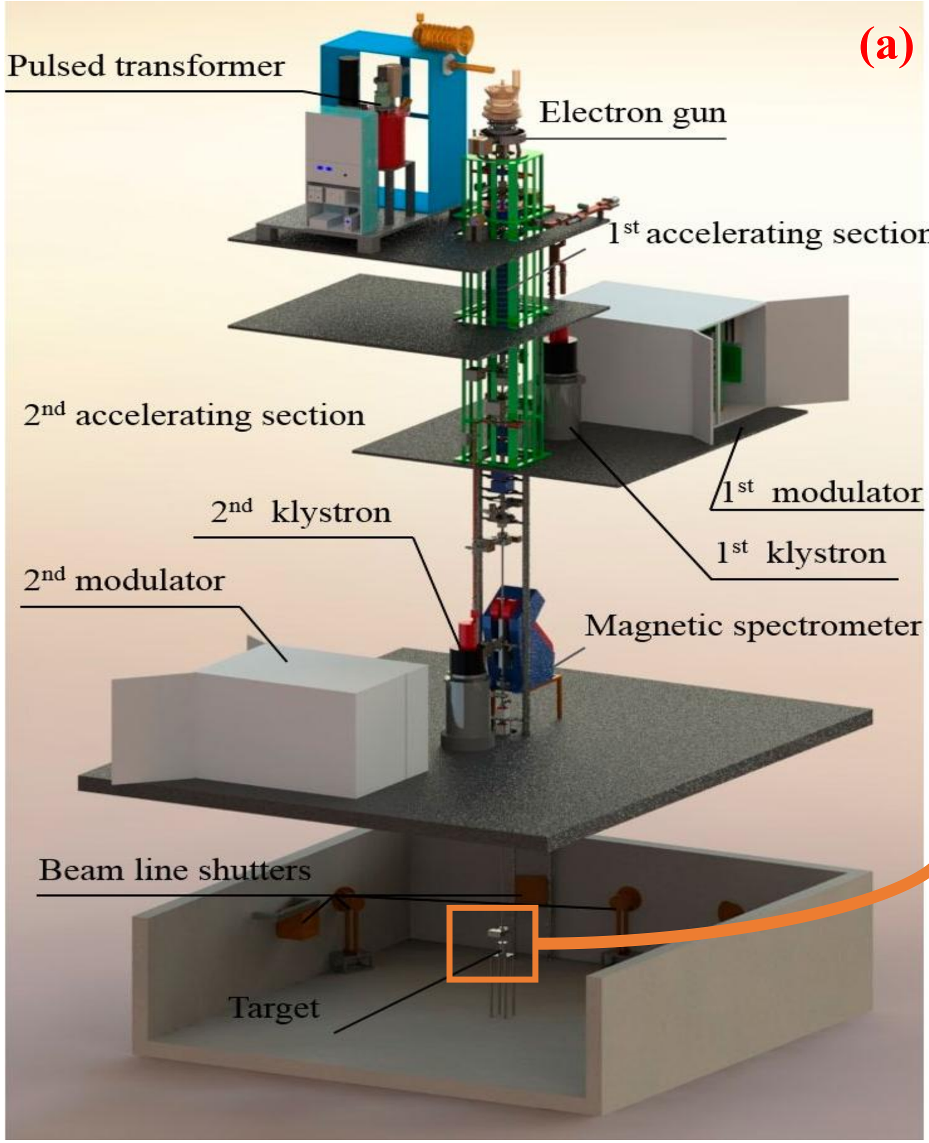
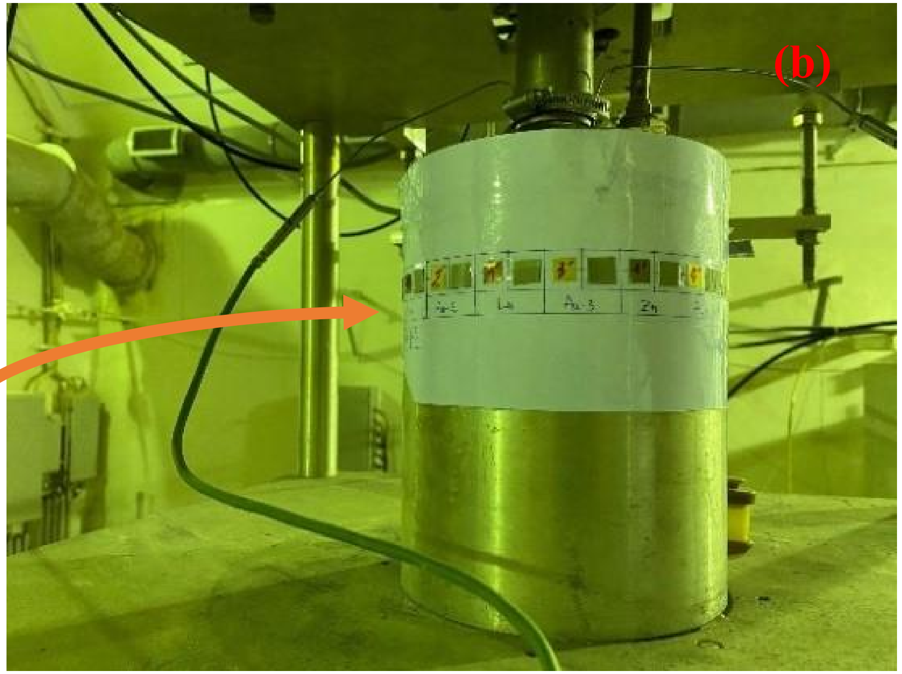
II. EXPERIMENT

II.1 Neutron Source



Parameters of electron beam using in activation, energy of beam is 110 MeV with frequency of 50 Hz, pulse width of 120 ns and the maxium current up to 1.8 A. The neutron flux up to $2.8 \times 10^9\ n\cdot(cm^2\cdot s)^{-1}$.



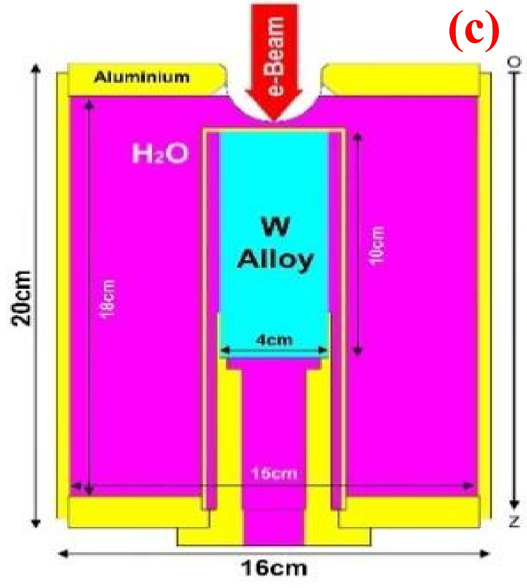


Fig.1: *(a) IREN system; (b) Photo of moderator at Target hall in IREN;(c) Inner of moderator.*

II.2 Finding optimal positon to activate samples

➢ **Comparing the reaction rate values of activated samples in different heights on surface of moderator**

The reaction rate (R) of (n,γ) of the activated metal foils with Cd cover ($R_{Zr,Cd}$) and without Cd cover (R_{Zr}) was determined as follows:

$$\boldsymbol{R_x\ or\ R_{x,Cd}} = \frac{N_{obs}\lambda(1-e^{-\lambda t_{cp}})}{n_0 \varepsilon I_\gamma (1-e^{-\lambda \tau})(1-e^{-\lambda t_i}) e^{-\lambda t_w} (1-e^{-\lambda t_c})} \quad (1)$$

Figure.2a : Experimental set-up for surveying irradiation positions at different heights .

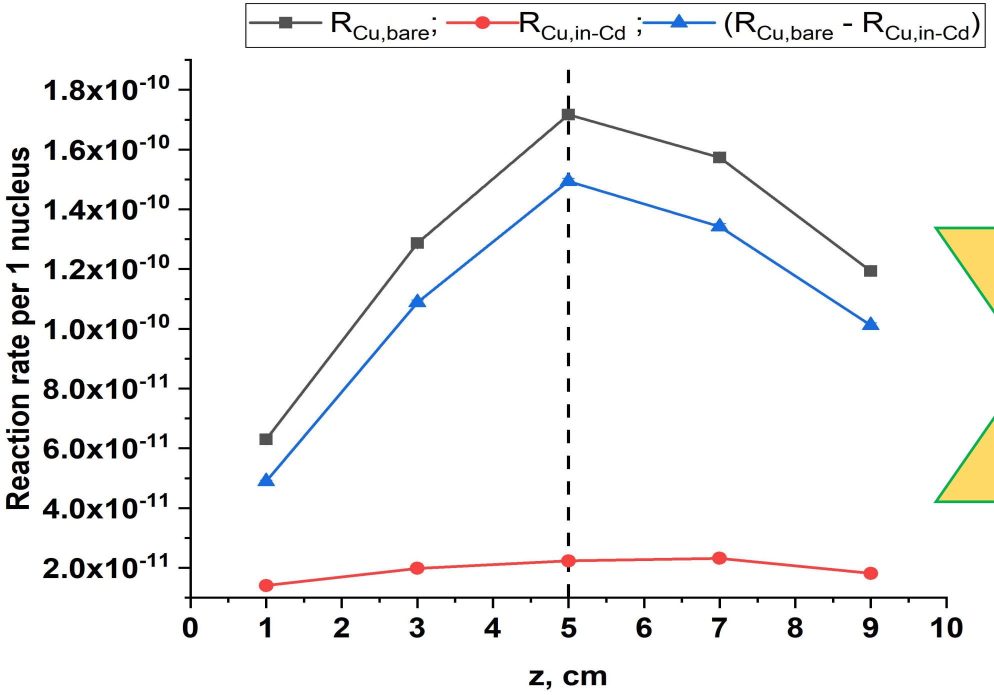


Figure.2b : Relationship between reaction rate and irradiation positions at different height from the top.

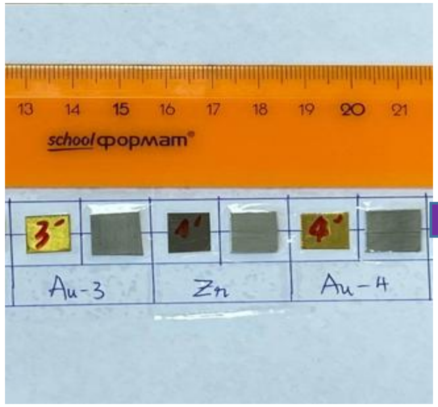
5cm is the optimal postion to irradiate samples

II.3 Irradiation and Spectra Measurement

Table.1 : Sample parameters of Au and Zr isotopes

Foils	Size [mm]	Weight [g]	Thickness[mm]	Purity [%]
Au	9 x 9	0.1514	0.1	99.99
Au-Cd	9 x 9	0.1494	0.1	99.99
Zr	10 x 9	0.0577	0.1	99.98
Zr-Cd	10 x 9	0.0551	0.1	99.98

Irradiated time : 15.95 hours



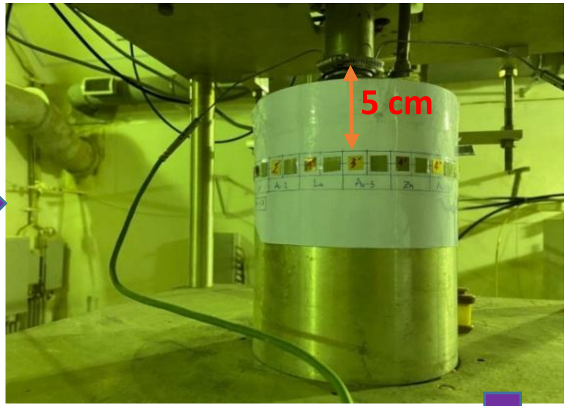
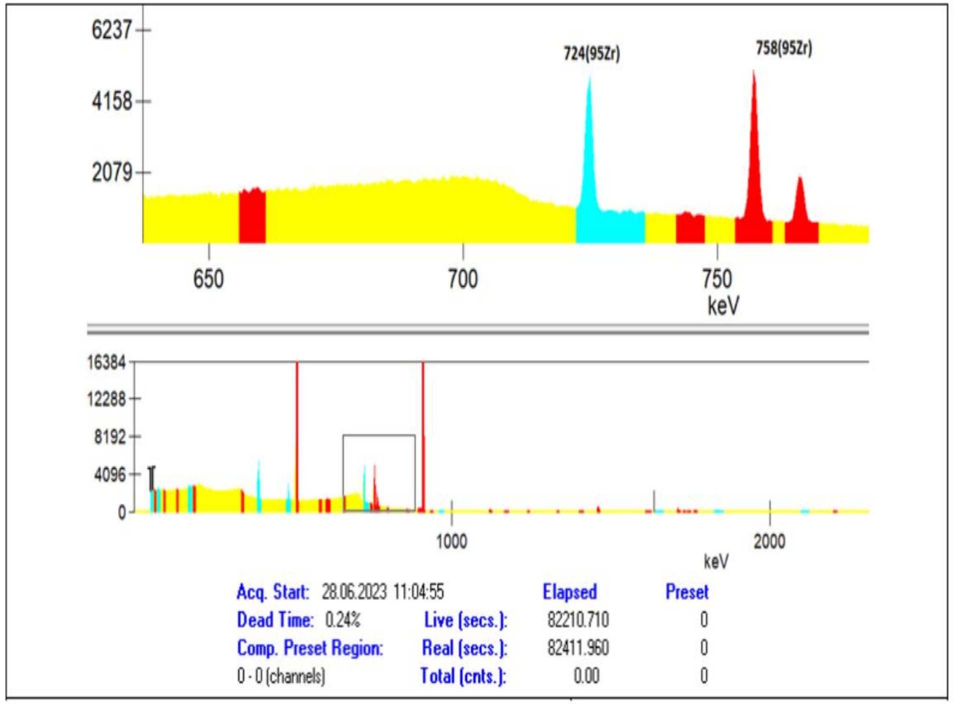


Fig.2c :*Automation system measurement and HPGe Detector*



Gamma spectrum of the $^{94}Zr(n,\gamma)^{95}Zr$ reaction

II.4 Data analysis

➢ **Determination of thermal cross section**

The thermal neutron cross-section for the $^{94}Zr(n,\gamma)^{95}Zr$ reaction, $\boldsymbol{\sigma_{0,Zr}}$ has been determined relative to the reference value of $\boldsymbol{\sigma_{0,Au} = 98.65 \pm 0.09}$ **barn** for the $^{197}Au(n,\gamma)^{198}Au$ standard reaction as follows:

$$\sigma_{0,Zr} = \sigma_{0,Au} \times \frac{R_{Zr} - F_{Zr,Cd}\, R_{Zr,Cd}}{R_{Au} - F_{Au,Cd}\, R_{Au,Cd}} \times \frac{G_{th,Au}}{G_{th,Zr}} \frac{g_{Au}}{g_{Zr}} \quad (2)$$

Where:

$\boldsymbol{\sigma_0}$	: the thermal neutron cross-section
$\boldsymbol{R_x}$ **and** $\boldsymbol{R_{x,Cd}}$	: reaction rates per atom for bare and Cd-covered (Zr or Au) isotope
$\boldsymbol{F_{x,cd}}$	: the cadmium correction factor
$\boldsymbol{G_{th}}$	: the thermal neutron self-shielding factor
$\boldsymbol{g_{Zr}}$	: the Westcott factor correction

II.4 Data analysis

➢ Determination of resonance integral

The resonance integral for the $^{94}Zr(n,\gamma)^{95}Zr$ reaction, $\mathbf{I_{0,Zr}}$ has been determined relative to the reference values of $\mathbf{I_0}$ **=1550 ± 28 barn** for the $^{197}Au\ (n,\gamma)^{198}Au$ standard reaction as follows:

$$I_{0,Zr}(\alpha) = I_{0,Au}(\alpha) \times \frac{(CR - F_{Cd})_{Au}}{(CR - F_{Cd})_{Zr}} \times \frac{\sigma_{0,X} * g_X * G_{Au}}{\sigma_{0,Au} * g_{Au} * G_{Zr}} \quad (3)$$

Where:

$\mathbf{I_0}$	: The resonance integral valued
$\mathbf{CR_x}$, $\mathbf{CR_{x,Cd}}$	: Cadmidum ratio for bare and Cd-covered isotope
$\mathbf{F_{x,cd}}$	: The cadmium correction factor
$\mathbf{G = G_{epi}/G_{th}}$	: The ratio of epithermal and thermal neutron self-shielding factor
$\mathbf{g_{Zr}}$	: The Westcott factor correction
$\boldsymbol{\alpha}$	: epithermal neutron spectrum shape factor

II.4 Data analysis

- **Conversion $I_0(\alpha)$ to I_0**

The resonance integral for the $^{94}Zr(n,\gamma)^{95}Zr$ reaction, $\mathbf{I_{0,Zr}}$ is converted from the values of $\mathbf{I_{0,Zr}(\alpha)}$ as follow expression:

$$I_{0,Zr}(\alpha) = (1\text{eV})^{\alpha}\left[\frac{I_{0,Zr} - 0.429 g\sigma_{0,Zr}}{(\bar{E}_r)^{\alpha}} + \frac{0.429 g\sigma_{0,Zr}}{(2\alpha+1)(E_{cd})^{\alpha}}\right] \quad (4)$$

Where:

$\boldsymbol{\sigma_0}$: thermal neutron cross-section for (n,γ) reaction.

$\boldsymbol{\alpha}$: epithermal neutron spectrum shape factor

$\boldsymbol{\bar{E}_r}$: effective resonance energy (eV)

$\boldsymbol{E_{cd}}$: Cadmium **Energy cut-off** 0.55eV

$\boldsymbol{I_o - 0.426 g\sigma_o}$: The reduced resonance integral

II.4 Data analysis

- **α -factor determinantion**

The combination of equations (3) and (4) using for two monitors (^{197}Au and ^{186}W) irradiated simultaneously under the same neutrons flux conditions, leading to the following for determining the epithermal neutrons α values:

$$\frac{G_{W}}{G_{Au}} \cdot \frac{(CR^{*}-1)_{W}}{(CR^{*}-1)_{Au}} = \frac{\left\{(Q_0-0.426)\left(\bar{E}_r\right)^{-\alpha}\right\}_{Au} + C_\alpha}{\left\{(Q_0-0.426)\left(\bar{E}_r\right)^{-\alpha}\right\}_{2} + C_\alpha} \qquad (5)$$

Where:

$$\boldsymbol{CR^{*}} = \frac{\boldsymbol{CR}}{\boldsymbol{F_{Cd}}}, \quad \boldsymbol{C_\alpha} = \frac{\mathbf{0.4264}}{(\mathbf{2}\boldsymbol{\alpha}+\mathbf{1})\boldsymbol{E_{cd}^{\alpha}}} \quad \text{and} \quad Q_0 = \frac{I_0}{\sigma_0}$$

$\alpha = -0.1793 \pm 0.0386$

$\bar{E}_r$: effective resonance energy (eV)

$\mathbf{G = G_{epi}/G_{th}}$: The ratio of epithermal and thermal neutron self-shielding

II.4 Data analysis

➢ **Correction factors**

The method described by **Trkov** is applied for calcualting neutron self-shielding effects for thermal ($\boldsymbol{G_{th}}$) and epithermal neutron ($\boldsymbol{G_{epi}}$) absorption by **MATSSF code program**

While Cadmium transition factor (**F$_{Cd}$**) is taken in Ref [*Elnimr1981] and* Westcott factor (**g**) *is from Ref [*Mughabghab*2003]*, shown in **Table 2**

Table.2 : Correction factors using in calculation

Isotope	G_{th}	G_{epi}	F_{Cd}	g
^{197}Au	0.8837	0.2142	1.009	1.0054
^{94}Zr	0.9997	0.9812	1.000	1.0004

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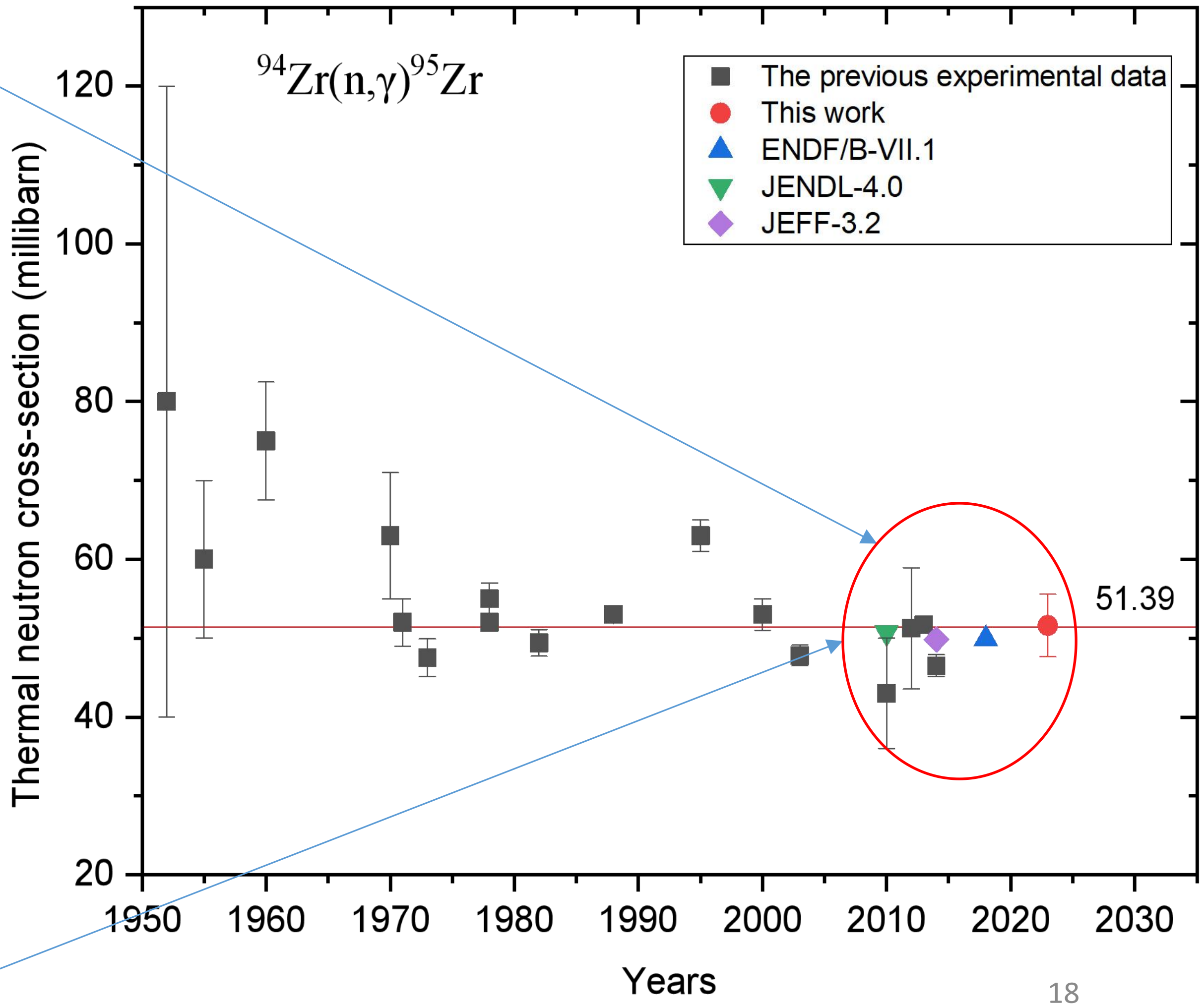
III. RESULTS

Thermal cross section of $^{94}Zr(n,\gamma)^{95}Zr$

Table.3a: Thermal neutron cross section of ^{94}Zr

Year	Author	Sig0 [mb]	dSig0 [mb]	Dif [%]
2023	This work	51.604	3.949	0.0
2014	Krane	46.5	1.4	11.0
		49.3	1.4	4.7
		47.8	1.2	8.0
		46.9	1.1	10.0
2013	Farina Arbocco	51.7	0.3	0.2
2012	Prajapati	51.25	7.68	0.7
2010	Jonah	43	7	20.0
2003	Nakamura	47.8	1.3	8.0
2000	HuanXiao-Long	53	2	2.6
1995	Rajput	63	2	18.1
1988	DeCorte	53	0.53	2.6
1982	Wyrick	49.4	1.7	4.5
1978	Rundberg	52		0.8
1978	Heft	55	2	6.2
1973	Santry	47.5	2.4	8.6
1971	Fulmer	52	3	0.8
1970	Ricabarra	63	8	18.1
1960	Lyon	75	7.5	31.2
1955	Brooksbank	60	10	14.0
1952	Pomerance	80	40	35.5
Weight Average		**51.39**		**0.4**
2018	**ENDF/B-VII.1**	49.88		3.3
2014	**JENDL-4.0**	50.69		1.7
2010	**JEFF-3.2**	49.82		3.4

Fig. 3a:Thermal cross section of $^{94}Zr(n,\gamma)^{95}Zr$

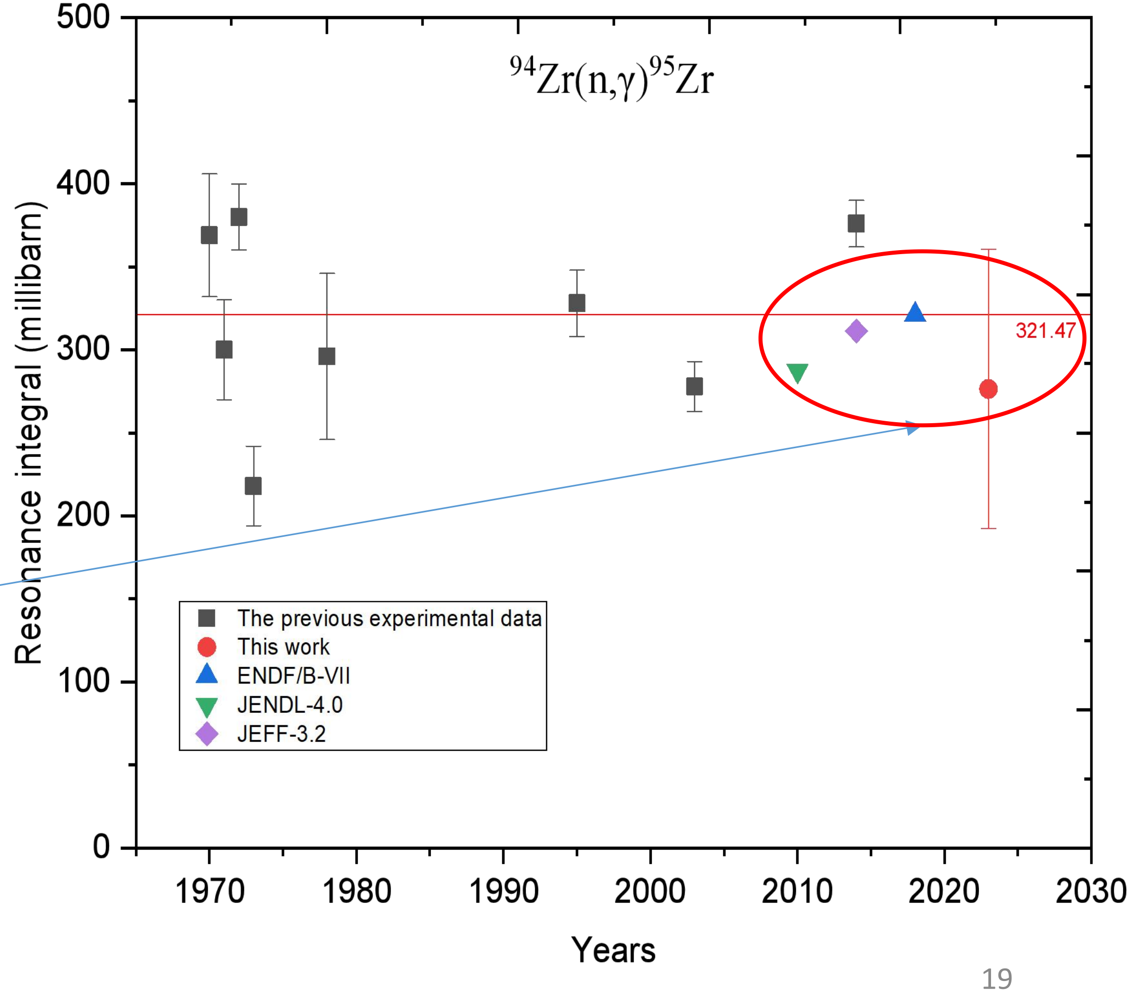


III. RESULTS

Table.3b : Resonance integral of $^{94}Zr(n,\gamma)^{95}Zr$				
Year	Author	I0 [mb]	dI0[mb]	Dif. [%]
2023	This work	276.354	84.04	0.0
2014	Krane	376	14	26.5
2003	Nakamura	278	15	0.6
1995	Rajput	328	20	15.7
1978	Heft	296	50	6.6
1973	Santry	218	24	26.8
1972	Van DerLinden	380	20	27.3
1971	Fulmer	300	30	7.9
1970	Ricabarra	369	37	25.1
Weight Average		**321.47**		**14.03**
2018	**ENDF/B-VII.1**	321.1		13.9
2014	**JENDL-4.0**	287.4		3.8
2010	**JEFF-3.1**	311.3		11.2

Resonance integral of $^{94}Zr(n,\gamma)^{95}Zr$

Fig. 3b: Resonace integral of $^{94}Zr(n,\gamma)^{95}Zr$



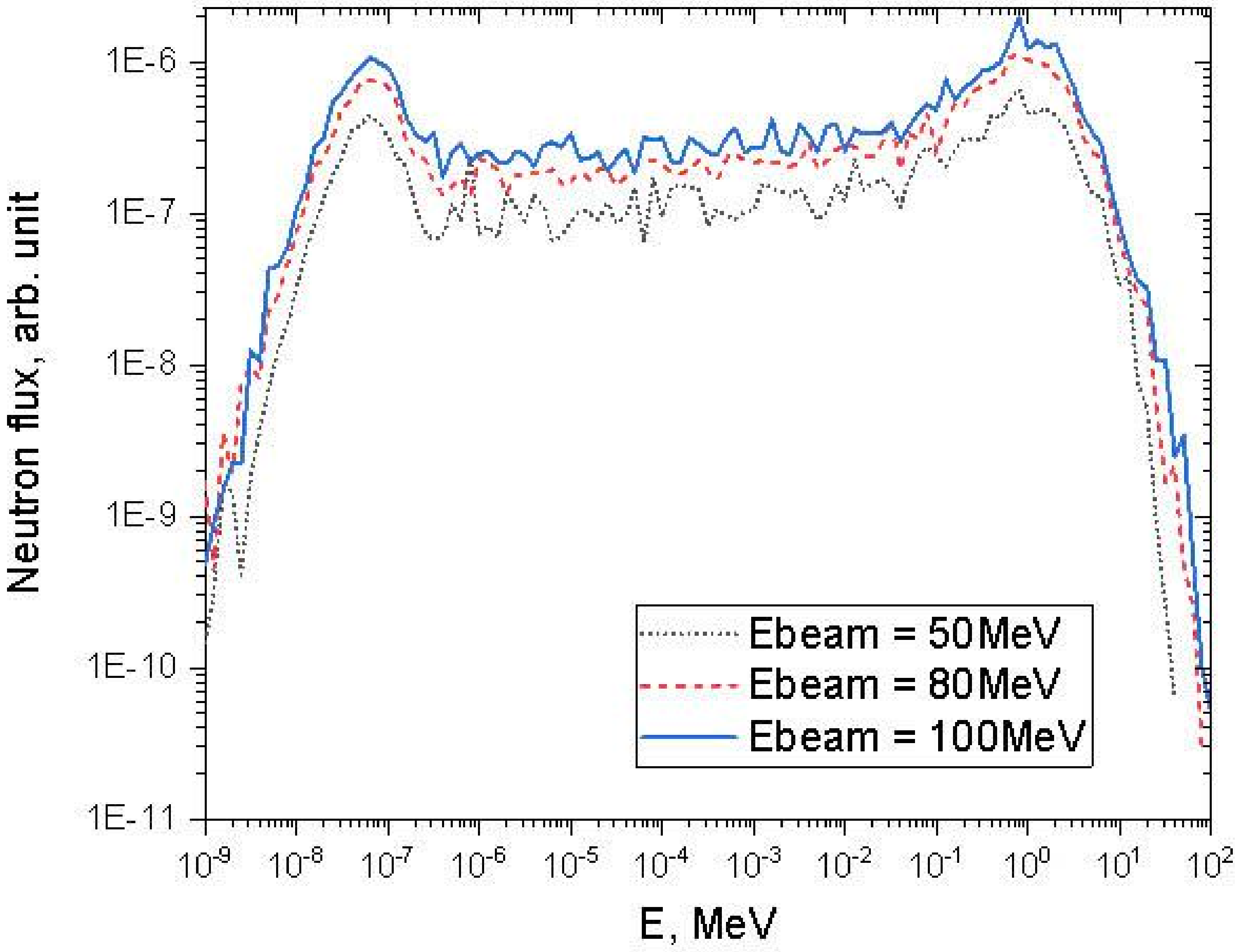
VI. CONCLUSION

- The present thermal cross section of $^{94}Zr(n,\gamma)^{95}Zr$ **reaction** was obtained **51.604 ± 3.949 mbarn** is in good agreement with the experimental results reported as well as evaluated value in international Library, only a minor discrepancy (<5%), indicating high reliability.
- The present resonance integral value of $^{94}Zr(n,\gamma)^{95}Zr$ **reaction** was found to be $\mathbf{I_{0,Zr} = 276.354 \pm 0.62}$ **mb**. The results **have not been measured much** in recent years, leading to differences ranging from **0.5 percent to 26 percent**. **However,** this result is very close to the evaluated values in the International Library with a deviation of about **11–13 percent** for both ENDF/B-VII and JEF-3.1, while that for JENDL-4.0 is **3.8 percent**. This shows great confidence and brings the current result closer to the actual value.

- This study contributes new experimental data while reinforcing confidence in the $\sigma_{0,Zr}$, $I_{0,Zr}$ quantities of ^{94}Zr isotope.
- This confirms the accuracy of our measurement methodology and data processing techniques, which are consistent with international research practices.

THANK FOR YOUR ATTENTION

Congratulation ISINN-31



Neutron flux, arb. unit
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
E, MeV
Ebeam = 50MeV
Ebeam = 80MeV
Ebeam = 100MeV

- R_x **hoặc** $R_{x,cd} = \frac{N_{obs}\lambda(1-e^{-\lambda t_{cp}})}{n_0 \varepsilon I_\gamma (1-e^{-\lambda\tau})(1-e^{-\lambda t_i}) e^{-\lambda t_w} (1-e^{-\lambda t_c})}$ (1)
- **Nobs** is the net count under the full energy peak collected during
- t_c the measurement time, etc., without the number of target nuclei
- ε is the detection efficiency, I_γ is the γ -ray intensity,
- λ is the decay constant, t_i is their radiation time, $t_w$waiting time is the twisting time
- t_{cp} is the pulse width and
- τ : the cycle period tcpis.

Phần giải thích

- The change in the observed reaction rates actually occurs because of the flux depression in the interior of the sample, which is due to the presence of strong and affects all nuclides equally, regardless of which one actually causes the depression.
- Strong resonances deplete the neutron spectrum at the resonance energy due to absorption and scattering, therefore the reaction rate is reduced because of the dip in the neutron spectrum. This is the so-called resonance self-shielding effect

Monitor	Size [mm]	Weight[g]	Thickness[mm]	Purity [%]
Au	9 x 9	0.1514	0.1	99.99
Au-cd	9 x 9	0.1494	0.1	99.99
Zr	10 x 9	0.0577	0.1	99.98
Zr-cd	10 x 9	0.0551	0.1	99.98
Cu	13 x 11	0.6058	0.5	99.74
Cu-cd	12 x 11	0.6152	0.5	99.74
W	10 x 9	0.3477	0.35	99.98
W-cd	10 x 9	0.3581	0.35	99.98

Table.1. : Sample parameters of Au, Zr và Cu isotopes

Table.1. : Sample parameters of Au and Zr isotopes

Monitor	Size [mm]	Weight[g]	Thickness[mm]	Purity [%]
Au	9 x 9	0.1514	0.1	99.99
Au-cd	9 x 9	0.1494	0.1	99.99
Zr	10 x 9	0.0577	0.1	99.98
Zr-cd	10 x 9	0.0551	0.1	99.98

Nuclide	G_{th}	G_{epi}
^{197}Au	0.8837	0.2142
^{63}Cu	0.9659	0.6980
^{94}Zr	0.9997	0.9812

Table.2 The neutron self-shielding coefficients of some isotopes

Table.2 The neutron self-shielding coefficients of some isotopes

Isotopes	G_{th}	G_{epi}
^{197}Au	0.8837	0.2142
^{94}Zr	0.9997	0.9812

Gamma attentuation	**Deadti**
$\boldsymbol{F_g = \frac{\mu t}{1-e^{-\mu t}}}$	$\boldsymbol{F_{dt} =}$
where: $\boldsymbol{\mu}$ [1/cm]: linear attentuation factor $\boldsymbol{t}$: thickness of sample [mm]	v Δt[%