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Neutron Flux Stability Measurement of Miniature Neutron Source Research Reactors using 0.1%Au-Al Alloy and Pure Cu wires

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ABSTRACT

The need to ascertain the neutron flux stability after the recent installation of permanent 1.0 mm cadmium lined in the larger outer irradiation channel A-3 was performed in this work. The specific activity ratios, inner-to-outer channel of Nigeria Research Reactor-1 (i.e. A-1/B-4, B-2/B-4, and B-3/B4) were determined averagely to be 2.06 with a percentage deviation error of 4.63 %. The inner-to-outer with cadmium lined (i.e. A-1/A-3, B-2/A-3, B-3/A-3) was found on the average to be 22.66 with percentage deviation error of 1.58%. Also, the outer-to-outer with cadmium (i.e. A-2/A-3) was obtained to be 11.55 with percentage deviation error of -0.87%. The values of resonance-to-thermal cross section of the inner channels oscillate in a stable trend and for the outer channel B-4, it was observed to be good. These stable trends in the obtained nuclear data $I_0(\alpha)$ and $Q_0(\alpha)$ values and the specific activity ratios indicates that the neutron flux distributions after installation of a cadmium lined in one of the large outer irradiation channel have not been affected. Thus, a normal routine activation of samples in the channels will continue. The cadmium lined provides a good platform for implementation of epithermal and fast Neutron Activation Analysis in NIRR-1.

Keywords: Flux distribution, Cadmium lined, Specific Activity Ratio, MNSR, NIRR-1.

INTRODUCTION

The irradiation sites in the research reactor are usually used to irradiate and analyze unknown samples, using the neutron activation technique through (n, γ) thermal neutron reactions [1]. The inner and outer irradiation channels of the MNSR in Nigeria Research Reactor-1 (NIRR-1) contain the thermal, epithermal and fast neutron fluxes.

The NIRR-1 is specifically designed for use in neutron activation analysis (NAA) and isotope production; therefore there is need for a careful and complete evaluation of flux stability and neutron flux parameters in the irradiation channels in order to optimize its utilization for NAA via relative, absolute and single comparator methods [2]. Low-power research reactors such as the Canadian Slowpoke and the Chinese MNSR, which run on the same fuel loading for over ten years, are known to exhibit stable neutron flux characteristics, thus eliminating the need for standard material in the measurement of induced activity in samples [3].

Recently, a permanent cadmium (Cd) lined irradiation channel was installed in one of the large outer channel of the Nigeria Research Reactor-1 code name NIRR-1 for use in epithermal and fast Neutron Activation Analysis procedures. This will enable the performance of neutron dosimetry for radiation protection. However, stable fast neutron flux for threshold nuclear reactions involving the ejection of more than one nuclear particles such as (n, p), (n, α), and (n, 2n) and typical examples includes; $^{16}O(n, p)^{16}N$, $^{14}N(n, 2n)^{13}N$, $^{29}Si(n, p)^{29}Al$, $^{27}Al(n, p)^{27}Mg$ and $^{27}Al(n, \alpha)^{24}Na$ are essential in detection of metal contamination in soil, analysis of oxygen content in a wide variety of matrices including geologic materials, coal, liquid fuels, ceramic materials, petroleum derivatives, fractions and chemical reaction products [4]. Other elements that are routinely analyzed by fast neutrons include Ag, Al, Au, Si, P, F, Cu, Mg, Mn, Fe, Zn, As, and Sn [5]. The use of fast and epithermal neutron was only done after a 1mm thick cadmium lined was installed in the large outer irradiation channel (A-3). In this work an experimental approach of induced activity by neutrons on 0.1%Au-Al and pure certified copper wires were evaluated hand-to-hand with a theoretical modeling of the neutron induced activities within all the irradiation channels of NIRR-1.

2. Theory

The activation cross section behavior inferred as the probability of inducing an (n, γ) process is expressed [9] by the corresponding cross section σ [barn = $10^{-24}cm^2$]. The (n, γ) cross sections are typically proportional to 1/v with several resonances superposed on this general behavior [6]. The resonances, and also the '1/v'-tail, are described by the Breit-Wigner equation [7]. In most cases the resonances are situated in the epithermal energy region. Only a few (n, γ) reactions of interest in the neutron activation analysis (NAA) show a significant deviation from the 1/v-dependence in the energy region below 1.5 eV, due to low lying resonances [8].

The reaction rate per nucleus of isotopes undergoing a certain neutron flux is given by [6]

$$R = \int_0^\infty \Phi_{th}(E).\sigma_{th}(E)\,dE \qquad (1)$$

where R is in [s^{-1}], $\Phi_{th}(E)$ in [$cm^{-2}.s^{-1}$] and $\sigma(E)$ in [cm^2].

Going by the (extended) Hogdahl convention which is based on two principle ingredients: the proportionality of the neutron cross section to induce reaction with 1/v up to E_{Cd} and the $1/E^{1+\sigma}$ shape of the epithermal neutron spectrum ($E > E_{Cd}$) [8]. In view of the equivalence of the reaction rate representations by the Equation (1), the total reaction rate can in any case be written as [10]:

$$R = \int_0^{V_{Cd}} \Phi(v).\sigma(v)\,dv + \int_0^{\infty} \Phi(E).\sigma(E)\,dE \qquad (2)$$

with V_{Cd} the neutron velocity corresponding to E_{Cd}. When the Hogdahl conditions are met, this can be considerably simplified to [9]:

$$R = \sigma_0.v_0.\int_0^{V_{Cd}} n(v)\,dv + \Psi \qquad (3)$$

$$where\ \Psi = \Phi_e.(1eV)^{\alpha} \int_{E_{Cd}}^{\infty} \sigma(E)/E^{1+\alpha}\,dE$$

$$R = \Phi.\sigma_0 + \Phi_e.I_0(\alpha) \qquad (4)$$

The nuclear reactions employed for the investigation of flux stability via specific activity ratios analysis are as follows [11];

1. ^{63}Cu (n, γ) ^{64}Cu (1346 keV; $T_{1/2}$ = 12.7 hrs)
2. ^{197}Au (n, γ) ^{198}Au (411.80 keV; $T_{1/2}$ = 2.7days)
3. ^{27}Al(n, p)^{27}Mg (1014 keV, 843 keV; $T_{1/2}$ = 9.46mins)
4. ^{27}Al (n, α) ^{24}Na (1368.6 keV, $T_{1/2}$ = 14.96 hrs)

The theoretical validation of the activity ratios in NIRR-1 irradiation sites (where A-1, B-2, and B-3 are the inner channels, A-3 is the outer channel with cadmium lined and B-4 is the outer without cadmium lined), were accomplished through the Equations below:

$$A_{sp(A\text{-}1,B\text{-}2,B\text{-}3)} = \Phi_{th}.\sigma_{th} + \Phi_{epi}.I_0(\alpha) \qquad (5)$$

$$A_{sp(A\text{-}3)}\,(\text{Cd-lined}) = \Phi_{Cd(epi)}.I_0(\alpha) \qquad (6)$$

$$A_{sp(B\text{-}4)} = \Phi_{th}.\sigma_{th} + \Phi_{epi}.I_0(\alpha) \qquad (7)$$

The neutron shaping factor (α), thermal-to-epithermal neutron flux ratio (*f*), thermal flux (Φ_{th}) and epithermal flux (Φ_{epi}) for all the NIRR-1 irradiation channels were evaluated following the approach of [3] and results shown in Table 1.

Table 1: Experimental Nuclear Data Employed in this work for NIRR-1

Irradiation Channels	*(f)*	(α)	Φ_{th} ($ncm^{-2}s^{-1}$)	Φ_{epi} ($ncm^{-2}s^{-1}$)
A-1 (inner)	18.4±0.34	0.046±0.005	5.00E+11	2.78E+10
B-2 (inner)	19.2±0.50	0.052±0.002	4.89E+11	2.55E+10
B-3 (inner)	19.1±0.04	0.048±0.004	4.99E+11	2.61E+10
A-3 (Cd-lined)	0.00001	0.024±0.002	4.22E+04	2.38E+10
B-4 (outer)	48.3±3.30	0.029±0.003	2.25E+11	1.39E+10

Thus, to be accurate in all relevant expressions, Q_o should be replaced by $Q_o(\alpha)$ (where $Q_o(\alpha)$ is the *α*-corrected Q_o to take care of the non-ideality of the epithermal spectrum)

$$Q_0(\alpha) = \frac{I_0}{\sigma_{th}}\left(\frac{Q_0 - 0.429}{E_\gamma^\alpha} + \frac{0.429}{(2\alpha+1).E_{Cd}^\alpha}\right) \quad (8)$$

Also, the non-ideal reactor situation, in which the resonance integral, I_o, needs to be modified with an α-dependent term because the I_o values, which are valid only for ideal spectra, is not true for a deviating spectra [4]. For the non-ideal conditions $I_o(\alpha)$ values ought to be used instead of I_o. The conversion of I_o to α-dependent terms takes the form [5]:

$$I_0(\alpha) = \left(\frac{I_0 - 0.429.\sigma_{th}}{E_\gamma^\alpha} + \frac{0.429.\sigma_{th}}{(2\alpha+1).E_{Cd}^\alpha}\right).E_a^\alpha$$
$$I_0(\alpha) = \int_{E_{Cd}}^{\infty} \alpha(E)\frac{E_a^\alpha}{E^{1+\alpha}}\mathrm{d}E \quad (9)$$

where E_γ^α = effective resonance energy, E_a^α = l eV – arbitrary energy, E_{Cd}^α = 0.55 eV – effective cadmium cut-off energy, σ_{th} = 2200 ms^{-1} (n, γ) Cross section and α = an experimentally determinable characteristics of the reactor channel. The results of evaluated $Q_o(\alpha)$ and $I_o(\alpha)$ values for ^{198}Au, ^{27}Mg, ^{24}Na, and ^{64}Cu and used in this work are shown in Table 2 and 3 below.

Table 2: Experimental obtained Resonance integral to thermal cross section of Au, Mg, Na, and Cu in NIRR-1 irradiation channels

Irradiation Positions	A-1 [Inner]	A-3 [Cd-lined Outer]	B-2[Inner]	B-3 [Inner]	B-4 [Outer]
Pro-Isotope	^{198}Au	^{198}Au	^{198}Au	^{198}Au	^{198}Au
Reaction	^{197}Au(n γ)	^{197}Au(n γ)	^{197}Au(n γ)	^{197}Au(n γ)	^{197}Au(n γ)
$Q_0(\alpha)$ [A]	17.03	15.05	17.21	17.09	14.92
Pro-Isotope	^{27}Mg	^{27}Mg	^{27}Mg	^{27}Mg	^{27}Mg
Reaction	^{27}Al(n p)	^{27}Al(n p)	^{27}Al(n p)	^{27}Al(n p)	^{27}Al(n p)
$Q_0(\alpha)$ [B]	0.79	0.53	0.82	0.79	0.52
Pro-Isotope	^{24}Na	^{24}Na	^{24}Na	^{24}Na	^{24}Na
Reaction	^{27}Al(n α)	^{27}Al(n α)	^{27}Al(n α)	^{27}Al(n α)	^{27}Al(n α)
$Q_0(\alpha)$ [C]	0.73	0.54	0.75	0.74	0.53
Pro-Isotope	^{64}Cu	^{64}Cu	^{64}Cu	^{64}Cu	^{64}Cu
Reaction	^{63}Cu(n γ)	^{63}Cu(n γ)	^{63}Cu(n γ)	^{63}Cu(n γ)	^{63}Cu(n γ)
$Q_0(\alpha)$ [D]	1.41	0.97	1.46	1.42	0.95

Therefore, theoretical validation making used of Table 2 and 3 of specific activity ratio of inner-to-outer was evaluated dividing Equation 5 and 7;

$$\frac{A_{sp(A-1,B-2,B-3)}}{A_{sp(B-4)}} = \frac{\left[\Phi_{th}.\sigma_{th} + \Phi_{epi}.I_0(\alpha)\right]_a}{\left[\Phi_{th}.\sigma_{th} + \Phi_{epi}.I_0(\alpha)\right]_b} \quad (10)$$

where $\left(\Phi_{th}\right)_a = 2\left(\Phi_{th}\right)_b$ (11)

$\left(\Phi_{epi}\right)_a = 2\left(\Phi_{epi}\right)_b$ (12)

Table 3: Experimental obtained Resonance Integral of Au, Mg, Na, and Cu in NIRR-1 irradiation channels

Irradiation Positions	A-1 [Inner]	A-3 [Cd-lined Outer]	B-2[Inner]	B-3 [Inner]	B-4 [Outer]
Pro-Isotope	^{198}Au	^{198}Au	^{198}Au	^{198}Au	^{198}Au
Reaction	^{197}Au(n γ)	^{197}Au(n γ)	^{197}Au(n γ)	^{197}Au(n γ)	^{197}Au(n γ)
$I_0(\alpha)$ [E]	1680.81	1485.41	1698.77268	1686.77852	1472.39282
Pro-Isotope	^{27}Mg	^{27}Mg	^{27}Mg	^{27}Mg	^{27}Mg
Reaction	^{27}Al(n p)	^{27}Al(n p)	^{27}Al(n p)	^{27}Al(n p)	^{27}Al(n p)
$I_0(\alpha)$ [F]	0.029	0.02	0.02987479	0.029094889	0.01884306
Pro-Isotope	^{24}Na	^{24}Na	^{24}Na	^{24}Na	^{24}Na
Reaction	^{27}Al(n α)	^{27}Al(n α)	^{27}Al(n α)	^{27}Al(n α)	^{27}Al(n α)
$I_0(\alpha)$ [G]	0.38	0.28	0.38722697	0.380104348	0.27374365
Pro-Isotope	^{64}Cu	^{64}Cu	^{64}Cu	^{64}Cu	^{64}Cu
Reaction	^{63}Cu(n γ)	^{63}Cu(n γ)	^{63}Cu(n γ)	^{63}Cu(n γ)	^{63}Cu(n γ)
$I_0(\alpha)$ [H]	5.61	3.87	5.79835444	5.671271229	3.76937146

From Table 1, the ratio of thermal and epithermal neutron fluxes for inner channels A-1 and outer channel B-2 is 2:1. Therefore Equation (10) becomes;

$$\frac{A_{sp(A-1,B-2,B-3)}}{A_{sp(B-4)}} = \frac{2\left[\left(\Phi_{th}\right)_b.\left(\sigma_{th}\right)_a + \left(\Phi_{epi}\right)_a.\left[I_0(\alpha)\right]_a\right]}{\left(\Phi_{th}\right)_b.\left(\sigma_{th}\right)_b + \left(\Phi_{epi}\right)_b.\left[I_0(\alpha)\right]_b} \quad (13)$$

In reference to nuclear reaction 1, the neutron flux relationship between inner channel [a] and outer channel [b] indicated in the relation below,

$\left(\sigma_{th}\right)_a = \left(\sigma_{th}\right)_b$ and $\frac{\left(\Phi_{epi}\right)_b}{\left(\Phi_{th}\right)_b} = f^{-1}$, Equation (13) becomes;

$$\frac{A_{sp(A-1,B-2,B-3)}}{A_{sp(B-4)}} = \frac{\left(2+2f^{-1}.I_0(\alpha)\right)_a}{\left(1+f^{-1}.I_0(\alpha)\right)_b}$$

$$\frac{A_{sp(A-1,B-2,B-3)}}{A_{sp(B-4)}} = \frac{2\left(f_{av}+I_0(\alpha)\right)_a}{\left[f_{av}+I_0(\alpha)\right]_b} = 2.16 \quad (14)$$

where f_{av} is average value of the thermal to epithermal flux ratio for A-1, B-2 and B-3 while $\left[\mathrm{I}_0(\alpha)\right]_a$ and $\left[\mathrm{I}_0(\alpha)\right]_\mathrm{b}$ are obtained from Table 3 row-**[H]** specifically with respect to nuclear reaction 1 above.

Similarly, the ratio of inner-to-outer with cadmium was validated by dividing Equation 5 and 6 as follows;

$$\frac{\mathrm{A_{sp(}}_{A-1,B-2,B-3)}}{\mathrm{A_{sp(}}_{A-3)}\ \text{(Cd-lined)}} = \frac{\left[\Phi_{th}\cdot\sigma_{\mathrm{th}} + \Phi_{\mathrm{epi}}\cdot I_o(\alpha)\right]_\mathrm{a}}{\left[\Phi_{\mathrm{epi}}\cdot I_0(\alpha)\right]_{\text{b-Cd-lined}}} \qquad (15)$$

$$\frac{\mathrm{A_{sp(}}_{A-1,B-2,B-3)}}{\mathrm{A_{sp(}}_{A-3)}\ \text{(Cd-lined)}} = \frac{\left[\Phi th + \Phi_{\mathrm{epi}}\cdot Q_0(\alpha)\right]_\mathrm{a}}{\left[\Phi_{\mathrm{epi}}\cdot Q_0(\alpha)\right]_{\text{b-Cd-lined}}} \qquad (16)$$

$$\frac{\mathrm{A_{sp(}}_{A-1,B-2,B-3)}}{\mathrm{A_{sp(}}_{A-3)}\ \text{(Cd-lined)}} = \frac{\left(\Phi_{\mathrm{epi}}\right)_\mathrm{a}\cdot\left[\left(f + Q_o(\alpha)\right)\right]_\mathrm{a}}{\frac{\left(\Phi_{\mathrm{epi}}\right)_\mathrm{a}}{1.10}\cdot\left[Q_0(\alpha)\right]_{\text{b-Cd-lined}}}$$

$$\frac{\mathrm{A_{sp(}}_{A-1,B-2,B-3)}}{\mathrm{A_{sp(}}_{A-3)}\ \text{(Cd-lined)}} = \frac{\left[1.10\times\left(f_{av} + Q_o(\alpha)\right)\right]_\mathrm{a}}{\left[Q_o(\alpha)\right]_{\text{b-Cd-lined}}} = 23.02 \qquad (17)$$

where subscript 'a' and 'b' represent inner and outer irradiation channels, f_{av} is the average value of thermal to epithermal neutron flux ratio for A-1, B-2, B-3 and $\left[Q_o(\alpha)\right]_\mathrm{a}$ and $\left[Q_o(\alpha)\right]_{\text{b-Cd-lined}}$ are obtained from Table 1 and 2, row-**[D].** In like manner, the theoretical evaluated specific activity values for inner-to-inner, outer-to-outer where obtained to be one (1) while between outer-to-outer with Cd-lined was found to be 11.45.

3. Experiment

The theory behind the experiment was base of the fact that detected peak intensities of irradiated samples under investigation depend solely on the induced activities. Thus, the specific intensity A_{sp} is obtained from the relation below [11]:

$$A_{sp} = \left(\phi_{th}\sigma_{th} + \phi_{ep}I_0\right)\frac{N_{av}}{M}P_i f_\gamma \varepsilon_p = \frac{N_p/t_m}{SDCm} \qquad (18)$$

Therefore, for irradiation channels; A-1, B-2, B-3, and B-4, the expression $A_{bare} = \dfrac{N_p/t_m}{SDCm}$ was employed, while for A-3 the expression $A_{Cd-lined} = \dfrac{\left(N_p\right)_{Cd}/t_m}{SDCm}$ was used.

where A_{bare} = activity of non shield monitored foils and, A_{Cd} = activity of Cd-lined channel of monitored foils, S = saturated factor $\left(1-e^{\lambda t_i}\right)$, D = decay factor $\left(e^{-\lambda t_d}\right)$, C = counting factor $\left(\frac{1-e^{-\lambda t_m}}{\lambda t_m}\right)$, m = mass of the monitored foils.

The miniature neutron source reactor, NIRR-1 was operated at half power of 15.5kW at a neutron thermal flux rate of 5.0E+11 n/cm^{2}s in the inner channels and 2.5 E+11 n/cm^{2}s for the outer channels [2]. The vials used were of 1mm wall thickness, 1 cm diameter, and 3cm length used for inner irradiations channels while 1mm wall thickness, 2.5 cm diameter, and 3 cm length for outer irradiation channels. Two monitors made of 0.1% Au-Al foil alloy; 0.1 mm thick, IRRM-530; weight from 0.0129 to 0.0134g were irradiated in A-3 and B-2 of NIRR-1 to check absolute neutron flux distribution. The irradiation time in B-2 lasted thirty minutes while in A-3 two hours. A waiting time of 1140 seconds was observed for the irradiation in B-2 before 60 seconds measurement was performed for the first gamma-ray measurements at 17cm from the HPGe detector's end-cap. After a waiting time of 76740seconds, the irradiated 0.1%Au-Al foil in B-2 was re-measured at 2cm position from the detector for 1800 seconds. We determined the specific activity in A-1, A-3, B-2, B-3, and B-4 based on the nuclear reactions 1-5 above. For the measurement of flux stability, five Cu wires of weights 0.0987g to 0.1388g were irradiated in channels; A-1, A-3, B-2, B-3, and B-4 based on two experimental procedures. This was aimed at maximizing precision and accuracy. The details about the procedures are summarized in Table 4-6 below.

Table 4: Average values of Specific activity (Bq/kg) of Cu wires obtained at different experimental procedures [a] and [b] for all used channels in NIRR-1

Irradiation Positions	A-3 Outer	B2 Inner	B3 Inner	B4 Outer	A1 Inner
Sample ID [a]	069M176	069M178	069M180	069M182	069M184
Sample ID [b]	069M163	069M167	069M171	069M165	069M169
Peak Energy (keV)	1346	1346	1346	1346	1346
Irradiation time (sec) [a]	300	60	60	600	199
Irradiation time (sec) [b]	300	60	60	120	60
Measuring time (sec) [a]	300	300	600	600	600
Measuring time (sec) [b]	600	600	600	600	600
Specific Activity (A_{sp}) [a]	1987.00	36631.74	45398.67	19570.72	39286.89
Specific Activity (A_{sp}) [b]	1870.41	40970.14	42453.39	20905.87	45214.85
Average Specific Activity	1828.70	38800.94	43926.03	21238.29	42250.87

Table 5: Values of Specific activity for $^{27}Al(n,p)^{27}Mg$ obtained in B-2 and A-3 of NIRR-1

Irradiation Positions	B-2 *	A-3 *	B-2 **	A-3 **
Sample ID	069M186	069M188	069M186	069M188
Weight	0.0129	0.0134	0.0129	0.0134
Peak Energy (keV)	1014	1014	1368.6	1368.6
Irradiation time (sec)	1800	7200	1800	7200
Waiting time (sec)	1140	480	76740	75120
Measuring time (sec)	600	600	1800	1800
Reaction	$^{27}Al(n,p)^{27}Mg$	$^{27}Al(n,p)^{27}Mg$	$^{27}Al(n,p)^{27}Mg$	$^{27}Al(n,p)^{27}Mg$
Specific Activity (A_{sp})	2163.718227	253.5546978	13801.99643	1945.249988

Table 6: Specific activity values for $^{197}Au(n, \gamma)^{198}Au$ obtained in B-2 and A-3 of NIRR-1

Irradiation Positions	B-2 *	A-3 *	B-2 **	A-3 **
Sample ID	069M186	069M188	069M186	069M188
Weight	0.0129	0.0134	0.0129	0.0134
Peak Energy (keV)	411.8	411.8	411.8	411.8
Irradiation time (sec)	1800	7200	1800	7200
Waiting time (sec)	1140	480	76740	75120
Measuring time (sec)	600	600	1800	1800
Reaction	$^{197}Au(n,\gamma)^{198}Au$	$^{197}Au(n,\gamma)^{198}Au$	$^{197}Au(n,\gamma)^{198}Au$	$^{197}Au(n,\gamma)^{198}Au$
Specific Activity (A_{sp})	421037.5063	31840.74768	5714584.957	460734.7741

** stands for first counting on HPGe detector, ** stands for second counting, [a] represent first experimental procedures, [b] represent second experimental set up.*

Table 7: Specific Activity Ratios between Irradiation Channels of NIRR-1

NIRR-1 Channel Ratio Relationship	Experimental (Specific Activity Ratios)	Theoretical (Specific Activity Ratios)	Percentage deviation (%)
Inner-to-inner (A1/B2)	1.09	1.02	-6.86
Inner-to-inner (B3/B2)	1.13	1.02	-10.78
Inner-to-inner (A1/B3)	0.96	1.02	5.88
Inner-to-outer (A1/B4)	2.09	2.16	3.24
Inner-to-outer (B2/B4)	1.92	2.16	11.11
Inner-to-outer (B3/B4)	2.17	2.16	-0.46
Inner-to-outer Cd-liner (A1/A3)	22.98	23.02	0.17
Inner-to-outer Cd-liner (B2/A3)	21.10	23.02	8.34
Inner-to-outer Cd-liner (B3/A3)	23.89	23.02	-3.78
Outer-to-outer Cd-liner (B4/A3)	11.55	11.45	-0.87

RESULTS AND DISCUSSION

Results of the experimental values (Table 2 & 3) of $Q_0(\alpha)$ and $I_0(\alpha)$ for ^{198}Au, ^{27}Mg, ^{24}Na, and ^{64}Cu obtained in A-1, A-3, B-2, B-3, and B-4 shows a very stable trend along the inner and outer channels. For the inner channels; A-1, B-2, and B-3, the values of $Q_0(\alpha)$ for the above mention isotopes revolved around 17-17.2 for ^{198}Au, 0.79-0.82 for ^{27}Mg, 0.73-0.75 for ^{24}Na, and 1.41-1.46 for ^{64}Cu while for $I_0(\alpha)$, the values for ^{198}Au, ^{27}Mg, ^{24}Na, and ^{64}Cu oscillate around 1680.81-1686.78, 0.028-0.029, 0.38-0.039, and 5.61-5.79 respectively. However, for the outer channel B-4, the values of $Q_0(\alpha)$ for ^{198}Au was 14.92 , ^{27}Mg was 0.52, ^{24}Na was 0.53 and ^{64}Cu was 0.95 and the $I_0(\alpha)$ for the above mentioned elements were 1472.39, 0.02, 0.27, and 3.67 respectively. Basically, the results obtained in the Cd-lined channel are indicated in Table 2 and 3 while the maximum value of $Q_0(\alpha)$ was obtained to be 15.05 for ^{198}Au and minimum of 0.53 for ^{27}Mg.

Results shown in Table 7, indicates that the specific activity ratios, inner-to-inner (i.e. A-1/B-2, B-2/B-3, and A-1/B-3) were found to be equal to 1.07, 1.08, and 1.09 respectively. Averagely these values yield 1.06 with percentage error of -3.92% compared well to the theoretical calculated value of 1.02 with deviation error of -0.058 %. From Table 7, the specific activity ratios, inner-to-outer (i.e. A-1/B-4, B-2/B-4, and B-3/B4) were determined to be 2.09, 1.92, and 2.17 respectively. On the average we obtained 2.66 (4.63%) which agreed very well with the theoretical calculated value of 2.16 obtained from Equation 17. However, the specific activity ratios, of inner-to-outer with cadmium (i.e. A-1/A-3, B-2/A-3, B-3/A-3) were found to be 22.98, 21.10, and 22.98 respectively. On the average we obtained 22.66 (1.58%) against 23.02 from theoretical evaluation (Equation 14). However, the outer-to-outer with cadmium (i.e. A-2/A-3) was obtained to be 11.55 (-0.87%) against 11.45. In general, there was a hallmark trend in the specific activity ratios of 2:1 inner-to-inner: outer-to-outer and inner-to-outer with Cd: outer-to-outer with Cd.
All these values (Table 2, 3, and 7) indicated that the neutron flux distributions have not been affected by the installation of the cadmium lined in the outer channel A-3. The absolute values of epithermal and fast neutron flux in the cadmium lined channel provide the platform for implementation of epithermal and fast Neutron Activation Analysis in NIRR-1.

CONCLUSION

Using 0.1%Au-Al alloy and cu wires to measure the specific activity ratios of (n γ), (n p) and (n α) reactions, the stability of the neutron fluxes of the Nigeria research Reactor-1 (NIRR-1) was established in this work. This work confirmed the fact that the stability of the neutron flux is one of the hallmarks of NIRR-1 and similar facilities, which run on same fuel loading for over 10 years such as the miniature neutron source reactor, design by the Chinese, has good neutron flux stability over long periods of time since the NIRR-1 has been in operation for more than seven (7) years. This has also been confirmed by the Neutron Shaping Factor (α) obtained as well as the resonance-to-thermal cross section $Q_0(\alpha)$ and the resonance integral data $I_0(\alpha)$ for all channels appear to be very stable. This work however, confirmed the installation of Cd-lined in A-3 and has basically expanded the margin scope of elemental investigation in all ramifications. Therefore, allows convenient neutron activation analysis of all elements of interest in any of the

channels A-1, A-3, B-2, B-3 and B-4 without the need to continually repeat the standardization measurements for all elements.

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