Characterization of the NAA#3 Irradiation Hole at the HANARO Research Reactor for the k_0-NAA Method

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1. Introduction

In the implementation of the k_0-based neutron activation analysis (k_0-NAA), there are two key experimental performances, i.e. the characterization of the neutron irradiation facility and the calibration of the gamma-ray spectrometer. The characterization of the irradiation facility is to determine the neutron spectrum parameters at the irradiation hole. The neutron spectrum parameters considered in this context are the deviation of the epithermal neutron flux distribution from the ideal $1/E$ law by a $1/E^{1+\alpha}$ shape (α), the ratio of the thermal to epithermal neutron flux (f), the ratio of the thermal to fast neutron flux (f_F) to evaluate interferences by threshold reactions [1], the neutron temperature (T_n) used for nuclides with the Westcott's g-factor different from unity [2,5]. The neutron spectrum parameters change with the reactor configuration and the irradiation hole position. Therefore, the characterization of the NAA#3 irradiation hole at the HANARO reactor is required once applying the k_0-NAA method.

2. Theory

2.1. Deviation of the Epithermal Neutron Distribution

The determination of α by the "bare triple-monitor" method [1,4] with a set of three monitors numbered "1", "2" & "3" is expressed as follows,

$$(a-b)Q_{0,1}(\alpha)G_{e,1}/G_{th,1} - aQ_{0,2}(\alpha)G_{e,2}/G_{th,2} + bQ_{0,3}(\alpha)G_{e,3}/G_{th,3} = 0 \qquad (1)$$

With

$$a = \left\{1 - \frac{A_{sp,2}}{A_{sp,1}} \cdot \frac{k_{o,Au}(1)}{k_{o,Au}(2)} \cdot \frac{\varepsilon_{p,1}}{\varepsilon_{p,2}}\right\}^{-1} \qquad (2)$$

$$b = \left\{1 - \frac{A_{sp,3}}{A_{sp,1}} \cdot \frac{k_{o,Au}(1)}{k_{o,Au}(3)} \cdot \frac{\varepsilon_{p,1}}{\varepsilon_{p,3}}\right\}^{-1} \qquad (3)$$

2.2. Ratio of the Thermal to Epithermal Neutron Flux

The f can be determined by the "bare bi-isotopic monitor" method [1,4] using a zirconium monitor with reactions "1" = ^{96}Zr(n,γ)^{97}Zr/^{97m}Nb and "2" = ^{94}Zr(n,γ)^{95}Zr as follows,

$$f = \frac{G_{e,1}\frac{k_{0,Au}(1)}{k_{0,Au}(2)} \cdot \frac{\varepsilon_{p,1}}{\varepsilon_{p,2}} \cdot Q_{0,1}(\alpha) - G_{e,2}\frac{A_{sp,1}}{A_{sp,2}} \cdot Q_{0,2}(\alpha)}{G_{th,2}\frac{A_{sp,1}}{A_{sp,2}} - G_{th,1}\frac{k_{0,Au}(1)}{k_{0,Au}(2)} \cdot \frac{\varepsilon_{p,1}}{\varepsilon_{p,2}}} \qquad (4)$$

2.3. Ratio of Thermal to Fast Neutron Flux

A threshold monitor (F) and a thermal monitor (T) should be co-irradiated for the reactions of F(n,x)G* [x = p, n', 2n, etc], and T(n,γ)T*,

$$f_F = \frac{A_{sp,T^*}}{A_{sp,G^*}} \times \frac{M_T \theta_F \overline{\sigma}_{r,F} \gamma_{G^*}}{M_F \theta_T \sigma_{o,T} \gamma_{T^*}} \times \frac{f}{f + Q_{o,T}(\alpha)} \times \frac{\varepsilon_{p,G^*}}{\varepsilon_{p,T^*}} \qquad (5)$$

where, $\overline{\sigma}_r$ is the ^{235}U fission-neutron averaged cross-section [1].

2.4. Westcott Formalism

The Høgdahl convention is restricted to the (n,γ) cross sections that follow the "1/v" law in the thermal neutron energy region for which Westcott's $g(T_n)$-factor, a function of the neutron temperature is equal to unity. This convention excludes a handling of the "non-1/v" (n,γ) reactions of nuclides with $g(T_n) \neq 1$. In the modified Westcott system the nuclear reaction rate for the (n,γ) reaction is written in the form [1]:

$$R = n v_0 \sigma_0 [G_{th} g(T_n) + G_e r(\alpha)\sqrt{T_n/T_0} \cdot s_0(\alpha)] \qquad (6)$$

with, $r(\alpha)\sqrt{T_n/T_0}$ is the modified spectral index.

3. Experimental

The location of the NAA#3 irradiation hole at the HANARO research reactor is shown in Fig. 1.

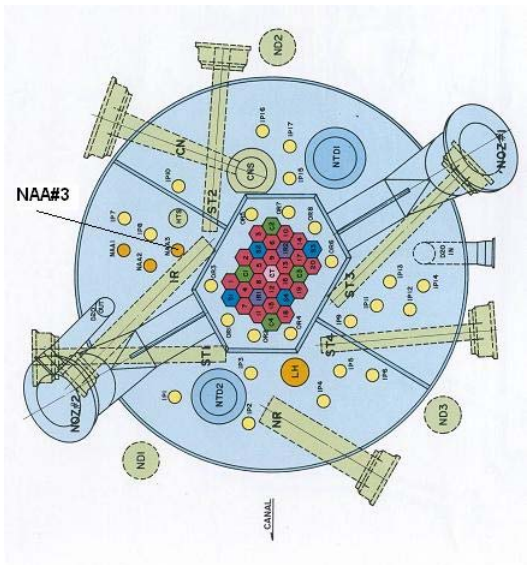

Fig. 1. Location of the NAA#3 irradiation hole on the HANARO research reactor

Monitors of Al-0.1% Au and Al-0.1% Lu in a wire shape produced by IRMM with weights of about 5 mg along with Zr and Ni foils with weights of about 10 mg were irradiated at the NAA#3 irradiation hole for 1 minute. After a decay time of 1 day, the Ni monitor was measured, and after a decay time of 2 to 3 days, the Au, Zr and Lu monitors were also measured on the calibrated gamma-ray spectrometer with counting times for the monitors from 0.5 to 2 hours.

The α and f were calculated by the "bare" irradiation method using ^{198}Au, ^{95}Zr and ^{97}Zr nuclides. The f_F was calculated by ^{198}Au and ^{58}Co nuclides induced by the ^{58}Ni(n, p) reaction. The T_n was calculated by ^{198}Au and ^{177}Lu nuclides via Westcott's factor [$g(T_n)$] for Lu, the modified spectral index $r(\alpha)\sqrt{T_n/T_0}$ and the ratio of the modified reduced resonance integral to the 2200 m/s cross section [$s_0(\alpha)$]. Table 1 shows the results of the neutron spectrum parameters determined experimentally at the NAA#3 irradiation hole of the HANARO reactor.

4. Results and Discussion

Table 1. Neutron spectrum parameters of the NAA#3 irradiation hole on the HANARO research reactor (unit n.cm^{-2}.s^{-1} for neutron fluxes).

Parameters	Mean*	±	SD*
α	0.155	±	0.052
f	84	±	7
f_F	1.4	±	0.2
T_n (^{o}C)	20	±	5
A_{sp}(Au)/ε_p	4.151×10^{13}	±	4.255×10^{11}
Φ_{th}	1.262×10^{14}	±	2.892×10^{12}
Φ_{epi}	1.495×10^{12}	±	4.691×10^{11}
Φ_f	9.057×10^{11}	±	1.697×10^{11}

*Mean and standard deviation (SD) values were obtained by three independent determinations.

The results of the determination of the neutron spectrum parameters in which the α, f, f_F and T_n values vary relatively largely from 8% to 33% (according to irradiations). However, the variation has no considerably affects on the final result of the calculation of the concentration because the error propagation of the parameters is in an indirect manner. It is an important impact for parameters that the error propagation is in a direct manner, i.e. the specific counting rate A_{sp}(Au) and the thermal neutron flux Φ_{th}. Therefore, as shown in Table 1, the A_{sp}(Au) and Φ_{th} are rather stable with a variation of only about 1-2%. The overall error of the neutron spectrum parameters being able to contribute to the concentration result is about 1-3.5%.

5. Conclusions

The neutron spectrum parameters such as α, f, f_F and T_n along with $r(\alpha)\sqrt{T_n/T_0}$ were determined at the NAA#3 irradiation hole of the HANARO research reactor. The preliminary results indicated that the neutron spectrum parameters at the NAA#3 irradiation hole have an acceptable quality for the application of the k_0-NAA method [3].

These neutron spectrum parameters were used for the determination of the elemental concentrations by the k_0-NAA method in some certified reference materials to evaluate the accuracy of the method which was found to be rather good with a relative accuracy generally within 12%.

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