Measurement of the Westcott Conventionality Thermal Neutron Flux and Suchlike at Irradiation Facilities of the KUR

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The thermal neutron flux and the epithermal index, i.e., the strength of the epithermal *dE/E* component relative to the neutron density including both thermal and epithermal neutrons, at the hydraulic conveyer (Hyd), pneumatic tube No. 2 (Pn-2) and slant exposure tube (Slant), i.e., principal exposure facilities of the Kyoto University Reactor (KUR), are measured by the multiple foil activation method using the Au(n, γ)Au-198 and Co(n, γ)Co-60(g+m) reactions. Although neutron flux varies with core configuration et al., e.g., number of fuel elements, the available values at Hyd are that the thermal neutron flux is $(1.07\pm0.03)\times10^{14}\,cm^{-2}sec^{-1}$, the epithermal index is 0.0373 ± 0.0009 and the fast neutron flux is $(3.8\pm0.2)\times10^{13}\,cm^{-2}sec^{-1}$. Moreover, thermal and fast t neutron flux distributions are low at the top and high at the bottom of an Al irradiation capsule of Hyd. The gradient is 14 % / 8 cm in height. The distributions in the horizontal direction are flat with a 2.2 cm diam.

1. Introduction

There are some experimental holes and irradiation facilities in the KUR for practicing various experiments. The irradiation facilities are used for the production of radioisotopes (RI), radioactive analysis, material testing, cross-section measurement and so forth. Therefore, determination of the neutron flux is of great importance for evaluating or predicting the activity or neutron fluence, i.e., flux time. Furthermore, recently, studies on nuclear transmutation management have been actively carried out. Concerning the experiments using reactors, measurement of the (n, γ) cross sections is required. In particular, when the (n, γ) reaction cross sections, normally listed values, are measured, it is necessary to determine the 2200 m sec^{-1} neutron flux. Accordingly, the Westcott conventionality thermal neutron flux [1], epithermal index and so forth are studied at Hyd: at the center of the KUR core, Pn-2: in the graphite reflectors and Slant: outside the reflectors; configurations of the facilities are illustrated in Figs. 1 and 2.

Furthermore, neutron flux distributions of thermal+epithermal (sum of thermal and epithermal) and fast in the irradiation capsules are measured. These distributions are useful for discussing the ununiformity of activation or setting up monitor foils for the measurement of the cross-sections.

2. Westcott conventionality thermal neutron flux using multiple foil activation method

According to the convention proposed by Westcott et al.[1], the effective cross section $\hat{\sigma}$ in the well-moderated thermal neutron reactors is expressed as

$$\hat{\sigma} = \sigma_0 (g + rs) \ , \tag{1}$$

where σ_0 is a 2200 m sec^{-1} cross section, g and s are functions of the temperature T and are measures of the departure of the cross-section law from the $1/v$ form in the thermal and epithermal regions, respectively. The former factor is the Westcott g-factor, which is tabulated by Westcott [2]; r is the epithermal index. If the cross section obeys a $1/v$ law, $g = 1$ and $s = 0$. Furthermore, s is defined as

$$s = \frac{1}{\sigma_0} \sqrt{\frac{4}{\pi} \frac{T}{T_0}} \ I'_0 \ , \tag{2}$$

where T_0 is the room temperature 293.6 K, and I_0' is a reduced resonance integral which is obtained by subtracting the $1/v$-term from an excess resonance integral I_0, which is given by $I'_0 = I_0 - 0.45\sigma_0$, if cadmium cutoff energy E_{Cd} is 0.5 eV.

Therefore, the reaction rate will have the form [3]

$$R = nv_0\sigma_0 \left(gG_{th} + r\sqrt{T/T_0}\, s_0 G_{epi} \right). \tag{3}$$

Here, n is the neutron density including both thermal and epithermal neutrons, and v_0 is 2200 m sec^{-1}. G_{th} and G_{epi} are the corrections of self-shielding for thermal and epithermal neutrons, respectively, and these are described in the following. G_{th} is calculated using [4]

$$G_{th} = \frac{1 - 2E_3(\tau_0)}{2\tau_0}, \qquad (\tau_0 = \Sigma_a t), \tag{4}$$

where E_3 is the exponential integral, Σ_a is the macroscopic absorption cross-section for 2200 m sec^{-1} neutrons, and t is the thickness of the detector. Moreover, Beckurts and Wirtz [5] propose a simple approximation for G_{epi} as

$$G_{epi} = \frac{1}{\sqrt{1 + 2\mu_{a_0}\delta}}\ , \tag{5}$$

where μ_{a0} is the mass absorption coefficient at the peak of a resonance and δ is the surface mass loading. s_0 is the invariant quantity of s and is expressed as $s_0 = s\sqrt{\frac{T_0}{T}} = \frac{1}{\sigma_0}\sqrt{\frac{4}{\pi}}\ I'_0$ [6]. Furthermore, to divide Eq. (3) by $\sigma_0 g G_{th}$,

$$\frac{R}{\sigma_0\, gG_{th}} = nv_0 + nv_0 r\sqrt{T/T_0}\,\frac{s_0 G_{epi}}{gG_{th}}. \tag{6}$$

Equation (6) is a linear equation accompanied by an intercept nv_0 (Westcott thermal neutron flux) and an inclination $nv_0 r\sqrt{T/T_0}$ (epithermal neutron flux). Exactly the same equation having a common intercept and inclination will be formed for the Au(n, γ)Au-198 and Co(n, γ)Co-60(g+m) reactions, if Au and Co are irradiated at the same time and at the same position [3].

Table 1 Nuclear data and parameters used

Reaction	σ_0 (barns) [7]	I_0 (barns) [7]	g (at 40°C)	G_{th}	G_{epi}
Au(n, γ)Au-198	98.65±0.09	1550±28	1.0064 [2]	0.999	0.992
Co(n, γ)Co-60(g+m)	37.18±0.06	74±2	1	0.999	0.997

3. Experimental

The activation detectors used were 0.1143%Au-Al alloy foils, 0.0314%Au-Al alloy wires and 0.483%Co-Al alloy foils. Therefore, $G_{th} \approx G_{epi} \approx 1$, since these detectors can be approximated to infinite dilution. In the case of Hyd, several tens mg of Au-Al and Co-Al were hermetically enclosed in a 5-mm-diameter quart tube, set in an Al capsule, and then irradiated at 5000 kW for 10 min. Induced activities were measured using calibrated high-purity Ge detectors (HPGe). Moreover, fast neutron fluxes were measured using the Ti(n,p)Sc-47 or that of -48 reactions. Arrangements of the detectors in the capsules for all the cases have been shown elsewhere [8, 9].

4. Results and discussion

Appearances of Eq. (6) for these three facilities are shown in Fig. 3. Results of the thermal neutron fluxes and so forth are tabulated in Table 2. The epithermal index varies from 0.011 to 0.047 depending on the facilities. It is clarified that by making the most of the distinctive qualities of each facility, measurement of the (n, γ) effective cross sections for various epithermal indexes is possible. Therefore, the effective cross section at $r\sqrt{T/T_0} = 0$, i.e., at the Maxwellian component only, on the extension line connecting two effective cross-sections measured at different facilities, will be available [10].

Relative distributions of the "thermal+epithermal" and the fast neutron fluxes in the irradiation capsules are shown in Figs. 4, 5 and 6. In these figures, thermal+epithermal distribution simply means the relative reaction rate of the Au(n, γ); therefore, in the cases of Hyd, Pn-2 and Slant, respectively, approximately 60, 70 and 17 % of the reaction rates are caused by epithermal neutrons.

Difference of the thermal neutron fluxes of Hyd 1st exp. and Hyd 2nd exp. in Fig. 3 is considerably dependent on the number of the fuel elements, which were 24 and 21, respectively.

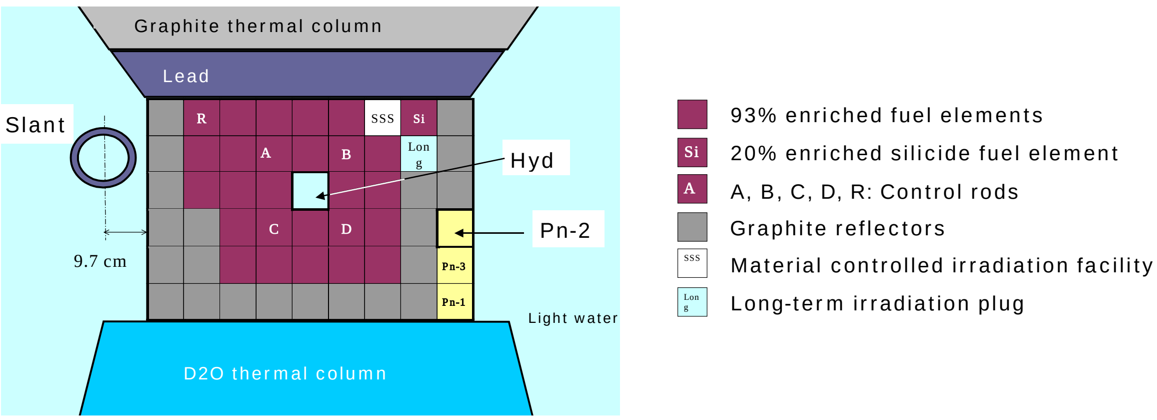

Fig.1 Horizontal core configuration

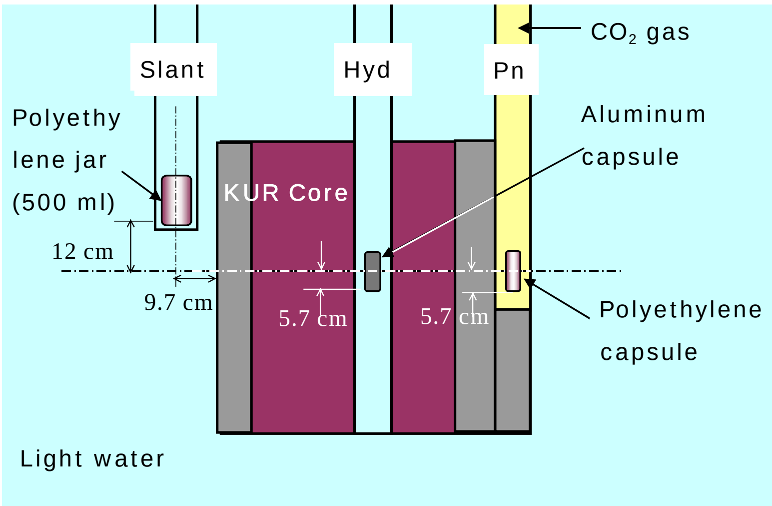

Fig. 2 Vertical configuration of the irradiation facilities

Table 2 Westcott thermal neutron flux and so forth at the irradiation facilities of the KUR

Facility: Detector position in a capsule:	Hyd (1st exp.) 1 cm above the bottom	Pn-2 Near the center	Slant 2 cm above the bottom
nv_0 (cm^{-2}sec^{-1})	$(1.07\pm0.03)\times10^{14}$	$(1.76\pm0.04)\times10^{13}$	$(1.09\pm0.03)\times10^{13}$
$nv_0 r\sqrt{T/T}$ (cm^{-2}sec^{-1})	$(4.00\pm0.10)\times10^{12}$	$(8.21\pm0.21)\times10^{11}$	$(1.18\pm0.03)\times10^{11}$
$r\sqrt{T/T_0}$	0.0373 ± 0.0009	0.0466 ± 0.0012	0.0108 ± 0.0004
Cd-ratio of Au (R_{Cd}) a)	2.53 ± 0.06	2.22 ± 0.06	6.3 ± 0.3
Fast neutron flux (cm^{-2}sec^{-1})	$(3.8\pm0.2)\times10^{13}$ b)	$(3.4\pm0.1)\times10^{12}$ c)	$(1.05\pm0.40)\times10^{12}$ b)

a) Calculated using $R_{Cd} = \dfrac{g + s_0 r\sqrt{T/T_0}}{r\sqrt{T/T_0}}\left[f_\delta s_0 + \dfrac{g}{K}\right]^{-1}$ where K is Westcott's K -factor which is tabulated by Westcott et al. [1], f_δ is transmission of the 4.9 eV neutrons through a Cd thickness δ.

b) Determined using the averaged cross section $\sigma = 17.7$ mb of the Ti(n,p)^{47}Sc reaction for the fission neutron spectrum of ^{235}U.

c) Determined using the averaged cross section $\sigma = 0.302$ mb of the Ti(n,p)^{48}Sc reaction.

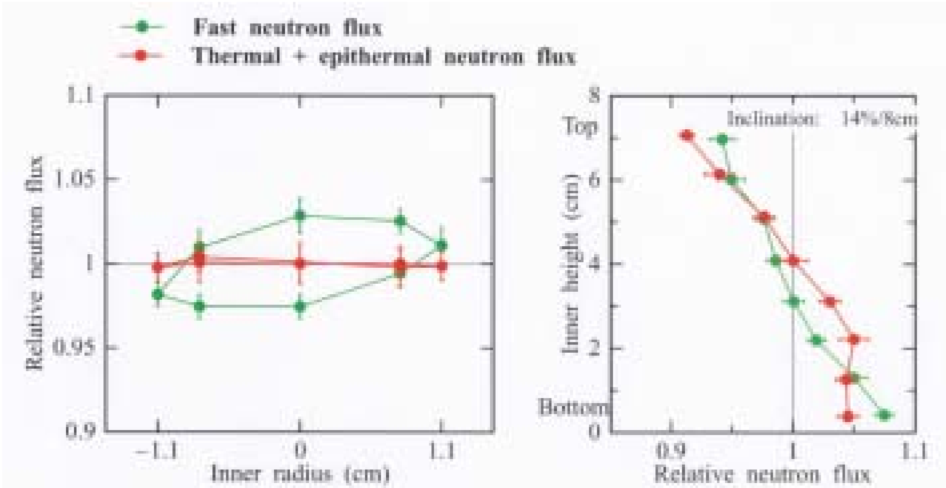

Fig. 4 Neutron flux distributions in an Al capsule of Hyd. Left: horizontal direction: along the inner wall of the capsule; Right: along the vertical axis

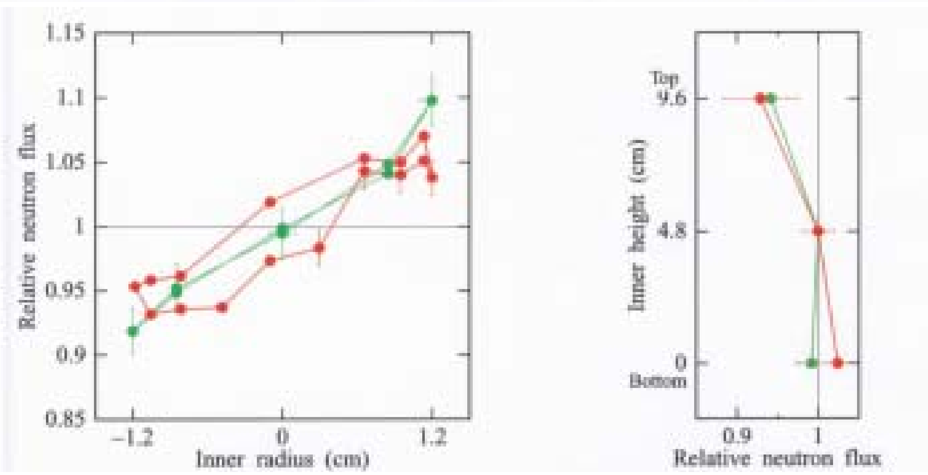

Fig. 5 Neutron flux distributions in a polyethylene capsule of Pn-2. Left: horizontal direction: along the inner wall of the capsule; Right: along the vertical axis

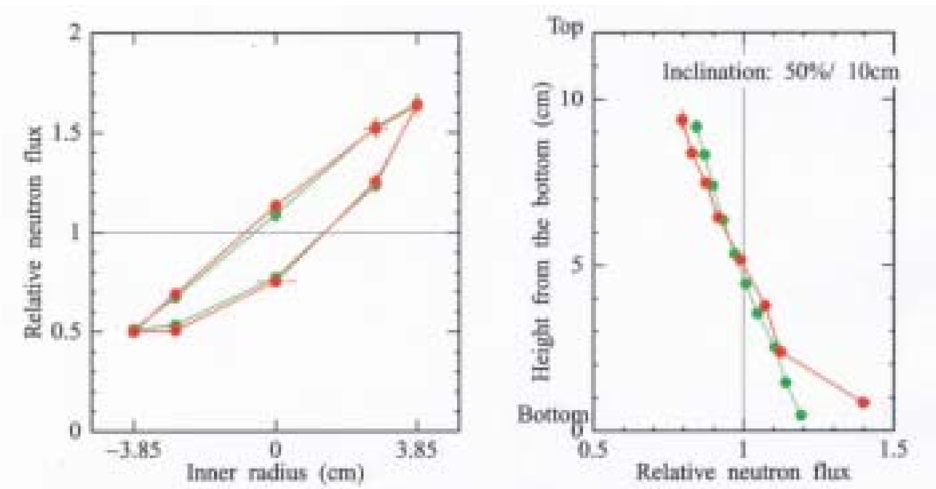

Fig. 6 Neutron flux distributions in a polyethylene jar of Slant. Left: horizontal direction: along the inner wall of the jar; Right: along the vertical axis

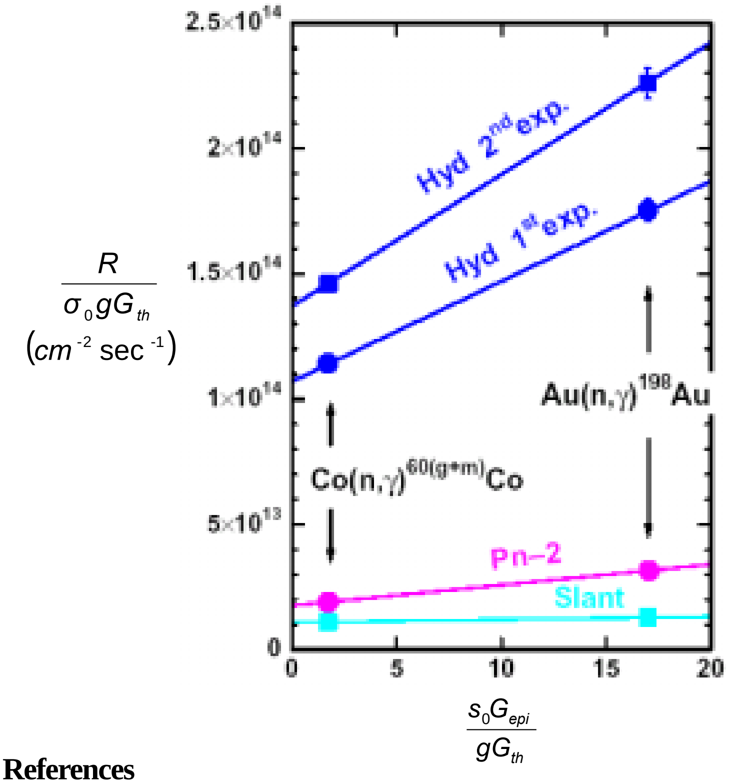

Fig. 3
Appearances of Eq. 4 for Hyd (1st and 2nd experiments), Pn-2 and Slant

Intercept: thermal neutron flux
Inclination: epithermal neutron flux

5. References

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