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Experimental Determination of the Spectral Indices $^{28}\rho$ and $^{25}\delta$ of the IPEN/MB-01 Reactor

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This experimental work aims to obtain the spectral indices $^{28}\rho$ and $^{25}\delta$ of the core of the IPEN/MB-01 nuclear reactor with a novice approach based on the direct gamma spectrometry of the irradiated fuel rods. The measurements were performed with high precision at the asymptotic central core region. The total and epithermal reaction ratios were obtained from the direct gamma spectrometry of a irradiated fuel element at the maximum neutron flux position. The gamma spectrometry was performed by a fuel rod scanning equipment with a collimator of 1 cm opening size. The data were acquired allowing the irradiation of the fuel rod to be bare or covered with cadmium sleeves of variable sizes. Correction factors were obtained both experimentally and from a calculation approach in order to correct the perturbations due to cadmium. Such calculations, carried out by the MCNP-4B, show the behaviour of these factors as a function of the cadmium sleeve length. The analysis shows that the correction factors are very sensitive to the nuclear data library used by MCNP-4 B; namely ENDF/B-V and ENDF/B-VI.5 libraries. The best results are obtained when the correction factors and the spectral indices are calculated with ENDF/B-VI.

***KEYWORDS:** reaction rate ratio, spectral indices, epithermal-to-thermal capture ratio, epithermal-to-thermal fission ratio, cadmium perturbation, cadmium correction factor, nuclear data testing.*

I. Introduction

Experiments involving determination of the reaction rates in the fuel pellets are of fundamental importance to correlate theory and experiment mainly concerning calculation methods and related nuclear data libraries. These experiments are normally performed through the irradiation of bare and cadmium covered fertile and/or fissile foils. Typical examples are the spectral indices $^{28}\rho$ and $^{25}\delta$ which provide the ratio of the epithermal to thermal neutron captures in ^{238}U and the ratio of the epithermal to thermal fission in ^{235}U respectively. For a long time, experiments involving reaction rate measurements have been carried out worldwide. The most famous spectral indices measurements are the ones performed in the TRX and BAPL critical facilities selected by the CSEWG 1) (Cross Section Evaluation Working Group) as benchmarks. Numerous researches 2,3,4) have assessed the adequacy of several nuclear data libraries by analyzing the CSEWG benchmarks. Historically, there has been a long standing problem related to the overprediction of the $^{28}\rho$ predicted by several nuclear data libraries2). Nowadays there has been a great progress in the calculation schemes so that the main uncertainty of the calculated reactor responses are mostly credited to the nuclear data used in the process. However, the effort placed in these areas has to be followed in the same level by experiments that have uncertainties lower than that inherent in the calculation methodologies. The available experimental support for $^{28}\rho$ possesses high uncertainties and makes use of approximated methods to take into account the cadmium perturbations. Aiming to contribute in these previous aspects, the purpose of this work is to present the experiments performed at IPEN/MB-01 reactor for the determination of its spectral indices $^{28}\rho$ and $^{25}\delta$. The procedure adopts a novice approach considering the direct gamma spectrometry of a specified length of an experimental fuel rod. The proposed method allows the measurements of $^{28}\rho$ and $^{25}\delta$ with high level of accuracy and eliminates most of the calculated corrections due to the cadmium perturbation.

II. Experiment Description

The IPEN/MB-01 reactor is a zero power-critical facility especially designed for measurement of a wide variety of reactor physics parameters to be used as a benchmark experimental data for checking the calculation methodologies and related nuclear data libraries commonly used in the field of reactor physics. This facility consists of a array of 28 x 26 UO_2 fuel rods, 4,3% enriched and clad by stainless steel (type 304) inside a light water tank. A complete description of the IPEN/MB-01 reactor may be found elsewhere 5).

The experiment was carried out at the asymptotic region of the reactor core. An experimental fuel rod (equal to the one used in the reactor) was irradiated at the central region of the reactor. The irradiation and the subsequent data acquisition use the central region of this fuel rod alternately bare and covered with cadmium sleeves (0,5 mm thickness) of 3, 4, 5, 7 and 10 centimeter length. The total and epithermal reaction rates were obtained by using a gamma spectrometry employing a fuel rod scanning equipment with a collimator opening size of 1 cm.

The fuel rod was irradiated for 1 hour and the gamma spectrometry was performed by a high pure germanium

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International Conference on Nuclear Data for Science and Technology, 2001, TSUKUBA, JAPAN

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detector (HPGe) during a decay period of seven days in steps of 1 hour. The experimental data are the integral counting of the photopeaks located at 277.6 and 293.3 keV of the ^{239}Np and ^{143}Ce respectively. All the measurements were performed at the standard rectangular configuration (28x26) of the IPEN/MB-01 reactor core as shown in **Fig. 1**.

The ^{238}U capture (C8) in the 1 cm length of the fuel rod is given by Nakajima [6]:

$$C8 = \frac{\lambda_{Np} C_{Np} \exp(\lambda_{Np} t_e)}{f_{\gamma_{Np}} I_{Np} \eta_{Np} \left[1-\exp(-\lambda_{Np} t_i)\right]\left[(1-\exp(-\lambda_{Np} t_c)\right]} \tag{1}$$

Similarly the ^{235}U fission rate (F5) is given by:

$$F5 = \frac{\lambda_{Ce} C_{Ce} F_{25} \exp(\lambda_{Ce} t_e)}{Y_{Ce} f_{\gamma_{Ce}} ICe \eta_{Ce} \left[1-\exp(-\lambda_{Ce} t_i)\right]\left[(1-\exp(-\lambda_{Ce} t_c)\right]} \tag{2}$$

where λ_{Np} is the ^{239}Np decay constant; C_{Np}, $f_{\gamma Np}$, I_{Np}, and η_{Np} are respectively the integral counts at the end of the irradiation, the fuel rod self-shielding factor, the gamma emission probability, the global counting efficiency, all for the ^{239}Np photopeak located at 277.6 keV; t_e is the counting waiting time, t_i is the irradiation time; t_c is the counting time; λ_{Ce} is the ^{143}Ce decay constant; C_{Ce}, $f_{\gamma Ce}$,I_{Ce}, η_{Ce} are respectively the integral counts at the end of the irradiation; the self-shielding factor, the gamma emission probability; the global efficiency all for the ^{143}Ce photopeak located at 293.3 keV; F_{25} is the ^{235}U relative fission density and Y_{Ce} is the effective fission yield of ^{143}Ce .

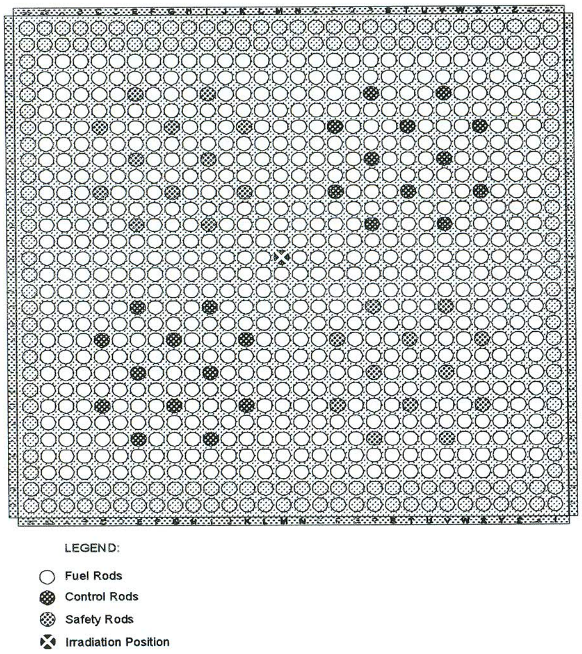

Fig.1 Rectangular configuration of the core of the IPEN/MB-01 reactor.

The irradiation time (t_i) and the power level (100w) are kept identical for the irradiation of the bare and cadmium covered fuel rod. The power level was monitored by both a reactor noise method and a detector placed far away from the core. Both of these techniques indicate very consistent power levels. The waiting time (t_e) was kept equal to zero during all the acquisitions.

Considering the ^{238}U neutron capture the different factors between the bare and cadmium covered cases are only the self-shielding factor $f_{\gamma Np}$ and the ^{239}Np integral counts (C_{Np}). The remaining quantities in equation (1) are identical. Consequently, the cadmium ratio (R_{cd}) for the ^{238}U neutron capture is :

$$^{28}R_{Cd} = \frac{(C_{Np} / f_\gamma)_{bare}}{(C_{Np} / f_\gamma)_{Cd}} \tag{3}$$

Similarly, the cadmium ratio for the ^{235}U neutron fission is given by:

$$^{25}R_{Cd} = \frac{(C_{Ce} F_{25} / f_\gamma)_{bare}}{(C_{Ce} F_{25} / f_\gamma)_{Cd}} \frac{Y_{cd}}{Y_{bare}} \tag{4}$$

where the ^{235}U relative fission density and the effective yield of ^{143}Ce (Y_{cd} and Y_{bare}) have to be considered distinct for the bare and cadmium covered cases.

The integral counting for the photopeaks of ^{239}Np and ^{143}Ce during the cooling period follow an exponential law. These data were then fitted in an exponential function using the RFIT [7] code. The amplitude coefficient of the exponential function for the bare and cadmium covered fuel rod are respectively the integral counting (C_{Np} and C_{ce}) needed in equations (3) and (4). RFIT also performed a complete statistics analysis on the experimental data as well as the uncertainty analysis of the problem. The analysis considered total correlation between bare and cadmium cases.

Finally the perturbed values of $^{28}\rho$ and $^{25}\delta$ are given by:

$$^{28}\rho = \frac{1}{^{28}R_{Cd} - 1} \tag{5}$$

$$^{25}\delta = \frac{1}{^{25}R_{Cd} - 1} \tag{6}$$

III. The Calculated Correction Factors

The calculated correction factors for the perturbation due to the cadmium sleeves were determined employing the very powerful modeling capabilities of the MCNP-4B code [8]. The geometry model adopted for this purpose is shown in Fig.2. A reflective boundary condition is used in all faces, thus simulating an infinite array of fuel rods. The experimental fuel rod is simulated in the central position of **Fig.2**. The calculations are performed to fuel rod bare and covered with cadmium sleeves of various sizes. Considering these conditions $^{28}\rho$ and $^{25}\delta$ are calculated to bare and cadmium covered case. A thermal energy cutoff of 0.625 eV was adopted for the unperturbed (bare) case. The calculated correction factor is defined as the ratio of the bare spectral indices to those covered with cadmium. These factors were determined respectively for $^{28}\rho$ and $^{25}\delta$ as a function of the cadmium sleeve length. The MCNP-4B calculations were performed using the ENDF/B-V and ENDF/B-VI.5 libraries.

One last consideration before the discussion of the determination of $^{28}\rho$ and $^{25}\delta$ is the question of how to treat the ratio of the self-shielding factors ($f_{\gamma Np}$ and $f_{\gamma Ce}$) for the bare and cadmium covered cases needed in equations (3) and (4). This question was addressed considering the determination of the $^{238}U(n,\gamma)$ and $^{235}U(n,f)$ reactions as a function of the position inside of the fuel pellets. The magnitude of the sources terms for the emission of the gamma radiation at 277.6 and 293.3 keV are proportional to these reaction rates. The ROLAIDS and XSDRNPM modules of AMPX-II [9)] and ISOSHIELD [10)] were employed for such a purpose. ROLAIDS was used to calculate the self-shielded $^{238}U(n,\gamma)$ and $^{235}U(n,f)$ cross sections across the pellet in a multigroup model. Ten regions were considered for this purpose. XSDRNPM was used for the calculations of the neutron transport calculations and the subsequent reaction rates. The analyses reveal that the ratios of the self-shielding factors of equations (3) and (4) were essentially 1.0

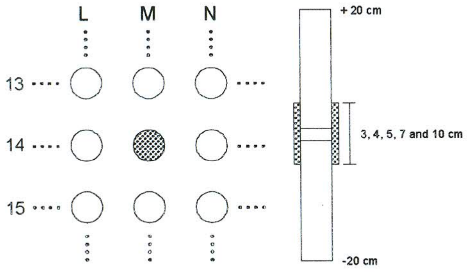

Fig. 2 Geometric model for determination of correction factors.

IV. Determination of $^{28}\rho$

The results obtained for the determination of $^{28}\rho$ are shown in **Fig. 3**. This figure shows the perturbed $^{28}\rho$* and its calculated correction factors (^{28}CF) as a function of the cadmium sleeve length.

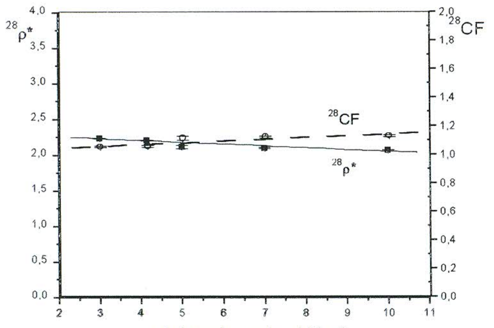

Fig. 3 The experimental perturbed values of $^{28}\rho$* as function of cadmium sleeve length.

The unperturbed $^{28}\rho$ is obtained as the product of the extrapolated values of both curves when the cadmium sleeve length goes to zero. The extrapolated value of the experimental $^{28}\rho$ can be interpreted as the value in the absence of cadmium but with its thermal energy cutoff unknown. The extrapolated calculated correction factor basically makes this transposition to the thermal cutoff of 0.625 eV. The final result for the experimental determination of the spectral index $^{28}\rho$ for the IPEN/MB-01 reactor core is given below. The extrapolated calculated correction factor was obtained with the ENDF/B-VI.5 library.

$$^{28}\rho = 2.3576 \pm 0.0078$$

An experimental cadmium correction factor can also be defined as:

$$^{28}CF = \frac{^{28}\rho}{^{28}\rho *} \qquad (7)$$

where $^{28}\rho$* is the perturbed value obtained for different cadmium sleeve length. ^{28}CF can be very helpful to verify the adequacy of the methodology employed to calculate the correction factors and related nuclear data library.

V. Determination of $^{25}\delta$

In contrast to the $^{28}\rho$ case, the determination of $^{25}\delta$ requires some additional quantities that have to be determined either from another experiment or by a calculation approach. The main problems here are the determination of the ^{235}U relative fission density and the ^{143}Ce effective yield. For this purpose the MCNP-4B code was employed to estimate the relative ^{235}U fission density. The same geometry model as used for the determination of the calculated correction factors was adopted for this purpose. Thus for bare fuel rods the relative ^{235}U fission density was calculated to be 97,3 %. For the cadmium covered case considering sleeves of 3,4,5,7 and 10 cm length the relative ^{235}U fission density is 84,87%, 84,34%, 83,63 %, 83,52%, 79,40%, respectively. The effective yield of ^{143}Ce is obtained weighting its yield due to ^{235}U and ^{238}U fission by their respective fission densities.

The final results of $^{25}\delta$ are shown in **Fig. 4**. This figure shows simultaneously the perturbed values of $^{25}\delta$ along with its calculated correction factors as a function of the cadmium sleeve length. It can be observed that the perturbed value of $^{25}\delta$ reaches a minimum value when the cadmium sleeve length goes to infinite. On the other hand , the behavior of the calculated correction factor shows an inverse trend. Therefore, the final $^{25}\delta$ can be obtained considering the product of both extrapolated values. In contrast to the $^{28}\rho$ case, the physical interpretation of the extrapolated values is not so straightforward.

The final result for the experimental determination of the $^{25}\delta$ of the IPEN/MB-01 reactor core is given below.

$$^{25}\delta = 0.1215 \pm 0.0005$$

Again here, an experimental correction factor can be defined as follows:

$$^{25}CF = \frac{^{25}\delta}{^{25}\delta *} \qquad (8)$$

where $^{25}\delta$ and $^{25}\delta$* are the unperturbed and perturbed values respectively.

The uncertainties of spectral indices were obtained considering total statistical correlation between the bare and covered fuel

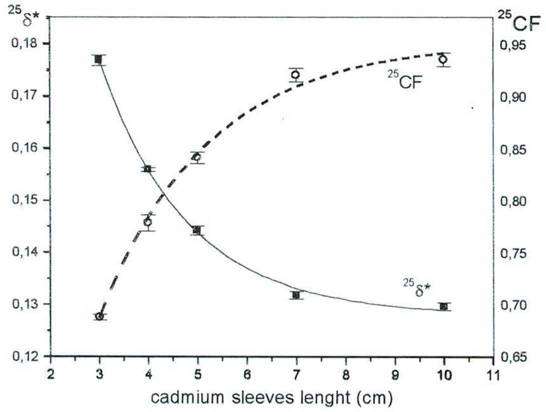

Fig. 4 Experimental disturbances values of $^{25}\delta^*$ as function of cadmium sleeve length.

VI. Results Discussions

Table 1 shows the ratio of the calculated and experimental cadmium correction factors. In general the agreement is better for longer cadmium sleeve length and for the spectral indices $^{28}\rho$. As for $^{25}\delta$, the results are sensitive to the cadmium sleeve length due to its high dependency on thermal neutron events. The comparisons also reveal that ^{28}CF is calculated better with ENDF/B-VI.5 and ^{25}CF is not sensitive to the nuclear data library.

A comparison between calculated and measured values of $^{28}\rho$ and $^{25}\delta$ is shown in **Table 2**. The calculated spectral indices $^{28}\rho$ and $^{25}\delta$ of the IPEN/MB-01 reactor were determined in the asymptotic with a fully three-dimensional MCNP-4B calculation. The analyses reveal that both $^{28}\rho$ and $^{25}\delta$ calculated with ENDF/B-VI.5 are in a better agreement with the experimental values.

Table 1 Ratios between calculated values(C) of ^{28}CF and ^{25}CF and experimental correction factors (E) .

cadmium sleeve length (cm)	**C / E**			
	^{28}CF $^{(a)}$	**^{28}CF $^{(b)}$**	**^{25}CF $^{(a)}$**	**^{25}CF $^{(b)}$**
3	1.0332	0.9888	1.1657	1.1612
4	1.0476	0.9577	1.1213	1.1275
5	1.0008	1.0124	1.0715	1.0739
7	1.0514	1.0021	1.0041	1.0027
10	(1)	1.0065	(1)	0.9958

(1) Not calculated. (a) ENDF/B-V; (b) ENDF/B-VI

Table 2 Ratios between calculated (C) and experimental (E) values of $^{28}\rho$ and $^{25}\delta$.

Spectral Index	C/E (1)	C/E (2)
$^{28}\rho$	1.039	1.022
$^{25}\delta$	1.057	1.033

(1) ENDF/B-V; (2) ENDF/B-VI

VII. Conclusions

This work uses a novice approach for the determination of $^{28}\rho$ and $^{25}\delta$ by means of a fuel rod gamma spectroscopy irradiated with and without cadmium sleeves. The methodology introduces some advantages compared to the traditional ones based on uranium foil irradiation [3,4,7] because of the smaller experimental error due to the higher amount of uranium. In addition to that there is no need to assemble and disassemble the special fuel rods to remove the uranium foils after irradiation which always induces a radiological difficulty.

The methodology used to obtain the cadmium correction factors by the monte carlo MCNP-4B code is original and showed better agreement when the ENDF/B-VI.5 library was used for the spectral index $^{28}\rho$. The same does not occur for the spectral index $^{25}\delta$ which shows very similar results for ENDF/B-V or ENDF/B-VI.5.

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