International Atomic Energy Agency

INDC(VN)-008
Distr.: L

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

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Vuong Huu Tan, Nguyen Canh Hai, Nguyen Trong Hiep
Nuclear Data Sector, Nuclear Research Institute
Dalat, Vietnam

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IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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Vuong Huu Tan, Nguyen Canh Hai, Nguyen Trong Hiep
Nuclear Data Sector
Nuclear Research Institute
1 Nguyen Tu Luc Street
Dalat, Vietnam
Telephone: +84-63-822191/829436
Telefax: +84-63-821101

ABSTRACT

Capture cross sections for the $^{238}U(n,\gamma)$ reaction were measured related to that of the $^{197}Au(n,\gamma)$ reaction on the filtered keV-neutron beams at the Dalat reactor using the activation method. Radioactivities of samples after irradiation were measured with HPGe detectors (50 mm^2 sensitive area, FWHM=150 eV for ^{55}Fe and 70 cc volume, FWHM=2.5 keV at 1332 keV γ-transition of ^{60}Co). The data obtained by the authors were compared with the evaluations in ENDF/B-VI and JEF-2 and also with the results from recent experimental works.

I. INTRODUCTION

Neutron capture cross sections are important for nuclear reaction theory, astrophysics and design of nuclear reactor. Neutron radiative capture cross section of ^{238}U in the unresolved resonance region is an important quantity for reactor calculation. The accuracy requirements of the evaluated values of radiative capture cross sections for ^{238}U in nuclear technology are considerable: 2% in the 1keV - 1MeV energy range and at most 3% to 5% in the 1-5 MeV energy range /1/. However, the new evaluated data for the $^{238}U(n,\gamma)$ reaction cross section appeared in recent works have been revised to be smaller by more than 5 to 10% than old evaluated data and/or most of the experimental data in the energy region from 10 keV to 300 keV /2/. Data from the available different measurements are scattered by more than 15% depending on the neutron energy region /3/. In such a situation, much interest has been paid to the radiative capture cross section measurements for ^{238}U in the neutron energy region from tens to hundreds keV. In this work the radiative capture cross section measurements for ^{238}U by activation method on the filtered neutron beams of 55 keV and 144 keV at the Dalat reactor have been described. Our measurements are carried out with ^{197}Au foils as standards that are irradiated simultaneously in neutron fields together with ^{238}U foils. ^{238}U and ^{197}Au foils have the same size. To overcome difficulties in determining the efficiency ratio for detecting of 75 keV and 411 keV gamma rays from ^{238}U and ^{197}Au activated foils, ^{238}U and ^{197}Au foils were irradiated on the filtered thermal neutron beam because the radiative capture cross sections for thermal neutrons were known very well. In this case most systematic uncertainties can be avoided. Therefore

corrections are often needed to take into account the resonance self-shielding, multiple scattering and γ-self absorption in samples.

II. EXPERIMENTAL METHOD

The experimental method of neutron capture cross section measurement for ^{238}U used in this work is the activation technique. It is completely selective for a given nuclide in a natural uranium sample and experiments are relatively simple to be carried out. Our experiments are performed with ^{197}Au foils as a standard that is irradiated simultaneously with ^{238}U foils. In this way most systematic uncertainties can be avoided. Uranium and gold foils used in this experiment were made in USA (Reactor Experiments INC, Belmont, California) with 1inch diameter. The thickness of ^{238}U foils is approximately 0.276 g/cm^2 and 0.087 g/cm^2 for ^{197}Au-foils. Irradiations were carried out on the filtered neutron beams at the piercing channel No.4 of the Dalat reactor. Characteristics of filtered neutron beams used in this experiment are given in Table 1 /4/. Activity of uranium foils after irradiation was measured by X-ray HPGe-spectrometer (50 mm^2 sensitive area, FWHM=150 eV for ^{55}Fe) which detects 75 keV gamma rays from decay of ^{239}U with half-life of 23.5 min. In order to measure activity of activated Au-foils we use the HPGe-70 cc detector with FWHM=2.5 keV at 1332 keV gamma transmission of ^{60}Co.

Table 1: *Filtered Neutron Beams Used in the Experiment*

Neutron	Filter Combination	Neutron Flux (n/cm^2/s)	R_{Cd} or FWHM
Thermal	98cmSi+10cmTi+ 35g/cm^{2}S	1.8x10^7	143
144 keV	98cmSi+10cmTi+0.2g/cm^{2}B^{10}	1.2x107	22 keV
55 keV	98cmSi+35g/cm^{2}S+0.2g/cm^{2}B^{10}	4.0x10^6	8 keV

In order to avoid determination of absolute efficiencies of HPGe-detectors for 75 keV and 411 keV gamma rays from ^{238}U and ^{197}Au activated foils, we have carried out irradiation of ^{238}U and ^{197}Au foils on the filtered thermal neutron beam. In this case the efficiency ratio can be obtained from well-known radiative capture cross sections of ^{238}U and ^{197}Au for thermal neutrons /8/.

The activity of samples irradiated on the filtered fast or thermal neutron beams with flux $\phi(E)$ is defined as following /5/:

$$A = S \int_{E1}^{E2} \int_{0}^{\infty} \phi_i(E) N_{nucl} \exp\{-[N_{nucl}\sigma_t(E)x]\}\sigma_a(E)dxdE \qquad (1)$$

where S is the sample area, $\Phi_i(E)$ - neutron flux of beams [n/cm^2/s]; Nnucl. - nuclear density of sample [nucl./cm^3]; $\sigma_t(E)$ - total neutron cross section [barn] ; $\sigma_a(E)$ - radiative

capture cross section [barn]; l - thickness of the irradiated sample [cm]; E1 and E2 - lower and upper limits of energy range of neutron beams. Uranium and gold foils used in our experiments could be regarded as thin target and we can apply the following approximation:

$$\exp(-N_0\sigma_t(E)) = 1 - N_0\sigma_t(E) + \frac{(N_0\sigma_t(E))^2}{2} \qquad (2)$$

with $N_0 = N_{nucl.}x$ is thickness of sample [nucl./cm^2]. Let define $<\sigma_a>$ and $<\sigma_t>$ cross sections averaged on the spectrum of filtered neutron beams and suppose $<\sigma_a\sigma_t> = <\sigma_a><\sigma_t>$, integrating equation (1) gives the results:

$$A_i = N<\sigma_a>[1 - \frac{N_0<\sigma_t>}{2}]<\phi_i> \qquad (3)$$

with $N = SN_0$

and $<\phi_i> = \int_{E1}^{E2} \phi_i(E)dE$ (4)

The activity of irradiated foils is related with the count C_i of HPGe-detectors by following:

$$A_i = \frac{C_i(1-L_m)(1+L_n)f(\lambda,t)}{\varepsilon_\gamma I_\gamma} \qquad (5)$$

$$f(\lambda,t) = \frac{\lambda}{(1-e^{-\lambda t1})e^{-\lambda t2}(1-e^{-\lambda t3})} \qquad (6)$$

where λ is the decay constant of activated nuclide; t1, t2, t3 are irradiating, cooling and measuring times respectively; ε_γ is detection efficiency of the detector; and I_γ is the branching ratio of the measured gamma ray; L_m and L_n are corrections for multiple scattering and γ-self absorption in sample. From formulas (1) to (6) described above we receive the expression for radiative capture cross section of ^{238}U on the filtered neutron beams in comparison with ^{197}Au standard as following:

$$<\sigma_a>^U = \frac{A^U N^{Au}}{A^{Au} N^U} \frac{(1 - N_0{}^{Au} <\sigma_t>^{Au} /2) <\sigma_a>^{Au}}{(1 - N_0{}^U <\sigma_t>^U /2)} \tag{7}$$

$$\frac{A^U}{A^{Au}} = \frac{C^U f(\lambda,t)^U I_\gamma{}^{Au} \varepsilon_\gamma{}^{Au}}{C^{Au} f(\lambda,t)^{Au} I_\gamma{}^U \varepsilon_\gamma{}^U} B \tag{8}$$

$$B = \frac{(1 - L_m{}^U)(1 + L_n{}^U)}{(1 - L_m{}^{Au})(1 + L_n{}^{Au})} \tag{9}$$

$$\frac{\varepsilon_\gamma{}^{Au}}{\varepsilon_\gamma{}^U} = \frac{A_{th}{}^U C_{th}{}^U f_{th}{}^U I_\gamma{}^{Au}}{A_{th}{}^{Au} C_{th}{}^{Au} f_{th}{}^{Au} I_\gamma{}^U B_{th}} \tag{10}$$

$$\frac{A_{th}{}^{Au}}{A_{th}{}^U} = \frac{N^{Au} <\sigma_a>_{th}{}^{Au}}{N^U <\sigma_a>_{th}{}^U} D_{th} \tag{11}$$

$$D_{th} = \frac{1 - N_0{}^{Au} <\sigma_t>_{th}{}^{Au} /2}{1 - N_0{}^U <\sigma_t>_{th}{}^U /2} \tag{12}$$

Where B and B_{th} are correction factors for foils irradiated in the filtered fast and thermal neutron beams; D and D_{th} - correction factors for neutron attenuation in foils irradiated in the filtered fast and thermal neutron beams. B and B_{th} can be given by calculation /6/. In our experiments irradiating and measuring procedures were carried out several times for every filtered neutron beam. Therefore, the average value <n> of reduced counts $n_k = C_i(k) f(\lambda, t_k)/N$ from m different measurements and its errors are determined as following:

$$<n> = \frac{\sum_1^m n_k / (\Delta n_k)^2}{\sum_1^m 1/(\Delta n_k)^2} \tag{13}$$

$$<\Delta n> = \sqrt{\frac{\sum_1^m [(n_k - <n>)/\Delta n_k]^2}{\sum_1^m 1/(\Delta n_k)^2}} \tag{14}$$

III. RESULTS AND DISCUSSION

In Table 2 we give the average values of nuclear constants and their errors used in our calculations. These values are taken in the works /5,7,8,9/ or interpolated linearly between two nearest values in the energy scale. The values of correction factors received by ourselves /6/ are given in Table 3. The radiative capture cross sections of ^{238}U with neutron energies of 55 keV and 144 keV obtained in this work are given in Table 4. Our accuracy is approximately 3%. The main uncertainties came from the nuclear constants of standards, statistics of the activity measurements, various corrections ect. The main errors are listed in Table 5.

For comparison the neutron radiative capture cross sections received by the authors for ^{238}U are plotted together with data from references. It can be seen from the figure that our results are in good agreement with measurements reported in the works /2,10/ and with data given in the work /12/. The largest error is from the nuclear constants of standards used in the calculation including total and radiative capture cross sections of gold for thermal and fast neutrons, the radiative capture cross section of uranium for thermal neutrons and total cross sections of uranium for thermal and fast neutrons. The second one is the background of the filtered neutron beams. In the case of the filtered thermal neutron beam the background was determined by irradiation with and without cadmium screen. For other filtered neutron beams faster neutron background is very low (2-3%) /11/, therefore its role in capture process is very little (less than 1%) because of the 1/v-dependence of capture cross section.

Table 2: *Nuclear Constants used in our calculations /5,7,8,9/*

Neutron	$<\sigma_a>^U$	$<\sigma_t>^U$	$<\sigma_a>^{Au}$	$<\sigma_t>^{Au}$
Thermal	2.7081+-0.0095 b	12.068+-0.121 b	98.65 +- 0.09 b	106.49+-0.016 b
55 keV		13.343+-0.051 b	433 +- 6 mb	11.60+-0.10 b
144 keV		11.551+-0.022 b	259 +- 5 mb	9.950+-0.013 b

Table 3: *Values of correction factors*

Neutron	$1-L_m^U$	$1+L_n^U$	$1-L_m^{Au}$	$1+L_n^{Au}$	B	D
Thermal	0.91	1.61	0.99	1.32	1.14	1.01006
55 keV	0.93	1.61	0.97	1.32	1.17	1.003166
144 keV	0.98	1.61	0.95	1.32	1.26	1.00275

Table 4: *The Radiative capture cross sections of ^{238}U received in our work*

Neutron	55 keV	144 keV
$<\sigma_a>$	292.3 +- 8.5 mb	152.5 +- 4.6 mb

Table 5: *Sources of error*

Source of errors	Error (%)
Capture cross sections of ^{197}Au for thermal(th) and fast(keV) neutrons	0.09 (th); 1.9(144keV); 1.4 (55KeV)
Capture cross section of ^{238}U for thermal(th) neutrons	0.35
Total cross sections of ^{197}Au for thermal(th) and fast(keV) neutrons	0.15(th); 0.13(144keV); 0.86(55keV)
Total neutron cross sections of ^{238}U for thermal(th) and fast(keV) neutrons	0.1(th); 0.19(144keV); 0.38(55keV)
Statistics	<= 2
Time	<= 0.05
Corrections for scattering and attenuation	<= 0.5
Background	<= 1
γ-self absorption in samples	<= 0.5
Weighting error of samples	<= 0.05

ACKNOWLEDGMENTS

The authors would like to thank the Vietnam National Research Program on Fundamental Sciences and the Dalat Nuclear Research Institute for financial support in carrying out this work. We are grateful to Prof. Pham Duy Hien and Dr. Tran Ha Anh for their continuous interest and valuable advices in research on nuclear data and nuclear reaction using filtered neutron beams at the Dalat reactor. The fruitful cooperation of Prof. Nguyen Tac Anh, Mr. Do Thanh Thao and Mr. Ho Manh Dung in setting up the measuring facilities is highly appreciated.

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APPENDIX
RESEARCH CONTRACTS ON NUCLEAR DATA AND NUCLEAR REACTIONS AT NUCLEAR DATA SECTOR (DNRI)
(1990-2000)

1. Study of Nuclear Reactions with Monoenergy Neutrons using Filtered Neutron Beams at the Dalat Nuclear Research Reactor for the period 1990-1992.
   Chief Scientific Investigator: Prof. Pham Duy Hien

2. Investigation of (n,γ) and $(n,n'\gamma)$ reactions for the period 1990-1992
   Chief Scientific Investigator: Mr. Luong Ngoc Chau

3. Utilization of Horizontal Experimetal Channels of the Dalat Nuclear Research Reactor for the period 1990-1995
   Chief Scientific Investigator: Dr. Vuong Huu Tan

4. Investigation of Average Characteristics of Nuclei in the Unresolved Resonance Region for the period 1996-2000
   Chief Scientific Investigator: Dr. Vuong Huu Tan

5. Applied Neutron Capture Gamma Ray Spectroscopy for the period 1996-2000
   Chief Scientific Investigator: Mr. Nguyen Trong Hiep

6. Development of the Fast Cyclic Activation Technique for Activation Cross Section Measurements of Isotopes with Short Half Lives for the period 1996-2000
   Chief Scientific Investigator: Mr. Nguyen Canh Hai

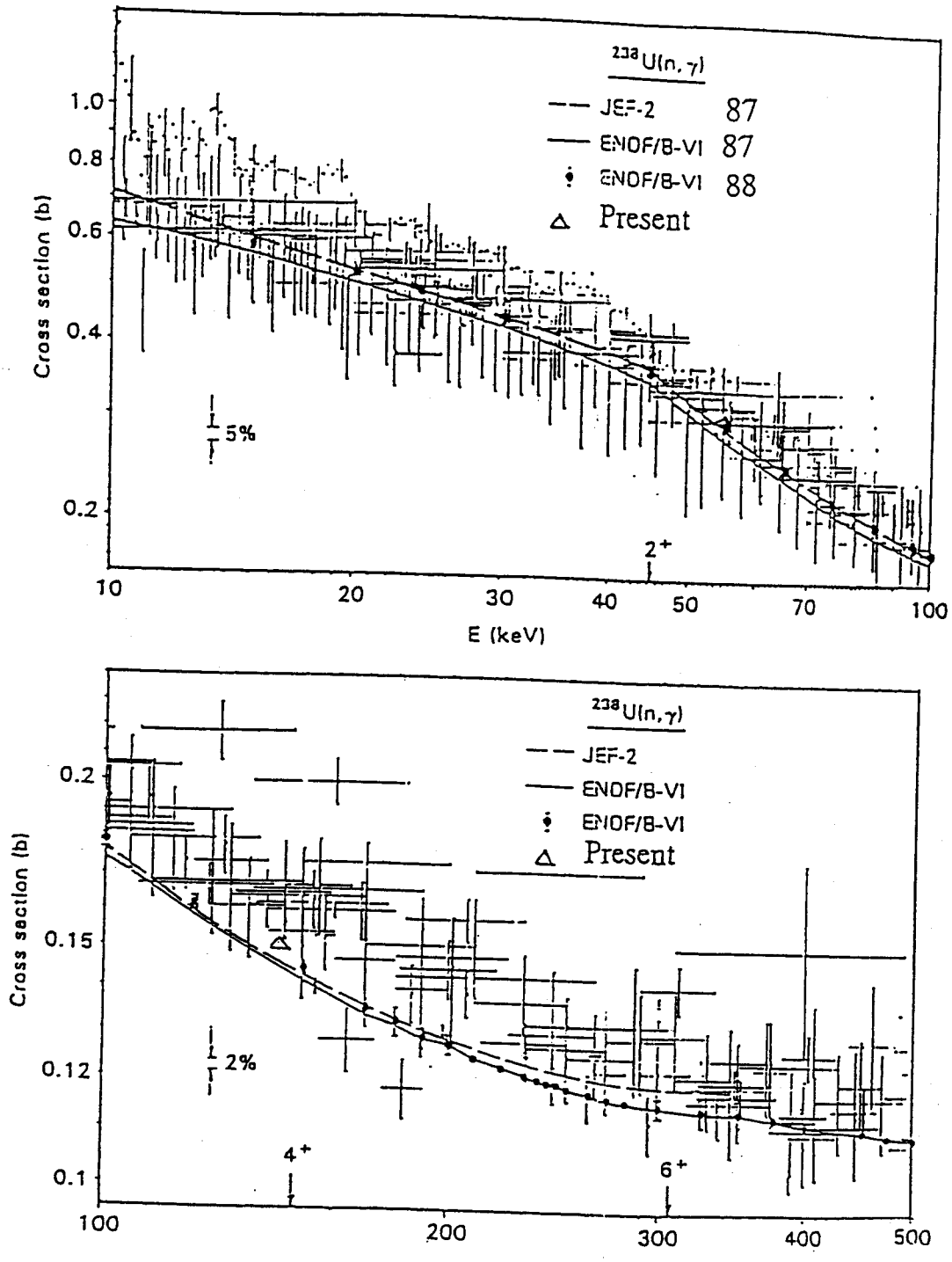

Figure : Average neutron radiative capture cross sections of U-238

Nuclear Data Section
International Atomic Energy Agency
P.O. Box 100
A-1400 Vienna
Austria

e-mail, INTERNET: SERVICES@IAEAND.IAEA.OR.AT
e-mail, BITNET: RNDS@IAEA1
fax: (43-1) 20607
cable: INATOM VIENNA
telex: 1-12645 atom a
telephone: (43-1) 2060-21710

online: TELNET or FTP: IAEAND.IAEA.OR.AT
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