International Atomic Energy Agency

INDC(ARG)-010
Distr.: G

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

INTEGRAL FISSION CROSS SECTION RATIOS OF Th232, U236 AND U238 RELATIVE TO U235 IN THE NEUTRON SPECTRUM PRODUCED BY 23.2 MeV DEUTERONS INCIDENT ON A THICK Be METAL TARGET

M.D. Bovisio de Ricabarra, L. Cohen de Porto, D. Waisman
and G.H. Ricabarra
Argentine National Atomic Commission
Avda. Libertador 8250, Buenos Aires, Argentina

August 1992

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

Reproduced by the IAEA in Austria
August 1992

INDC(ARG)-010
Distr.: G

INTEGRAL FISSION CROSS SECTION RATIOS OF Th232, U236 AND U238 RELATIVE TO U235 IN THE NEUTRON SPECTRUM PRODUCED BY 23.2 MeV DEUTERONS INCIDENT ON A THICK Be METAL TARGET

M.D. Bovisio de Ricabarra, L. Cohen de Porto, D. Waisman
and G.H. Ricabarra
Argentine National Atomic Commission
Avda. Libertador 8250, Buenos Aires, Argentina

August 1992

INTEGRAL FISSION CROSS SECTION RATIOS OF Th232, U236 AND U238 RELATIVE TO U235 IN THE NEUTRON SPECTRUM PRODUCED BY 23.2 MeV DEUTERONS INCIDENT ON A THICK Be METAL TARGET

M. D. Bovisio de Ricabarra, L. Cohen de Porto, D. Waisman and G. H. Ricabarra

Argentine National Atomic Commission
Avda. Libertador 8250, Buenos Aires, Argentina

Abstract

Integral neutron fission cross section ratios have been measured for Th232 /U238, U238/U235 and U236/U235 in the neutron field produced by bombardment of a thick Be metal target with 23.2 MeV deuterons. Validation of Th232, U236, U238 fission cross sections in a high energy neutron continuum spectrum is the object of this work. The neutron spectrum in the irradiation site has been obtained by unfolding of the neutron induced activity of eleven selected reactions. The average standard deviation between calculated activities with SAND-II unfolding code and the experimental input activities was 2.5 %. Calculated values of the fission cross section ratios were obtained from the ENDF/B-V evaluated library of cross sections and the measured spectrum. These ratios were not sensitive (<0.7%) to quite different SAND-II input spectra assumed in the low energy spectrum range (0.5 to 2 MeV). Analysis of error sources, errors propagation and their correlations was made and the correlation matrix of the experimental results was calculated. The experimental and calculated values obtained are consistent within the errors. Examination of the fissile ratios measured in other continuum neutron spectra shows a similar consistency in the spectrum produced by 7 MeV deuterons on Be. However in Cf252 and thermal U235 fission neutron spectra, a large discrepancy is found for Th232.

Introduction

Th232/U238, U238/U235 and U236/U235 fission cross section ratios are important for several reasons : 1º- Th232, U238, U236 and U235 are used in neutron dosimetry applications for both fission and fusion technology. 2º- Dosimetry applications for neutron fields in radioisotope production cyclotrons. 3º- Th232 or U238 may be a constituent of the blanket of fission, fusion and accelerator breeder systems.

These integral cross sections have been measured in a Cf252 fission neutron spectrum[1], in the U235 fission spectrum produced by thermal neutrons[2,3] and in the neutron spectrum produced by 7 MeV deuterons impinging on a beryllium target[4]. The average neutron energy of these spectra ranges from ≈ 2 to 2.8 MeV. However in the high neutron energy range these cross sections have not been validated.

The object of this work is the validation of Th232, U238, U236 and U235 fission cross section in the high energy neutron spectrum produced by 23.2 MeV deuterons in a thick beryllium target.

In a previous work[3] we have measured the integral fission cross section ratios of Th232 to U238 by two independent techniques in a fission spectrum produced by thermal neutrons in U235. These techniques were fission chamber and solid state nuclear track detection of fission fragments. The excellent agreement obtained between the two techniques for the fission cross section ratio (<1%) and the agreement of the SSNTD optical efficiency measured by us (0.991) with the careful measurement made by J.H. Roberts et al.[5] (0.988), shows that the SSNTD technique can be used instead of fission chamber detection.

SSNTD packets (electroplated fission deposits plus mica track detectors) were irradiated to measure the fission ratios. Activation foil packets were used to obtain the neutron spectrum shape by unfolding technique. The SSNTD packet and the foil activation packet can be irradiated together and ensure a better space resolution (a few mm).

The unfolded neutron spectrum was used to calculate the integral fission cross section ratios from the evaluated differential cross sections.

Irradiation Site and Experimental Set-up

Experiments were made at the tandar accelerator of the CNEA in a specially built neutron shielded facility, ≈ 1.5 x 2 m room, 2 m concrete shield on all side. The target was built with two metallic 1.5 mm thick beryllium plates. The deuteron beam impinged on a 1 mm diameter spot. The target was refrigerated with freon. The deuteron beam energy was 23.2 MeV and the maximum current was expected to be ≈ 1 μA. The detectors were placed at 41 mm from the beam spot in the Be target at approximately 0 degree. The experimental set-up is shown in fig. 1.

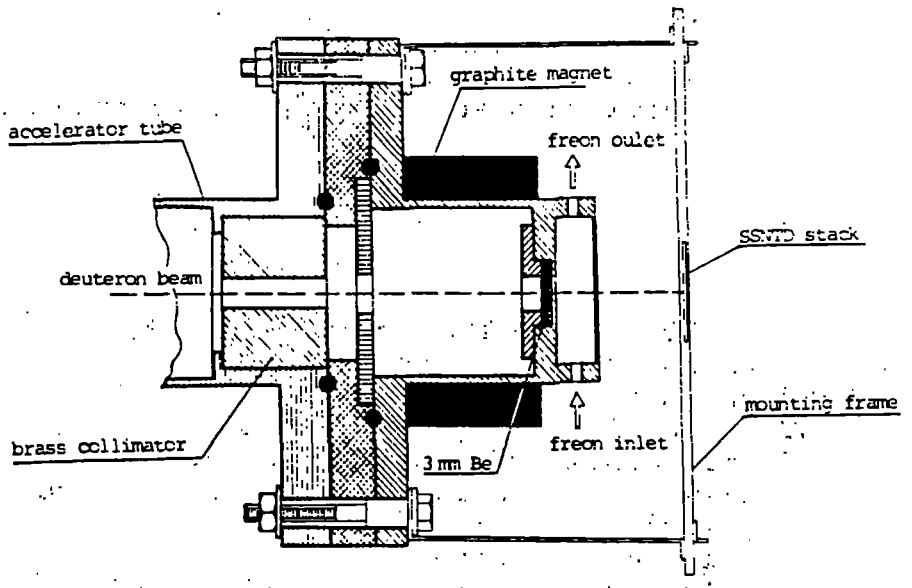

Fig. 1. Irradiation Site and Experimental Set-up.

Three types of irradiation were made :

a) Short irradiations (12 to 30 minutes) at low beam current (≈50 nA) for fission ratio measurements. U235, U236 enriched U (UENR,UEN6), depleted U (UDEP), natural U (UNAT) and Th232 (TH) electroplated deposits and mica track detectors were closely packed in SSNTD stacks. The mica SSNTD detectors were etched and the fis-

sion tracks counted to determine the fission ratios. A cadmium shield behind the irradiated stack was used to eliminate low energy neutrons back scattered by the room walls.

b) Long activation irradiation at about 1 μA for spectrum unfolding. An 11 foils activation stack rapped in thin aluminum paper was used. Two runs of 24.7 h and 34.6 h irradiation time were made. Correction for not constant flux was made, taken into account the deuteron current variation and reaction half lives. The current was obtained from the faraday cup of the accelerator tube.

c) Irradiation of In, U235 and U238 with and without a cadmium shield behind the samples, to determine the correction for thermal neutrons activation in n,γ spectrum unfolding reactions measurements.

In irradiations type a) and b) both stacks were irradiated together, even if only one stack was counted, to have exactly the same spectrum.

Neutron Spectrum.

The neutron spectrum from 23.2 MeV deuteron bombardment on a thick Be target has been investigated by Lone et al.[6] with TOF techniques and provides a reasonable input spectrum guess for SAND-II unfolding code. This spectrum is referenced as Lone1 throughout this work.

All measurements were normalized to the stack back and to 1/2" diameter. So the unfolded spectrum is the 'effective' spectrum at irradiation location (4.1 cm from the Be target and averaged from 0 to 8.8 degrees) and includes any possible perturbation due to absorption and scattering in the refrigeration system and the stack.

The flux distribution inside the activation and SSNTD stacks was determined by measuring the Na24 activity of Al27(n,α)reaction in aluminum foils intercalated between the stacks foils. From Q-spline smoothing of the Na24 activity distribution, the flux in each foil was determined. The ratios of the flux in the back of the stack to the foils flux, fGeo, were used to normalize all activities to the same position. A $1/r^2$ fitting of the Na24 distribution was also tried and shows no significant difference in the normalization factors,fGeo, obtained. From fitting of two runs the back of the stack to the Be target distance, d = 40.8 ±1% mm, was obtained. The angular or radial flux, determined by counting the radial fission distribution in a UENR foil, shows that the stack was correctly centered . This distribution was used to calculate the correction factor for different foil diameter, fDiam. The angular distribution agrees within the errors with that reported by Lone et al[6]. fDiam differs 0.5% if it is calculated with Lone et al. angular distribution.

Neutron Spectrum Unfolding

Activation Data Reduction

The reactions selected in order to cover a large energy range, 0.3 to 23 MeV, are listed in Table 1 : Cu65(n,p)Ni65, In115(n,n')In115m, Al27(n,α)Na24, Zr90(n,2n)Zr89, Au197(n,2n)Au196, Nb93(n,2n)Nb92m, Co59(n,2n)Co58, Ni58(n,p)Co58, Mn55(n,2n)Mn54 and Fe54(n,p)Mn54. A preliminary evaluation of expected activity and energy sensitivity range of each reaction with Lone1 spectrum, as well as a careful study of decay schemes[7] and activities from other isotopes in the sample, were made.

The activities were measured in a 20% reverse HP-Ge diode and a 4096 MCA and transferred to an IBM compatible PC to obtain the in-

finite dilution saturated activities, A∞-Exp.

In short, the following corrections were applied : 1) ray efficiency in the Ge diode, Eff. 2) True coincidences summing-up[8], fSum, ≈1% at 10cm from the diode, was calculated with Andreev et al.[9] formalism neglecting angular correlation[10]. 3) Correction for beam intensity variations during irradiation. 4) fG, self-absorption in the sample (1-2%), assuming exponential approximation (photonic absorption coefficients from Shirley[7]). 5) fGeo, normalization to the back stack flux. 6) -4.6% correction in gold reactions, due to different foil diameter (1cm), fDiam. 7) -12% correction for slow neutron activation in Au197(n,γ) Au198 reaction, fn.

Table 1. Activation Reactions and Gamma Correction Factors

Reaction	Half Life	Energy (KeV)	Branch	fG	fSum	Eff. $\times 10^{3}$
Cu65(n,p)Ni65	2.5200h	1481.9	0.2350	0.994	0.999	1.120
Cu65(n,p)Ni65		1115.6	0.1480	0.993	1.004	1.430
In115(n,n')In115m	4.4860h	336.3	0.4590	0.994	1.000	4.150
Al27(n,α)Na24	15.020h	1368.6	0.9999	0.999	1.003	1.147
Au197(n,)Au198	2.6935d	411.8	0.9550	0.987	1.000	3.440
Zr90(n,2n)Zr89	3.2680d	909.2	0.9914	0.988	1.014	1.673
Au197(n,2n)Au196	6.1830d	355.6	0.8700	0.983	1.014	3.909
Au197(n,2n)Au196		332.9	0.2290	0.983	1.019	4.163
Nb93(n,2n)Nb92m	10.150d	934.5	0.9900	0.974	1.007	1.624
Co59(n,2n)Co58	70.916d	810.8	0.9950	0.996	1.008	1.796
Ni58(n,p)Co58	70.916d	810.8	0.9950	0.992	1.008	1.796
Mn55(n,2n)Mn54	312.20d	834.8	0.9998	0.997	1.000	1.750
Fe54(n,p)Mn54	312.20d	834.8	0.9998	0.998	1.000	1.750

fG = gamma self-absorption correction factor
fSum = true coincidences summing-up correction factor
Eff. = efficiency at 10 cm foil to detector distance

In Eff there is 2 % error from the uncertainty in the calibration sources intensity plus 0.5 % in the efficiency determination. In all cases counting statistics was around 0.1% and the standard deviation bellow 0.5 %. Extrapolation and saturation calculations errors due to half life uncertainties were always negligible. The error due to γ ray branching, amounts to 1% in 356 keV Au196 photopeak and ≈ 2% in the 1115 and 1481 keV Ni65 photopeaks. fG and fSum errors were assumed to be equal to half the correction. The relative error in fGeo was estimated between 0.2% and 0. % according to foil location in the stack. For gold reactions the error arisen from fDiam is 0.5% and in the Au197(n,γ) reaction the error from fn is 2%. These errors added in quadrature amount to 3%.

Two activation runs were made, normalized to the same irradiation flux and averaged. The averaged activities standard deviation is 0.62%. The averaged saturated measured activities per atom, A∞-Exp, were used as input in the unfolding code SAND-II to get the neutron spectrum (Table 2).

Unfolding

SAND-II code[11,12] was used to determine the best fit neutron spectrum from the set of the 11 infinite diluted saturated measured activities. SAND-II capability to obtain a correct spectrum depends on the cross sections data and a reasonable guess of the

trial input spectrum.

Most cross section data up to 20 MeV with 5 to 10 % uncertainty, was taken from Manokhin et al.[13], these cross sections data are known with 5 to 10% uncertainty. Mn54(n,2n), Au197(n,2n), Fe54(n,p) and Ni58 (n,p) cross sections up to 20 MeV are the recommended values of Zhao Wenrong et al[14]. The n,2n reactions of Au197, Co59, Nb93 and Zr90 as well as the n,p reactions of Fe54 and Ni58, from 20 up to 30 MeV are from GreenWood[15] and normalized to be consistent with those up to 20 MeV. The Cu65(n,p)Ni65 reaction was renormalized taken into account the latest quoted cross sections[16].

The neutron spectrum from 23.2 MeV deuterons on Be, Lone1, was used as input spectrum.

The results from SAND-II code, after 9 iterations are in Table 2, where Aω-SAND is the calculated activity, dAv is the dispersion of Aω-Exp, E/C is the ratio of the measured to the calculated activity. Range is the energy span from the lower to the upper energy foil sensibility (activity bellow 5%). The standard deviation is 2.58%.

Table 2. SAND Iteration Results After 9 Iterations

Reaction	Aω-Exp d/s/atom	dAv %	Aω-SAND d/s/atom	E/C-1 %	Range MeV
Cu65(n,p)Ni65	3.80E-17	0.94	3.927E-17	-3.24	6.3-18.2
In115(n,n)In115m	8.55E-16	0.93	8.448E-16	1.21	1.3-13.6
Al27(n,α)Na24	1.97E-16	1.98	1.990E-16	-1.00	8.1-17.2
Au197(n,g)Au198	2.12E-16	0.54	2.125E-16	-0.22	0.3-12.3
Zr90(n,2n)Zr89	7.75E-16	0.38	7.603E-16	1.93	13.2-21.6
Au197(n,2n)Au196	3.00E-15	0.13	2.915E-15	2.92	9.7-18.4
Nb93(n,2n)Nb92m	5.90E-16	0.10	5.837E+16	1.07	10.5-19.2
Co59(n,2n)Co58	7.67E-16	0.59	7.571E-16	1.30	12.1-20.5
Ni58(n,p)Co58	1.61E-15	0.18	1.558E-15	3.36	3.6-15.0
Mn55(n,2n)Mn54	7.85E-16	0.35	8.157E-16	-3.76	11.7-20.2
Fe54(n,p)Mn54	1.33E-15	0.70	1.380E-15	-3.59	4.0-15.6
% Standard Deviation :		0.62		2.58	

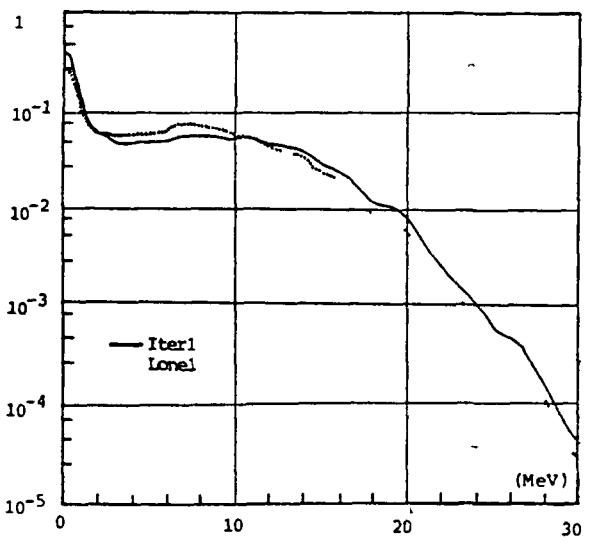

Fig. 2. SAND-II Output Spectrum Iter1 and Input Spectrum Lone1.

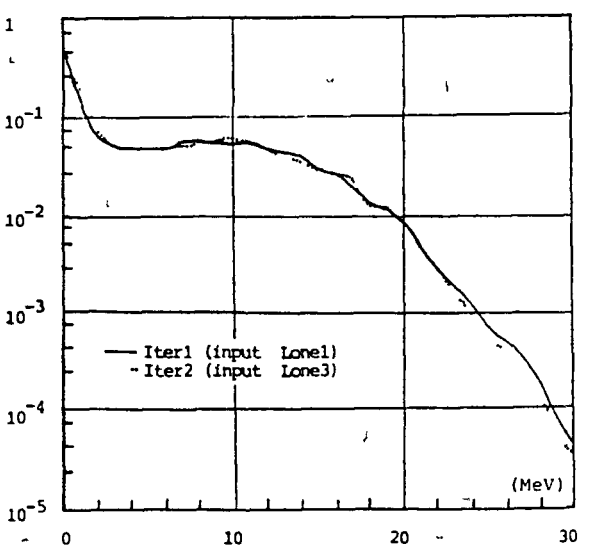

Fig. 3. Comparison of Iter1 and Iter2 Unfolded Spectra.

The solution spectrum as well as the input spectrum are shown in fig. 2. This output spectrum is referenced as Iter1.

Another input spectrum (Lone3), constant from 0.3 to 17 MeV and equal to Lone1 above 17 MeV, was also tried to test the dependence of the results on the input spectrum. The solution was achieved after 22 iterations (standard deviation=2.48%) and the neutron spectrum obtained, Iter2, is very close to Iter1, Fig. 3.

The integral fission cross sections, $\langle\sigma f\rangle$, of U235, U236, U238 and Th232 were calculated with these spectra and ENDF/B-V fission cross sections[17,18] up to 20 MeV. U235 cross section from 20 to 30 MeV is from Carlson et al[19] and normalized to ENDF/B-V. U238 and Th232 above 20 MeV were obtained from the ratio to U235, quoted by Lisowski[20]. $\langle\sigma f\rangle$ ratios calculated with Iter1 and Iter2 spectra agree better than 1%.

Table 3. Comparison of Two SAND Output Spectra

	Spectrum		Iter 1/2 - 1
	Iter1	Iter2	%
$\langle\sigma_{f\,Th232}\rangle / \langle\sigma_{f\,U238}\rangle$	0.3211	0.3192	-0.6
$\langle\sigma_{f\,Th232}\rangle / \langle\sigma_{f\,U235}\rangle$	0.1420	0.1410	-0.7
$\langle\sigma_{f\,U238}\rangle / \langle\sigma_{f\,U235}\rangle$	0.4421	0.4416	-0.1
$\langle\sigma_{f\,U236}\rangle / \langle\sigma_{f\,U235}$	0.6960	0.7011	-0.7

Fission Cross Section Ratios Measurement

To measure the cross section ratios the SSNTD stacks were irradiated together with a mock-up activation stack. A cadmium shield behind the stack was used to eliminate the small fraction of fissions produced in the U235 deposit by thermal and epithermal back reflection neutrons. An In cadmium ratio made at the irradiation site showed that without the cadmium shield this fraction would have been 2 to 3%. The contribution of low epithermal neutrons to the U235 fissions was estimated to be ≈ 0.1%.

The mica SSNTD detectors were etched and the fission tracks were counted after irradiation, as described in previous works[3,21]. Mass assay was based in $2\pi\alpha$ counting for uranium deposits and counting of Pa233 produced by thermal neutrons in Th232 for thorium deposits.

Table 4. Isotopic Composition and Constants of Uranium Deposits

	U234	U235	U236	U238
UENR (%)	0.57±.88%	95.27±.01%	0.0	4.16±.12%
UDEF (%)	0.0	0.0023±2%	0.0	99.9977
UNAT (%)	0.0055±4%	0.72±.7%	0.0	99.2745
UEN6 (%)	0.0	4.57±.1%	92.96±.05%	2.47±.2%
T1/2 (year)	2.445E5±.29%	7.04E8±.07%	2.342E7±.06%	4.47E9±.05%
$\langle\sigma f\rangle$ (barn)*	1.612±5%	1.520±5%	1.058±5%	0.6720±5%

* $\langle\sigma f\rangle$: Integral fission cross section in Iter1

Fissions per atom were determined, taken into account deposits mass and isotopic composition, from the counted tracks after cor-

rection for fission fragments absorption in the deposit, small flux differences due to position in the stack and different foil diameter. The isotopic composition of UENR, UEN6 and UDEP deposits was taken from the supplier (Oak Ridge,USAEC) and that of UNAT from a previous work[3] (Table 4).

Fission fragments absorption in the deposit (≈ 200 μg/cm² thick) was calculated taken into account the anisotropy of the angular fission fragment distribution because the angular and linear moment given to the nucleus by incident neutrons[22]. The anisotropy (W(0°)/W(90°)) was obtained from Simmons and Henkel[23]. The fragment absorption correction (1-I) is ≈2% for foils facing the beam and negligible for those facing away. I is the net inefficiency defined by Carlson[22].

To get U238 fissions in natural uranium 1.6 % correction was applied to correct for U235 fissions. The fissions from 0.57% U234 and 4.16% U238 in UENR amounts to 2.5%. In UEN6 the fission correction, from 4.5% U238, is 8.8%. The UENR, UEN6 and UDEP fissions were 3.8% corrected for different diameter (1.5 cm).

Two experiences were made for each ratio. Most experiences were made with a pair of foils, both foils facing or facing away the neutron beam. For Th232/U238 ratio, one experience (T02) was made with two back to back UNAT foils, one UDEP and one TH facing the beam. The stack foils and foil orientation of each experience are detailed in Table 5.

From the fissions per atom of U238 in UNAT and UDEF, U235 in UENR, U236 in UEN6 and Th232 in TH, the experimental integral fission cross section ratios ⟨σf⟩ of each experience were obtained and averaged. The three Th232/U238 ⟨σf⟩ ratios of run T02 were averaged prior average with T04. The experimental ⟨σf⟩ ratios from each run and final average results are in Table 5.

Table 5. Experimental Spectrum Averaged Fission Cross Section Ratios

	Nº	EXP	FOILS	⟨σf⟩ RATIO	χ^2	
Th232/U238		T02	TH12 / UN10	0.3110±3.18%		A,A
Th232/U238		T02	TH12 / UN2	0.3084±3.18%		A,B
Th232/U238		T02	TH12 / UDEF	0.3071±3.20%		A,A
Th232/U238	3	AVG	(T02)	0.3088±2.83%	0.26	
Th232/U238		T04	TH14 / UN10	0.3235±3.08%		B,B
Th232/U238	2	AVG	(T02 + T04)	0.3162±2.3%	1.50	
U238/U235		T03	UN10 / UENR	0.4569±2.42%		A,A
U238/U235		T06	UDEF / UENR	0.4521±2.15%		B,B
U238/U235	2	AVG	(T03 + T06)	0.4545±1.9%	0.17	
U236/U235		T06	UEN6 / UENR	0.7110±2.10%		B,B
U236/U235		T05	UEN6 / UENR	0.7051±3.07%		B,B
U236/U235	2	AVG	(T05 + T06)	0.7081±2.1%	0.09	

Last column : First and second foil orientation, A facing the neutron source, B facing away.

Discussion of Experimental Fission Rates Errors

The two main elements to be considered in the error estimation are the mass assay and the fission track counting statistics.

Errors in U deposits mass assay depends on α counting statis-

tics, uncertainties in the disintegration α rate per mg and corrections for α self absorption and α backscattering in the foil backing, fBack. UNAT α rate error comes from U238 α rate and the measured factor fexp = 2.054 ±0.5%[a]. The UENR deposit has a mass calibration from the supplier that differs 1% from our mass assay, therefore the error has been increased 1% (UENR cor). The error in TH foils mass assay arises from counting statistics, monitor weight and flux perturbation correction, Fth[a], errors.

Second we have systematic errors arising from fission rates

Table 6. Error Sources for Experimental Fission Rates

Source of Error	Error %	% Propagation of Error in Fission Rates				
		UNAT	UDEP	UENR	UEN6	TH
Random errors						
Tracks counting		1.5-1.7	1.3-1.7	1.0	1.0	1.8
α counting		0.28	0.28	0.11	.43-2.3	-
counting		-	-	-	-	1.8
Position in stack	2-5	0.2	.2-.3	0.2	0.2	0.2
Systematic errors						
U Isotopic composition[b]	a	.011	.000	0.82	.008	-
U-α decay half lives[c]	a	0.05	0.05	0.27	0.06	-
(measured constants)						
UNAT fexp[d]	0.5	0.50	-	-	-	-
UENR fcor[e]	1.0	-	-	1.0	-	-
U Deposit Area[b]	1.0	.002	.002	.003	.001	-
TH Deposit Area[f]	2.0	-	-	-	-	.017
Distance to target[g]	1.0	.05-.08	.05-.08	.004	.004	.005
Th monitor weight[f]	.01	-	-	-	-	0.01
(derived constants)						
α range(U3O8)[c]	10	0.13	0.11	0.12	0.10	-
fis.range (U3O8)[c]	10	0-.14	0-.13	0-.15	0	-
fis.range (ThO2)[f]	30	-	-	-	-	0-.26
fBack (Al)[h]	0.1	0.1	-	-	-	0.1
fBack (monel)[i]	0.3	-	0.3	0.3	0.3	-
= $\nu/\langle\nu\rangle$[j]	2.0	0-.02	0-.02	0-.02	0	0-.02
a_e[k]	2.5-7.8	0-.02	0-.02	0-.02	0	0-.02
(calculated constants)						
Th232 Fth[f]	0.5	-	-	-	-	0.5
Isotopes $\langle\sigma f\rangle$[b]	5.0	.115	.000	0.16	0.52	-
different diameter[i]	0.5	-	0.5	0.5	0.5	-
Final error		1.6-1.8	1.5-1.8	1.8	1.4-2.6	2.6

[a] Table 4.
[b] Correlated for measurements with U foils of the same material.
[c] Correlated for all measurements with U foils.
[d] Correlated for measurements with UNAT deposits not otherwise.
[e] Correlated for measurements with UENR deposit not otherwise.
[f] Correlated for all measurements with Th foils.
[g] Correlated for all measurements.
[h] Correlated for measurements with UNAT and TH deposits.
[i] Correlated for measurements with UDEP, UENR and UEN6 foils.
[j] = nucleus ν to fission fragments $\langle\nu\rangle$, used in (1-I) calculation. Correlated for all measures.
[k] $1-a_e/2$ = fission fragments angular distribution, used in (1-I) calculation. Correlated for measures with foils of the same material and UNAT with UDEP foils.

corrections. The fission fragment correction (1-I) error basically depends on the assumed error for fission fragments range[3] (10% in U3O8, 30% in ThO2). Fissions from other isotopes correction (fOI) error depends on isotopic composition and <σf> uncertainties. fGeo error comes from uncertainties in foils stack position (<0.4mm) and stack to source distance. The sources of errors and their propagation are listed in Table 6.

These errors together with the transformation matrix of fission rates were used to get the fission rates covariance matrix and errors as described in Ref. 24,25. With this matrix was calculated the covariance matrix of fission ratios. In same manner covariance matrix of average ratios was obtained in two steps. First to collapse the three ratios of experience T02 and from this 6x6 covariance matrix the three final average fission cross sections ratios, χ^2 and correlation matrix, tables 5 and 7 were obtained. To collapse the ratios we also try least square fit, as outlined by Smith[25] and no significant difference was found.

Table 7. Correlation Matrix for Experimental Fission Cross Section Ratios

	1	2	3	4
TH232/U238	1.000			
U238/U235	-0.032	1.000		
U236/U235	-0.005	0.526	1.000	
TH232/U235	0.761	0.623	0.337	1.000

Discussion and Results

In Table 8 the experimental fission cross section ratios of <σfTh232>, <σfU238> and <σfU236> to <σfU235> and <σfTh232>/<σfU238> are compared with those calculated with the evaluated ENDF/B-V cross sections averaged with the SAND-II unfolded spectrum, Iter1. The calculated <σf> ratios are consistent within the errors with the experimental values.

Table 8. Experimental and Calculated Integral Fission Cross Section Ratio Results

<σf> Ratio	Calculated	Experimental	C/E-1
Th232/U238	0.3211	0.3162±2.3%	1.5%
U238/U235	0.4421	0.4545±1.9%	-2.8%
U236/U235	0.6960	0.7081±2.1%	-1.7%
Th232/U235	0.1420	0.1437±2.9%	-1.2%

In Table 9, calculated and experimental ratios of the fissile isotopes measured in other neutron spectra are compared : a) fission spectrum of Cf252, b) fission spectrum from thermal neutrons on U235, c) spectrum produced by 7 MeV deuteron on a thick Be target. Similar consistency is observed in the spectrum from 7 MeV deuterons. However for fission spectra of Cf252 and U235, still persists a non explained discrepancy, 10% to 20%, particularly for

Th232.

Table 9. Fission Cross Section Ratios in Different Neutron Spectra

<σf> Ratio	Spectrum	Exp	Calc[a]	C/E-1 %	Ref
	7MeV d,Be	0.2580	0.2608	1.1	4
Th232	7MeV d,Be		0.2640[b]	2.3	4
———	Ther Fiss	0.2640	0.2464	-7.1	3
U238	Ther Fiss	0.2665		-8.2	2
	Cf252	0.2740	0.2489	-10.1	1
	23MeV d,Be	0.3162	0.3211	1.5	c
U238	7MeV d,Be	0.3780	0.3850	1.9	4
———	Cf252	0.2681	0.2540	-5.6	1
U235	Cf252	0.2741		-7.9	1
	23MeV d,Be	0.4545	0.4421	-2.8	c
U236	7MeV d,Be	0.6235	0.6620	6.5	4
———	7MeV d,Be		0.6670[b]	7.0	4
U235	23MeV d,Be	0.7081	0.6960	-1.7	c
Th232	7MeV d,Be	0.0975	0.1003	2.9	4
———	Cf252	0.0735	0.0630	-16.6	1
U235	Cf252	0.0751		-19.2	1
	23MeV d,Be	0.1437	0.1420	-1.2	c

[a] Most values calculated with ENDF/B-V
[b] Calculated with JENDL-2
[c] This paper

References

1. W. Mannhart, 'Handbook on Nuclear Activation Data', Tech. Rep. Series № 273, IAEA (1987). (Part 2-4, pp 420,421,425,426).
2. A.Fabry, W.N.McElroy, J.A.Grundl, G.E.Jansen, 'Neutron Cross Sections for Reactor Dosimetry', Vol. I (review papers), IAEA-280, 233, Vienna (1978).
3. M. Bovisio de Ficabarra, L. Cohen de Porto, D. Waisman, G.H. Ficabarra, 'Nuclear Data for Science and Technology', 123-126 (1988), Saikon Publishing Co., Proc. Int. Conf.,May 30-June 3, 1988, Mito, Japan. (Ed. Igarasi, JAE)
4. Y.Watanabe, J.W.Meadows, D.L.Smith, Ann. Nucl. Energy, 14, 563 -569 (1987).
5. J.H.Roberts, F.H.Ruddy, R.Gold, Nucl. Tracks, 8, 365 (1983).
6. M.A.Lone, C.B.Bigham, J.S.Fraser, H.R.Schneider,T.K.Alexander, A.J.Ferguson, A.B.McDonald, Nuclear Instr. Methods, 143, 331-344, (1977).
7. V.S.Shirley, 'Tables Radioactive Isotopes , J. Wiley & Sons, N. Y. (1986).
8. K.Dabertin, U.Schtzig, Nucl. Instr. Meth., 158, 471-477(1979).
9. D.S.Andreev et al., Izv. Akad. Naut. SSSR, Ser. Fiz., 37, 1609 (1973).
10. G.J. McCallum, G.E. Coote, Nucl. Instr. Meth., 130, 189(1975).
11. S. Berg, F.G. Hawkins, AFWL-TR-67-41, Vol. I (1967).

12. S. Berg, W.N. McElroy, AFWL-TR-67-41, Vol. II (1967).
13. V.N. Manokhin et al., 'Handbook on Nuclear Activation Data', Tech. Rep. Series Nº 273, IAEA (1987). (Part 2-3, pp 305-309)
14. Zhao Wenrong et al., 'Compilation of Measurements and Evaluation of Nuclear Activation Cross Sections for Nuclear Data Applications', INDC(CPR)-16 (1989).
15. L.R.Greenwood et al., Nucl. Science Eng., 72, 175-190 (1979).
16. H.M.Agraval et al., 'Progress Rep. on Nucl. Data Research of Fed. Rep. Germany', 4/1/88-3/31/89, INDC-34/LN+Special (1989).
17. ENDF/B-V Standards Library, IAEA-NDS-13.
18. ENDF/B-V Dosimetry Library, IAEA-NDS-24.
19. A.B. Carlson et al., 'Nuclear Datafor Science and Technology', 1029-1032,(1988). (id. Ref 3)
20. P.W. Lisowski et al., 'Nuclear Data for Science and Technology', 97-99, (1988). (id. Ref 3).
21. M.D.B. Ricabarra, D.Waisman, CNEA-453 (1979).
22. G.W. Carlson, Nucl. Instr. Methods, 119, 97 (1971).
23. J.E. Simmons, R.L. Henkel, Physic Rev., 120, 1981 (1960).
24. D.L.Smith, ANL/NDM-62 (1981).
25. D.L. Smith, Nucl. Instr. Methods, A257, 361-364, (1987).