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FAST REACTOR INTEGRAL EXPERIMENTS FOR VALIDATING THE CROSS-SECTION DATA FOR HIGHER PLUTONIUM ISOTOPES

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1. INTRODUCTION.

The fast spectrum measurements carried out by the CEA for validating the data for the higher isotopes of plutonium are of three types:

(a) Effective multiplication measurements:
k_∞ measurements made for a series of test zones with different plutonium vectors, (8%, 18% and 44% Pu-240) by means of cell substitution reactivity worth measurements at the core centre. These are:
the PLUTO programme OP10, OP40, OP50, OP11, OP41
where OP10 (8% Pu-240), OP40 (18% Pu-240) and OP50 (44% Pu-240) were cores without sodium and
OP11 (8% Pu-240) and OP41 (18% Pu-240) were cores with sodium,
Buckling measurements in a series of cores:
ZOCO1 with 8%, 18% and 44% Pu-240
ZONA2 with 8%, 18% and 44% Pu-240

(b) Fission ratio measurements made using fission chambers at the central position of the cores:
Fission ratios (relative to U-235 fission) for Pu-240, Pu-241 and Pu-242 in:
OP10, OP40, OP50, OP11, OP41 and Z3
ZOCO1 with 8%, and 18% Pu-240
ZONA3 with 8%, and 18% Pu-240
together with the cores R1, R3, Z3, HO,
Measurements have also been made of fission ratios for Pu-238 and Am-241 in:
RONA3, ZONA1, ZONA3 and ZOCA1 (all with 8% Pu-240).

(c) Irradiations of isotopic samples in PHENIX, the PROFIL1 and PROFIL2 programmes. These give information about capture and (n,2n) cross-sections relative to U-235 fission together with some information on fission cross-sections. Measurements have also been made for Np-237, Pu-238, Am-241 and Am-243.

2. DISCUSSION OF THE RESULTS OF JEF-2.2 ANALYSES OF THE MEASUREMENTS.

The results are presented in the following tables. In some cases the quoted uncertainties are perhaps optimistic. For example, the accuracy quoted for the U-238/U-235 fission ratio measurement in OP40 is ±0.5% whereas ±3% is probably more realistic for threshold fission reactions measured in critical facilities (taking into account modelling approximations in the representation of the detectors in the cell calculation) and ±2% for fission ratios in fissile isotopes. Similarly, the measurement of U-238 capture is difficult and probably has an uncertainty greater than the quoted ±1.5% (perhaps ±3% also). In the interpretation of the PROFIL experiments there are probably also modelling approximations in the calculations. Discrepancies between measurement and calculation could be due to errors in calculation of the core spectra, in particular for threshold fission reactions, such as U-238, Pu-240 and Pu-242 fission.

Effective multiplication.

The values of k_∞ or the values of k_{eff} corresponding to a measured buckling show no clear trends with the plutonium vector. One must rely on the general cross-section adjustment studies to draw conclusions from these (and indeed for all of the results).

U-235

Capture. The measurements of the capture to fission ratio made in PROFIL1 and 2 indicate an underestimation of the ratio by about 7% ±1% for JEF-2.2.

(n,2n). The (n,2n) reaction rate ratio relative to U-235 fission has also been measured, the small underestimation being within the range of the uncertainty, 4% ±4%.

U-238

Capture. Measurements of the ratio C(U-238)/F(U-235) have been made in OP10, OP50, PROFIL1 and PROFIL2. For these measurements the JEF-2.2 calculations underestimate the ratio by about 3% ±2% on average. However there are many more experiments which give information on this ratio which must be taken into account.

Fission. The ratio F(U-238)/F(U-235) is sensitive to the accuracy of the calculation of the spectrum as well as the data for these cross-sections. The ratio is well predicted in the PROFIL1 measurement but shows a wide range of

discrepancies in the OP series of measurements , with an average overestimation of about 4% ±2%.

(n,2n). The (n,2n) cross-section has been measured in PROFIL1, the underestimation obtained in the JEF-2.2 calculation being about a factor of 4. However the result is regarded with some caution because there is only the one measurement.

Np-237

Capture. Measurements of the capture ratio C(Np-237)/F(U-235) have been made in PROFIL2. These indicate an underestimation of the ratio by about 6% ±4% for JEF-2.2.

(n,2n). The (n,2n) reaction rate ratio has also been measured in PROFIL2. The JEF-2.2 calculation overestimates the value by 20% ±15%.

Pu-238

Fission. The ratio F(Pu-238)/F(U-235) has been measured in RONA3 and ZONA1. In both cores the JEF-2.2 calculations overestimate the ratio by about 25% ±2%.

Capture. The ratio C(Pu-238)/F(U-235) has been measured in PROFIL1 and PROFIL2. The small underestimation is within the uncertainty of the measurement, 3% ±3%.

Pu-239

Fission. The fission ratio measurements F(Pu-239)/F(U-235) is well predicted in the PROFIL2 experiment (to within the ±2% accuracy). In the OP series of experiments the JEF-2.2 calculations give an average underestimation of the ratio by about 3%.

Capture. For the ratio C(Pu-239)/F(U-235) the PROFIL measurements indicate an underestimation by about 4% ±2%. The net effect is a small underestimation of the alpha value of Pu-239. However, account must be taken of the many other experiments which give information on these ratios.

(n,2n). For the (n,2n) value of Pu-239 the JEF-2.2 data significantly underestimate the PROFIL measured values. The cross-section should be increased by about 60%.

Pu-240

Capture. The ratio C(Pu-240)/F(U-235) has been measured in PROFIL1 and PROFIL2. The JEF-2.2 calculations overestimate the measured ratio by 11% ±2%.

Fission. The fission ratio measurements F(Pu-240)/F(U-235) made in the OP series of cores show a wide range of discrepancies between measurement and calculation, ranging from agreement to within the uncertainties of about ±3% to an overestimation of 7% in OP10 and 16% in OP40. However there is also an overestimation of the F(U-238)/F(U-235) ratio in OP40 by 6%, suggesting that there might be a discrepancy in the high energy spectrum. When the fission ratio is considered relative to U-238 fission, F(Pu-240)/F(U-238), the discrepancies are less marked and are mostly within the uncertainties of measurement.

(n,2n). The (n,2n) reaction rate ratio has been measured in both PROFIL1 and 2, the average underestimation being within the average uncertainty of the measurements, 8% ±14%.

Pu-241

Capture. The ratio C(Pu-241)/F(U-235) has been measured in both PROFIL1 and PROFIL2. The JEF-2.2 calculations overestimate the measured ratio by 22% ±4%.

Fission. The fission ratio has been measured in a large number of cores and the values are within the uncertainties on the measurements.

(n,2n). The (n,2n) reaction rate ratio has been measured in PROFIL1, the overestimation being within the uncertainty of the measurement, 4% ±4%.

Pu-242

Capture. The ratio C(Pu-242)/F(U-235) has been measured in both PROFIL1 and 2. The JEF-2.2 calculation overestimates the measured ratio by 15% ±4%.

Fission. The fission ratio, when related to the U-238 fission rate, F(Pu-242)/F(U-238), is within the uncertainty of the measurements, ±3%, in the two ZONA3 and ZOCO1 cores and the PROFIL1 measurement F(Pu-242)/F(U-235), is predicted to within the uncertainty, -6% ±9%. However ,the measurements of F(Pu-242)/F(U-235) made in the OP10 and OP40 cores are

overestimated by 9% ±3% and 16% ±3%, respectively, results which are difficult to reconcile with the others.

Am-241

Capture. The ratio C(Am-241)/F(U-235) has been measured in both PROFIL1 and PROFIL2. The JEF-2.2 calculations overestimate the measured ratio by 3% ±1%.

Fission. The fission ratio measurements F(Am-241)/F(U-235) made in RONA3, ZONA1, ZONA3(8% Pu-240) and ZOCO1(8% Pu-240) show such a wide scatter of results that one must surely discount them.

Am-243

Capture. The ratio C(Am-243)/F(U-235) has been measured in PROFIL1. The JEF-2.2 calculations underestimate the measured ratio by 4% ±5%, that is, within the uncertainty.

Cadarache, 1 December 1994.

	K_PLUS			
	E	C	C/E-1 in pcm	Uncertainties in pcm
OP10	0.98535	0.99034	506	311
OP40	0.93250	0.93486	253	400
OP50	0.98027	0.98305	284	292
OP11	1.01580	1.03305	1698	387
OP41	0.97470	0.98039	583	367

= 1.7 %

Keff				
	E	C	C/E-1 in pcm	
ZOCO1 8%	1.00000	0.99634	-366	
ZOCO1 18%	1.00000	0.99283	-717	
ZOCO1 44%	1.00000	0.99894	-106	
ZONA2 8%	1.00000	1.00511	511	
ZONA2 18%	1.00000	1.01246	1246	
ZONA2 44%	1.00000	1.02455	2455	

= 2.5 %

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Comparison Calculation /Experiment Jef2/Ecco				
OP10	*E*	*C*	C/E-1	***Uncertainties***
f8/f5	2.016E-02	2.048E-02	1.6%	2.6%
c8/f5	1.403E-01	1.367E-01	-2.5%	1.5%
f9/f5	9.326E-01	9.035E-01	-3.1%	1.0%
f40/f5	1.641E-01	1.760E-01	7.3%	3.2%
f41/f5	1.260E+00	1.316E+00	4.4%	3.7%
f42/f5	1.079E-01	1.176E-01	8.9%	3.2%
OP40	*E*	*C*	C/E-1	***Uncertainties***
f8/f5	1.950E-02	2.069E-02	6.1%	0.5%
f9/f5	9.280E-01	9.068E-01	-2.3%	1.7%
f40/f5	1.600E-01	1.759E-01	9.9%	3.0%
f41/f5	1.290E+00	1.316E+00	2.0%	3.8%
f42/f5	1.020E-01	1.180E-01	15.7%	2.8%
OP50	*E*	*C*	C/E-1	***Uncertainties***
f8/f5	2.000E-02	2.052E-02	2.6%	1.0%
c8/f5	1.410E-01	1.370E-01	-2.9%	1.4%
f9/f5	9.200E-01	9.048E-01	-1.6%	1.3%
f40/f5	1.630E-01	1.760E-01	7.9%	2.9%
OP11	*E*	*C*	C/E-1	***Uncertainties***
f8/f5	2.025E-02	2.035E-02	0.5%	1.4%
f9/f5	9.950E-01	9.561E-01	-3.9%	0.7%
f40/f5	1.893E-01	1.864E-01	-1.6%	3.7%
f41/f5	1.330E+00	1.330E+00	0.0%	3.7%
f42/f5	1.304E-01	1.257E-01	-3.6%	3.4%
OP41	*E*	*C*	C/E-1	***Uncertainties***
f8/f5	1.960E-02	2.052E-02	4.7%	1.0%
f9/f5	9.970E-01	9.581E-01	-3.9%	2.8%
f40/f5	1.870E-01	1.860E-01	-0.5%	2.7%
f41/f5	1.330E+00	1.329E+00	0.0%	3.8%
f42/f5	1.270E-01	1.258E-01	-1.0%	2.4%

Fe/F5 4 ± 2 %.

can draw any simply conclusions from these analyses

Pu240f/U8f				
	Experiment	Uncertainty	Calculation	C/E-1
Core	E	in %	C	in %
R1	8.10	3.2	7.98	-1.4
R3	8.36	4.2	8.59	2.8
Z3	8.11	4.3	8.70	7.2
HO	6.70	3.1	7.11	6.2
ZONA3 8%	8.07	2.5	8.14	0.9
ZONA3 18%	8.38	2.5	8.13	-2.9
ZOCO1 8%	6.93	3	6.99	0.8
ZOCO1 44%	6.83	3	6.98	2.2

Pu241f /U5f				
	Experiment	Uncertainty	Calculation	C/E-1
Core	E	in %	C	in %
R1	1.31	3.0	1.34	2.5
R3	1.32	3.4	1.34	1.2
Z3	1.31	3.0	1.32	0.7
HO	1.34	2.6	1.34	-0.1
ZONA3 8%	1.30	3.0	1.32	1.5
ZONA3 18%	1.28	3.0	1.32	3.0
ZONA3 44%	1.31	3.0	1.32	0.5
ZOCO1 8%	1.31	3.5	1.34	2.3
ZOCO1 18%	1.32	3.5	1.34	1.4
ZOCO1 44%	1.33	3.5	1.34	0.6

results consistent

Pu242f /U8f				
	Experiment	Uncertainty	Calculation	C/E-1
Core	E	in %	C	in %
ZONA3 8%	5.53	2.5	5.62	1.6
ZONA3 44%	5.55	2.5	5.61	1.1
ZOCO1 8%	5.09	3.0	5.20	2.2
ZOCO1 44%	5.19	3.0	5.17	-0.4

results consistent

Pu238f /U5f				
	Experiment	Uncertainty	Calculation	C/E-1
Core	E	in %	C	in %
RONA3 Ermine	0.456	2.1	0.58	27.7
ZONA1 Ermine	0.530	2.3	0.66	24.9

25% high

Am241f /U5f				
	Experiment	Uncertainty	Calculation	C/E-1
Core	E	in %	C	in %
RONA3 Ermine	0.2180	7.0	0.14	-34.3
ZONA1 Ermine	0.2290	6.4	0.19	-15.3
ZONA3 8%	0.1200	3.8	0.14	14.5
ZOCO1 8%	0.2430	7.3	0.26	8.1

large spread of values

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Dans le tableau suivant, on compare les résultats obtenus pour les deux campagnes d'irradiation **PROFIL1** et **PROFIL2**:

	PROFIL1	PROFIL2	C/E moyen et incertitude (%)	Résultats JEF1 /6/
σ_c^{235U}	0.93 ± 1.7 %	0.92 ± 1.7 %	0.93 ± 1.2 %	0.97 ± 1.4 %
$\sigma_{n,2n}^{235U}$	0.95 ± 5.0 %	0.96 ± 5.0 %	0.96 ± 3.5 %	
σ_c^{238U}	0.95 ± 2.3 %	0.96 ± 2.3 %	0.96 ± 1.6 %	0.95 ± 1.6 %
σ_f^{238U}	1.00 ± 1.4 %		1.00 ± 1.4 %	
$\sigma_{n,2n}^{238U}$	0.27 ± 6.0 %		0.27 ± 6.0 %	
σ_c^{238Pu}	0.97 ± 4.0 %	0.98 ± 4.0 %	0.97 ± 2.8 %	0.95 ± 2.8 %
σ_c^{239Pu}	0.96 ± 3.0 %	0.95 ± 3.0%	0.96 ± 2.1 %	0.97 ± 1.8 %
σ_f^{239Pu}		1.00 ± 2.2 %	1.00 ± 2.2 %	
$\sigma_{n,2n}^{239Pu}$	0.65 ± 15.0 %	0.58 ± 15.0 %	0.62 ± 10.6 %	1.38 ± 10.6 %
σ_c^{240Pu}	1.10 ± 2.2 %	1.12 ± 2.2 %	1.11 ± 1.6 %	1.06 ± 1.6 %
$\sigma_{n,2n}^{240Pu}$	0.95 ± 20 %	0.88 ± 20 %	0.92 ± 14.1 %	0.83 ± 14.1 %
σ_c^{241Pu}	1.24 ± 4.1 %	1.17 ± 5.9 %	1.22 ± 3.6 %	1.11 ± 3.7 %
σ_f^{241Pu}	0.98 ± 3.3 %		0.98 ± 3.3 %	
$\sigma_{n,2n}^{241Pu}$	1.04 ± 4.1 %		1.04 ± 4.1 %	
σ_c^{242Pu}	1.18 ± 3.5 %	1.11 ± 4.3 %	1.15 ± 2.8 %	1.16 ± 3.5 %
σ_f^{242Pu}	0.94 ± 8.6 %		0.94 ± 8.6 %	
σ_c^{243Am}	0.96 ± 5.0 %		0.96 ± 5.0 %	0.94 ± 5.0 %
σ_c^{241Am}	1.03 ± 1.7 %	1.03 ± 0.9 %	1.03 ± 1.0 %	1.03 ± 1.4 %
σ^{237Np}		0.94 ± 4.1 %	0.94 ± 4.1 %	0.90 ± 4.1 %
$\sigma_{n,2n}^{237Np}$		1.20 ± 15.0 %	1.20 ± 15.0 %	1.19 ± 15.0 %

Tous les taux ont été rapportés aux fissions de l'^{235}U.

e. Fast feels that -4% on ^{238}U is unrealistic.

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