DE LA RECHERCHE À L'INDUSTRIE

Application of EGPT in the analysis of small-sample reactivity worth experiments

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OUTLINE

- Introduction
- Selected experiments
- Analysis methodology
- Application to ^{103}Rh capture
- Conclusions and perspectives

INTRODUCTION

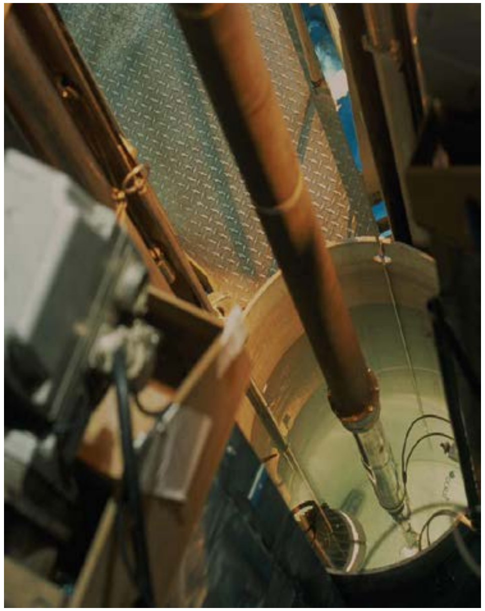
- **Specificities of *small-sample reactivity worth* (SSRW) experiments with respect to other kinds of RW experiments (void coefficient, doppler, absorber efficiency…)**

  - Small in terms of geometrical size (∅ ≈ 1cm. L ≈ 10cm)
    ⇨ Low sensitivity to flux gradiants

  - Small in terms of reactivity worth (1-10 pcm)
    ⇨ No influence on the global production of neutrons in a critical assembly (<0.1%)

  - Limited number of isotopes / elements

  - Under special spectral conditions, possibility to emphasis one type of reaction (capture, scattering)



⇨ In suitable conditions, SSRW can be related to limited number of parameters that make such experiments relevant for nuclear data improvement

INTRODUCTION

- **Computing SSRW can be a tricky issue**

$$\Delta\rho = \frac{k_2 - k_1}{k_2 k_1}$$

⇨ The more k_1 is close to k_2, the higher convergence criteria must be required

- **Moreover, SSRW is often the first step before computing sensitivity coefficients for nuclear data analysis / feedback**

$$S(\Delta\rho) = \frac{1}{\Delta\rho}\left(\frac{\delta\rho_2}{\frac{\delta\sigma_i}{\sigma_i}} - \frac{\delta\rho_1}{\frac{\delta\sigma_i}{\sigma_i}}\right) = \frac{S(\rho_2) - S(\rho_1)}{\Delta\rho}$$

⇨ In addition to the computation limits of $\Delta\rho$ in case of small RW, sensitivities to reactivities ρ can be several orders of magnitude higher than $\Delta\rho$

⇨ Potential issues of « zero / zero »

Various methods for calculating SSRW experiments

Methods for SSRW calculation	Deterministic code	Probabilistic code
Eigen-value difference (EV)	+ Easy to implement/use - Model simplifications (energy, geometry, leakage model…) - Numerical convergence issues	+ Exact method - Huge computation time
Standard perturbation theory (SPT)	+ (Almost) no convergence issues ($\Delta\phi \Rightarrow \Delta\sigma$) - Not implemented in every code (sometimes, only 1st order SPT)	+ Best method in case of exact SPT - Mostly 1st order SPT - Convergence issues with scattering effects

⇨ Recent implementation of IFP-based perturbation methods in Monte-Carlo codes (TRIPOLI, SERPENT, MCNP…) is a huge improvement for an accurate calculation of SSRW

What about the sensitivity analysis of SSRW?

Methods for sensitivity analysis of SSRW	Deterministic code	Probabilistic code
Equivalent Generalized Perturbation Theory (EGPT)	+ All sensitivity vectors available in a single calculation - Numerical convergence issues linked to the computation of $\Delta\rho$ and $\Delta S(\rho)$	- Convergence issues due to the difference of two sensitivity computations
Direct Perturbation (DP)	+ Easy to implement/use + Can be applied at several stages (ENDF files. micro-lib. macro-lib…) - Required home-made scripts to perturbate the data	- Convergence issues - No available methods for doing « perturbations of perturbations »

⇨ **Reliability of the EGPT method in the analysis of SSRW experiments?**
See P. Ros et al., « A revision of sensitivity analysis for small reactivity effects in ZPRs", Proc. Of ICAPP, avril 2017 conference, Kyoto, Japan

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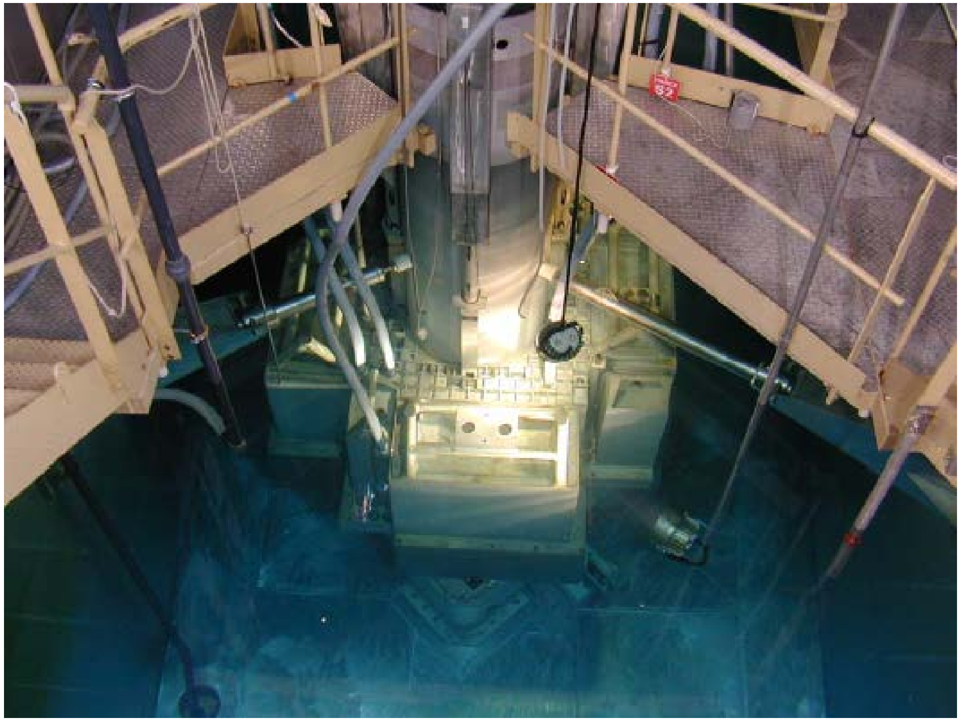
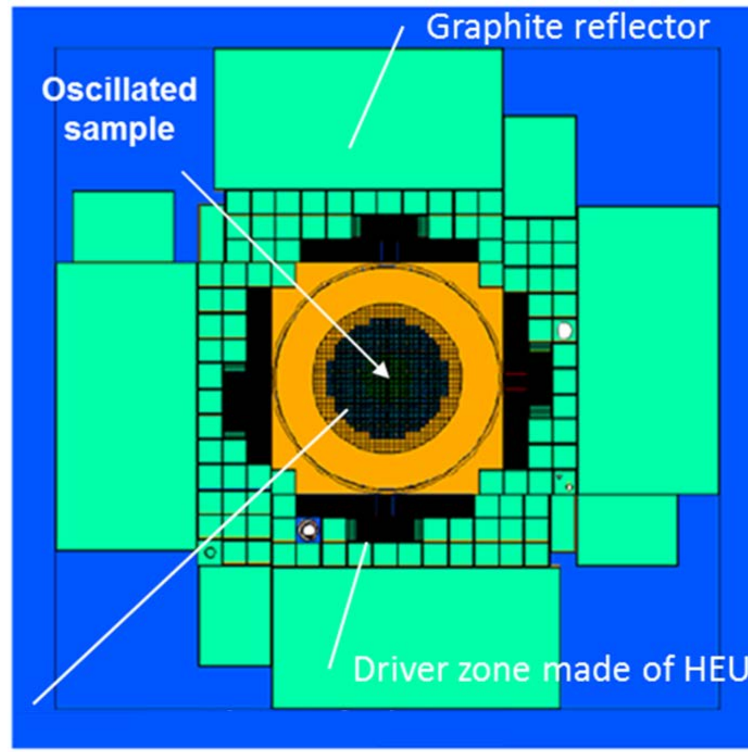
SELECTED EXPERIMENTS
The Minerve Reactor (CEA Cadarache)





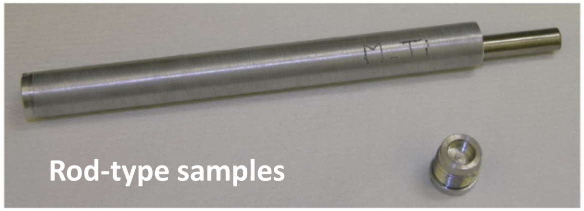
- **MINERVE Characteristics**
  - Pool-type reactor (100W max)
  - Light Water at ambiant temperature
  - Reflector: large graphite blocks
  - Driver zone: MTR elements (UAl plates, >90% ^{235}U)
  - Test zone: thermal or fast spectrum configurations

SELECTED EXPERIMENTS
The MAESTRO experiment (2012-2016)

Validation of nuclear on a large range of materials used in GEN-II/GEN-III reactor cores

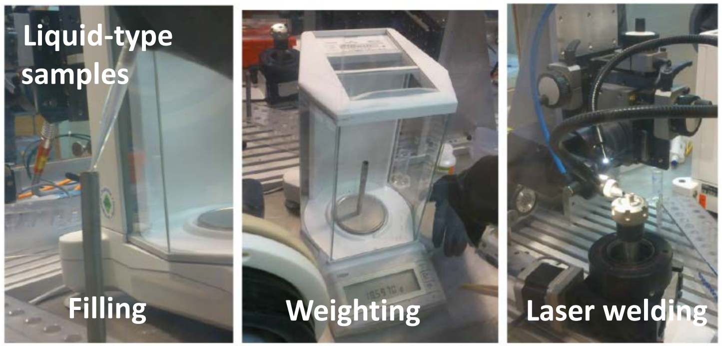
More than 60 samples :

- Moderating materials: H_2O, ^{nat}Be, ^{nat}C, CH_2
- Structural materials: ^{nat}Mg, ^{nat}Al, ^{nat}Cl, ^{nat}Ca, ^{nat}Ti, ^{nat}Cr, ^{nat}Fe, ^{nat}Ni, ^{nat}Cu, ^{nat}Zn, ^{nat}Zr, ^{nat}Mo, ^{nat}Sn
- Detection materials: ^{nat}V, ^{nat}Mn, ^{nat}Co, ^{nat}Nb, **^{nat}Rh**
- Absorbing materials: ^{nat}Ag, ^{nat}In, ^{nat}Cd ^{nat}Eu, ^{nat}Gd, ^{nat}Dy, ^{nat}Er, ^{nat}Hf ^{153}Eu, ^{107}Ag, ^{nat}Cs
- Industrial alloys: Zy4, M5, SS304, SS316, Inconel-800
- Calibration materials ^{nat}Au, ^{6}Li, ^{10}B

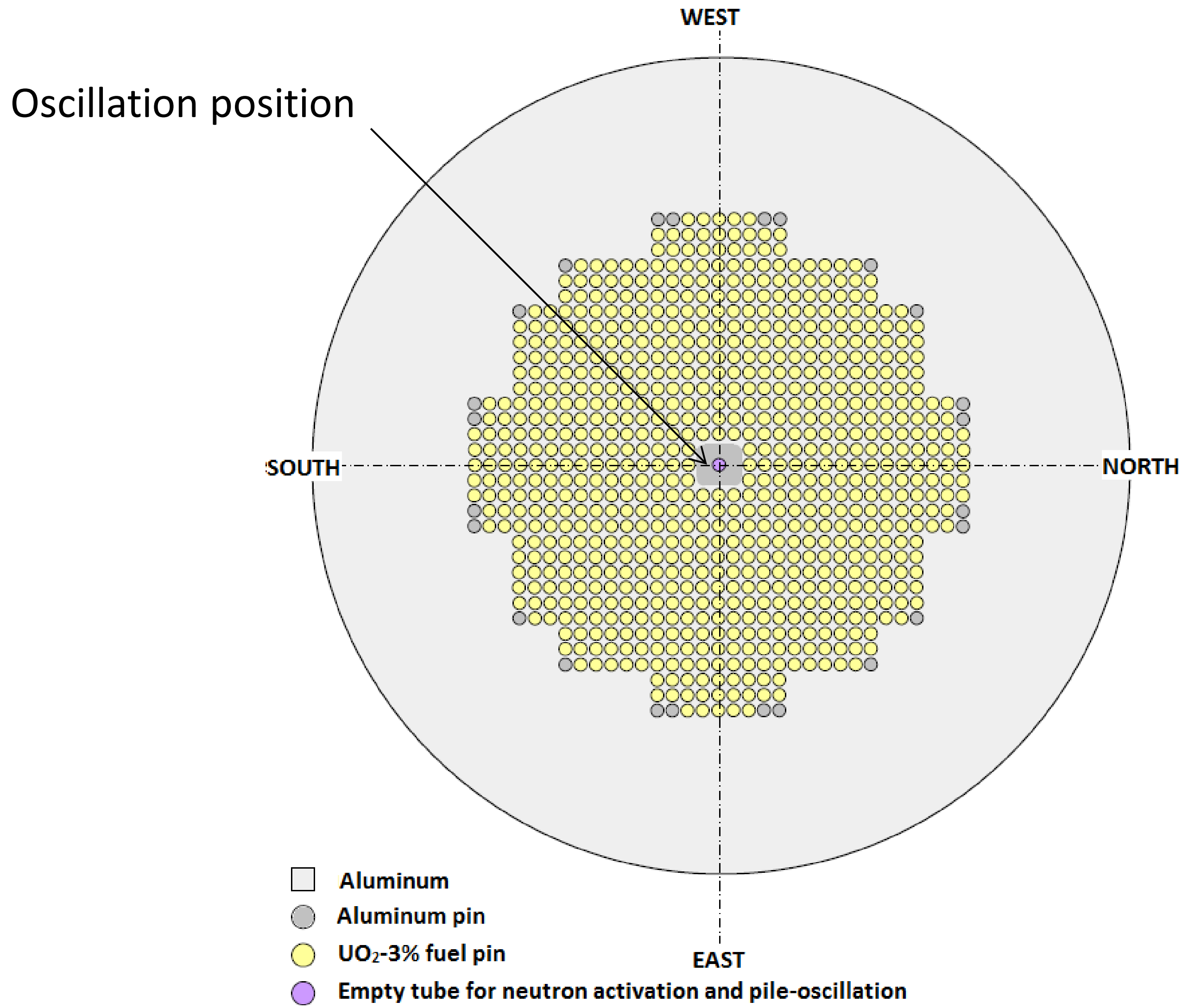


- **Both pile oscillation and neutron activation experiments**

- **10-30cm long tubes filled with materials of different physical forms**
  - Pure rods
  - Liquid solutions
  - Powder mixed with Al_2O_3 diluant



The MAESTRO core configuration



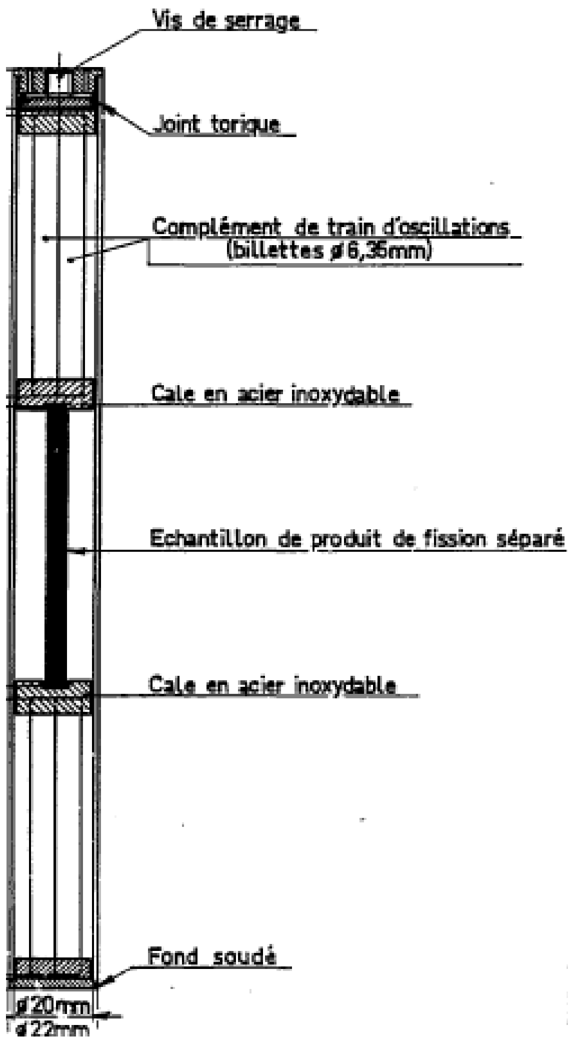
SELECTED EXPERIMENTS
The ERMINE-V experiment (1974-1979)

Validation of the integral capture of fission products in SCFR in support to SUPER-PHENIX

- **Various kinds of samples in 3-10cm long tubes:**
  - Individual fission products: ^{141}Pr, ^{133}Cs, ^{99}Tc, **^{103}Rh**, ^{98}Mo, ^{100}Mo, ^{104}Ru, ^{108}Pd, ^{142}Ce, ^{146}Nd, ^{148}Nd, ^{150}Nd, ^{152}Nd
  - Irradiated fuel pins from PHENIX and RAPSODIE

- **Both pile oscillation and neutron activation experiments**

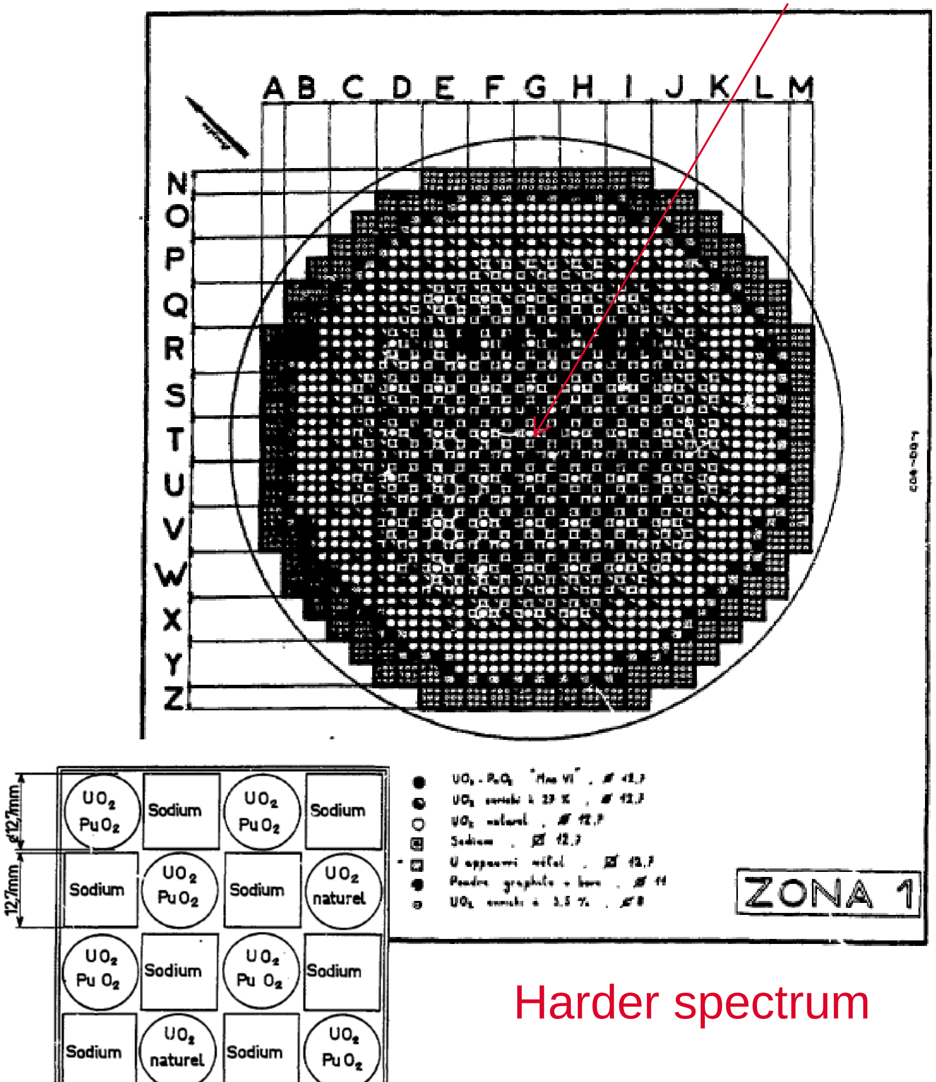
- **In parallel of the PROFIL and PROFIL-2 irradiation experiments in PHENIX**



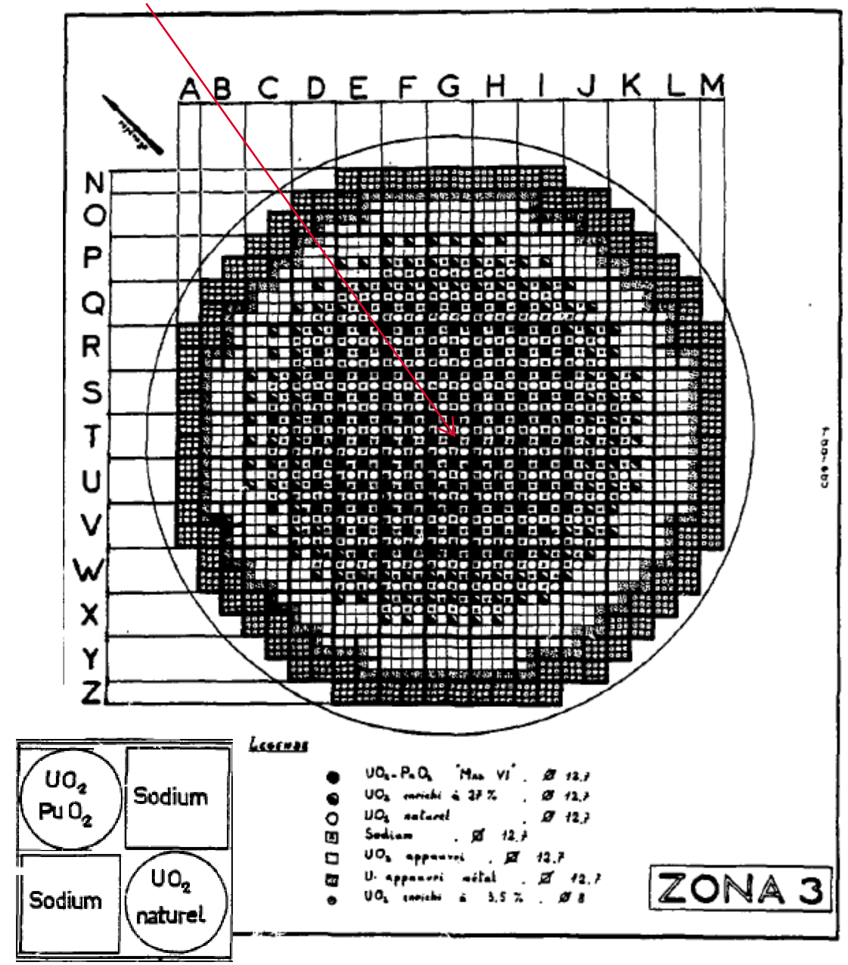
SELECTED EXPERIMENTS
The ERMINE-V experiment (1974-1979)

The ERMINE-5 experiment (1974-1979)

Oscillation position



Harder spectrum



Softer spectrum

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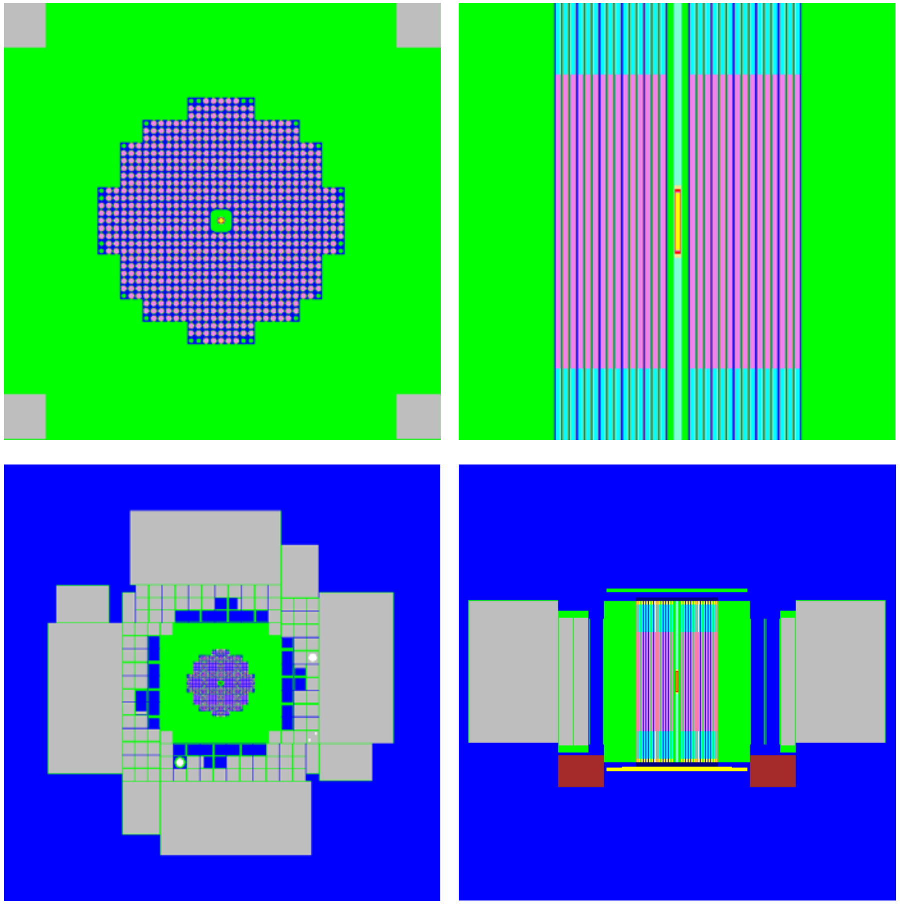
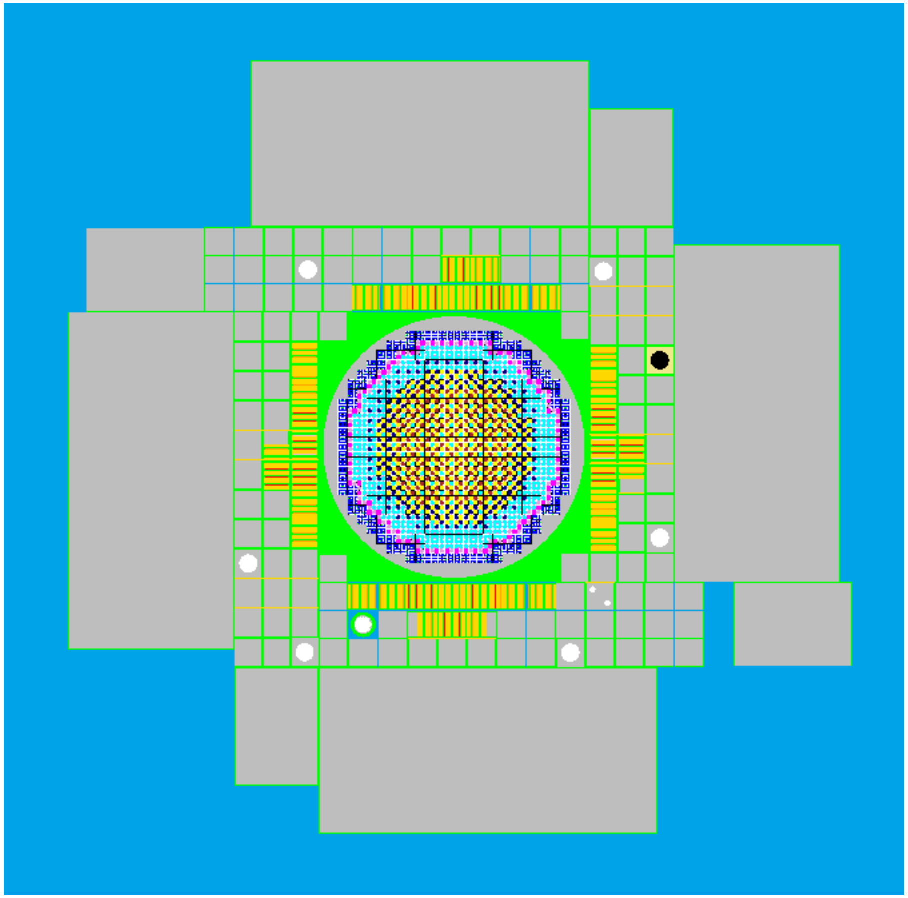
TRIPOLI-4 modeling

MAESTRO core

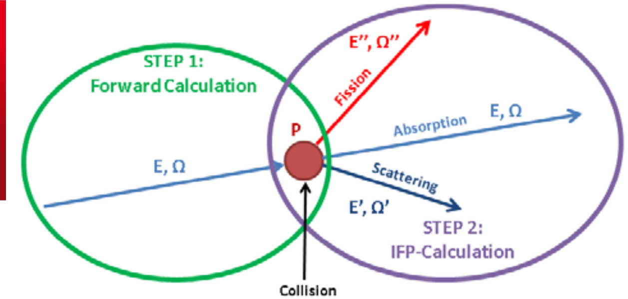


ERMINE-V / ZONA 1 core



DE LA RECHERCHE À L'INDUSTRIE

cea den **ANALYSIS METHODOLOGY**



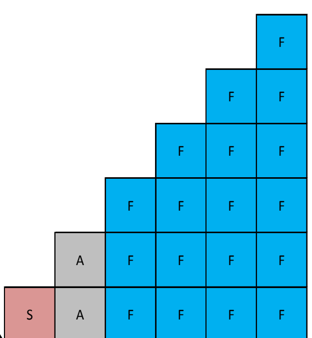
Computation of SSRW

- **Exact SPT method in TRIPOLI-4**
  - Continuous energy forward flux calculation + collision locus storage
  - Continuous energy adjoint flux calculation for each stored collision
  - Computation of the reactivity worth with various collapsing options
  - ⇨ **$10^3 – 10^4$ h.CPU per sample**

Computation of sensitivity coefficents to SSRW

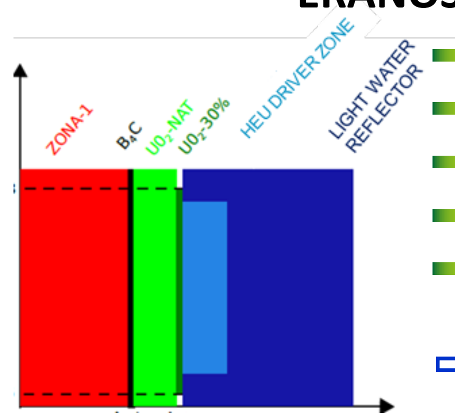
- **Computation of sensitivities with deterministic methods**

APOLLO-2.8



- 2D/XY 13x13 lattice
- Critical buckling
- 281g self-shielding
- P_{ij}–multicell method
- SPT computation for senstivity to reactivity
- ⇨ **2 min per sample**

ERANOS-2.3



- 2D/RZ full core model
- 1968g XS self-shielding
- Collapsing to 33g
- S_n method (BISTRO)
- EGPT computation for sensitivity to RW
- ⇨ **10 min per sample**

EGPT method vs Direct Perturbation method

- **DP method**
  - 1 nominal RW calculation
  - 1 RW calculation with modified XS

- **EGPT method**
  - 1 sensitivity calculation (fine mesh = 281G) for the unperturbed reactivity $S(\rho_1)$
  - 1 sensitivity calculation (fine mesh = 281G) for the perturbed reactivity $S(\rho_2)$
  - Computation of sensitivity coefficients by $S(\Delta\rho)=(S(\rho_2)- S(\rho_1))/\Delta\rho$ in MATLAB
  - Collapsing on various possible meshes (15, 26, 33…)

- **Application on $\Delta\rho_{Rh}$ in the MAESTRO experiment**

Sensitivity method	**1-group sensitivity coefficient (%/%)**		
	Rh capture	^{235}U Nu_tot	^{1}H elastic scat.
EGPT	0.918	-0.855	-0.738
DP	0.930	-0.870	-0.834

⇨ The EGPT is consistent with the direct perturbation method

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APPLICATION TO ^{103}RH CAPTURE

Calculation / Experiment comparison

Experiment	C/E-1 TRIPOLI-4DEV + JEFF-3.2
MAESTRO	1.4% ± 1.4%
ERMINE-V/ZONA1	-5.5 ± 1.5%
ERMINE-V/ZONA3	0.2 ± 1.5%

Preliminary

- **ERMINE-V ⇨ only measurement uncert + MC convergence**
- **In the current analysis, an arbitrary 3% uncertainty will be added to account for technological uncertainty (fuel composition, density, dimensions…)**

EGPT on ^{103}Rh RW – MAESTRO experiment

Sensitivity coefficients (%/%) on $\Delta\rho_{Rh}$

	CAPT	FISS	EL+INEL	NU	SUM
Rh103	**0.902**		**-0.001**		**0.901**
H1	**0.014**		**-0.738**		**-0.724**
O16	0.003		-0.010		-0.007
Al27	-0.031		0.005		-0.026
U235	**0.067**	**-0.532**	**~0**	**-0.818**	**-1.283**
U238	0.172	-0.104	-0.002	-0.127	-0.061

⇨ **Large indirect effects due nuclear data influencing either:**

- the number of neutrons at thermal energy: ^{1}H(n,el), ^{235}U(n,f), ^{238}U(n,γ)

- the integral fission rate over the reactor core: ^{235,238}U(ν), ^{235,238}U(n,f)

APPLICATION TO ^{103}RH CAPTURE

EGPT on ^{103}Rh RW : not the relevant indicator

- **In most cases, reactivity worth are normalized to reference samples to cancel many sources of ucnertainties on the evaluation of the fission integral:**
  - Nuclear data
  - Core technological uncertainties (fuel enrichment, impurities, clad dimensions, lattice pitch…)

- **So the EGPT should not be applied on single RW but on ratio of RW**

$$S(\Delta\rho) = \frac{1}{\Delta\rho}\left(\frac{\delta\rho_2}{\frac{\delta\sigma_i}{\sigma_i}} - \frac{\delta\rho_1}{\frac{\delta\sigma_i}{\sigma_i}}\right)$$

$$S(\Delta\rho_{ref}) = \frac{1}{\Delta\rho}\left(\frac{\delta\rho_{ref,2}}{\frac{\delta\sigma_i}{\sigma_i}} - \frac{\delta\rho_{ref,1}}{\frac{\delta\sigma_i}{\sigma_i}}\right)$$

$$S\left(\frac{\Delta\rho}{\Delta\rho_{ref}}\right) = \frac{\delta\left(\frac{\Delta\rho}{\Delta\rho_{ref}}\right)}{\delta\sigma_i/\sigma_i} = S(\Delta\rho) - S(\Delta\rho_{ref})$$

Generalization with *n* reference samples

$$S\left(\frac{\Delta\rho}{\Delta\rho_{ref}}\right) = S(\Delta\rho) - \sum_{i=1}^{n} S(\Delta\rho_{ref,i})\frac{\Delta\rho_{ref,i}}{\sum_j^n \Delta\rho_{ref,j}}$$

APPLICATION TO ^{103}RH CAPTURE

EGPT on individual RW – MAESTRO experiment

Sensitivity coefficients (%/%) on $\Delta\rho_{Rh}$

	CAPT	FISS	EL+INEL	NU	SUM
Rh103	**0.902**		**-0.001**		**0.901**
H1	**0.014**		**-0.738**		**-0.724**
O16	0.003		-0.010		-0.007
Al27	-0.031		0.005		-0.026
U235	**0.067**	**-0.532**	**~0**	**-0.818**	**-1.283**
U238	0.172	-0.104	-0.002	-0.127	-0.061

Sensitivity coefficients (%/%) on $\Delta\rho_{Li6}$

	CAPT	FISS	EL+INEL	NU	SUM
Li6	**0.892**				**0.892**
H1	**0.049**		**-0.460**		**-0.411**
O16	0.003		-0.011		-0.008
Al27	-0.052		0.003		-0.049
U235	**0.050**	**-0.718**	**~0**	**-0.858**	**-1.526**
U238	0.192	-0.112	-0.003	-0.138	-0.061

EGPT on ratio of RW – MAESTRO experiment

Sensitivity coefficients (%/%) on $\Delta\rho_{Rh} / \Delta\rho_{Li6}$

	CAPT	FISS	EL+INEL	NU	SUM
Rh103	**0.902**				**0.902**
Li6	**-0.892**				**-0.892**
H1	**-0.035**		**-0.278**		**-0.313**
O16	0.003		-0.011		-0.008
Al27	-0.052		0.003		-0.049
U235	**0.017**	**-0.186**	**~0**	**-0.040**	**0.243**
U238	-0.020	-0.008	~0	-0.011	0.000

APPLICATION TO ^{103}RH CAPTURE

EGPT on individual RW – ERMINE-V/ZONA3 experiment

Sensitivity coefficients (%/%) on $\Delta\rho_{Rh}$

	CAPT	FISS	EL	INEL	NU	SUM
U235	-0.006	0.023	0.000	0.000	0.040	0.057
U238	-0.408	0.127	0.069	-0.013	0.205	-0.018
Pu239	**-0.099**	**0.533**	**0.007**	**0.000**	**0.827**	**1.268**
Pu240	-0.031	0.034	0.002	0.000	0.050	0.056
Pu241	**-0.010**	**0.092**	**0.001**	**0.000**	**0.143**	**0.225**
O16	**-0.005**		**0.143**	**-0.001**		**0.138**
Na23	-0.004		0.081	-0.001		0.075
Rh103	**0.874**		**0.010**	**0.110**		**0.995**

Sensitivity coefficients (%/%) on $\Delta\rho_{U235}$

	CAPT	FISS	EL	INEL	NU	SUM
U235	**-0.168**	**1.193**	**0.000**	**-0.019**	**1.798**	**2.804**
U238	**-0.236**	**0.184**	**0.063**	**-0.039**	**0.292**	**0.266**
Pu239	**-0.032**	**0.369**	**0.006**	**-0.001**	**0.597**	**0.940**
Pu240	-0.011	0.045	0.002	0.000	0.066	0.101
Pu241	**-0.005**	**0.043**	**0.001**	**0.000**	**0.075**	**0.113**
O16	**-0.006**		**0.123**	**-0.001**		**0.116**
Na23	-0.002		0.072	-0.005		0.064
Rh103	0.000		0.000	0.000		0.000

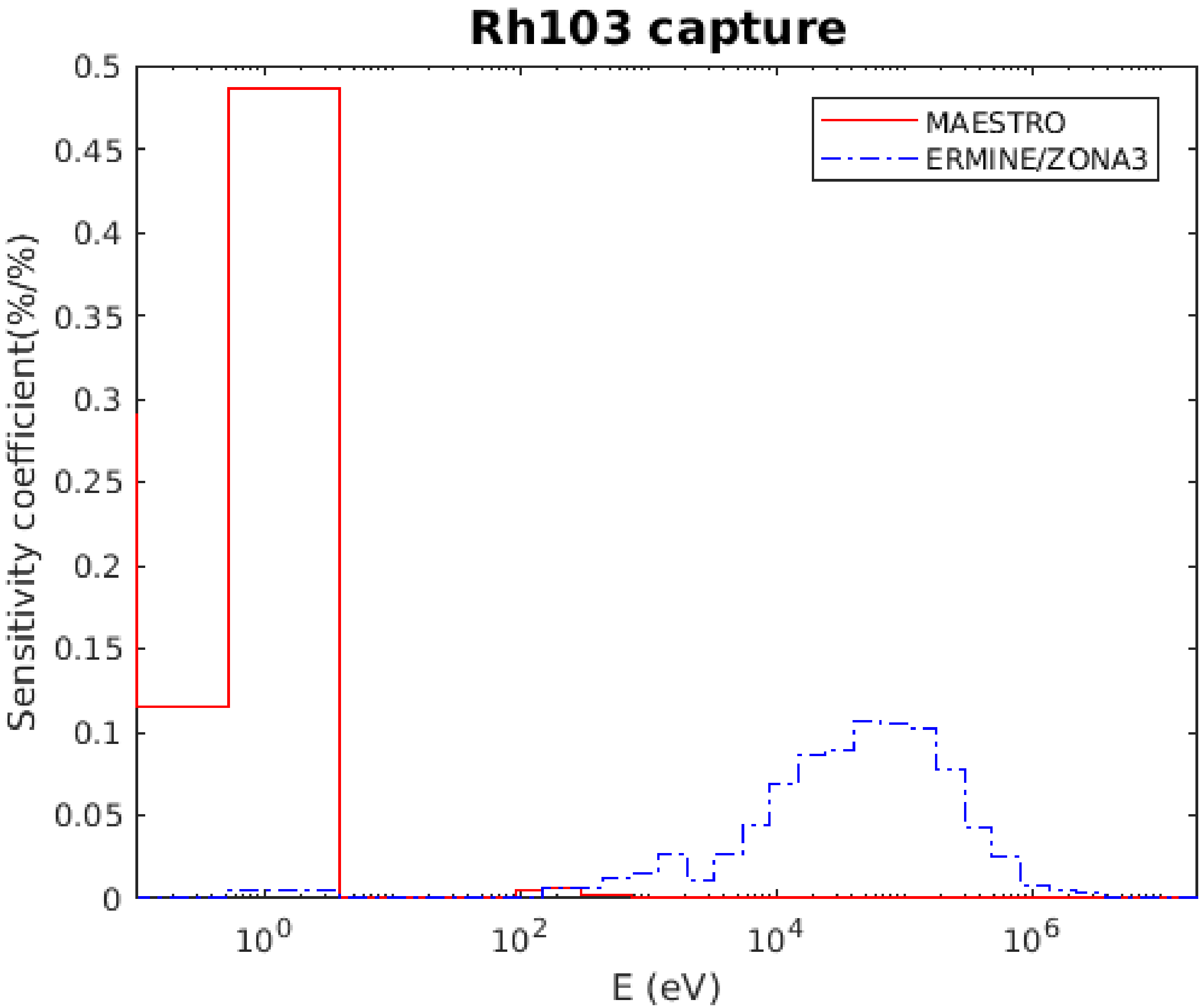
EGPT on ratio of RW – ERMINE-V/ZONA3 experiment

Sensitivity coefficients (%/%) on $\Delta\rho_{Rh} / \Delta\rho_{U235}$

	CAPT	FISS	EL	INEL	NU	SUM
U235	**0.163**	**-1.171**	**0.000**	**0.019**	**-1.759**	**-2.747**
U238	**-0.172**	**-0.057**	**0.007**	**0.026**	**-0.088**	**-0.284**
Pu239	**-0.067**	**0.164**	**0.001**	**0.001**	**0.230**	**0.328**
Pu240	-0.020	-0.011	0.000	0.000	-0.015	-0.045
Pu241	**-0.006**	**0.049**	**0.000**	**0.000**	**0.068**	**0.111**
O16	0.002		0.020	0.000		0.022
Na23	-0.002		0.009	0.004		0.011
Rh103	**0.874**		**0.010**	**0.110**		**0.995**

APPLICATION TO ^{103}RH CAPTURE

Sensitivity profile



APPLICATION TO ^{103}RH CAPTURE

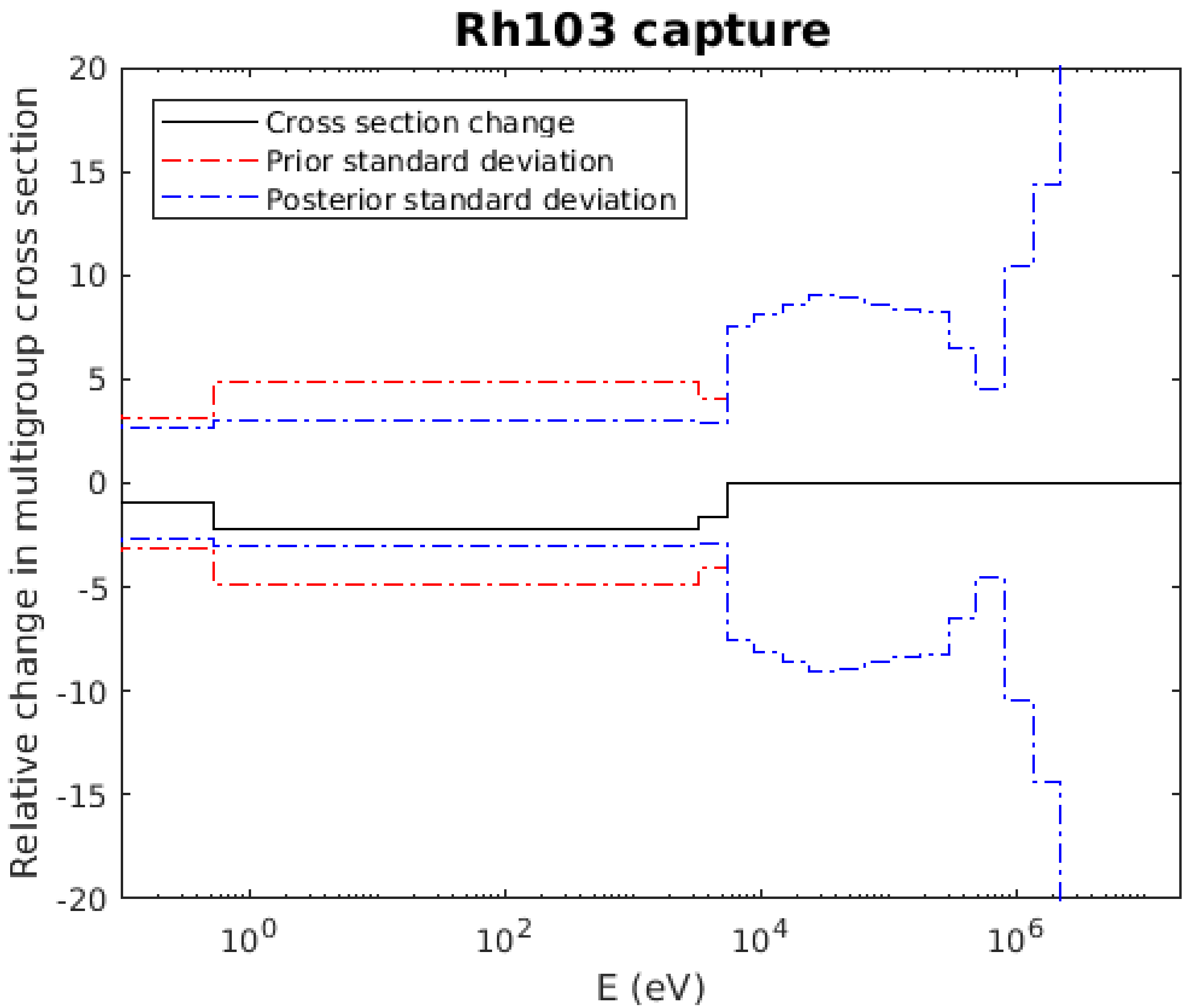
Prior nuclear data covariances

COMAC_V2 set

Isotope	Origin of covariance files			
	Cross sections	Multiplicity	Thermal PFNS	Fast PFNS
U235	ENDF/B-VII.1	JENDL-4.0-up1	CEA	ENDF/B-VII.1
U238	CEA	JENDL-4.0-up1		JENDL-4.0-up1
Pu239	CEA	JENDL-4.0-up1	CEA	JENDL-4.0-up1
Pu240	CEA	JENDL-4.0-up1		JENDL-4.0-up1
Pu241	ENDF/B-VII.1	JENDL-4.0		JENDL-4.0
H1	ENDF/B-VII.1			
Li6	JEFF-3.2			
O16	JENDL-4.0			
Na23	CEA = JEFF32			
Zr90	ENDF/B-VII.1			
Zr91	ENDF/B-VII.1			
Rh103	ENDF/B-VII.1			

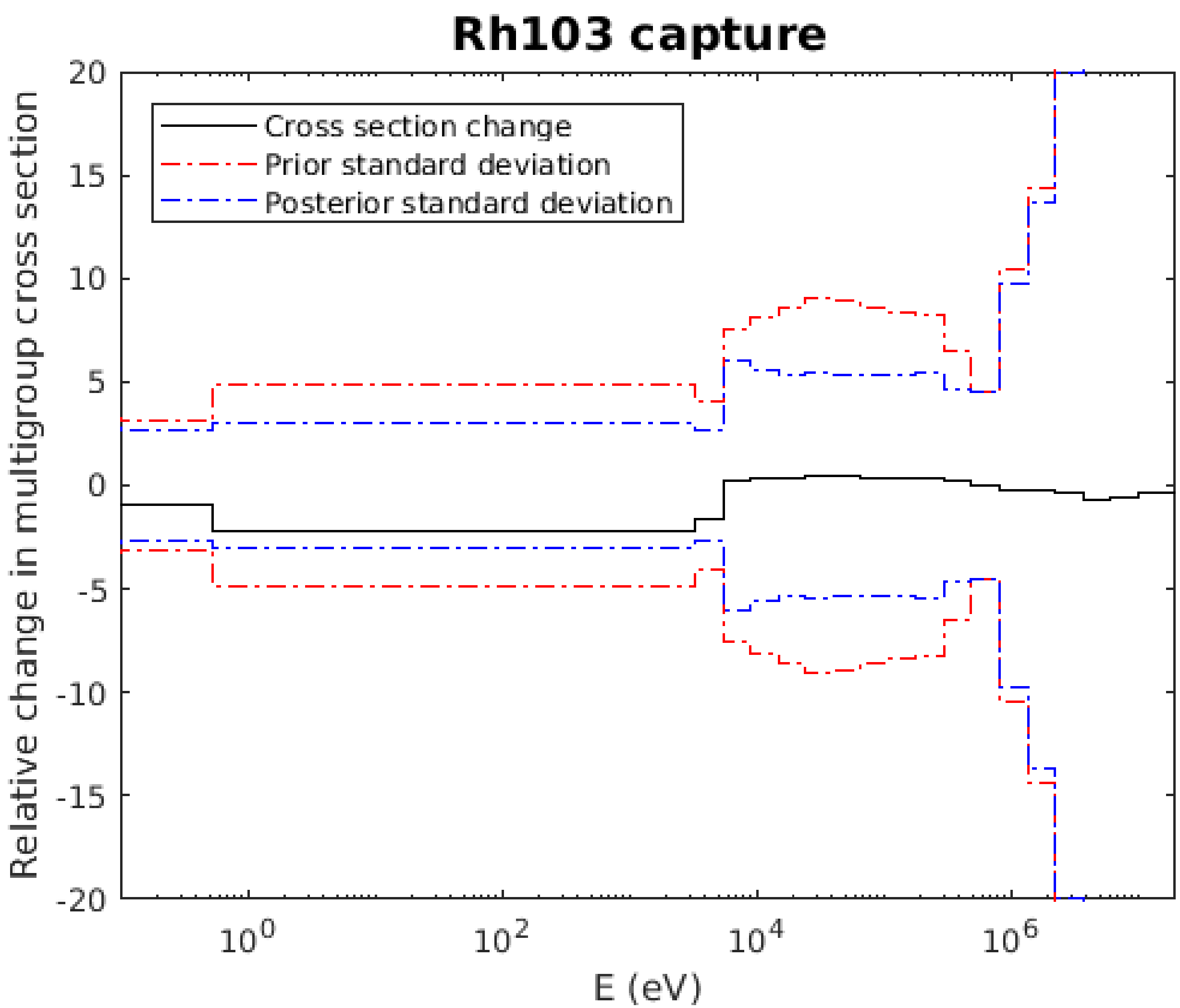
APPLICATION TO ^{103}RH CAPTURE

Result of the adjustment procedure MAESTRO experiment



APPLICATION TO ^{103}RH CAPTURE

Result of the adjustment procedure
MAESTRO + ERMINE-V/ZONA3 experiment



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CONCLUSIONS AND PERSPECTIVES

Key-points

- **Computing EGPT for SSRW experiments must account for the RW normalisation**
- **Using a reference sample of similar behavior minimizes the influence of indirect terms in the analysis of SSRW**
- **Combining independant thermal and fast spectrum experiments was applied for a significant uncertainty reduction on the ^{103}Rh capture cross section**
  - 1eV – 10 keV 5% ⇨ 3%
  - 10 keV – 1MeV 8% ⇨ 5%

Perspectives

- **Finalisation of S/U analysis for ERMINE-V experiments**
- **Computation of ERANOS sensitivities for RRR/SEG experiments**
- **Consistent assimilation of MINERVE/MAESTRO + RRR/SEG experiments for the list of common isotopes:** *Mo-95, Mo-98, Mo-100, Rh-103, Cs-133, Ag-109, Sm-149, Eu-153, Nb, Co, Cd, Fe, Ni, Mo, Mn, Au, Cu, Zr, C*

CONCLUSIONS AND PERSPECTIVES

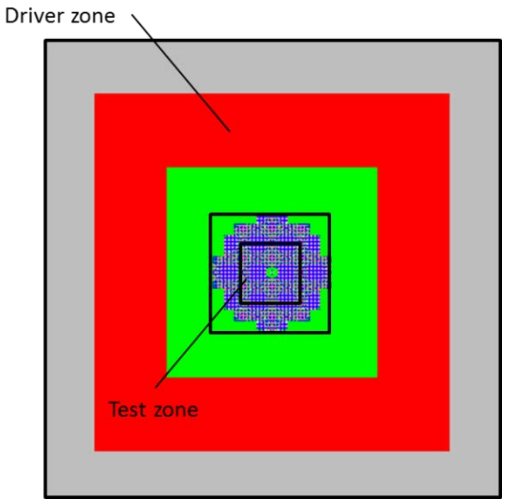
Open question to investigate

- **In the case of experimental results reported as infinite diluted reactivity worth (e.g. RRR/SEG), which mass to consider to apply the EGPT? Is the balance between indirect and direct contributions sensitive to the magnitude of the RW? Limit range for linear assumption?**
  - Large masses: + no convergence issues
    - increase of self-shielding effects
  - Small masses: + closer to the real experiment
    - convergence issues

  ⇨ Test of increasing concentrations for the sample mass

- **In fast spectrum experiments, are the EGPT profiles influenced by the size of the geometrical model?**

  ⇨ Test of various model sizes



- **Can Monte-Carlo methods replace deterministic ones for SSRW sensitivities? Minimum acceptable RW value?**

  ⇨ EGPT benchmark to be done between various deterministic (APOLLO2, ERANOS) and Monte-Carlo (SERPENT, TRIPOLI, MCNP) codes

THANK YOU
FOR YOUR ATTENTION

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