Programme ILL (action 2.1.1)
Des tests des modèles à l'évaluation (Action 2.2)

FROM RESEARCH TO INDUSTRY

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8/03/2022, RVST DER, Skype

IRESNE I Research Institute for Nuclear Systems for Low Carbon Energy Production

Outline

- **Measurements of fission product yields with the LOHENGRIN spectrometer of ILL by CEA/ILL/LPSC collaboration**
- **Fission Product Yield Evaluation in the framework of JEFF-4**
- **Fission Product Yields for Applications**

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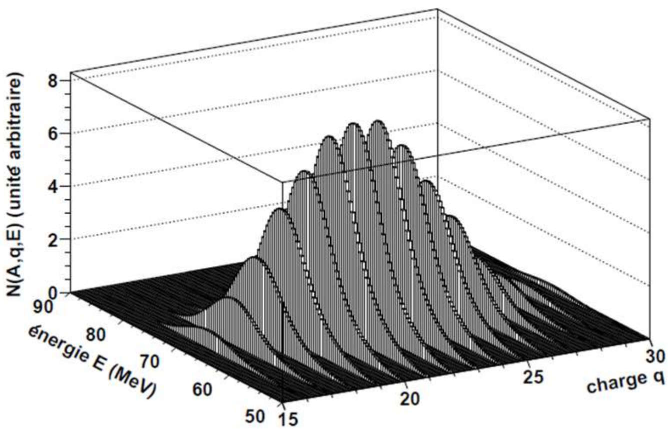
How to measure mass yields at LOHENGRIN



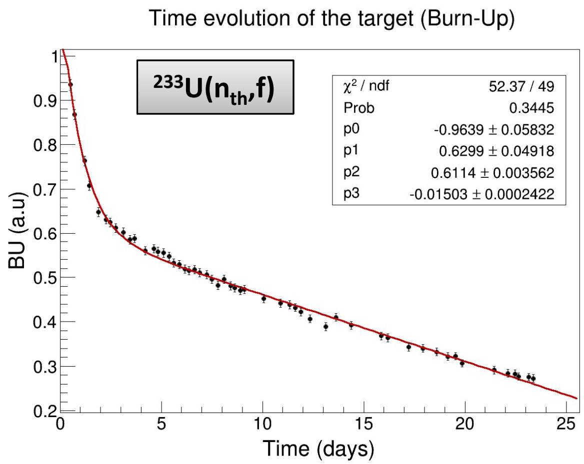
Relative measurements

$$\mathcal{N}(A) = \sum_q \int_{E_k} \frac{\mathcal{N}(A,q,E_k)dE_k}{BU(t)}$$

Absolute assessment

$$Y(A) = \frac{\mathcal{N}(A)}{\sum_A \mathcal{N}(A)}$$

$$\sum_{Heavy\ A} Y(A) = 1$$



Main issue : burning of the target BU(t) and beam time

- Choices E_k, q distributions must be made
- Correlations between E_k and q make the analysis more complex
- Tremendous effort over 15 years to reduce the uncertainties and handle bias !

Current data taking :

- 3 E_k scan & 1 q scan to measure a mass yield (at least)
- For some masses (high electronic conversion) more scan are mandatory

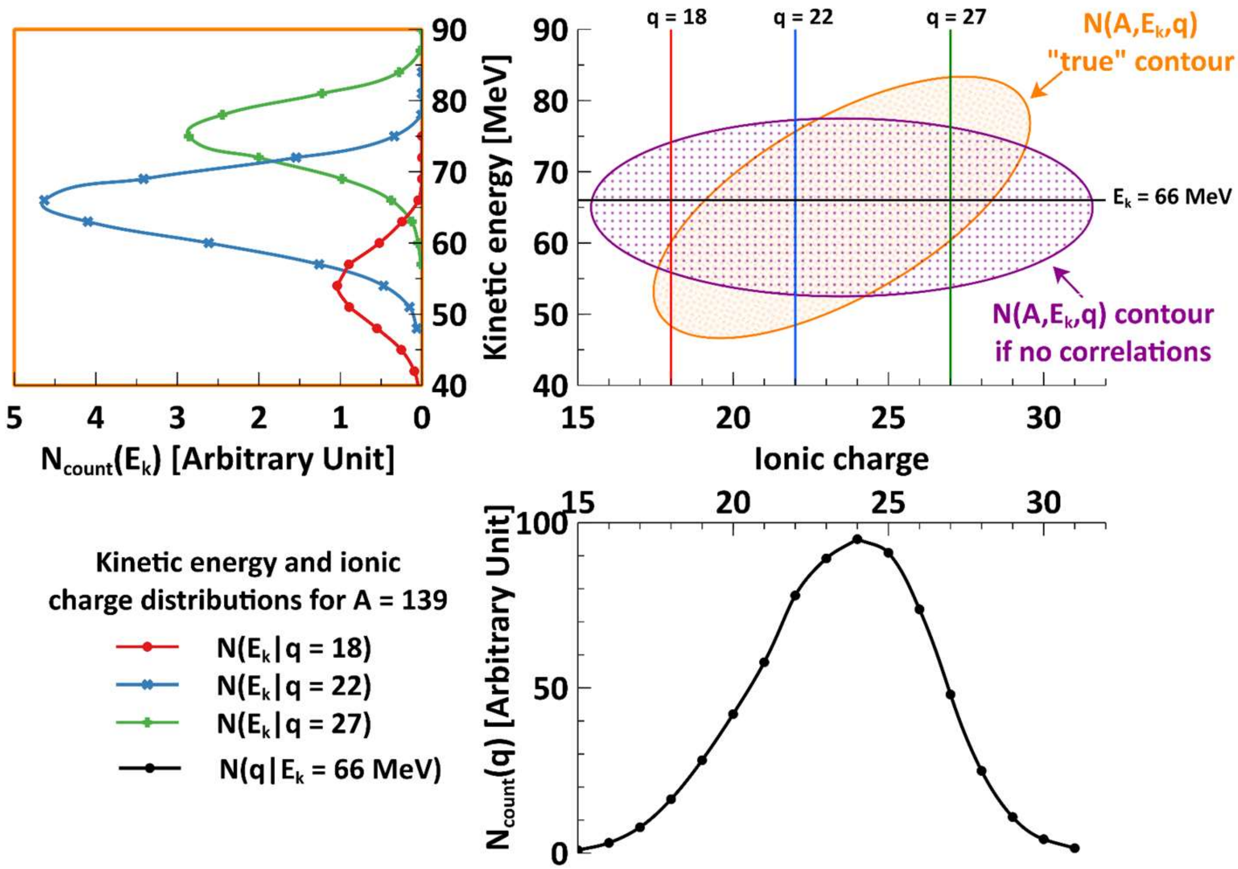
Correlation (E_k,q)

Fission Fragment « capture » electrons in the target and though the cover

$$q = Z - n_{e^-}$$

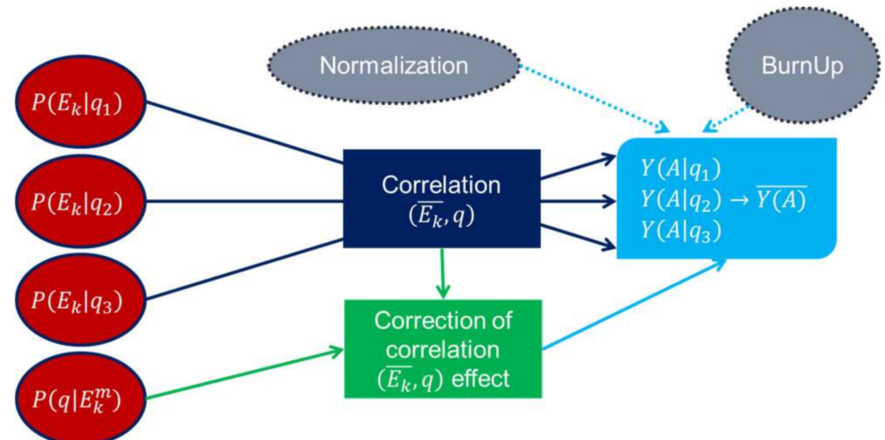
$$n_{e^-} \in [10 - 40] \leftrightarrow [3s - 5s] \leftrightarrow [M - O]$$

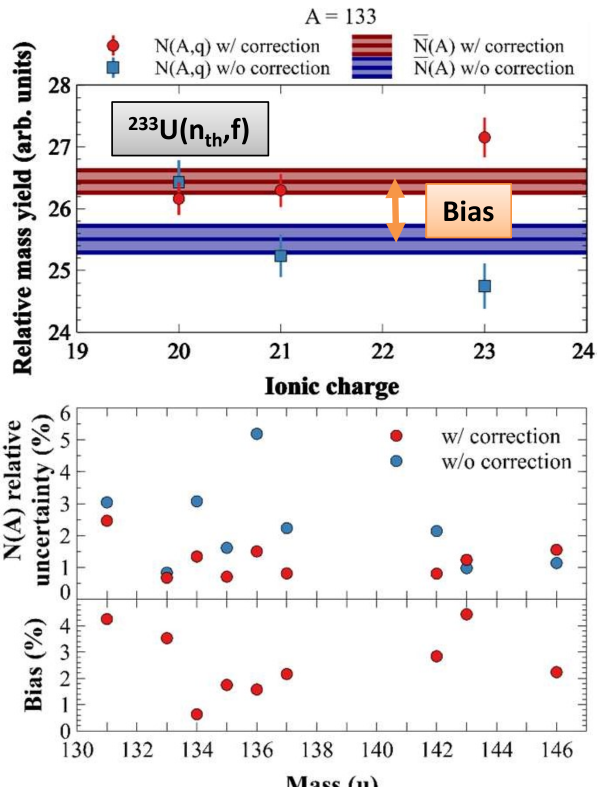
The average ionic charge depends on the kinetic energy and the nuclear charge of the fission fragment

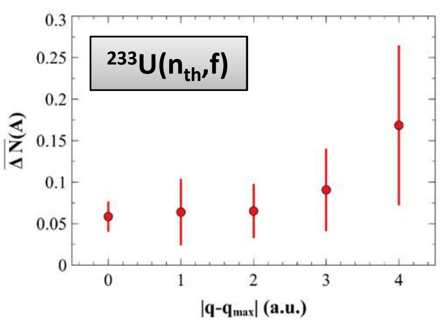


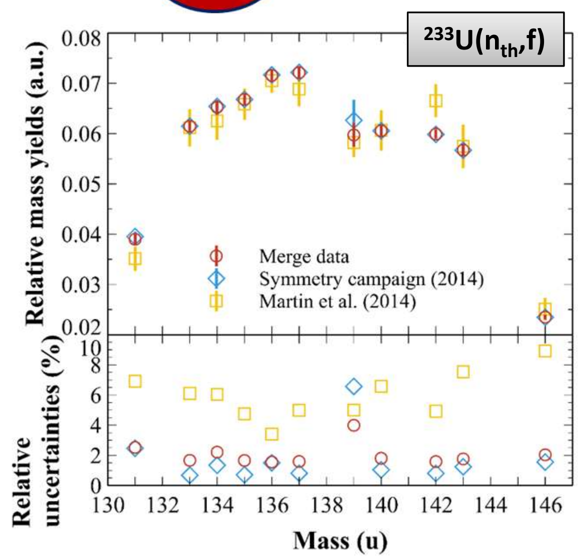
How to analyze such amount of data

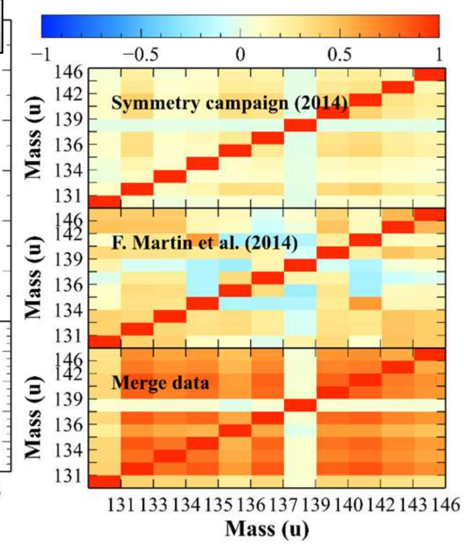
~ 280 scans → ~ 5500 points
~ 15 steps to go from count rate to absolute fission mass yields
→ uncertainty propagation complex
→ Use of Total Monte Carlo techniques : sample count rates and "reroll the experiment"





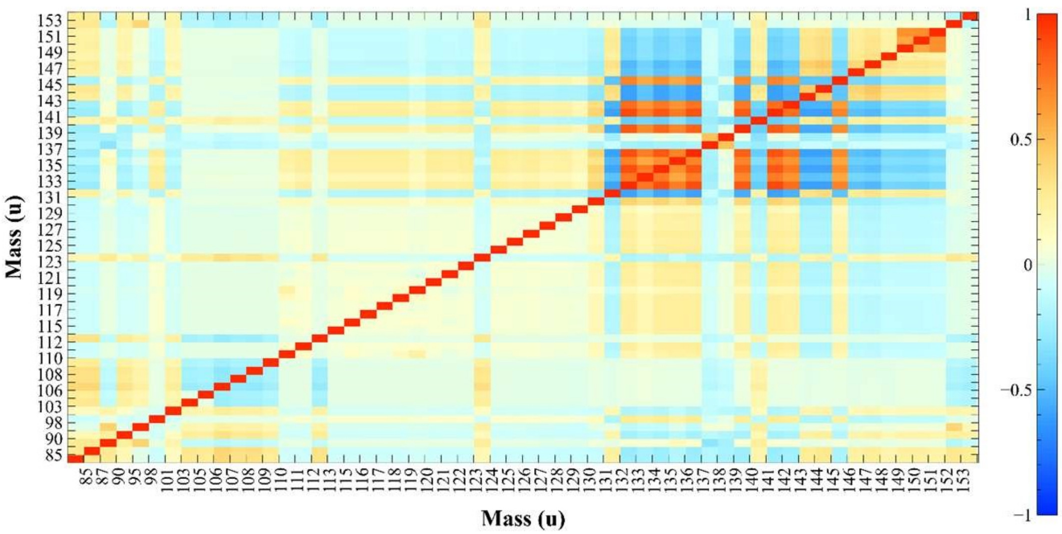


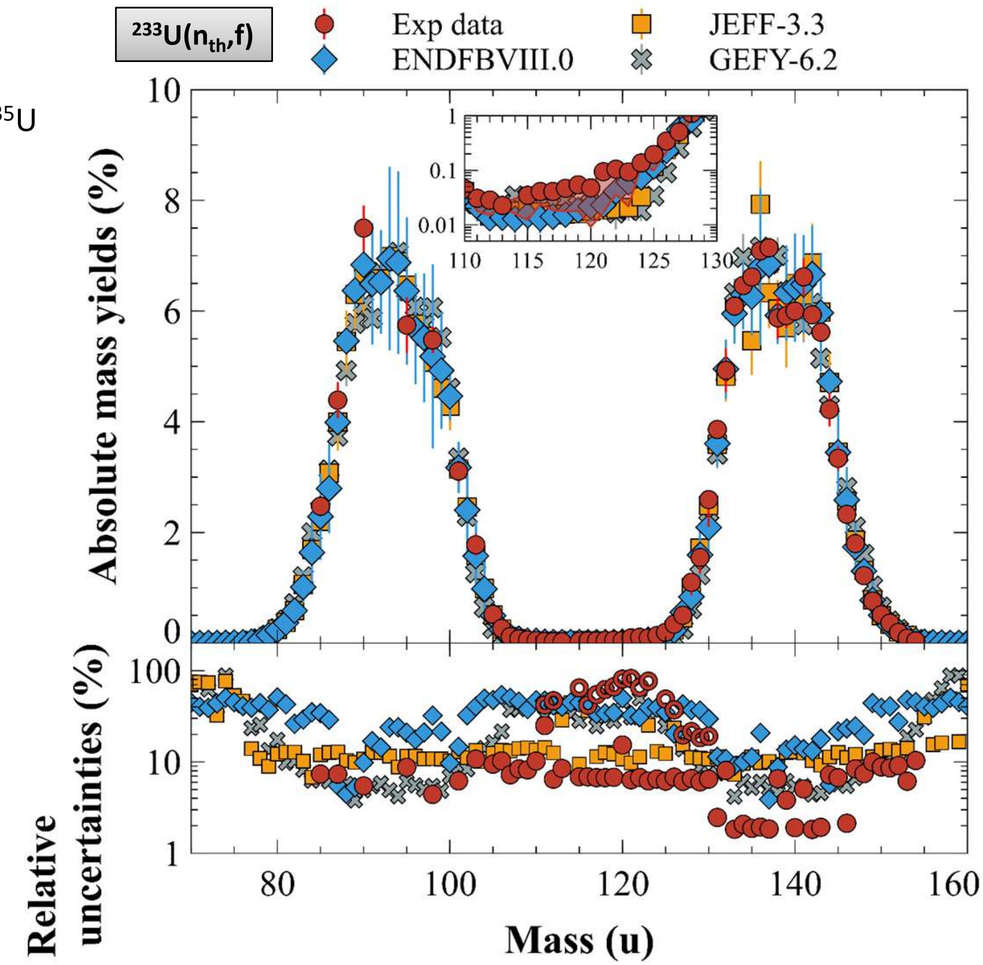




Mass yields : Some highlights

- Heavy peak : ☑
- Reduce uncertainties and handle bias : ☑
  Starting with **uncertainties around 6-10%** (^{235}U + ^{241}Am + ^{239}Pu) → 10 years of efforts to reduce uncertainty around **2-3%** (^{233}U + $^{239,241}Pu$)
- Self normalization + Correlation matrix : ☑
  (^{233}U + ^{241}Pu)

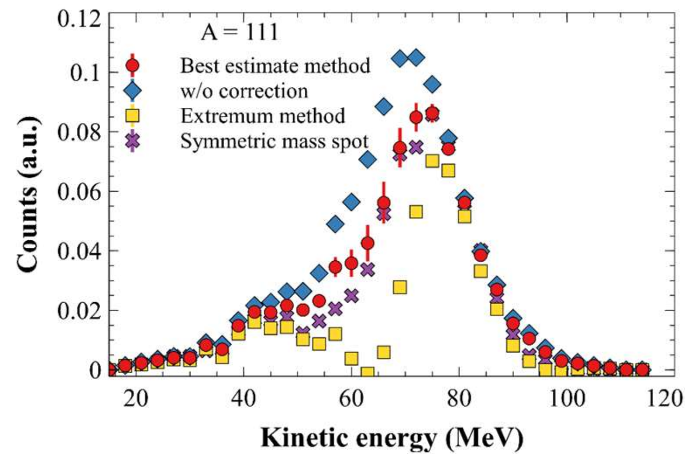




Mass yields : Some highlights

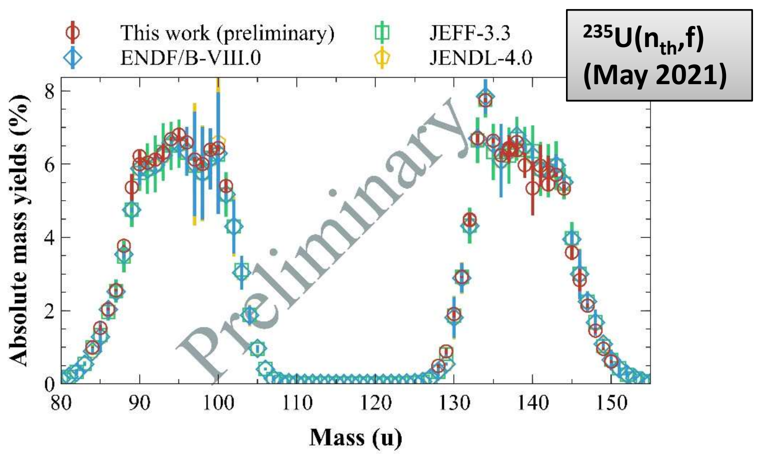
- Main contributor to fission studies @ LOHENGRIN
- Relative mass yield uncertainties around 2% are achievable in both heavy and light peaks

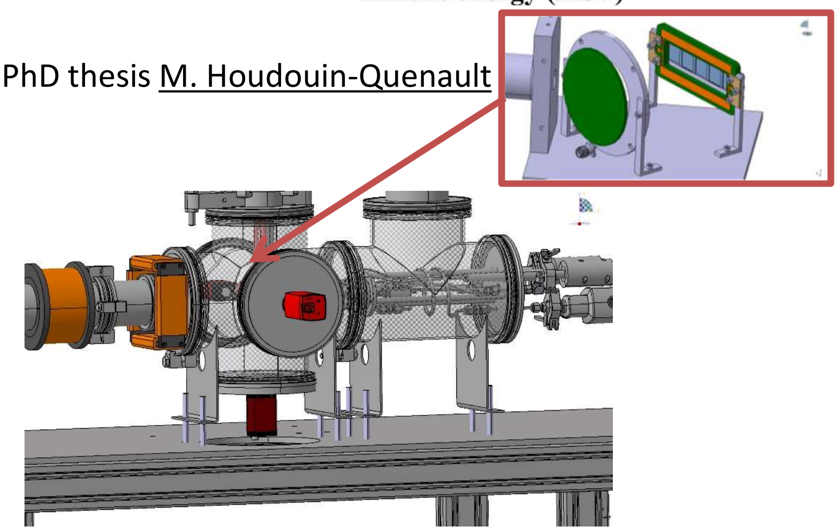
- Isotopic yield can be measured by using γ spectroscopy
- → limited by decay data precision



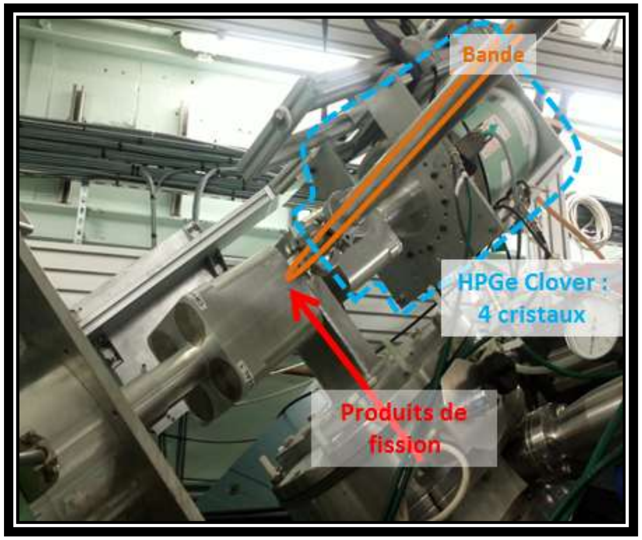
- Ongoing development of new ToF detector to improve the LOHENGRIN sensibility in the symmetry mass region
- Measurement of $^{235}U(n_{th},f)$ fission mass yields -> $^{239}Pu(n_{th}, f)$; $^{245}Cm(n_{th}, f)$
- Ancillary observables in order to improve the understanding of the fission process and improve models such as FIFRELIN "Research of precision for the applications, feed the fundamental science"

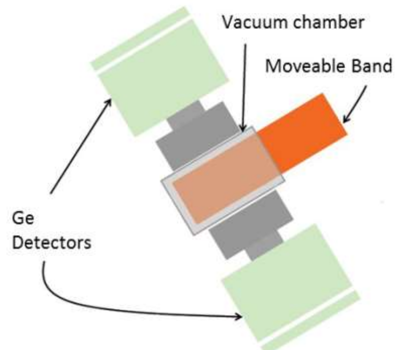
PhD thesis M. Houdouin-Quenault

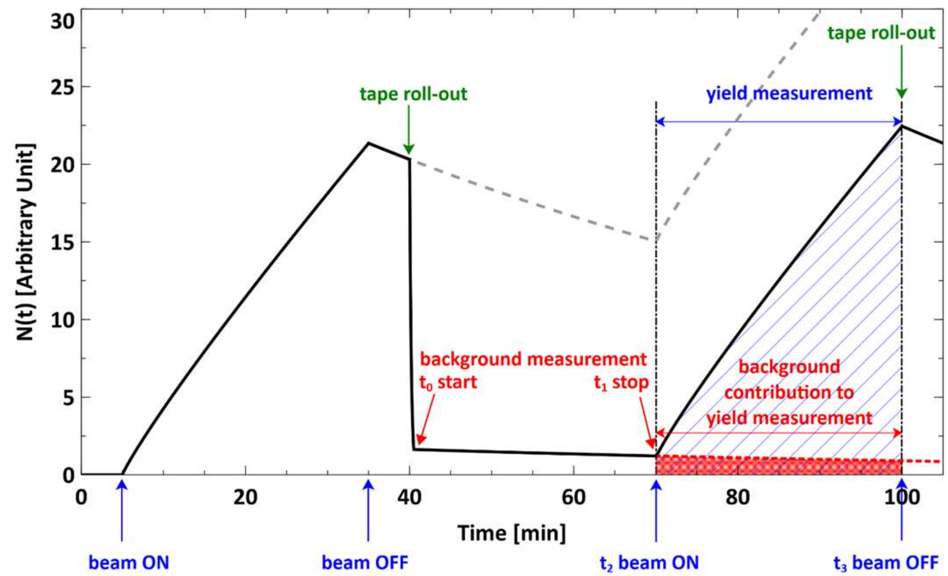




Isotopic and isomeric yield program







High Purity Germanium (HPGe)

Assess fission fragment nuclear charge through γ measurements

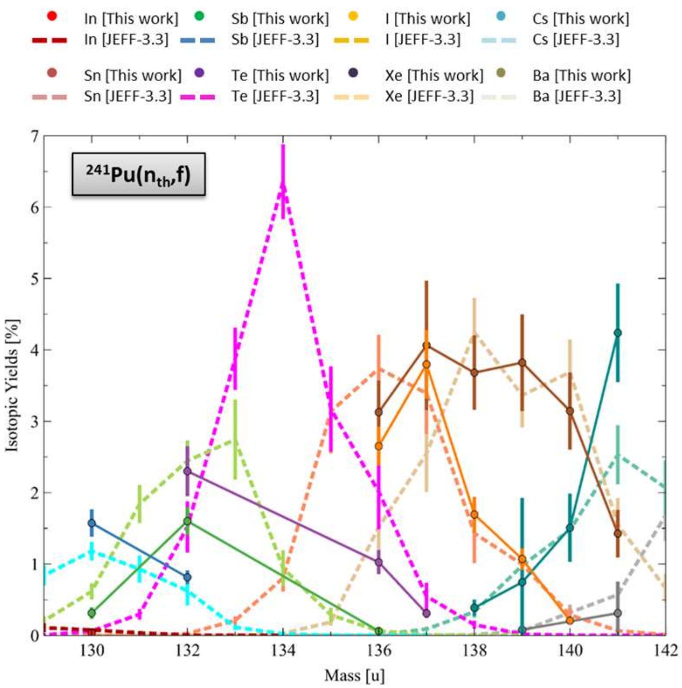
→ Current solution to study isotopic yields in the heavy mass region
→Results are dependent of the knowledge of fission fragment nuclear structure scheme

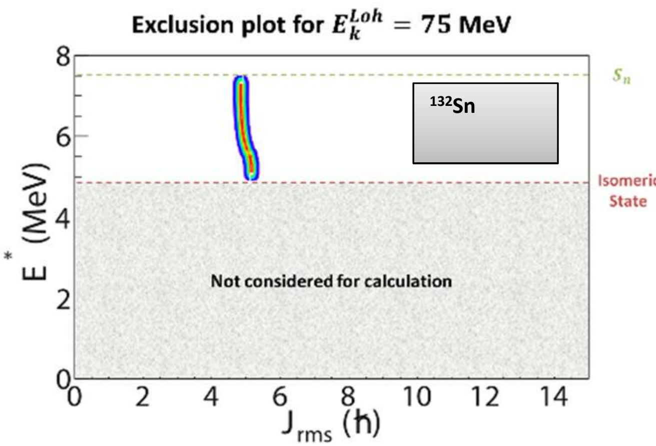
Difference with mass yields

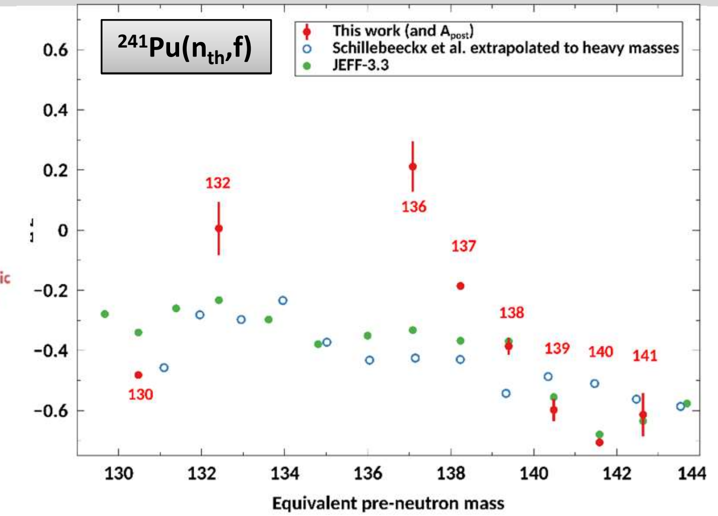
Only ionic charge distribution is measured with γ detectors

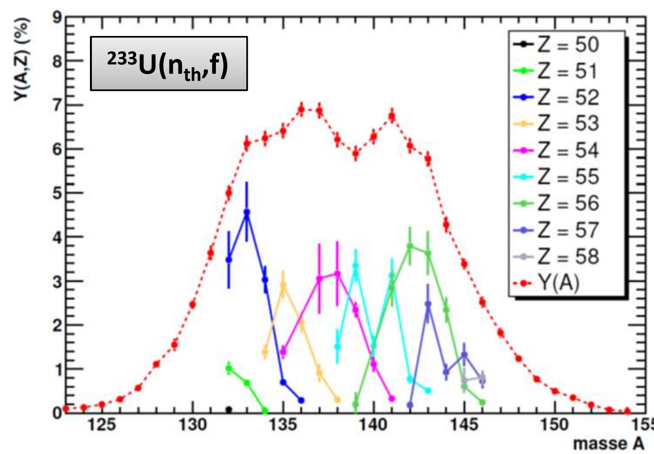
- Implantation of isotopes on the tape and the vacuum chamber
- Tape roll out : only the chamber frame “contains” isotopes
- Measurement of the “frame decay”

Isotopic and isomeric yield program : Some Highlights









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Before the Age of Libraries

- during the 1960's and 70's, UK was pioneered by E.A.C. Crouch at Harwell
  → Crouch 1, 2 and 3 Libraries
- In the past other groups in France and Austria have also produced evaluations.
  However only the UK and US evaluations have developed evaluated files completely independently of the other evaluations

- Up to about 1973, several fission yield evaluations were done on a limited number of yield sets E.A.C. Crouch (UK) and B.F. Rider (USA)
  → 1972 M.E. MEEK, B.F. RIDER, Compilation of Fission Product Yields
  → 1977 evaluations of E.A.C. Crouch, Atomic Data and Nuclear Data Tables, vol.19, no. 5.

- In 1980's evaluation efforts was taken over by M.F. James et al. (UK) and T.R. England et al. (USA) Respectively

- in 1981 the UK work was continued by M.F. James et al.
  - largely based on the Crouch experimental measurement database
  - improved file which was called UKFY1

- in 1986, UKFY1 was adopted by the Nuclear Energy Agency for the fission product yield called the Joint Evaluated File, or JEF.

- In 1987, the first ENDF-formatted file of evaluated fission yields was created in China and included in the CENDL-1 Library.

- At the same time, A.C. Wahl made a thorough evaluation of independent fission yields which he used to obtain best values for the parameters of his models. For this purpose he also evaluated cumulative and chain yields for selected fission reactions.
  → His model parameters were used by the other evaluators for the calculation of charge distributions and estimation of unmeasured yields, which was the first, still restricted, form of international cooperation.

FY Libraries and generations

- European FY Libraries

JEF	1986	UKFY1
JEF-2.1	June 1990	UKFY2
JEF-2.2	Jun. 1993	UKFY3
JEFF-3.1	May 2005	UKFY-3.6A
JEFF-3.1.1	Janv. 2009	UKFY3.6A
JEFF 3.3	Nov. 2017	UKFY3.7

UKFY1, UKFY2 →

- mass yields = chain yields
  → ignores neutron emission
  → incorrect calculation of nuclide inventories
- yields for nuclides that were not stable or included in the JEF decay data

UKFY3 – UKFY3.7 →

Chain, cumulative,
Fractional cumulative,
Fractional independent
Independent yields

- ENDF (USA) FY Libraries by T.R. England, B.F. Rider based on A.C. Wahl Systematics

ENDF/B-VI DIST-JUN93 REV1-OCT92 → EVAL-JUL89 T.R. ENGLAND, B.F. RIDER
ENDF/B-VII DIST-DEC06 REV1-OCT92
ENDF/B-VII.1 DIST-DEC06 REV1-OCT92
ENDF/B-VIII.0 DIST-FEB18 REV1-OCT92

Synthesis in CRP
IAEA-TECDOC-1168
Dec. 2000

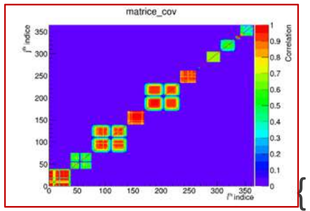
- A GEneral description of Fission (GEF) Observables by K. -H. Schmidt and B. Jurado

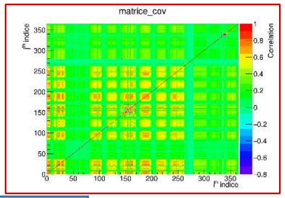
GEFY-3.3 Mars 2013 - GEFY-6.2 Juin 2018 → 6 distributed lib. at the NEA over 17 versions
→ large number of parameters marginalized on JEFF3.1.1 evaluation data

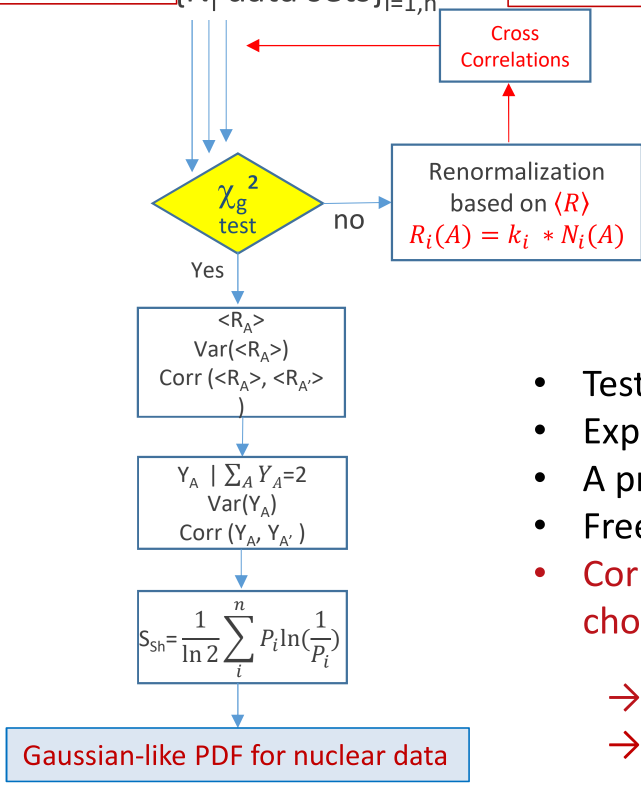
- Japanese Libraries

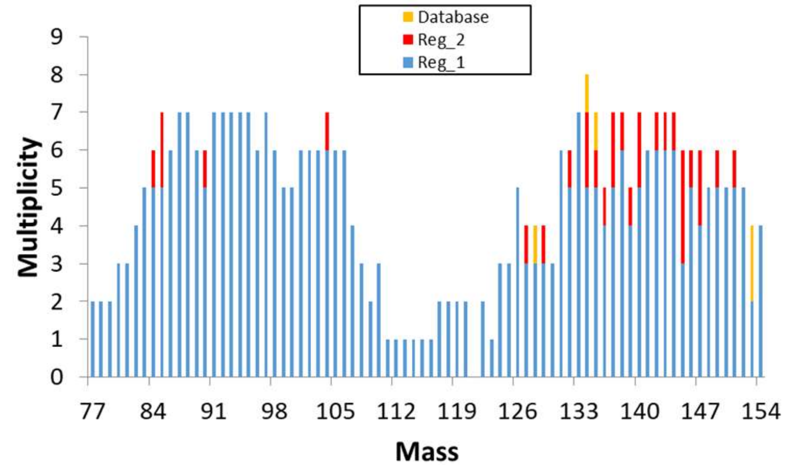
JENDL-4 DIST-MAY10 → original data taken from ENDF/B-VII files.

New methodology of Fission yields evaluation → non-unique solutions



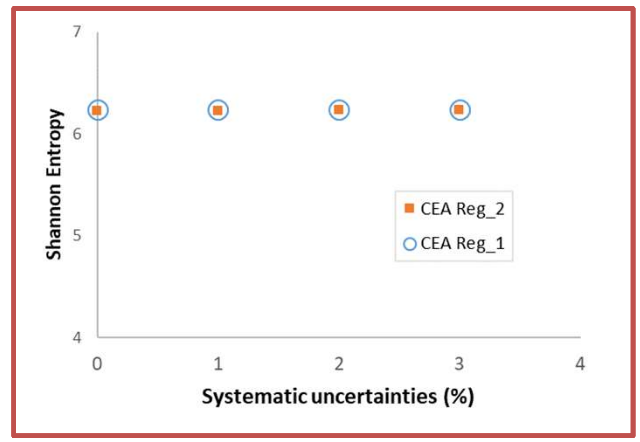




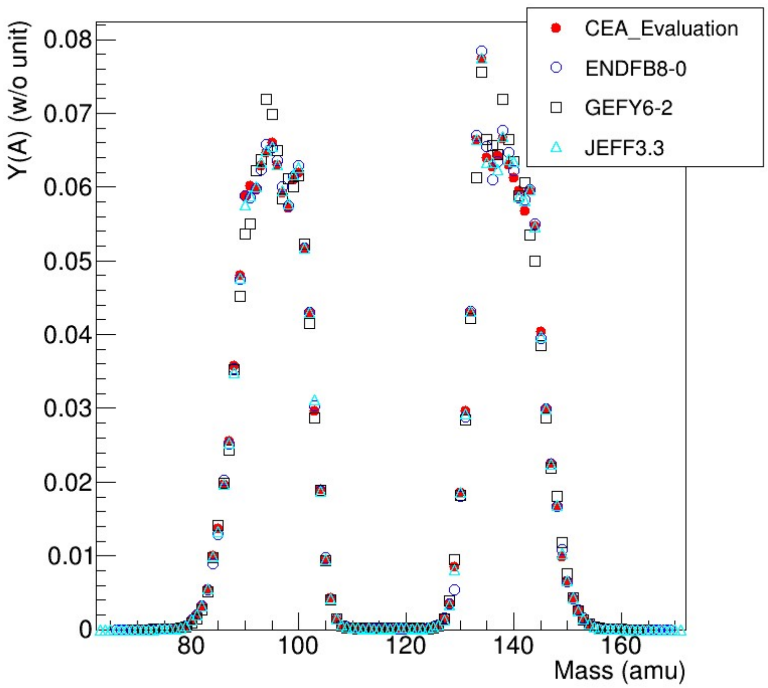


- Test of dataset for a Gaussian-like evaluation
- Explicit Experimental correlations analyzed
- A priori Exp correlation tested
- Free of model analysis
- Correlation matrix are consistent in all choices of analysis

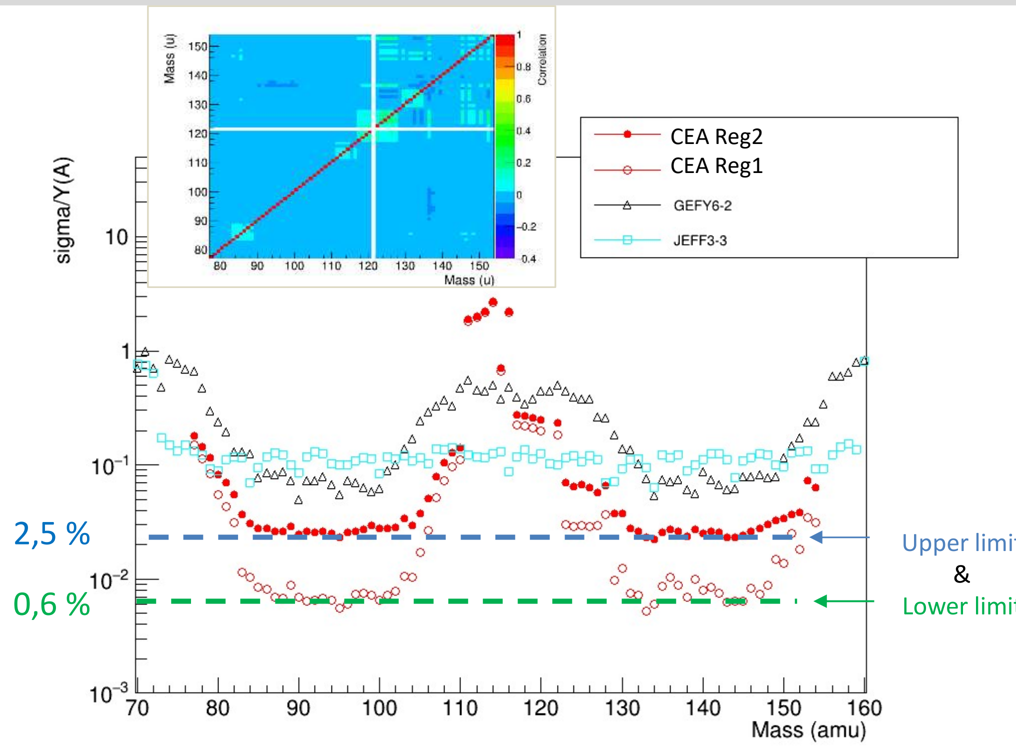
→ Values; standard deviations; correlations
→ Ergodic analysis path



Mass yield evaluation : values, uncertainties, correlations



Test of CEA evaluation			Consevative
	DOF	Lim=1-CL	P-value
JEFF3.3	77	0,003	0,594
ENDF-BVIII.0	77	0,003	0
GEF6.2	77	0,003	0



- Uncertainty band : Lower and upper limits for given datasets
- correlation matrix do not depend with analysis choices

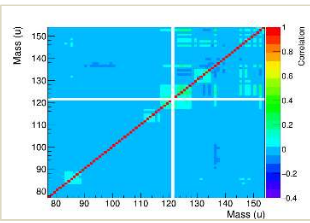
→ Mass yield evaluation free of model

Isotopic and isomeric yield evaluations → complete and consistent

$$Y(A,Z,E_k,m) = Y(A).P(Z|A).P(E_k|A,Z).P(m|A,Z,E_k)$$

Mass Charge Kinetic energy Isomeric ➤ distributions

Typically Thermal neutron induced fission



Y_{A1}
Y_{A2}
Y_{A3}
...
Y_{An}
Z_1
Z_2
...
Z_n
$P(E_k|A,Z)$
IR_1
IR_2
...
IR_n

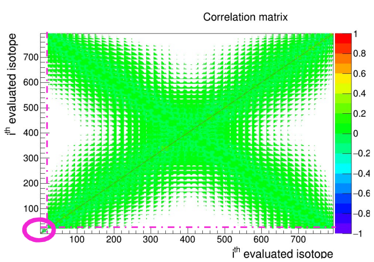
$$\sum_Z Y(A) = 2$$

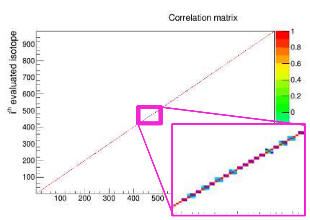
complete Y(A) datasets

$$\sum_Z P(Z|A) = 1$$

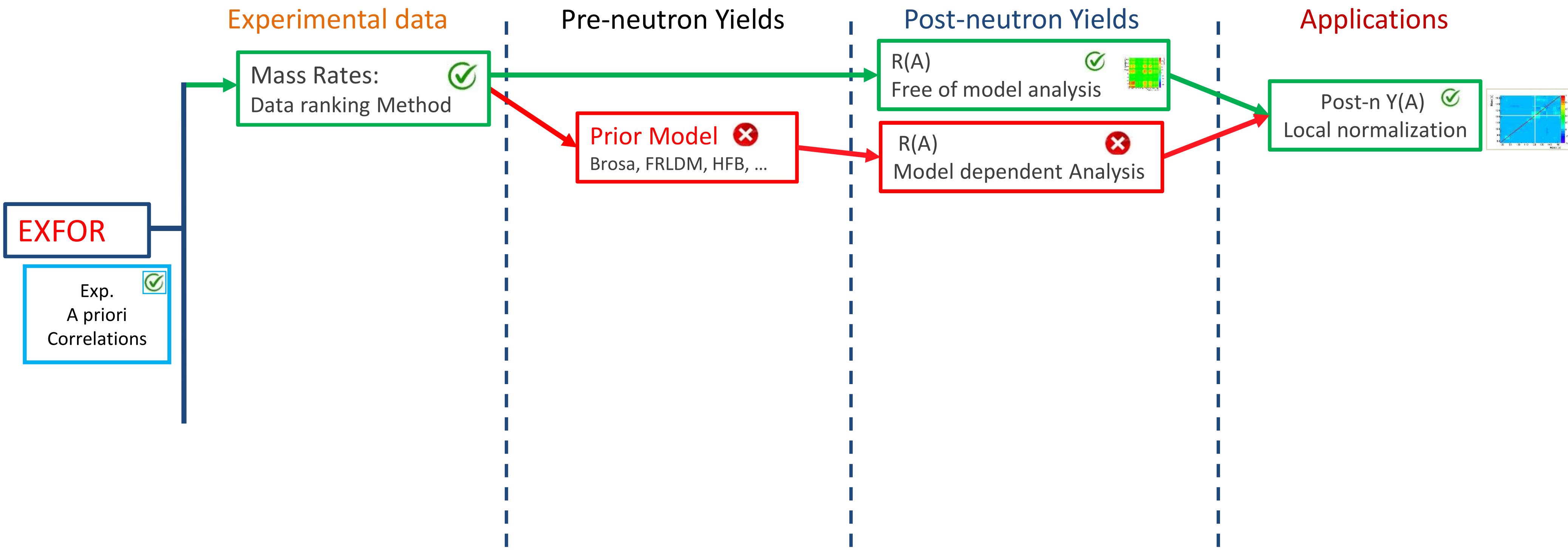
Uncomplete (A,Z) datasets

$$\sum_I IR(m|A,Z) = 1$$





JEFF4 Goal - CEA-NLL collaboration → $^{235}U(n_{th},f)$ complete and consistent evaluation



- achieved
- ongoing
- To do

PhD thesis S.M. Cheikh

JEFF4 Goal - CEA-NLL collaboration → ^{235}U(n_{th},f) complete and consistent evaluation

Experimental data | Pre-neutron Yields | Post-neutron Yields | Applications

EXFOR

Exp.
A priori
Correlations ✓

Mass Rates: ✓
Data ranking Method

Neutron emission ✗
Data ranking method

Isotopic Rates: ✓
Data ranking method

Prior Model ✗
Brosa, FRLDM, HFB, …

Prior Models ✓
FIFRELIN, GEF

Phenomenological models
Wahl, … ✓

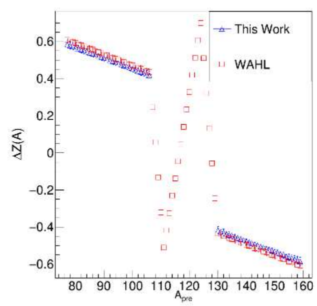
R(A) ✓
Free of model analysis

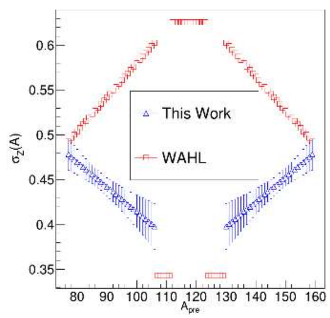
R(A) ✗
Model dependent Analysis

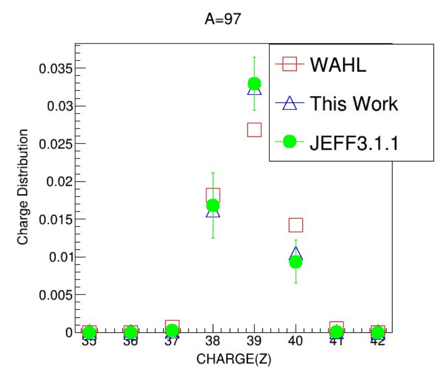
R(Z|A) ✓
Model dependent
Analysis

Post-n Y(A) ✓
Local normalization

Post-n P(Z|A) ✓
Local normalization







✓ → achieved

✓ → ongoing

✗ → To do

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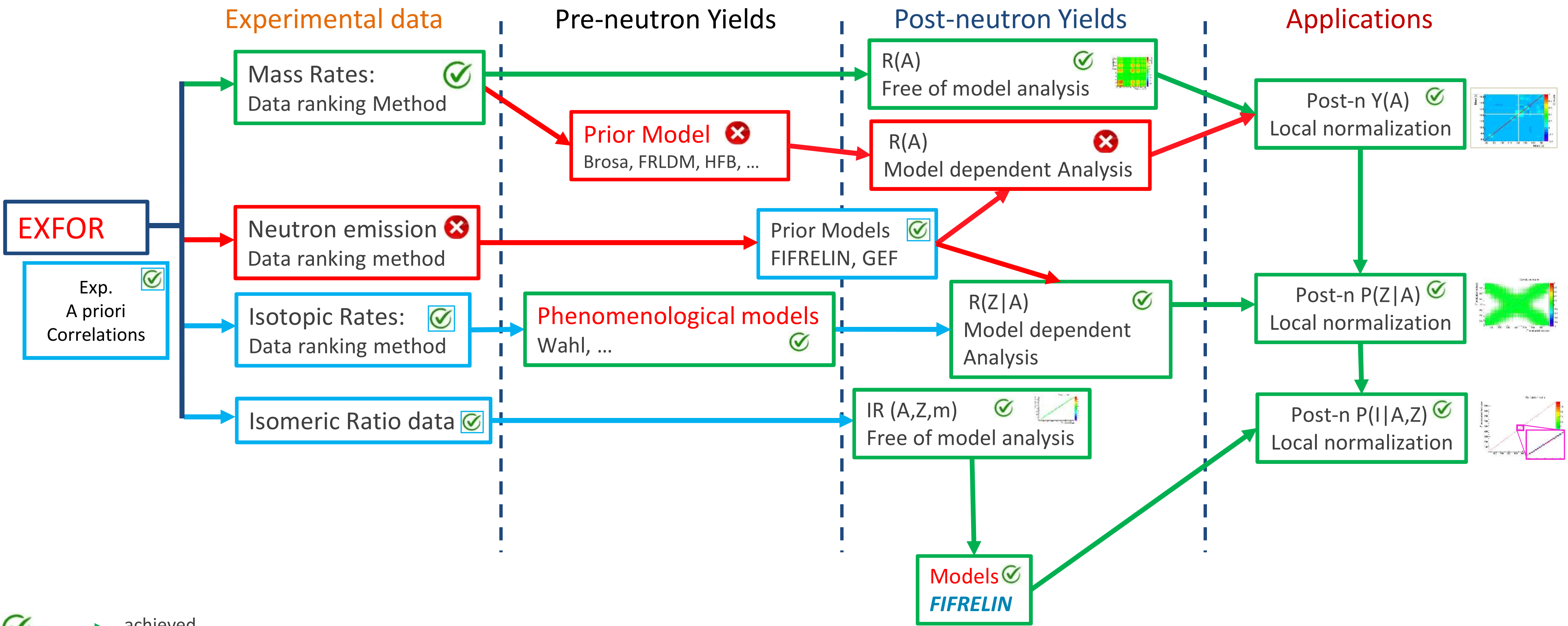

achieved

ongoing

To do

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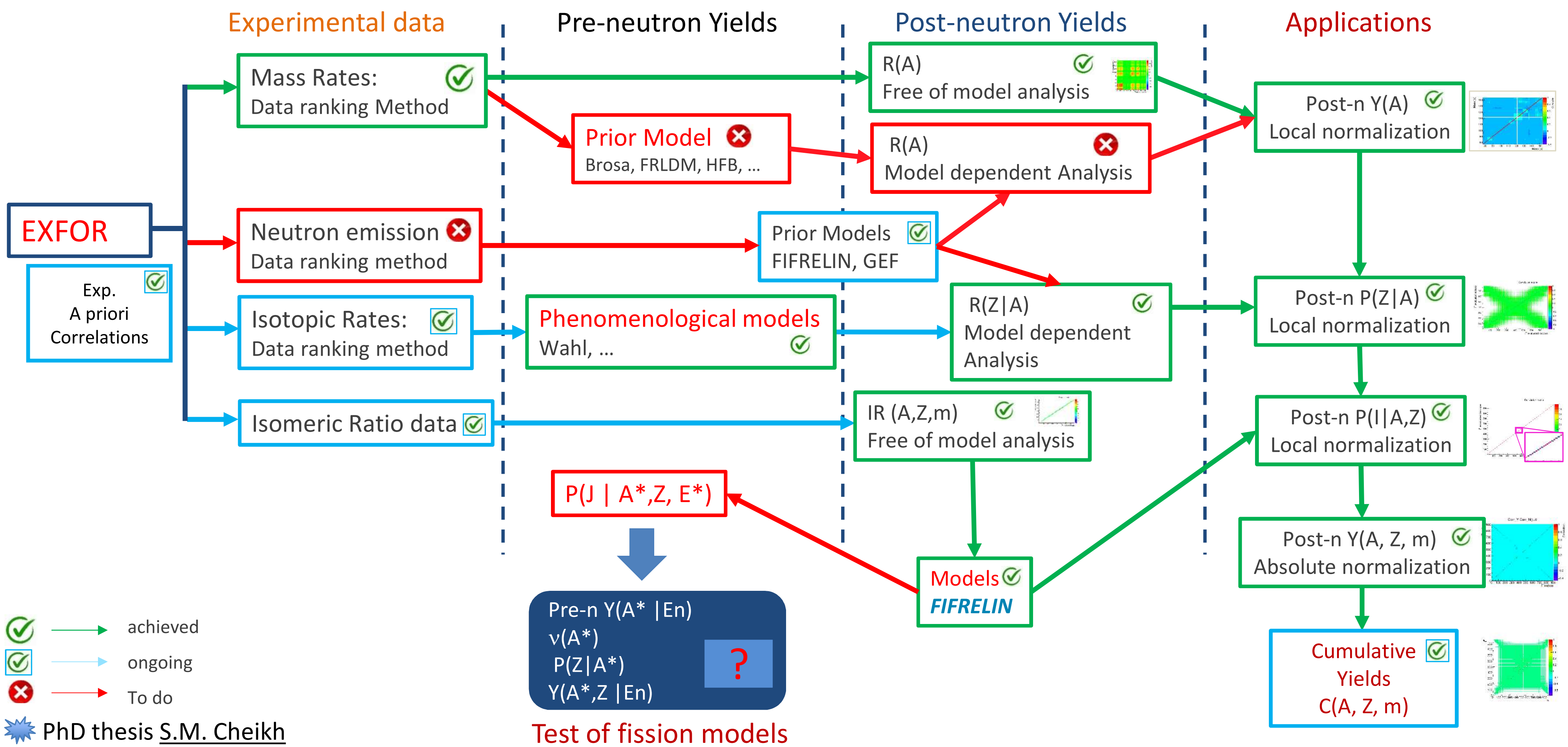

Encadrements de thèses

1. **Sidi M. Cheikh**, direction de thèse O. Serot (20%), G. Kessedjian (80%)
   Sujet : Evaluation des rendements de fission des actinides d'intérêt pour le cycle du combustible **(en cours, 2020-2023)**

2. **M. Houdouin-Quenault**, G. Kessedjian (LPSC, 50%) A. Chebboubi (CEA 25%), C. Sage (25%)
   Sujet : Nouvelles mesures de précision des rendements de fission de l'235U(nth, f) pour l'étude de fission et l'évaluation des données nucléaires. **(en cours, 2020-2023)**

3. **Jehaan Nicholson** : direction de thèse O. Serot (CEA 15%), A. Chebboubi (CEA 50%) and G. Kessedjian (LPSC, 35%)
   Sujet : Etude de la dépendance en énergie cinétique des rendements isotopiques et isomériques induits par la fission thermique auprès du spectromètre de masse Lohengrin de l'Institut Lau Langevin (Grenoble, France), **soutenue le 10 septembre 2021.**

4. **S. Julien Laferrière** : direction de thèse G. Kessedjian (LPSC, 50%), O. Serot (CEA 25%), A. Chebboubi (CEA 25%)
   Sujet : Etude expérimentale et théorique des rendements isotopiques et isomériques induits par la fission thermique du 241Pu. **Soutenue le 5 oct. 2018.**

Encadrements de stages M1 & M2

Stage M2, J. de Garidel-Thoron Stage M2, (2022, en cours) : Evaluation des distributions en énergie cinétique des fragments de fission de l'U ; GK
Stage M1 Aurélie … : Spectre beta des PF
Stage M1 Florien Géhin (2021) : Analyse de distributions isotopiques du $^{241}Pu(n_{th}, f)$; AC
Stage M2 Sidi Mohamed Cheikh (2020) : évaluation des rendements en masse de la réaction $^{235}U(n_{th}, f)$; AC, OS
Stage M1 Sidi Mohamed Cheikh (2019) : évaluation des rendements en masse de la réaction $^{235}U(n_{th}, f)$; GK
Stage M1 Lea-Thombansen (2018) : Étude des rendements des isomères nanosecondes produits par la réaction de fission ^{241}Pu (nth,f), GK
Stage M2 Jehaan Nicholson (2018) : Etude du rapport isomérique de l'^{98}Y
Stage M2 Brieuc Voirin (2017) : développement de méthodes statistiques pour l'évaluation des rendements de fission, GK
Stage M1 Franco … (2016) : covariance efficacité des BEGe

Publications :

- A. Chebboubi, G. Kessedjian et al., Eur. Phys. J. A **57**: 335(2021)
- S. Julien-Laferrière, A. Chebboubi, G. Kessedjian, O. Serot, O. Litaize, A. Blanc, U. Köster, O. Méplan, M. Ramdhane, and C. Sage , Phys. Rev. C **102**, 034602 (2020)
- Y.H.Kim et al., NIM B, Vol. 463, Pages 269-271, (2020)
- S. Julien-Laferrière, A. Chebboubi, G. Kessedjian, Olivier Serot., EPJ N - Nuclear Sciences & Technologies, EDP Sciences, 4, pp.25 (2018)
- B. Voirin, G. Kessedjian, A. Chebboubi, Olivier Serot, S. Julien-Laferriere et al., EPJ N - Nuclear Sciences & Technologies, EDP Sciences, 4, pp.26 (2018)
- Y.K. Gupta, D.C. Biswas, O. Serot, D. Bernard, O. Litaize et al., Phys.Rev.C, 96 (1), pp.014608, (2017) -> Pu239

-

Thank you for your attention

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