DE LA RECHERCHE À L'INDUSTRIE

www.cea.fr

# Things we have (maybe) not talked about !

DE LA RECHERCHE À L'INDUSTRIE

# $(n,xn\gamma)$ : what else !

www.cea.fr

# Content

- Introduction
- Actinides Optical Model Potentials
- Fission yields
- neutrons and gamma spectra in fission
- Fission barriers and cross sections

# INTRODUCTION

# Why this talk ?

- ESNT used to be Structure only and is ready for reactions !

- ESNT Scientific Council was unanimous to organize this one

- ESNT Scientific Council mentioned that other problems have to be discussed around actinides

- Try to find out what a next Workshop could deal with ?

# ACTINIDES OMP

# IMPACT OF THE COUPLING SCHEME

**IAEA**
International Atomic Energy Agency

**INDC(NDS)-0597**
**Distr. J+NM**

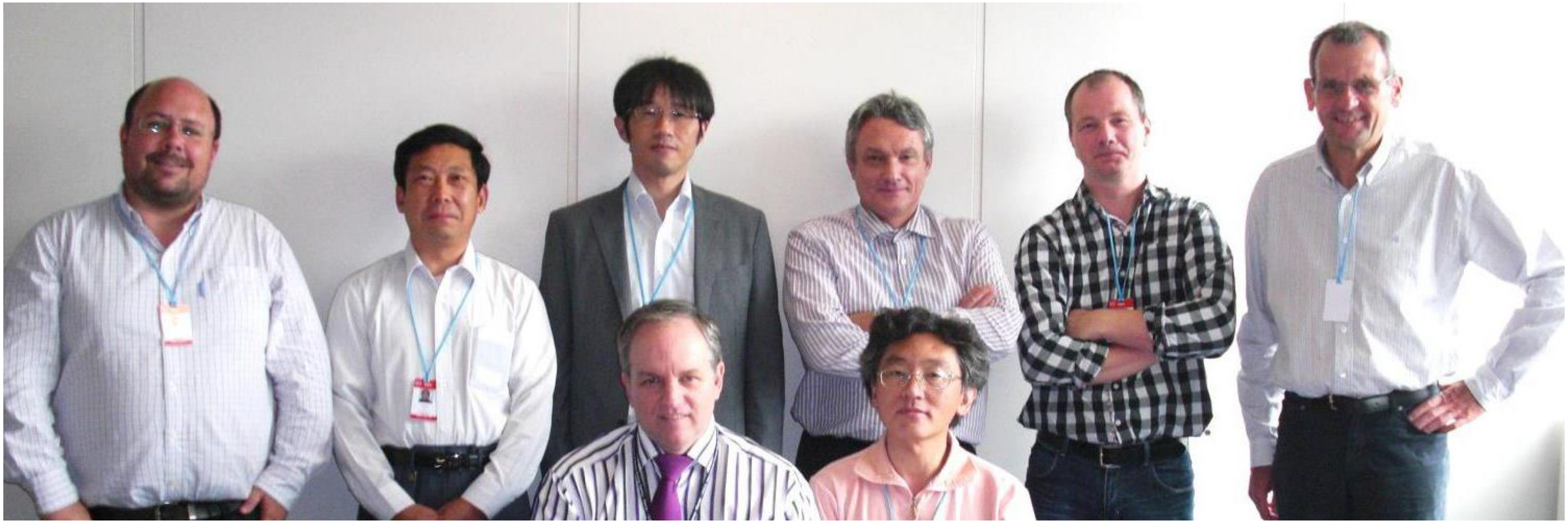
**INDC International Nuclear Data Committee**

**Summary Report**

**Technical Meeting on**

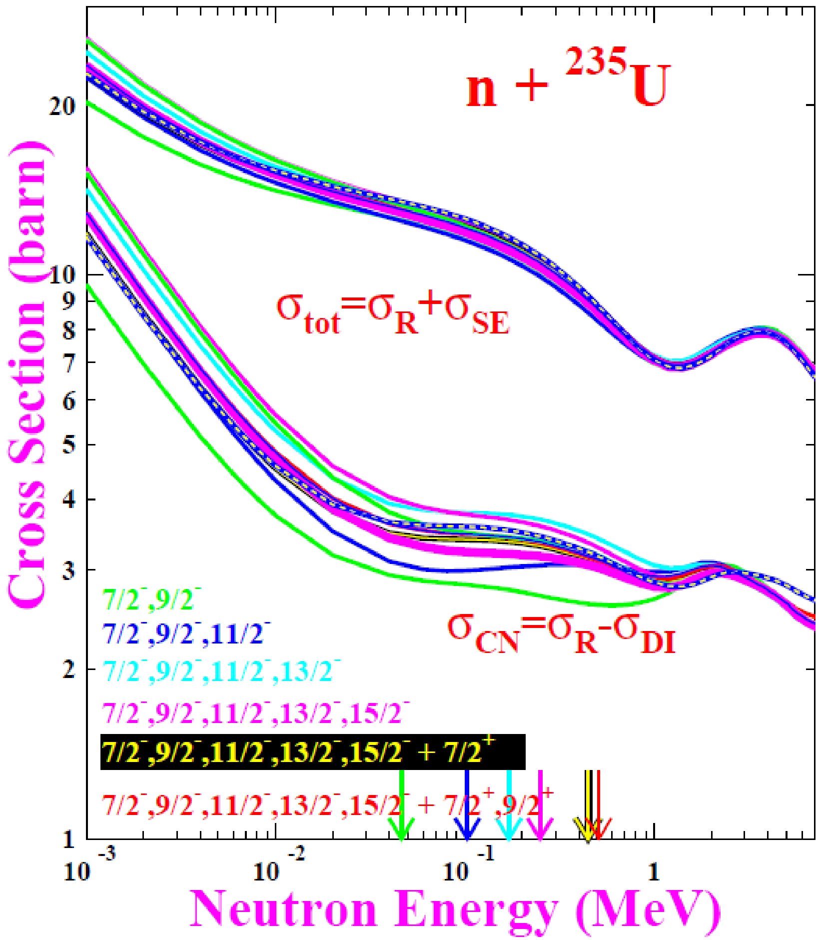
**Inelastic Scattering and Capture Cross-section Data of Major Actinides in the Fast Neutron Region**

IAEA Headquarters
Vienna, Austria
6 – 9 September 2011



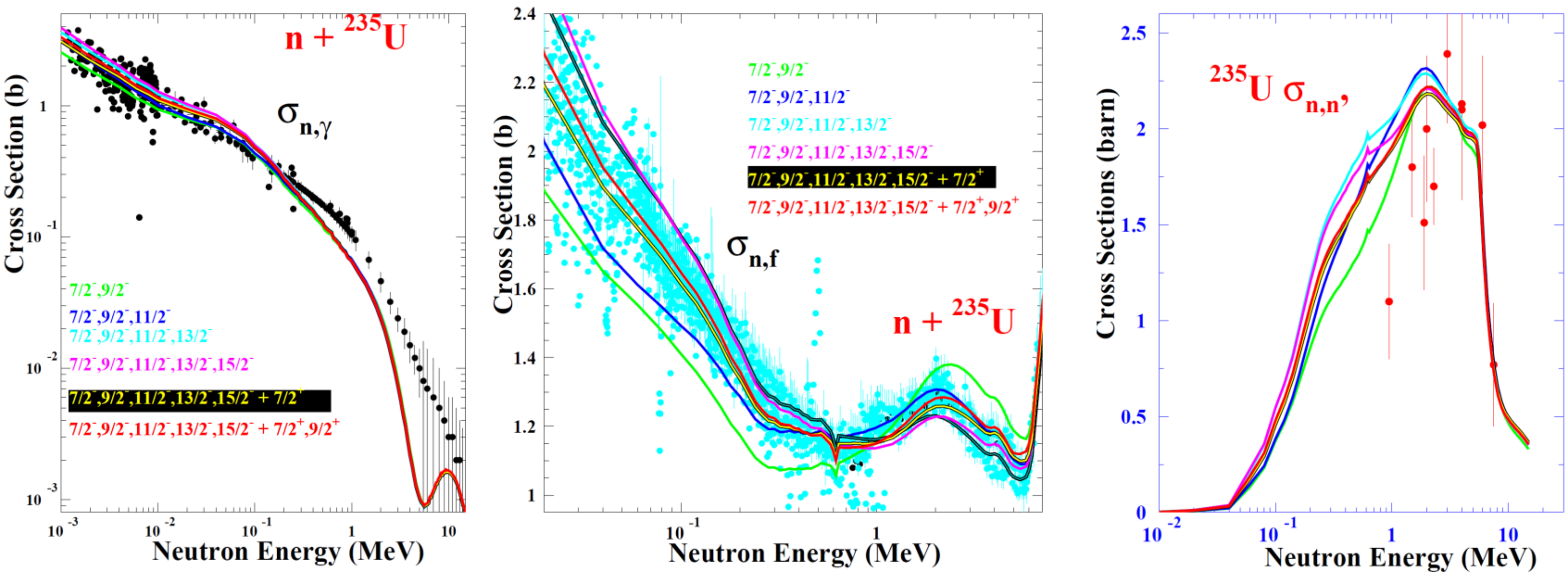
# IMPACT OF THE COUPLING SCHEME (P. Romain)

## OMP - CCC ↔ which coupling scheme ?



## CCC : coupling scheme effects on statistical model caculations

### Cross Sections behaviour

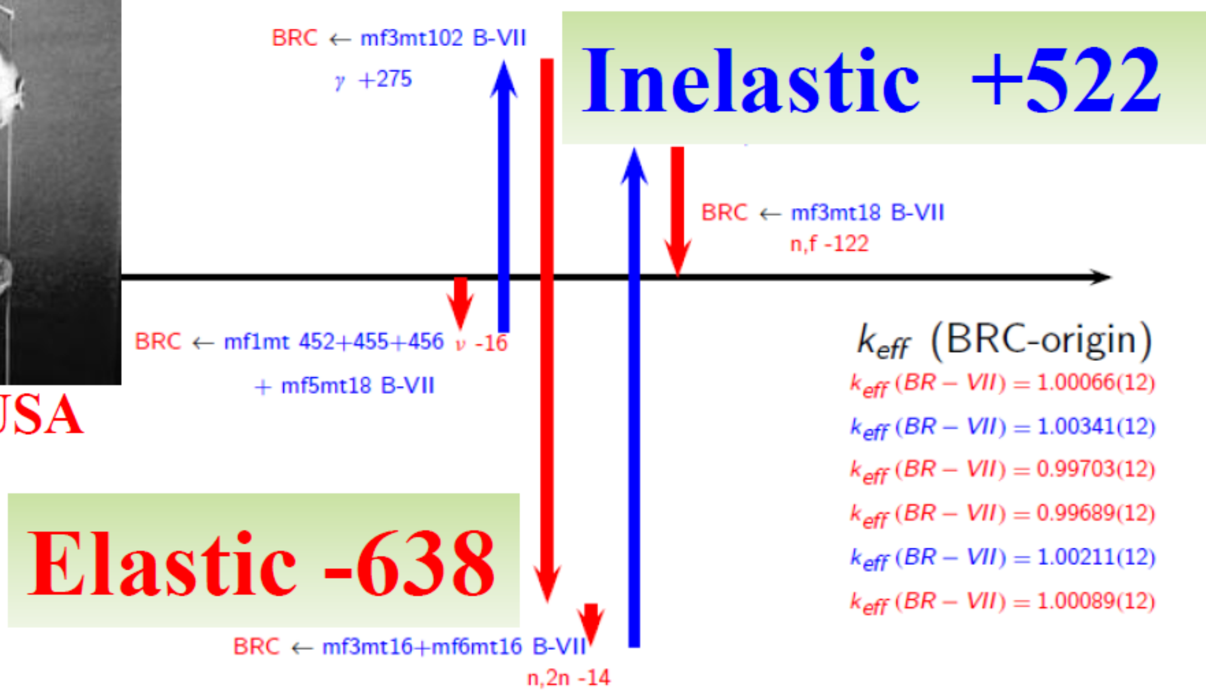


# Large compensations effects noted !

But as known from B. Morillon study (calculations MCNP5)

JEZEBEL $k_{eff}(BRC) = 1.00082(11)$ $k_{eff}(B\text{-}VII) = 1.00060(12)$

LANL, USA




A.J. Plompen, T. Kawano and RC, Technical report INDC(NDS)-0597 ( IAEA,Vienna,2012)
*http://www-nds.iaea.org/publications/indc/indc-nds-0597.pdf*



Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

# FISSION YIELDS

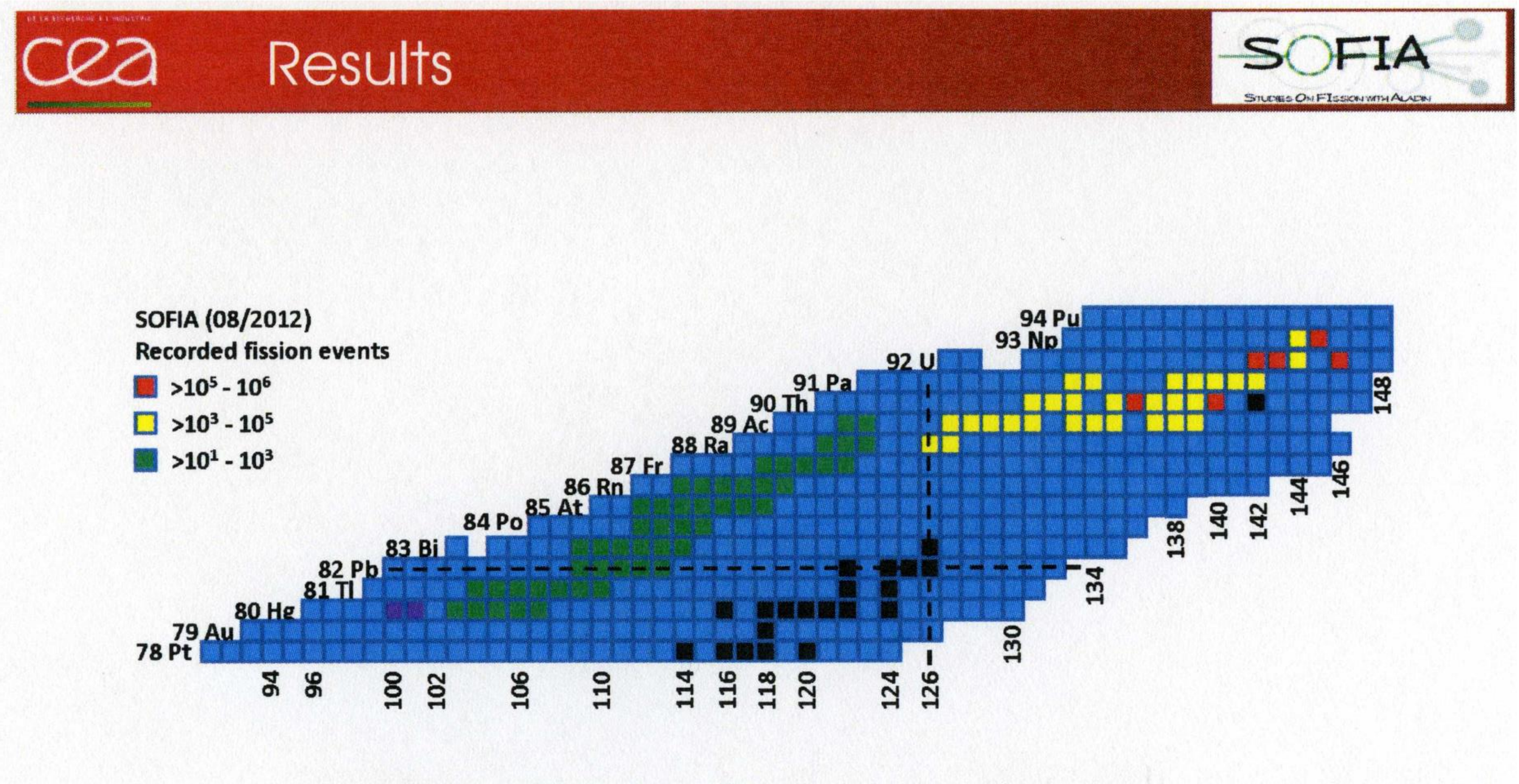
# FISSION YIELD : IMPORTANT ACTIVITY !

Experimental :

- SOFIA@GSI (nuclei with Z,A < $^{238}$U, E* not exactly known, many fissioning systems)

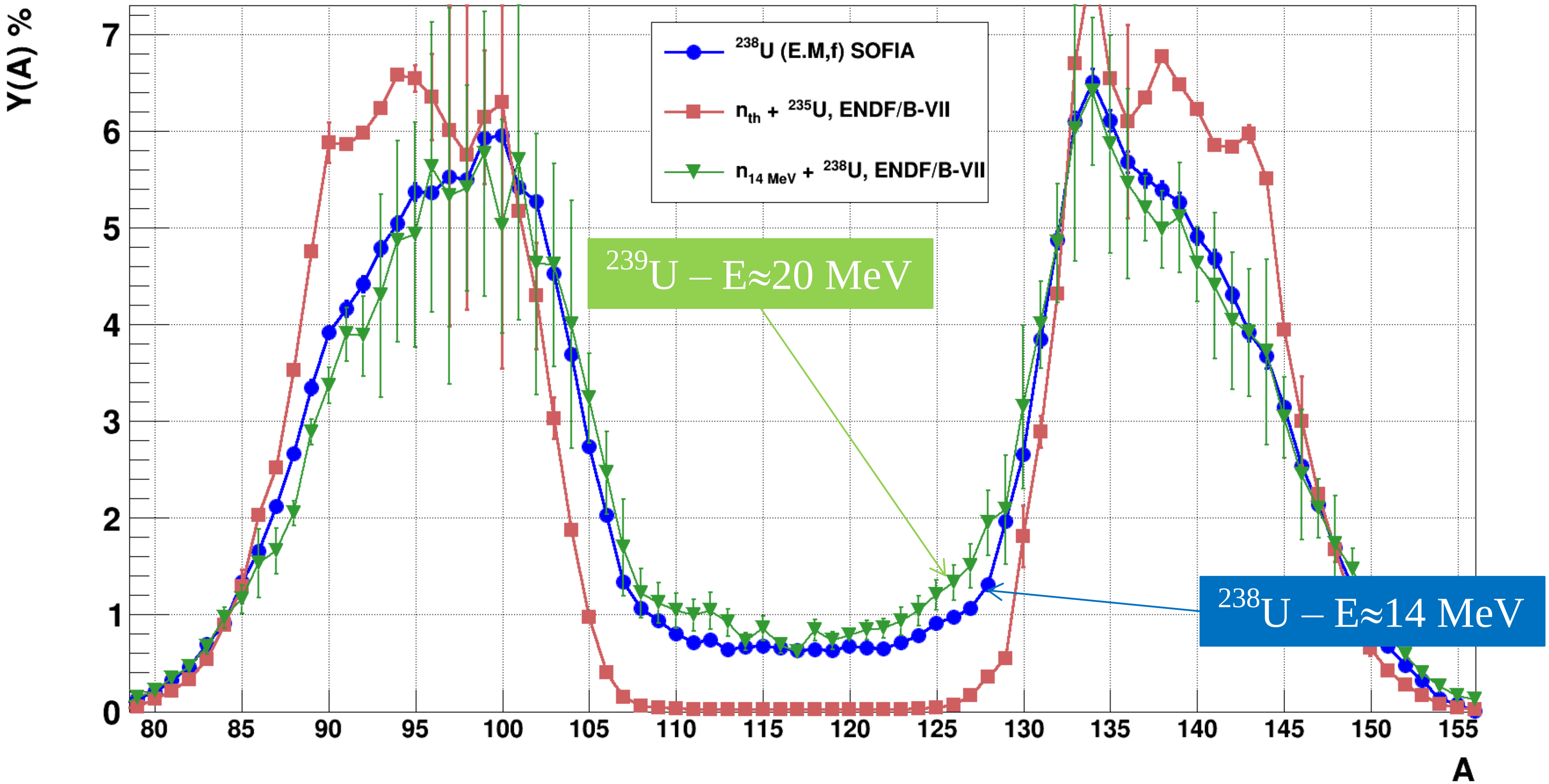
# SOFIA (J. Taieb)

SOFIA = measurement of fission yields in inverse kinematics after fragmentation of a $^{238}U$ and Coulomb excitation on a heavy target to induced virtual-photo-fission



# SOFIA (J. Taieb)

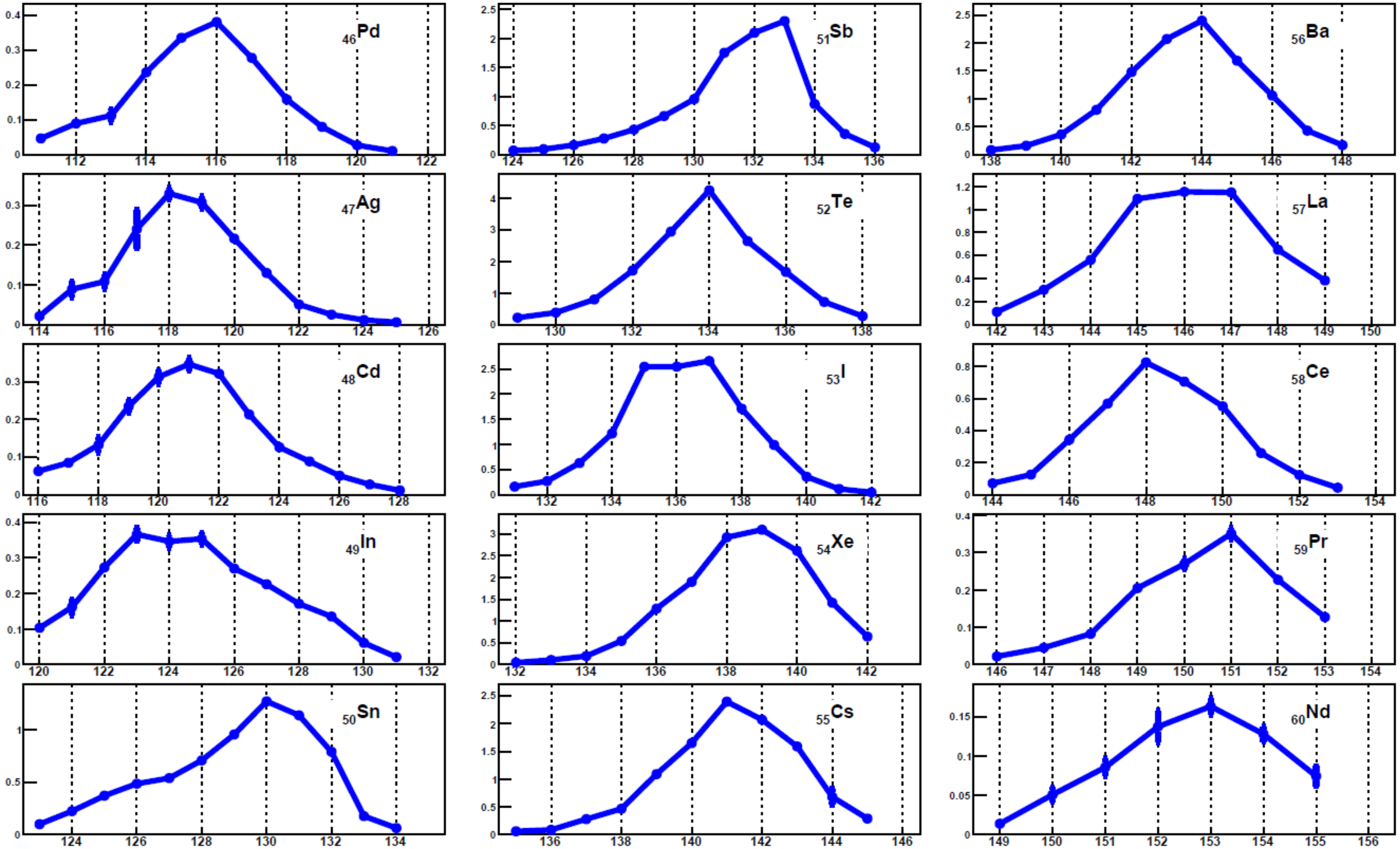
SOFIA = measurement of fission yields in inverse kinematics after fragmentation of a $^{238}U$




⇒ very precise measurement

# SOFIA (J. Taieb)

SOFIA = measurement of fission yields in inverse kinematics after fragmentation of a $^{238}U$ and Coulomb excitation on a heavy target to induced virtual-photo-fission



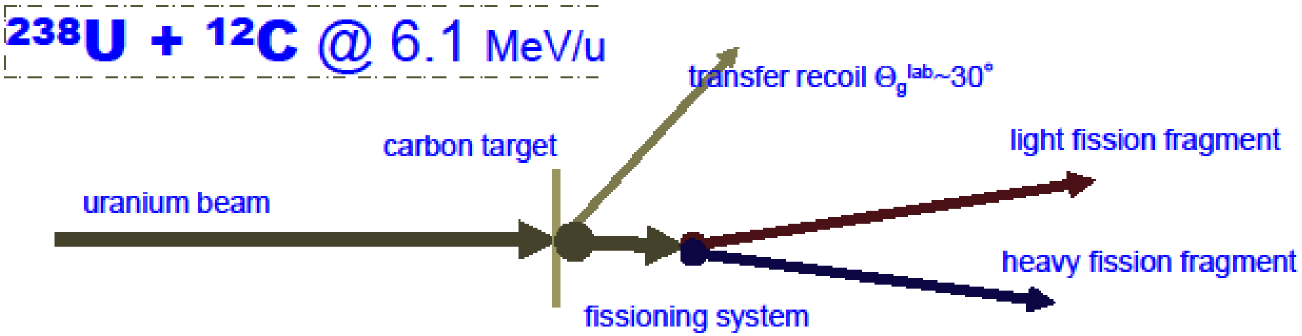

⇒ Access to isotopic yields for all (including heavy) fission fragments for the first time !

# FISSION YIELD : IMPORTANT ACTIVITY !

Experimental :

- SOFIA@GSI (nuclei with Z,A < $^{238}$U, E* not exactly known, many fissioning systems)
- Fission@GANIL (nuclei with Z,A > $^{238}$U, E* much better known, few fissioning systems)

## Transfer-induced fission in inverse kinematics




**Transfer reaction**

- U, Np, Pu, Am, Cm

different **E***

**Fusion reaction**

$^{250}$Cf E*=45 MeV

**inverse kinematics**

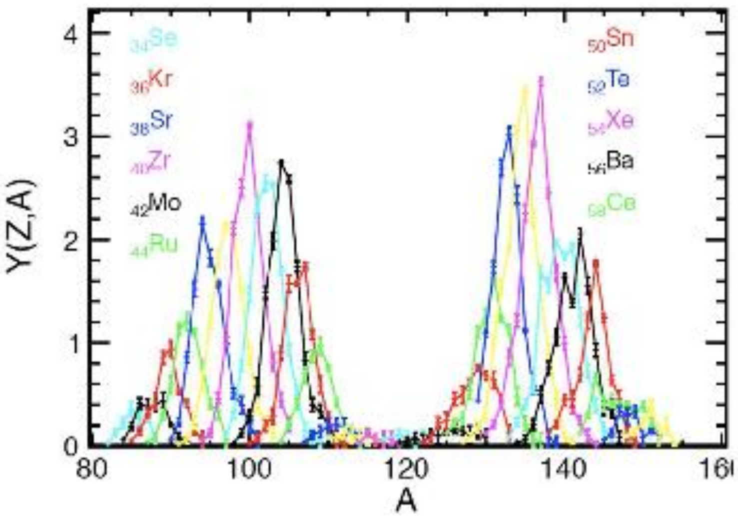
-restricted angular distribution

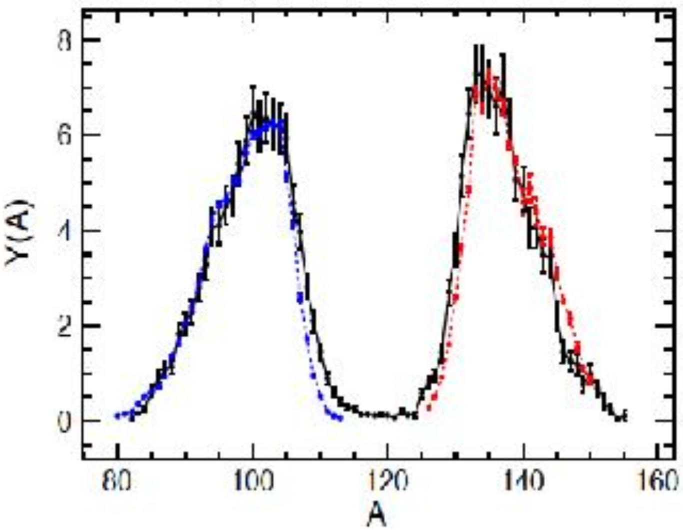
-Kinematical push that makes possible Z measurement

# FISSION@GANIL (Fanny Farget)

Isotopic yields for $^{12}C(^{238}U,^{240,241}Pu)^{10,9}Be$ transfer channel

$^{240,241}Pu$



# FISSION YIELD : IMPORTANT ACTIVITY !

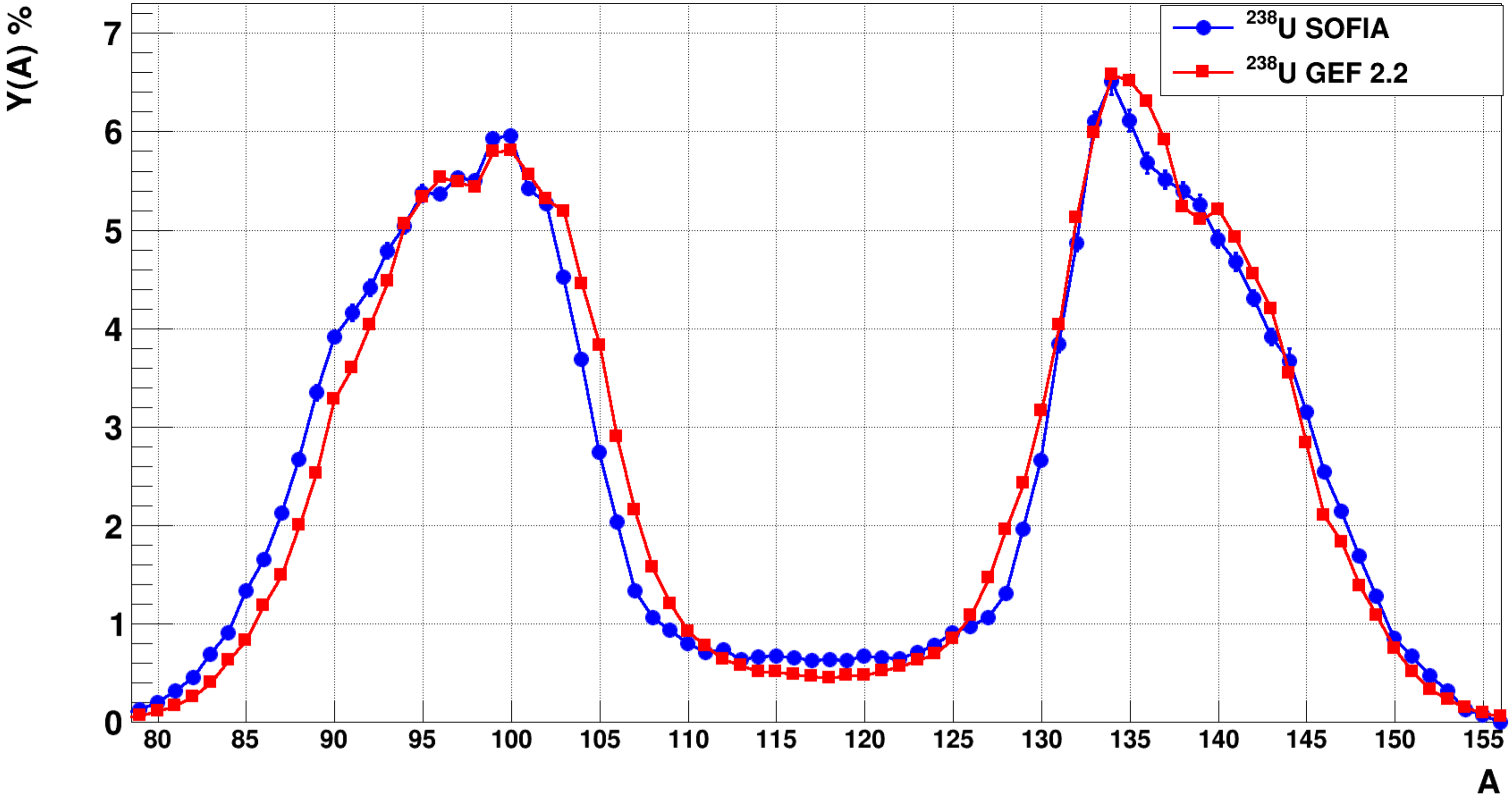
Experimental :

- SOFIA@GSI (nuclei with Z,A < $^{238}$U, E* not exactly known, many fissioning systems)
- Fission@GANIL (nuclei with Z,A > $^{238}$U, E* much better known, few fissioning systems)
- Future experiment@NFS
  - …

Theoretical :

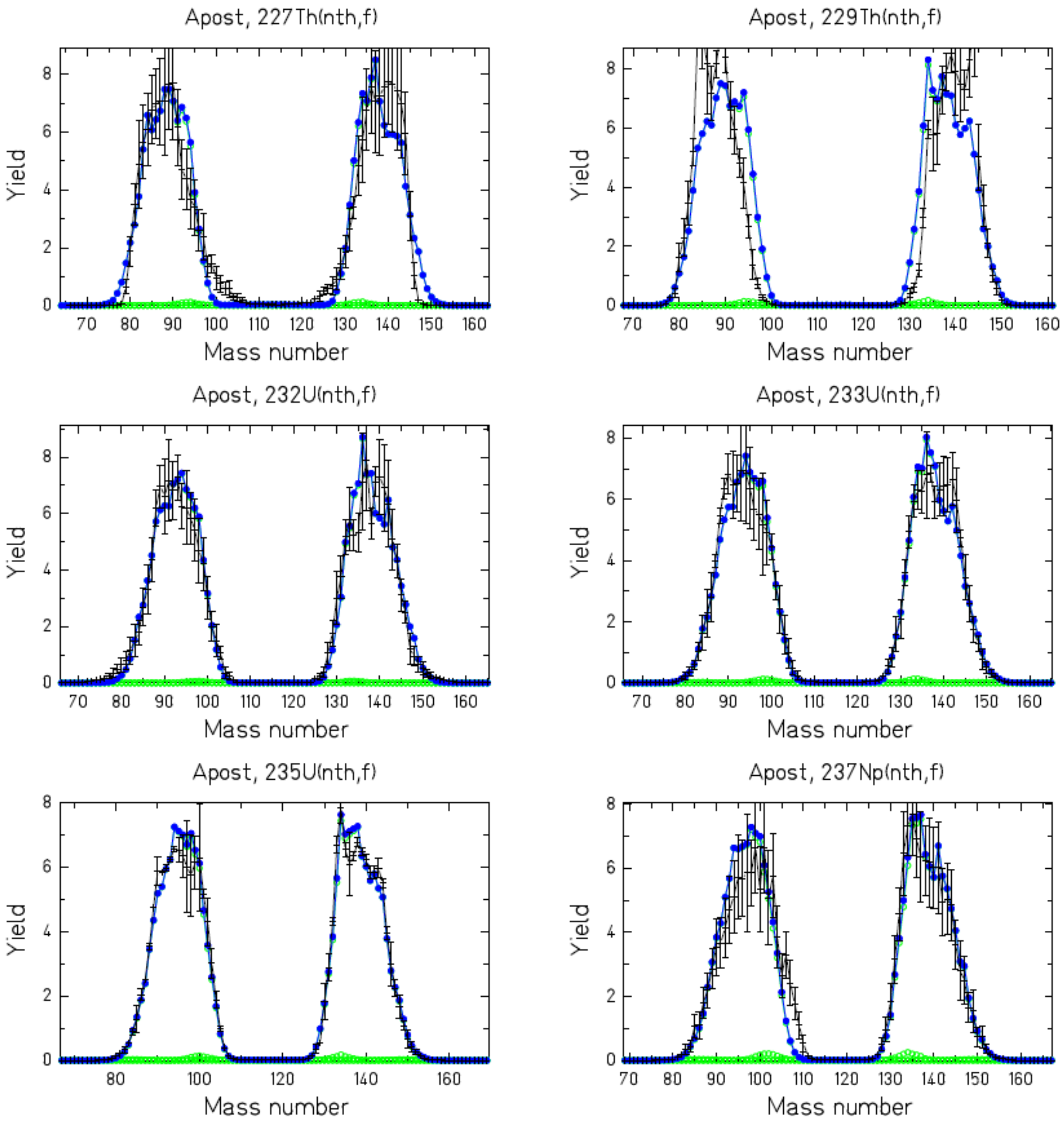
- GEF@GSI

# GEF code (Karl-Heinz Schmidt)

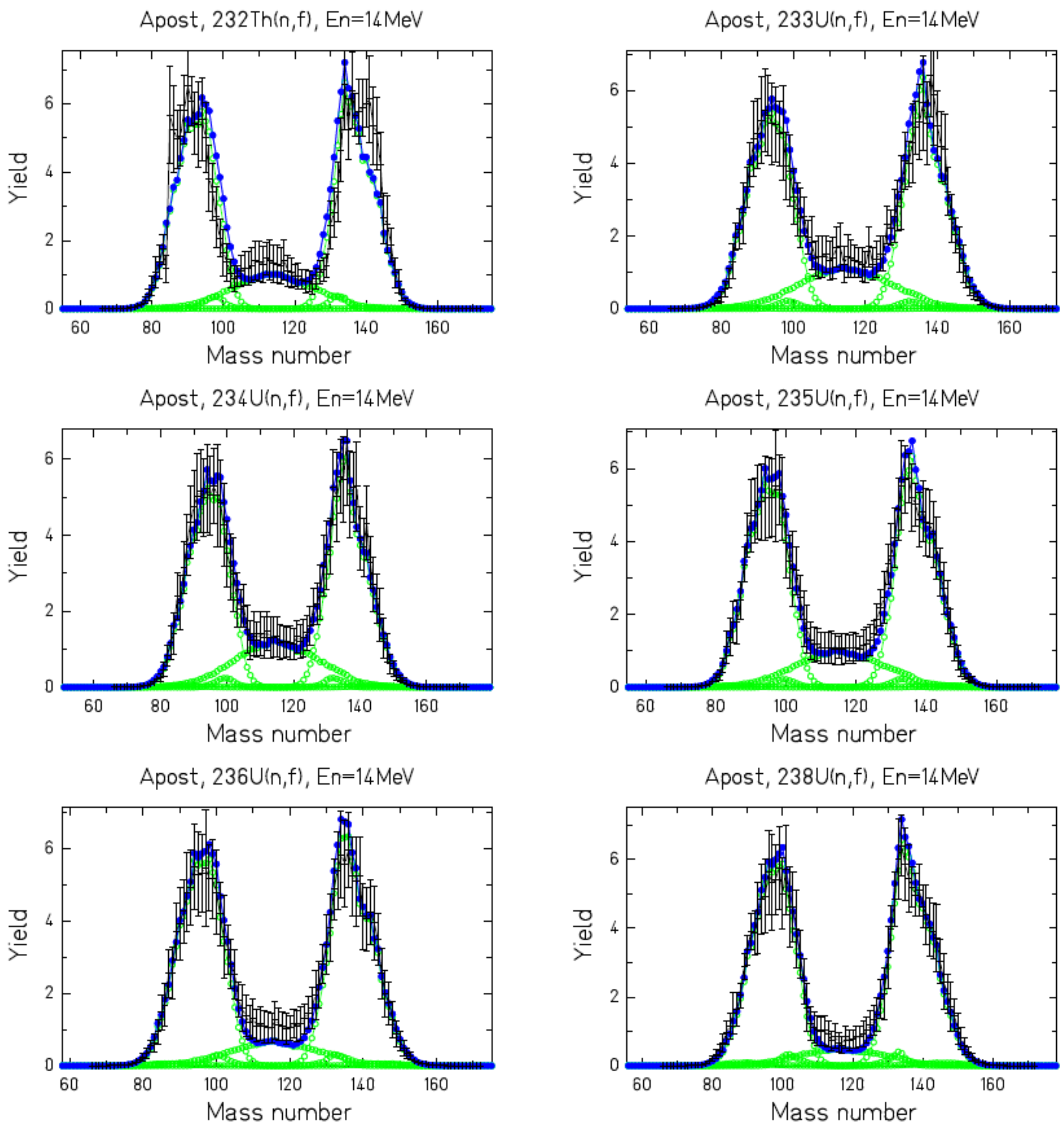



⇒ very good fitting power

# GEF code (Karl-Heinz Schmidt)



# GEF code (Karl-Heinz Schmidt)



# FISSION YIELD : IMPORTANT ACTIVITY !

Experimental :

- SOFIA@GSI (nuclei with Z,A < $^{238}U$, E* not exactly known, many fissioning systems)
- Fission@GANIL (nuclei with Z,A > $^{238}U$, E* much better known, few fissioning systems)
- Future experiment@NFS
- …

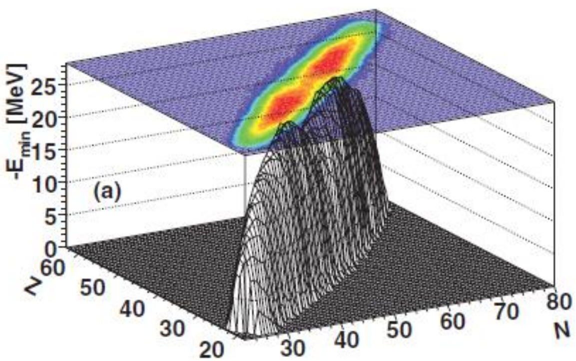
Theoretical :

- GEF@GSI
- SPY@(DAM-DSM)

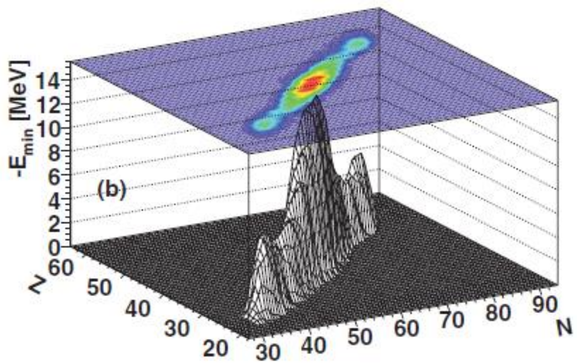
# SPY CODE (J.F. Lemaitre)

Energy balance at scission : - microscopic PES using HFB+D1S
- d=5 fm (Coulomb and nuclear energy)

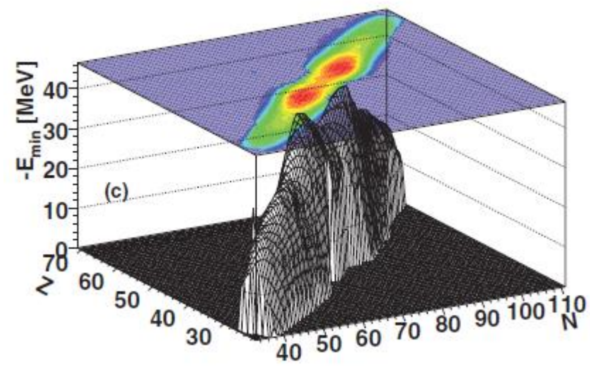
$^{180}$Hg




$^{198}$Hg

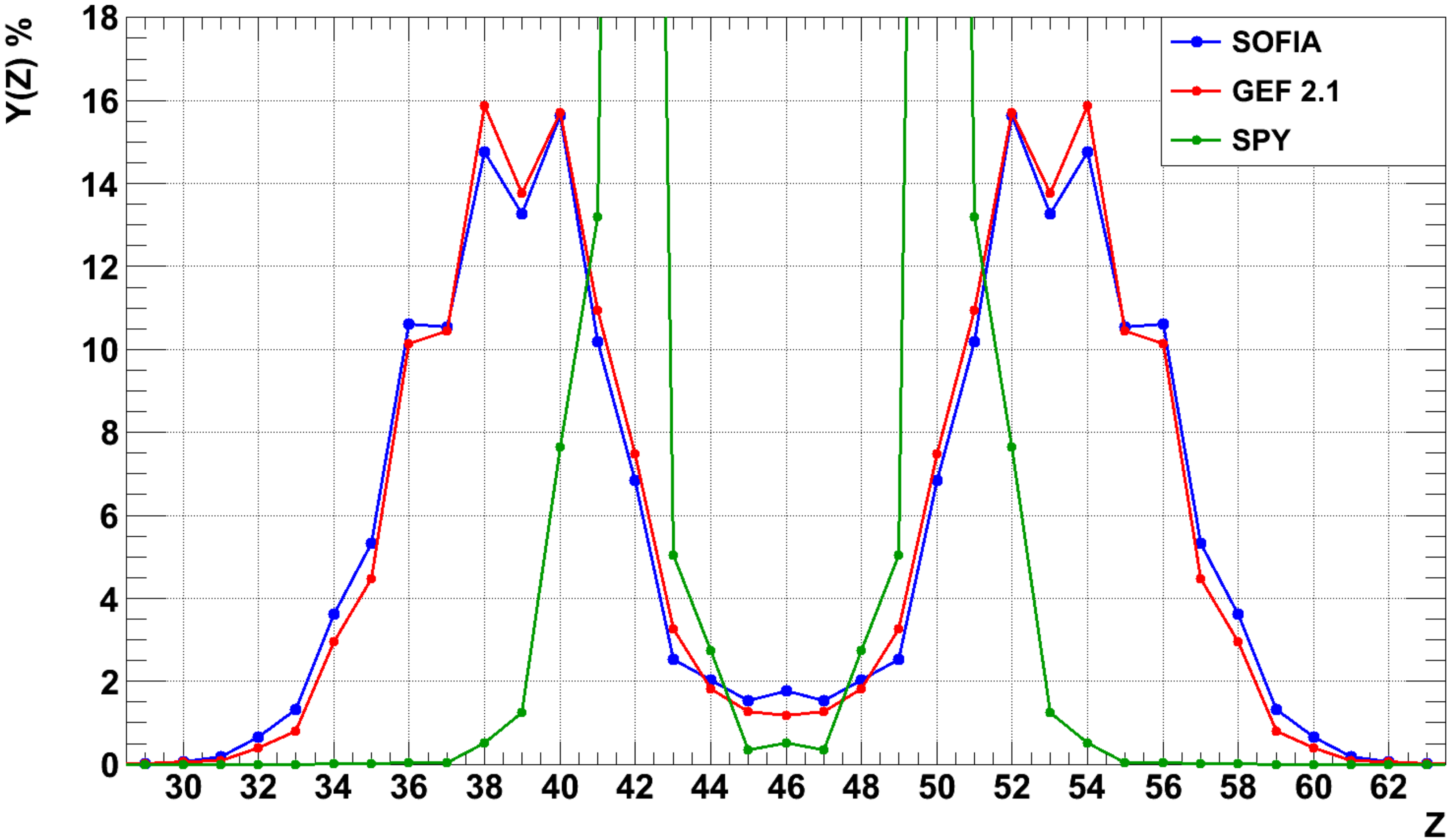



$^{235}$U




SPY provides qualitative features !

# SPY CODE (J.F. Lemaitre)

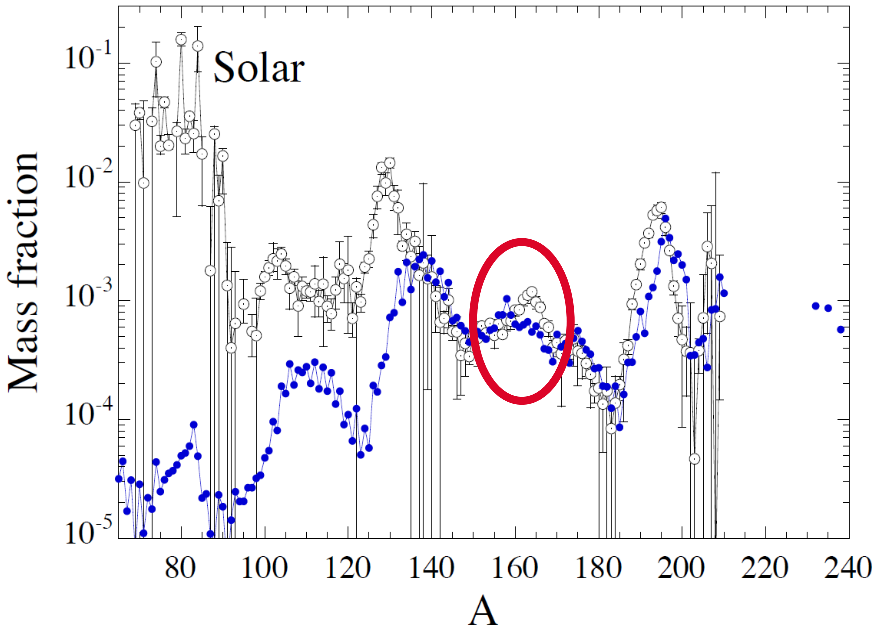



SPY is not (yet) a fitting code !

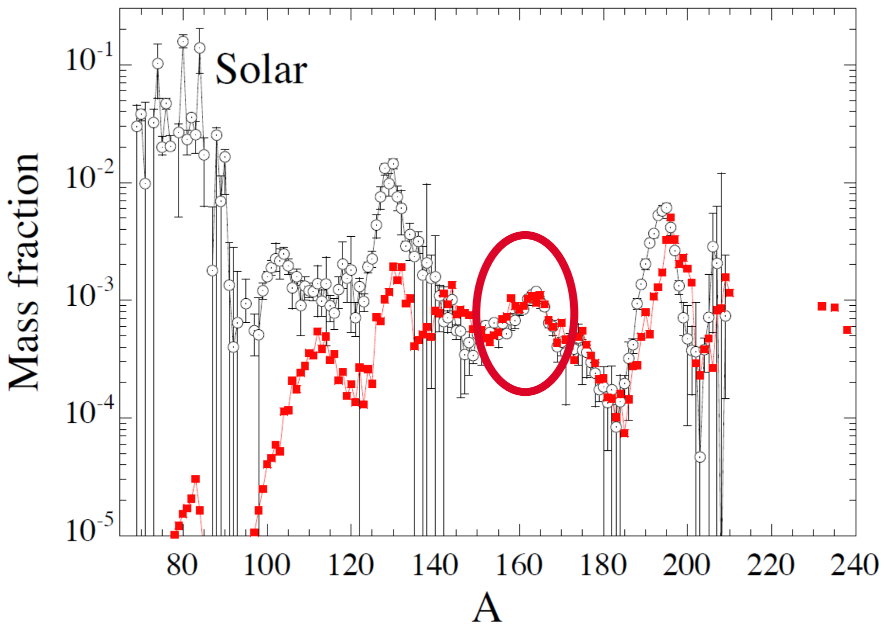
# SPY CODE & SOLAR ABUNDANCIES (1/2)

**Solar abundancies for 140 < A < 200 : r-nuclei !**

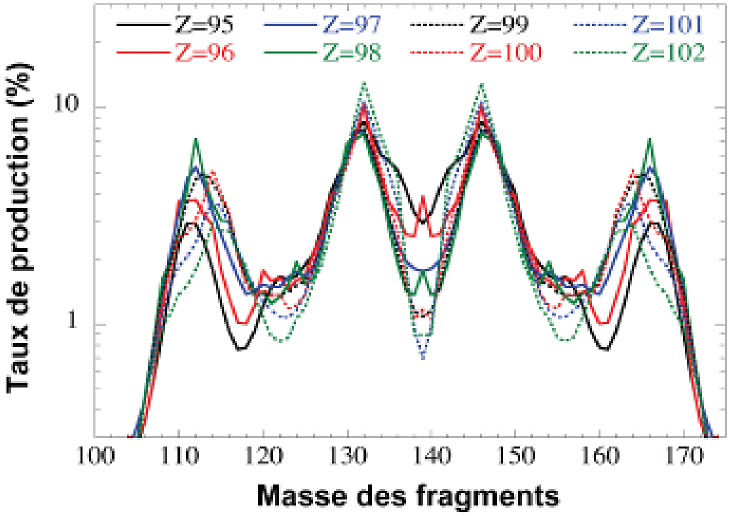
**GEF**

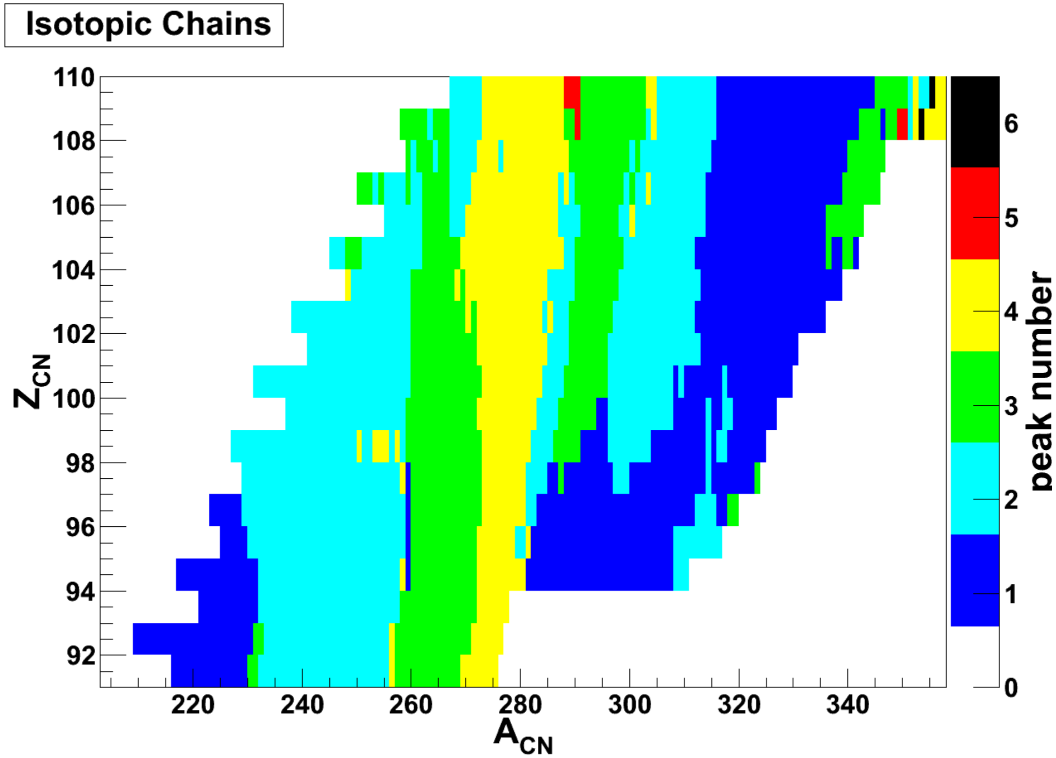



**SPY**



# doubly asymetric fission !



# FISSION YIELD : IMPORTANT ACTIVITY !

Experimental :

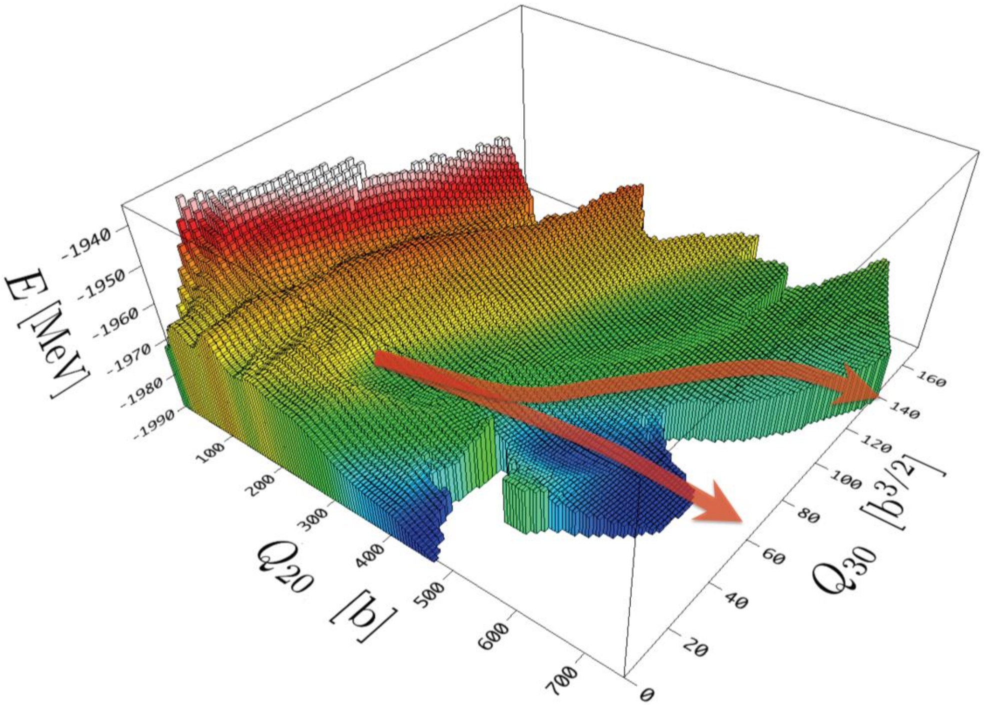
- SOFIA@GSI (nuclei with Z,A < $^{238}U$, E* not exactly known, many fissioning systems)
- Fission@GANIL (nuclei with Z,A > $^{238}U$, E* much better known, few fissioning systems)
- Future experiment@NFS
- …

Theoretical :

- GEF@GSI
- SPY@(DAM-DSM)
- Dubray@DAM

# FISSION YIELD (N. Dubray)

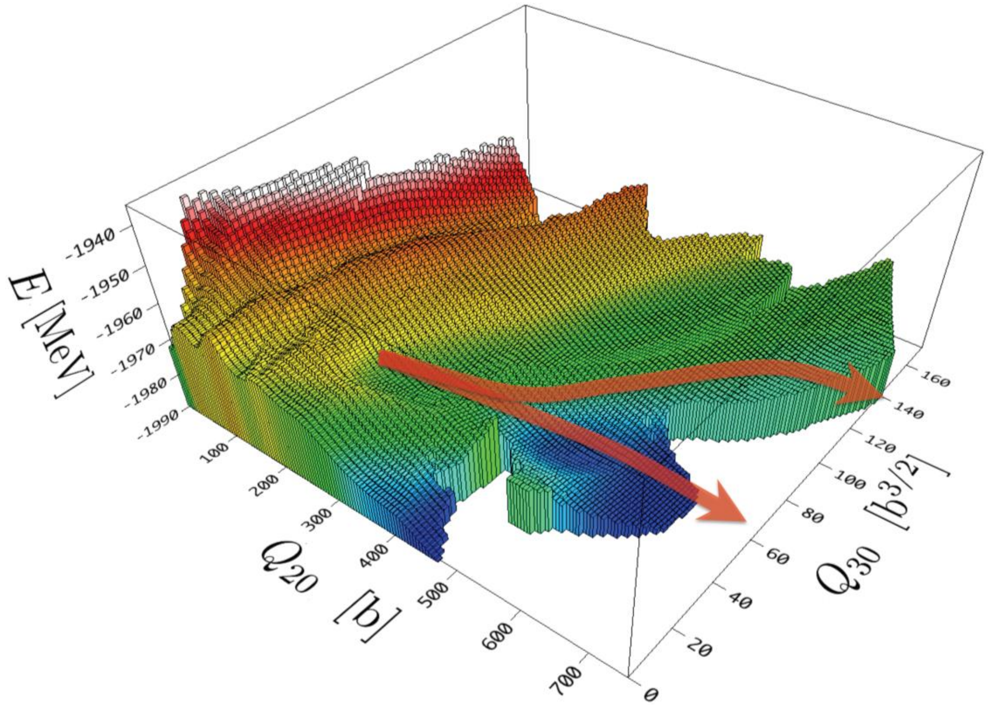
Microscopic PES generation (more than 2D needed to remove discontinuities)




Wave function propagation to calculate yields (OK in 2D / soon in nD)

# FISSION YIELD (N. Dubray)

Microscopic PES generation (more than 2D needed to remove discontinuities)




Wave function propagation to calculate yields (OK in 2D / soon in nD)

# NEUTRONS AND GAMMA SPECTRA FROM FISSION

# NEUTRON & GAMMA SPECTRA : IMPORTANT ACTIVITY !

Experimental :

- SOFIA@GSI (gamma coming years)
- VAMOS@GANIL (gamma coming years)
- Experiment@DIF

# GAMMA SPECTRA : EXISTING DATA & NEEDS

**Thermal fission**

- 3 spectra for 235U, 239Pu measured in the 60'
- New measurements are underway (S. Obersted et al.)

**Fast fission**

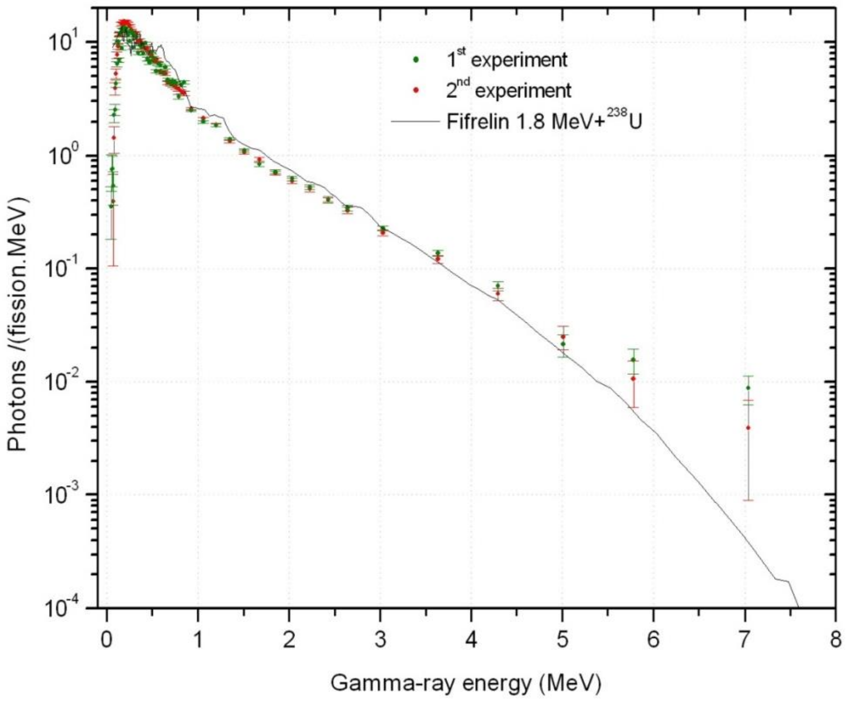
- One relative measurement of the mean total energy for $^{235}U$, $^{237}Np$ and $^{232}Th$ fission for 2-15 MeV neutron
- No measurement for $^{238}U$ or $^{239}Pu$
- No spectrum nor multiplicity for $^{235}U$

**New data :**

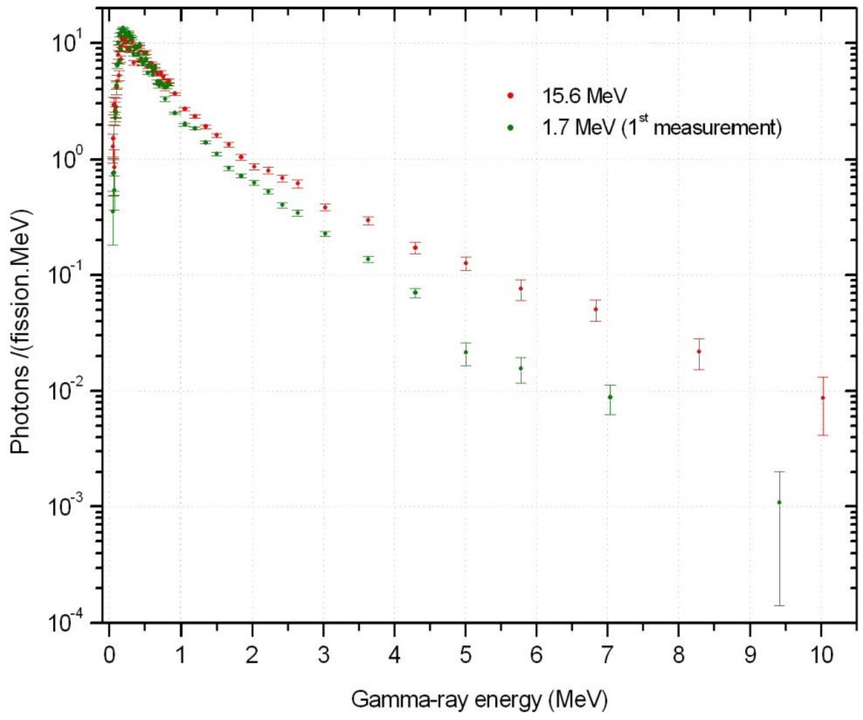
- would give new insights in the fission process : angular momentum of the fragments, neutron/gamma competition…
- NEA (OECD) requests measurement of :
  - ✓ prompt fission γ-ray spectrum shape from 0 to 10 MeV
  - ✓ mean total energy and multiplicity (±7.5% max)
  - ✓ thermal and fast neutron-induced fission of 235U et 239Pu

# GAMMA SPECTRA : NEW DATA@DIF (J.M. Laborie)

Data on 238U@1.8 MeV




Effect of the incident neutron energy



IAEA
International Atomic Energy Agency

INDC(NDS)-0608
Distr. AI+MN+NM

**INDC International Nuclear Data Committee**

Summary Report

Second Research Coordination Meeting on

**Prompt Fission Neutron Spectra of Major Actinides**

IAEA Headquarters
Vienna, Austria

13 – 16 December 2011

**Third meeting held in October 2013 : Report in preparation**

# Prompt neutron spectra $^{239}Pu(n,f)$



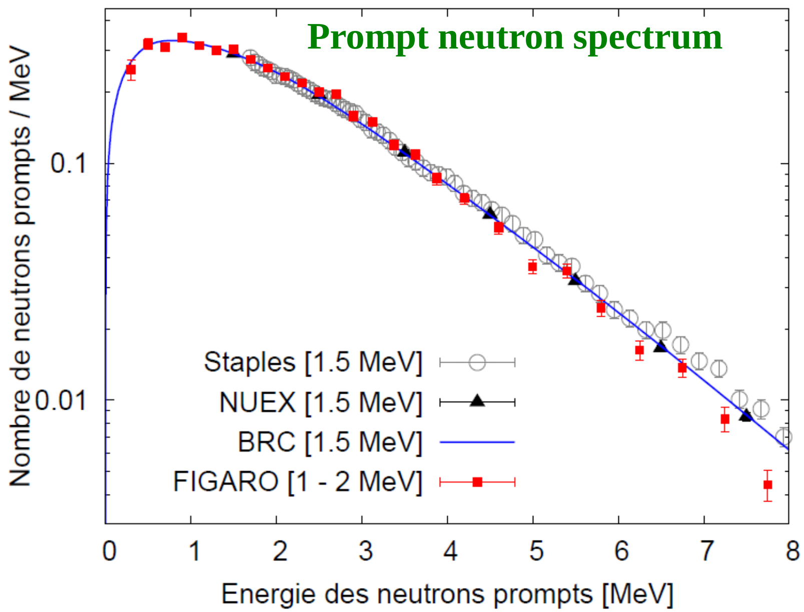
## ▪ Why ?

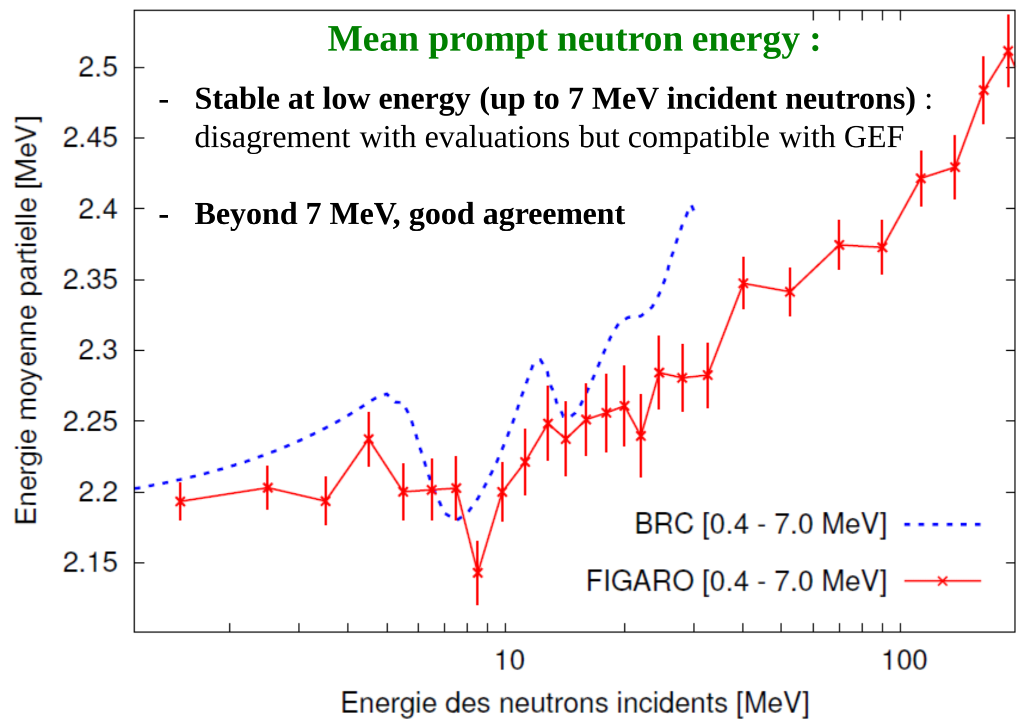
- Important data for **criticity** : spectra shapes impacts $K_{eff}$
- High energy prompt neutrons **damages reactors' vessels**.
- **Constrains evaluations (BRC, JEFF, ENDF-BVII) et theoretical approaches.**
- **Only few spectra known :** thermal and only 5 mesaurements below 3.5 MeV

## ▪ DAM / NNSA Collaboration

**27 spectra for incident neutrons from 1 up to 200 MeV**

## ▪ Results:



# NEUTRON SPECTRA (A. Chatillon)

PHYSICAL REVIEW C **89**, 014611 (2014)

**Measurement of prompt neutron spectra from the $^{239}$Pu$(n,f)$ fission reaction for incident neutron energies from 1 to 200 MeV**

A. Chatillon,* G. Bélier, T. Granier, B. Laurent, B. Morillon, and J. Taieb
*CEA, DAM, DIF, F-91297 Arpajon, France*

R. C. Haight, M. Devlin, R. O. Nelson, S. Noda, and J. M. O'Donnell
*LANSCE, Los Alamos National Laboratory, MS H855, Los Alamos, New Mexico 87545, USA*

(Received 28 October 2013; published 15 January 2014)

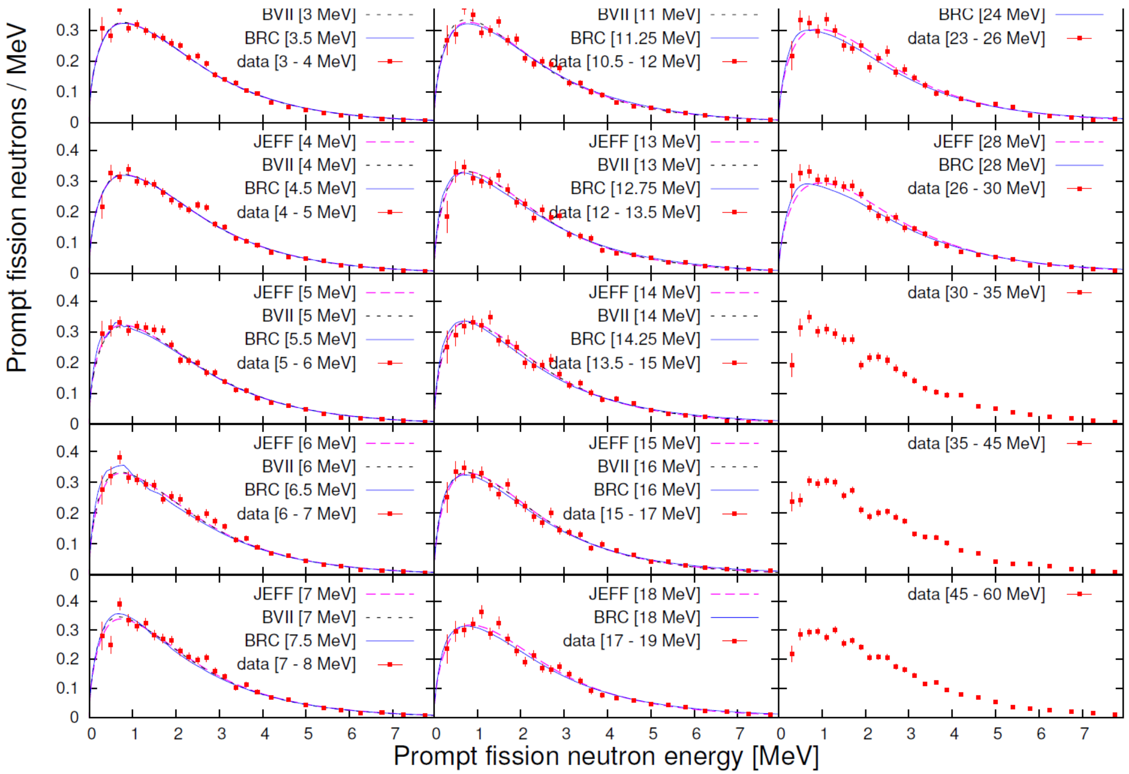



FIG. 6. PFNS for several beam energies (indicated inside the square brackets). Experimental data (points) are compared to BRC calculation (full line), JEFF 3.1 (dashed line) and ENDF/BVII.1 (dotted line) evaluations.

# NEUTRON & GAMMA SPECTRA : IMPORTANT ACTIVITY !

Experimental :

- SOFIA@FELISE (approx . ten years)
- Experiment@DIF
- Future experiment@GANIL(FALSTAFF)
- …

Theoretical :

- GEF@GSI

# GEF code (Karl-Heinz Schmidt)

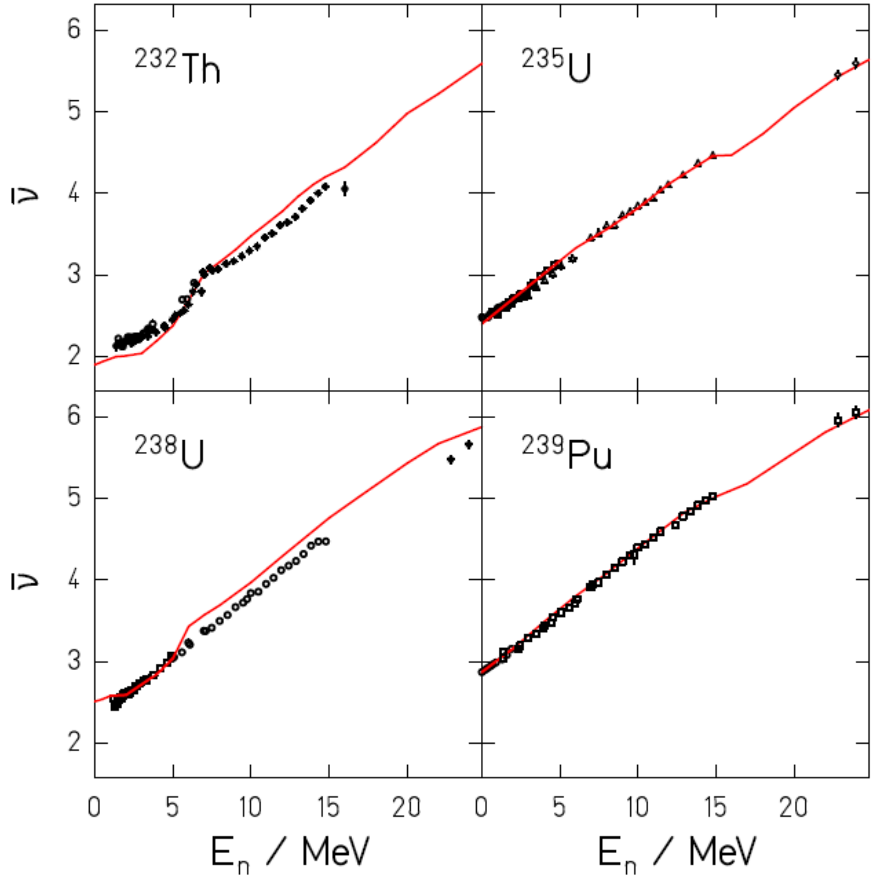



Figure 76: Measured prompt-neutron multiplicity for $^{232}$Th(n,f), $^{235}$U(n,f), $^{238}$U(n,f), and $^{239}$Pu(n,f) (black symbols, different symbols are used for different experiments) as a function of neutron energy (data from ref. [152]) in comparison with the result of the GEF code (red line).

# GEF code (Karl-Heinz Schmidt)

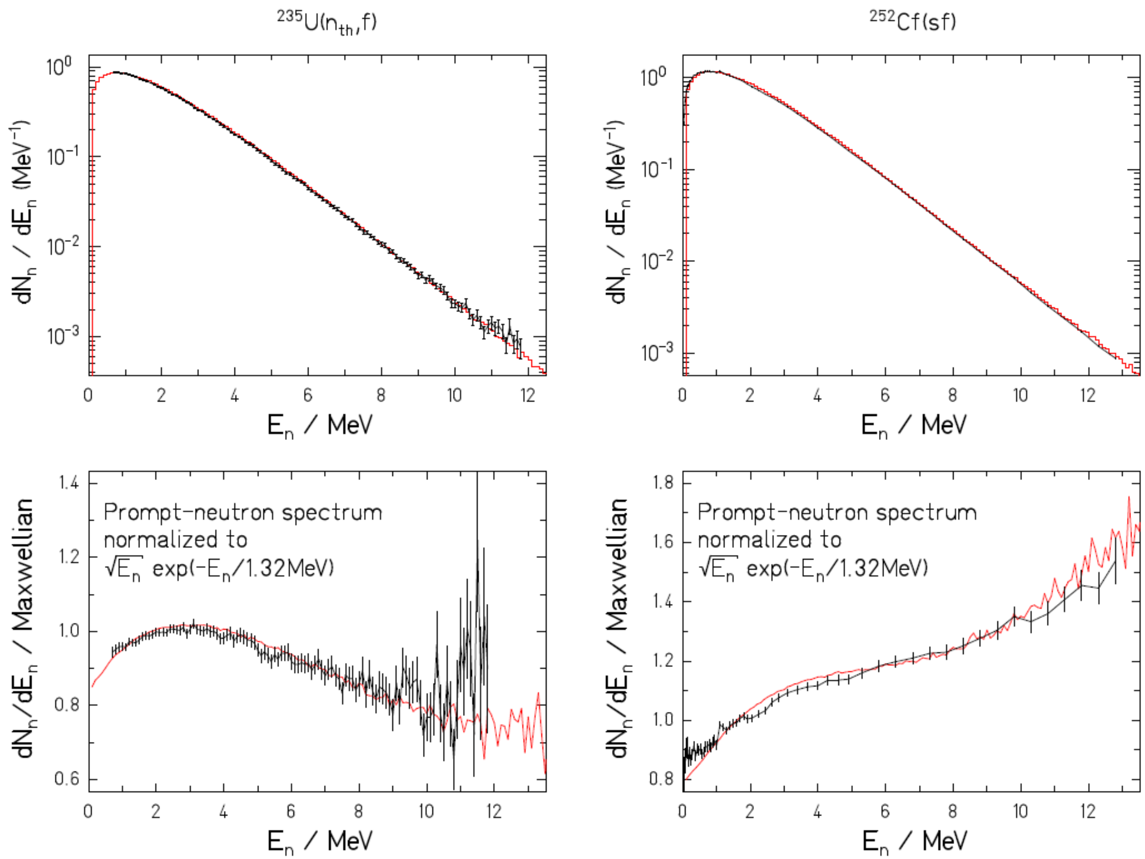



Figure 80: Experimental prompt-fission-neutron spectra (black lines and error bars) for $^{235}$U($n_{th}$,f) [158] (left panels) and $^{252}$Cf(sf) [159] (right panels) in comparison with the result of the GEF code (red lines) in logarithmic scale. In the lowest panels, all spectra have been normalized to a Maxwellian with $T = 1.32$ MeV.

# NEUTRON & GAMMA SPECTRA : IMPORTANT ACTIVITY !

Experimental :

- SOFIA@GSI (next years)
- Experiment@DIF
- Future experiment@GANIL(FALSTAFF)
- …

Theoretical :

- GEF@GSI
- FIFRELIN@CADARACHE

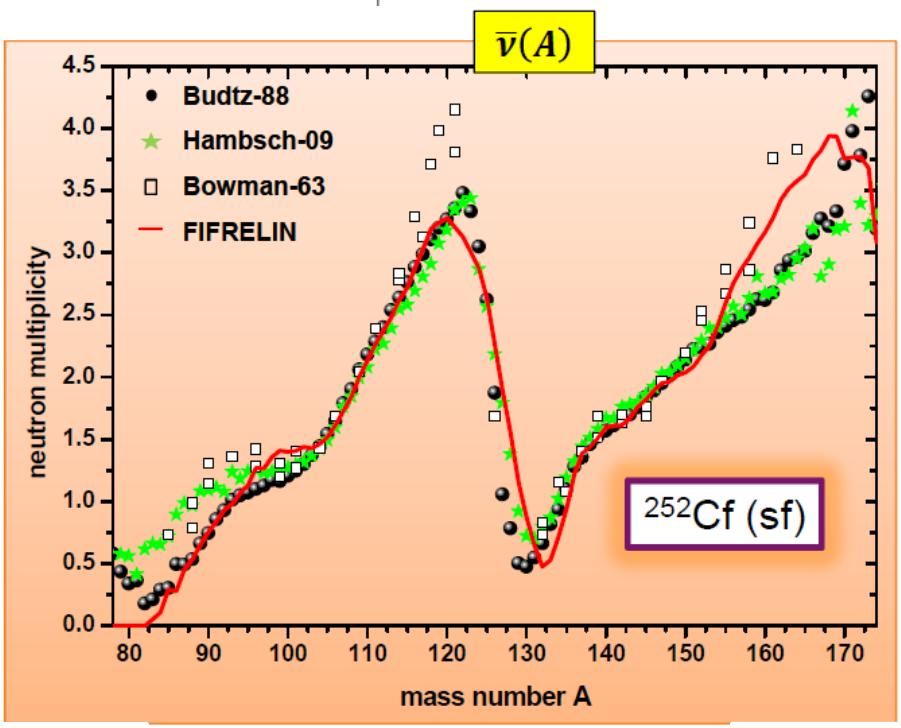
# FIFRELIN code (Oliver Litaize)

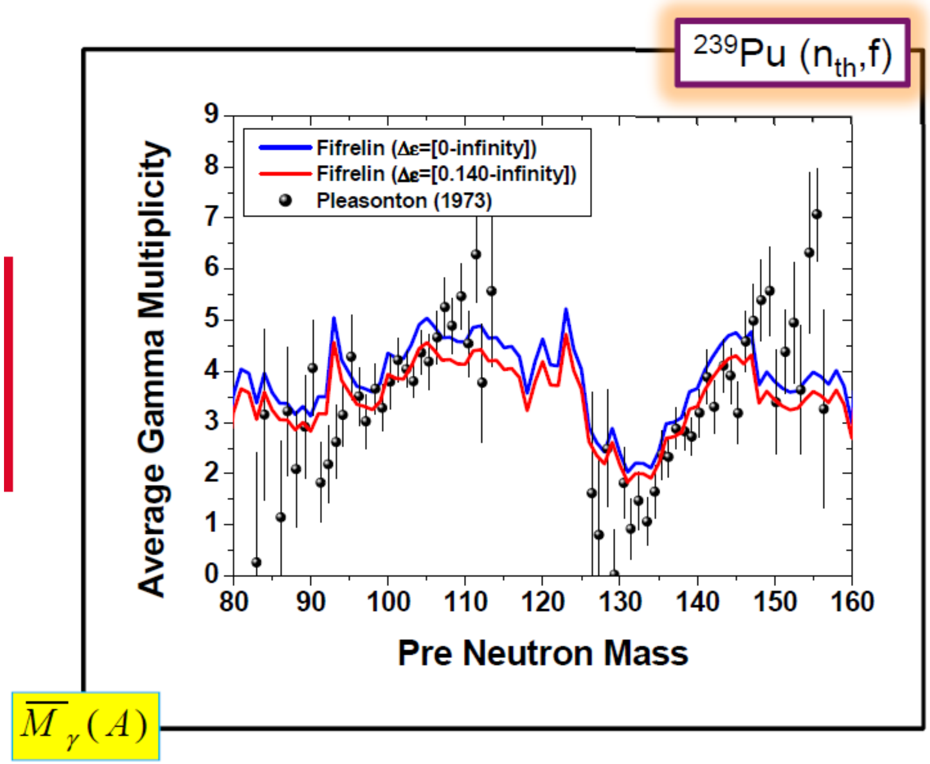
- ***The FIFRELIN Monte Carlo code*** has been developed at Cadarache centre (CEA-DEN) to simulate the Fission Fragment de-excitation through prompt neutron/gamma/electron emission in order to investigate fission observables (prompt spectra, multiplicities, energy release) ***in a single consistent calculation scheme***.

PHYSICAL REVIEW C **82**, 054616 (2010)

**Investigation of phenomenological models for the Monte Carlo simulation of the prompt fission neutron and $\gamma$ emission**

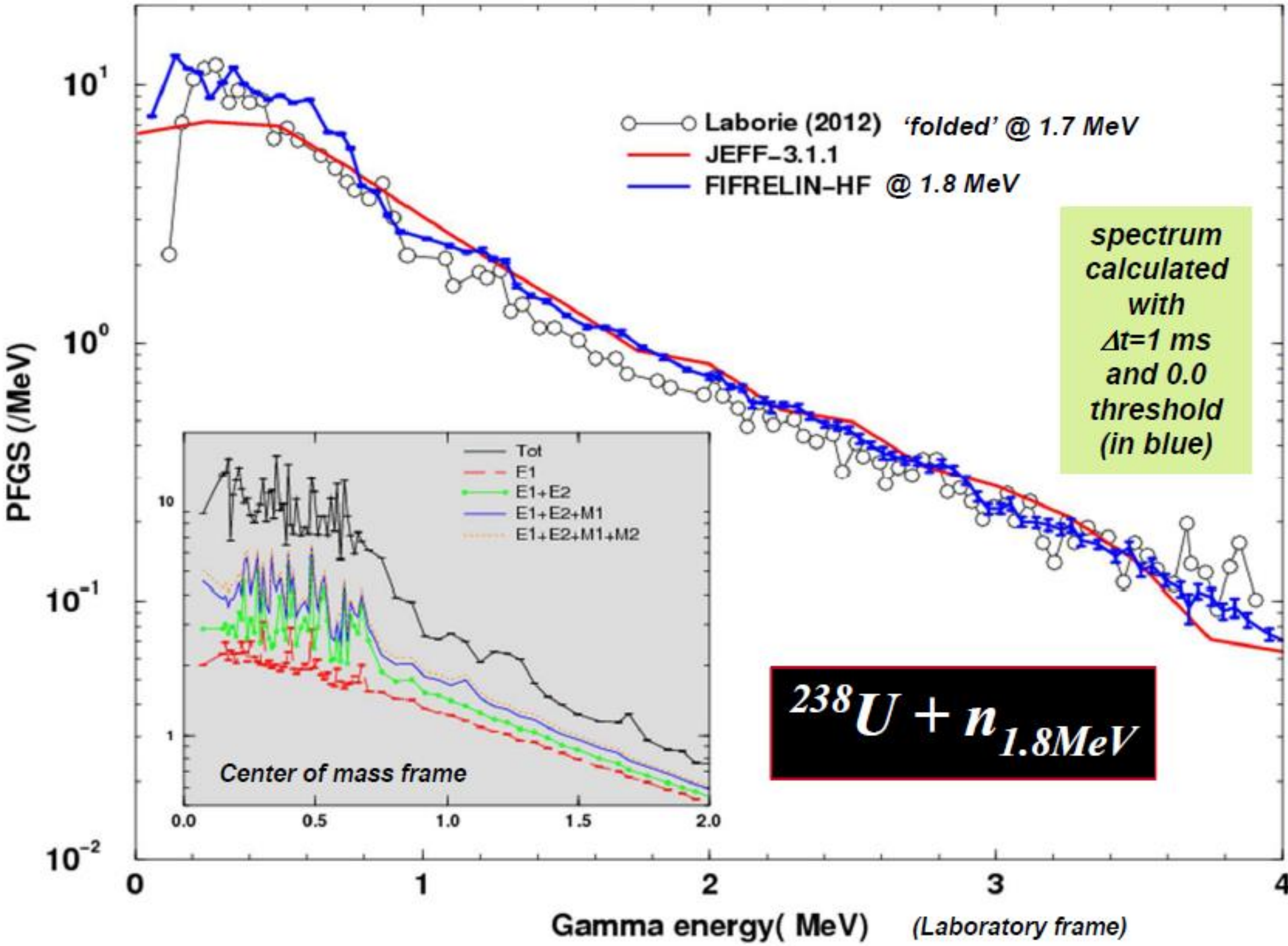
O. Litaize and O. Serot
*CEA Cadarache, F-13108 Saint Paul lez Durance, France*
(Received 19 July 2010; published 29 November 2010)



# FIFRELIN code (Oliver Litaize)

- ***The FIFRELIN Monte Carlo code*** has been developed at Cadarache centre (CEA-DEN) to simulate the Fission Fragment de-excitation through prompt neutron/gamma/electron emission in order to investigate fission observables (prompt




- ***Prompt Fission Gamma Multiplicity (PFGM)***
  - JEFF-3.1.1

    $\overline{M}_{\gamma} = 8.2$

  - FIFRELIN-HF

    with threshold : **0,1 MeV**

    time window : **10 ns**

    $\overline{M}_{\gamma} \approx 9.0$

    $< E_{\gamma}^{tot} > \approx 7.04$

    $< \varepsilon_{\gamma} > \approx 0.78$

# NEUTRON & GAMMA SPECTRA : IMPORTANT ACTIVITY !

Experimental :

- SOFIA@GSI (next years)
- Experiment@DIF
- Future experiment@GANIL(FALSTAFF)
- …

Theoretical :

- GEF@GSI
- FIFRELIN@CADARACHE
- CGM/F@LANL

DE LA RECHERCHE À L'INDUSTRIE

cea

# NEUTRON & GAMMA SPECTRA (P. TALOU)

## Recent code CGM/F

- Monte Carlo Hauser-Feshbach code
- Applied to the de-excitation of primary fission fragments by evaporation of n and $\gamma$
- Correlations and distributions for both n and $\gamma$
- Prompt fission $\gamma$-ray spectra

Publications


``Isomer Production Ratios and the Angular Momentum Distribution of Fission Fragments,'' I.Stetcu, P.Talou, T.Kawano, and M.Jandel, Phys. Rev. C **88**, 044603 (2013).

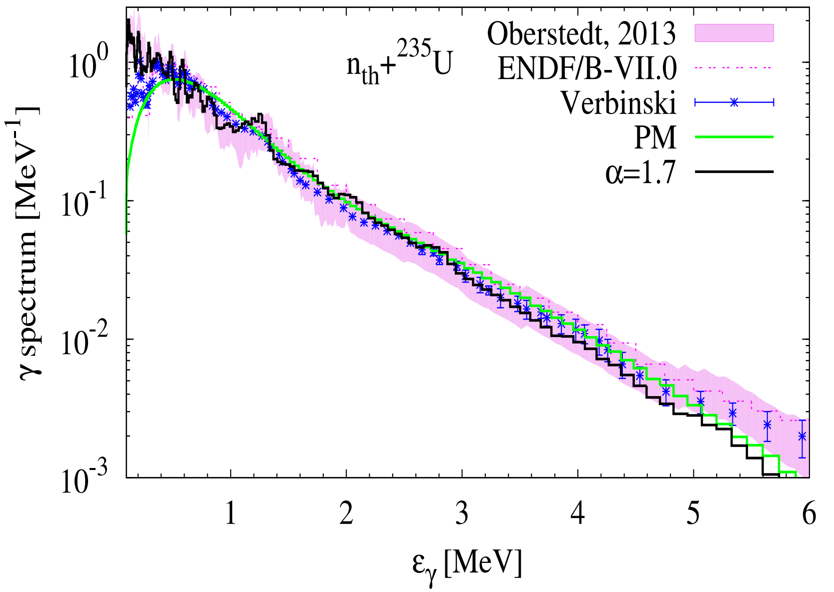
``Prompt gamma-ray production in neutron-induced fission of 239Pu,” J.L.Ullmann, E.M.Bond, T.A.Bredeweg, A.Couture, R.C.Haight, M.Jandel, T.Kawano, H.Y.Lee, J.M.O’Donnell, A.C.Hayes, I.Stetcu, T.N.Taddeucci, P.Talou, D.J.Vieira, J.B.Wilhelmy, J.A.Becker, A.Chyzh, J.Gostic, R.Henderson, E.Kwan, and C.Y.Wu, Phys. Rev. C **87**, 044607 (2013).

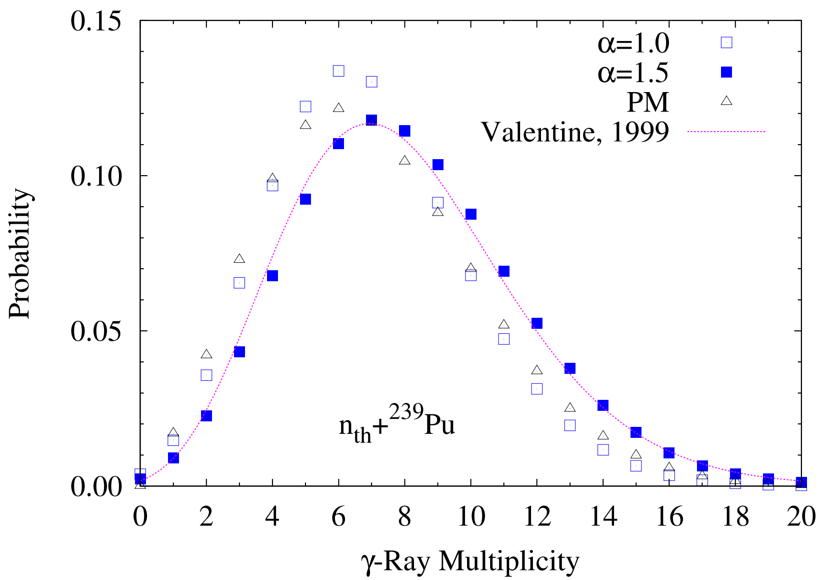
“Monte Carlo Hauser-Feshbach Predictions of Prompt Fission Gamma Rays - Application to $n_{th}+^{235}U$, $n_{th}+^{239}Pu$ and $^{252}Cf$ (sf),” B.Becker, P.Talou, T.Kawano, Y.Danon, and I.Stetcu, Phys. Rev. C **87**, 014617 (2013).

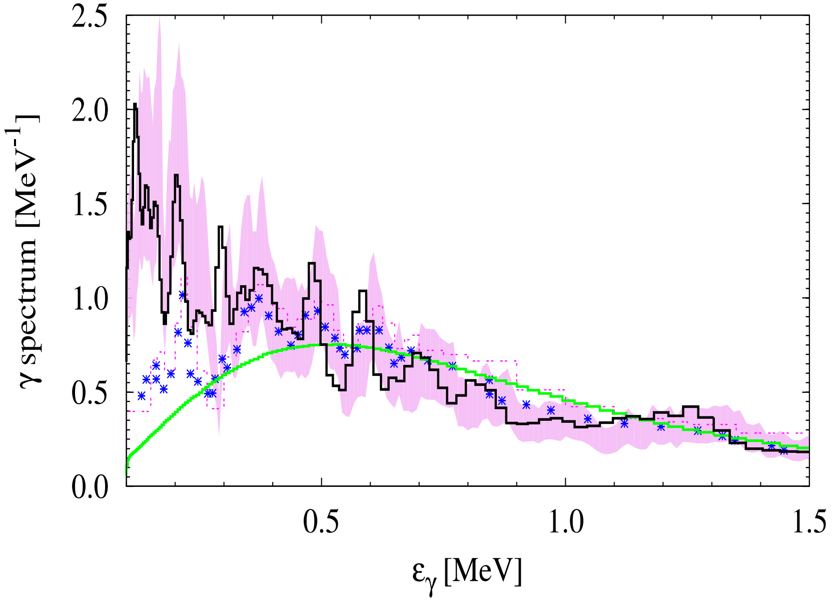
“Advanced Monte Carlo Modeling of Prompt Fission Neutrons for Thermal and Fast Neutron-Induced Fission Reaction on Pu-239”, P.Talou, B.Becker, T.Kawano, M.B.Chadwick and Y.Danon, Phys. Rev. C **83**, 064612 (2011).

# EXAMPLES OF γ-RAY RESULTS

- Prompt fission γ-ray results
  - γ-ray spectrum
  - Multiplicity-dependent γ-ray spectra
  - $P(N_\gamma)$
  - Spectroscopy of fission fragments
  - γ-γ correlations
  - etc.



# NEUTRON & GAMMA SPECTRA : IMPORTANT ACTIVITY !

Experimental :

- SOFIA@GSI (next years)
- Experiment@DIF
- Future experiment@GANIL(FALSTAFF)
- …

Theoretical :

- GEF@GSI
- FIFRELIN@CADARACHE
- TALOU@LANL
- Micro-macro : Möller@LANL ?
- Pure Micro : Dubray@BIII

# MICROSCOPIC NEUTRON MULTIPLICITIES

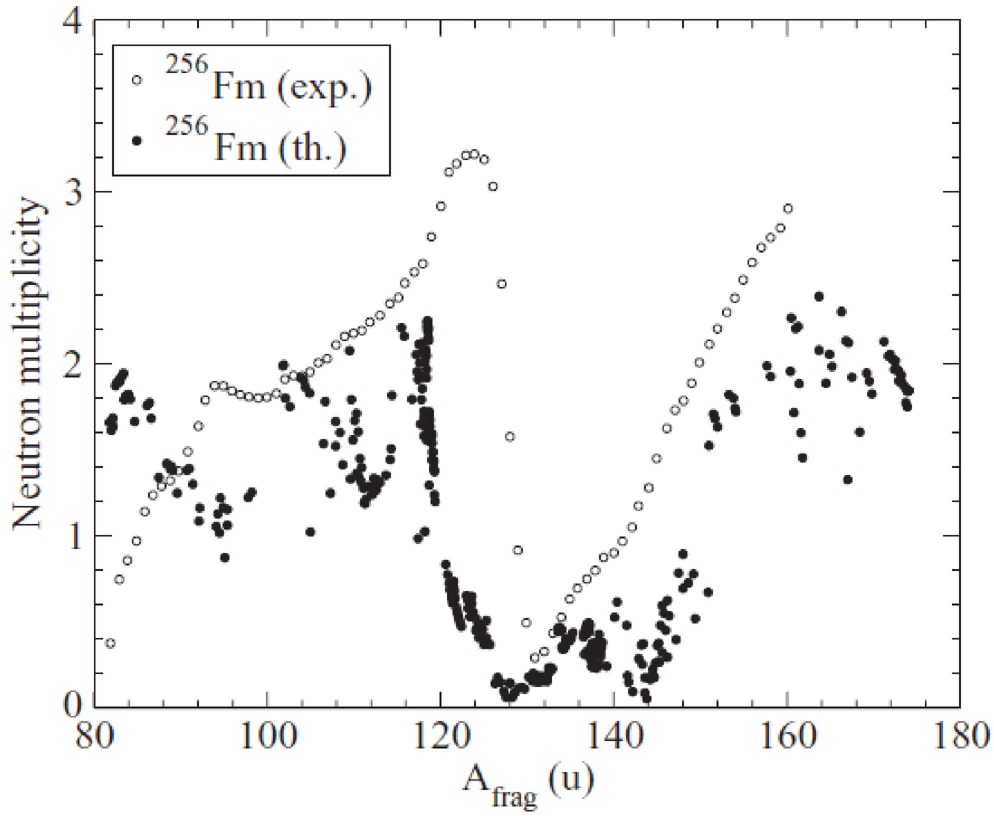



FIG. 15. $^{256}$Fm. Neutron multiplicity versus fragment mass. Comparison between predictions (solid symbols) and data [47] (empty symbols).

Not yet at the level of accuracy for applications !

# FISSION BARRIERS (PATHS)

# &

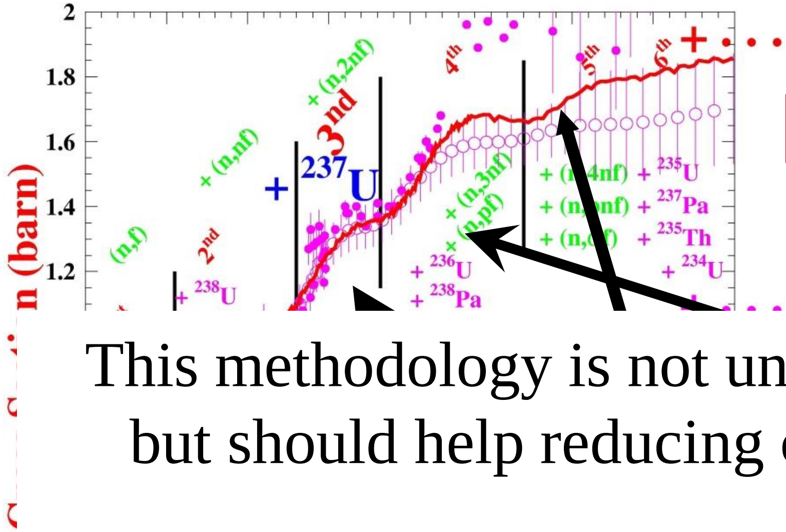
# CROSS SECTIONS

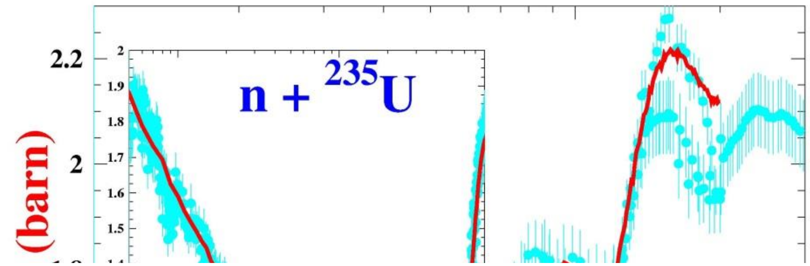
# FISSION (status of microscopic approaches)

Fission cross section calculation :

- barriers heights and widths
- broken symetries on top of barriers (ld enhancements)

$\Rightarrow$ Very good fits can be performed when data are available using a very demanding coherent approach

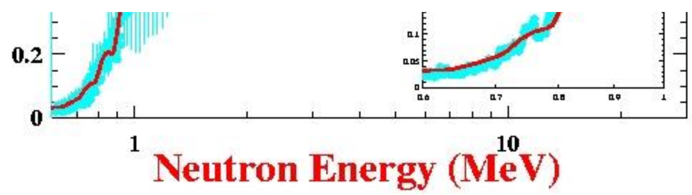



This methodology is not universal / necessary for applications but should help reducing compensations between channels

//

Coherence between (n,xn) and (n,xnγ)



# FISSION (status of microscopic approaches)

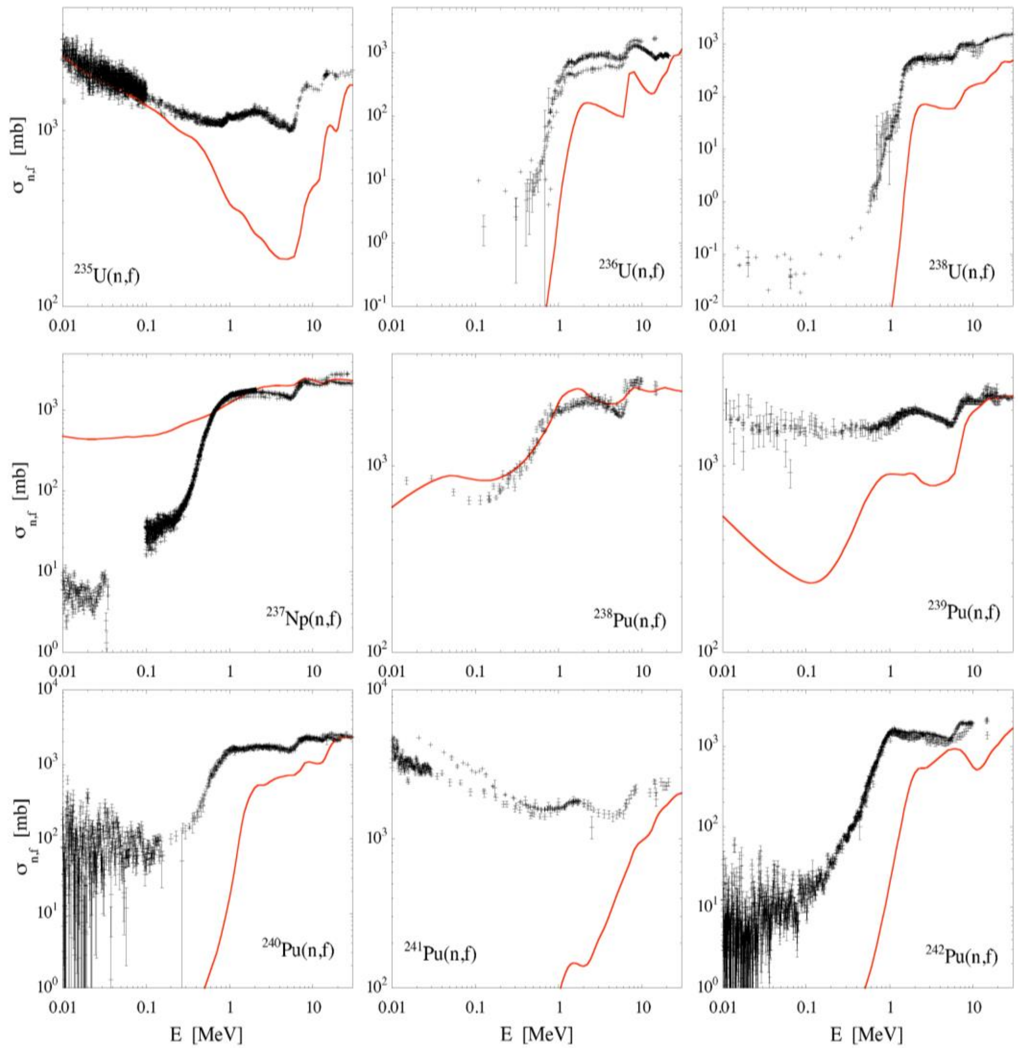
Fission cross section calculation :

- barriers heights and widths
- broken symetries on top of barriers (ld enhancements)

$\Rightarrow$ Very good fits can be performed when data are available using a very demanding coherent approach

$\Rightarrow$ Without data : extrapolations are dangerous (interpolations less)
microscopic approaches ?

# FISSION (status of microscopic approaches)




⇒ Not sufficient for applications.

⇒ Default calculations after few adjustments : but still not enough for applications

# FISSION (status of microscopic approaches)

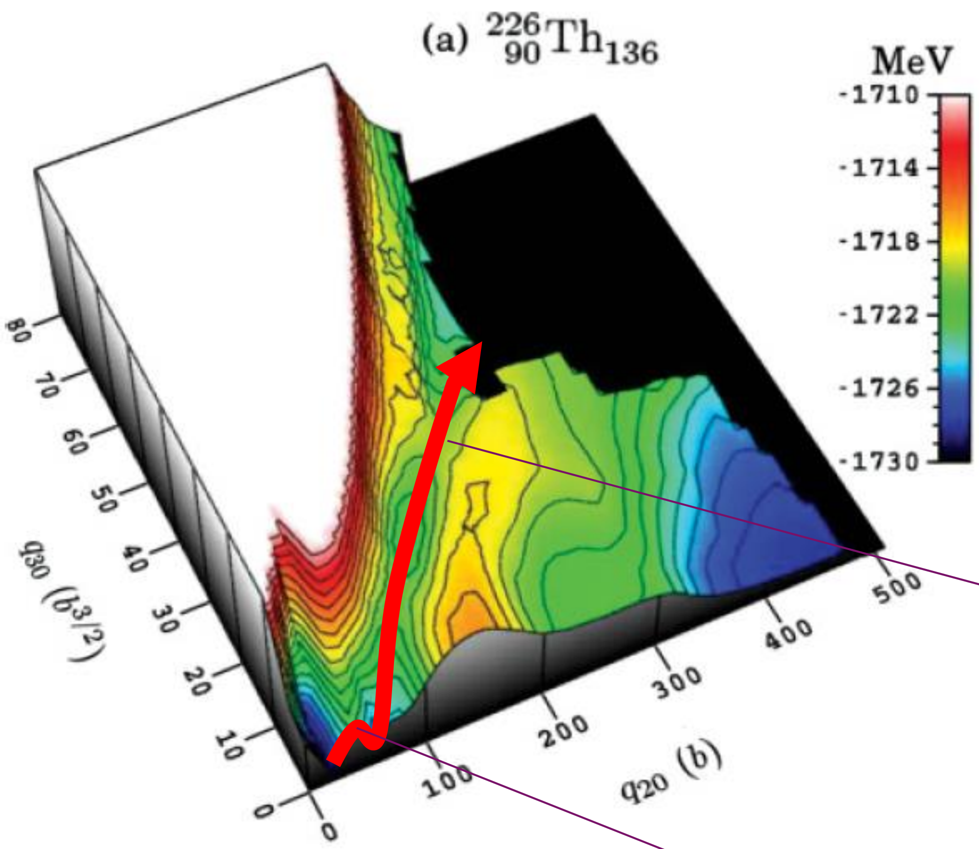
Fission cross section calculation :

- barriers heights and widths
- broken symetries on top of barriers (ld enhancements)

$\Rightarrow$ Very good fits can be performed when data are available using a very demanding coherent approach

$\Rightarrow$ Without data : extrapolations are dangerous (interpolations less)
microscopic approaches can only provide with trends

# FISSION (status of microscopic approaches)




⇒ Second barrier : mass asymetry (factor 2 in lds)

⇒ First barrier : axial symetry

What about triaxial symetry : extra enhancement in lds

# CONCLUSIONS ?

# CONCLUSIONS

- Several experimental programs and results
- Several theoretical approaches more or less fundamental

$\Rightarrow$ All these people should interact to fill the gaps

**Still a lot of work to do !**