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**Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies**

***19 - 30 May 2008***

**Fission Measurements.**
**Part 2**

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# Outline – Part II

## Status of fission data on minor actinides

- Libraries
- Previous data
- New results

## The measurements at n_TOF

## Other methods (surrogate)

## Conclusions

# Data analysis

Number of counts at $E_n$

Background

$$\sigma_f(E_n) = \frac{C_{^AX}(E_n) - B_{^AX}(E_n)}{\Phi(E_n)\cdot N_{^AX}\cdot \varepsilon \cdot cf}$$

Neutron flux

Atoms/barn of the sample

Efficiency

Other correction factors (dead-time, …)

$^AX$ sample being investigated

$E_n$ neutron energy

$$ratio(E_n) = \frac{C_{^AX} - B_{^AX}}{\Phi(E_n)\cdot N_{^AX}\cdot\varepsilon_{^AX}\cdot cf_{^AX}} \bigg/ \frac{C_{^{235}U} - B_{^{235}U}}{\Phi(E_n)\cdot N_{^{235}U}\cdot\varepsilon_{^{235}U}\cdot cf_{^{235}U}}$$

$$ratio(E_n) = \frac{C_{^AX} - B_{^AX}}{C_{^{235}U} - B_{^{235}U}}\cdot\frac{N_{^{235}U}\cdot\varepsilon_{^{235}U}\cdot cf_{^{235}U}}{N_{^AX}\cdot\varepsilon_{^AX}\cdot cf_{^AX}}$$

In the ratio, the neutron flux cancels out

# Data analysis

$$\sigma_f\left({}^{A}X, E_n\right) = \text{ratio}\left(E_n\right) \cdot \sigma_f\left({}^{235}U, E_n\right)$$

Standard cross-section used as reference (from evaluated data file)

$$\text{ratio}(E_n) = \frac{C_{{}^{A}X} - B_{{}^{A}X}}{C_{{}^{235}U} - B_{{}^{235}U}} \cdot \frac{N_{{}^{235}U} \cdot \varepsilon_{{}^{235}U} \cdot cf_{{}^{235}U}}{N_{{}^{A}X} \cdot \varepsilon_{{}^{A}X} \cdot cf_{{}^{A}X}}$$

Things to **remember** about the use of $^{235}U$ (or $^{239}Pu$) as reference samples:

- reference samples typically mounted inside the **same chamber** for same efficiency
- all samples with the **same area** to avoid correction for the flux interception
- if possible, **same thickness**, to minimize efficiency corrections ($\varepsilon$)
- approximately **same count-rate**, to minimize dead-time correction (cf)
- need to correct for **anysotropy** in angular distribution of fission fragments (particularly important at high energy). Included in the factor cf.

# Possible sources of background

Several sources of background may affect the measurements of fission cross-sections:

- electronic noise ………………………………………………………….
- $\alpha$-particle from radioactive decay of samples ……………
- spontaneous fission ……………………………………………………

runs with no beam

- ambient neutrons ………………………………………………………………………….
- neutrons scattered from the detector and surrounding material ……

sample outside beam

- wrap-around neutrons ………………………………………………… **measured with filters**
- resolution function ……………………………………………………… **simulations (mainly)**

It is preferable to try and **minimize** all possibile sources of background, to increase signal-to-background ratio and minimize uncertainty on background subtraction:

- **high neutron flux** (to minimize ambient background and natural radioactivity)
- minimize **mass** of the detector and surrounding material (for neutron scattering)

# Uncertainty analysis

When extracting the fission cross-sections with ratio method, **uncertainties** related to:

| | |
|---|---|
| • **mass** of the sample and of the reference | typically, 1 % |
| • presence of other isotopes (**contaminants**) in the samples | depends on the sample |
| • **background** subtraction | depends on the sample |
| • **wrap-around** neutrons | depends on the facility |
| • **efficiency** and **dead-time** corrections | depends on detector, few % |
| • neutron beam **attenuation** | depends on set-up, < 1% |
| • **evaluated cross-sections** used as reference | typically, 1-3 % |

In addition, other possible sources of uncertainty are:

- sample **non-uniformity** (combined with beam non-uniformity)
- **misallignement** between sample and reference (don't intercept the same neutron flux)

## Sensitivity analysis shows that current uncertainties for MA are too high for the design of Gen IV e ADS burners

***Table 4.*** *ABTR, SFR, EFR: Uncertainty Reduction Requirements to Meet Integral Parameter Target Accuracies*

| Isotope Cross-Section | Energy Range | Uncertainty (%) Initial | Uncertainty (%) Target |
|---|---|---|---|
| U238 $\sigma_{inel}$ | 19.6 - 6.07 MeV | 29.3 | 20.1 |
| | 6.07 - 2.23 MeV | 19.8 | 4.6 |
| | 2.23 - 1.35 MeV | 20.6 | 4.5 |
| | 1.35 - 0.498 MeV | 11.6 | 5.5 |
| Pu241 $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 14.2 | 6.5 |
| | 2.23 - 1.35 MeV | 21.3 | 5.8 |
| | 1.35 - 0.498 MeV | 16.6 | 3.4 |
| | 498 - 183 keV | 13.5 | 2.6 |
| | 183 - 67.4 keV | 19.9 | 2.6 |
| | 67.4 - 24.8 keV | 8.7 | 3.3 |
| | 24.8 - 9.12 keV | 11.3 | 3.5 |
| | 9.12 - 2.03 keV | 10.4 | 5.4 |
| | 2.03 - 0.454 keV | 12.7 | 4.4 |
| | 454 - 22.6 eV | 19.4 | 8.6 |
| U238 $\sigma_{capt}$ | 24.8 - 9.12 keV | 9.4 | 3.8 |

| Isotope Cross-Section | Energy Range | Uncertainty (%) Initial | Uncertainty (%) Target |
|---|---|---|---|
| Fe56 $\sigma_{inel}$ | 19.6 - 6.07 MeV | 13.0 | 8.9 |
| | 6.07 - 2.23 MeV | 7.2 | 4.1 |
| | 2.23 - 1.35 MeV | 25.4 | 3.3 |
| | 1.35 - 0.498 MeV | 16.1 | 3.2 |
| Pu239 $\sigma_{capt}$ | 1.35 - 0.498 MeV | 18.2 | 10.1 |
| | 498 - 183 keV | 11.6 | 6.5 |
| | 183 - 67.4 keV | 9.0 | 5.6 |
| | 67.4 - 24.8 keV | 10.1 | 6.3 |
| | 24.8 - 9.12 keV | 7.4 | 5.5 |
| | 9.12 - 2.03 keV | 15.5 | 6.7 |
| O16 $\sigma_{capt}$ | 19.6 - 6.07 MeV | 100.0 | 62.3 |
| | 6.07 - 2.23 MeV | 100.0 | 39.5 |
| Na23 $\sigma_{inel}$ | 2.23 - 1.35 MeV | 12.6 | 9.3 |
| | 1.35 - 0.498 MeV | 28.0 | 4.0 |
| Cm244 $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 31.3 | 8.2 |
| | 2.23 - 1.35 MeV | 43.8 | 8.2 |
| | 1.35 - 0.498 MeV | 50.0 | 5.1 |
| | 498 - 183 keV | 36.5 | 12.1 |

| Isotope Cross-Section | Energy Range | Uncertainty (%) Initial | Uncertainty (%) Target |
|---|---|---|---|
| Am242m $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 23.4 | 8.0 |
| | 2.23 - 1.35 MeV | 19.7 | 8.2 |
| | 1.35 - 0.498 MeV | 16.5 | 4.3 |
| | 498 - 183 keV | 16.6 | 3.1 |
| | 183 - 67.4 keV | 16.6 | 3.1 |
| | 67.4 - 24.8 keV | 14.4 | 4.1 |
| | 24.8 - 9.12 keV | 11.8 | 4.3 |
| | 9.12 - 2.03 keV | 12.4 | 6.5 |
| | 2.03 - 0.454 keV | 12.2 | 5.2 |
| Pu240 $\sigma_{fiss}$ | 19.6 - 6.07 MeV | 9.6 | 8.6 |
| | 6.07 - 2.23 MeV | 4.8 | 2.8 |
| | 2.23 - 1.35 MeV | 5.7 | 2.6 |
| | 1.35 - 0.498 MeV | 5.8 | 1.8 |
| | 498 - 183 keV | 3.9 | 3.9 |
| | 2.03 - 0.454 keV | 21.6 | 12.4 |

Source: Aliberti, Palmiotti, Salvatores, NEMEA-4 workshop, Prague 2007

**Table 5.** *ABTR, SFR, EFR, GFR, LFR, ADMAB: Uncertainty Reduction Requirements to Meet Integral Parameter Target Accuracies*

| Isotope Cross-Section | Energy Range | Uncertainty (%) Initial | Uncertainty (%) Target |
|---|---|---|---|
| U238 $\sigma_{inel}$ | 19.6 - 6.07 MeV | 29.3 | 9.0 |
| | 6.07 - 2.23 MeV | 19.8 | 2.0 |
| | 2.23 - 1.35 MeV | 20.6 | 2.1 |
| | 1.35 - 0.498 MeV | 11.6 | 2.3 |
| | 498 - 183 keV | 4.2 | 3.8 |
| | 183 - 67.4 keV | 11.0 | 4.2 |
| Pu241 $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 14.2 | 5.0 |
| | 2.23 - 1.35 MeV | 21.3 | 3.9 |
| | 1.35 - 0.498 MeV | 16.6 | 2.1 |
| | 498 - 183 keV | 13.5 | 1.7 |
| | 183 - 67.4 keV | 19.9 | 1.7 |
| | 67.4 - 24.8 keV | 8.7 | 1.9 |
| | 24.8 - 9.12 keV | 11.3 | 2.0 |
| | 9.12 - 2.03 keV | 10.4 | 2.1 |
| | 2.03 - 0.454 keV | 12.7 | 2.7 |
| | 454 - 22.6 eV | 19.4 | 5.4 |
| Cm244 $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 31.3 | 3.0 |
| | 2.23 - 1.35 MeV | 43.8 | 2.6 |
| | 1.35 - 0.498 MeV | 50.0 | 1.5 |
| | 498 - 183 keV | 36.5 | 4.0 |
| | 183 - 67.4 keV | 47.6 | 7.3 |
| U238 $\sigma_{capt}$ | 24.8 - 9.12 keV | 9.4 | 1.8 |
| | 9.12 - 2.03 keV | 3.1 | 1.8 |
| Fe56 $\sigma_{inel}$ | 6.07 - 2.23 MeV | 7.2 | 2.6 |
| | 2.23 - 1.35 MeV | 25.4 | 1.7 |
| | 1.35 - 0.498 MeV | 16.1 | 1.5 |

| Isotope Cross-Section | Energy Range | Uncertainty (%) Initial | Uncertainty (%) Target |
|---|---|---|---|
| B10 $\sigma_{capt}$ | 498 - 183 keV | 15.0 | 2.9 |
| | 183 - 67.4 keV | 10.0 | 2.7 |
| | 67.4 - 24.8 keV | 10.0 | 3.3 |
| | 24.8 - 9.12 keV | 8.0 | 3.9 |
| | 9.12 - 2.03 keV | 8.0 | 6.0 |
| Pu239 $\sigma_{capt}$ | 1.35 - 0.498 MeV | 18.2 | 6.6 |
| | 498 - 183 keV | 11.6 | 4.4 |
| | 183 - 67.4 keV | 9.0 | 4.0 |
| | 67.4 - 24.8 keV | 10.1 | 4.2 |
| | 24.8 - 9.12 keV | 7.4 | 3.8 |
| | 9.12 - 2.03 keV | 15.5 | 3.2 |
| O16 $\sigma_{capt}$ | 19.6 - 6.07 MeV | 100.0 | 37.9 |
| | 6.07 - 2.23 MeV | 100.0 | 37.9 |
| Am243 $\sigma_{inel}$ | 6.07 - 2.23 MeV | 17.9 | 4.9 |
| | 2.23 - 1.35 MeV | 35.3 | 3.9 |
| | 1.35 - 0.498 MeV | 42.2 | 2.3 |
| | 498 - 183 keV | 41.0 | 3.7 |
| | 183 - 67.4 keV | 79.5 | 3.7 |
| | 67.4 - 24.8 keV | 80.8 | 12.4 |
| Am242m $\sigma_{fiss}$ | 1.35 - 0.498 MeV | 23.4 | 21.4 |
| | 498 - 183 keV | 16.5 | 6.3 |
| | 183 - 67.4 keV | 16.6 | 4.7 |
| | 67.4 - 24.8 keV | 16.6 | 4.8 |
| | 24.8 - 9.12 keV | 14.4 | 5.6 |
| | 2.04 - 0.454 keV | 11.8 | 5.9 |
| Na23 $\sigma_{inel}$ | 1.35 - 0.498 MeV | 28.0 | 10.5 |

| Isotope Cross-Section | Energy Range | Uncertainty (%) Initial | Uncertainty (%) Target |
|---|---|---|---|
| Pu240 $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 4.8 | 2.9 |
| | 2.23 - 1.35 MeV | 5.7 | 2.6 |
| | 1.35 - 0.498 MeV | 5.8 | 1.6 |
| | 498 - 183 keV | 3.9 | 3.7 |
| | 2.03 - 0.454 keV | 21.6 | 11.8 |
| Si28 $\sigma_{capt}$ | 19.6 - 6.07 MeV | 52.9 | 7.2 |
| Si28 $\sigma_{inel}$ | 6.07 - 2.23 MeV | 13.5 | 3.9 |
| | 2.23 - 1.35 MeV | 50.0 | 7.4 |
| Pb206 $\sigma_{inel}$ | 6.07 - 2.23 MeV | 5.5 | 4.2 |
| | 2.23 - 1.35 MeV | 14.2 | 4.0 |
| | 1.35 - 0.498 MeV | 9.2 | 4.7 |
| Pb207 $\sigma_{inel}$ | 6.07 - 2.23 MeV | 5.0 | 4.9 |
| | 2.23 - 1.35 MeV | 13.8 | 6.0 |
| | 1.35 - 0.498 MeV | 11.3 | 3.6 |
| Pb $\sigma_{inel}$ | 6.07 - 2.23 MeV | 5.4 | 3.0 |
| Am243 $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 11.0 | 2.3 |
| | 2.23 - 1.35 MeV | 6.0 | 1.9 |
| | 1.35 - 0.498 MeV | 9.2 | 1.7 |
| Bi209 $\sigma_{inel}$ | 2.23 - 1.35 MeV | 34.1 | 2.8 |
| | 1.35 - 0.498 MeV | 41.8 | 4.3 |
| N15 $\sigma_{el}$ | 2.23 - 1.35 MeV | 5.0 | 3.1 |
| | 1.35 - 0.498 MeV | 5.0 | 1.2 |
| | 498 - 183 keV | 5.0 | 1.9 |
| | 183 - 67.4 keV | 5.0 | 2.3 |
| Zr90 $\sigma_{inel}$ | 6.07 - 2.23 MeV | 18.0 | 3.3 |

***Table 2.*** *Uncertainty Reduction Requirements Needed to Meet Integral Parameter Target Accuracies*

| Isotope | Cross-Section | Energy Range | Uncert. (%) Initial | Uncert. (%) Target | Isotope | Cross-Section | Energy Range | Uncert. (%) Initial | Uncert. (%) Target |
|---|---|---|---|---|---|---|---|---|---|
| Cm244 | $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 31.3 | 3.0 | Bi209 | $\sigma_{inel}$ | 2.23 - 1.35 MeV | 34.1 | 2.8 |
| | | 2.23 - 1.35 MeV | 43.8 | 2.6 | | | 1.35 - 0.498 MeV | 41.8 | 4.2 |
| | | 1.35 - 0.498 MeV | 50.0 | 1.5 | Am243 | $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 11.0 | 2.3 |
| Fe56 | $\sigma_{inel}$ | 6.07 - 2.23 MeV | 7.2 | 2.5 | | | 1.35 - 0.498 MeV | 9.2 | 1.6 |
| | | 2.23 - 1.35 MeV | 25.4 | 1.6 | Cm244 | $\nu$ | 6.07 - 2.23 MeV | 11.1 | 2.5 |
| | | 1.35 - 0.498 MeV | 16.1 | 1.5 | | | 1.35 - 0.498 MeV | 5.5 | 1.3 |
| Am243 | $\sigma_{inel}$ | 1.35 - 0.498 MeV | 42.2 | 2.3 | N15 | $\sigma_{el}$ | 1.35 - 0.498 MeV | 5.0 | 1.2 |
| | | 498 - 183 keV | 41.0 | 3.6 | Pb | $\sigma_{inel}$ | 6.07 - 2.23 MeV | 5.4 | 2.9 |
| | | 183 - 67.4 keV | 79.5 | 3.7 | Zr90 | $\sigma_{inel}$ | 6.07 - 2.23 MeV | 18.0 | 3.3 |
| Pu241 | $\sigma_{fiss}$ | 1.35 - 0.498 MeV | 16.6 | 2.1 | Pu238 | $\sigma_{fiss}$ | 2.23 - 1.35 MeV | 33.8 | 6.0 |
| | | 498 - 183 keV | 13.5 | 1.7 | | | 1.35 - 0.498 MeV | 17.1 | 3.4 |
| | | 183 - 67.4 keV | 19.9 | 1.7 | | | 498 - 183 keV | 17.1 | 3.9 |
| Am241 | $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 11.7 | 1.7 | Cm242 | $\sigma_{fiss}$ | 6.07 - 2.23 MeV | 52.6 | 26 |
| | | 2.23 - 1.35 MeV | 9.8 | 1.4 | | | 498 - 183 keV | 66.0 | 28.4 |
| | | 1.35 - 0.498 MeV | 8.3 | 1.2 | Pu238 | $\nu$ | 1.35 - 0.498 MeV | 7.0 | 2.8 |
| Cm245 | $\sigma_{fiss}$ | 1.35 - 0.498 MeV | 49.4 | 3.3 | | | 498 - 183 keV | 7.0 | 3.4 |
| | | 498 - 183 keV | 37.2 | 2.9 | Am242m | $\sigma_{fiss}$ | 498 - 183 keV | 16.6 | 4.8 |
| | | 183 - 67.4 keV | 47.5 | 2.9 | | | 183 - 67.4 keV | 16.6 | 4.8 |
| | | 67.4 - 24.8 keV | 26.5 | 3.2 | | | | | |

Need to improve accuracy to less than **3 %** on most MA, from few keV to several MeV

Source: Aliberti, Palmiotti, Salvatores, NEMEA-4 workshop, Prague 2007

# Retrieving cross-sections

**Experimental data** are collected in a database (EXFOR) available on many Web sites

- data in a specific format
- various information on the measurement

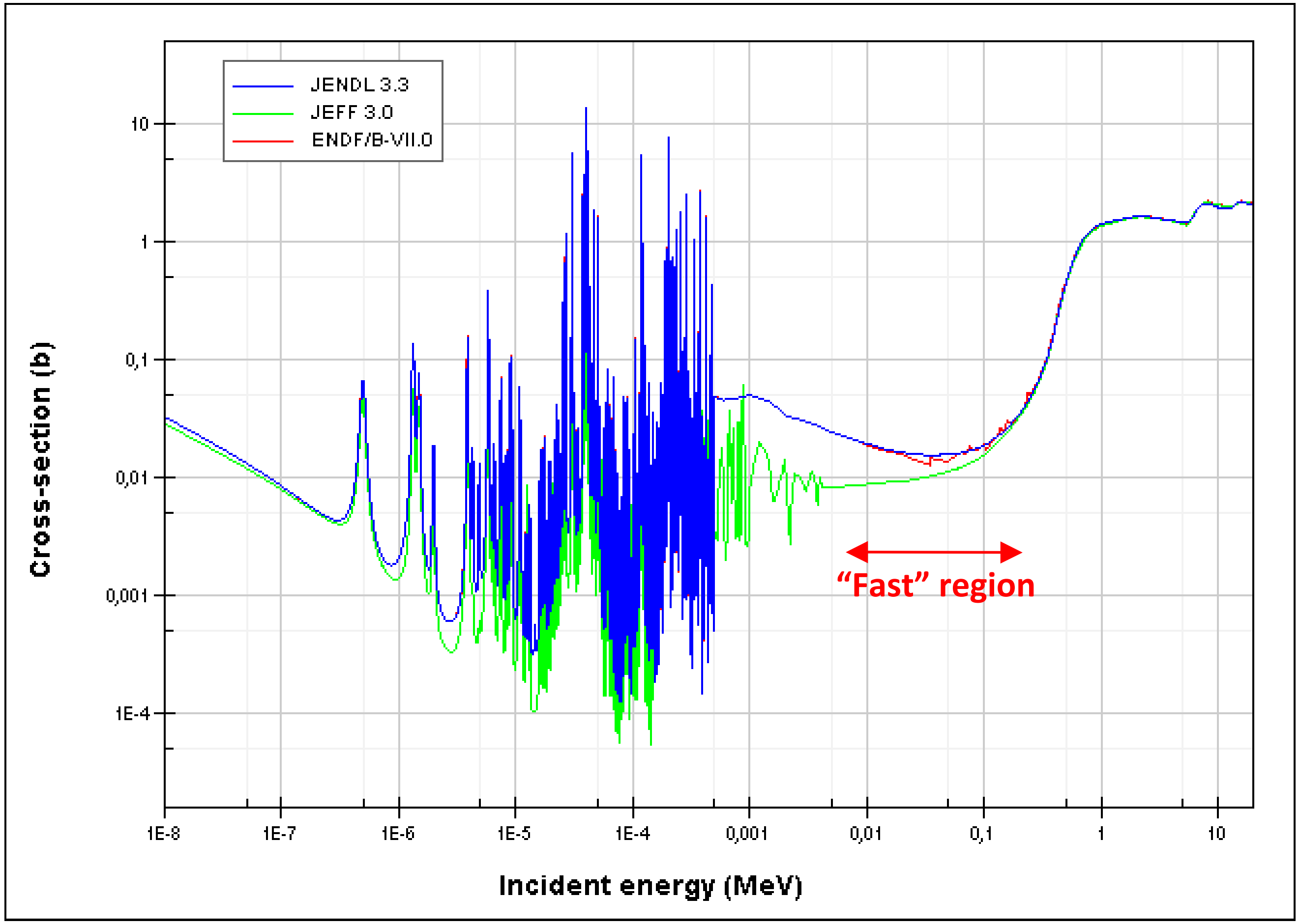
**Evaluated data** are a combination of theoretical calculations and experimental data available.
Collected in different databases, available on Web:

- ENDF (American database)
- JEFF (European)
- JENDL (Japanese)
- BRONDL (Russian)

Most important web sites for cross-section retrieval: IAEA, NEA, NNDC, Korean, etc…
Various programs allow to retreive data and make plots.
In the following, used the the program Janis 3.0 www.nea.fr/janis
**Ask Alberto if interested in excercises on how to retrive data.**

# The $^{237}Np(n,f)$ cross-sections

# The $^{237}Np(n,f)$ reaction: evaluated data libraries



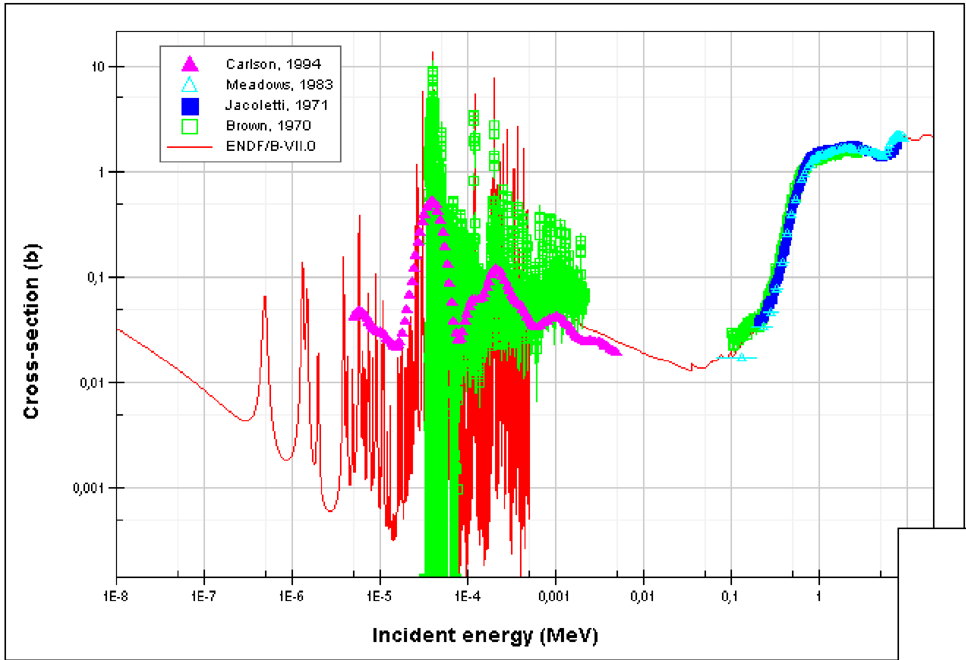

One of the most abundant minor actinides produced.

Important for transmutation projects

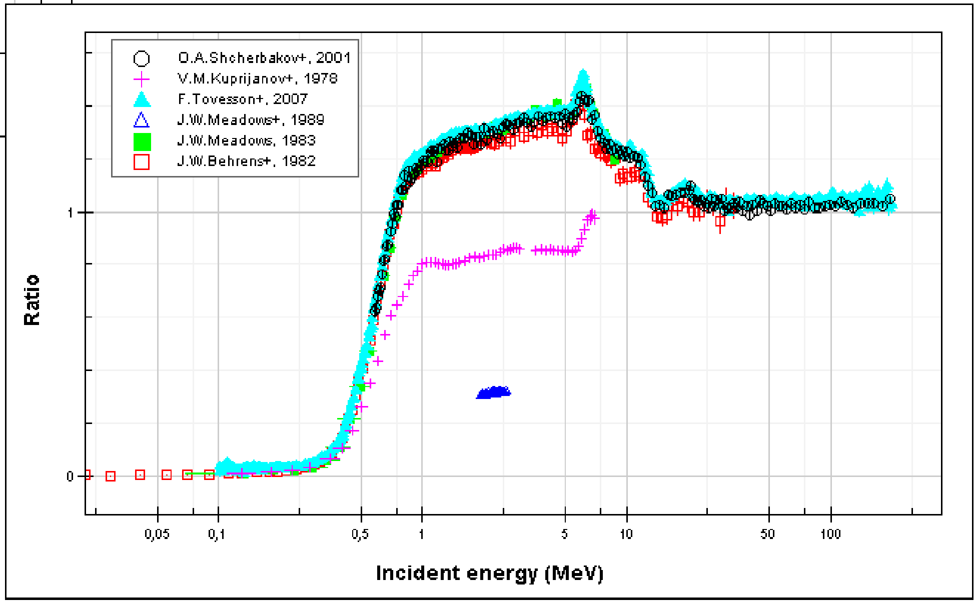
Need accurate fission cross-section data for accurate prediction of transmutation rates and to reduce uncertainty in safety parameters of reactors.

Discrepancies between major cross-section databases exist in the energy region important for fast reactors.

# The $^{237}Np(n,f)$ reaction: data




Few data below threshold (still important for transmutation projects, 5 % of the cross-section is there ).



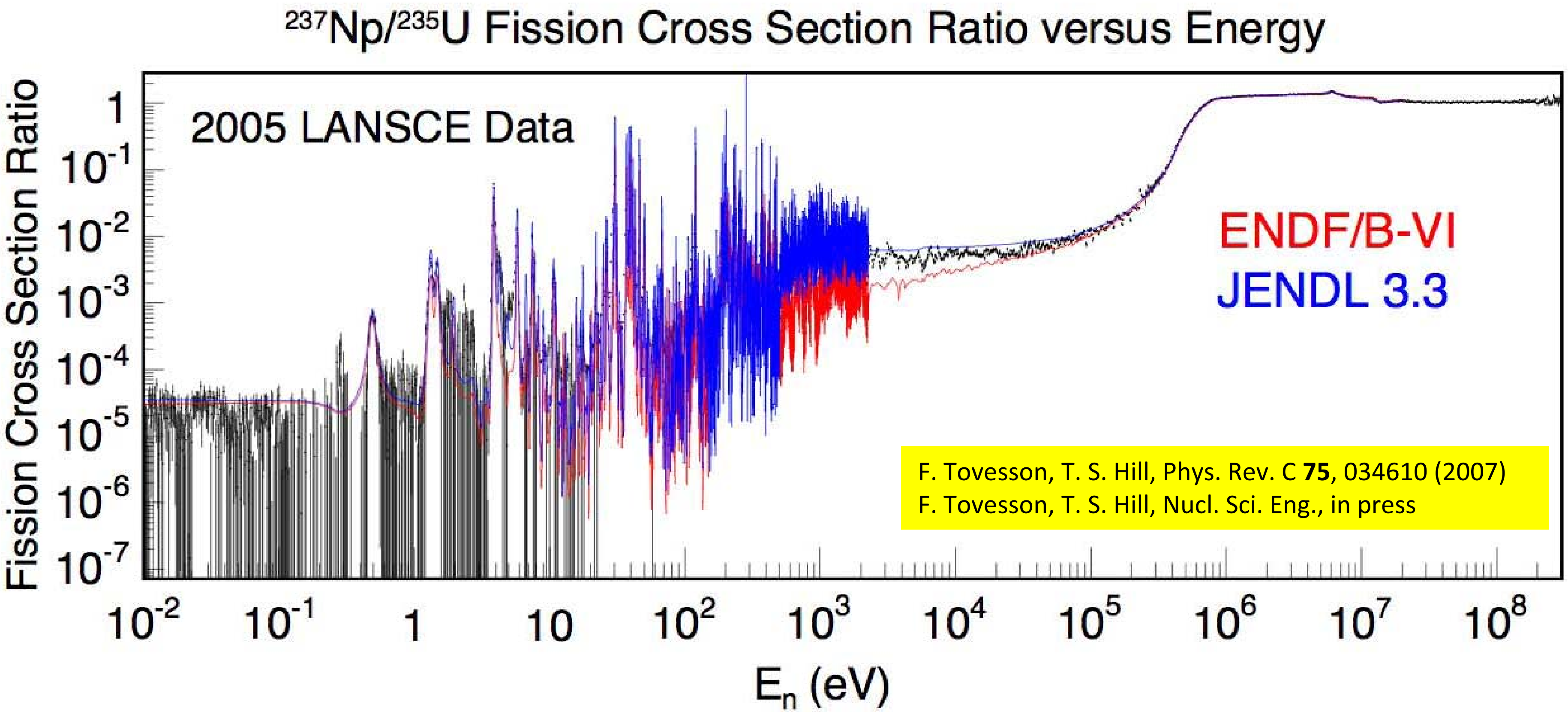

Above threshold, uncertainties of the order of 10 %.

Evaluation based on data of Meadows (and Lisosky).

No single measurement covering the entire energy range

# The $^{237}Np(n,f)$ reaction: new results

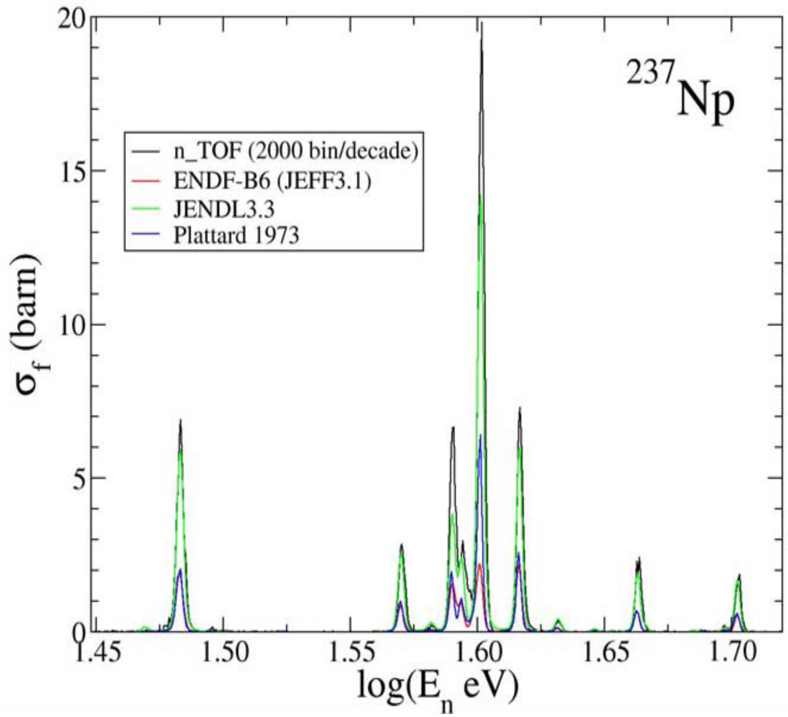
Recent data from LANL and n_TOF (shown later).




F. Tovesson, T. S. Hill, Phys. Rev. C **75**, 034610 (2007)
F. Tovesson, T. S. Hill, Nucl. Sci. Eng., in press

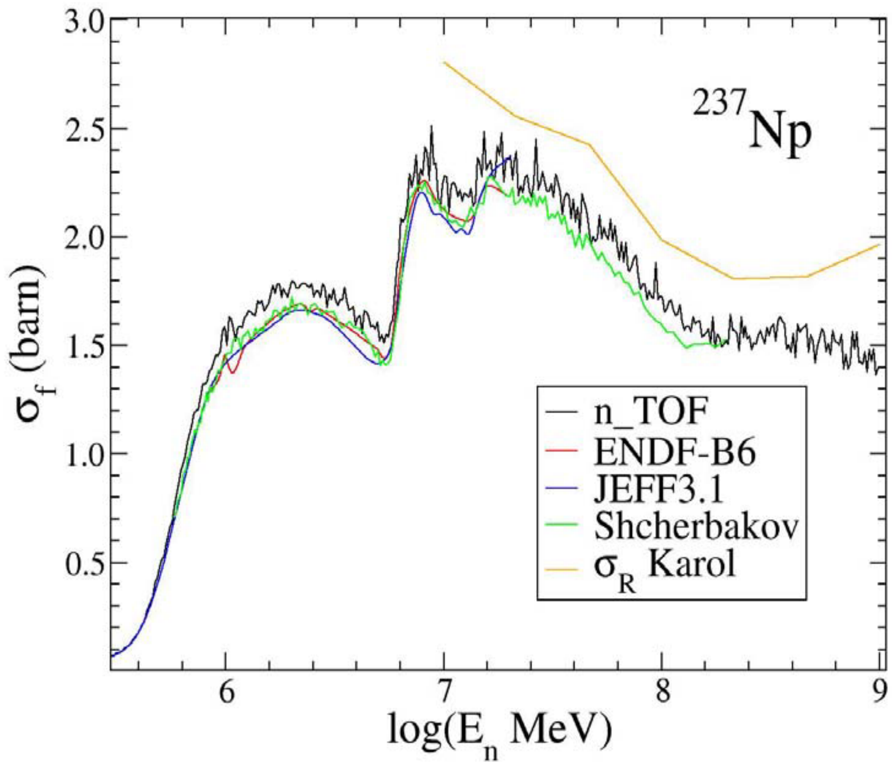
Systematic uncertainties limited to 1.5% over large region. Together with n_TOF data, should resolve existing discrepancies and improve accuracy of databases.
First "unique" measurement from thermal to 200 MeV.

# The 237Np(n,f) cross-sections at n_TOF




Data taken with Parallel Plate Avalanche Counter (coincidence method)

Analysis still in progress

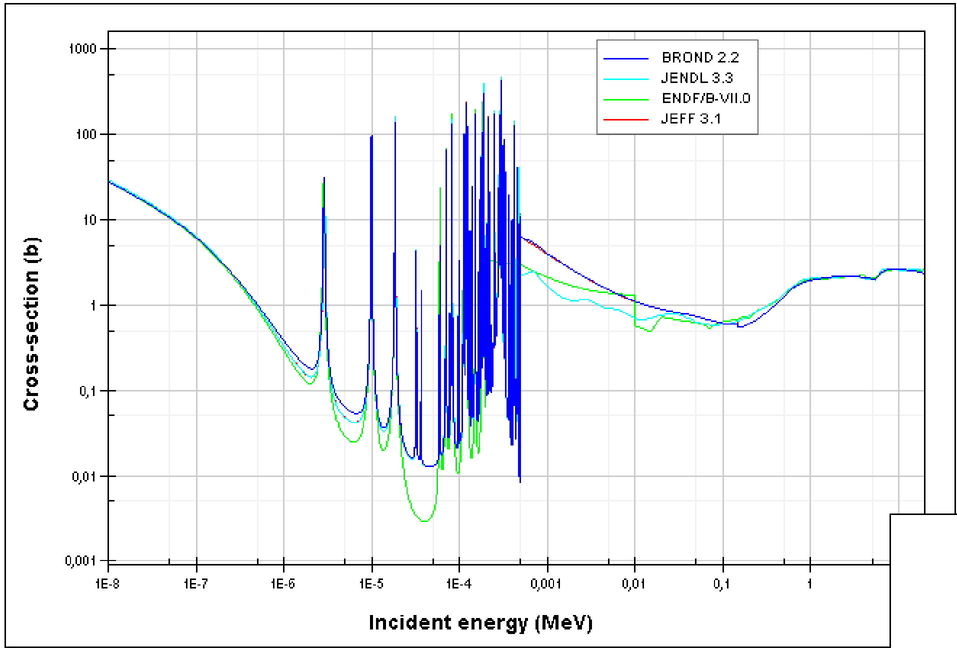



Big discrepancy with database observed for resonances below threshold.

Above threshold the agreement is better, but differences with databases of ~10 % observed.

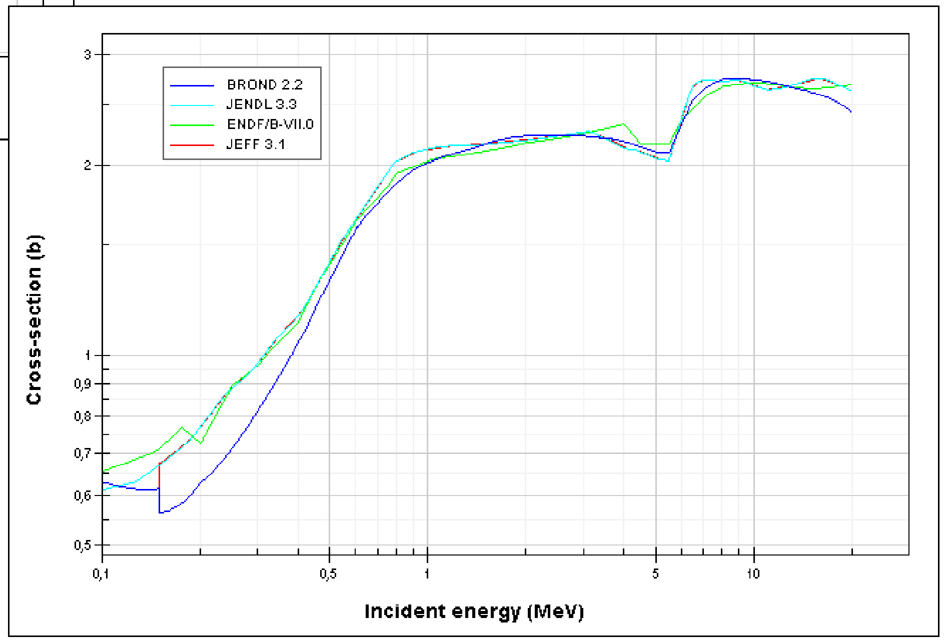
# The Pu(n,f) cross-sections

# The $^{238}Pu(n,f)$ reaction: evaluated data libraries




Important for new generation reactors

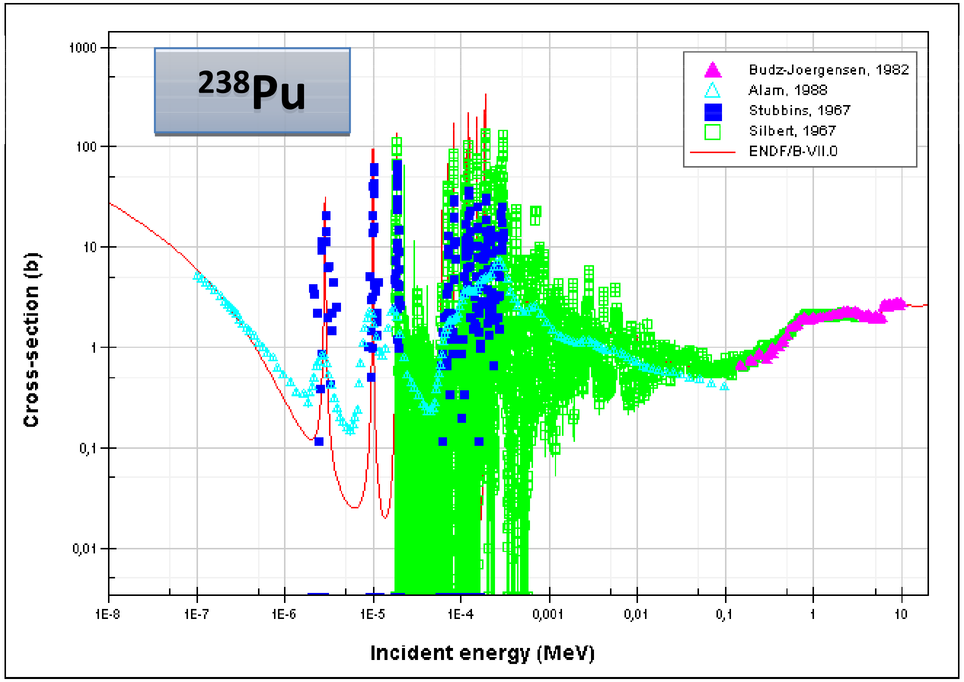
Differences between databases in the eV region and in the Unresolved Resonance Region




Sensitivity analysis indicates that current uncertainty too big in the region 200 keV – 2 MeV

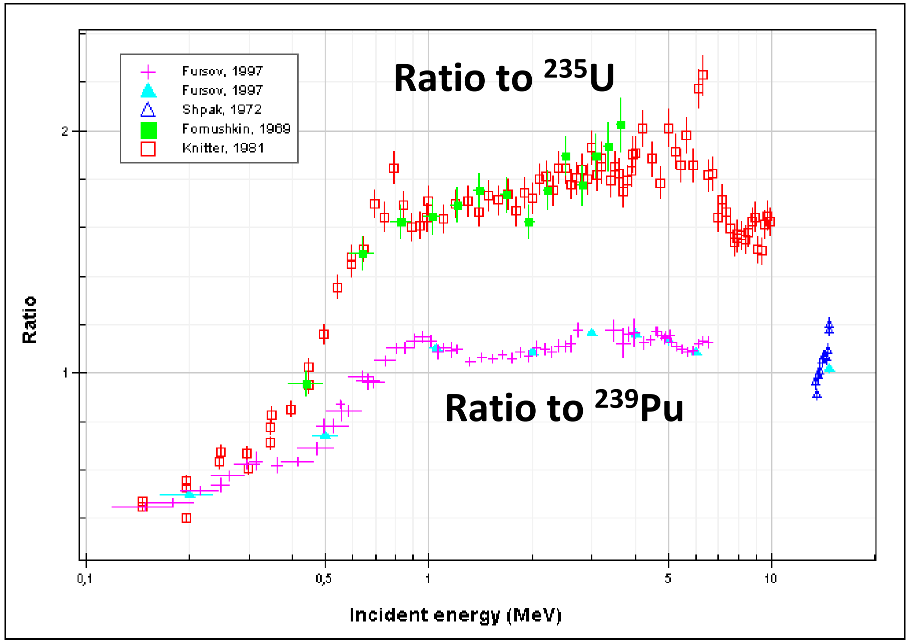
- from 20 % down to 5 %

# The $^{238}$Pu(n,f) reaction: the data



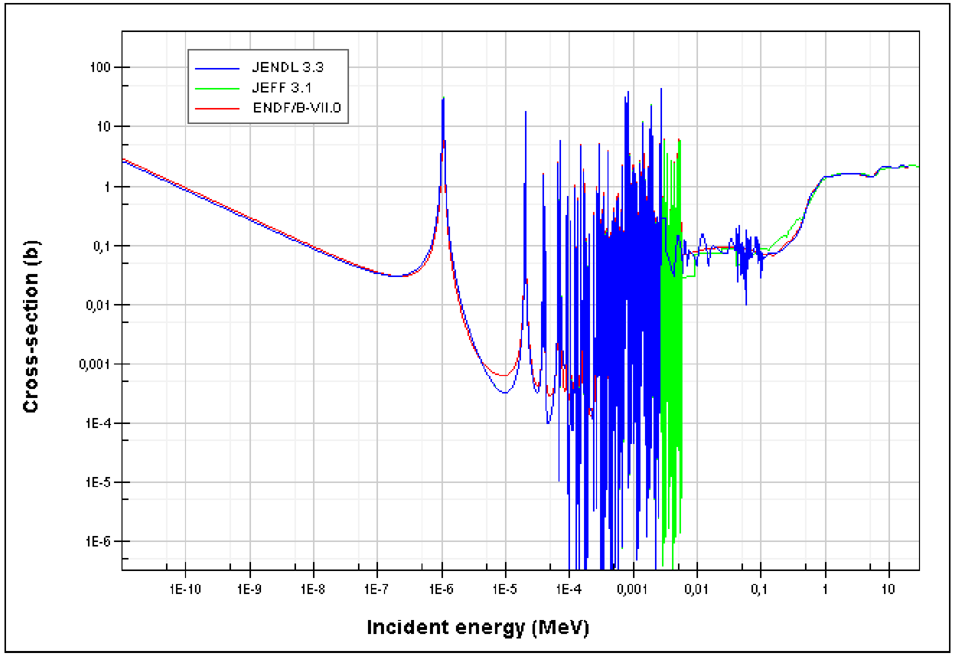

Below threshold few data available (and with scarse energy resolution)

Above 1 MeV few data available (but mostly agree)



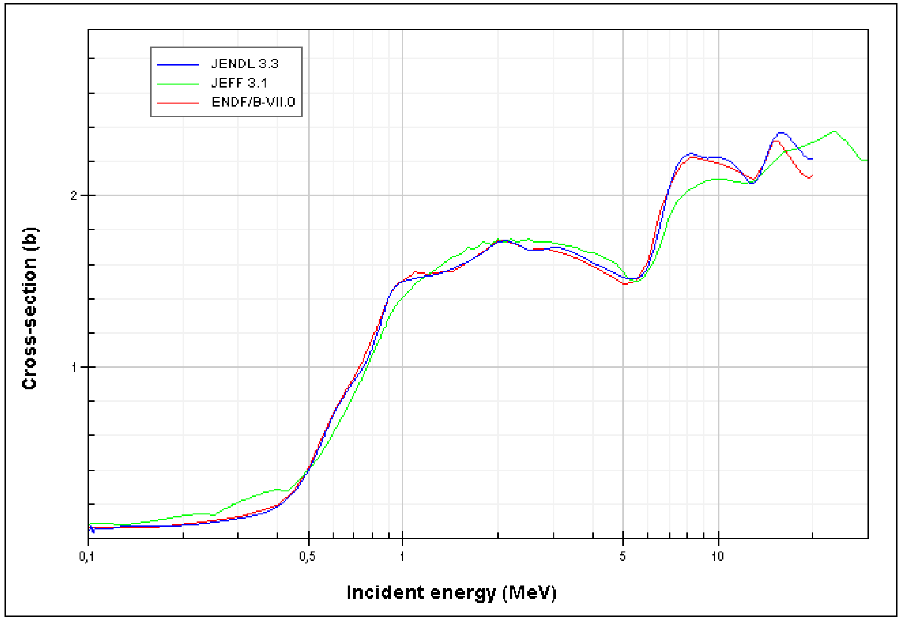

ENDF based on Fomushkin, Fursov, Silbert

# The $^{240}$Pu(n,f) reaction: evaluated data libraries




Important for new generation reactors and for waste burn-up

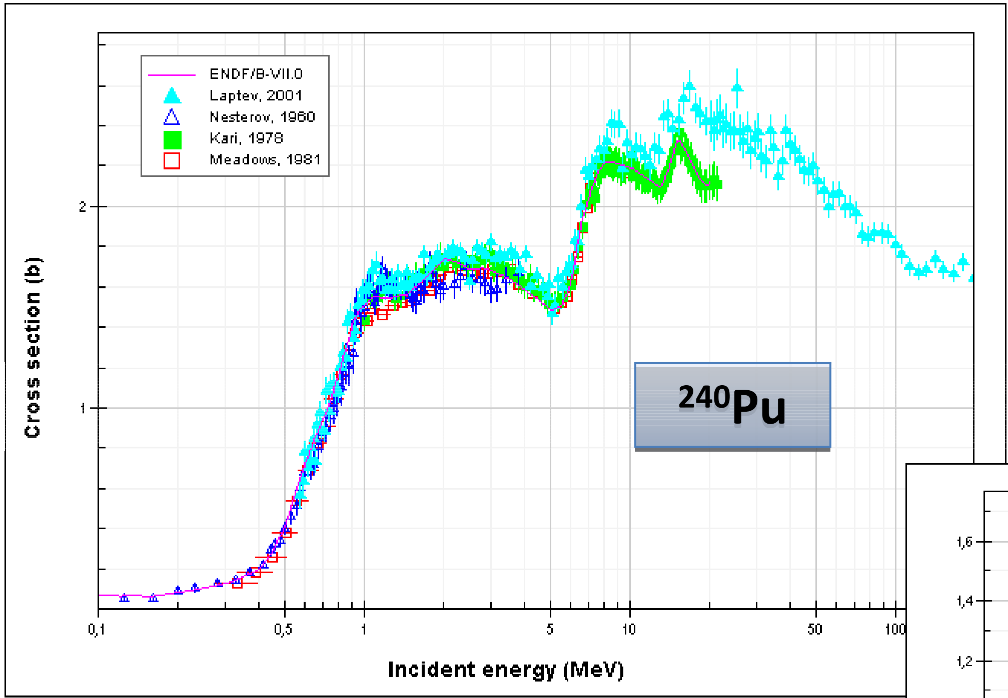
Small differences between databases, but still too high for new applications.




Sensitivity analysis indicates that it is necessary to reduce uncertainties:

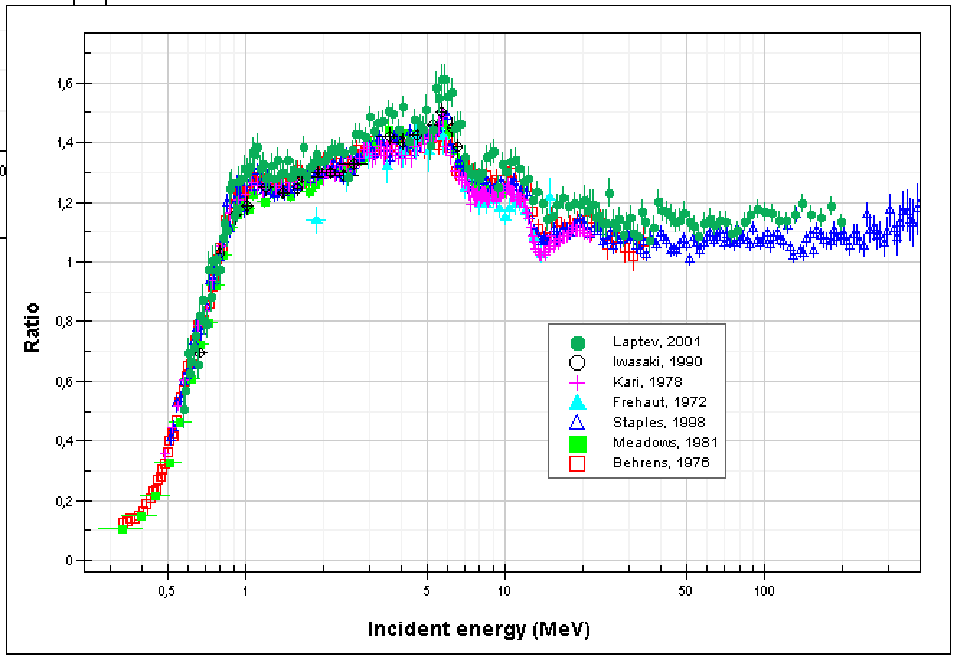
- **0.5-2 MeV from 20 % to 1 %**
- **2-6 MeV from 6 % to 2 %**

# The $^{240}$Pu(n,f) reaction: the data



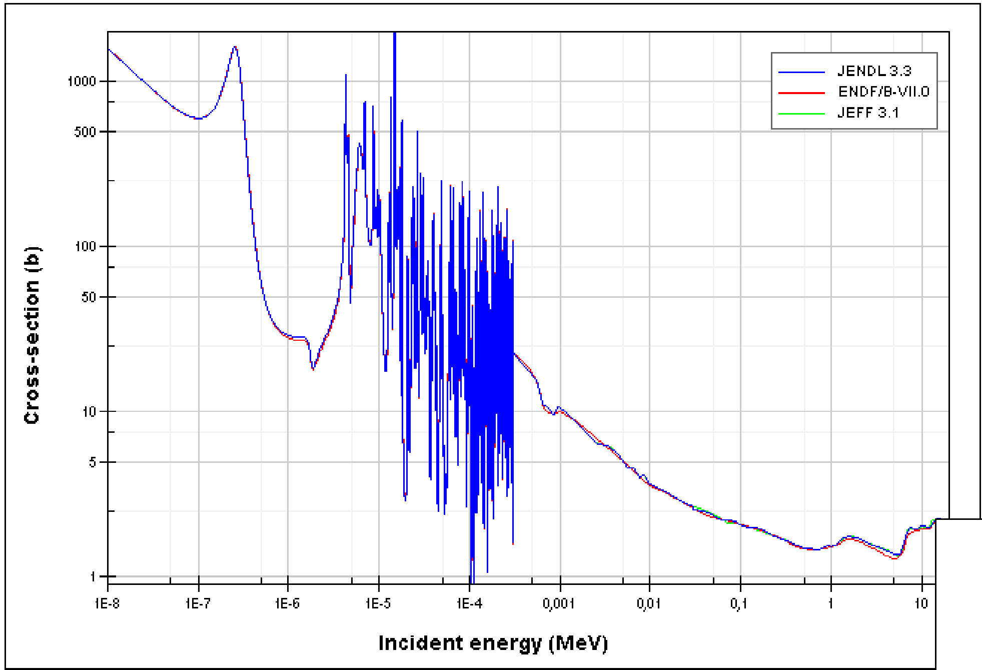

Recent data (Laptev 2001) are systematically higher than previous data and evaluations.

Need extension to high energy.



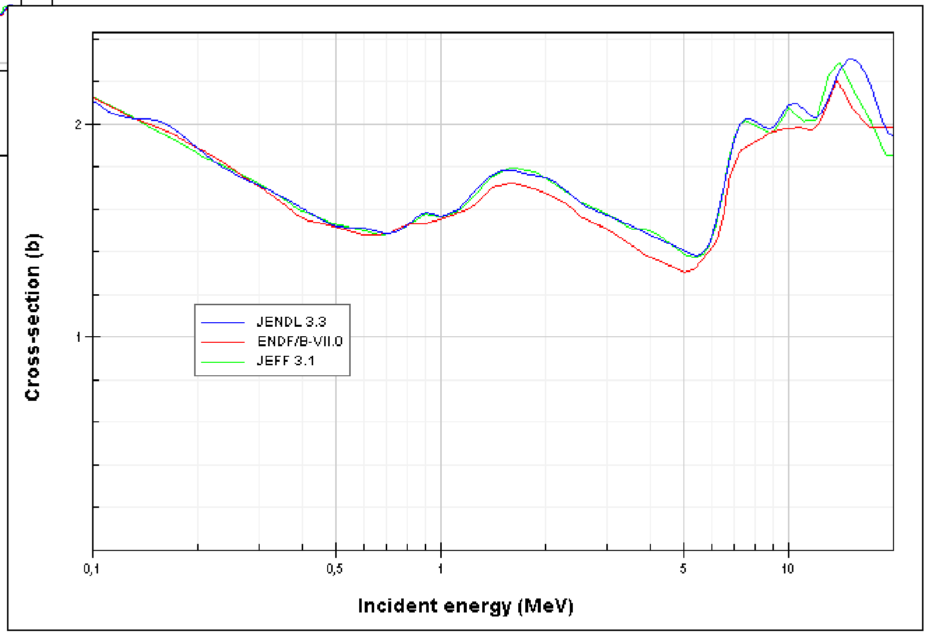

ENDF based on compromise between Behrens, Kadi, Meadows,

# The $^{241}$Pu(n,f) reaction: evaluated data libraries




Important for new generation reactors.

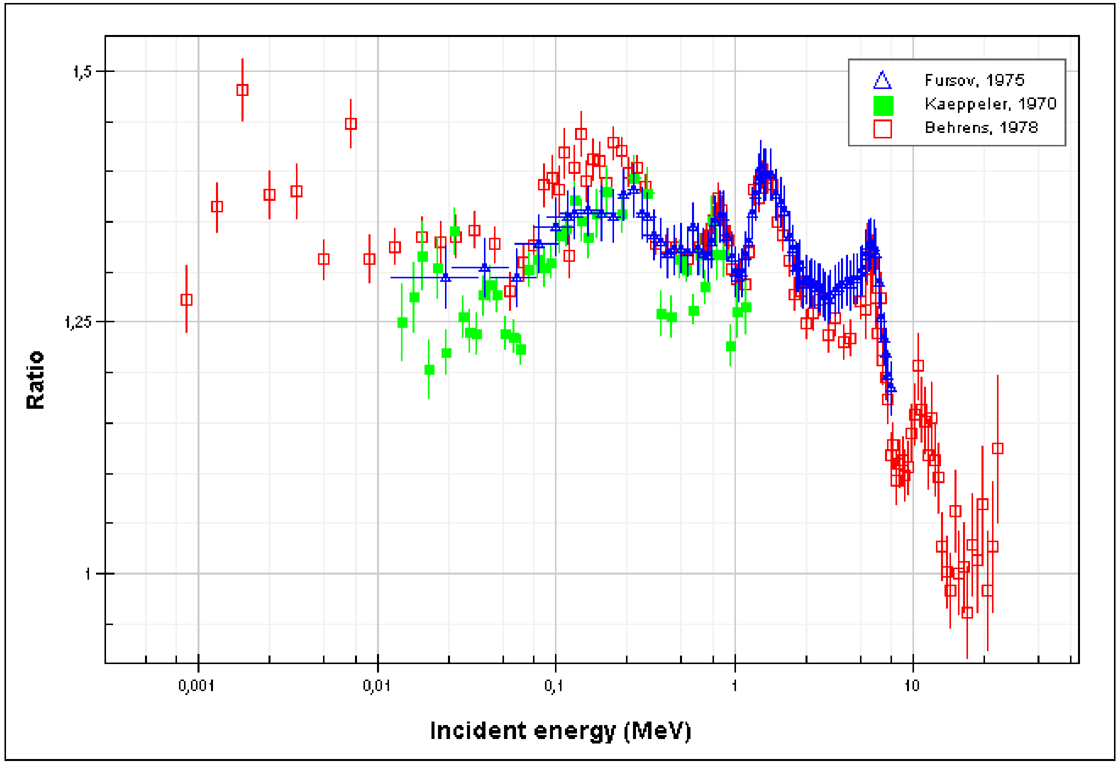
Differences between databases mainly above 1 MeV




Sensitivity analysis indicates that current uncertainty too big in the region 50 keV – 1 MeV

- **from 15 % down to 2 %**

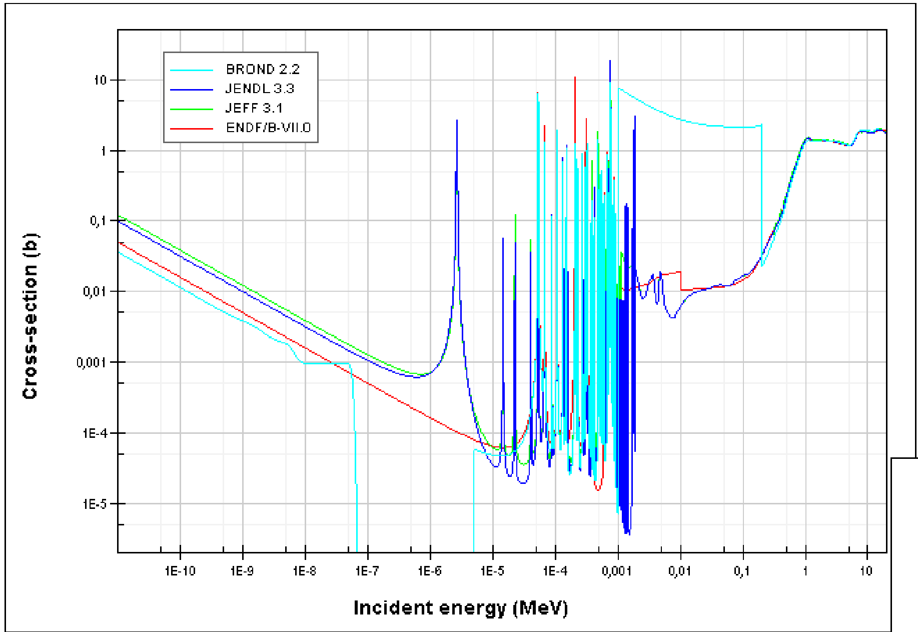
# The $^{241}$Pu (n,f) reaction: the data




Data are scarce and with some discrepancies

ENDF currently based only on Behrens

# The $^{242}$Pu(n,f) reaction: evaluated data libraries

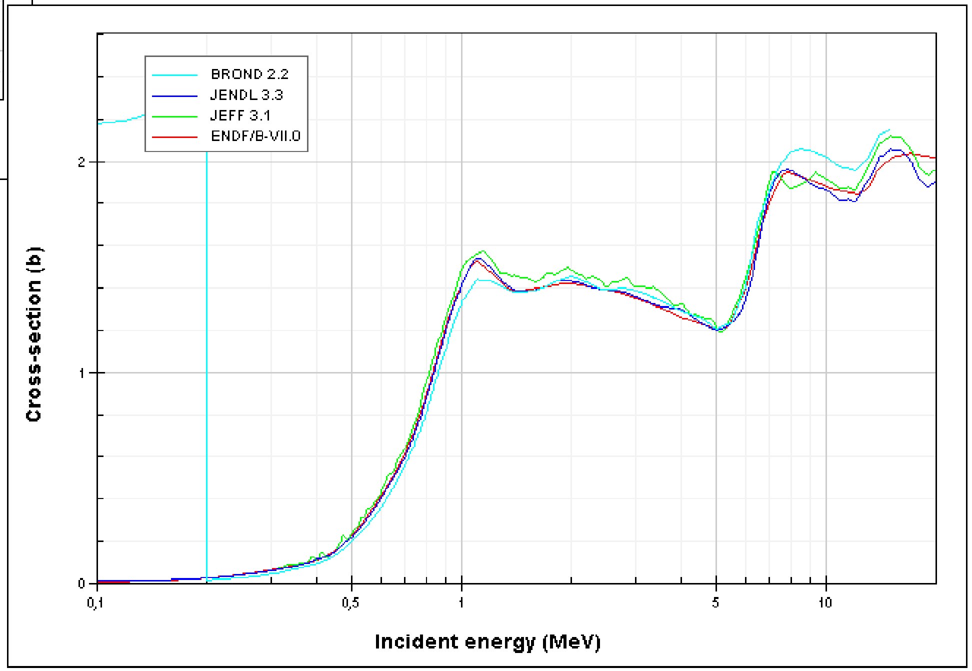



Important for waste transmutation.

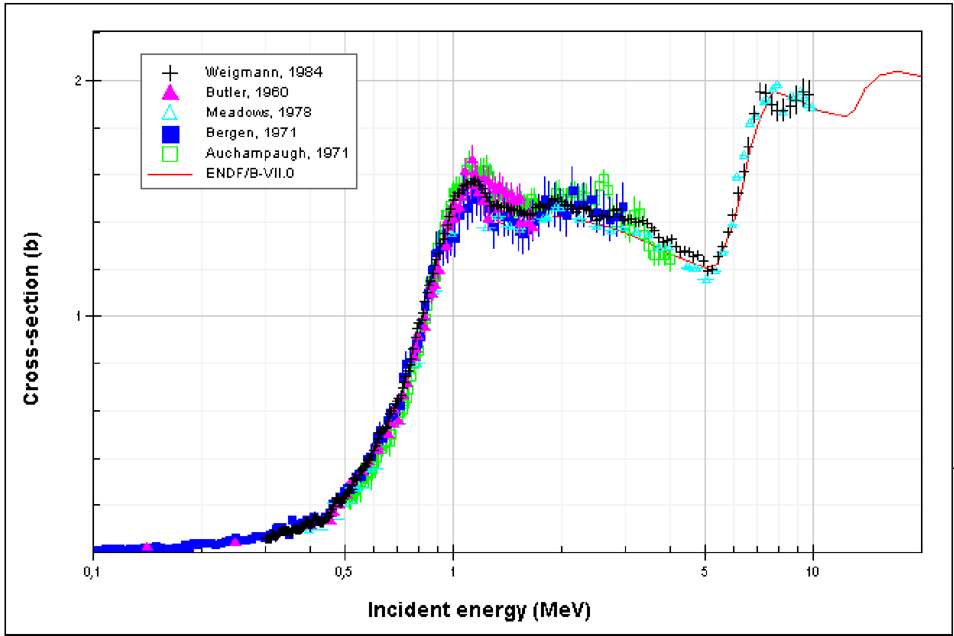
Problems at low energy.

Better agreement at high energy.

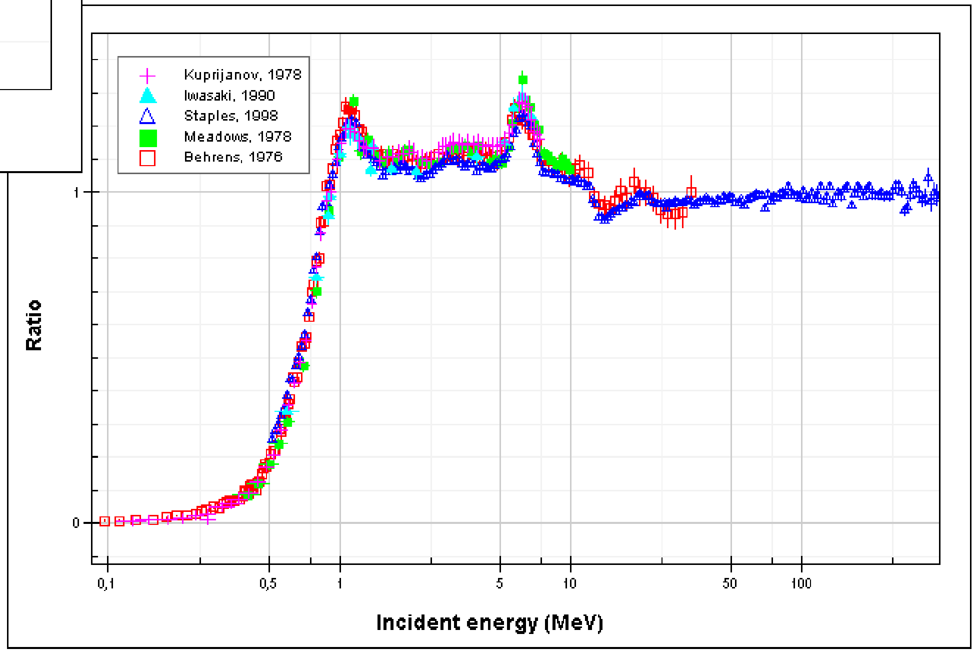
Need some improvement, but not high priority.



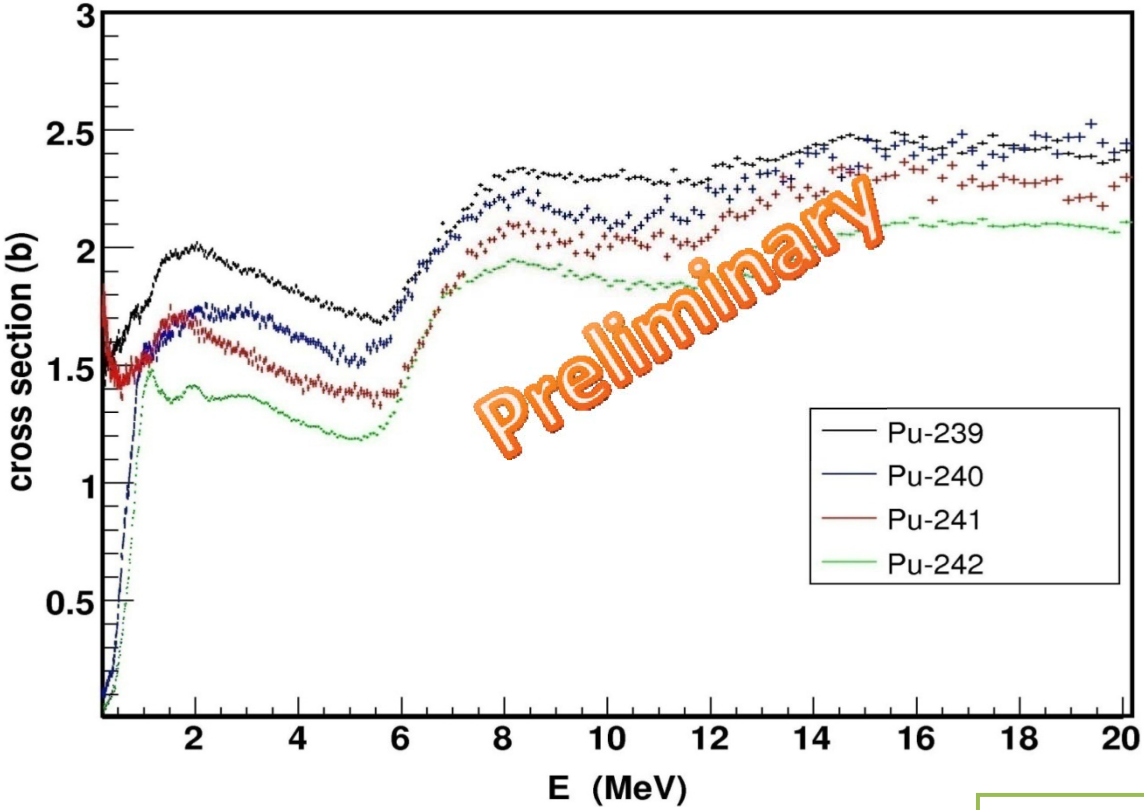
# The $^{242}Pu(n,f)$ reaction: the data




There are different data sets, mostly in agreement between each other.



# The $^{239-241}$Pu (n,f) reaction: new results from LANL




Expecting offical release of the data soon.

Some private notes (from different Conferences).

In general, first measurements in the whole energy region

**$^{240}$Pu:** new data mostly agree with evaluations in URR and first chance fission.

Significant discrepancies at higher energy

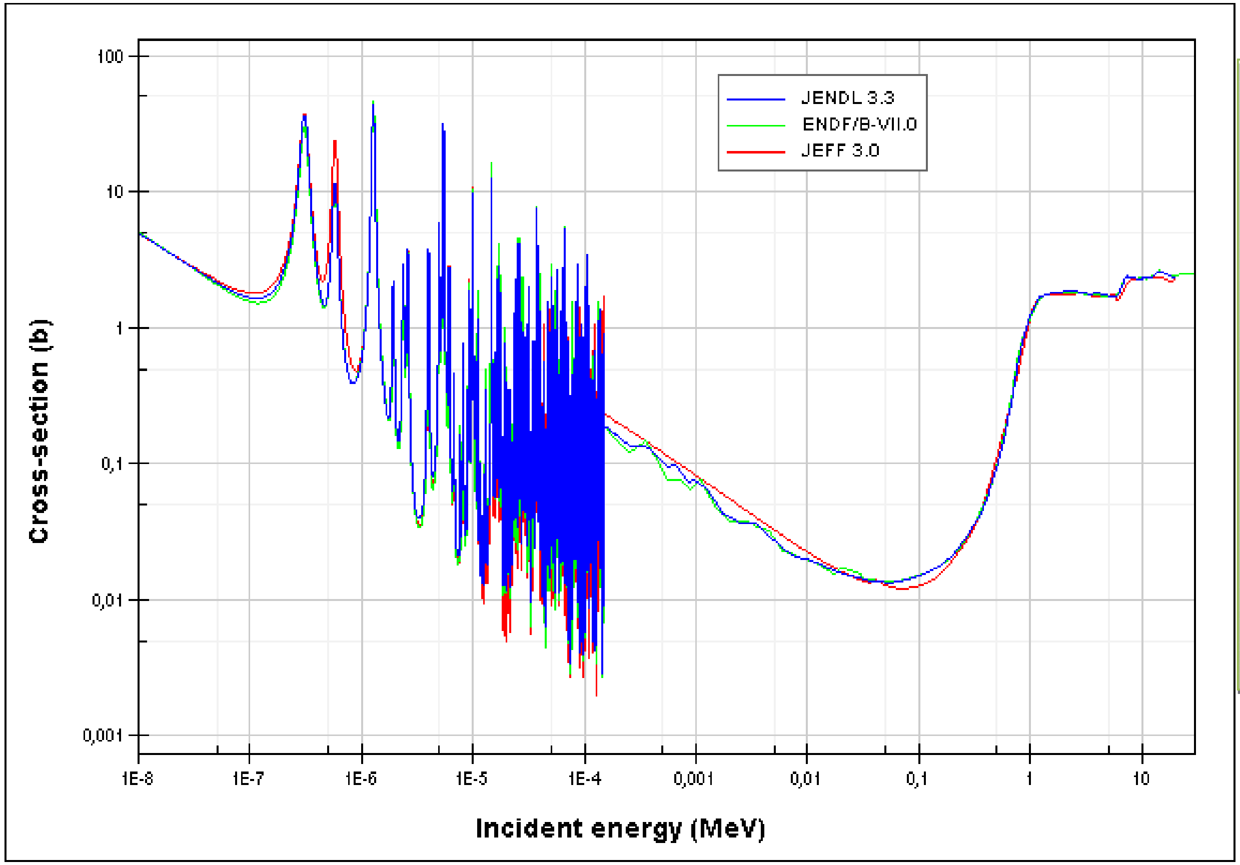
**$^{241}$Pu:** new data agree better with ENDF, while JENDL is systematically higher.

**$^{242}$Pu:** new data mostly agree with evaluations below threshold

ENDF and JENDL underestimate first change fission and overestimate second chance (by a few %)

# The Am(n,f) cross-sections

# The $^{241}Am(n,f)$ reaction: evaluated data libraries




Important for Gen IV and trasmutation projects

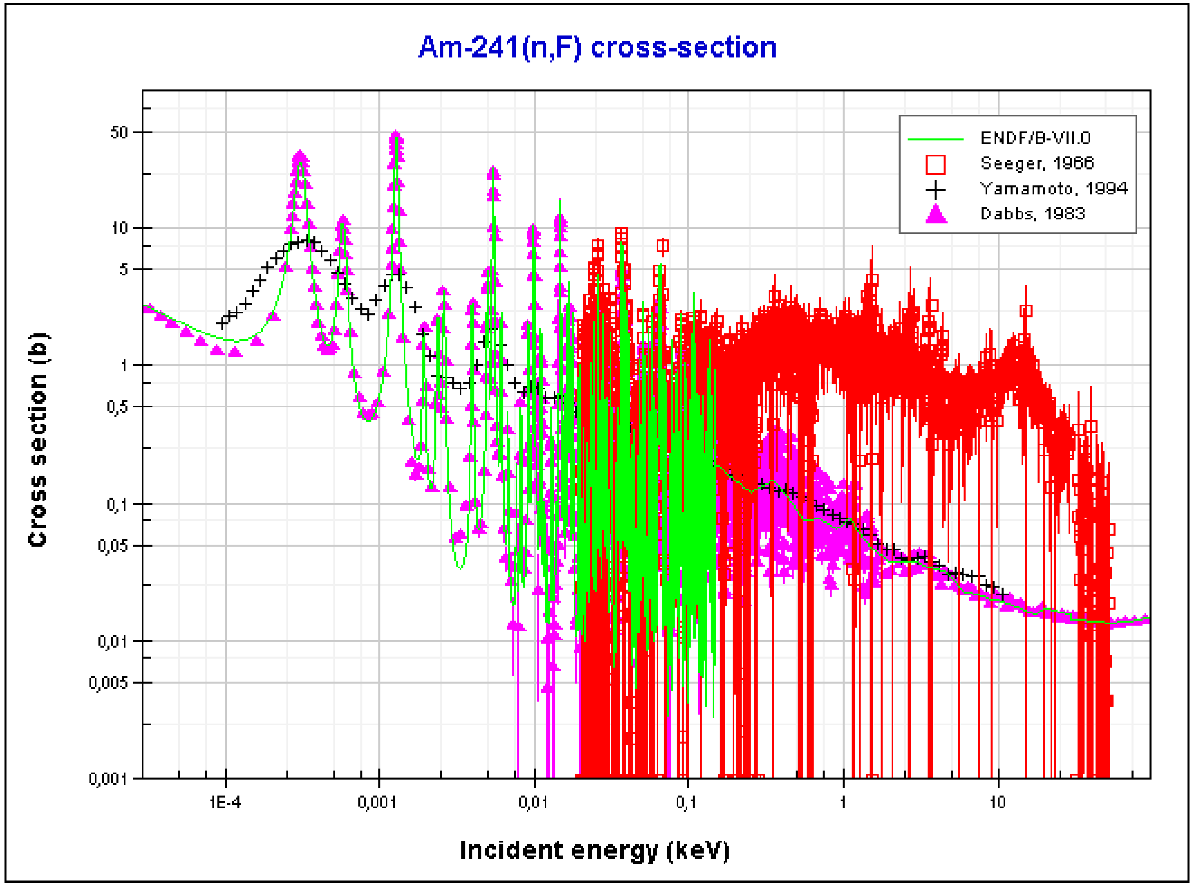
ENDF and JENDL mostly agree, JEFF shows differences below threshold (up to 10 % in the keV region)

Above threshold situation much better (but still not enough)

A recent sensitivity analysis indicates that uncertainty has to be reduced at high energy:

- **500 keV – 6 MeV** **from 10 % to 2 %**

# The $^{241}$Am(n,f) reaction: data at low energy

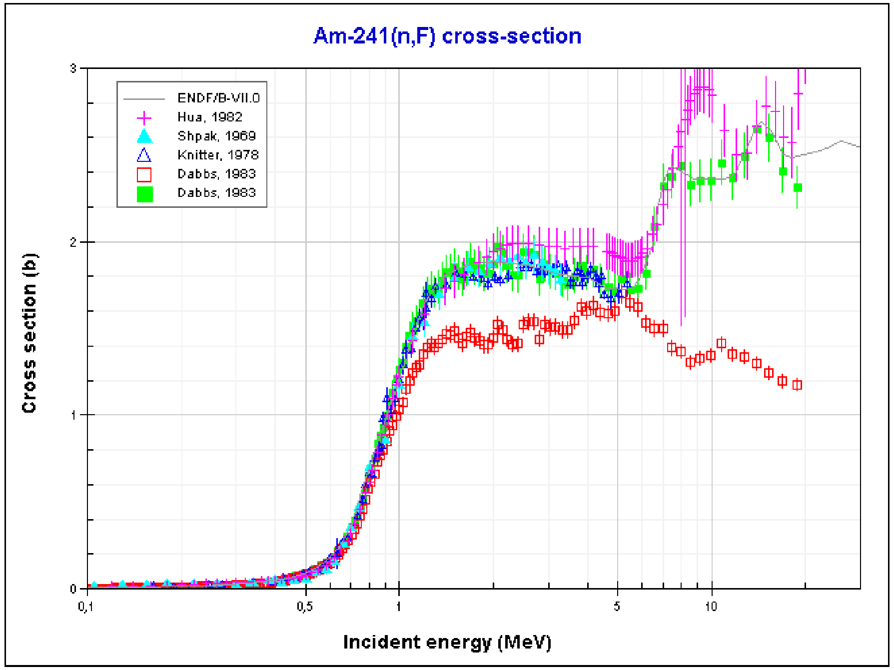


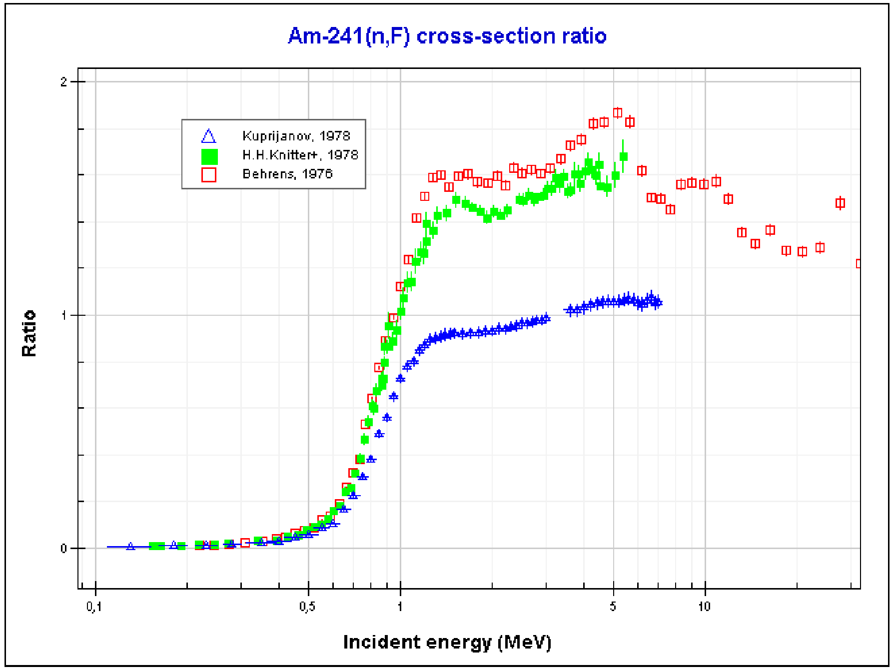

Evaluation obtaned by adjusting theoretical cross-sections as need to match the available experimental data

At low energy, ENDF and JENDL libraries mainly based on one data set (Dabbs 1983).

Need more data (high resolution and high accuracy) to check databases
Different data sets in different energy regions.
Data collected at n_TOF for this isotope, from thermal to 200 MeV

# The $^{241}$Am(n,f) reaction: data at low energy

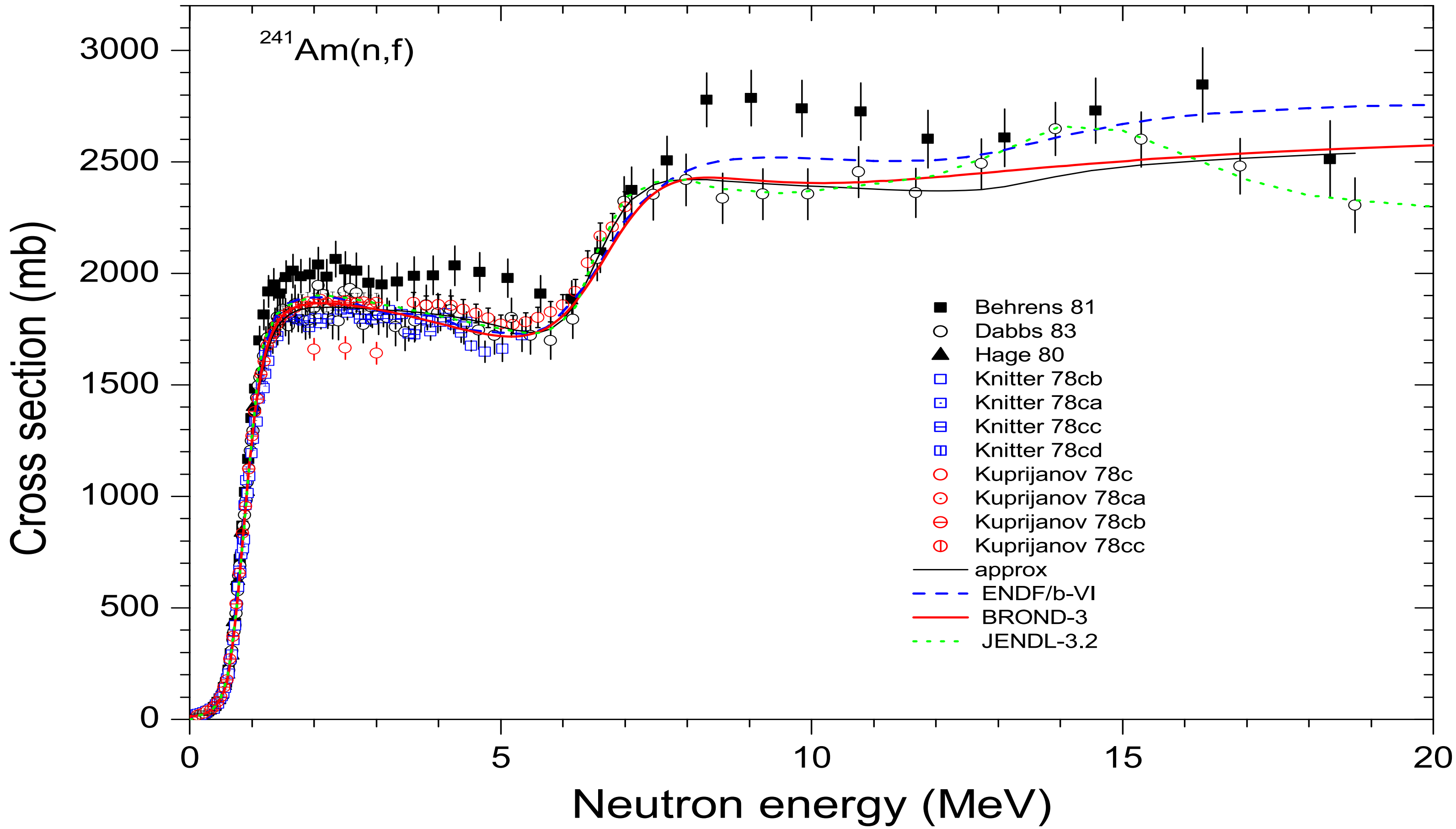



Above threshold, discrepancies between data of 15 %. Current evaluation mainly based on Dabbs-83.

Need new data to solve accuracy and improve uncertainties in current databases

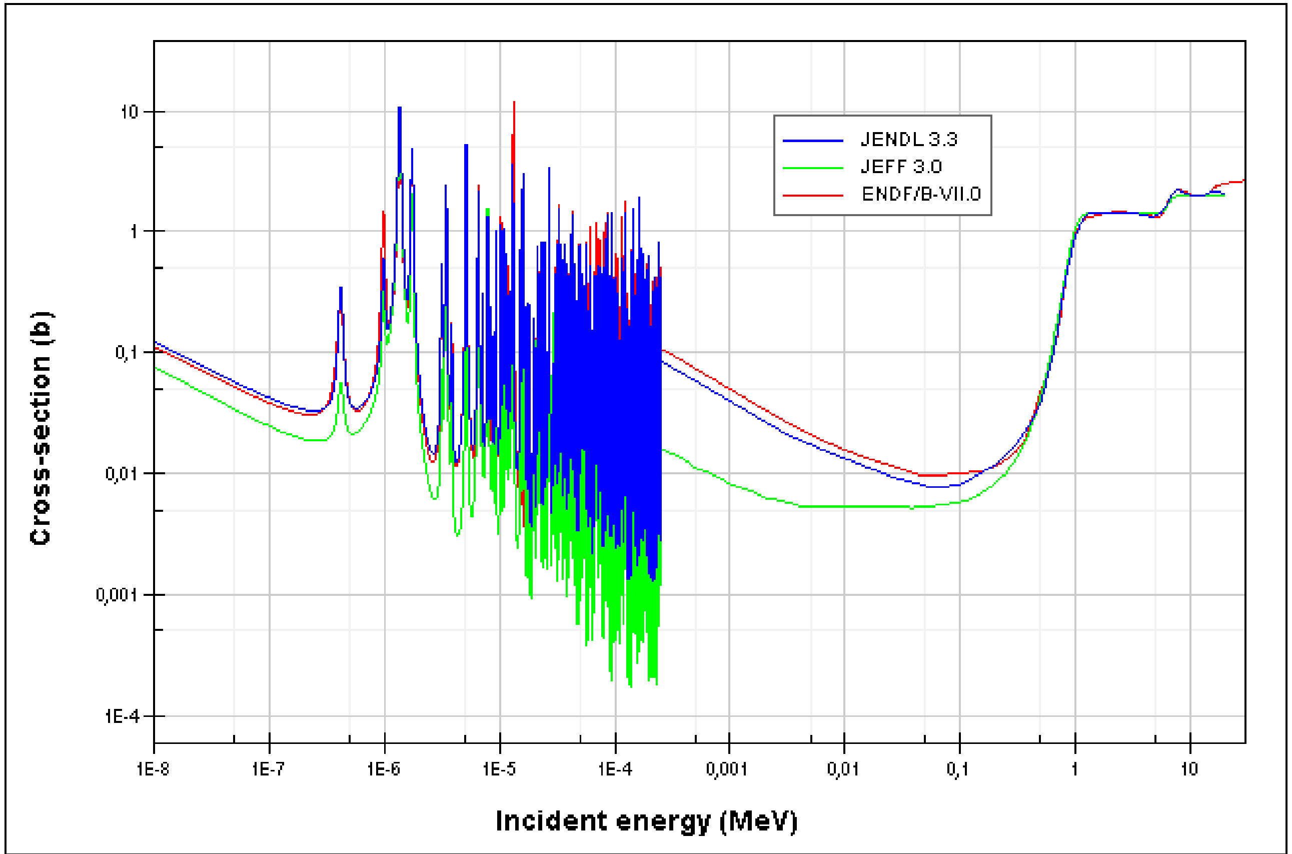
# The $^{241}$Am(n,f) reaction: data above threshold




No data exist in the whole energy region

New data have been collected at n_TOF from themal to 200 MeV

# The $^{243}$Am(n,f) reaction: evaluated data libraries




Important isotope for Gen IV and transmutation

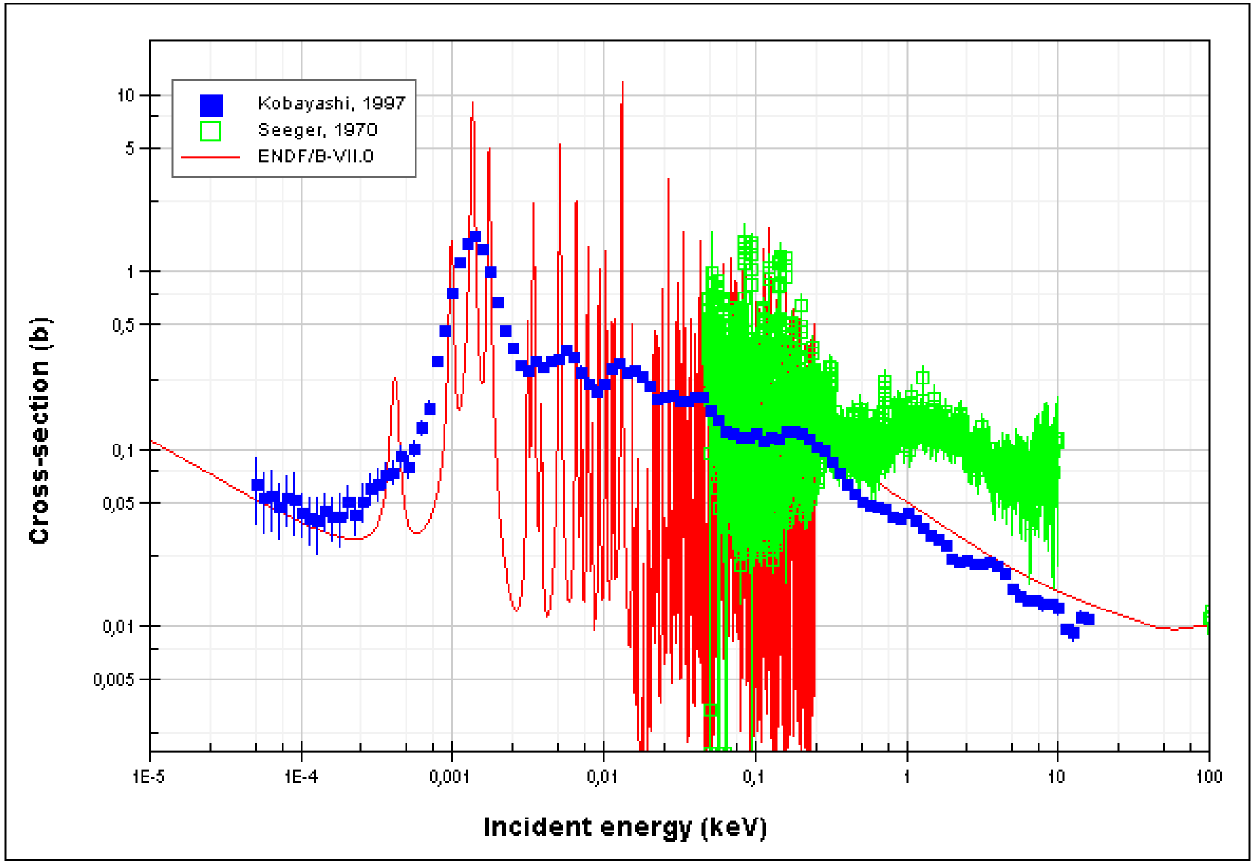
ENDF and JENDL mostly agree, JEFF much lower, in the energy region below threshold (up to 4 times smaller !!)

Need to improve accuracy at all energies !

Results of sensitivity analysis:

- **20 – 200 keV** **from 80 % to 20 %**
- **200 keV – 2 MeV** **from 40 % to 3 %**
- **3 – 6 MeV** **from 18 % to 5 %**

# The $^{243}$Am(n,f) reaction: data at low energy



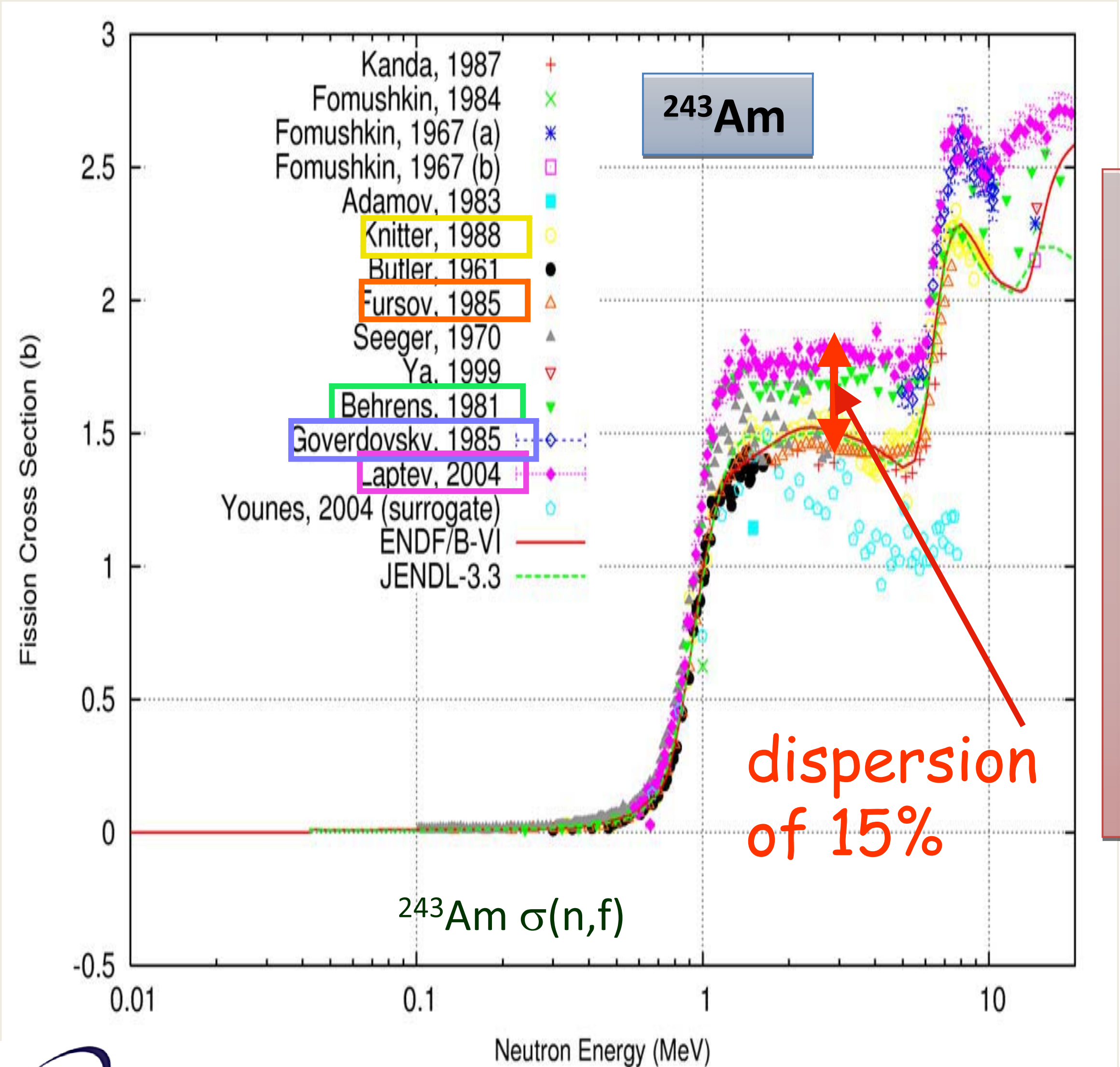

Very few data below threshold, and with bad energy resolution.

Different data sets in different energy regions.

Evaluation mainly based on theoretical models, adjusted to reproduce in average measured cross-sections.

At low energy, need more data (high resolution and high accuracy)
Experimental difficulty: contamination of $^{242m}$Am !!

# The $^{243}$Am(n,f) reaction: data above threshold

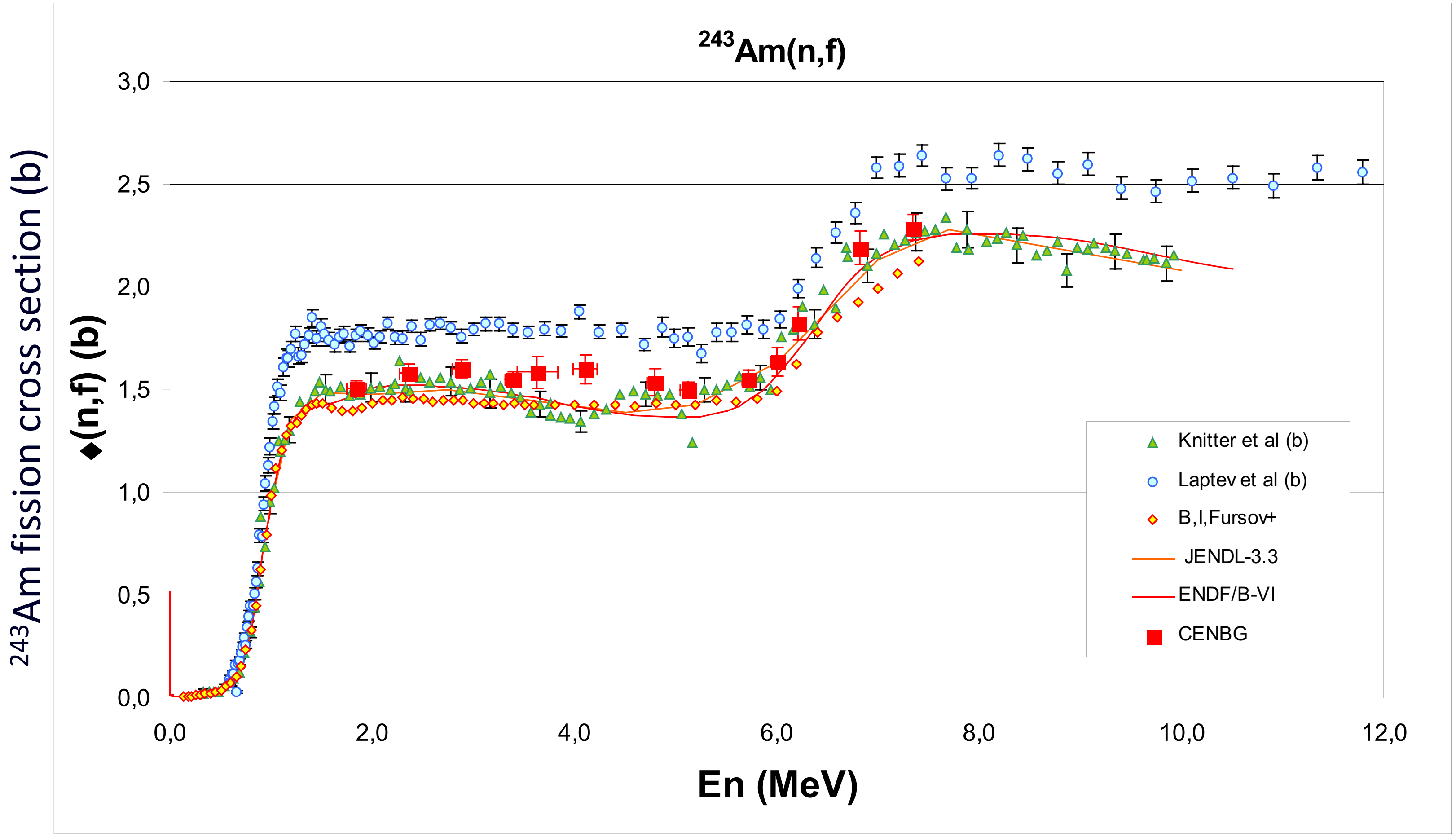



Above threshold, measured cross-sections tend to cluster in two distinct groups, separated by 15 %.

Current evaluation consider the “low” cluster (the high cluster disagrees with average cross-sections from reactors).

New data are now coming out (mostly confirming the low cluster)

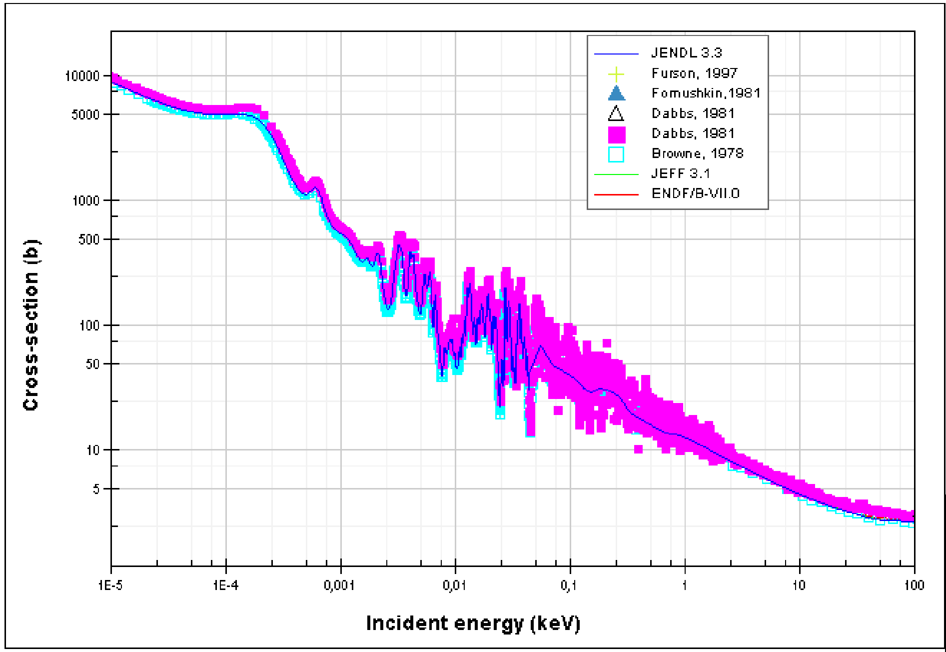
# The $^{243}Am(n,f)$ reaction: new results




Recent data from CENBG (Aiche et al., NUMADE workshop)
New data from n_TOF

Confirm database

# The $^{242m}Am(n,f)$ reaction: data



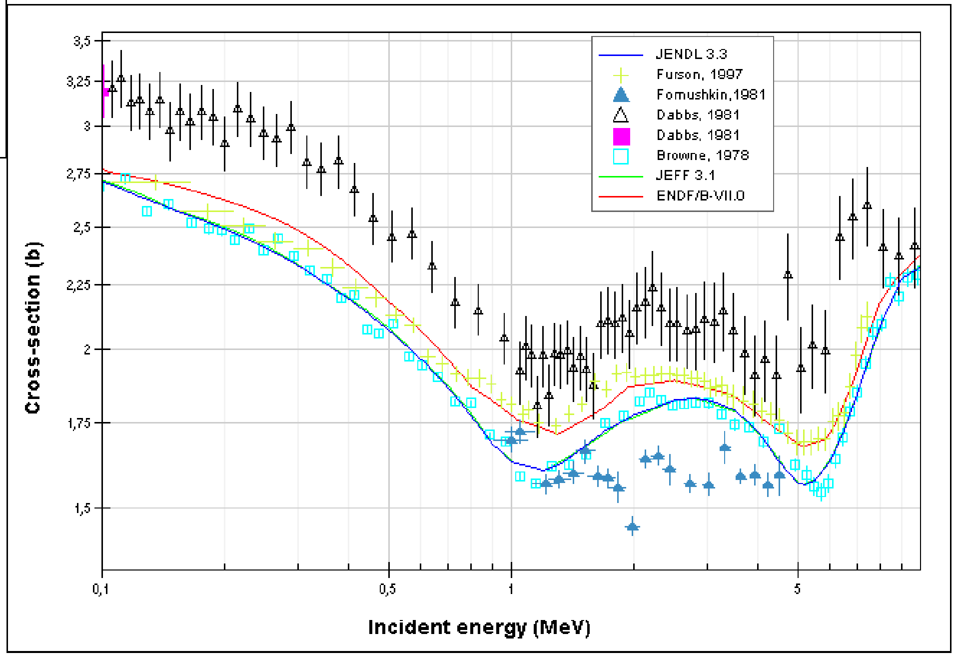

Evaluated databases mostly in agreement

Very high cross-section at low energy ($10^4$ b !!)

Difficult measurement, due to very short half life ($t_{1/2}$=141 y)

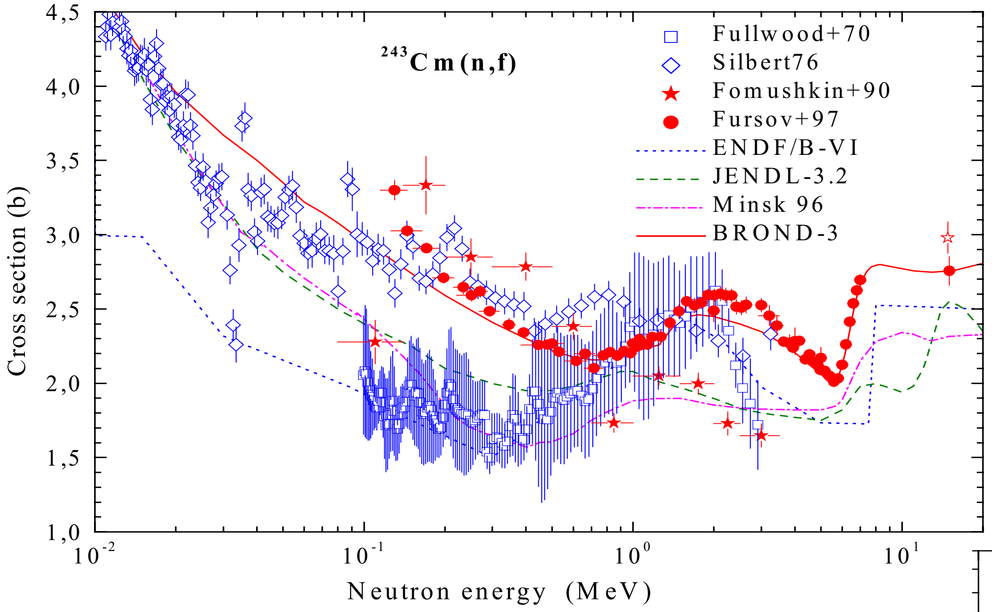
At high energy, problem with one data set.

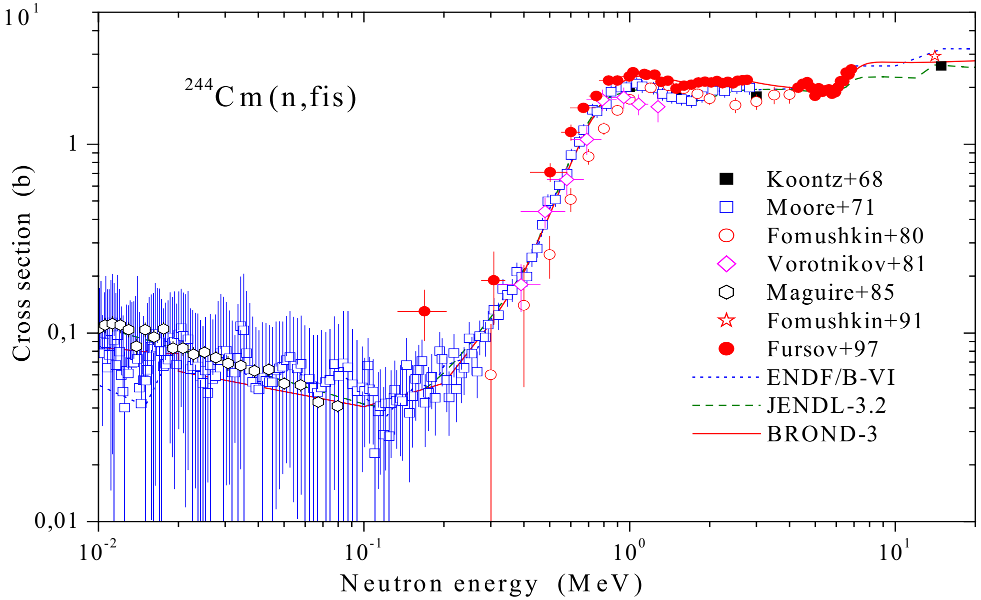
Need more data



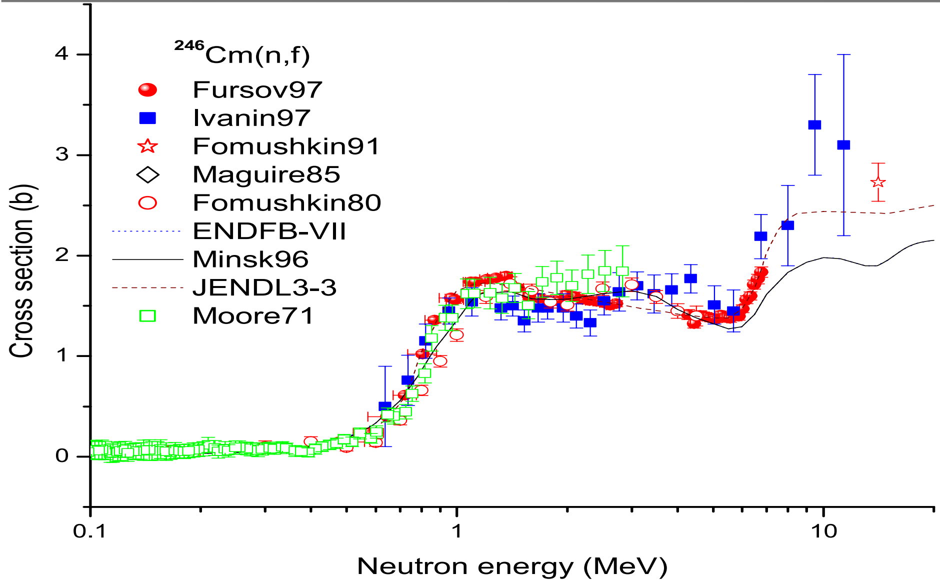
# The Cm(n,f) cross-sections

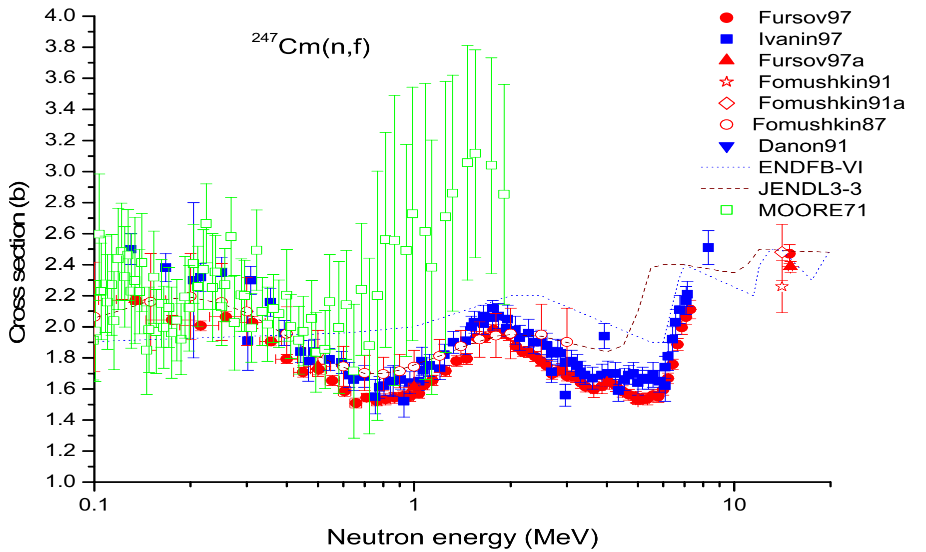
# The $^{243-244}$Cm(n,f) reaction

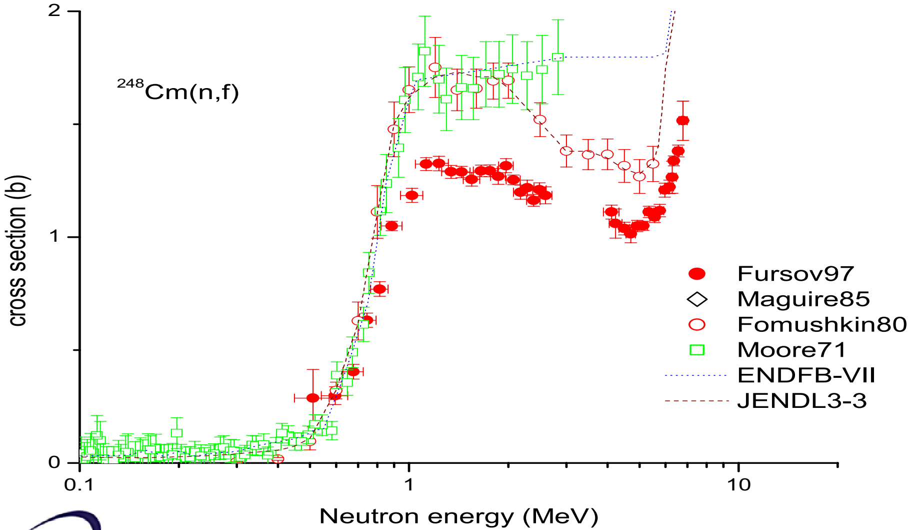


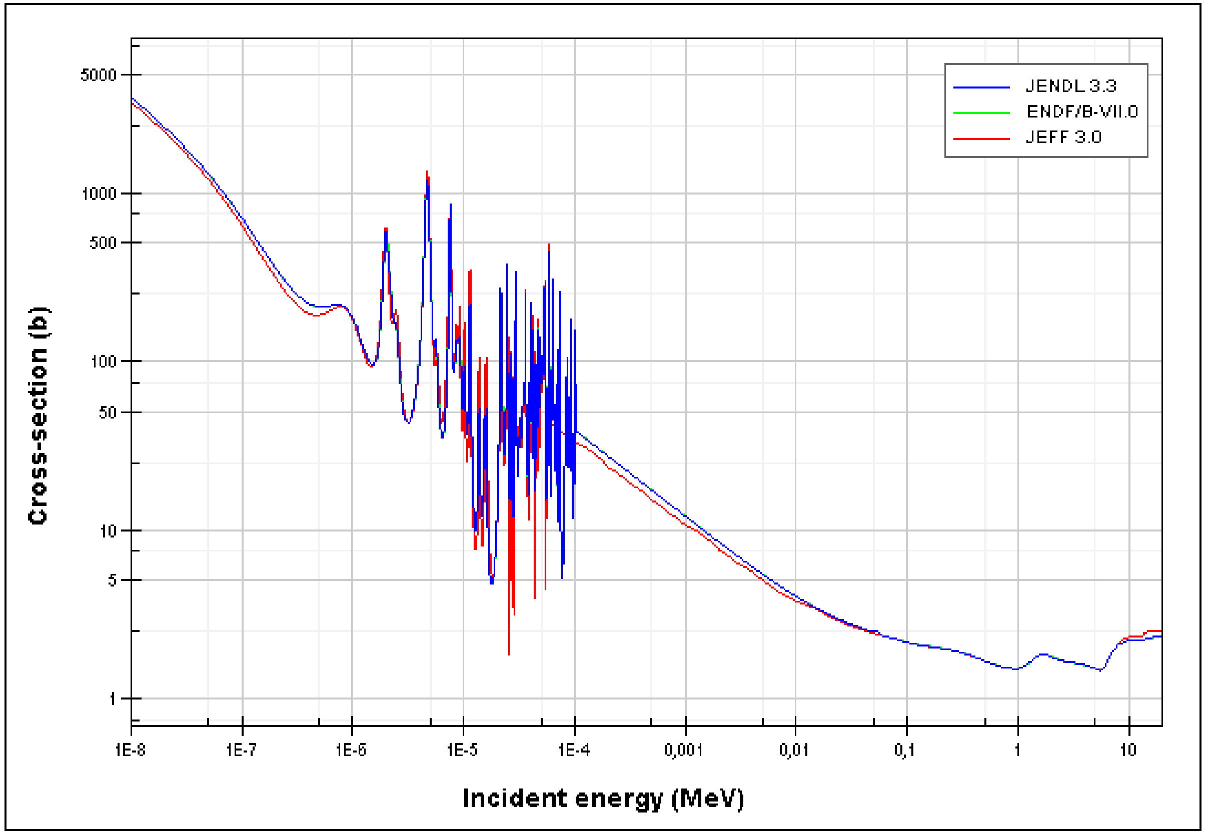
# The $^{246-248}Cm(n,f)$ reaction



# The $^{245}Cm(n,f)$ reaction: evaluated data libraries



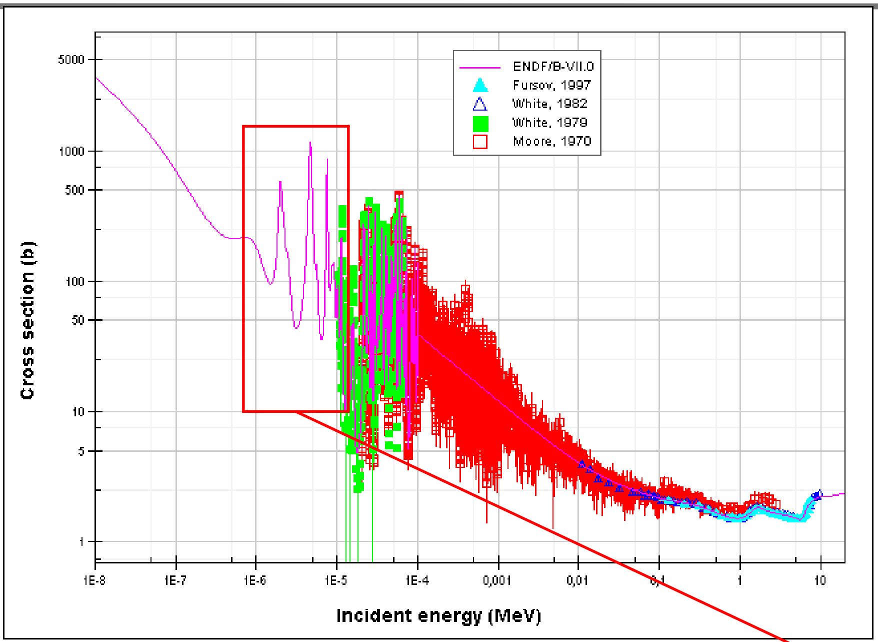

Important isotope for Gen IV and transmutation of nuclear waste

Databases mostly agree, apart for minor details

Results of sensitivity analysis:

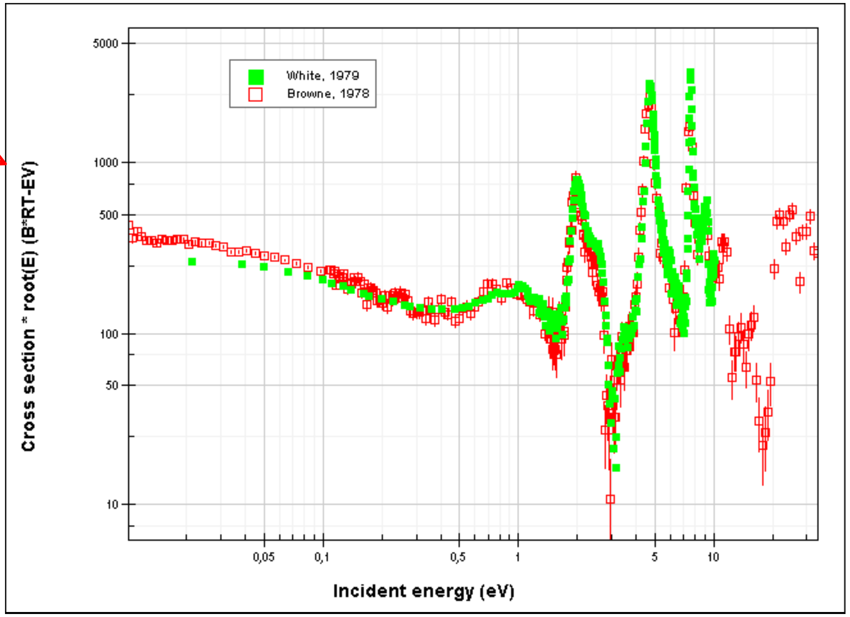
- **20 – 70 keV from 20 % to 3 %**
- **70 keV – 2 MeV from 40 % to 3 %**

# The $^{245}$Cm(n,f) reaction: data at low energy




Few data available on this isotope at low energy (very difficult to measure because of the a-activity).

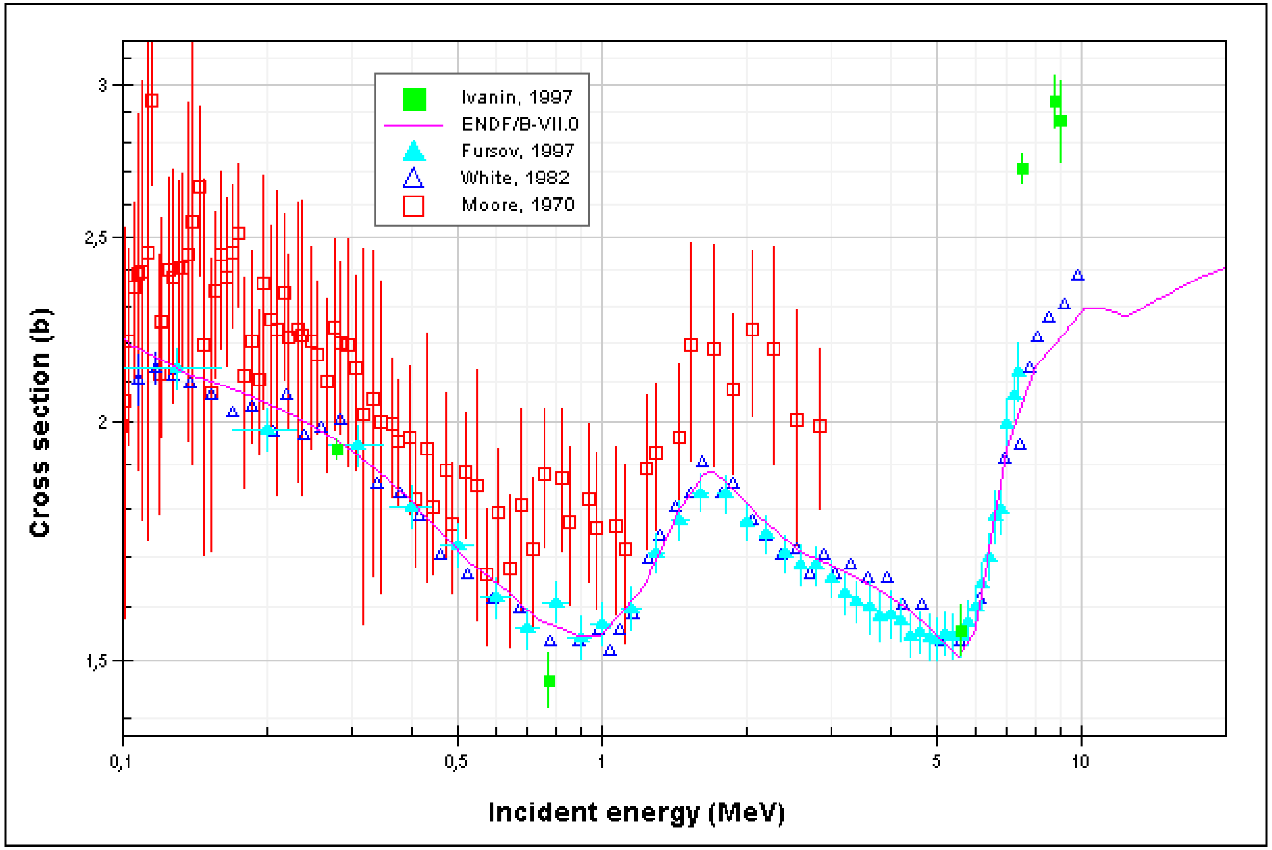
Different data sets cover different energy regions.




Strongest resonances well defined (except a few details)

Need better resolution and higher accuracy data up to 100 keV

# The $^{245}Cm(n,f)$ reaction: data at high energy




Up to a few MeV, ENDF based on calculations adapted to Fursov-'97.

Some data show higher cross-sections.

Need to be checked, and cross-sections extended at higher energy.

Difficult measurement due to the short half-life

New results are coming out (n_TOF, Russia)

# The n_TOF results

# The n_TOF data

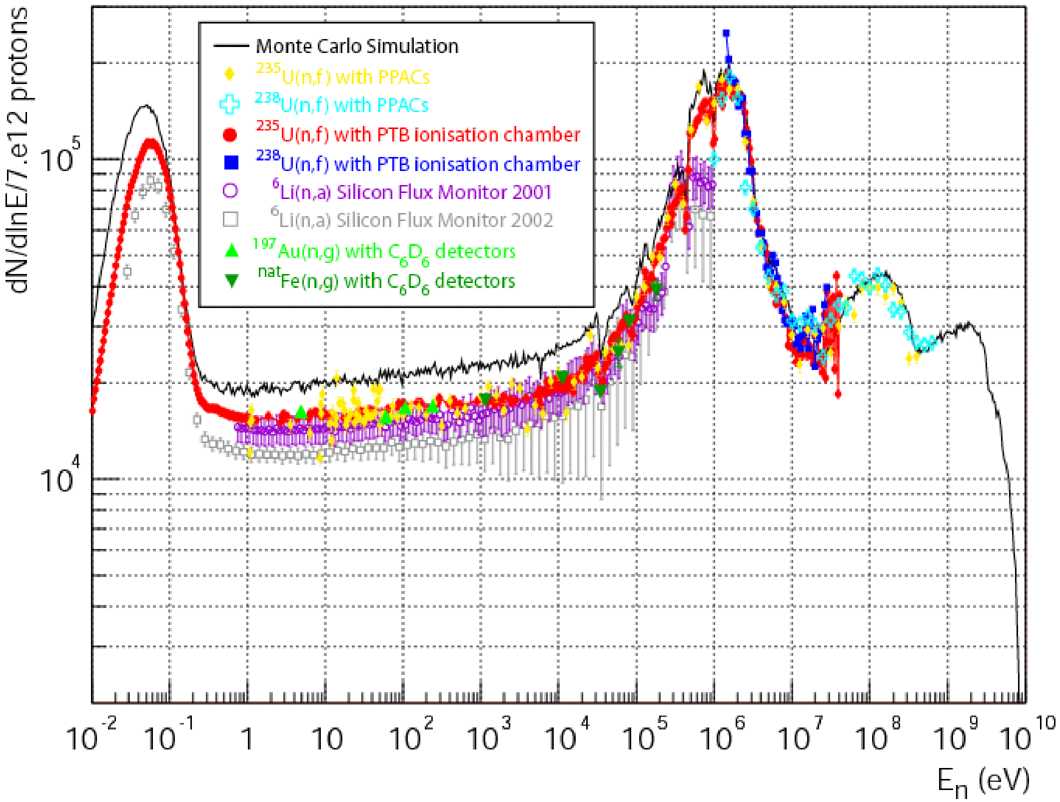
Need new and accurate data on neutron induced fission on MA:

- Wide **energy range** (easier to check normalization)
- **High resolution** for Resolved Resonance Region
- Minimize possible contribution of the **background**
- **Extend measurements** at higher energies (> 20 MeV)
- Include new data in the **evalution**, and consider data previously neglected (if any).

New data on fission cross-sections have been collected at the **n_TOF facility** cat CERN, taking advantage of the innovative features of neutron beam

The aim is to provide accurate cross-section data that could help fulfilling the requests.

# Neutron flux at n_TOF



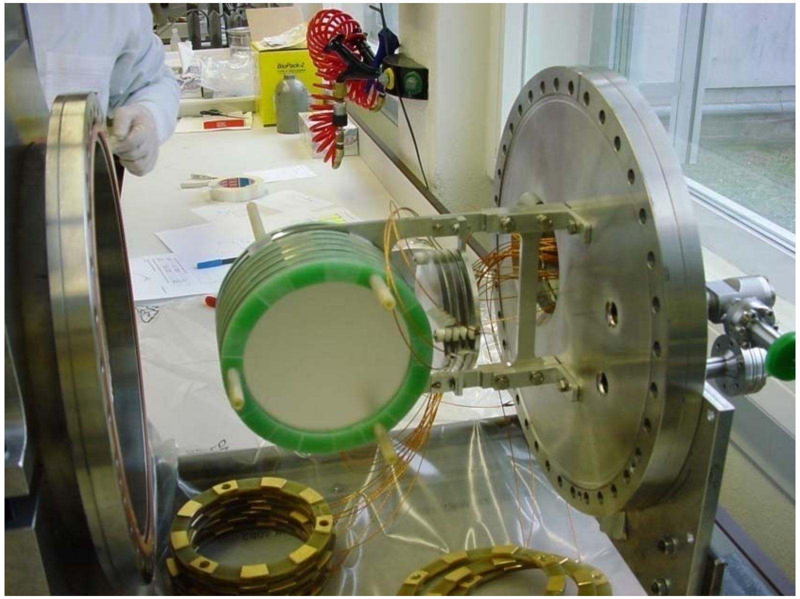

Main advantages of the n_TOF neutron beam:

- Wide energy range (from thermal to 1 GeV)
- high instantaneous neutron flux
- good energy resolution
- low background

State-of-the-art detectors and acquisition systems

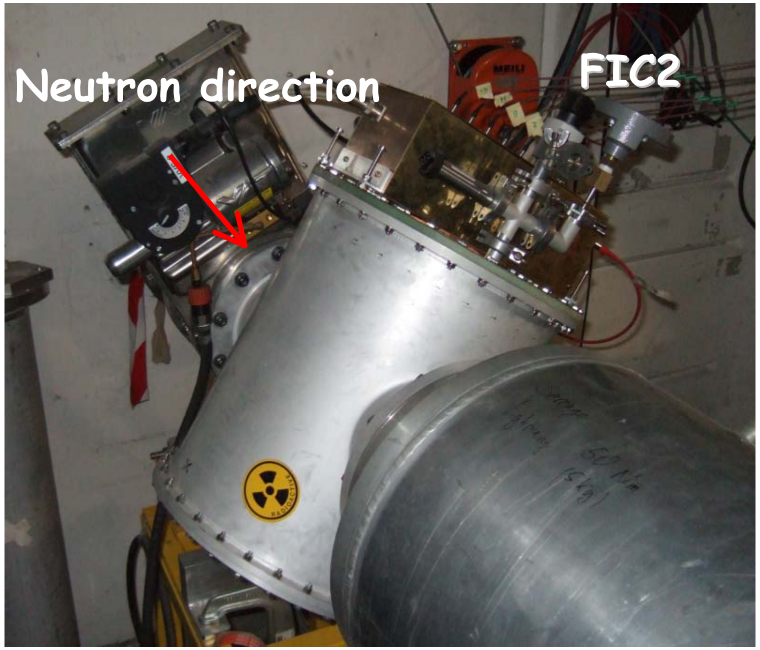
Clear advantages of the n_TOF facilities for measuring cross-sections of radioactive isotopes

# The fission measurements at n_TOF



**The fast ionization chamber (FIC):**

- Detect only one fission fragment (still efficiency around 100 %)
- Stack of up to 10 samples in the beam
- Does not require very thin samples




**Measured isotopes:**

- **$^{235}$U, $^{238}$U** (standard reference)
- **$^{232}$Th, $^{233}$U, $^{234}$U, $^{236}$U** (Th/U cycle)
- **$^{237}$Np, $^{241,243}$Am, $^{245}$Cm** (transmutation and Gen IV)

# The n_TOF samples

| Isotope | Total mass (mg) | Mass uncertainty (%) | Half-life | Activity (sample) |
|---|---|---|---|---|
| $^{235}$U | 31.8 (2 samples) | 1.57 | 7.04E8 y | 0.2 kBq |
| $^{233}$U | 28.8 (4 samples) | 1.73 | 1.6E5 y | 5 MBq |
| $^{241}$Am | 2.26 (8 samples) | 1.33 | 432 y | 76 MBq |
| $^{243}$Am | 4.8 (8 samples) | 2.0 | 7370 | 7.4 MBq |
| $^{245}$Cm | 1.71 (4 samples) | 1.75 | 8500 y | 0.2 GBq |

$dN/dt=N_{at}\cdot \ln 2/t_{1/2}$

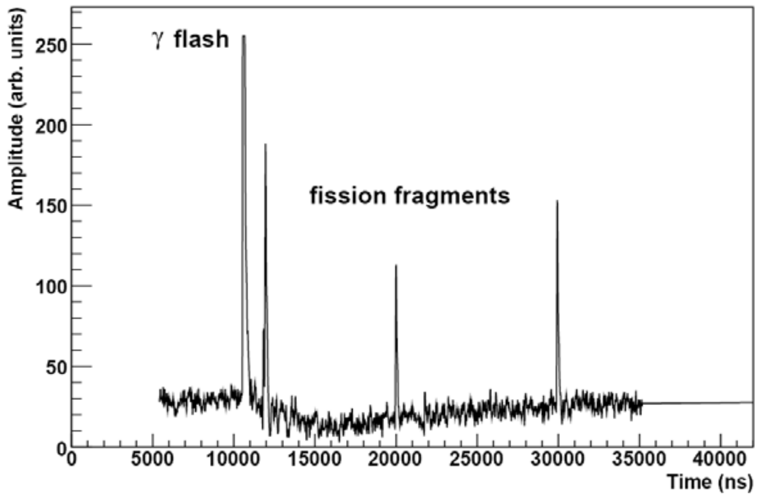
1 y = 3.15e7 s

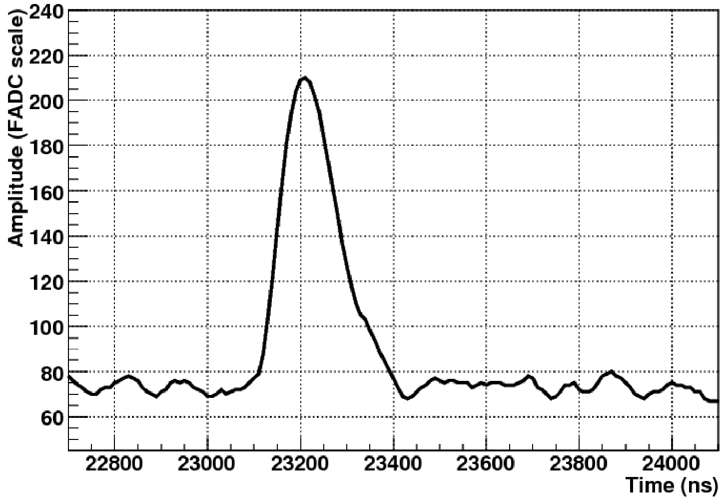
$^{243}$Am is contaminated at 2.6% with $^{241}$Am

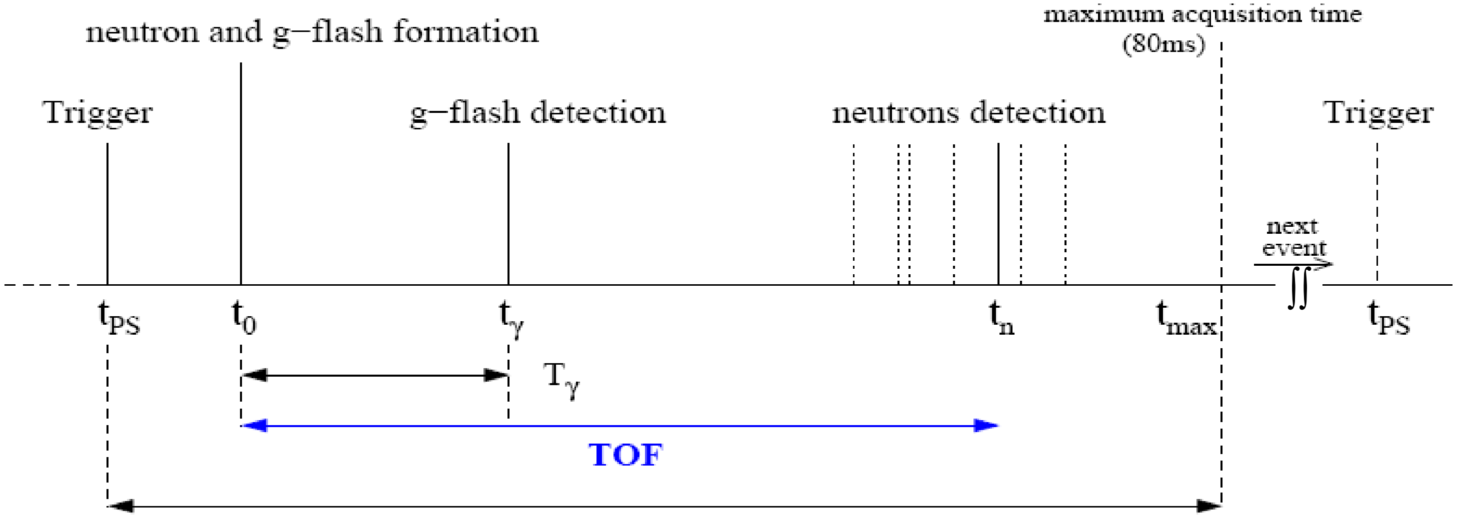
$^{245}$Cm is contaminated at 6.6 % with $^{244}$Cm ($t_{1/2}$=18 y)

SF typically $10^{-7}$-$10^{-10}$, except for $^{244}$Cm for which $10^{-4}$

# Time-of-flight reconstruction



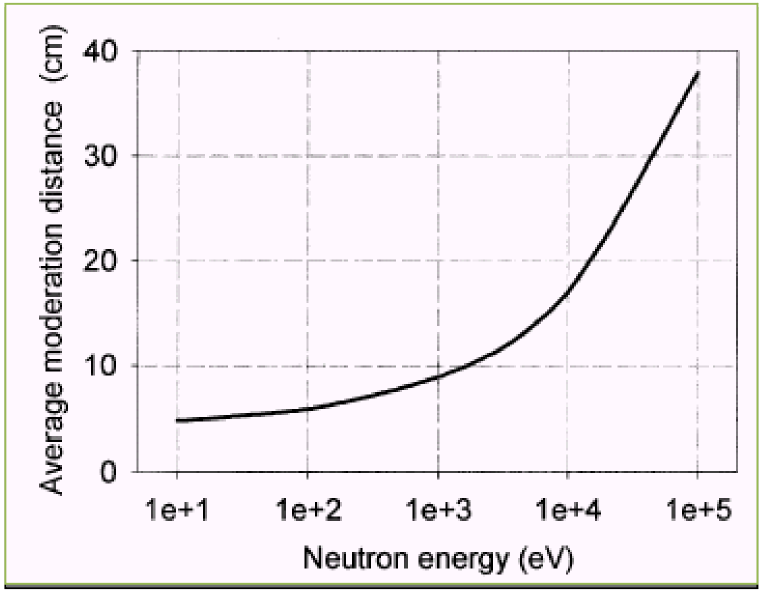



# Calibration of neutron energy in ToF measurements

The neutron energy (at low energy) is determined from the time-of-flight according to:

$$E = \left( \frac{72.2977 \cdot L}{ToF - T_c} \right)^2$$

**L** = flight path length
**ToF** = time of flight
$\mathbf{T_c}$=correction term



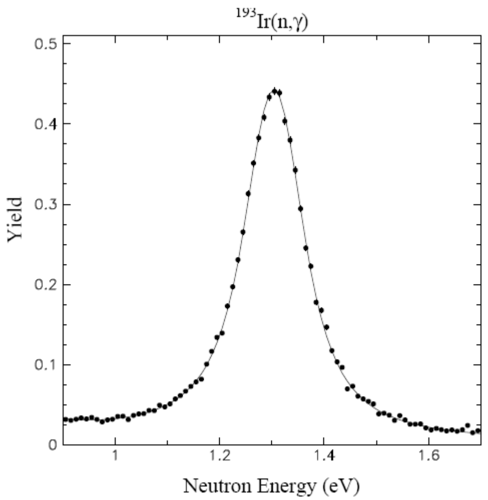

The "time-start" (or **physical reference**) for the time-of-flight is typically given by a **"prompt flash"** ($\gamma$-rays, high-energy charged particles, etc…).

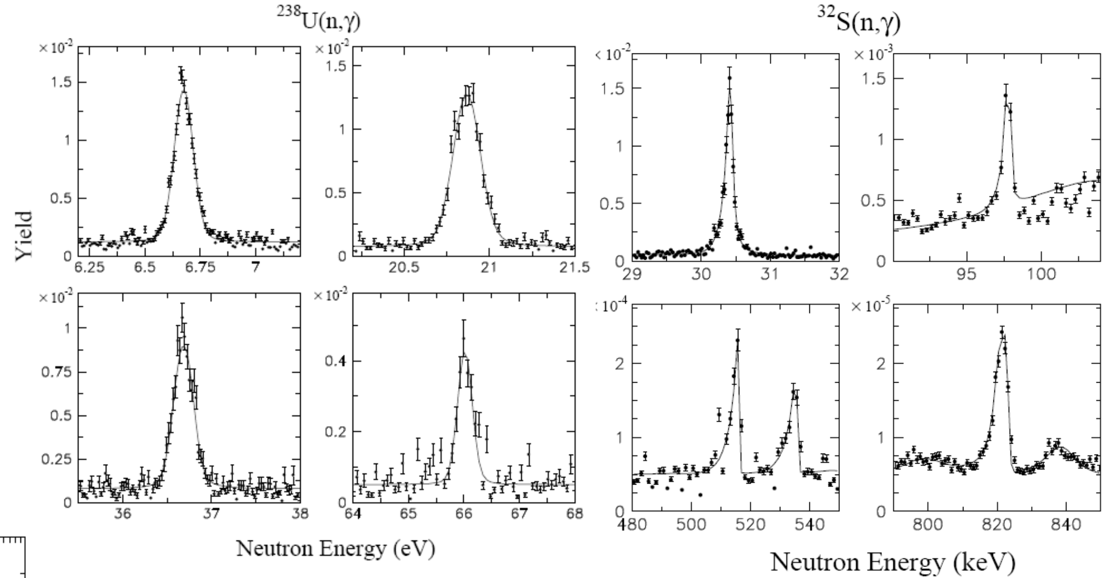
In **moderated** neutron beams, L does not coincide with the **geometric distance** from neutron source, since neutrons **travel** some distance inside the target/moderator.

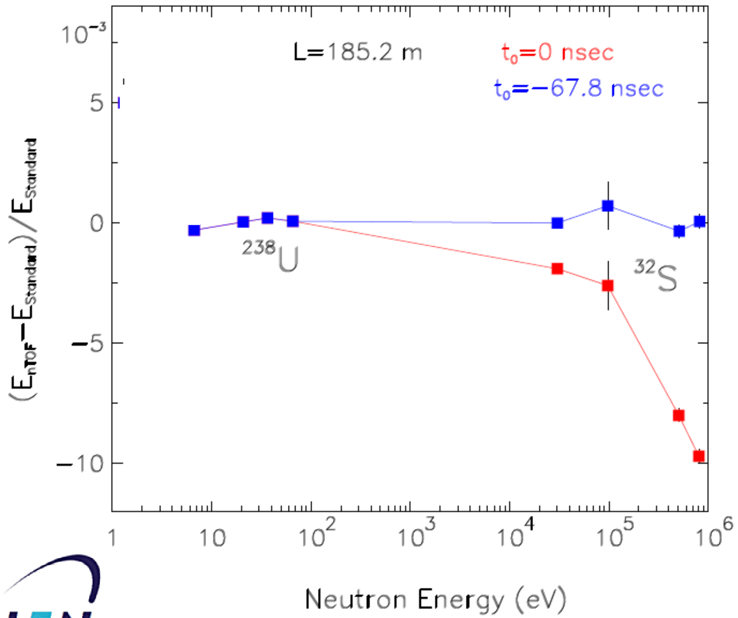
The "moderation distance" **v·t** depends on the neutron energy (t=moderation time).

Necessary to calibratate the neutron energy with respect to energy standards

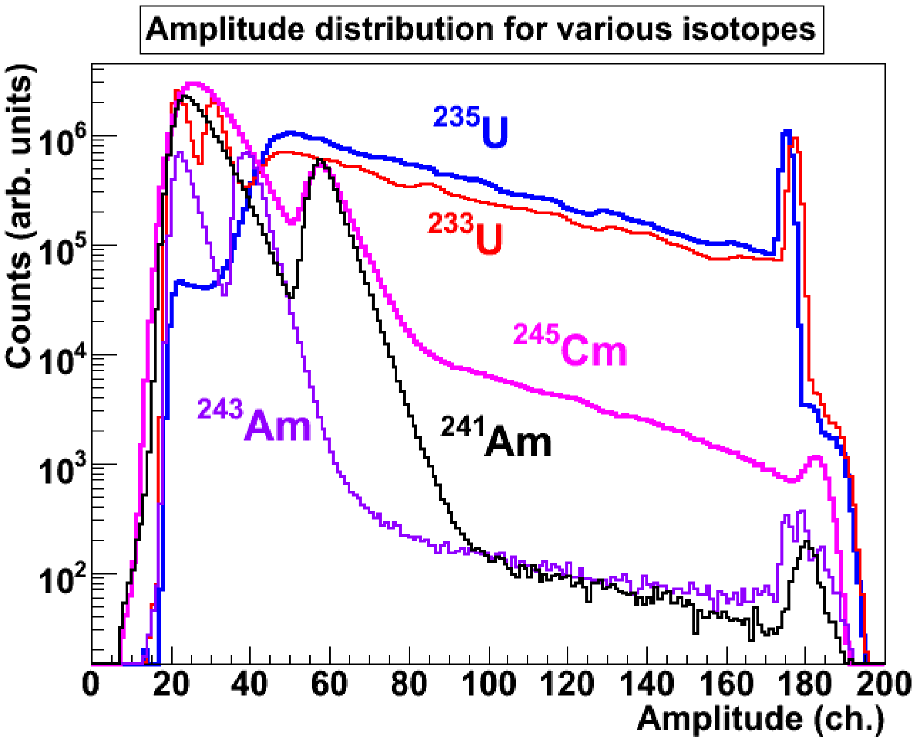
# Calibration of neutron energy in ToF measurements



# The pulse height distribution




First step of data analysis: determine the height of each recorded signal (amplitude).

Also determined area of the signal (proportional to energy deposited in the gas).

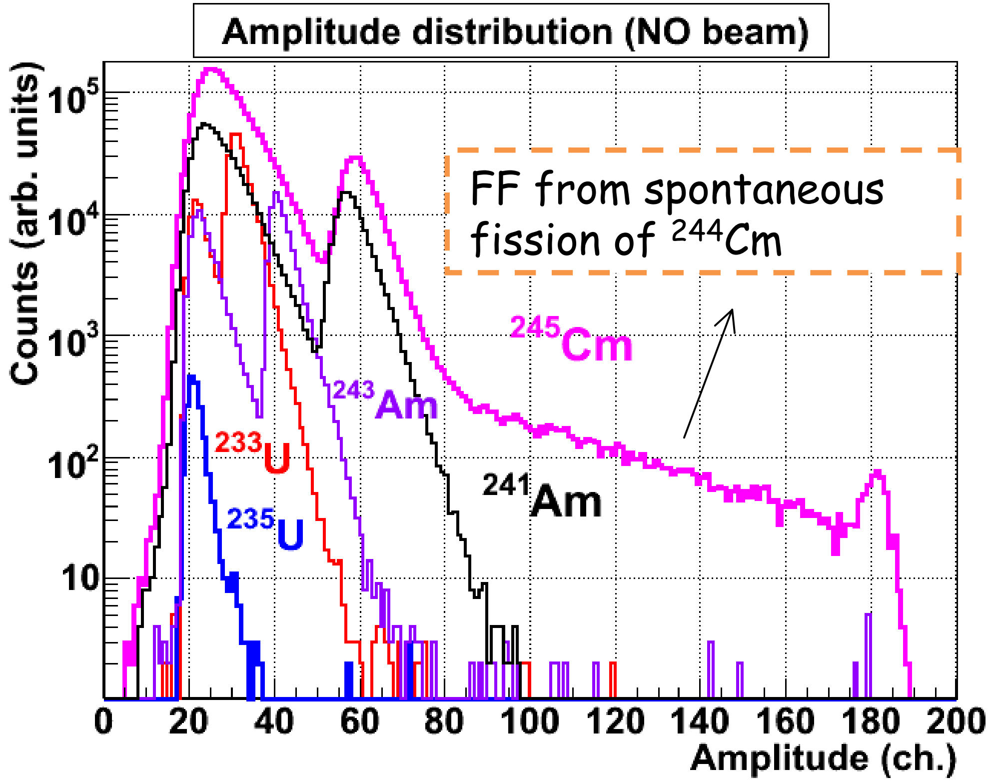
A distribution of the amplitude is constructed for different isotopes

Choose an appropriate threshold for background rejection

Notes: the $^{235}$U is virtually background-free, and the amplitude distribution is as expected from simulations of the energy deposited in the gas.

All other isotopes show a large $\alpha$-background (in some cases pile-up of $\alpha$-particles)

# Background determination and subtraction



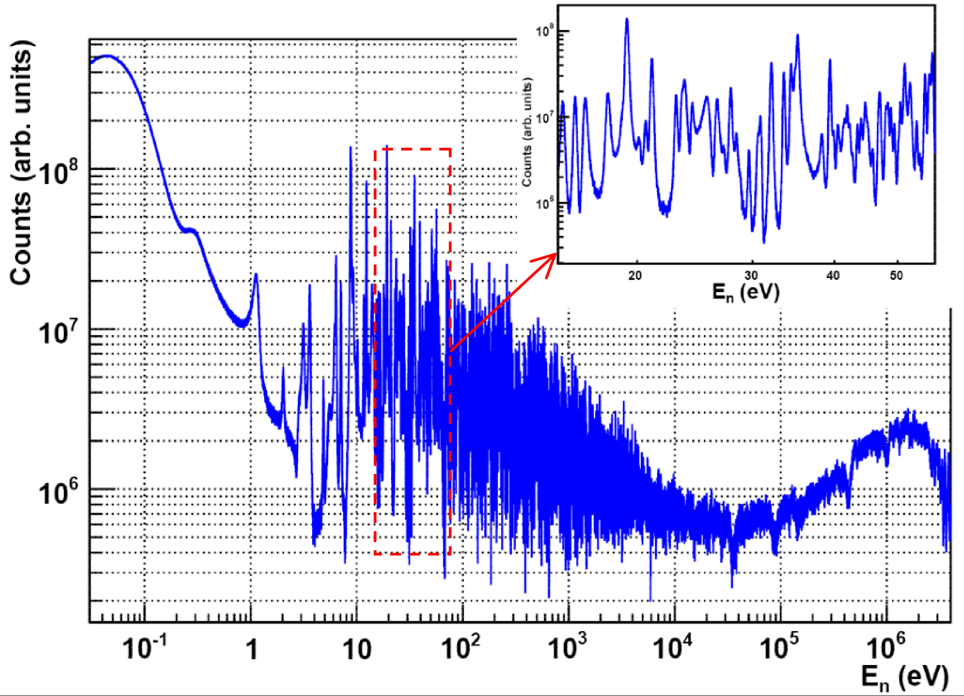

The background produced by electronic noise and a-decay can be estimated with measurement without the neutron beam.

It allows also to check presence of spontaneous fission

For some samples, the $\alpha$-background is very large, and extends at high amplitude, due to pile-up (this is the case of $^{241}$Am and $^{245}$Cm)

Threshold on amplitude is the primary method for $\alpha$-background and electronic noise rejection. However, for some isotopes, a large background is still present above threshold, and HAS TO BE SUBTRACTED

# The $^{235}U(n,f)$ reactions

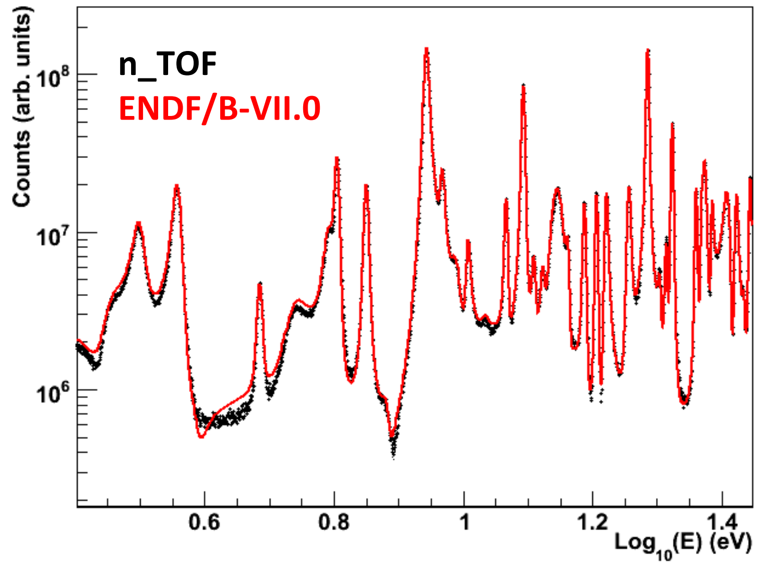



First reaction to be analysed.

Gives an idea of the background and energy resolution.

NOTE: complete energy range in ONE measurement only

$$C(E_n) = \sigma_f(E_n) \cdot \Phi(E_n) \cdot N_{^{235}U} \cdot \varepsilon \cdot cf$$




Few observations:

There is essentially no difference between n_TOF data and evaluated data.

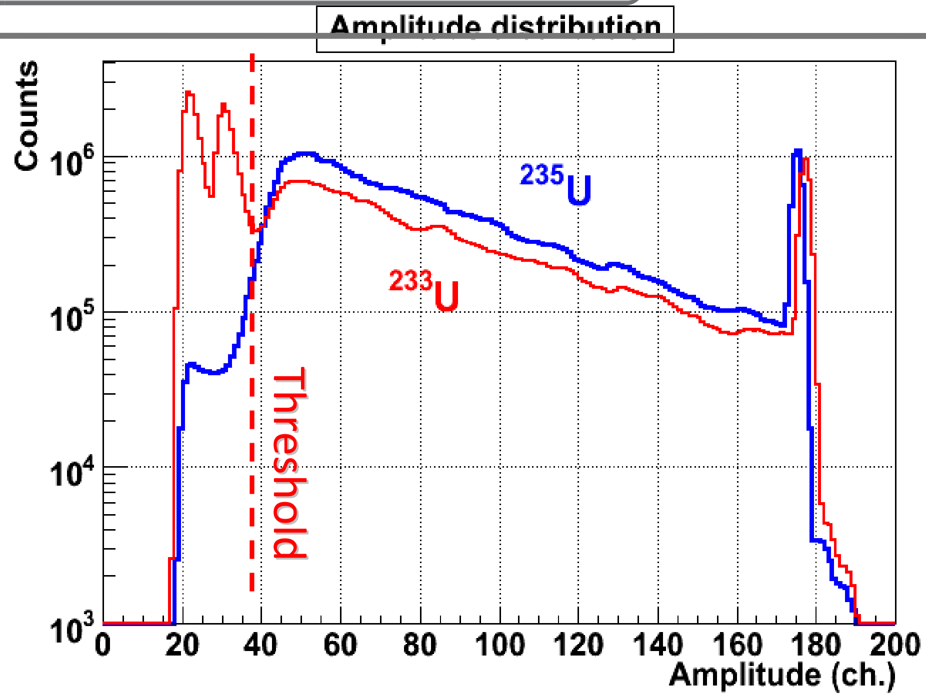
Good situation in terms of background and resolution

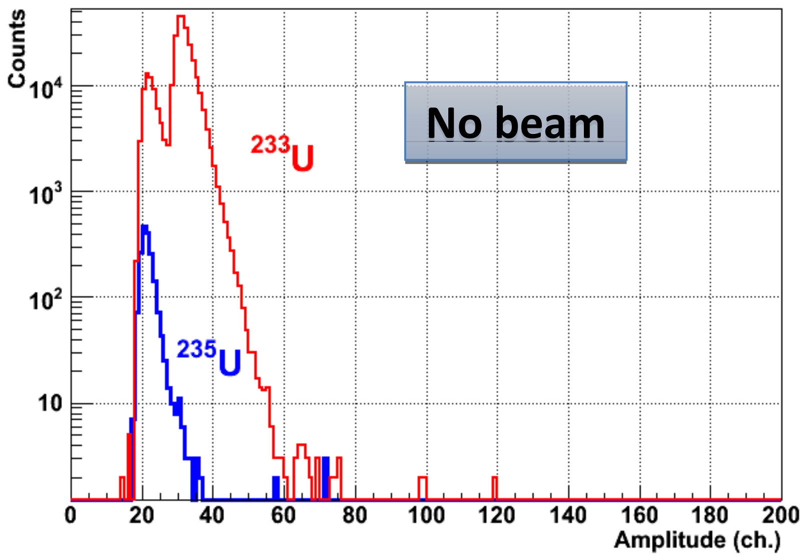
# The $^{233}U(n,f)$ reaction

$^{233}U$ has higher $\alpha$-background with respect to $^{235}U$

- **0.2 kBq** ($^{235}U$)
- **5 MBq** ($^{233}U$)

Threshold on amplitude important to reject background

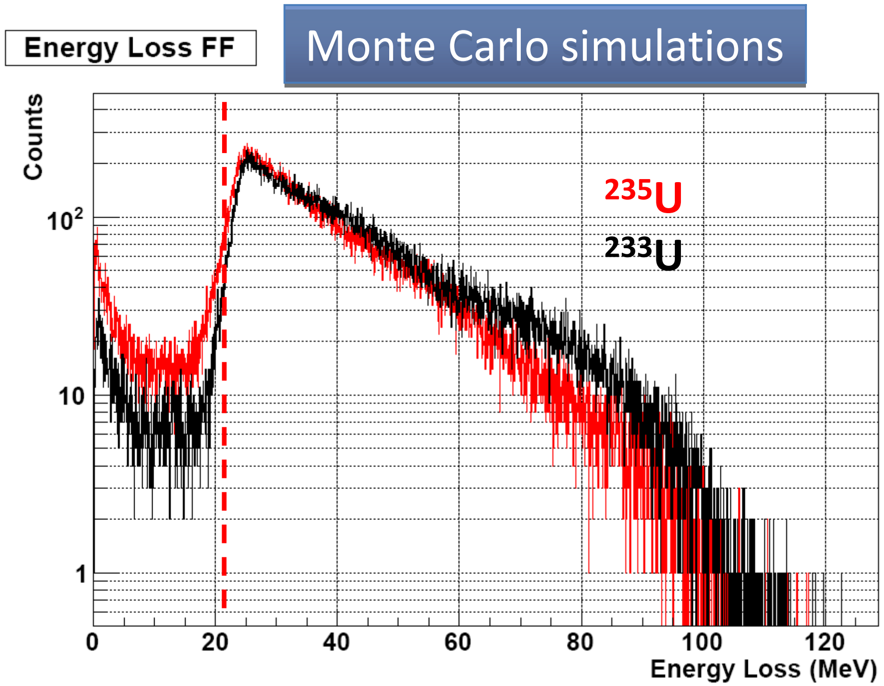



If same threshold is applied, in principle $^{233}U$ and $^{235}U$ should have the same efficiency.

In reality it is not so, because the target thickness is different

# The $^{233}U(n,f)$ reaction




$^{233}U$ is a thinner target than 235U

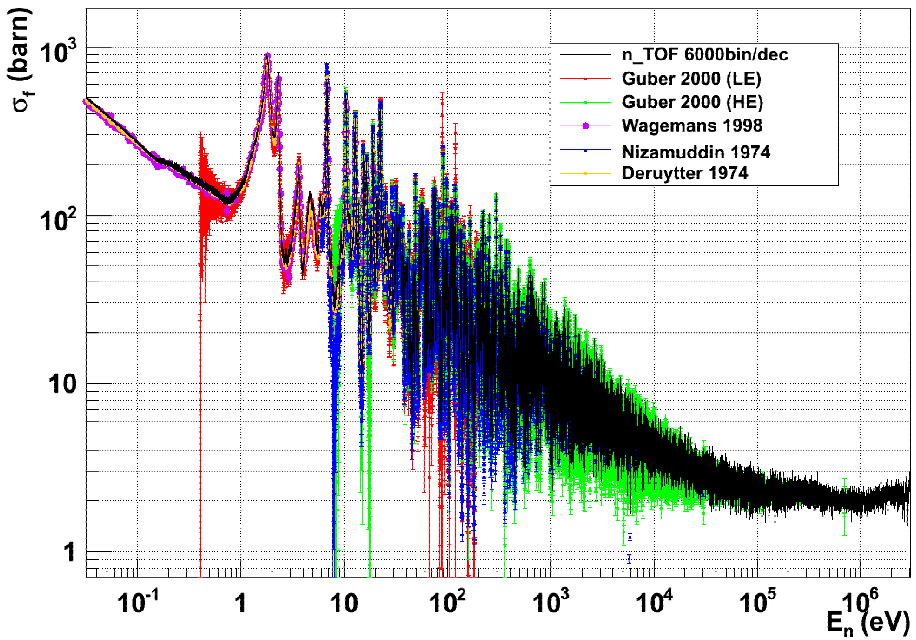
Fewer fragments are stopped inside the sample or come out with energy below threshold

Difference in detection efficiency of 3 %

If accuracies of few percent is required, small effects (like differences in efficiency due to different target thickness), may affect the uncertainty.

Such effects can only be estimated with very realistic Monte Carlo simulations.

# The $^{233}U(n,f)$ reaction at n_TOF

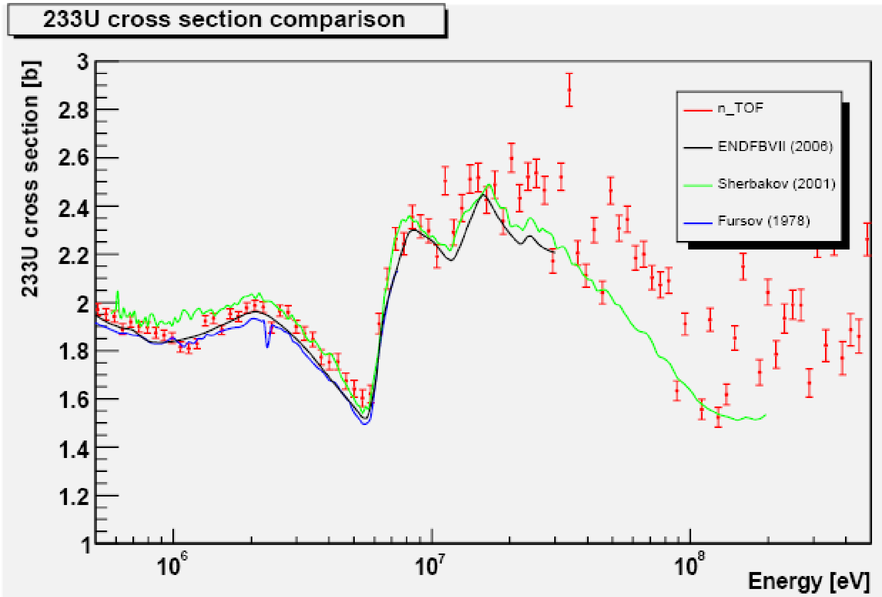



M. Calviani et al., **ND 2007** e **Phys. Rev. C**, in preparazione

Fission cross-sections measured for the first time **simultaneously** from thermal energy to 500 MeV.

Reached **accuracy** ~ 3 %

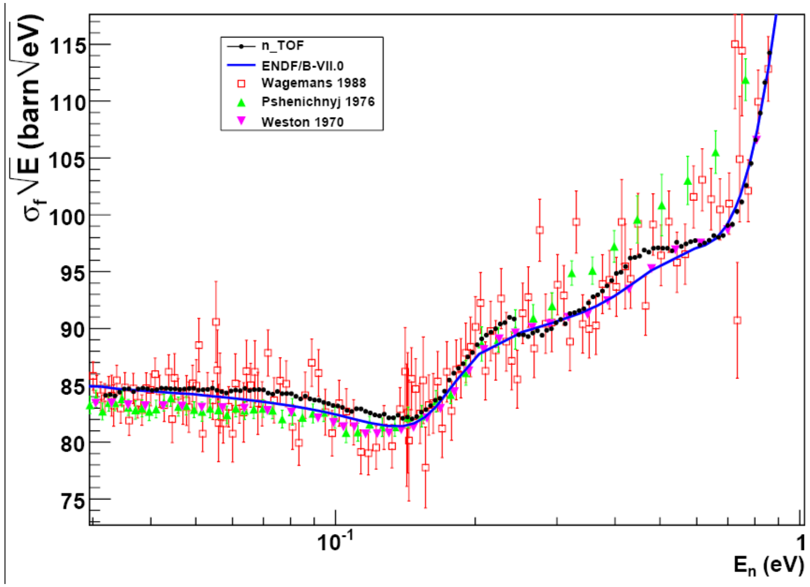
**Risolved** resonance region extended up to 10 keV

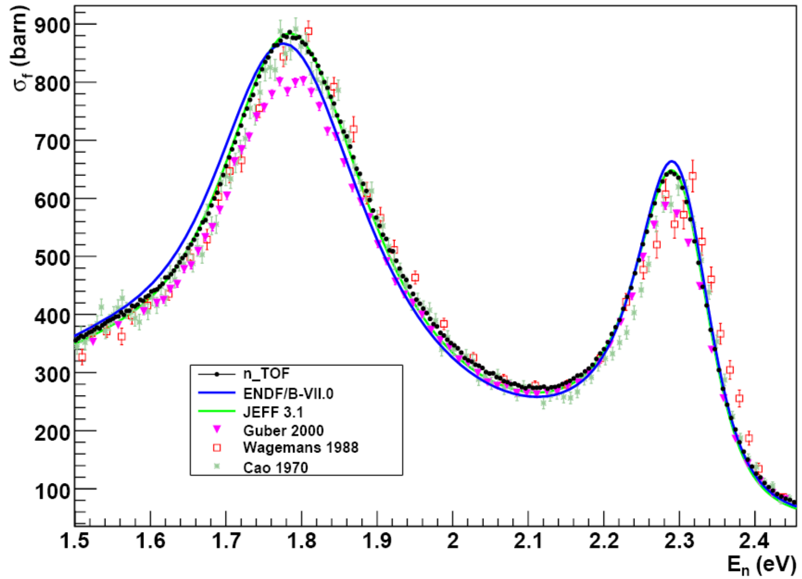


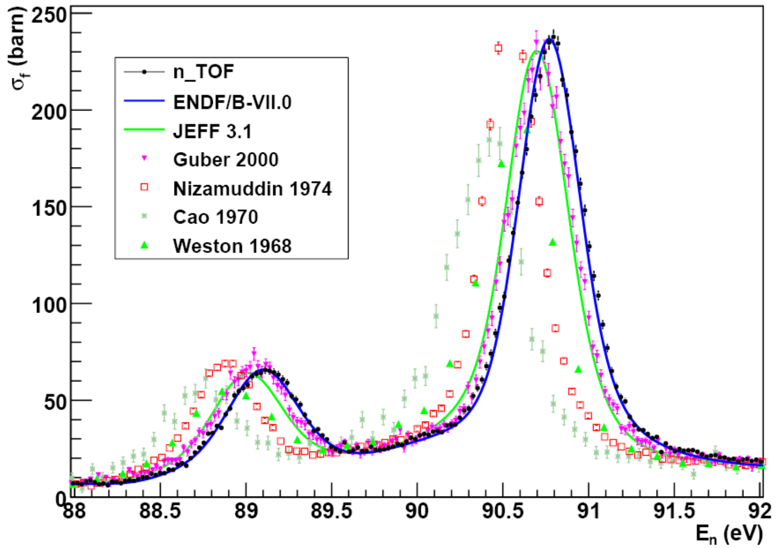

Important new data for advanced reactor technology (U/Th fuel cycle).

F. Belloni et al., **Nucl. Sci. Eng.**, in preparazione

# The $^{233}$U(n,f) reaction: the RRR



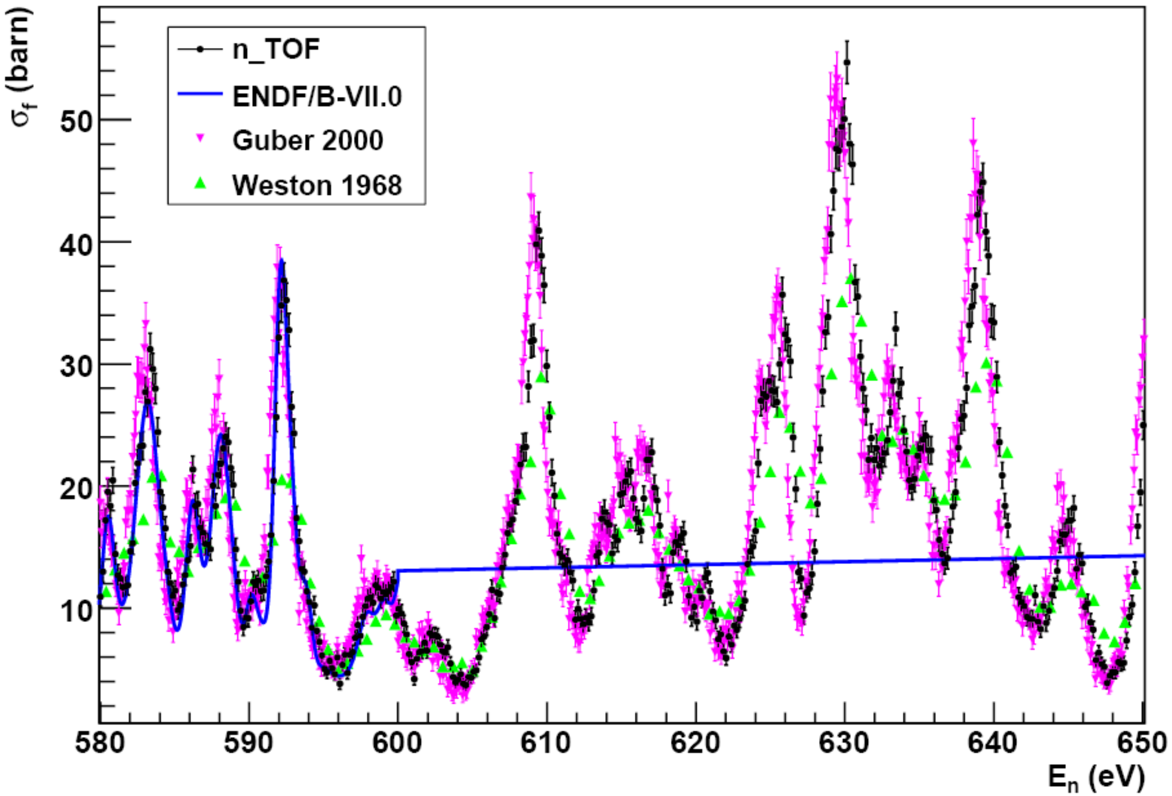




In general, at low energy, current databases seem to work pretty well.

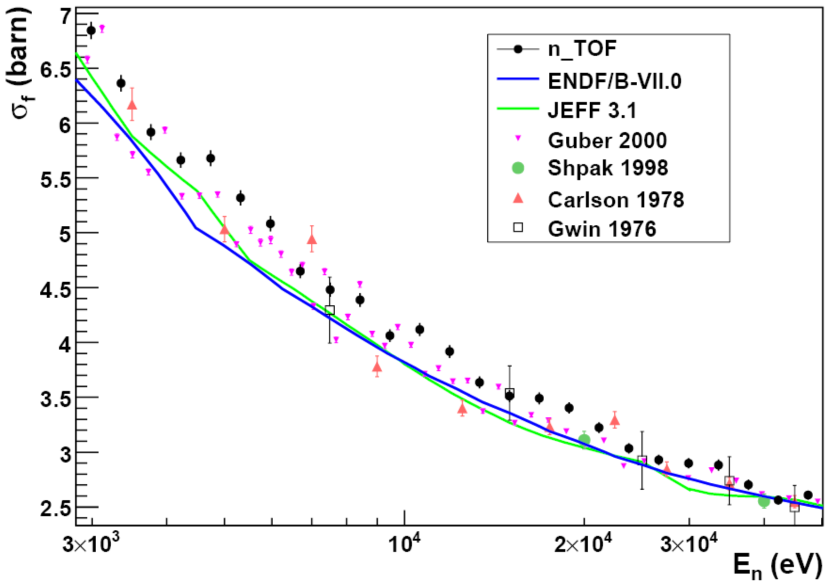
Few details need to be considered, such as energy and strength of individual resonances.

# The $^{233}U(n,f)$ reaction: the RRR




The recent data (Guber 2000 and n_TOF) can extend Resolved Resonance Region, thanks to better resolution.
Important for self-shielding calculations in reactors based on U/Th fuel cycle

# The $^{233}U(n,f)$ reaction: the URR

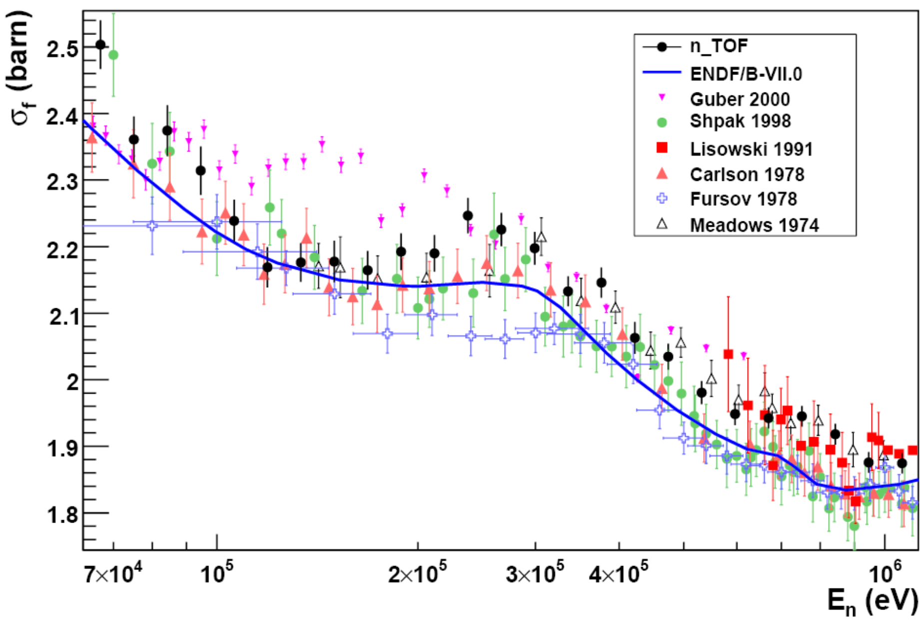



In the Unresolved Resonance Region and at higher energy, databases systematically underestimate cross-section.

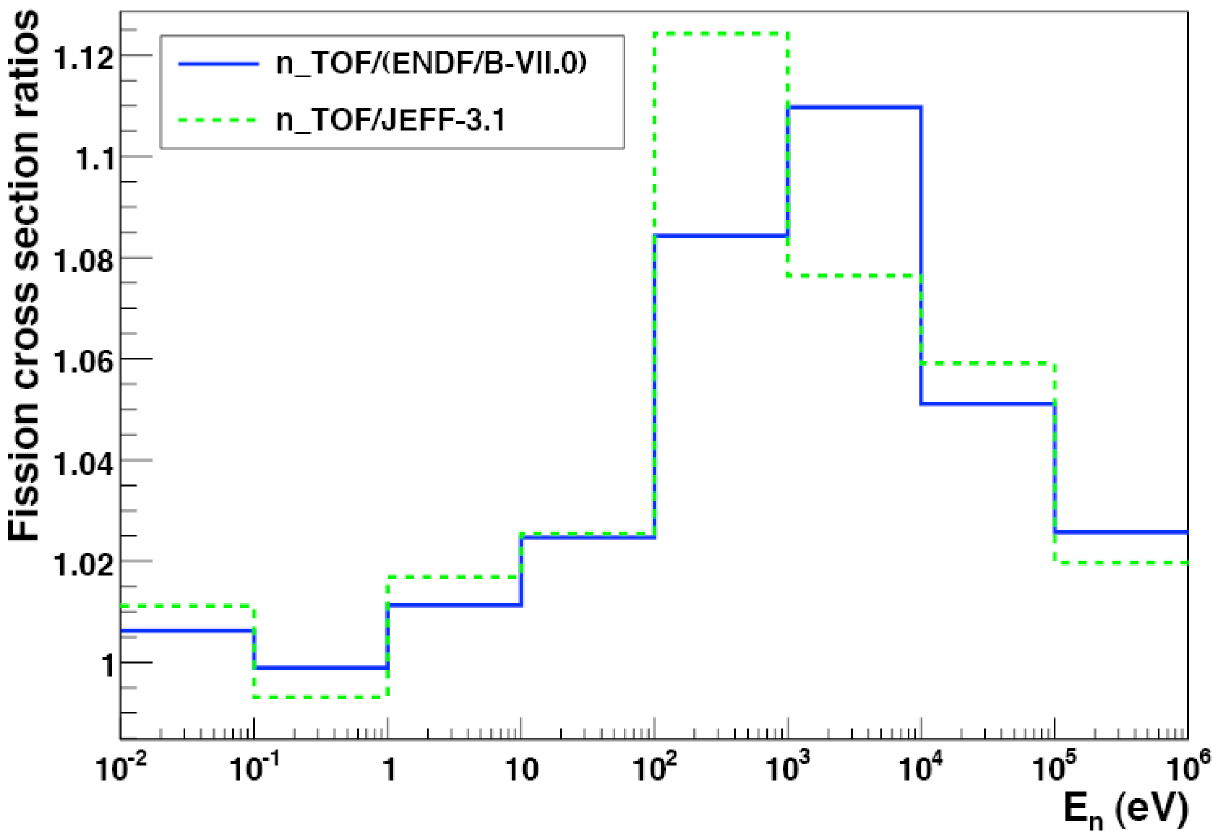
The effect is NOT negligible

There seems to be a problem with the evaluations:

- based on an old measurement
- all other ones are higher (similarly to n_TOF)



# The $^{233}$U(n,f) reaction: group cross-sections

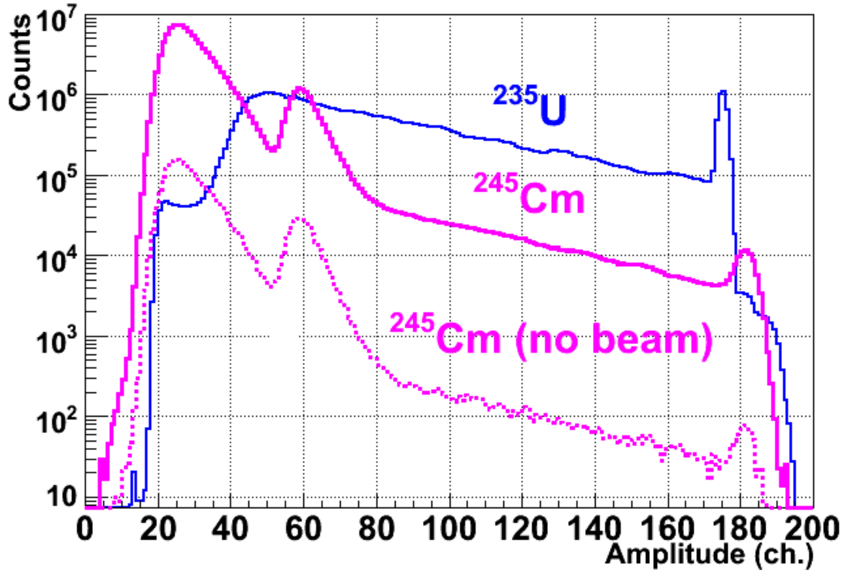



At thermal energy, agreement between data and evaluated libraries within 1 % !!

At high energy, evaluated cross-section are underestimated by up to 12 % !!

Typical example of importance of accurate new data in the whole energy region.

# The $^{245}Cm(n,f)$ reaction at n_TOF



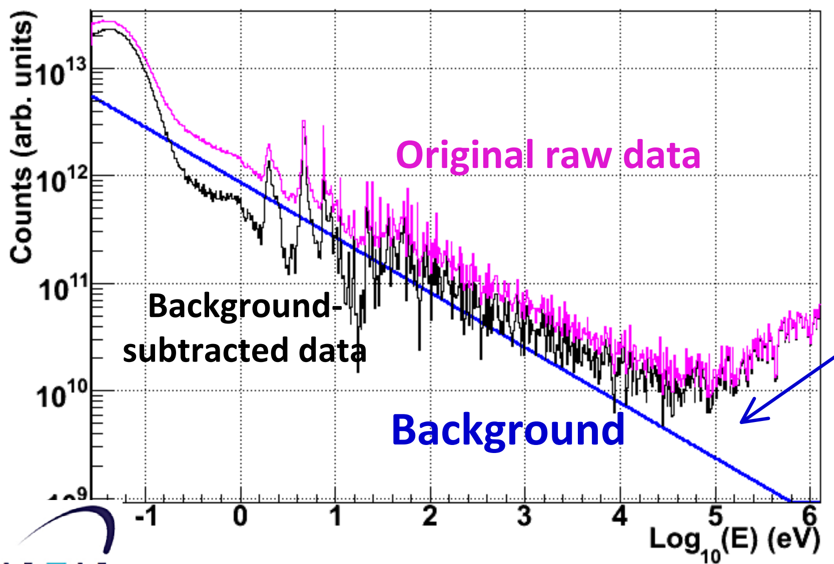

$^{245}Cm$ + 6.6% $^{244}Cm$ contamination

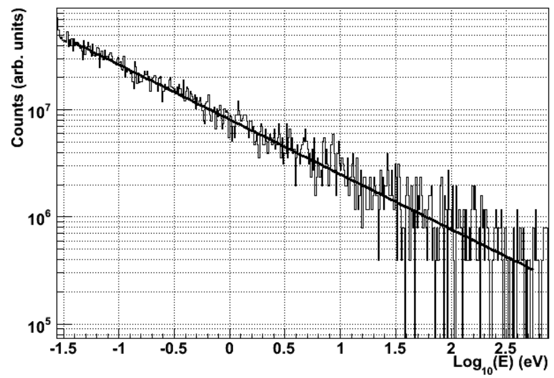
- **0.4 GBq** activity

Very large $\alpha$ background

Spontaneous fission background from $^{244}Cm$

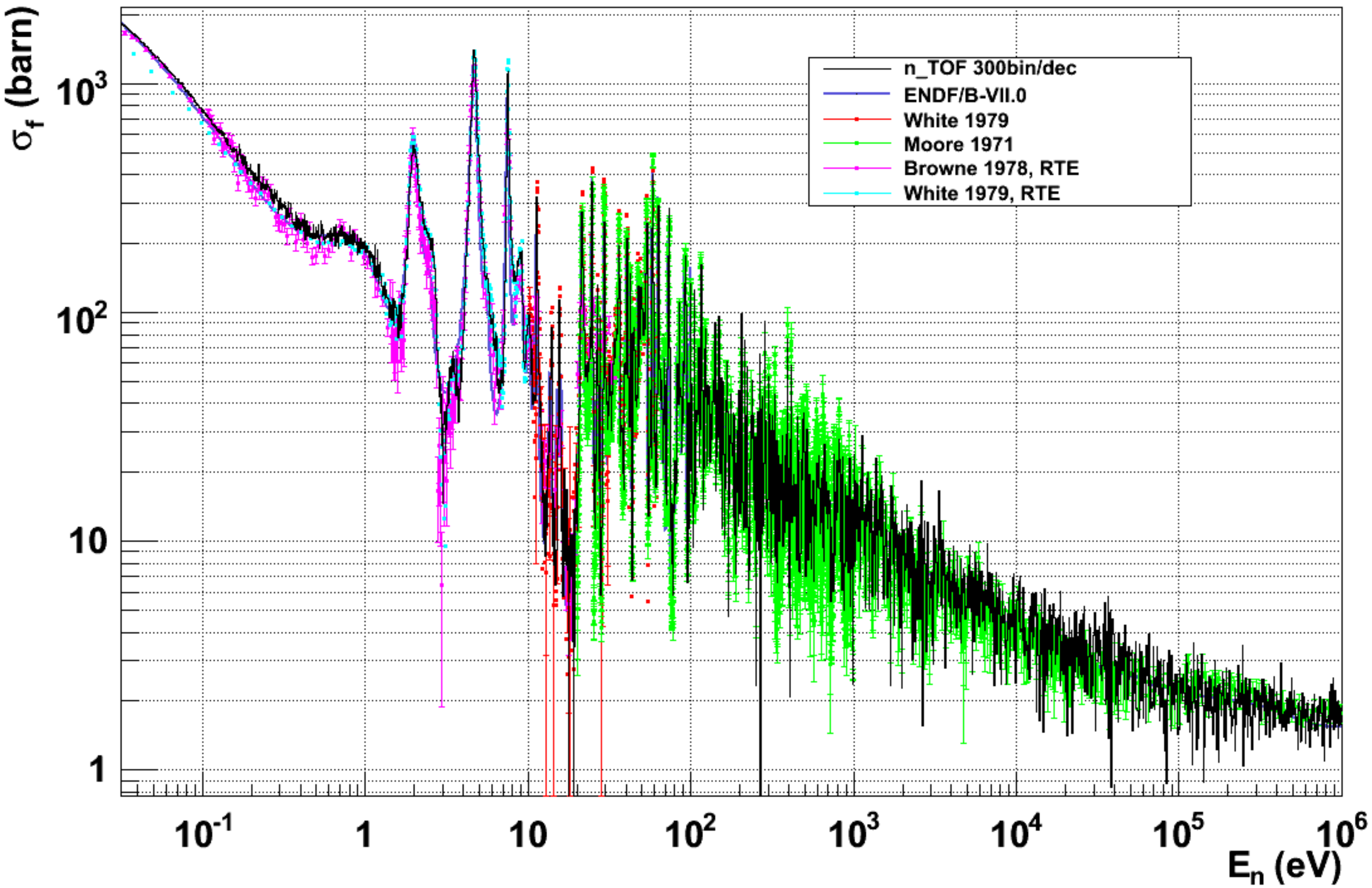
Due to the $\alpha$ pile-up a higher threshold must be applied (with the corresponding efficiency correction)



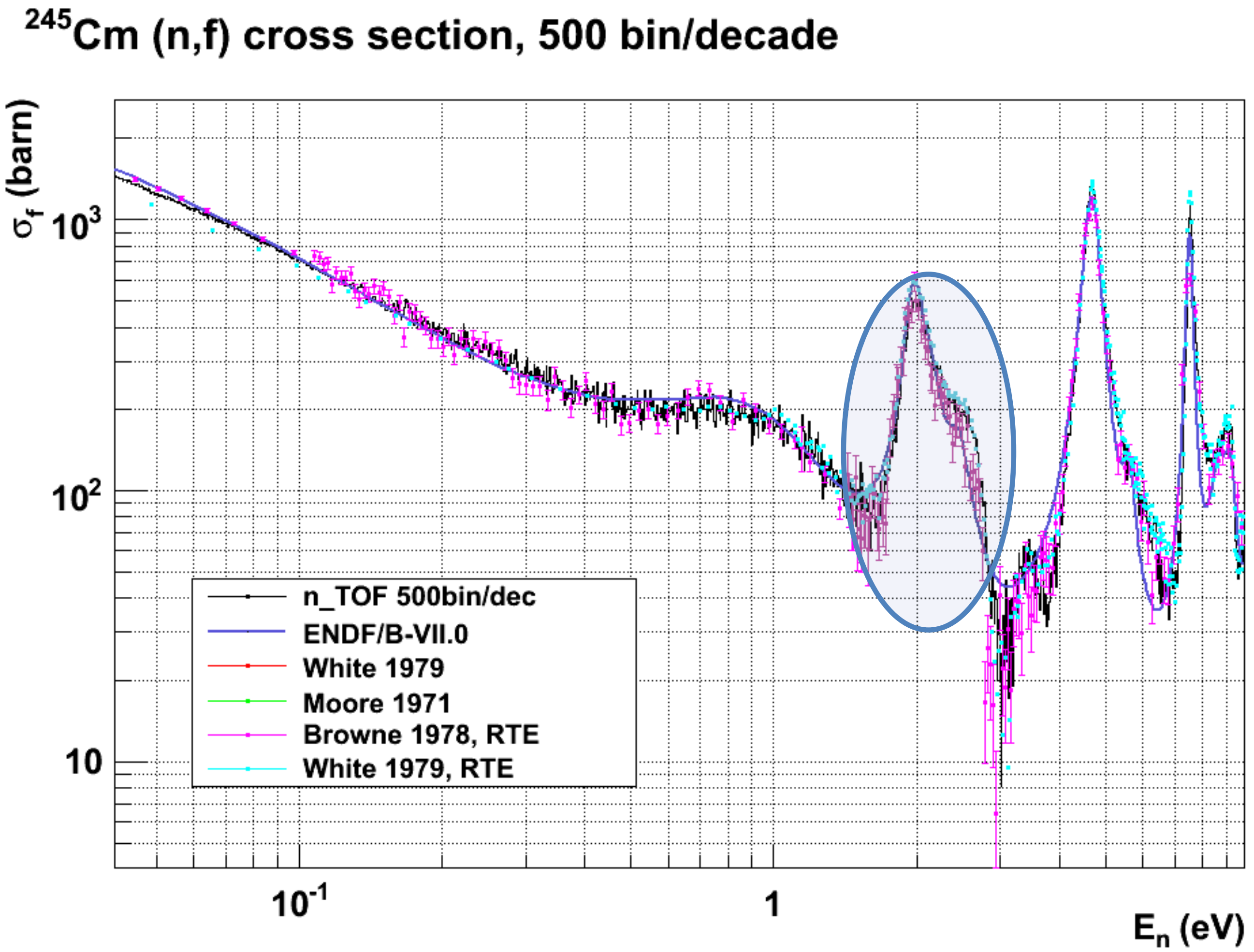

Residual $\alpha$ and SF background estimated with no beam runs

# The results of $^{245}$Cm(n,f) at low energy




Fission measurement on $^{245}$Cm at n_TOF among the most **accurate and complete** (unique measurement in a large energy range).

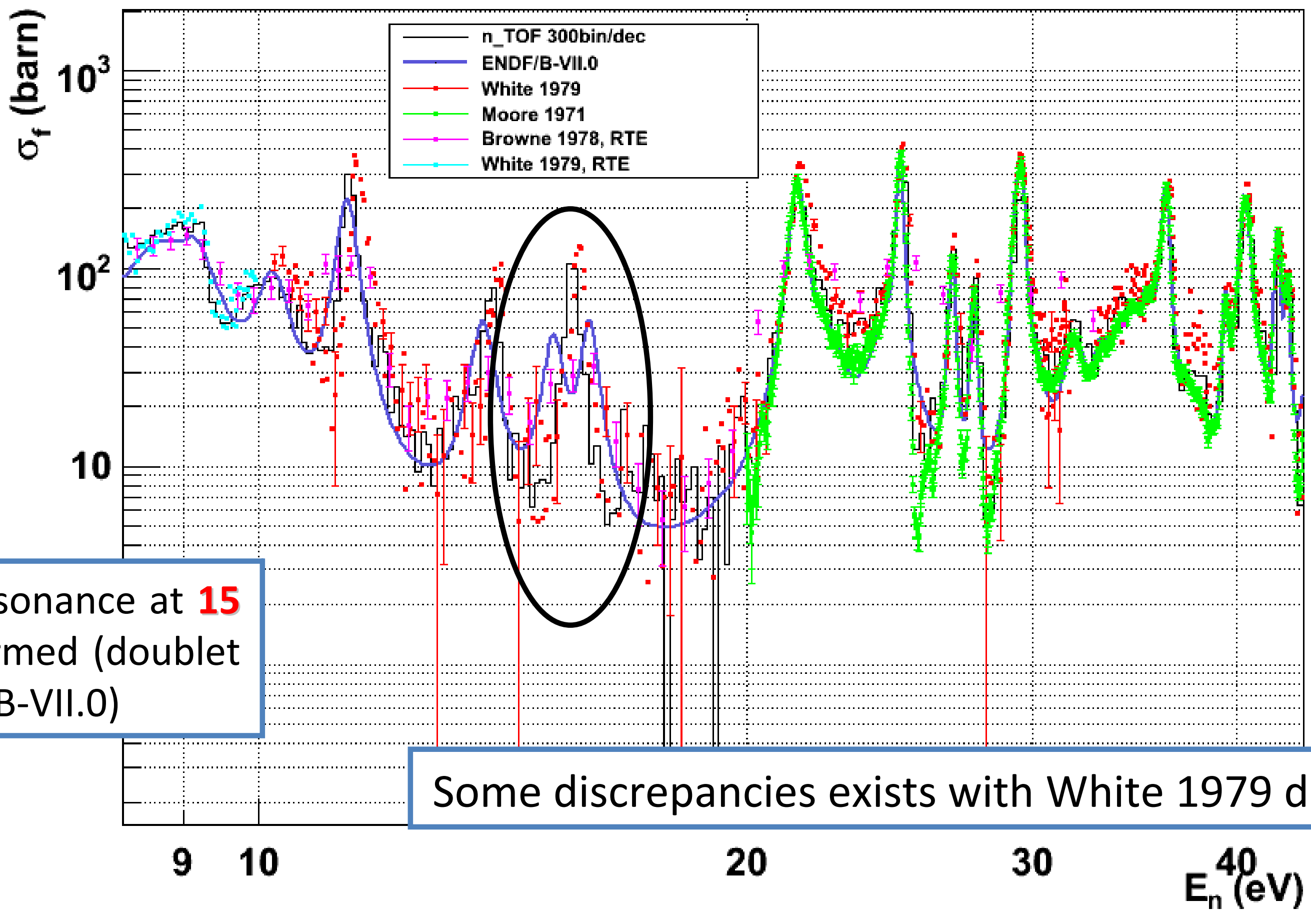
# Comparison with previous data




Resonance shoulder (from 2 eV to 5 eV) higher than ENDF/B-VII.0
Good agreement with previous data

# Comparison with previous data (2)

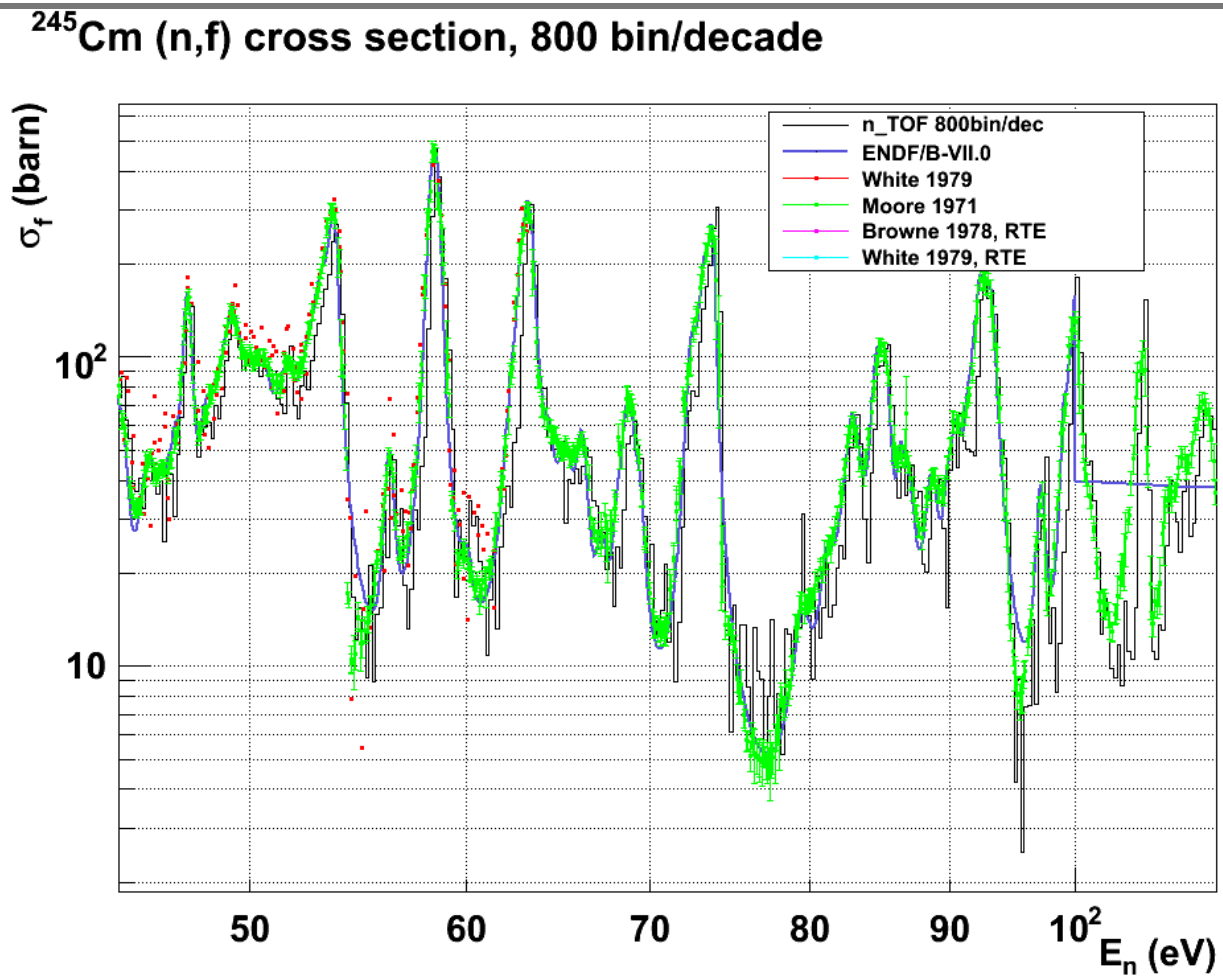
$^{245}$Cm (n,f) cross section, 300 bin/decade




Single resonance at **15 eV** confirmed (doublet in ENDF/B-VII.0)

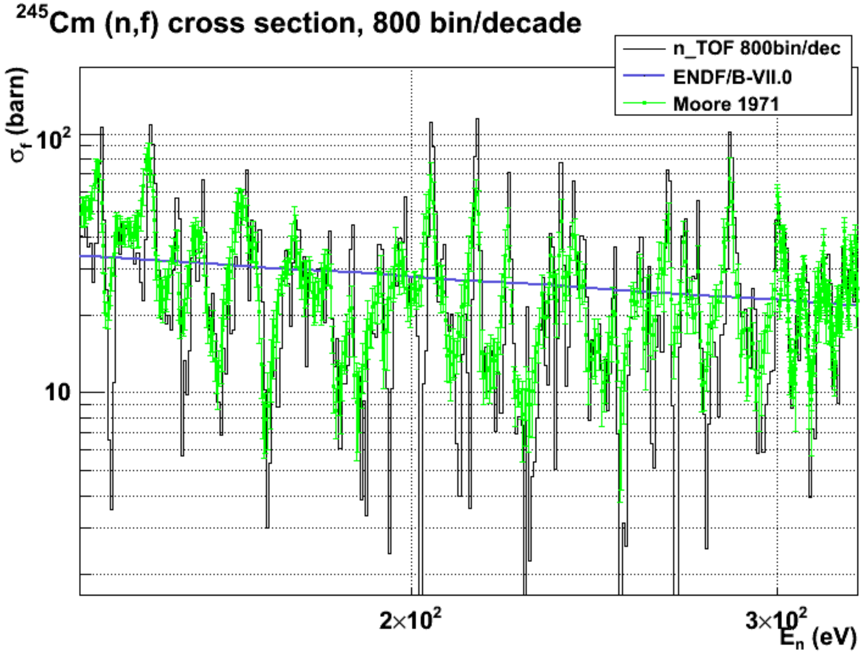
Some discrepancies exists with White 1979 data

# Comparison with previous data (3)



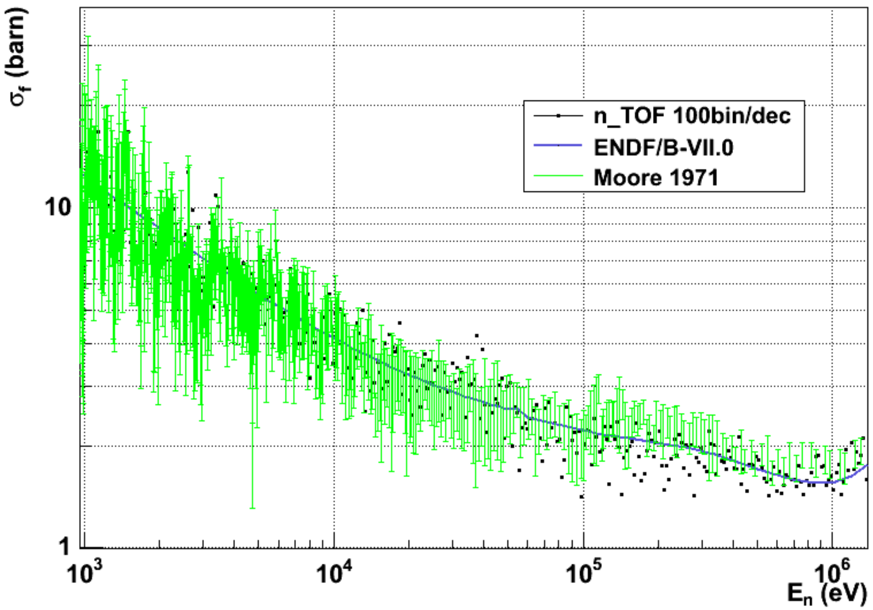

• Resolution similar to Moore et al. (on which ENDF/B-VII.0 is based)

# The $^{245}Cm(n,f)$ reaction: high energy



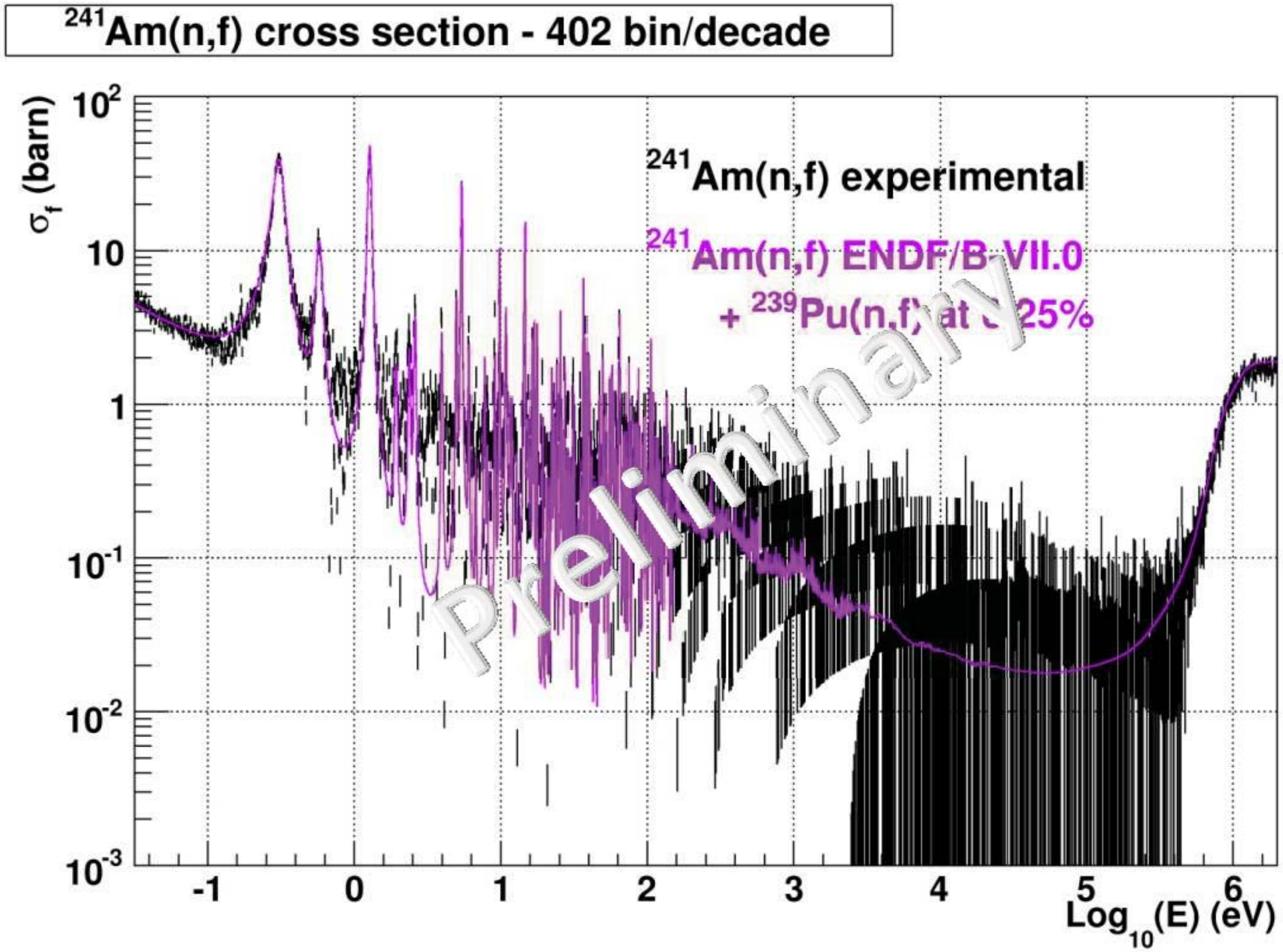

In the case of $^{245}$Cm, at n_TOF able to resolve resonances up to 500 eV (ENDF/B-VII.0 RRR ends at 100 eV)

Unresolved Resonance Region

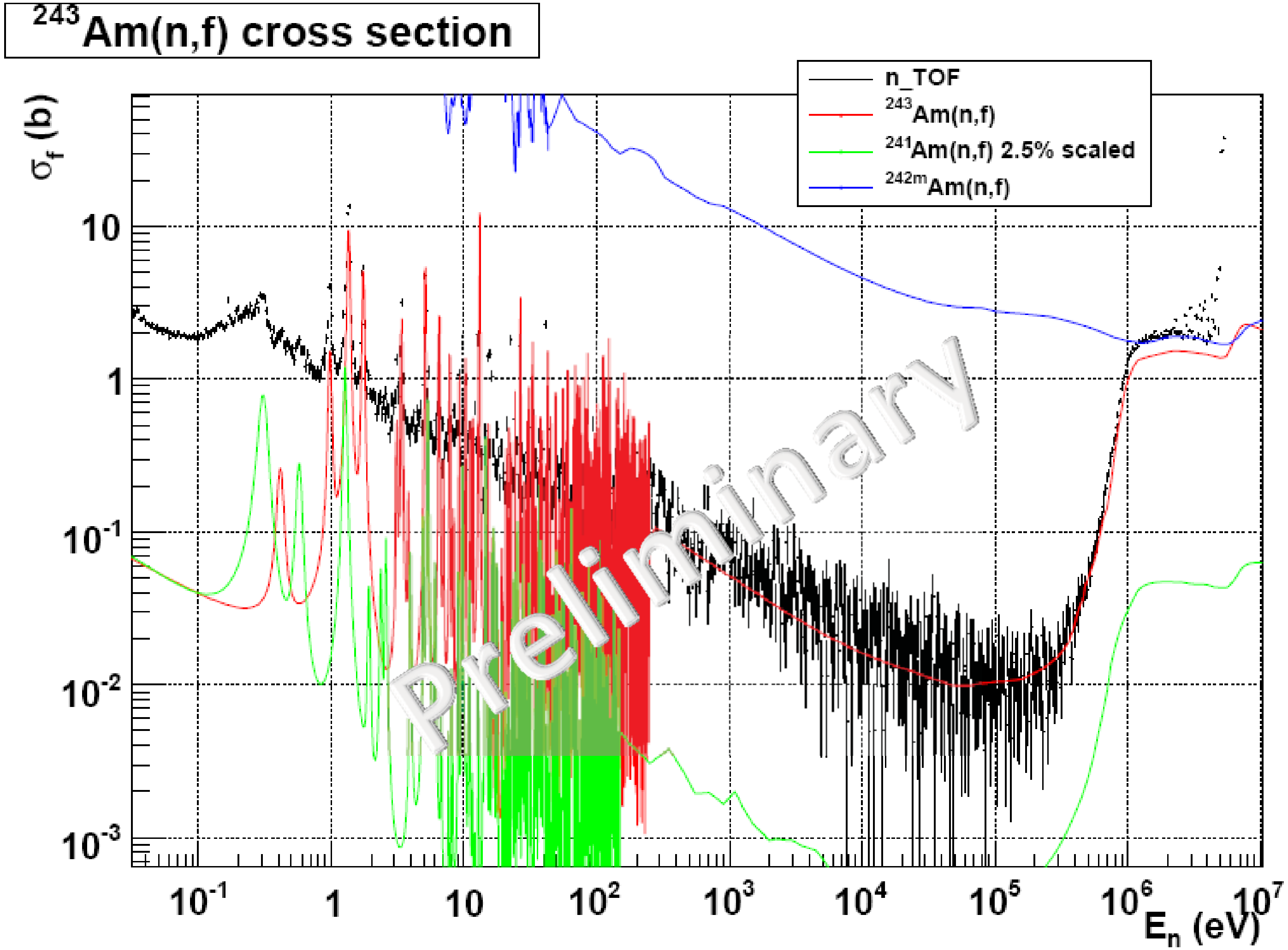



In the Unresolved Resonance Region, n_TOF data confirm recent ENDF/B-VII.0 evaluation

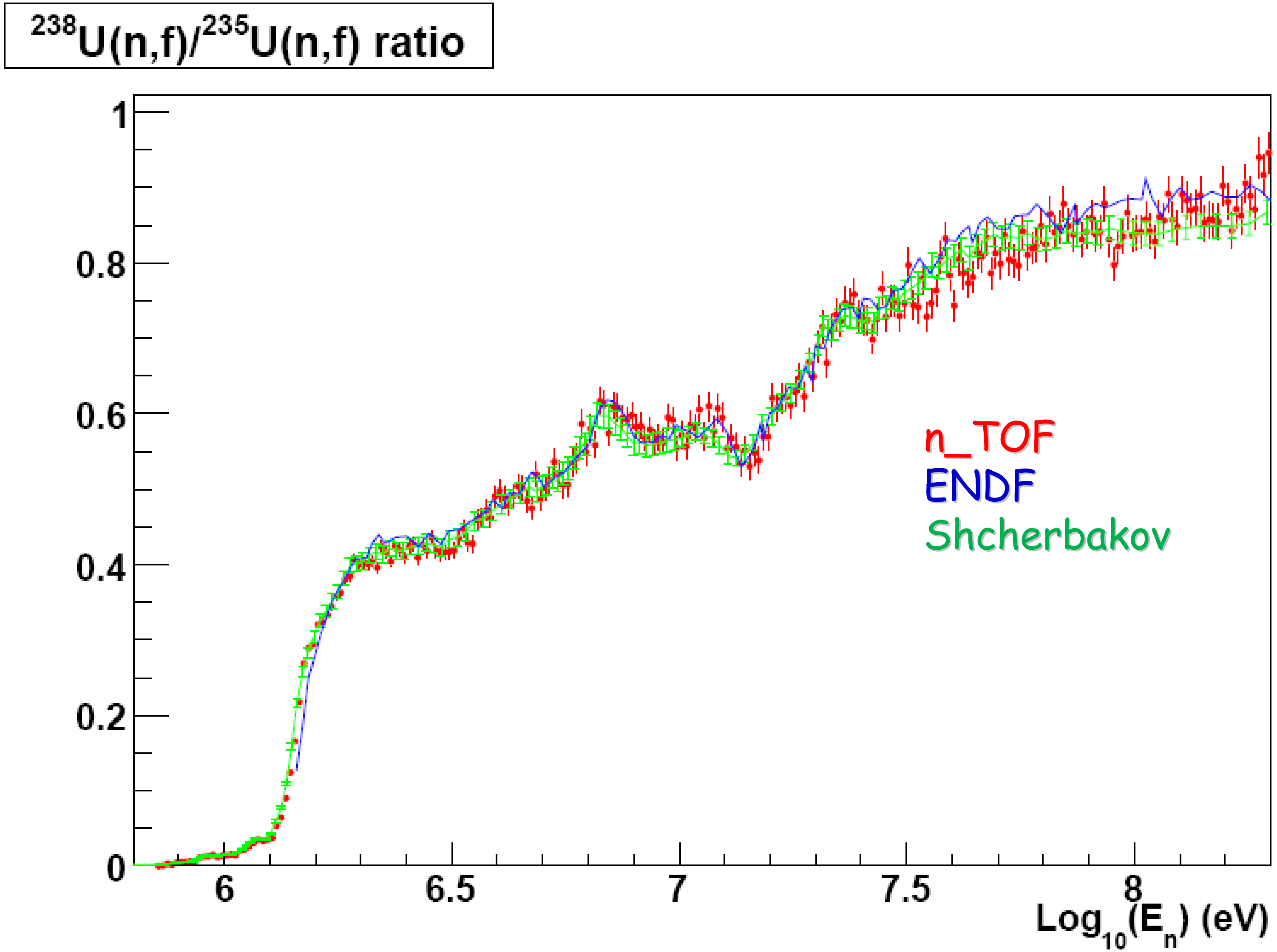
# The $^{241}$Am(n,f) reaction at n_TOF



# The $^{243}$Am(n,f) reaction at n_TOF

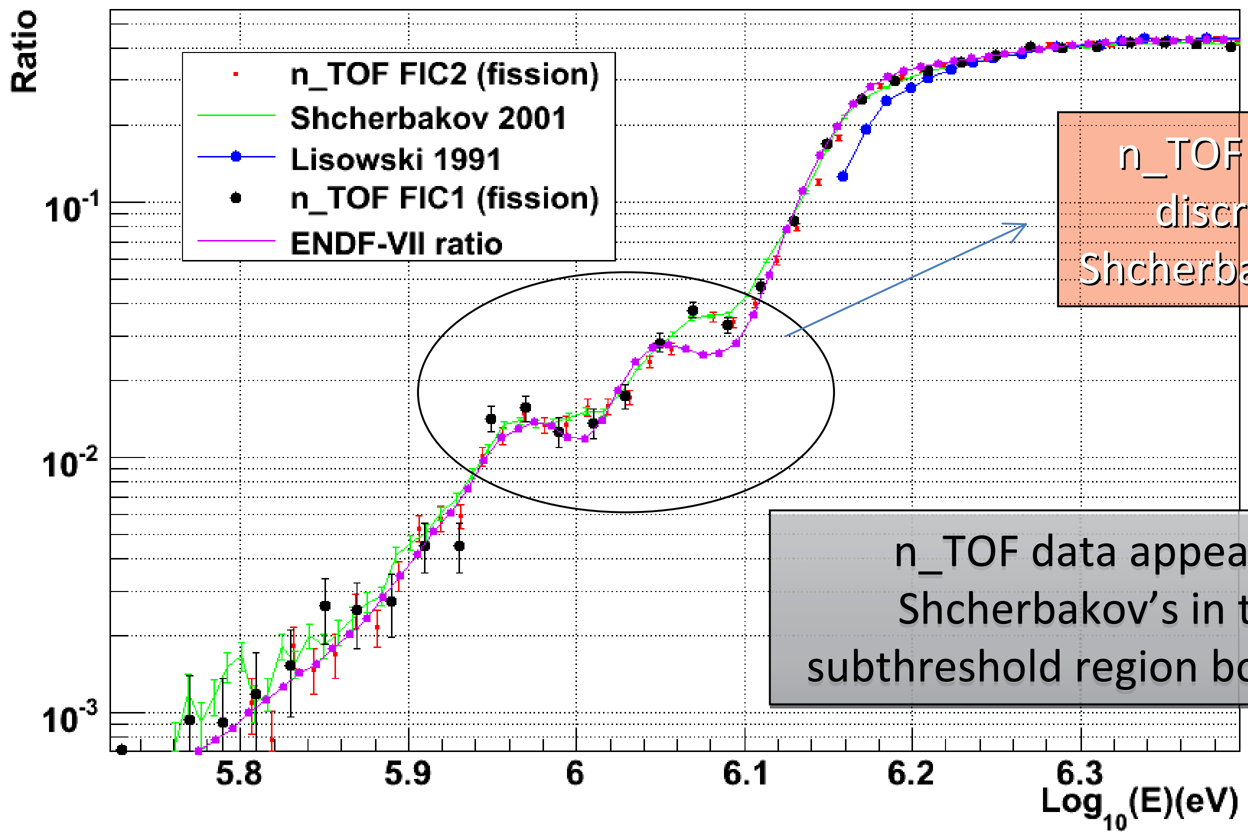


# The $^{238}U(n,f)/^{235}U(n,f)$ cross-section ratio



# The $^{238}U(n,f)/^{235}U(n,f)$ ratio

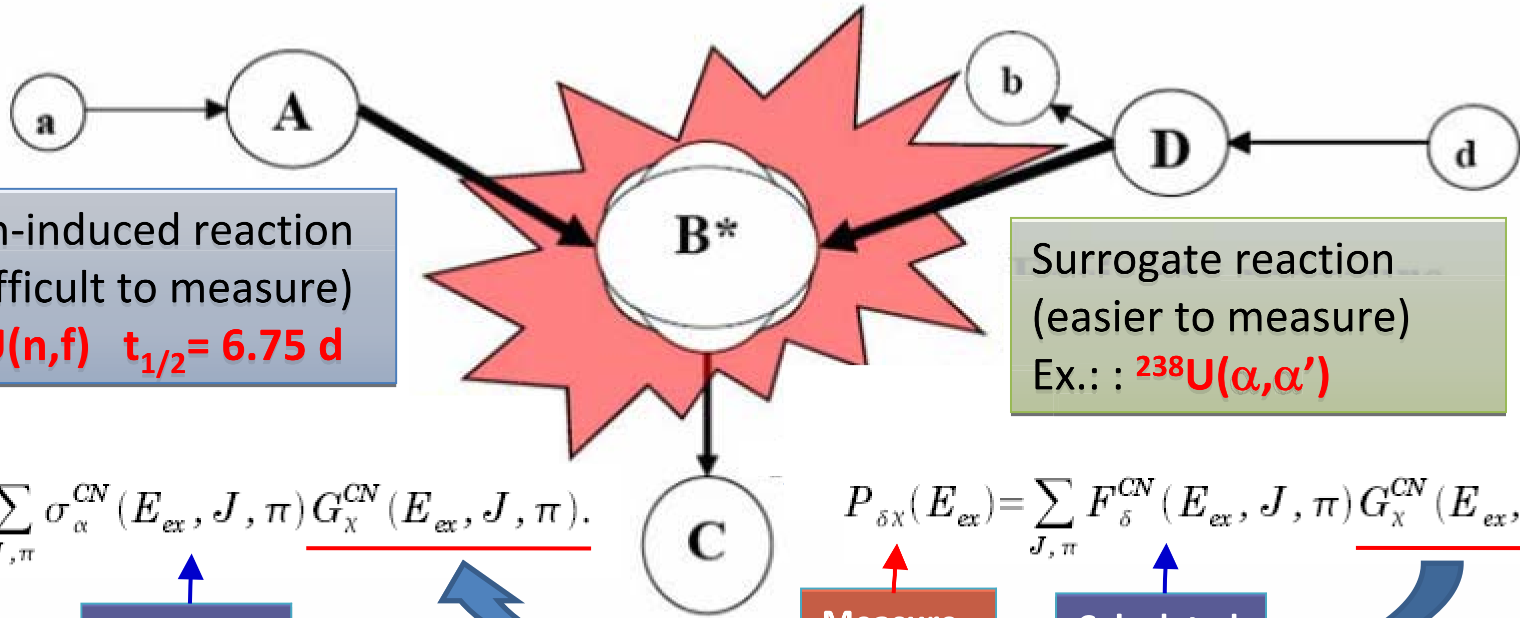
(sub) threshold region




n_TOF data confirms some discrepancies between Shcherbakov and ENDF/B-VII.0

n_TOF data appears to be similar to Shcherbakov's in the threshold and subthreshold region both in shape and value

# The surrogate method




Neutron-induced reaction
(very difficult to measure)
Ex.: $^{237}U(n,f)$   $t_{1/2} = 6.75$ d

Surrogate reaction
(easier to measure)
Ex.: : $^{238}U(\alpha,\alpha')$

$$\sigma_{\alpha\chi}(E_a)=\sum_{J,\pi}\sigma_{\alpha}^{CN}(E_{ex},J,\pi)\,G_{\chi}^{CN}(E_{ex},J,\pi).$$

Calculated

$$P_{\delta\chi}(E_{ex})=\sum_{J,\pi}F_{\delta}^{CN}(E_{ex},J,\pi)\,G_{\chi}^{CN}(E_{ex},J,\pi)$$

Measure

Calculated

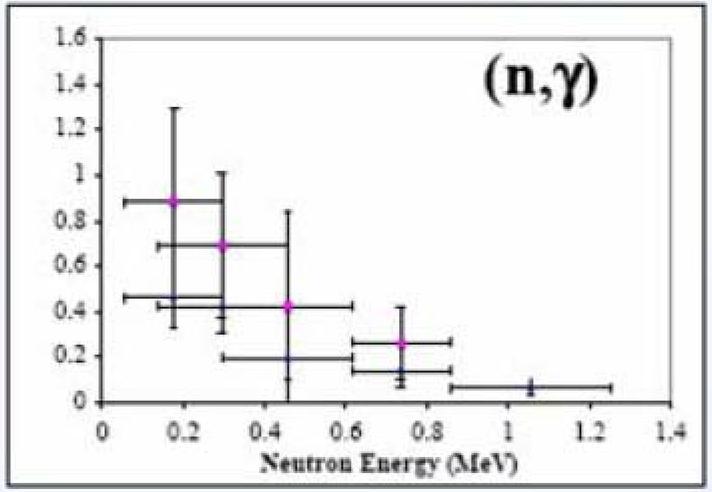
A surrogate reaction is a reaction that leads to the **same Compound Nucleus** as the neutron-induced reaction.

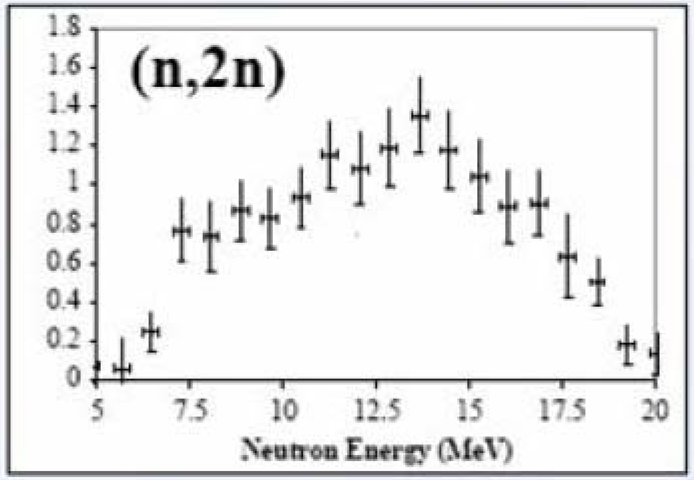
Basic assumption: the **formation** and **decay** of CN are **independent** on each other.

In a surrogate reaction, the Compound Nucleus can be selected by detecting the outgoing particle (b) in coincidence with the products of CN decay.

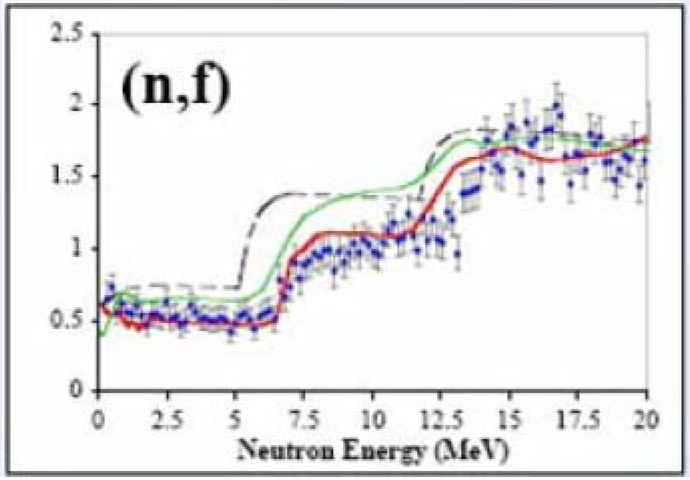
# The surrogate method

Surrogate reaction: $^{238}U(\alpha,\alpha')$ at $E_\alpha$= 55 MeV (PRC 73, 054605, 2006)




1. Direct cross section measurement for $^{237}U$ is difficult because of the short half-life, 6.75 d
2. Using the surrogate technique, reaction cross sections for the (n,γ), (n,2n), and (n,f) channels can be determined with an accuracy of 10 – 30%



# The surrogate method

Fission cross-sections that can be possibly studied with surrogate reactions:

| | |
|---|---|
| $^{237}Np(n,f)$ | $^{238}U(^{3}He,t)^{238}Np$ |
| $^{236}U(n,f)$ | $^{238}U(^{3}He,\alpha)^{237}U$ |
| $^{242}Cm(n,f)$ | $^{243}Am(^{3}He,t)^{243}Cm$ |
| $^{243}Cm(n,f)$ | $^{243}Am(^{3}He,d)^{244}Cm$ |
| $^{244}Cm(n,f)$ | $^{243}Am(^{3}He,p)^{245}Cm$ |

….

Main problem associated with the angular momentum of the CN (in surrogate reactions may be substantially different from the neutron-induced reaction).

Several model-dependent corrections have to be applied.

In some cases, the only possibility to estimate fission cross-sections

# Conclusions

There is strong need of **accurate new data** on neutron-induced fission cross-section of several isotopes involved in **advanced nuclear reactors**.

Since a few years, renewed efforts on the experimental side, with **improved facilities** and **experimental techniques**.

Important contribution comes from the n_TOF facility at CERN: **$^{232}$Th, $^{233}$U, $^{234}$U, $^{235}$U, $^{236}$U, $^{238}$U, $^{237}$Np, $^{241}$Am, $^{243}$Am** and **$^{245}$Cm**

Energy range from **thermal** to several **MeV** (in some cases up to 500 MeV)

Preliminary results indicate that current accuracy **can be improved**, at least for some isotopes (lower **background**, consistent **normalization** in the whole energy range, better **energy resolution**, etc…)

**Few percent accuracy** may be reachable for some isotopes.

Measuring all what is needed will take efforts and contribution from many facilities around the world, **BUT IT IS NECESSARY**.

Thank you for your attention