Neutron-induced fission cross sections: What have we learned from experiment?

Arjan Plompen

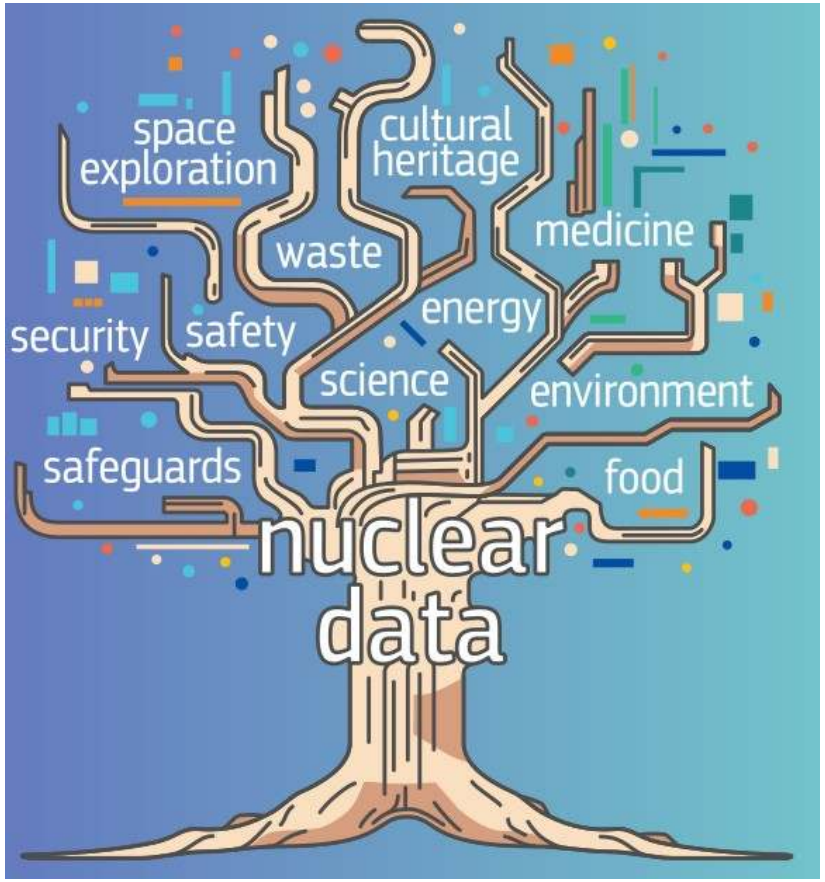
ESNT Workshop: Dynamics of Nuclear Fission

16-19 December 2024, CEA Saclay

European Commission

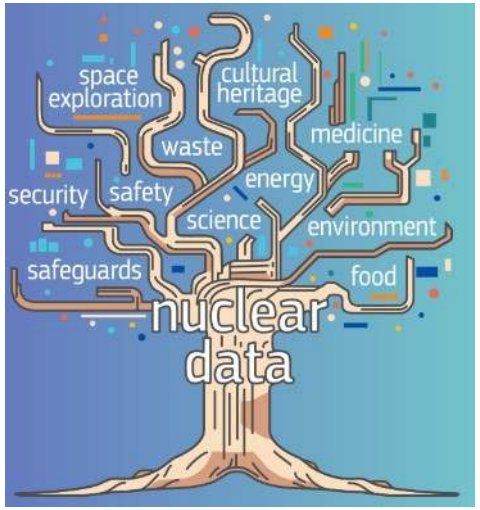
Introduction

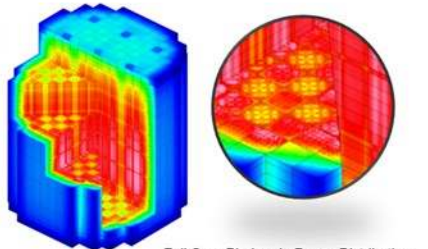
- Interest in fission is in both application and basic science
- Application: nuclear energy, waste management, security, forensics
- Basic science: astrophysics r-process, nuclear physics of fission
- Fission has many aspects
  - Spontaneous
  - Reaction-induced (g, n, p, d, t, h, a, HI)
  - Yields, angular and energy distribution of FF, n, g, ternary particles
  - Experiment vs theory – need for cross fertilization

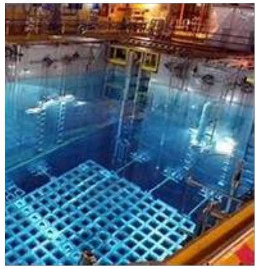


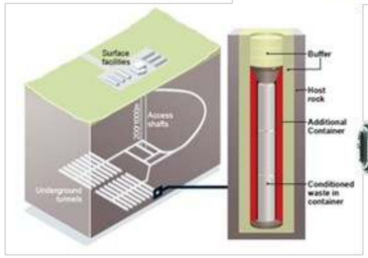
Role of nuclear data for tomorrow's solutions

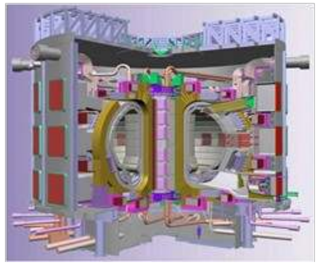
- Modelling is needed at every step of nuclear development
- Scoping, design, testing, operation, safety analyses, waste and spent fuel management
- Good modelling allows savings and shortening of development
- **Good data are essential to good modelling**

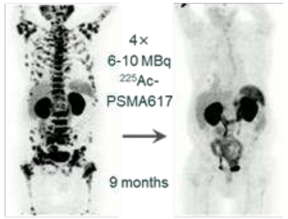






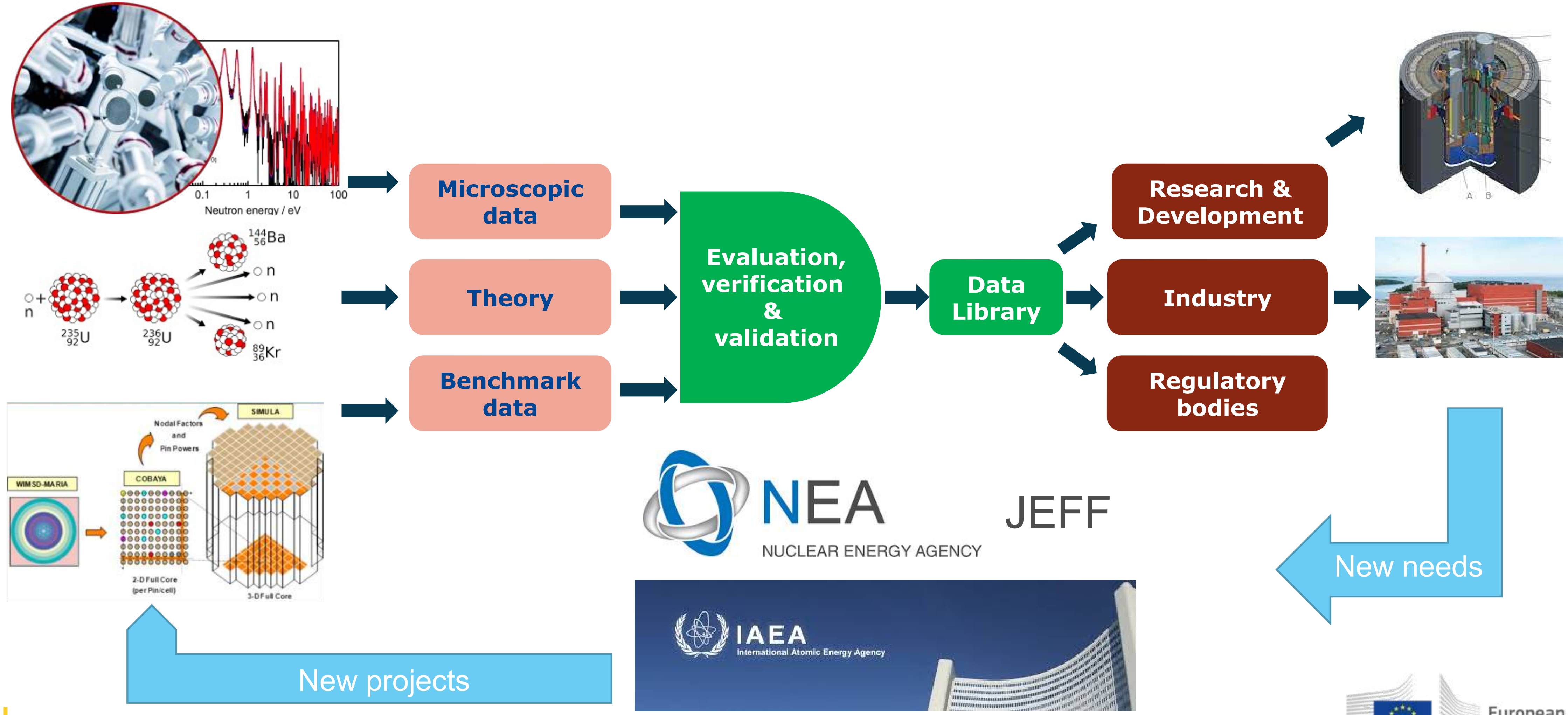






[C. Kratochwil *et al.*, J. Nucl. Med. 57 (2016) 1941]

From science to application



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Advanced reactor applications SMR/AMR

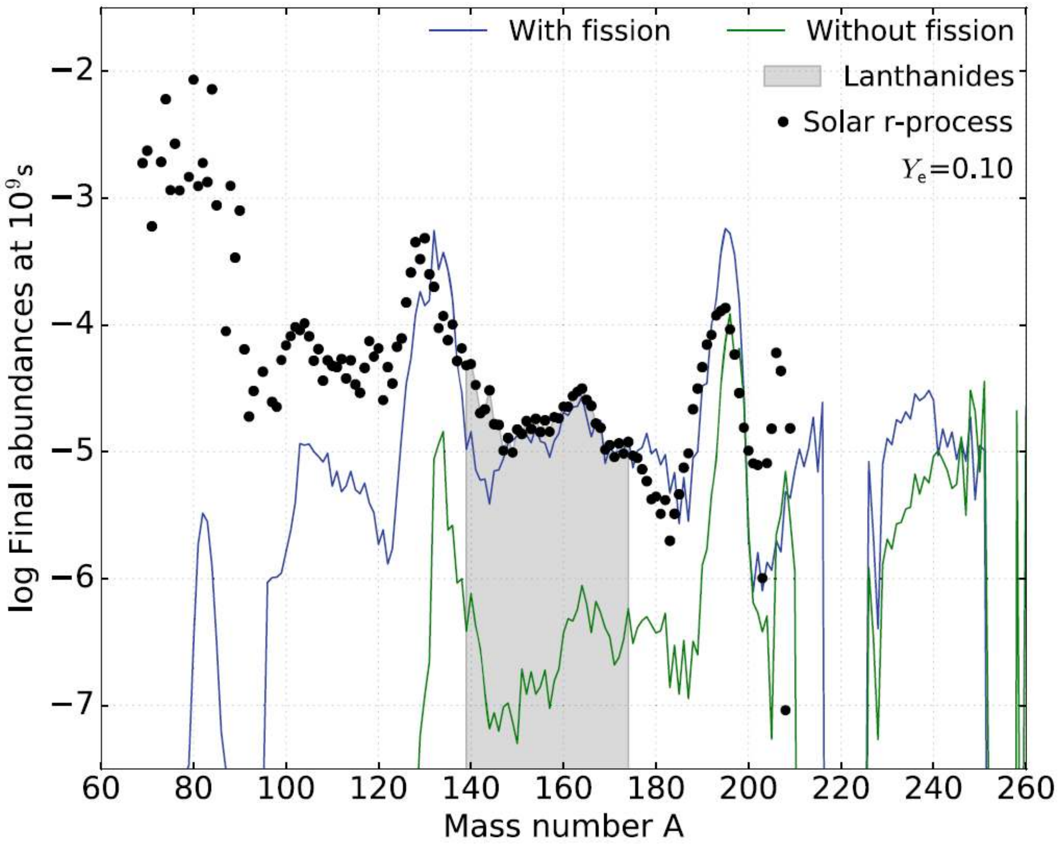
- Example of fission energy
- Present day and prospective
  - High Priority Request List
    - Emphasis on HLW mgmt.
    - Minor actinides
    - ≥2% uncertainty
    - ^{235,238}U only standards
  - Major actinides under-represented

NEA
NUCLEAR ENERGY AGENCY
ABOUT US TOPICS NEWS AND RESOURCE

ID	View	Target	Reaction	Quantity	Energy range
19H		94-PU-238	(n,f)	SIG	9 keV-6 MeV
21H		95-AM-241	(n,f)	SIG	180 keV-20 MeV
22H		95-AM-242M	(n,f)	SIG	0.5 keV-6 MeV
25H		96-CM-244	(n,f)	SIG	65 keV-6 MeV
27H		96-CM-245	(n,f)	SIG	0.5 keV-6 MeV
35H		94-PU-241	(n,f)	SIG	0.5 eV-1.35 MeV
37H		94-PU-240	(n,f)	SIG	0.5 keV-5 MeV
39H		94-PU-242	(n,f)	SIG	200 keV-20 MeV

ID	View	Target	Reaction	Quantity	Energy range	Sec.E/Angle	Accuracy
100S STD		92-U-235	(n,f),(p,f)	SIG	100 MeV-500 MeV		5
101S STD		92-U-238	(n,f),(p,f)	SIG	100 MeV-500 MeV		5

Relevance of fission for astrophysics



- r-process

J. Lippuner, L.F. Roberts, Astrophys. J. Suppl. S. **233**, 18 (2017).

- Large impact of fission
- Direct measurements inaccessible
- Indirect measurements…
- Mostly model calculations
- Requires trustable models calibrated with data that are available

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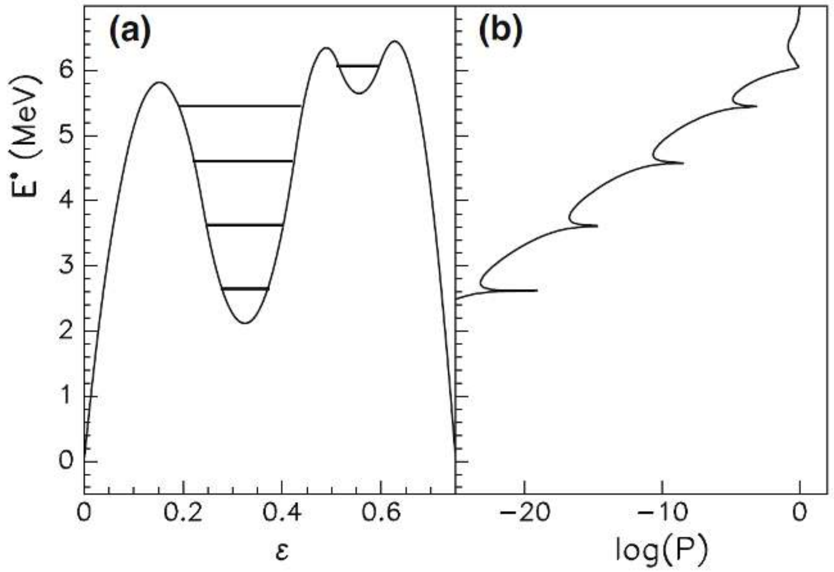
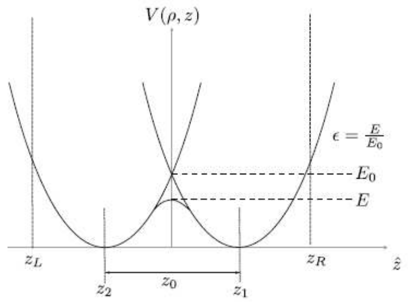
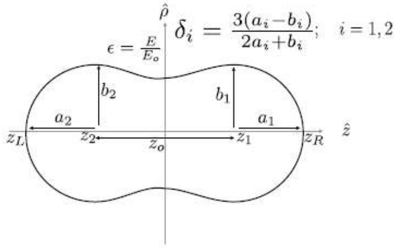
Introduction - scope

- Fission is a wide field effectively covered by ESNT program this week.
- Here
    - neutron-induced fission
    - experiments ~ 20 years
    - relevance for theory
    - no experimental challenges
    - need for evaluations & evaluators

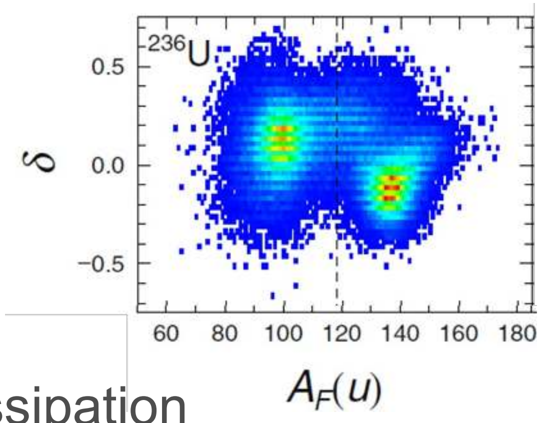


Introduction – aspects of theory





- Reaction side – usual suspects
  - What are the fissioning systems?
  - Excitation energy
  - Spin distribution
  - Competition with other channels
- Ingredients
  - S-matrix, R-matrix
  - Optical model and psf
  - Pre-equilibrium
  - Level densities
- Fission process itself
  - Potential energy surface
  - Barriers – spin, E_x dependence
  - Class-II states
  - Transition states
  - Fission widths – dissipation
- In principle all aspects of nuclear modelling are involved.



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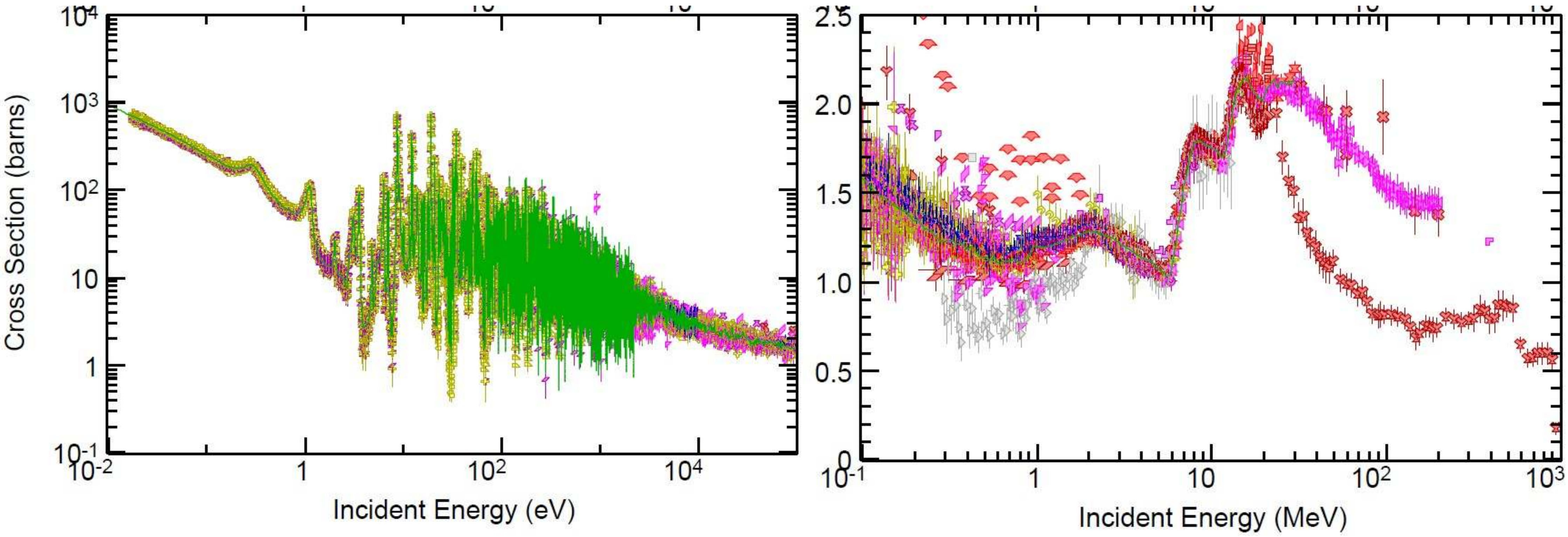
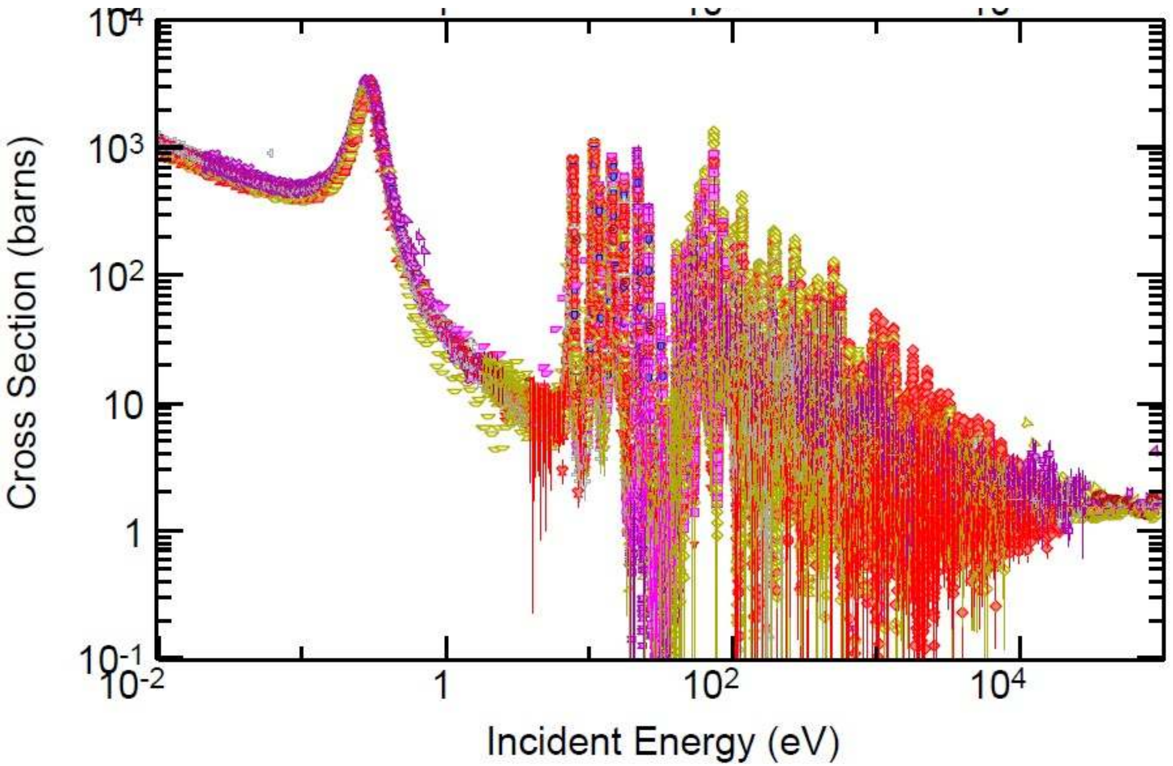
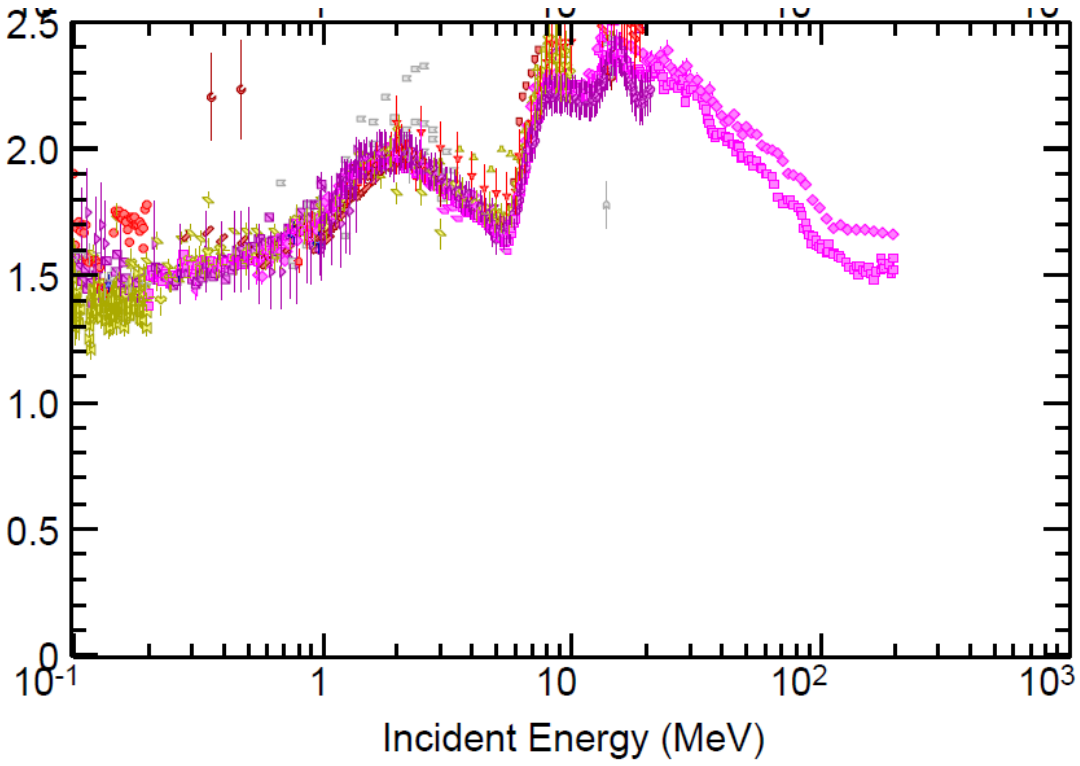
Status of the data major actinides

$^{235}U(n,f)$ experimental data

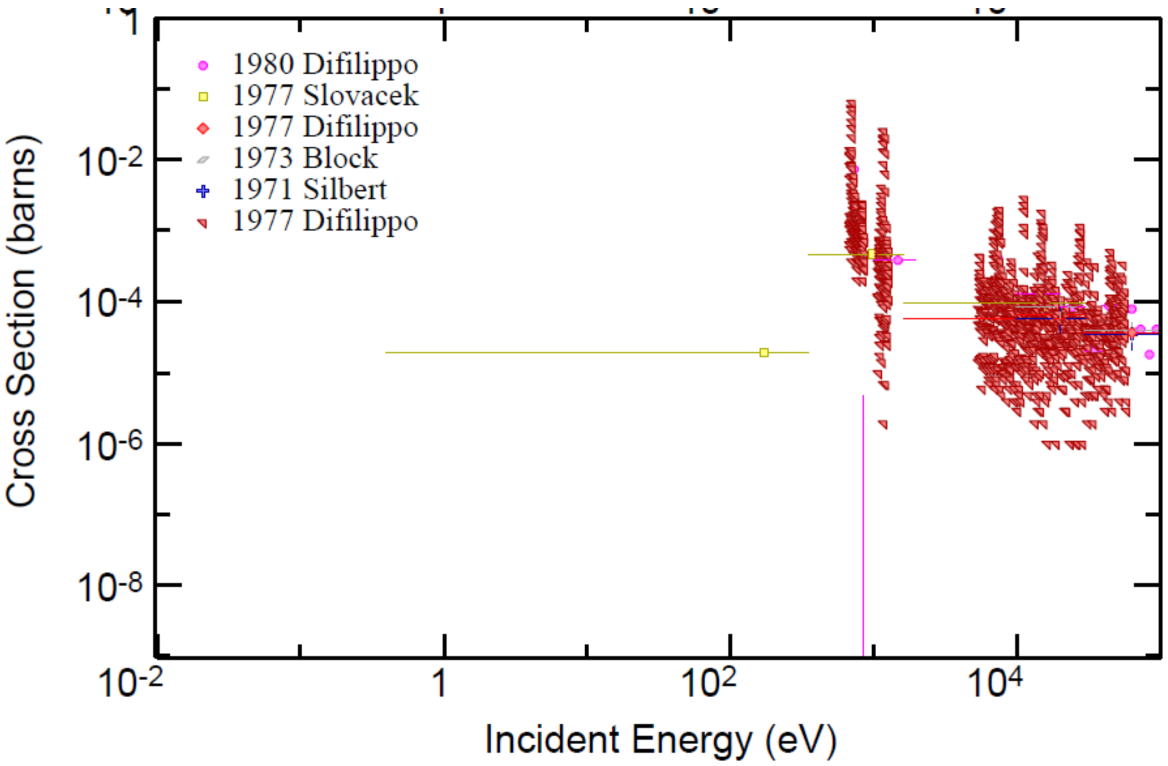


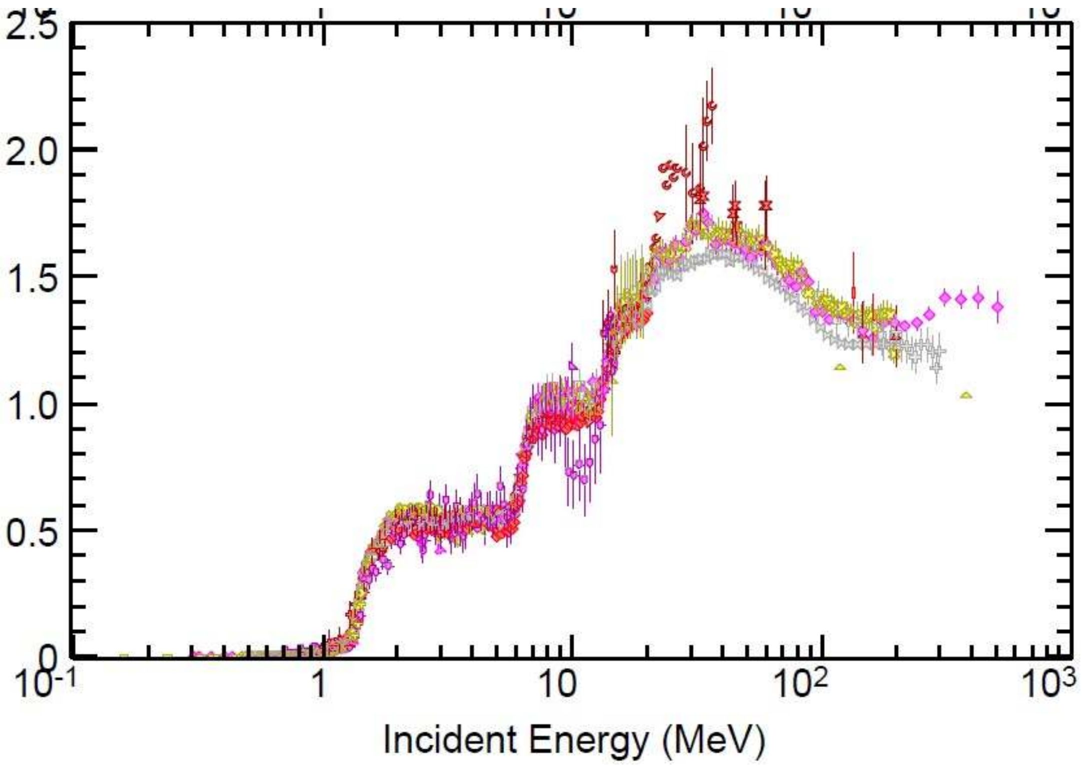
$^{239}Pu(n,f)$ experimental data





$^{238}U(n,f)$ experimental data



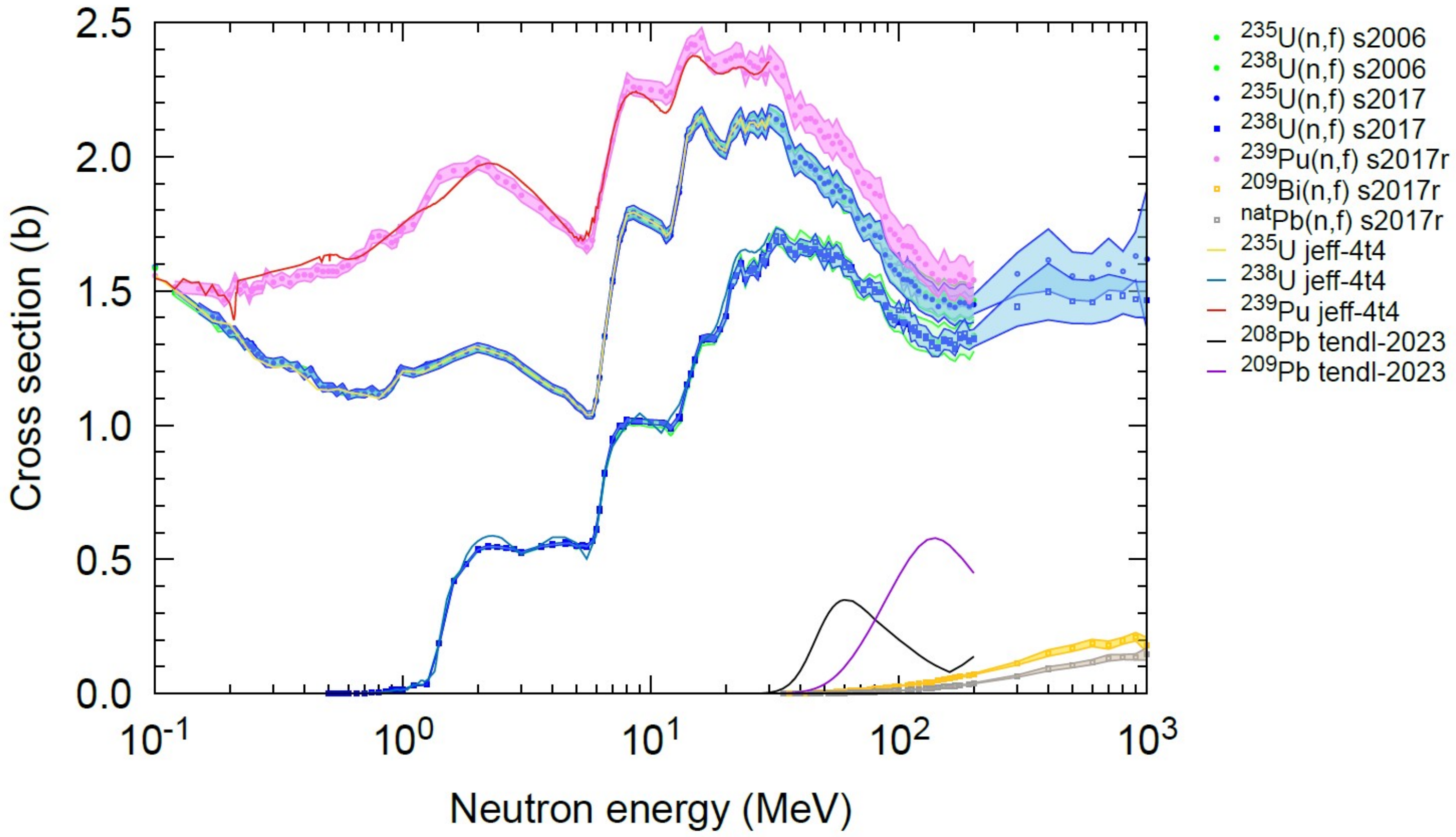


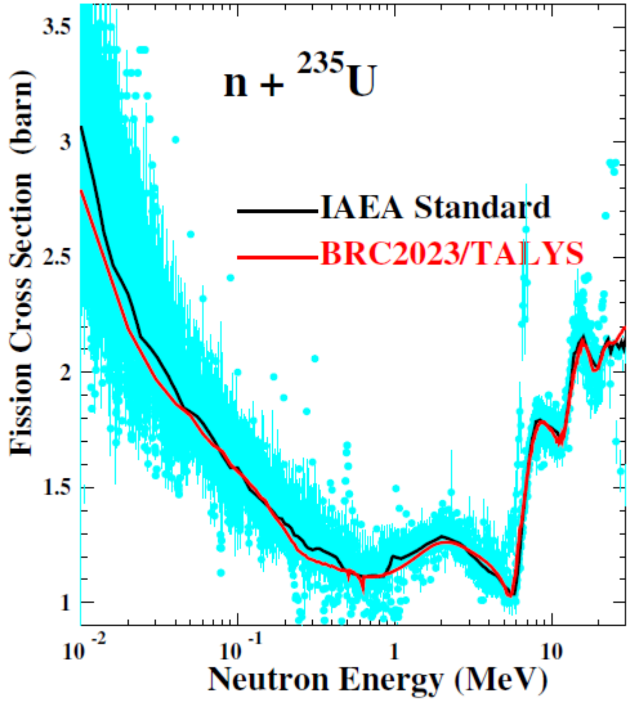
General trends n-induced fission cross section

- Main physics is well known
  - Fissile vs non-fissile nuclides systematics (odd-even effects)
  - 1st, 2nd… chance fission (evidence reducing with excitation energy)
  - Sub-barrier fission – class II states
  - Convergence towards similar cross sections at high energy for nearby nuclides
- There appears to be plenty of data
  - Major actinides versus minor actinides
  - Common targets vs exotic targets
- However,
  - the stakes are high (major actinides 1-2% already high uncertainty)
  - for small uncertainties (<10%) issues due to scatter and discrepancies

Status of the data major actinide evaluations

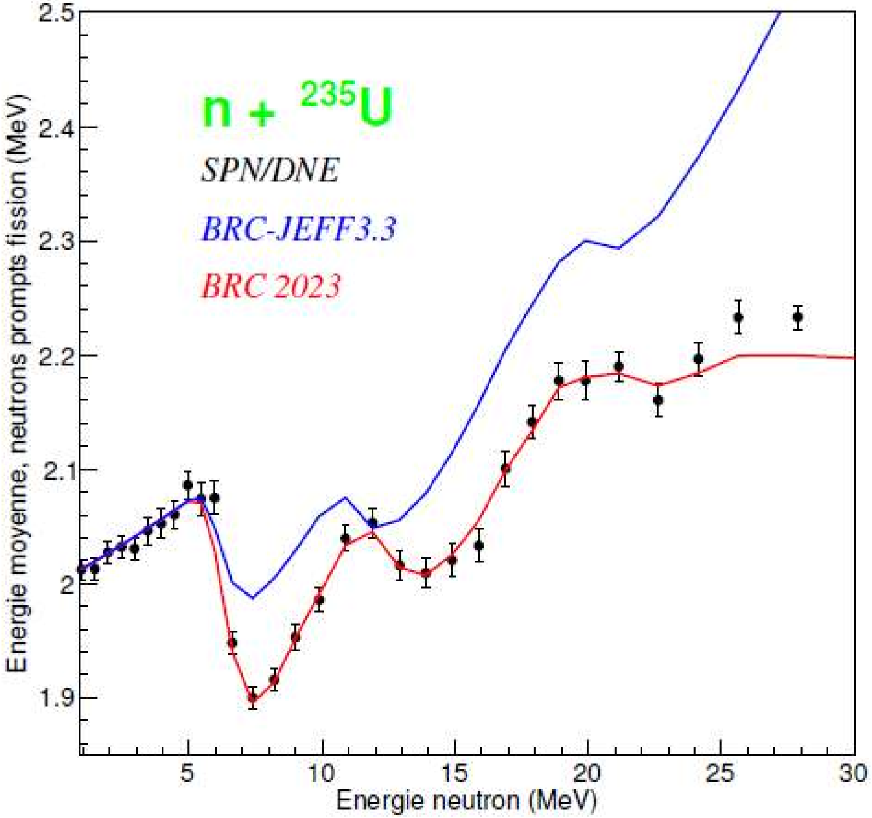
Standards – experiment based evaluation



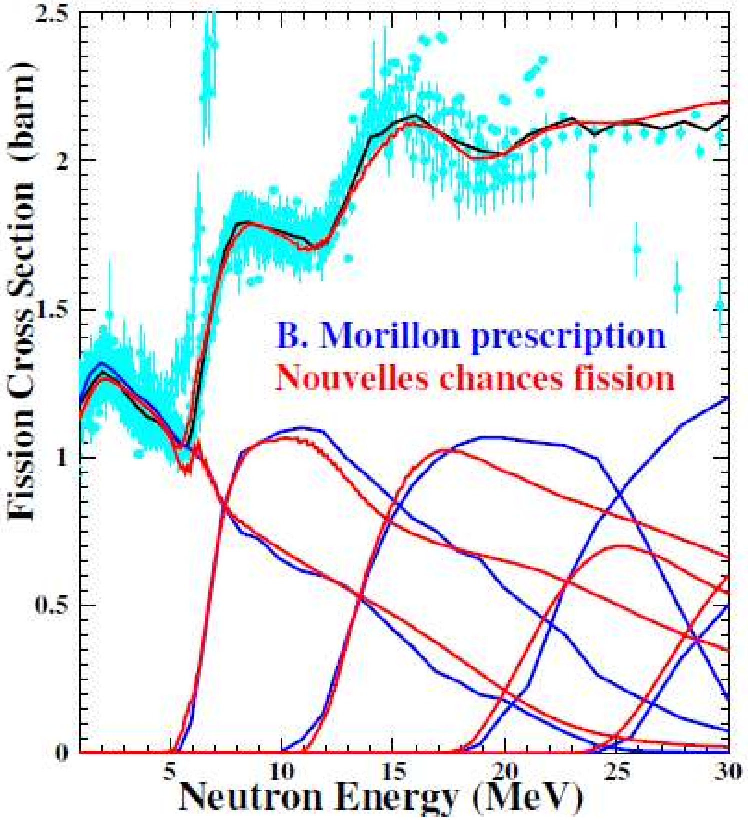


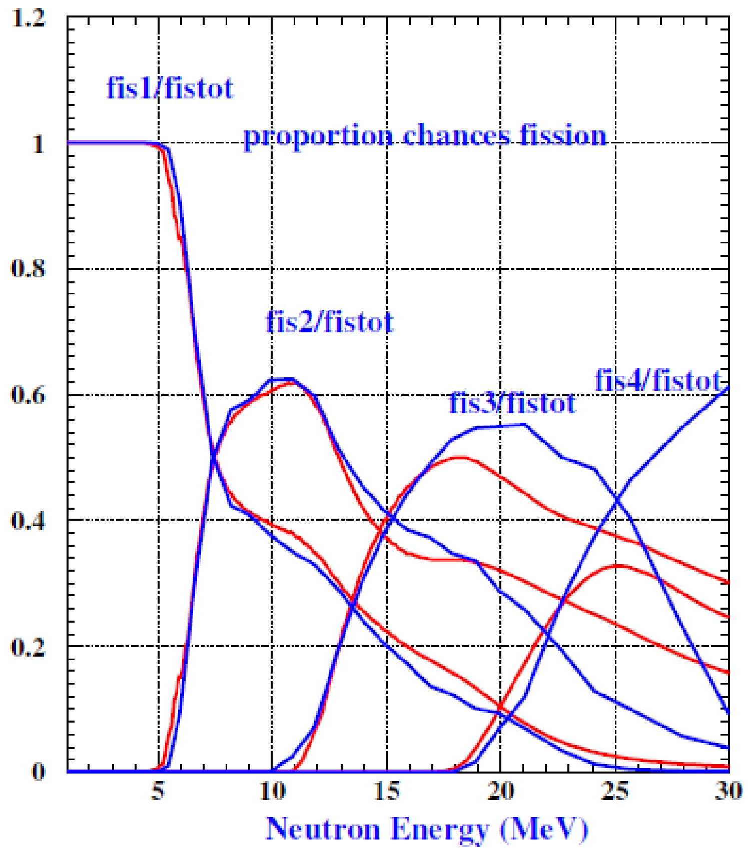
P. Romain jefdoc2252

On the way to JEFF-4.0: ^{235}U-4t4



Standard within 2-4%





B. Mauss new pfns spectra->mean energy, prc & jefdoc2252

P. Romain jefdoc2252

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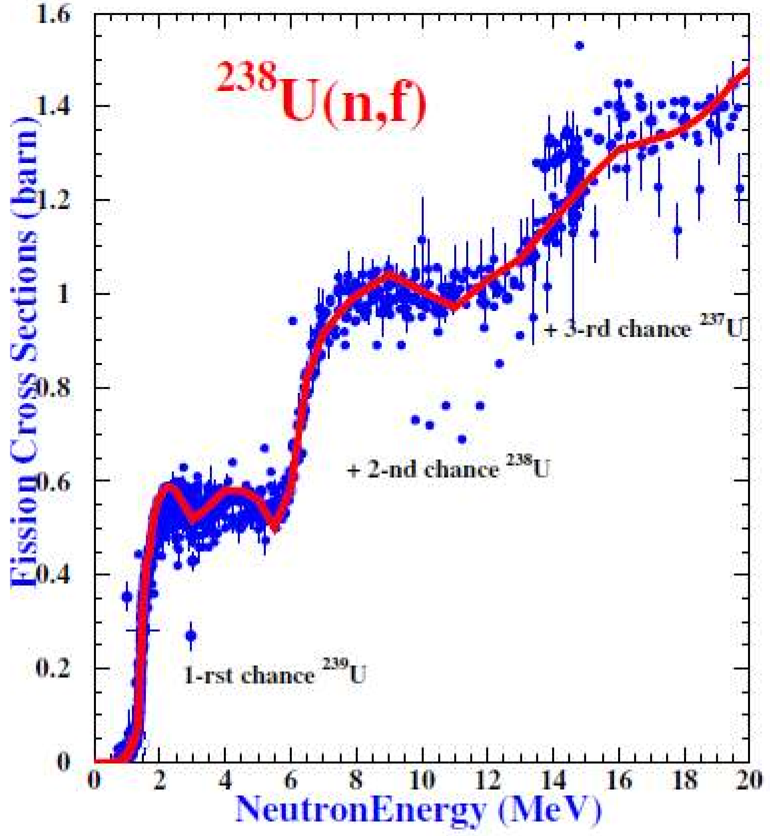
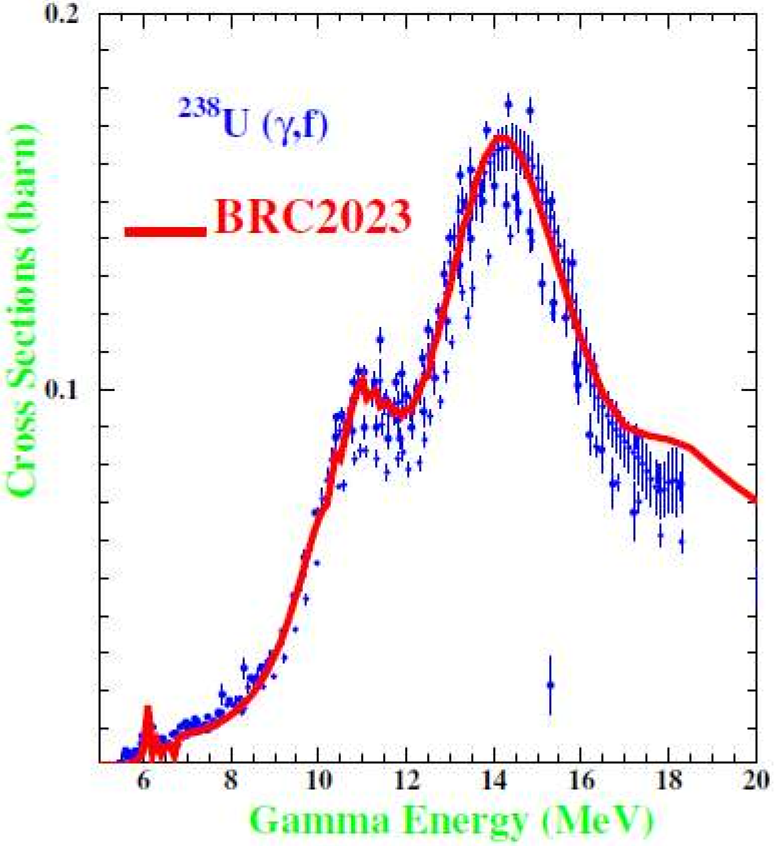
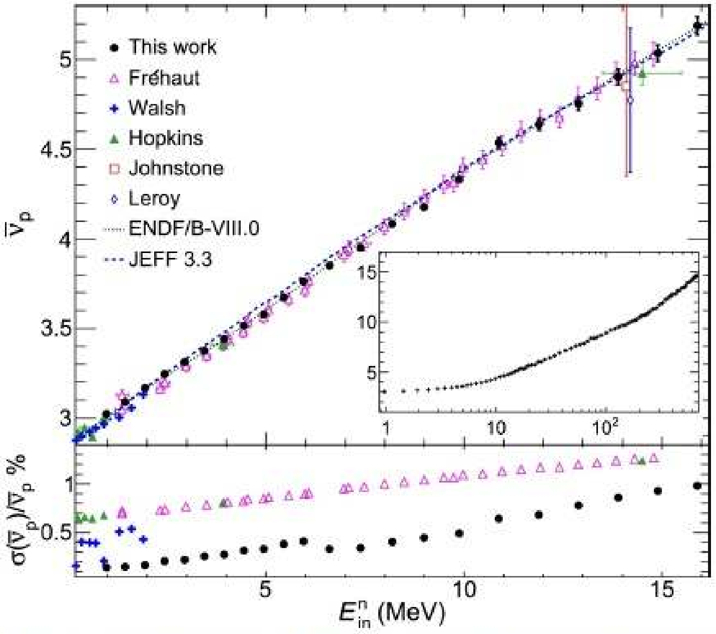
On the way to JEFF-4.0: ^{238}U-4t4



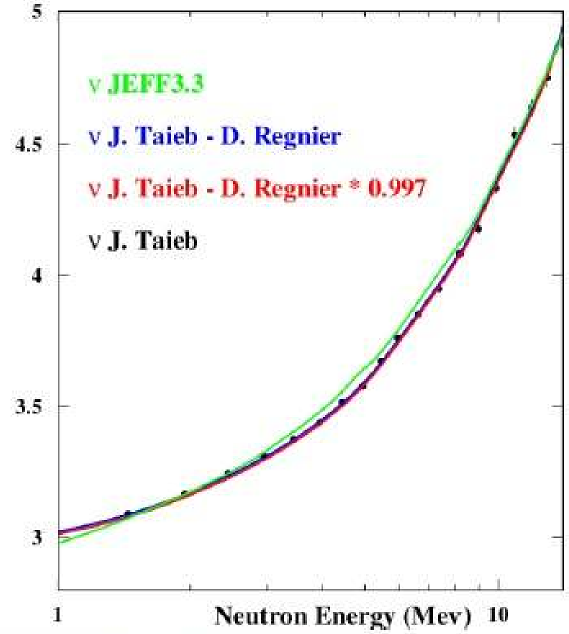


P. Romain jefdoc2290

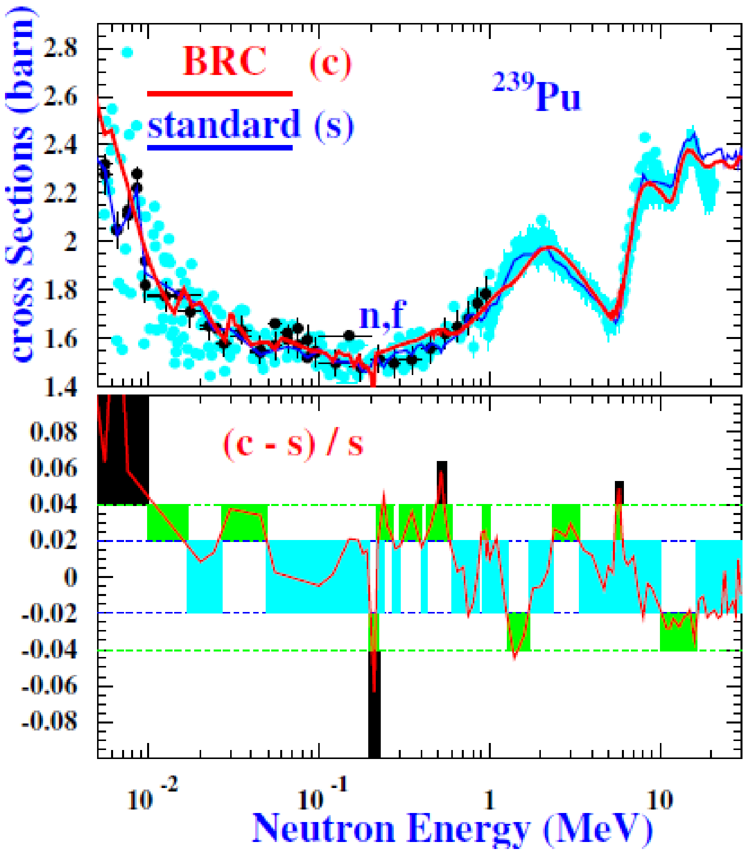
On the way to JEFF-4.0: ^{239}Pu-4t4



Exp. $\bar{\nu}$, P. Marini *et al*, Physics Letters B835,(2022) 137513.

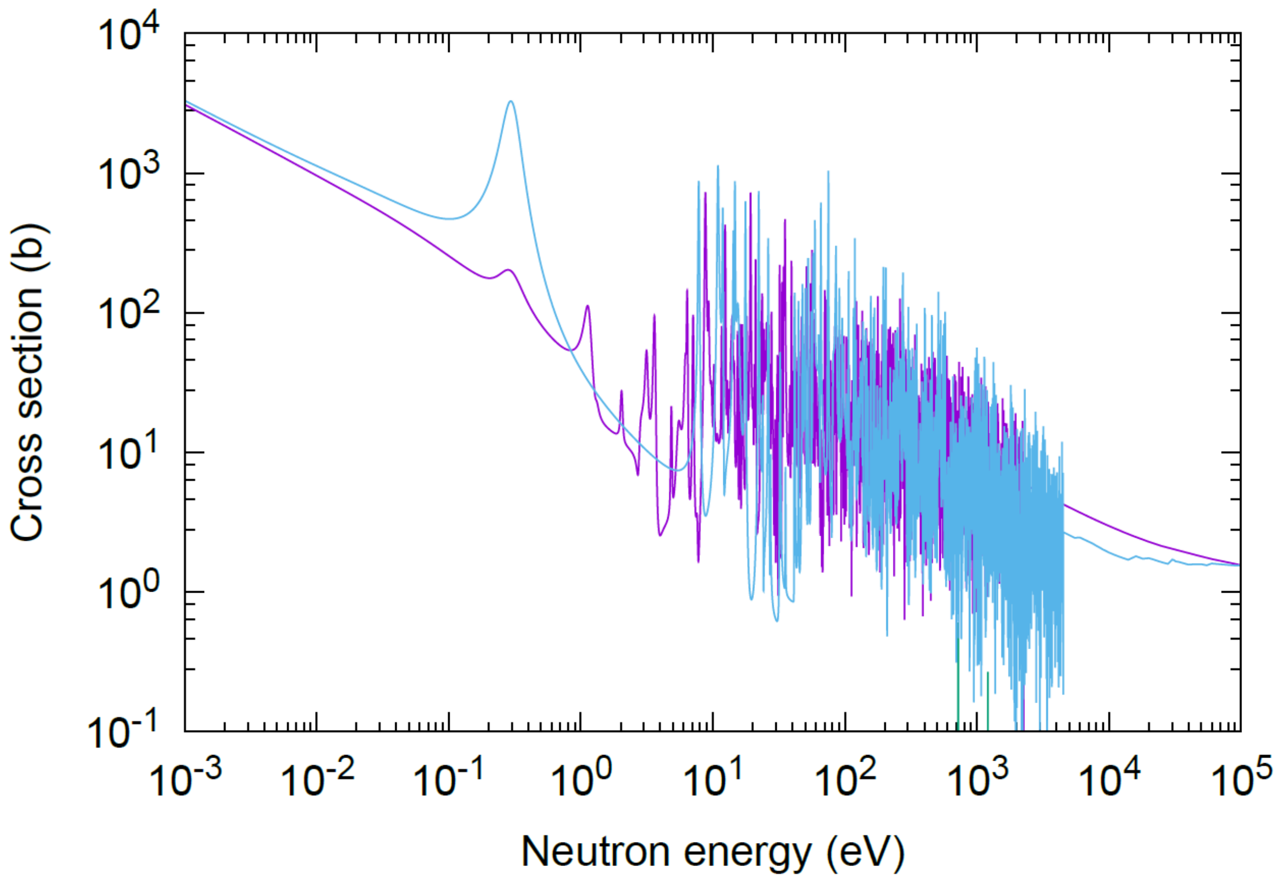


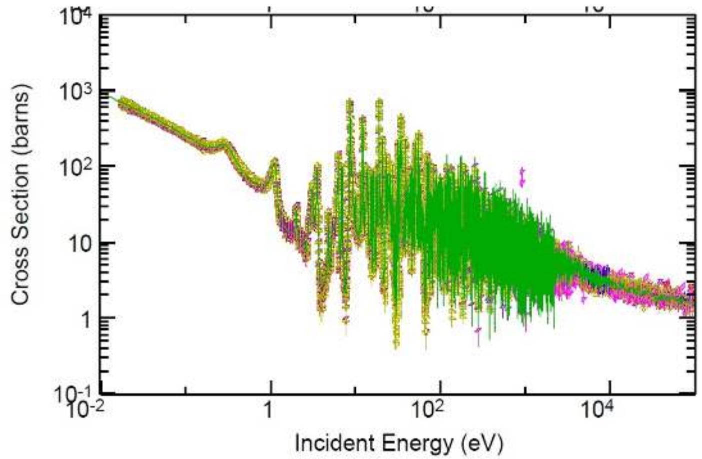
Computed $\bar{\nu}$ of this evaluation.

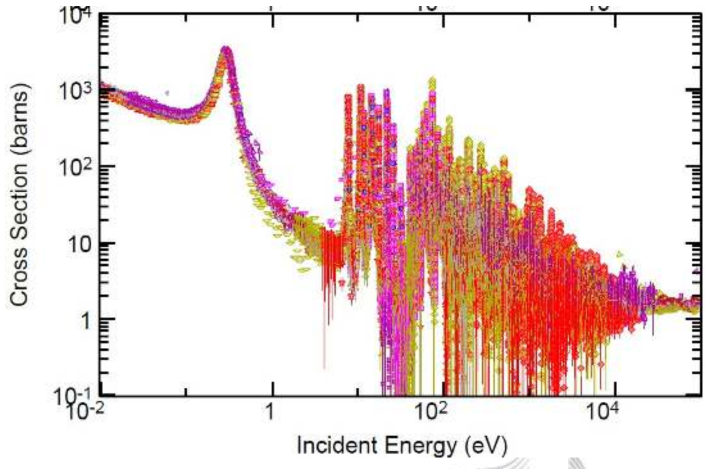


P. Chau jefdoc2187

Resonance region – ^{235}U, ^{239}Pu

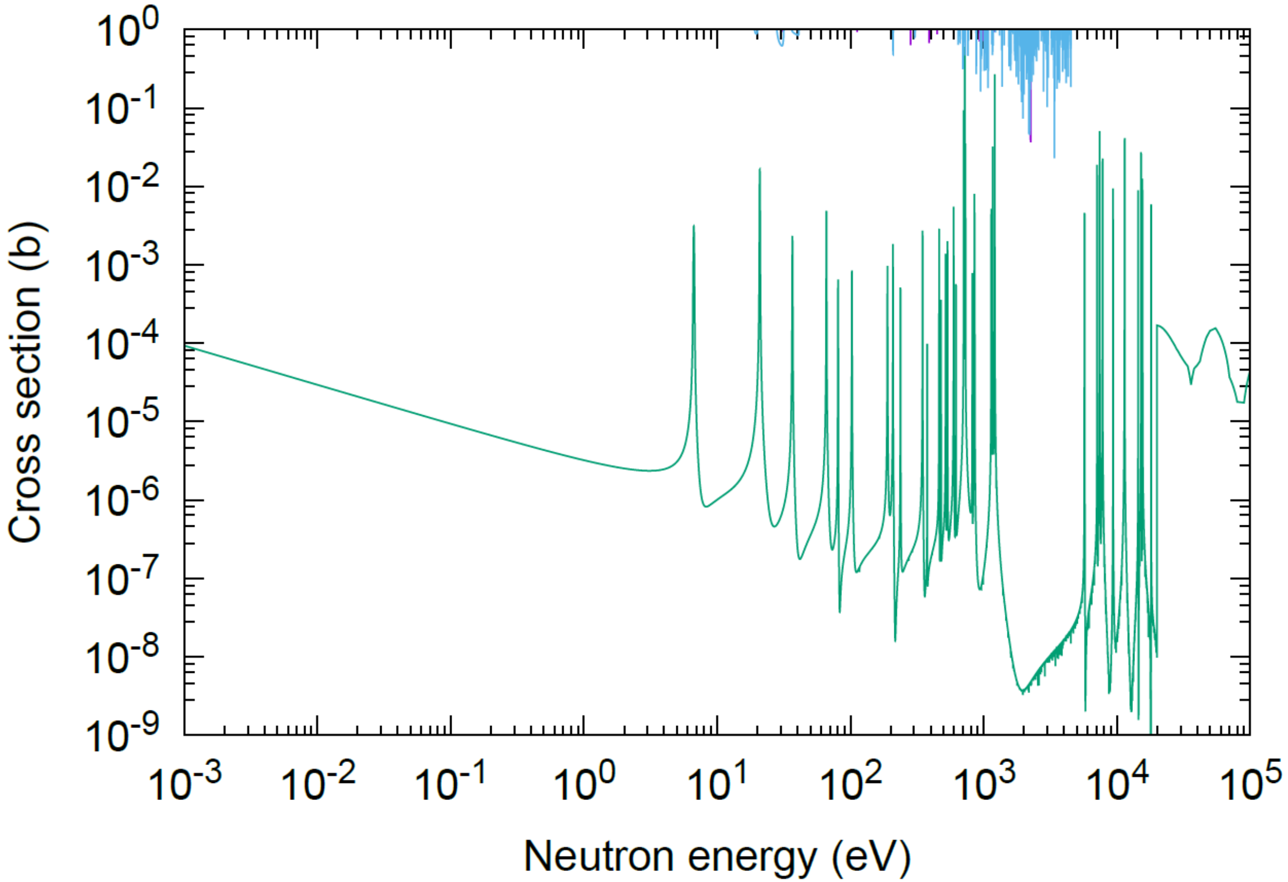


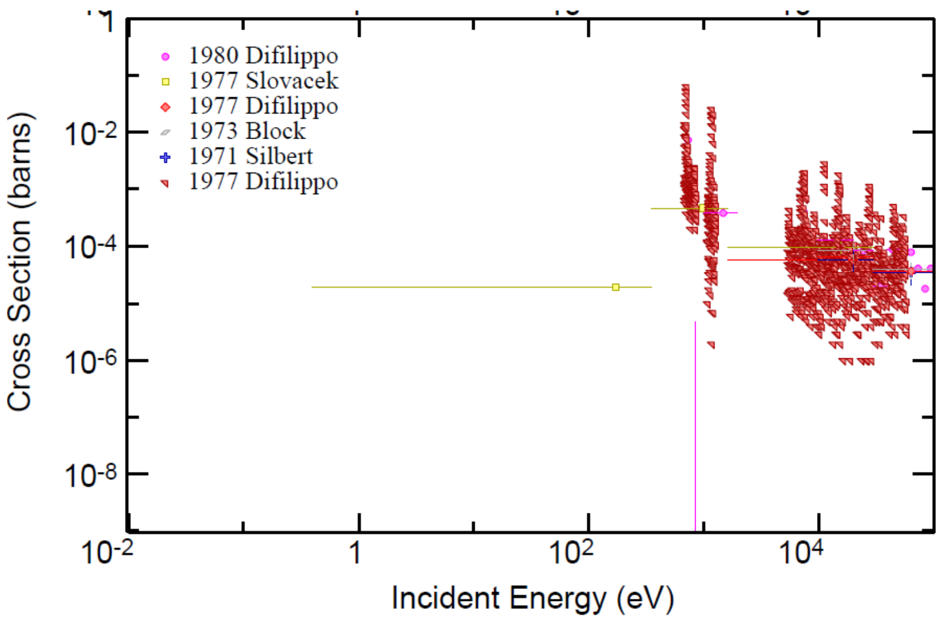




G. Noguere jefdocs-xxxx&-yyyy

Resonance region – ^{238}U





S. Kopecky jefdoc-zzzz, G. Noguere jefdoc-aaaa

General trends n-induced fission cross section

- Standards appear well-established
- Seems due to a large database
- However:
  - How strong is the metrological basis?
  - What is the traceability of the results?
  - Is the dog biting its own tale?
  - There are many ratio results.
  - What is the absolute underpinning?
  - For the standards project to resolve.
  - Transparency of the traceability chain?

Absolute methods
Transmission, associated particles, self-normalizing methods…

Cross sections based on absolute methods
$^{1}H(n,n)^{1}H$, $^{6}Li(n,t)^{4}He$, $^{10}B(n,a)^{7}Li$, $^{12}C(n,n)^{12}C$, $^{197}Au(n,g)^{198}Au$, some other results

Cross sections based on ratios to the above
$^{235}U(n,f)$, $^{238}U(n,f)$, $^{239}Pu(n,f)$…

Cross sections based on ratios to the above
$^{235}U(n,f)$, $^{238}U(n,f)$, $^{239}Pu(n,f)$, MA(n,f)…

General trends n-induced fission cross section

- Models are not perfect
  - Not easy to represent experiment accurately
  - Not easy to correct deficient experimental data
- Why? Many answers
- Users want best physics…
  - And can't wait for it
  - Some say: Frankenstein evaluations
  - We must know what we don't know and be clever about fixes
  - Fixes are physics in progress

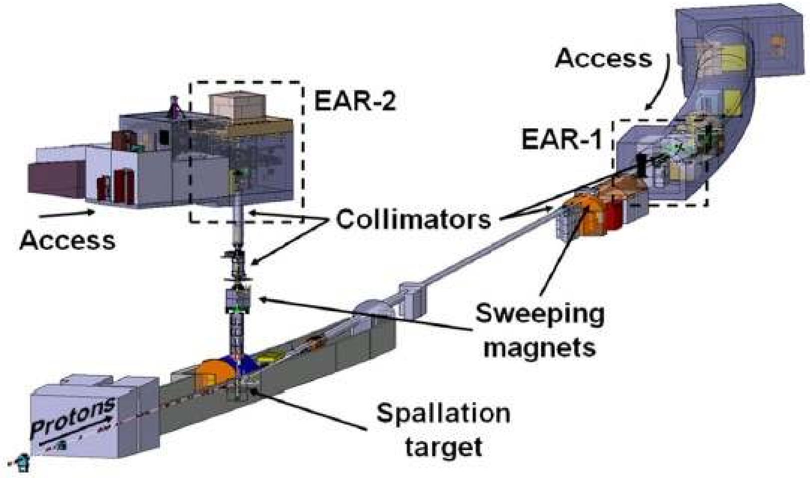
- Overlapping resonances
  - R- or S-matrix incompletely defined
  - Resonance interference tough to crack – affects fission even in RR

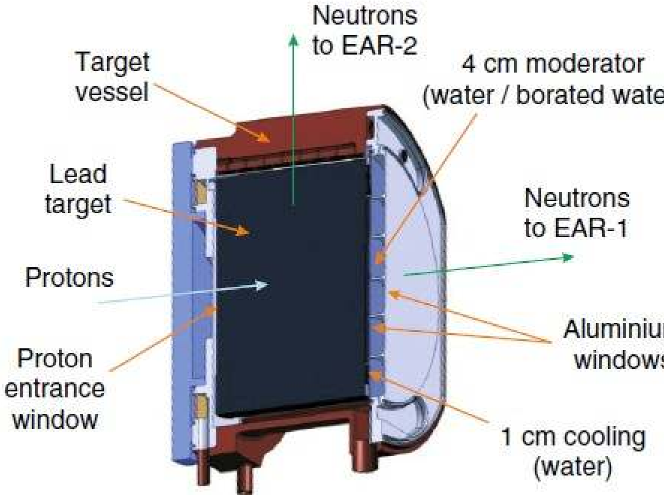
- Unresolved range and fast range
  - There is no decisive many body theory
  - Many parameter theories: parameters hard to fix
  - Microscopic vs statistical theory…

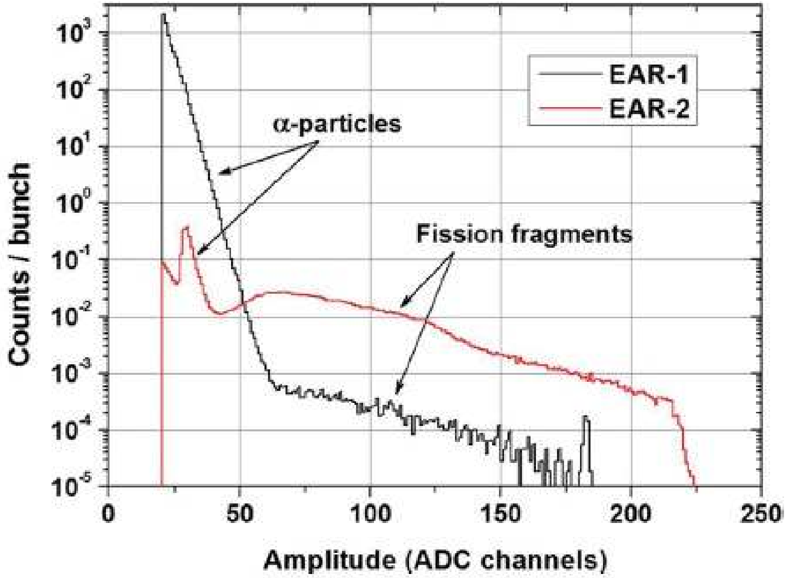
Status of other data

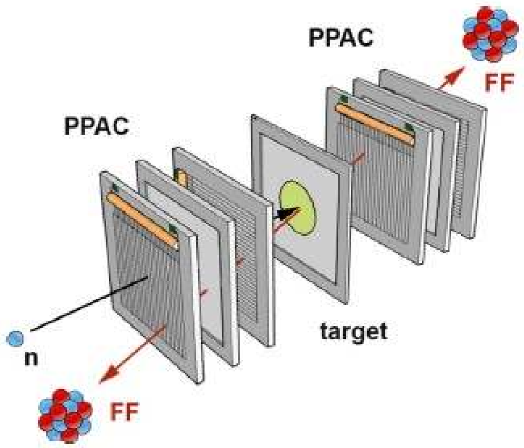
Recent results

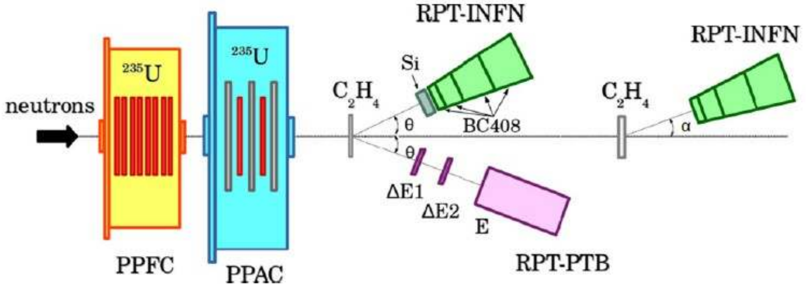
Experiments at n_TOF





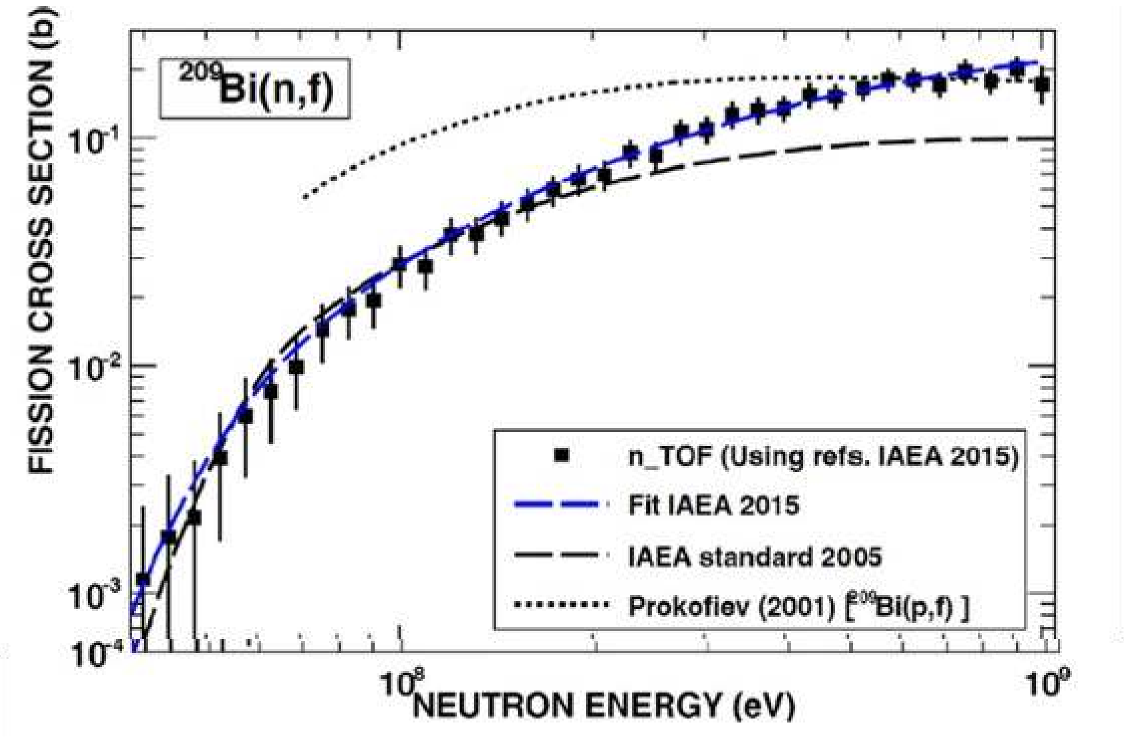


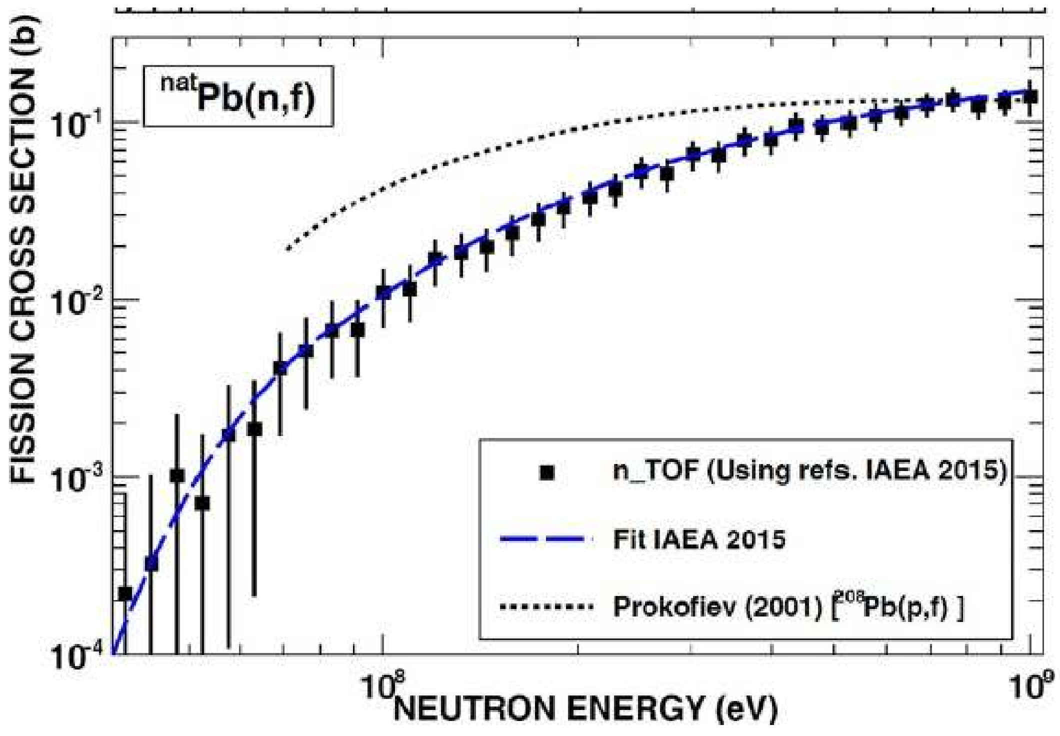




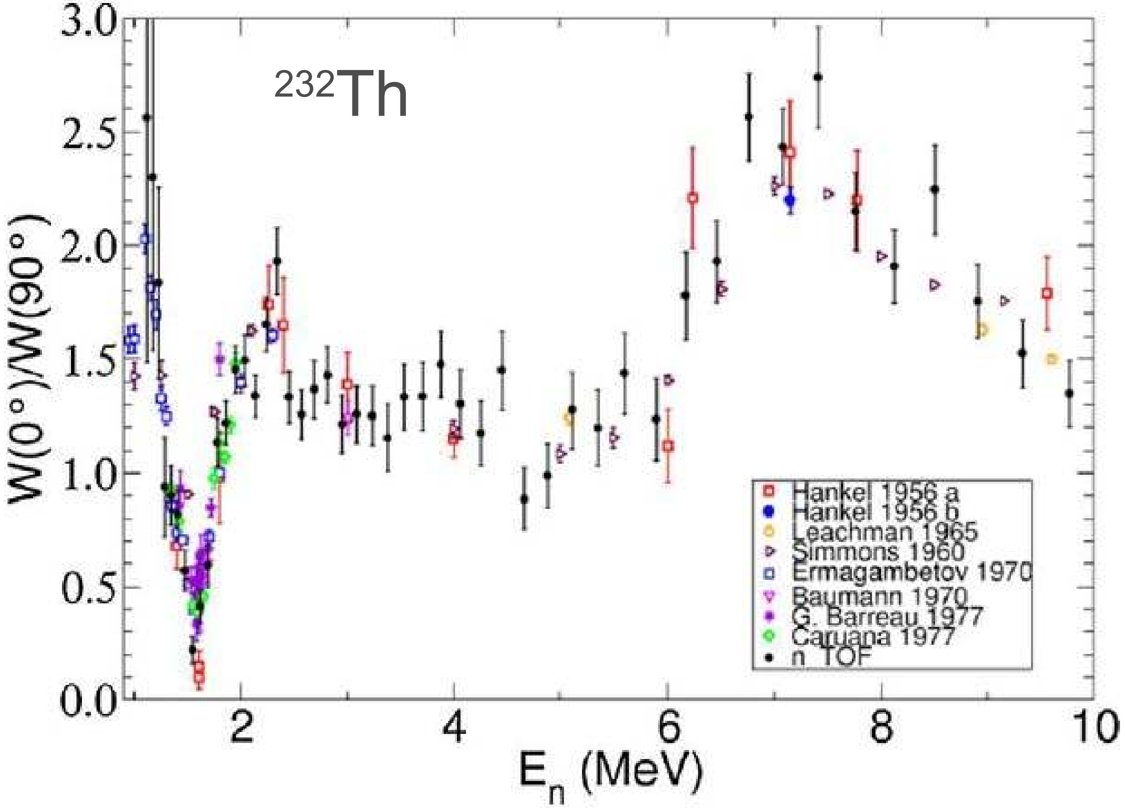
N. Colonna et al. Eur. Phys. J. A (2020) 56:48

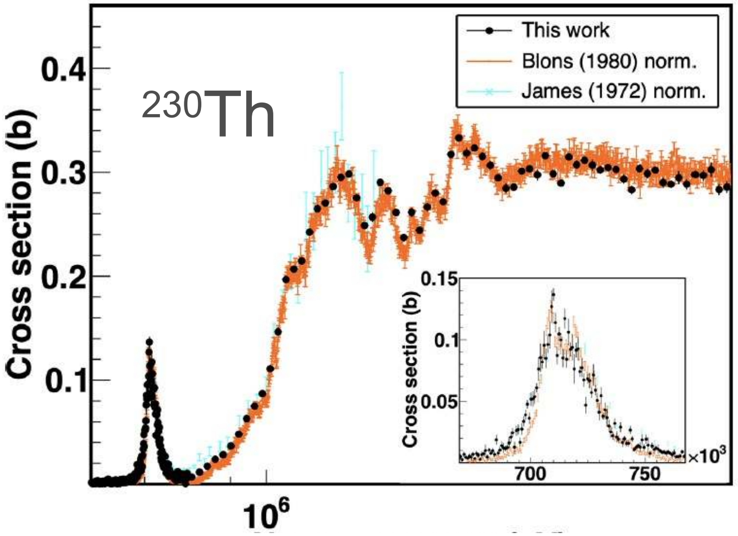
High energy, Bi(n,f) and Pb(n,f)

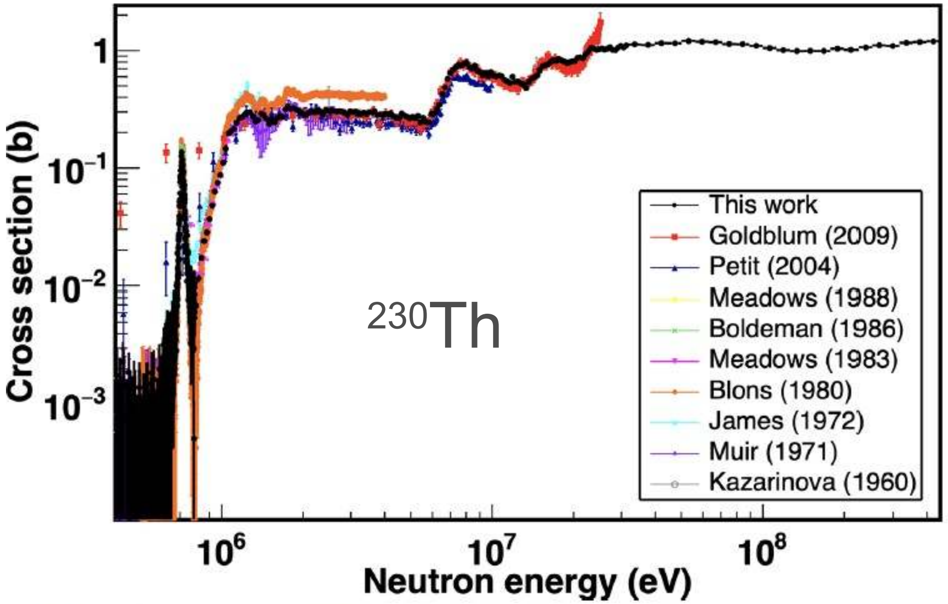




^{230}Th(n,f) and ^{232}Th(n,f)







V. Michalopoulou PHYSICAL REVIEW C **108**, 014616 (2023)

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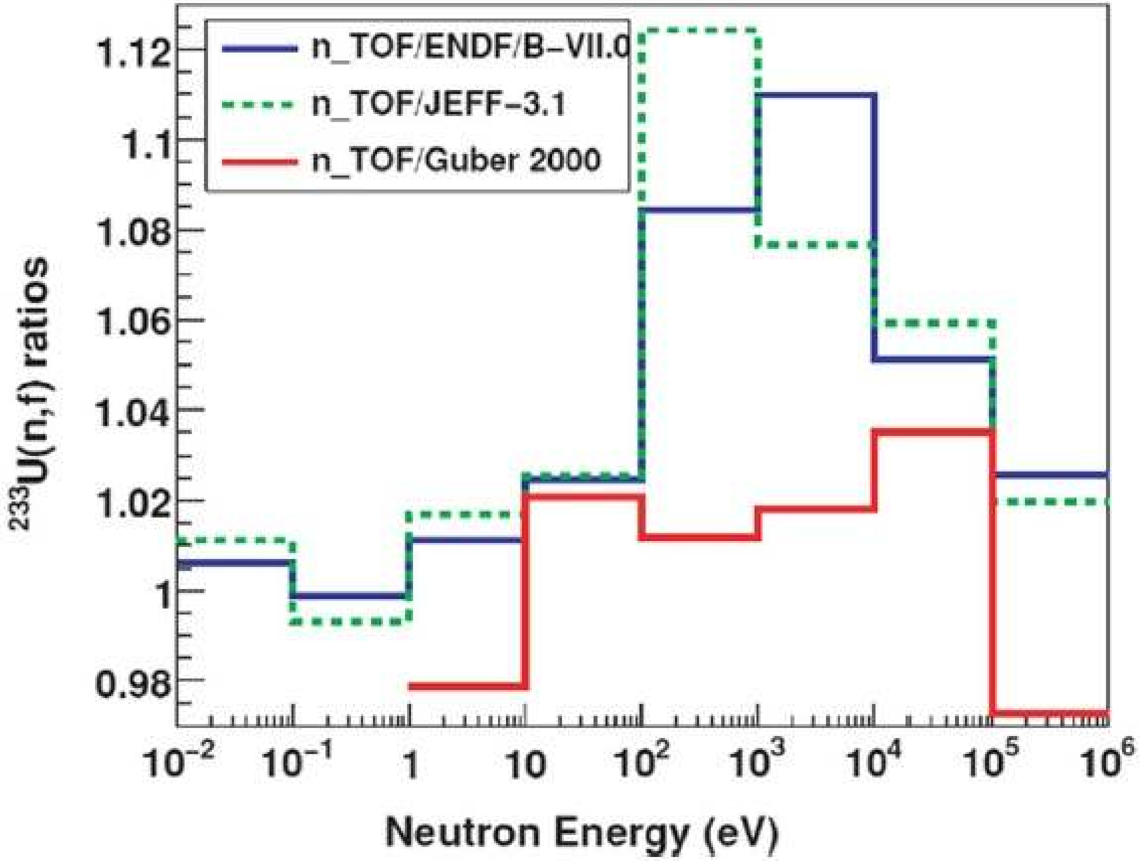
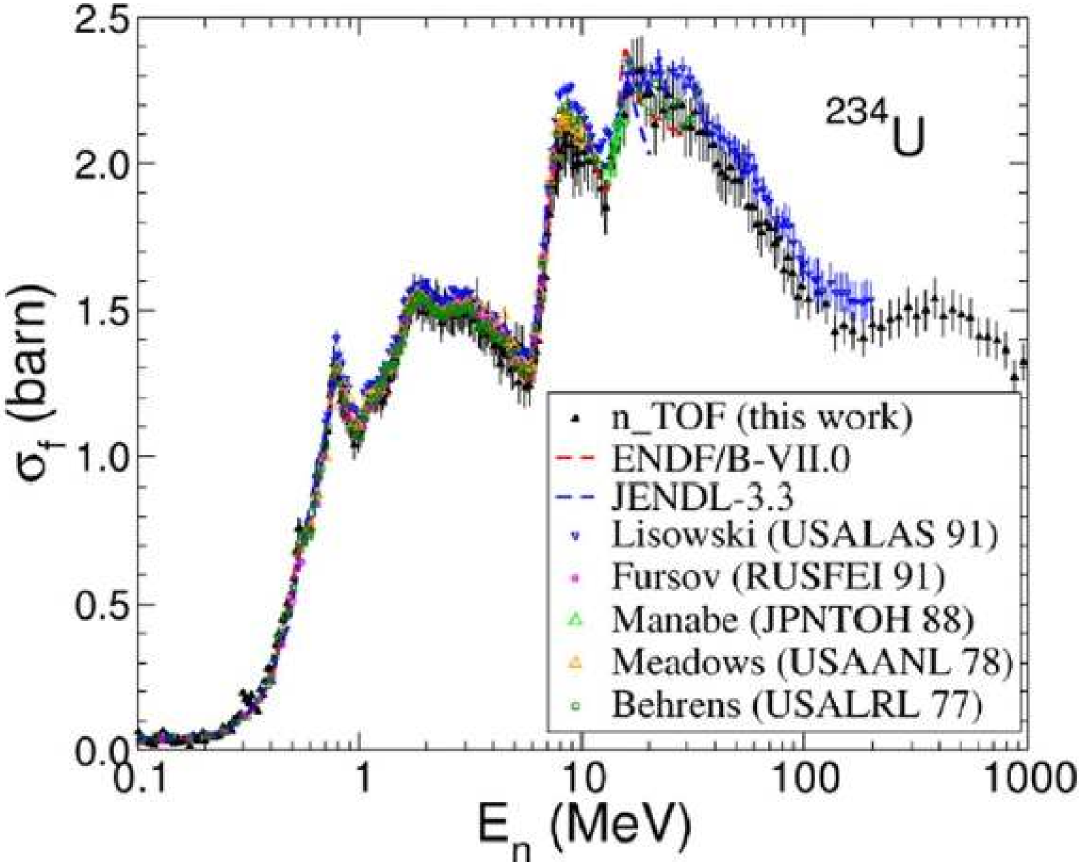
$^{233}U(n,f)$ and $^{234}U(n,f)$





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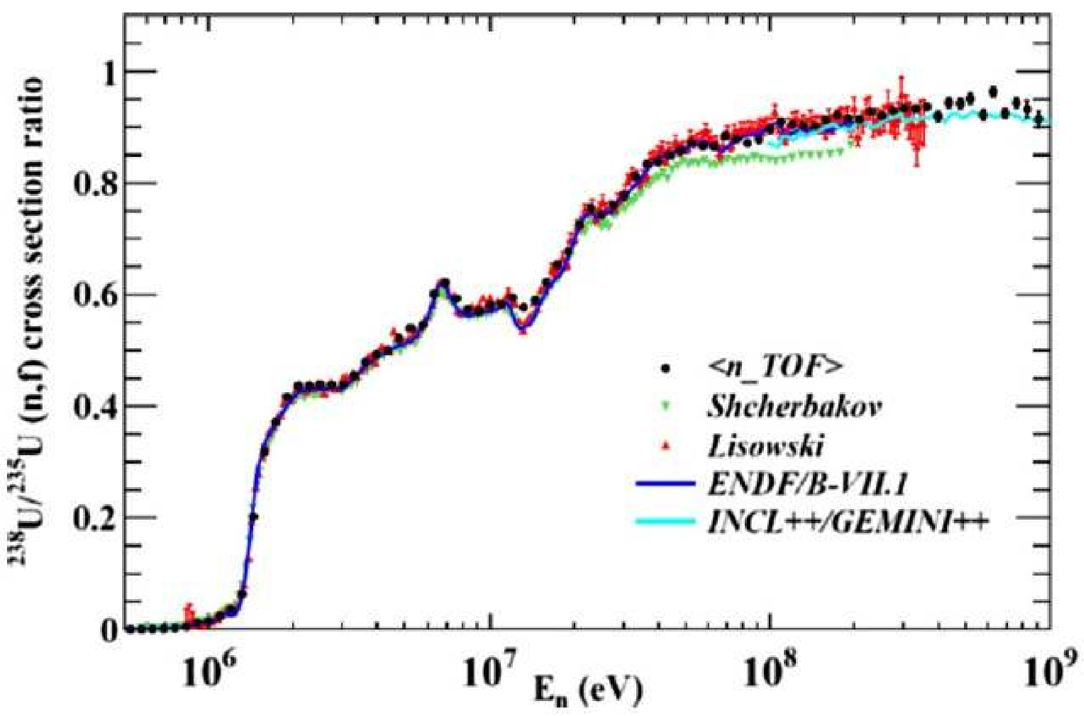
^{238}U(n,f) relative to ^{235}U(n,f); some ^{238}U(p,f)



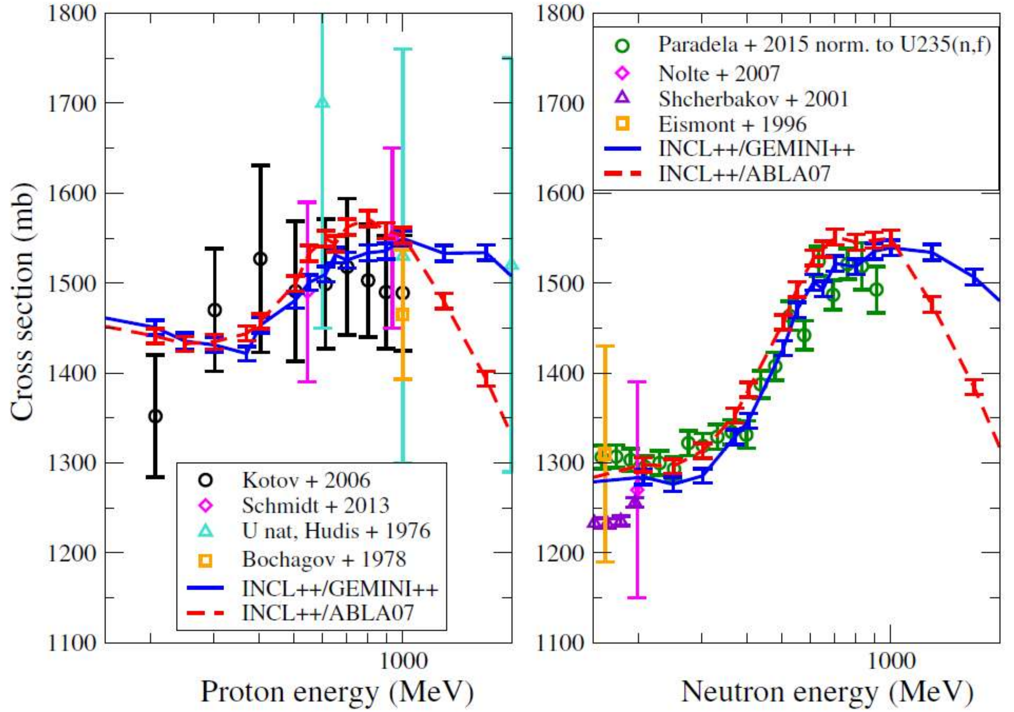
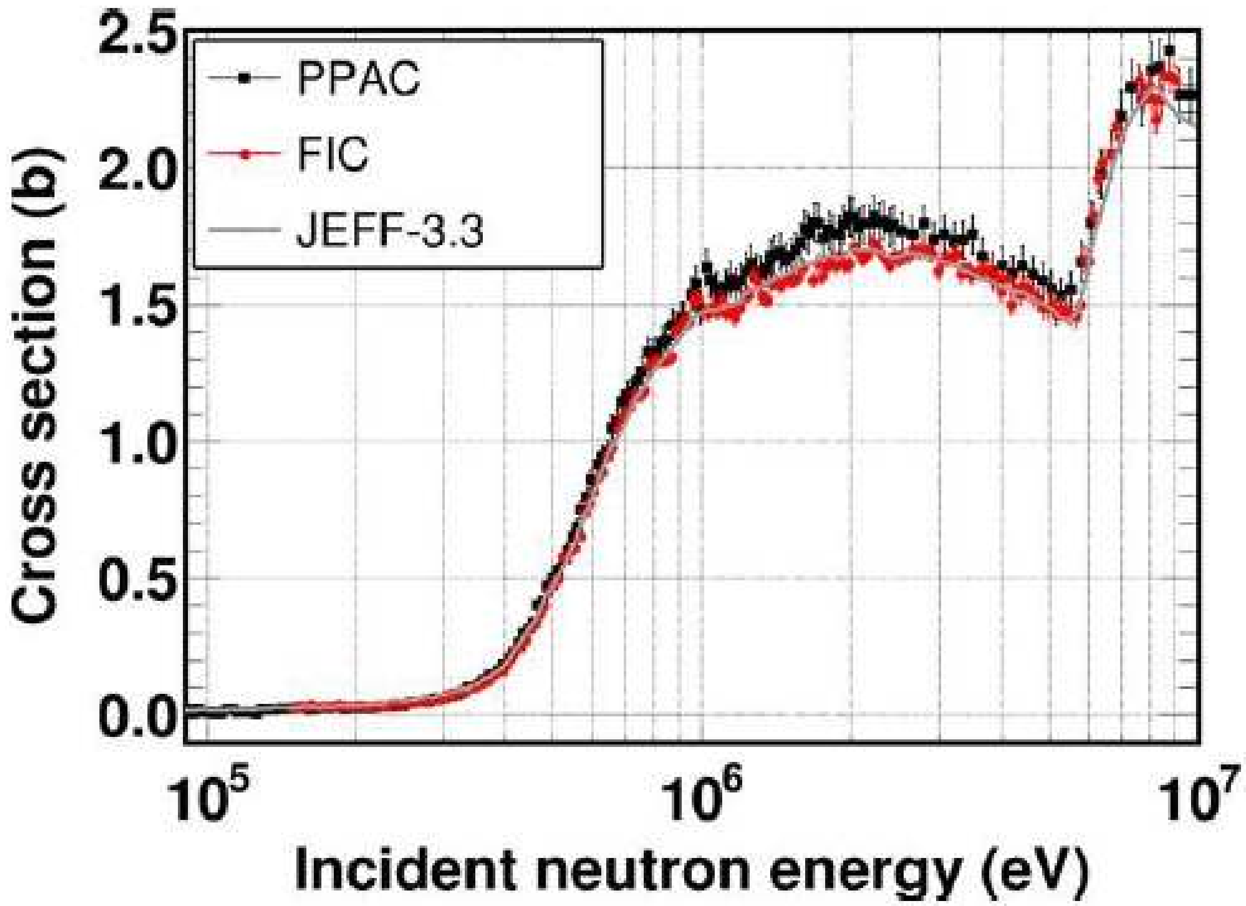
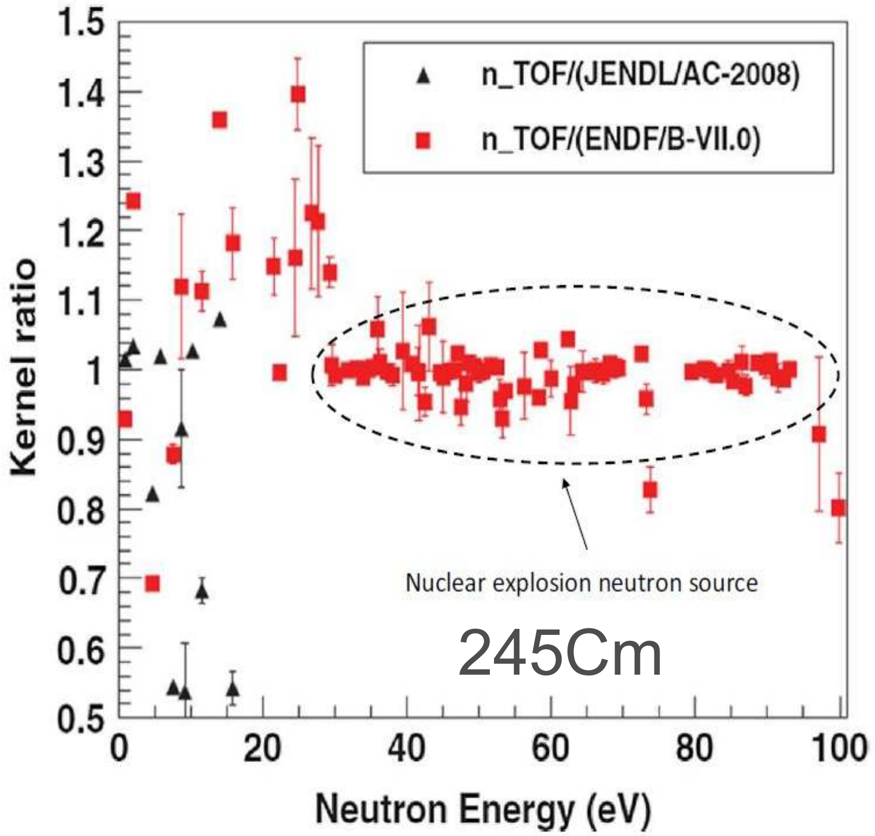


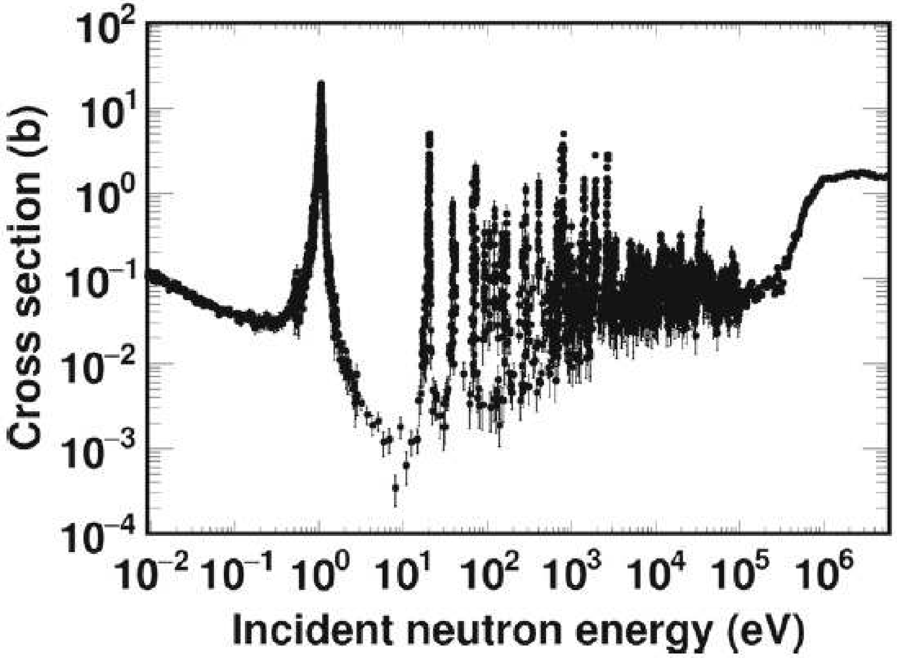
Fig. 2 The fission cross section of ^{238}U from 100 MeV to 3 GeV. Left panel: ^{238}U(p,f); right panel: ^{238}U(n,f). Solid lines: INCL/GEMINI

$^{237}Np(n,f)$ and $^{245}Cm(n,f)$

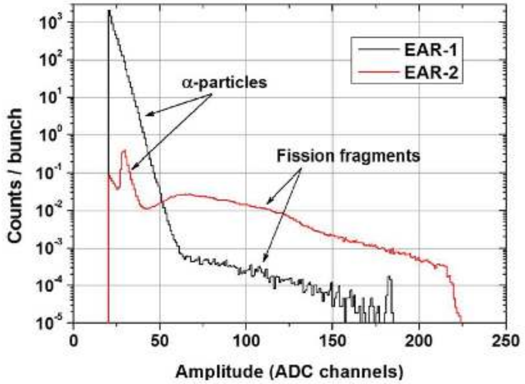




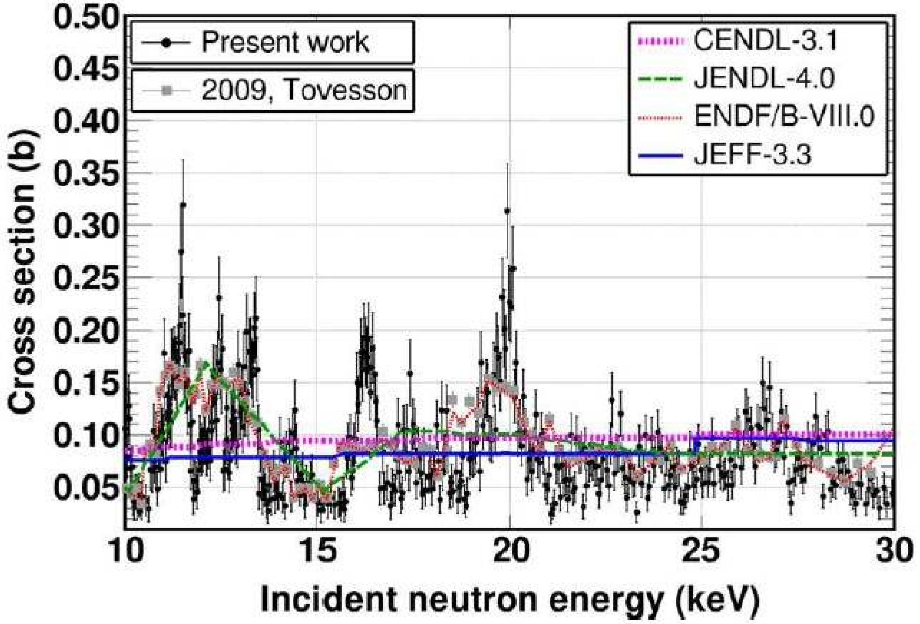
$^{240}Pu(n,f)$



Cross section (b)
Incident neutron energy (eV)

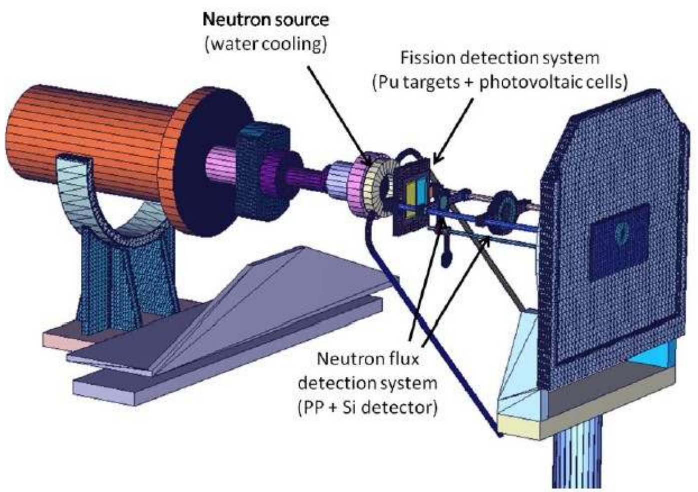


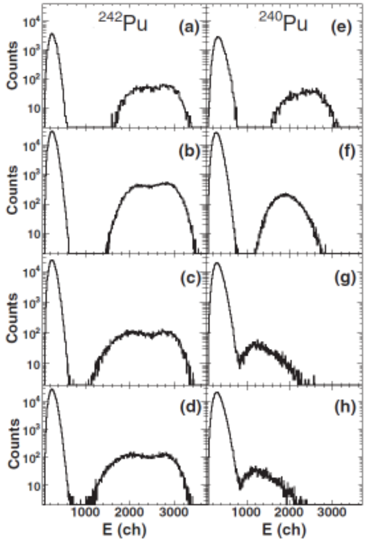
EAR-1
EAR-2
α-particles
Fission fragments
Counts / bunch
Amplitude (ADC channels)

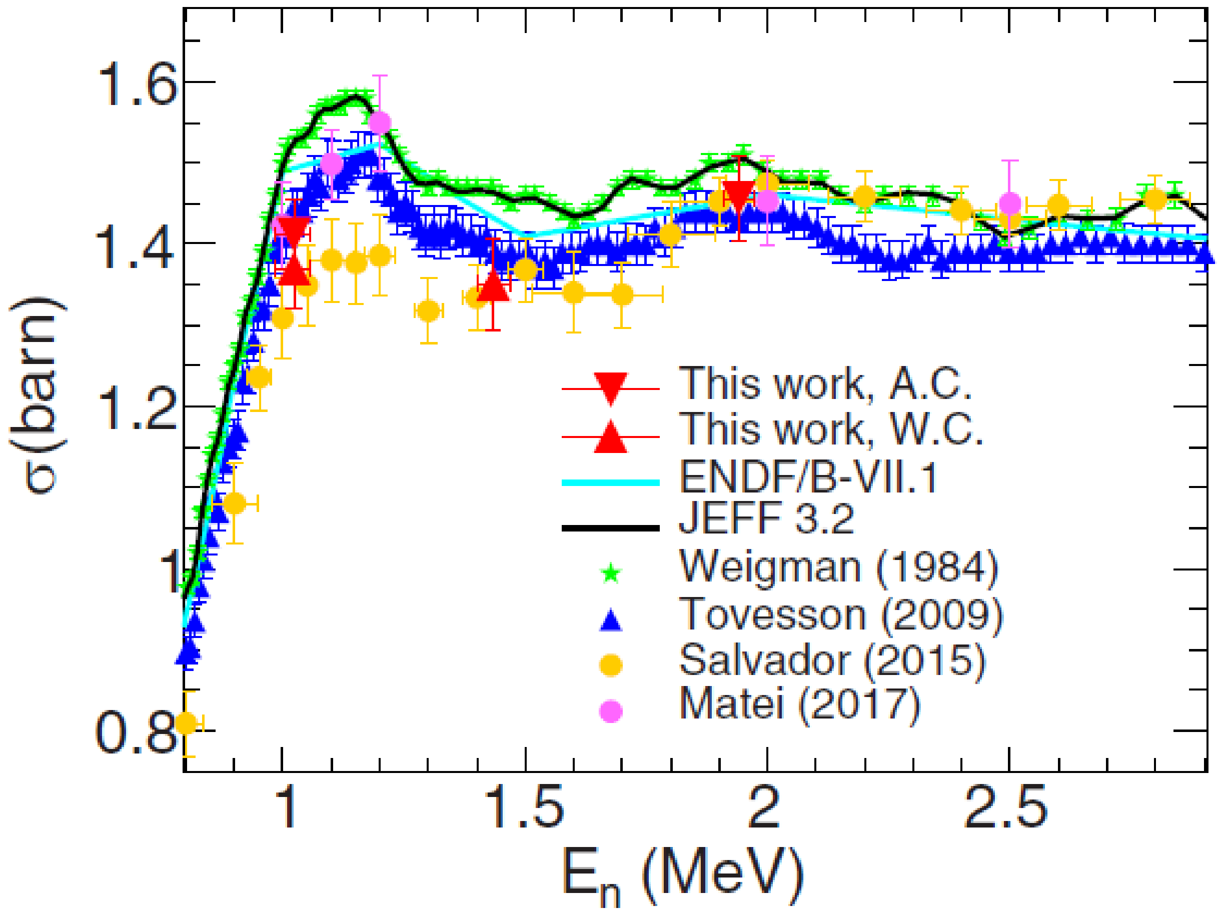


Present work
2009, Tovesson
CENDL-3.1
JENDL-4.0
ENDF/B-VIII.0
JEFF-3.3
Cross section (b)
Incident neutron energy (keV)

^{242}Pu absolute fluence reference (NPL, BRC)



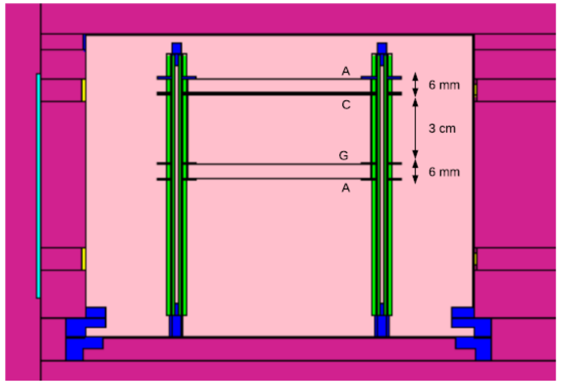


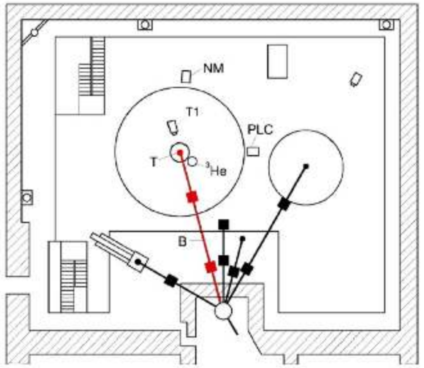


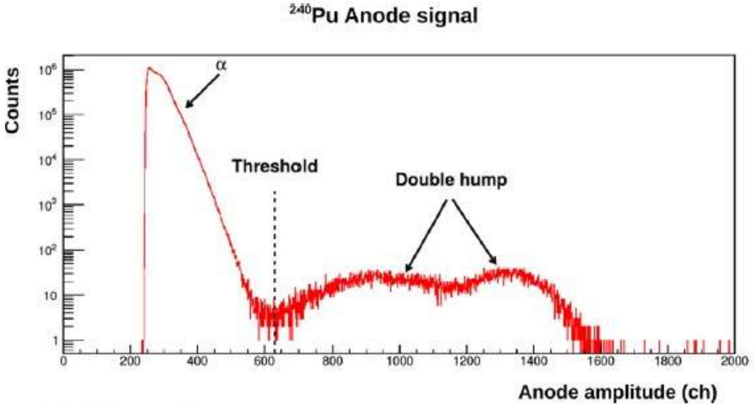
P. Marini PHYSICAL REVIEW C **96**, 054604 (2017)

C. Matei PHYSICAL REVIEW C **95**, 024606 (2017)

^{240,242}Pu&^{238}U(n,f) absolute fluence reference







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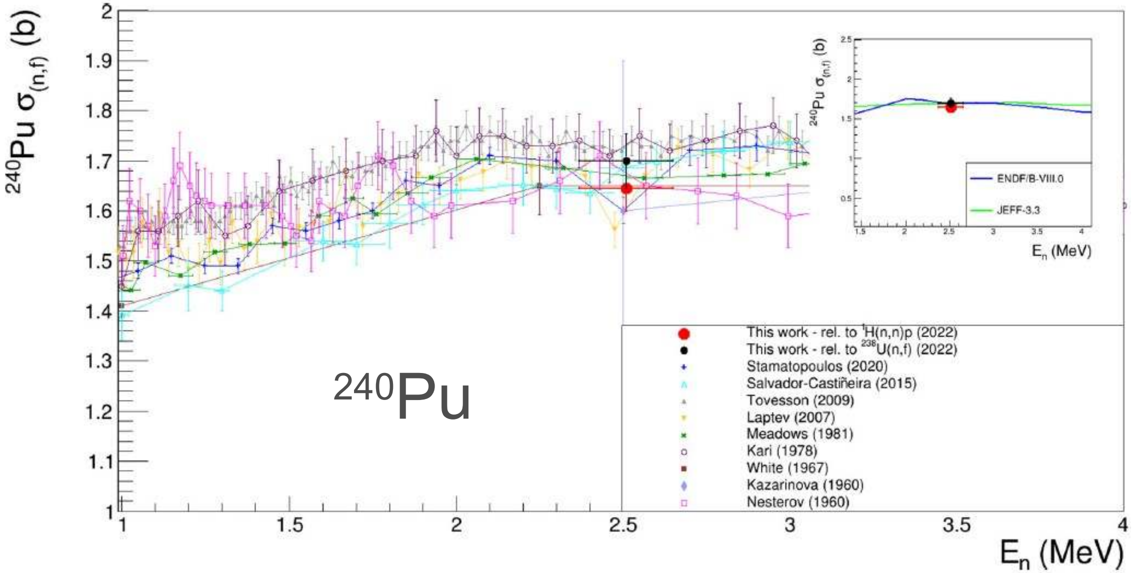

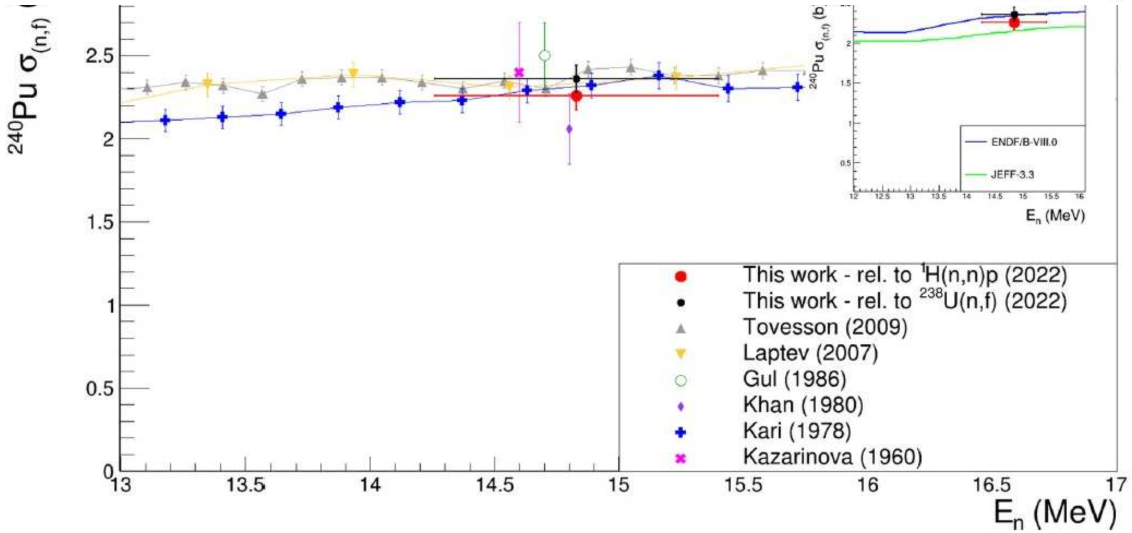

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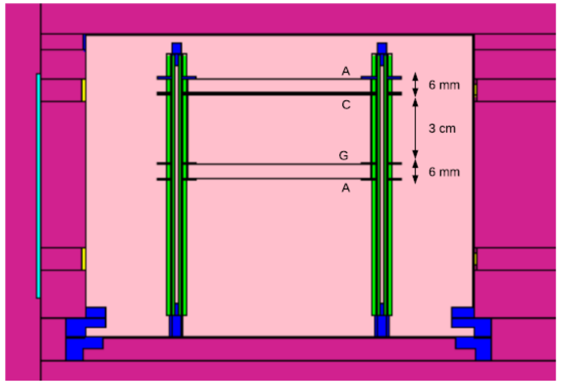

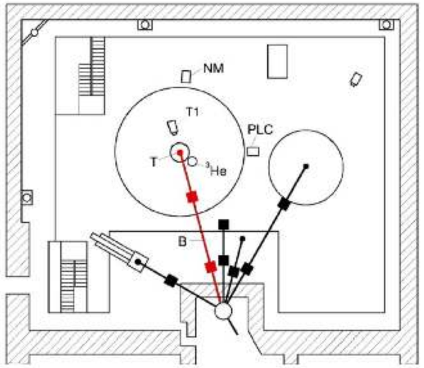

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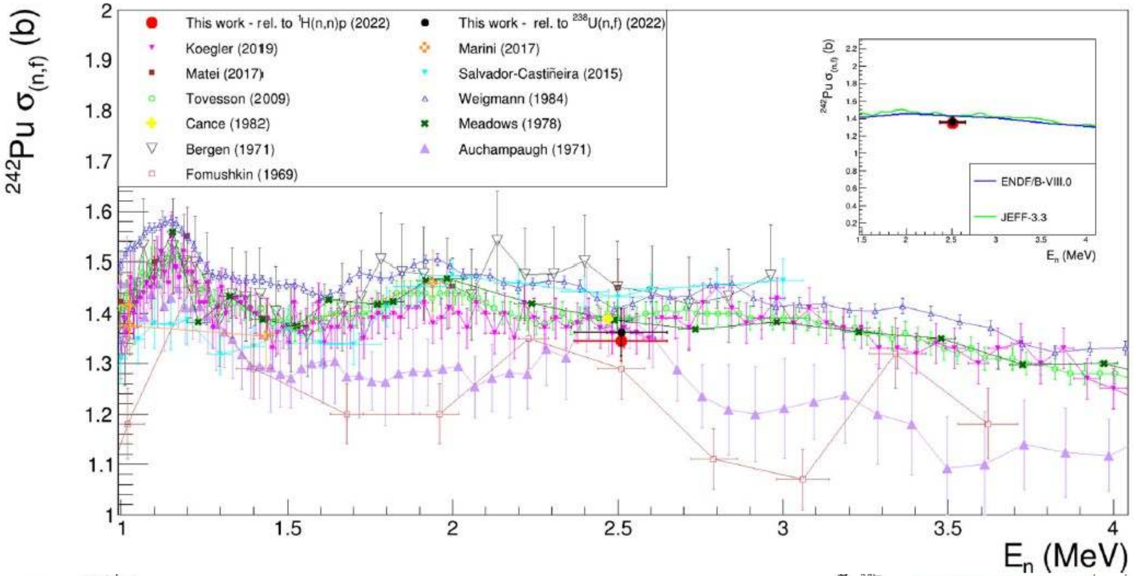

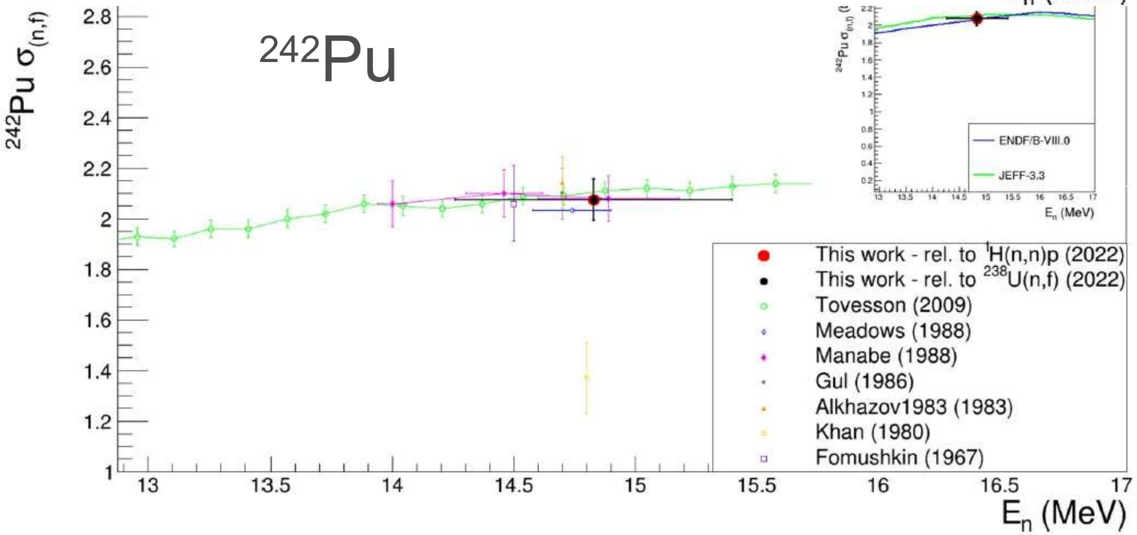

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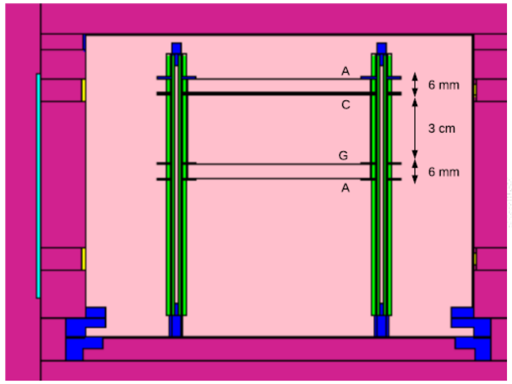

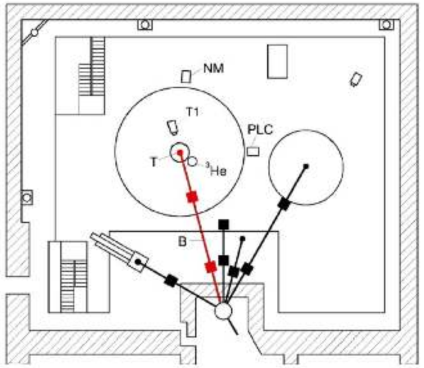

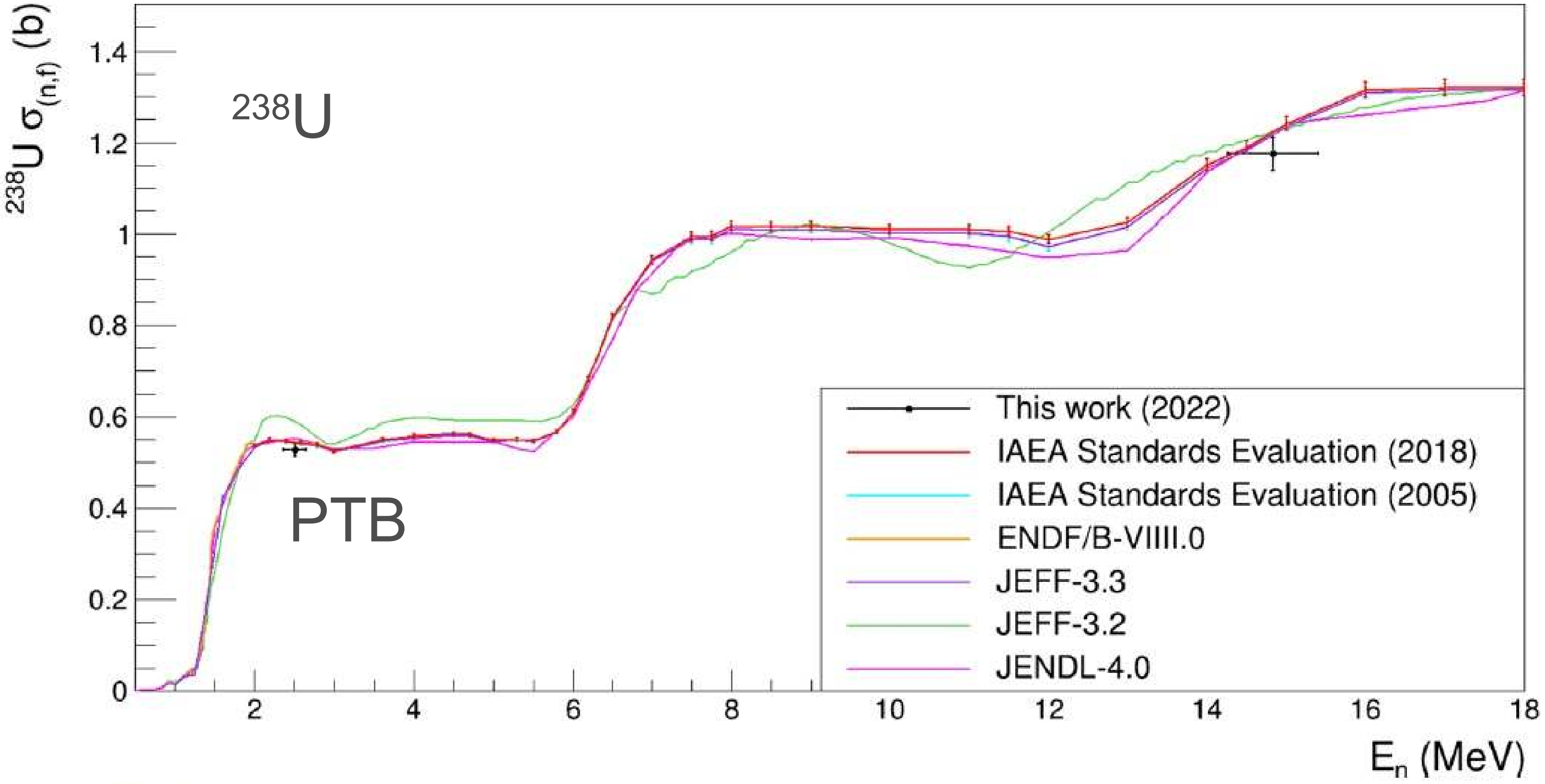

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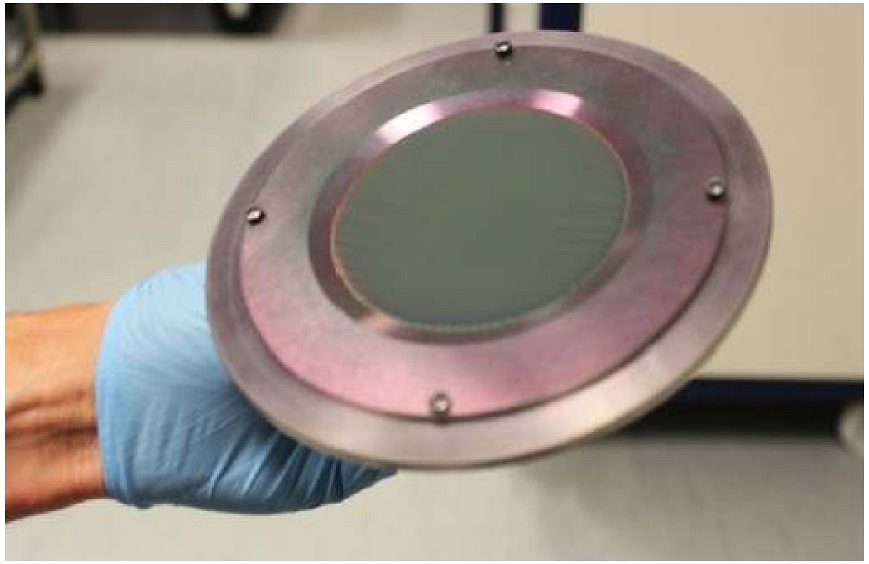
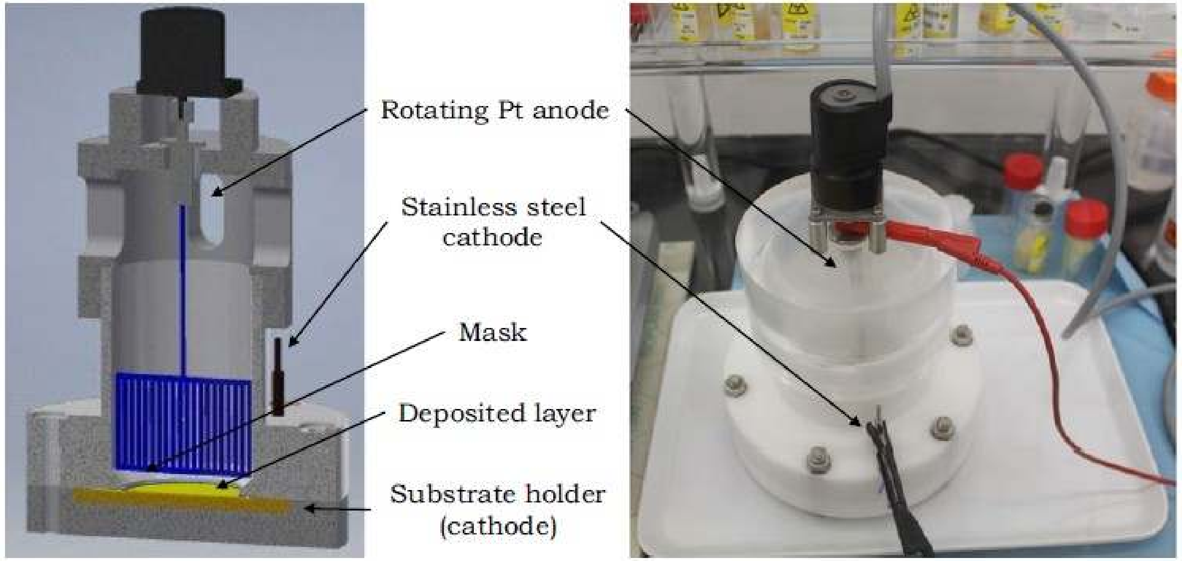
European Commission

Good targets are essential to good data





General trends in experiments for new data

- Many new good results
- Large focus on minor actinides
- Many ratios to $^{235}U(n,f)$
- Few attempts at 'absolute results'
- There is an uncertainty barrier of about 3%

- JEFF-4 will have first new evaluations for minor actinides after many years of EU projects focussing on measurements (G. Noguere, M. Diakaki)
- More work is of interest
- Data are rich and allow systematic analysis (chains $^{233,234,235,236,238}U$-$^{239,240,242}Pu$,Th-Cm)

Outlook

Recent results

Outlook

- New data sets on the way
  - N_TOF: $^{241,243}Am$, $^{239,241}Pu$, $^{235,238}U$ vs $^{1}H(n,n)^{1}H$ by two methods for the latter
  - LANL
- Complete evaluations are needed addressing all reaction channels and products
  - Data are also tackled: inelastic, nu-bar, pfns, fy…

From science to application

Who, where and how?

European Commission

From science to application (1, status)

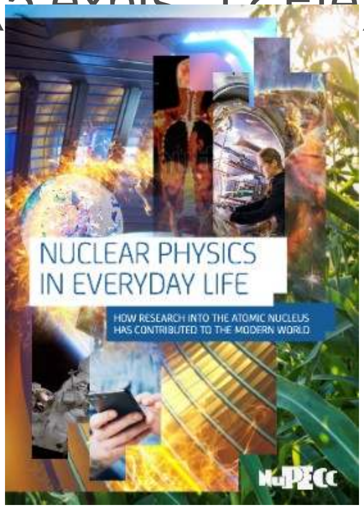
- A large part of nuclear scientific knowledge is not part of nuclear data libraries and hence not available for use in applications
- Proton-induced and neutron-induced reaction data for spallation sources and dosimetry (MYRRHA, ESS, therapy, aircraft, space)
- Photon-induced reaction data (Isotope production)
- Alpha, deuteron induced neutron source and isotope production data
- Reliable radioactive decay data (source term, dosimetry, medicine)

- There is a considerable amount of nuclear scientific research where Europe is leading (CERN, GANIL, GSI, … - NUPECC).
- There have been a number of European ND projects with the main emphasis on measurements.
- **However, the nuclear data life cycle leading from science to application is bound to fall short of the needs.**
- **Also for the data in greatest need: neutron data**

From science to application (2, what it takes)

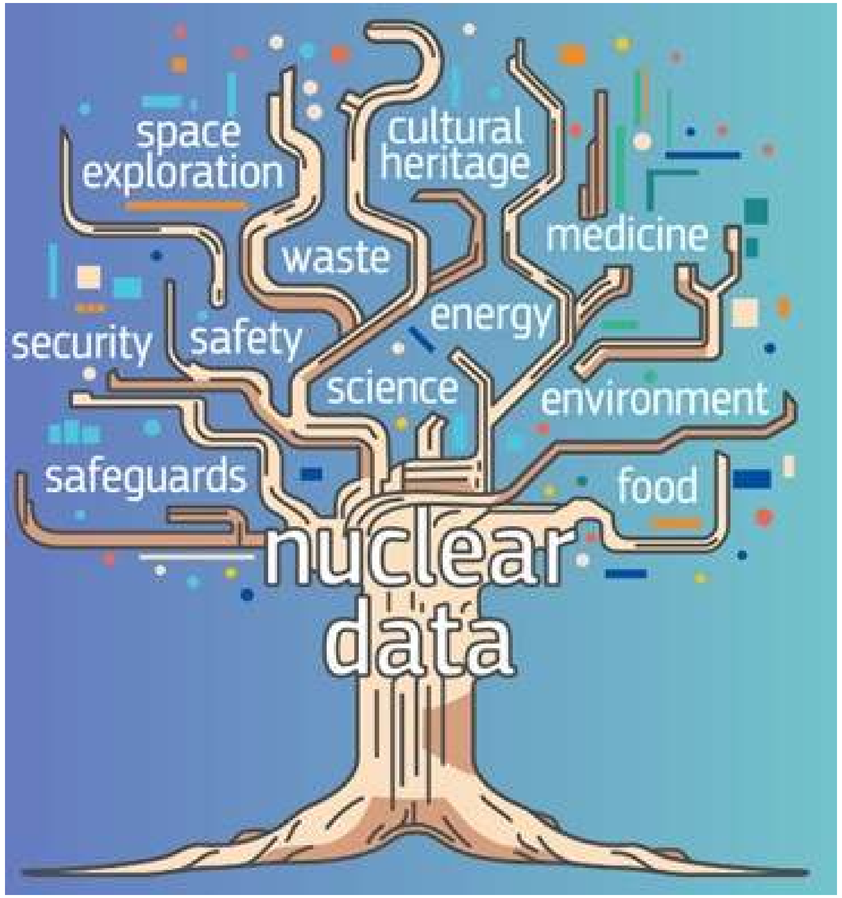
- A well-functioning nuclear data life cycle requires resources we can rely on in the form of skilled staff and research infrastructure for
- Comprehensive accurate measurements
- Evaluated nuclear data libraries
- Established processing routes
- Quality assurance through benchmarking and validation
- Feedback-loops with users

- As an example, we currently lack the experts for nuclear data evaluation:
- Resonance analysis, (2 expts, 0.2? Fte)
- Reaction modelling (7 expts, 1? Fte)
- Fission yields (4 expts, 2? Fte)
- Decay data (5 expts, 1? Fte)



From science to application (3, improving)

- **We need a strong commitment to**
  - Jointly plan and coordinate our resources to maintain the nuclear data life cycle
  - Develop and maintain an effective cooperation
  - Provide an attractive environment of nuclear data research and development for a new generation working in the interest of tomorrow’s nuclear solutions



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Thank you

EU Science Hub
Joint-research-centre.ec.europa.eu

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