European Commission

Cross Section Measurements and Uncertainties of Cross Section Data

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Contents

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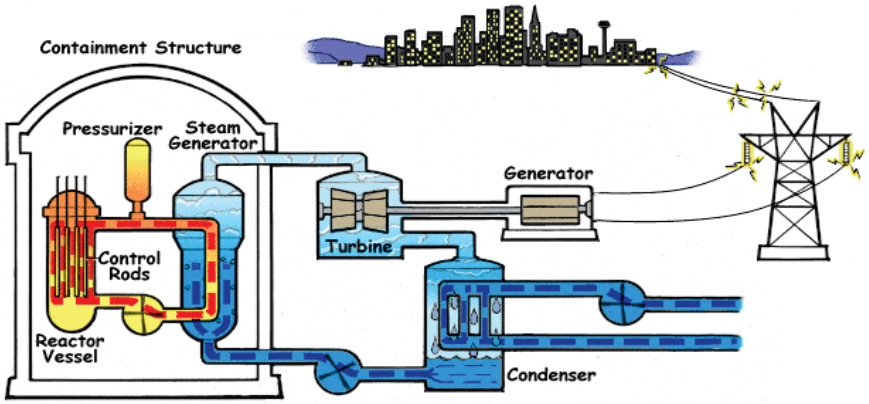
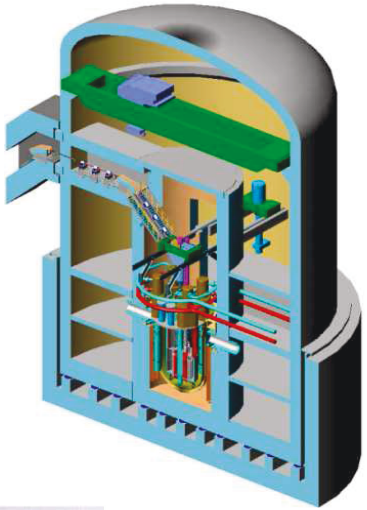
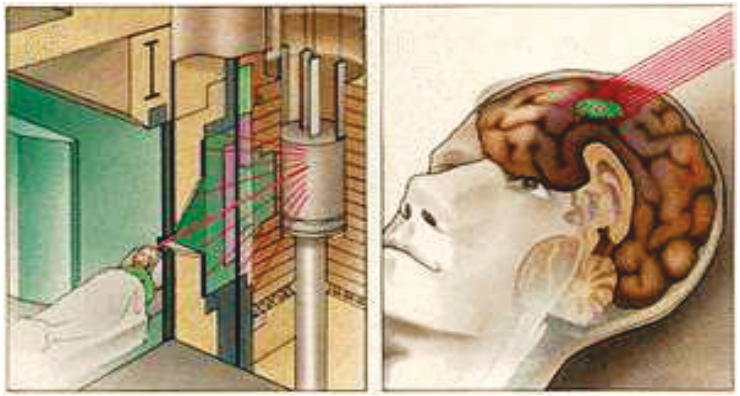
- Role of nuclear data
- Role of fission quantities
- Motivation from the perspective of reactor/fuel cycle physics
- General introduction to fission experiments
- Cross-section measurements
- Experiments for other fission quantities
- International collaboration

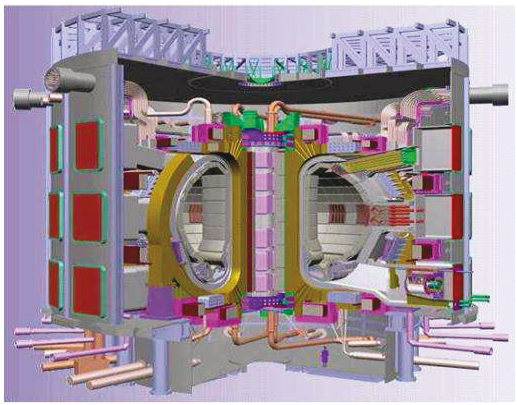
Role of nuclear data

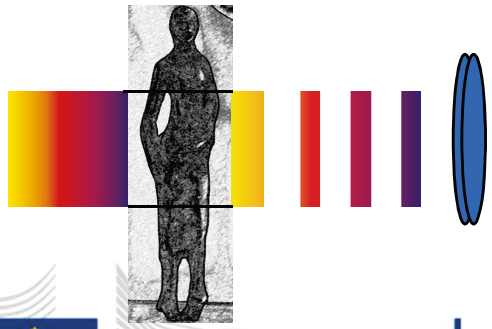
- **Nuclear energy: fission and fusion, Radiation protection, Nuclear medicine, (Nuclear) security, Object and materials analysis**
- **Science: Reactions and structure of nuclei, Astrophysics, Basic science**











Role of nuclear data

- **SRA**
  Strategic Research Agenda

- **SNETP**
  Strategic Nuclear Energy Technology Platform

LWRs

More and better quality data

Availability of accurate nuclear data (cross sections, decay constants, branching ratios, etc.) is the basis for precise reactor calculations both for current (applications to higher burn-up, plant life extension) and new generation reactors. Additional experimental measurements and their detailed analysis and interpretation are required in a broad range of neutron energies and materials. This is particularly true for fuels containing minor actinides for their transmutation in fast spectra.

New test facilities and advanced measuring techniques are necessary to support the envisaged developments in nuclear engineering simulation.

Role of nuclear data

- **SRA**
  Strategic Research Agenda

- **SNETP**
  Strategic Nuclear Energy Technology Platform

Advanced fuel cycles

Multiple recycling fuel; HLW

On the other hand, the deployment of these advanced fuel cycles needs significant R&D to meet technological challenges on:

- new fuels (targets) bearing significant amount of MA, and their fabrication technology,
- new recycling technologies based on the advanced aqueous and pyrometallurgic technologies, adapted to the high active and hot fuels,
- the technologies of the different Fast nuclear systems (FNR and ADS), including new materials, thermo-hydraulics, simulation tools and nuclear data and in the case of ADS the coupling of an accelerator and a subcritical core. This point is

Role of nuclear data

- **SRA**
  Strategic Research Agenda

- **SNETP**
  Strategic Nuclear Energy Technology Platform

5.1.3 Modelling, simulation and methods

Modelling and simulation significantly support vendors, regulators and operators in the reactor design effort, safety assessment, licensing and issue resolution during plant operation.

Theoretical models and codes form the basis of simulations. They are inherently dependent on nuclear data and also on experimental facilities providing detailed measurements for the validation of codes. Pre- and post-processing are necessary to handle these large sets of high resolution data and enable proper visualisation of complex phenomena.

Role of nuclear data

- **SRA**
  Strategic Research Agenda

- **SNETP**
  Strategic Nuclear Energy Technology Platform

Support to innovation

GFR

Analysis tools and experimental qualification

Benchmarking and qualifying codes should be continued for both core neutronics and thermal hydraulics codes making use of existing core physics experiments and commissioning new experimental studies where appropriate. On the neutronic side, 3D deterministic calculation scheme will be used after validation on reference Monte-Carlo calculations on key configurations. Uncertainty analyses will include the nuclear data part. A precise evaluation of reactivity coefficients is a key point for GFR's safety assessment.

Role of nuclear data

The Safety Research
in the European Strategic Research Agenda (SRA)
of the Sustainable Nuclear Energy Technology Platform (SNE-TP)

G.B. Bruna, IRSN, France, E. Scott-de-Martinville, IRSN, France,
P. Storey, HSE, United-Kingdom, V. Teschendorff, GRS, Germany,
M.A. Zimmermann, PSI, Switzerland

E U R O S A F E

Towards Convergence of Technical Nuclear Safety Practices in Europe

2. Safety Research

The connection between safety research and regulation is crucial [REF. 3]. In view of limited resources, it is obvious that the first priority must be given to the activities that support the regulator in solving pending safety issues, but, beyond that, it is mandatory to maintain a sufficiently broad layer of basic research, which comprises the development of simulation tools, assessment methods, data banks and experimental programmes carried-out in dedicated facilities with their laboratory infrastructure.

4. Issues in Current Reactor Research and Development

Among the main fields of interest and endeavour, we mention:

- Generation of extended data libraries to include new materials and up-date existing data in energy regions relevant to safety analysis, as well as the generation of accurate covariances matrices (relevant to uncertainty analysis) for all relevant isotopes in the libraries,

- Improvements in the cross-sections generation processes,

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Role of nuclear data

How well can we calculate neutron fields, reaction rates, nuclide inventories, radioactivity, dose rates, decay heat, …?

What is the penalty for inaccuracy?
Safety margins for reactivity, power distribution, reactivity coefficients, burnup/time to refuel, enrichment, shielding, spent fuel storage, …
Limits what we may learn from expensive integral experiments.

Boltzmann: Neutron transport

$$\frac{1}{v}\frac{\partial f}{\partial t} + \mathbf{\Omega}\cdot\nabla f + \Sigma_T f = S + \int dE' d\mathbf{\Omega}' \, f(E',\mathbf{\Omega}')\Sigma_S(E'\to E, \mathbf{\Omega}'\to\mathbf{\Omega})$$

$$S = S_{PF} + S_{dn} + S_{\alpha n} + S_{\text{ext}}$$

$$S_{PF} = \sum_i N_i \int dE' \, f(E')\overline{\nu}_i(E')\sigma_{F,i}(E')f_{P,i}(E',E)$$

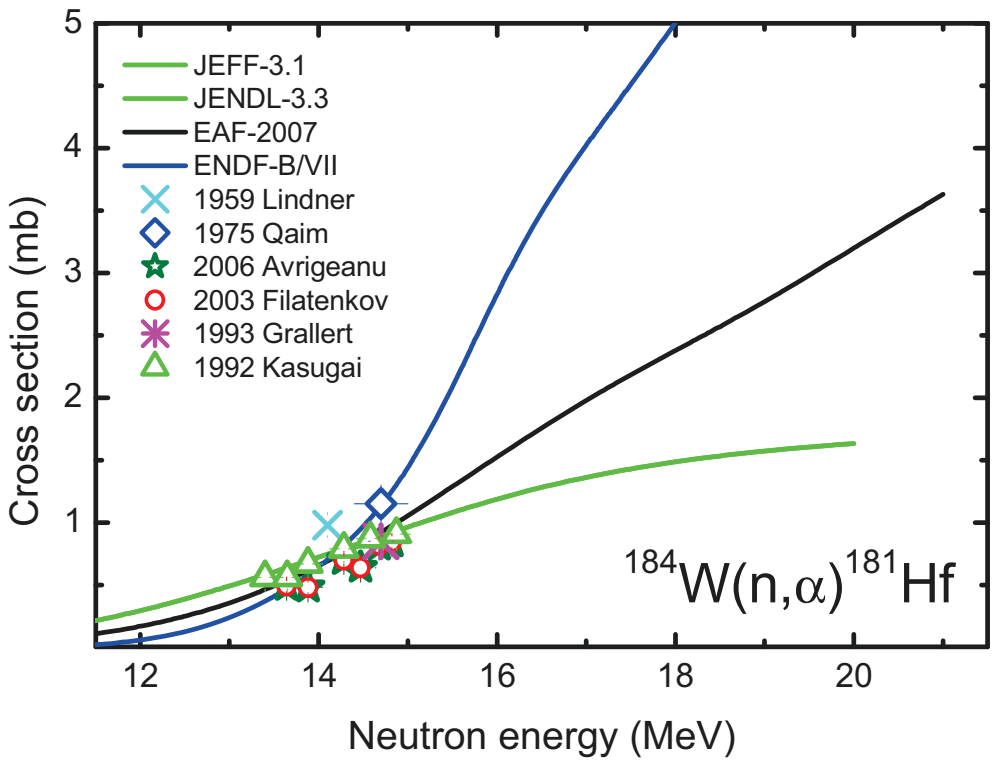
$$\Sigma_S(E\to E', \mathbf{\Omega}\to\mathbf{\Omega}') = \sum_i N_i \frac{d^2\sigma_{s,i}}{dE' d\Omega'}(E, E', \mathbf{\Omega}\cdot\mathbf{\Omega}')$$

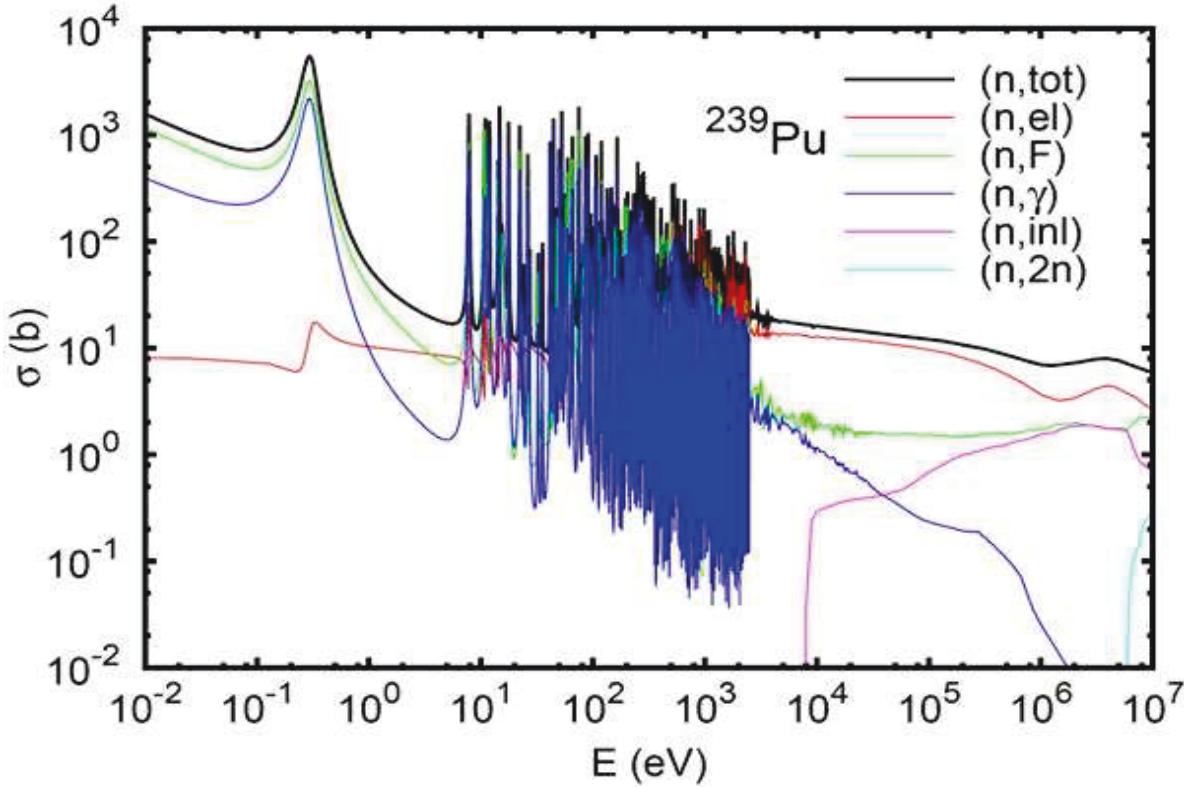
$$\Sigma_T = \sum_i N_i \sigma_{T,i}$$

Bateman: Nuclide evolution

$$\frac{dN_i}{dt} = -\lambda_i N_i - r_i N_i + \sum_{j\neq i}\left\{\lambda_{j\to i} + r_{j\to i}\right\} N_j$$

Role of nuclear data measurements





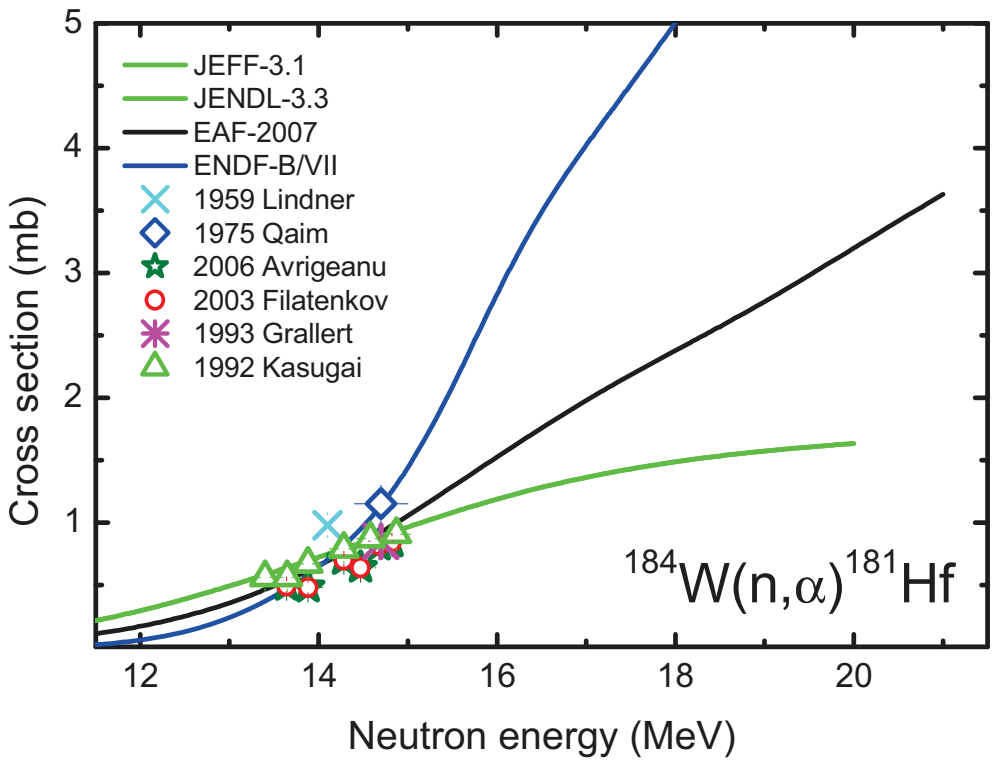
Nuclear modeling lacks accuracy for detailed predictions of cross sections

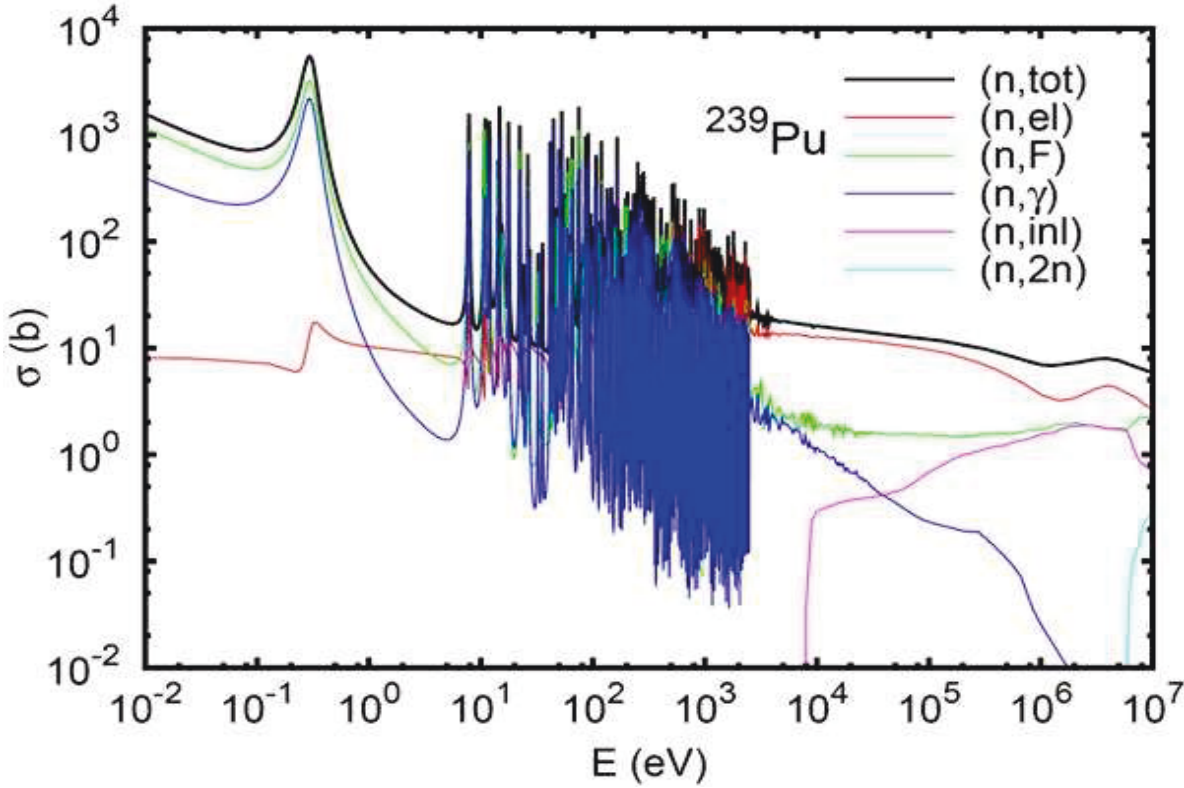
Resonance parameters are effectively stochastic variables: level energies, partial widths

Data are needed for

developing models
determining model parameters
benchmark model parameter databases and
overall model performance checks

Role of nuclear data measurements



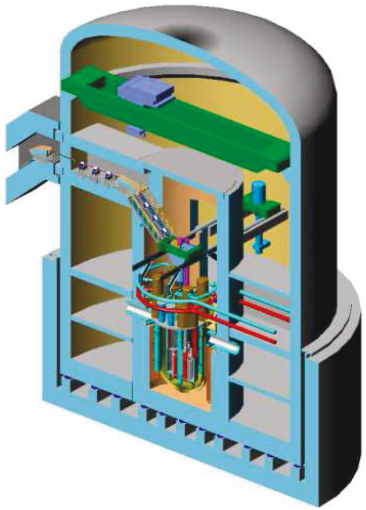


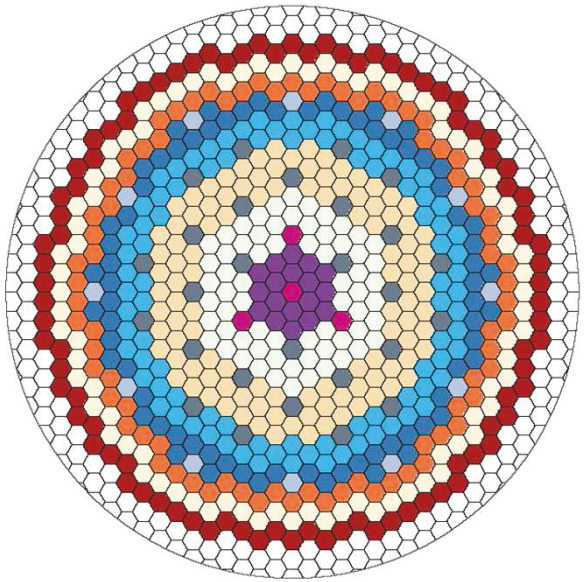
Nuclear modeling lacks accuracy for detailed predictions of cross sections, however

Modeling is essential for

extracting physical parameters from a measurement,
interpolating and extrapolating experimental results,
making an educated guess about the unmeasurable,
providing complete physically consistent databases.

Role of scattering and capture quantities





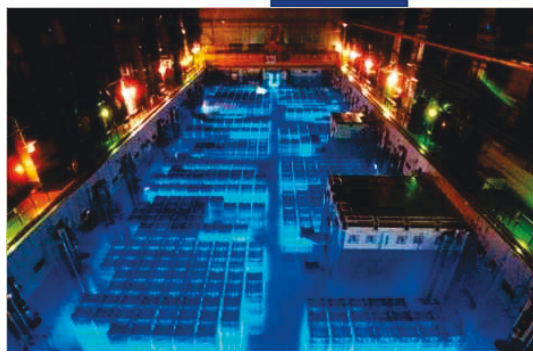
- σ_T : Mean free path (total c.s.)
- $d\sigma_{el}/d\Omega$: Angular distribution for leakage and reflection
- σ_{inl}: Mean energy loss per coll.: partial cross sections, angular distributions, gamma source term
- σ_{cap}: Radiative capture cross section, also $\sigma_{n,\gamma}$.

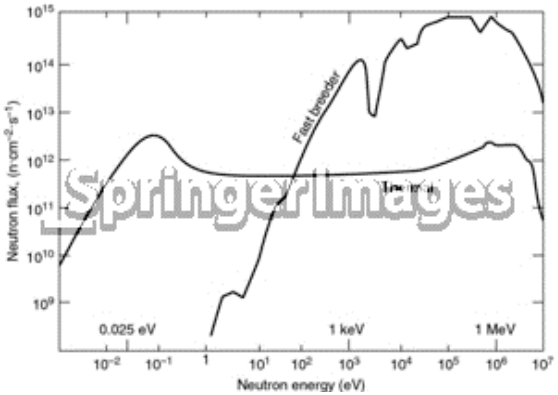
Neutron loss (neutron economy)

Transmutation $^{A}Z+n \rightarrow {}^{(A+1)}Z$

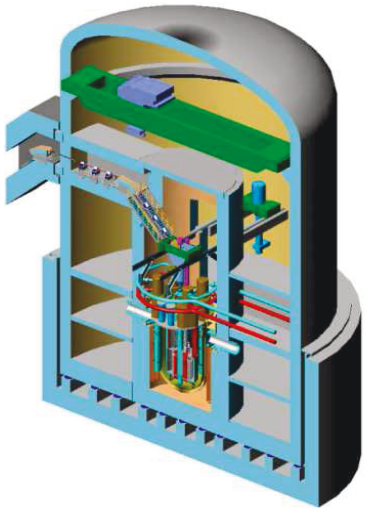
Prompt gamma source term

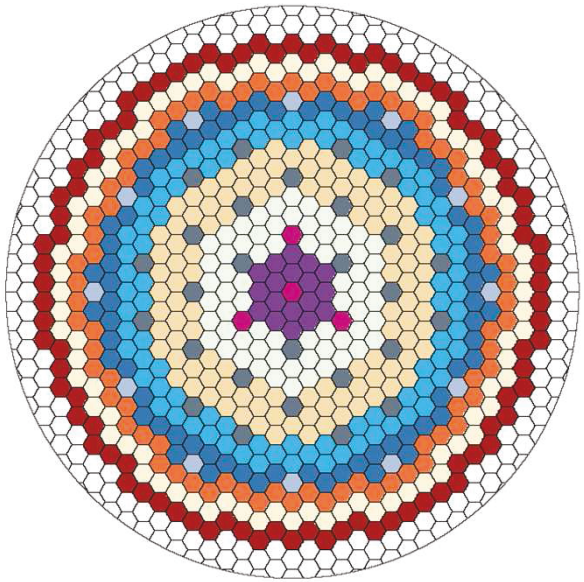
Source of residual radioactivity



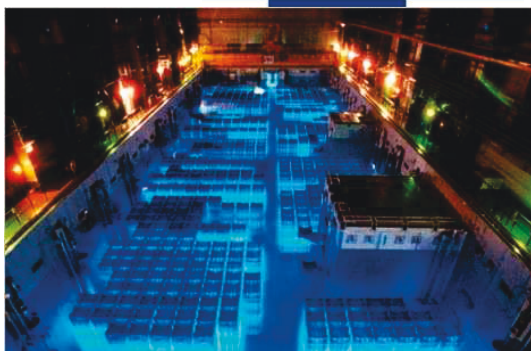


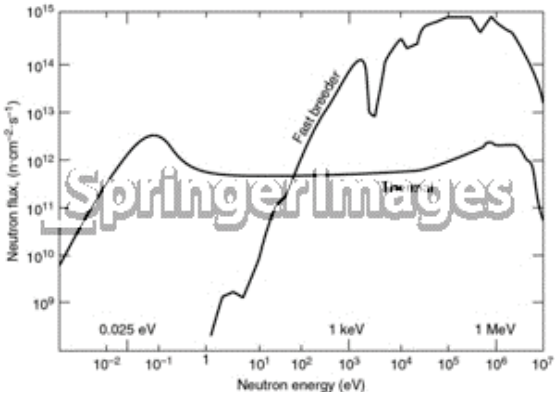
Role of fission quantities





- σ_f : Fission rate $\sigma_f \phi n$
- ν : Neutron production rate $\nu \sigma_f \phi n$
- χ_ν: Neutron source term $\chi_\nu \nu \sigma_f \phi n$
- **TKE:** thermal power (fuel)
- **FY:** source for …
- **Prompt γ,β:** heating non-fuel, dose rates, shielding
- ν_d: Reactor kinetics
- **Delayed γ,β :** Decay heat, dose rates, shielding





Sensitivity analysis

Quantitative underpinning of requests

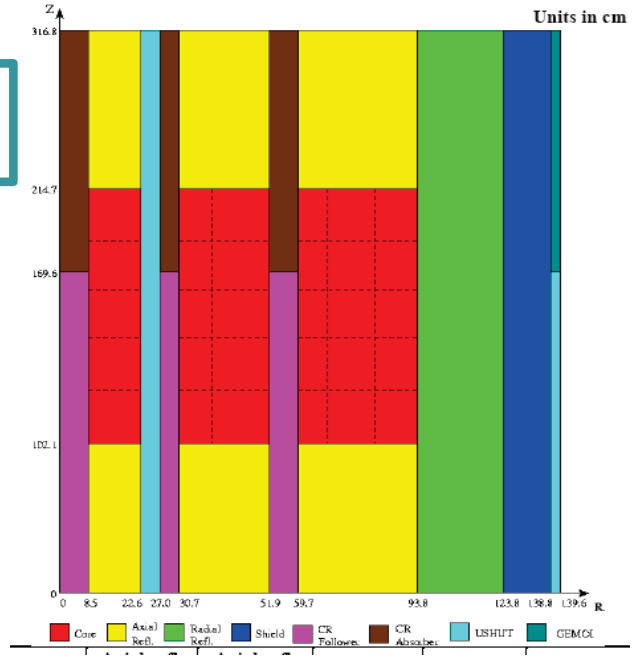
- **System modeling**
  - A simple principle…
  - Conceptual systems
  - Group cross sections

$$\mathbf{Q} = \mathbf{f}(p)$$

$\mathbf{f}$

p

  - Future
    i. Better capabilities
    ii. More modeling
    iii. Actual designs (design dependence)
    iv. Better feedback from experiments



$\mathbf{Q}$

Multiplication factor (BOL)	300 pcm
Power peak (BOL)	2%
Burn-up reactivity swing	300 pcm
Reactivity coefficients (coolant void and Doppler – BOL)	7%
Major nuclide density at end of irradiation cycle	2%
Other nuclide density at end of irradiation cycle	10%

Sensitivity analysis

Back propagation

System uncertainty limits L_i:

$$r_i(\mathbf{Q}) < L_i \quad \text{for } 1 \leq i \leq k$$

Equivalently for the parameters:

$$\sum_{a,b} S_{ia} S_{ib} C_{ab}(\mathbf{p}) r_a(\mathbf{p}) r_b(\mathbf{p}) < L_i^2, \quad i = 1..k$$

For each Q_i an ellipsoid in $\mathbf{r}(\mathbf{p})$-space

$$\min\left(\sum_a \frac{\lambda_a}{r_a^2(\mathbf{p})}\right)$$

The cost parameters λ_a may be changed according to the relative difficulty of obtaining low uncertainties for the parameter p_a.

$r_i(x)$: relative uncertainty of x

r_i(x): relative uncertainty of x

Leave a domain of acceptable uncertainties
Allows a range of solutions that is hard to visualize or delineate

Cost function minimization is used to find the best route to the final goal

An r_a(p) more accurate than needed will relax requirements on other parameters

Sensitivity coefficient: $S_{ia} \equiv \frac{p_a}{f_i}\frac{\partial f_i}{\partial p_a}$

$$C_{ab}(\mathbf{p}) \equiv \frac{V_{ab}(\mathbf{p})}{u_a(\mathbf{p}) u_b(\mathbf{p})}$$

Sensitivity analyses

- **Subgroup-26**

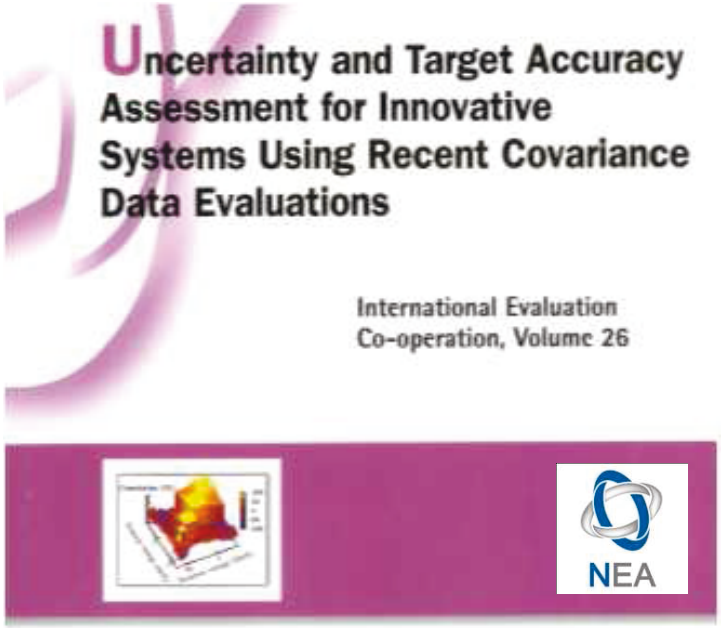
  Final report and several additional references (Salvatores et al., Aliberti et al.)

Fast reactors

- ABTR, EFR, SFR (Na)
- LFR, ADMAB (Pb)
- GFR (gas)

Thermal reactors

- PWR
- VHTR



- **N. Garcia Herranz et al.,** Propagation of statistical and nuclear data uncertainties in Monte Carlo burn-up calculations, Ann.Nucl.En. 35 (2008) 714

- **N. Garcia Herranz et al.,** Nuclear data requirements for the ADS conceptual design EFIT: uncertainty and sensitivity study, Ann. Nucl. En. 37 (2010) 1570

Subgroup-26 – tables per system

Table 26. SFR: uncertainty reduction requirements needed to meet integral parameter target accuracies

Isotope	Cross-Section	Energy range	Uncertainty (%)			
			Initial	Required		
				$\lambda=1$	$\lambda\neq1$ [(a)]	$\lambda\neq1$ [(b)]
U238	σ_{capt}	24.8 - 9.12 keV	9	4	3	3
	σ_{inel}	6.07 - 0.498 MeV	20	5	6	10
Pu238	σ_{capt}	183 - 24.8 keV	20	12	12	10
	σ_{fiss}	6.07 – 0.09 MeV	20	3	3	3
	ν	1.35 - 0.067 MeV	7	3	3	2
Pu239	σ_{capt}	498 – 2.03 keV	12	6	4	4
	σ_{inel}	6.07 – 0.498 MeV	25	12	15	22
Pu240	σ_{capt}	498 - 9 keV	12	5	5	4
	σ_{fiss}	6.07 – 0.0045 MeV	10	2	2	2
	ν	2.23 – 0.183 MeV	4	2	2	1

Very tight requirements; accurate measurements are required

Sensitiviy analysis example shows …

Use of data in reactor modeling

Use of uncertainties in reactor modeling

Role of data uncertainties

Role of uncertainty correlation

The benefits of sensitivity analysis to identify important issues in
nuclear data, and
the impact of data uncertainties on your problem.

Other ways of identifying needs

Importance diagrams

Activation data

UKAEA report 552
Handbook of activation data
EASY-2007 (2009)

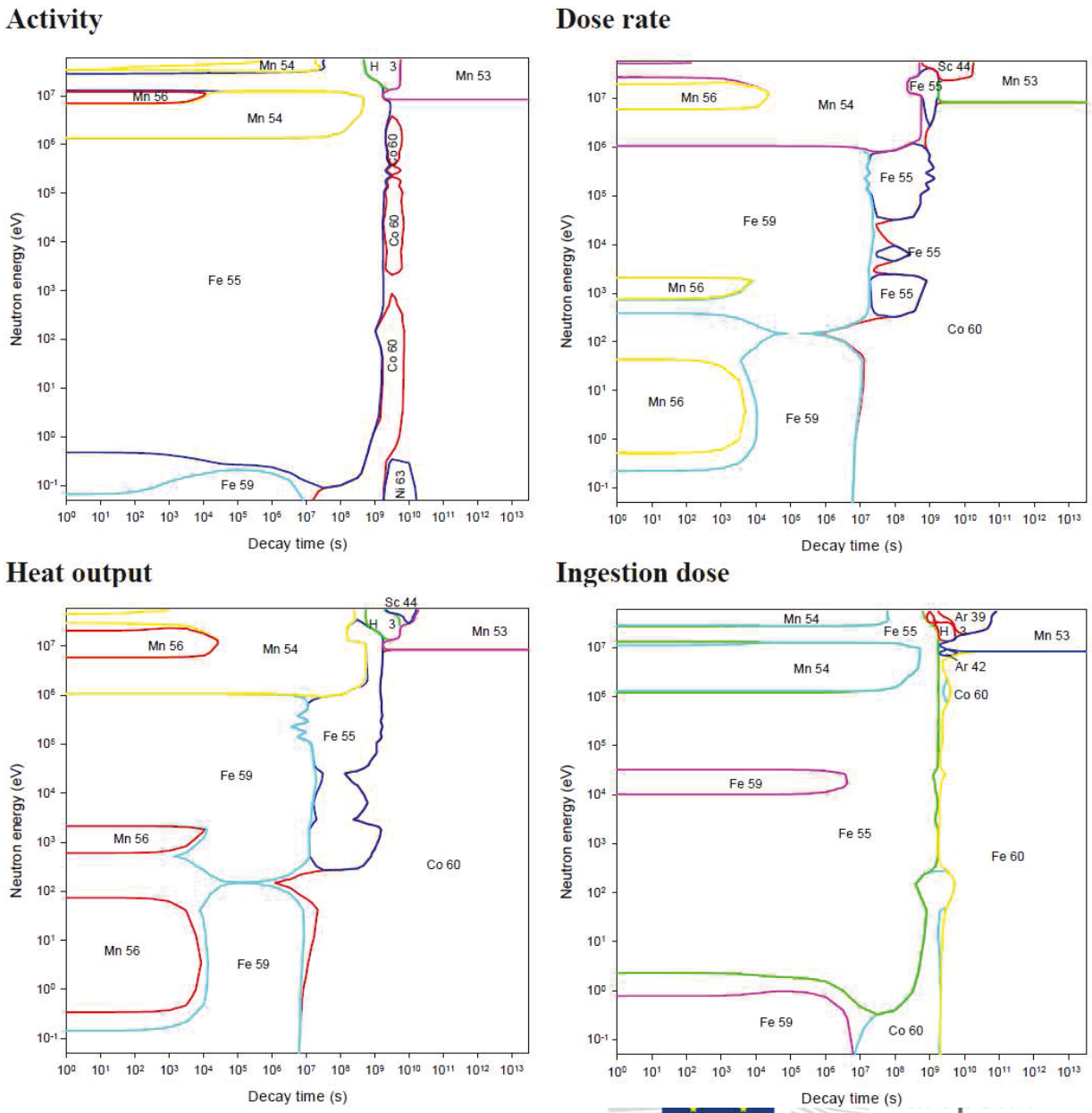
Example: iron

Vertical axis: neutron energy

Horizontal axis: time

E_n: 25 meV – 20 MeV

Time: 1-10^{13} s or 1 s – 3 10^5 y



Nuclear data needs

Established network and procedures

- **Feedback from users and validation**
- **New measurement and evaluation**
- **Quality cycle**

International fora (WPEC, JEFF, OECD-NEA, IAEA)

Collaborations between interested partners

High priority request list for nuclear data (OECD-NEA)

www.oecd-nea.fr/html/dbdata/hprl

Measurements of nuclear data

Decay data measurements

Half life

Type: γ, CE, β^-, β^+, ε, n, α, SF

Emission energies, spectra, probabilities

Residual nuclide level and decay scheme

Nuclear structure studies

Gammasphere, Euroball, Eurogam,

Exogam, Jurogam, Miniball, Agata, Greta,

various smaller setups.

Large specialized community

Radionuclide metrology

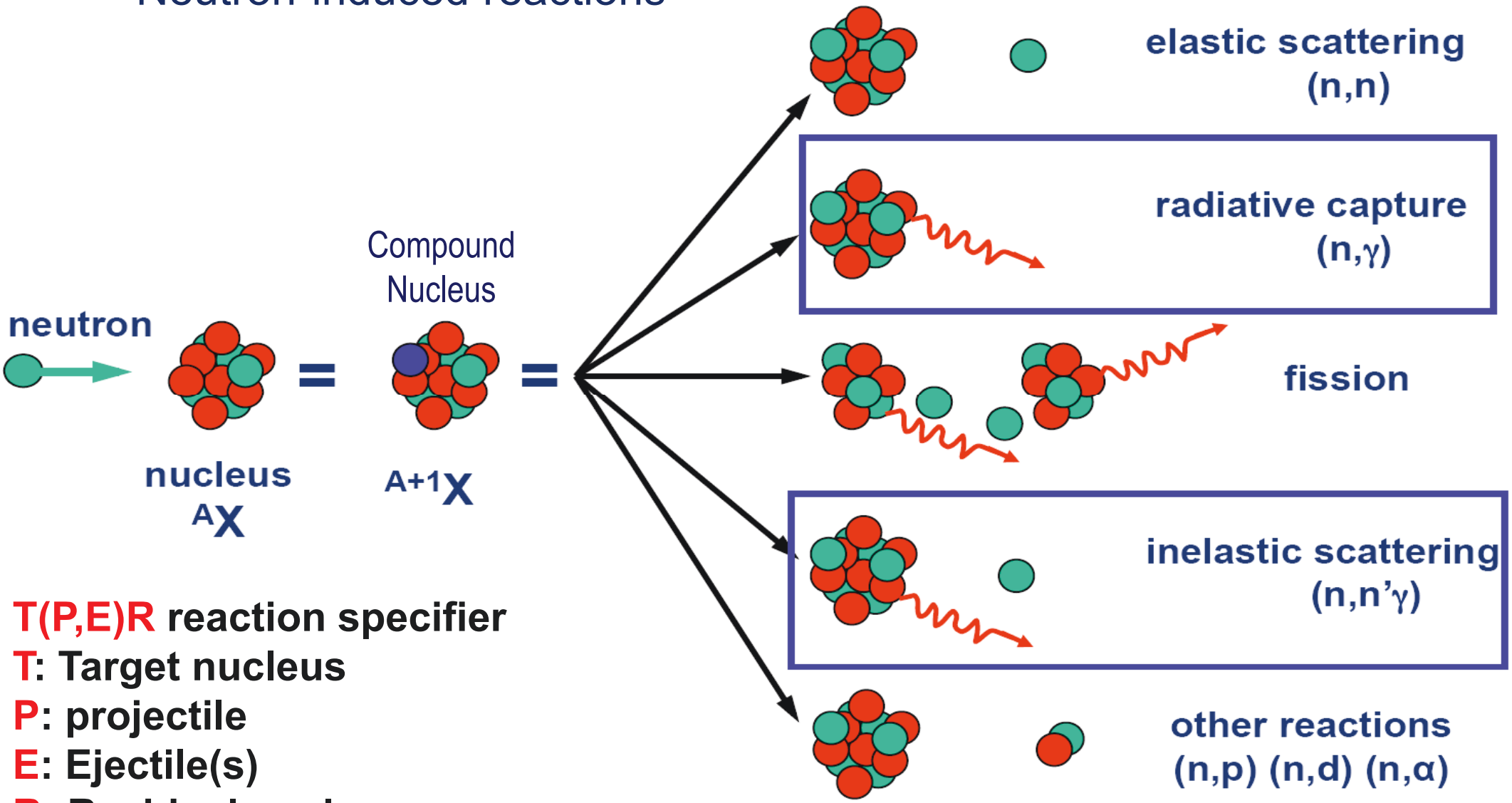
Accurate data for calibration sources

Accurate sources (α,β,γ,F)

Methods of measurement

Measurements of nuclear reaction data

Neutron-induced reactions



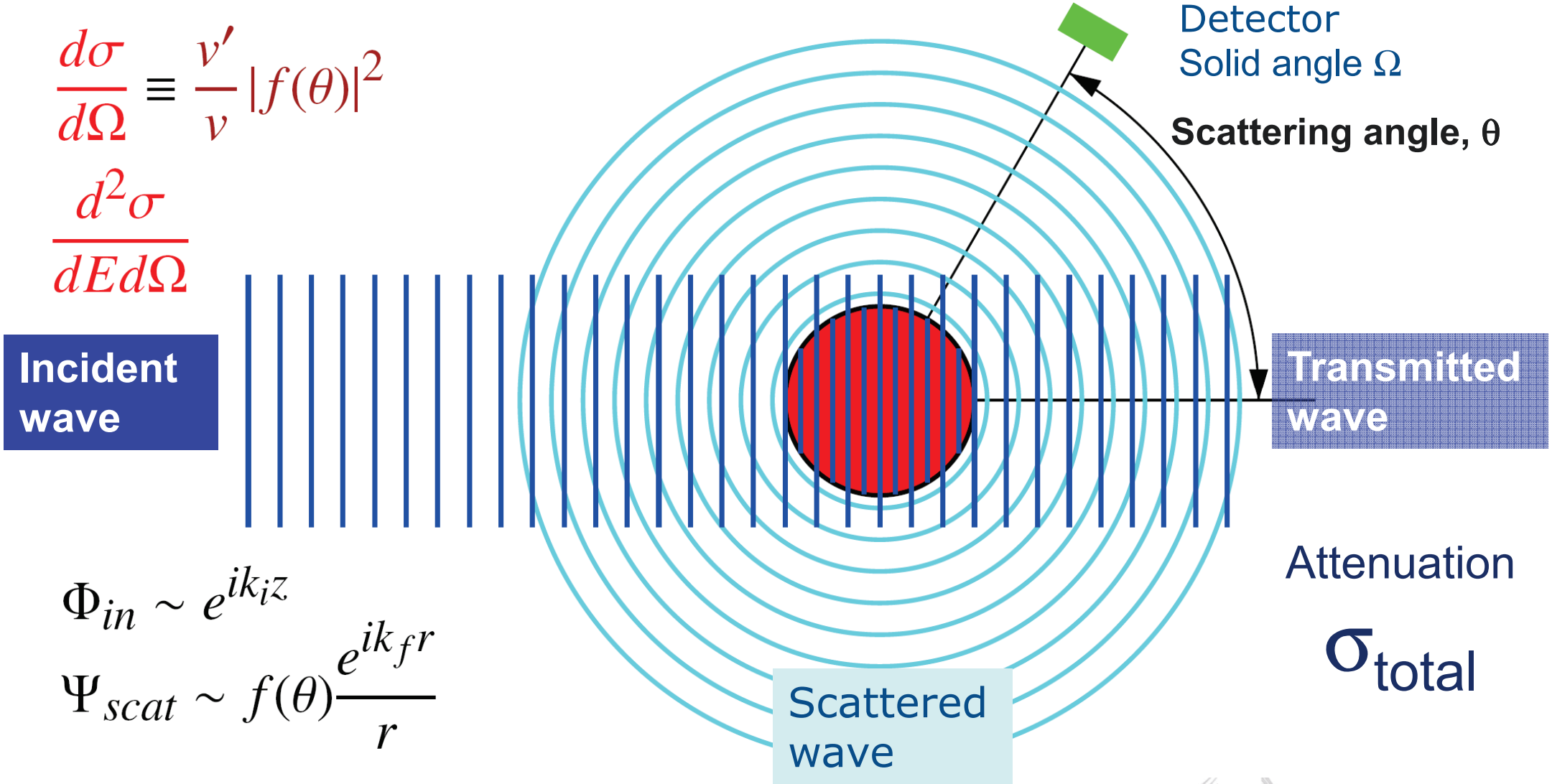
T(P,E)R reaction specifier
T: Target nucleus
P: projectile
E: Ejectile(s)
R: Residual nucleus

Measurements of nuclear reaction data

Reaction rates: cross section

$$\frac{d\sigma}{d\Omega} \equiv \frac{v'}{v}|f(\theta)|^2$$

$$\frac{d^2\sigma}{dEd\Omega}$$



$$\Phi_{in} \sim e^{ik_i z}$$

$$\Psi_{scat} \sim f(\theta)\frac{e^{ik_f r}}{r}$$

Attenuation

σ_{total}

Measurements of nuclear reaction data

Definition and measurements of cross section

$$\sigma \equiv \frac{\text{Reaction rate}}{\text{flux}} \text{(per target nucleus)} = \frac{\dot{R}}{\Phi}$$

$$\sigma = \frac{\text{\# reactions}}{\text{fluence}} \text{(per target nucleus)} = \frac{R}{F}$$

$$F = \Phi t,\ R = \dot{R} t,\ t = \text{measurement time}$$

Rate must be specified

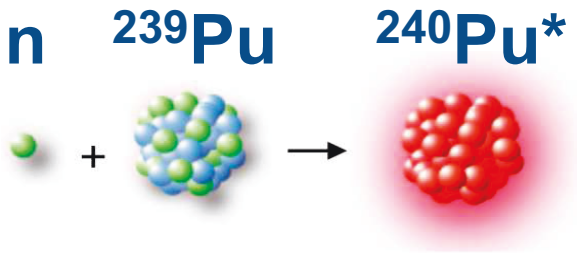
- Process (fission, elastic, …)
- Energy of particle(s) (E, E')
- Angle of particle(s) (θ, dΩ')
- Number of particles, …

Measurements

- Rate of process
- Fluence/normalization
- Number of target nuclides
- Influence parameters (temperature, humidity, …)

Measurements of nuclear reaction data

The resonance range, resolvable and unresolvable structures



Excitation: n + ^{239}Pu

J^{π} = 0^+ & 1^+ (s-waves, low E_n)

$\Gamma \approx 50$ meV

$\tau \approx 1.3\ 10^{-14}$ s

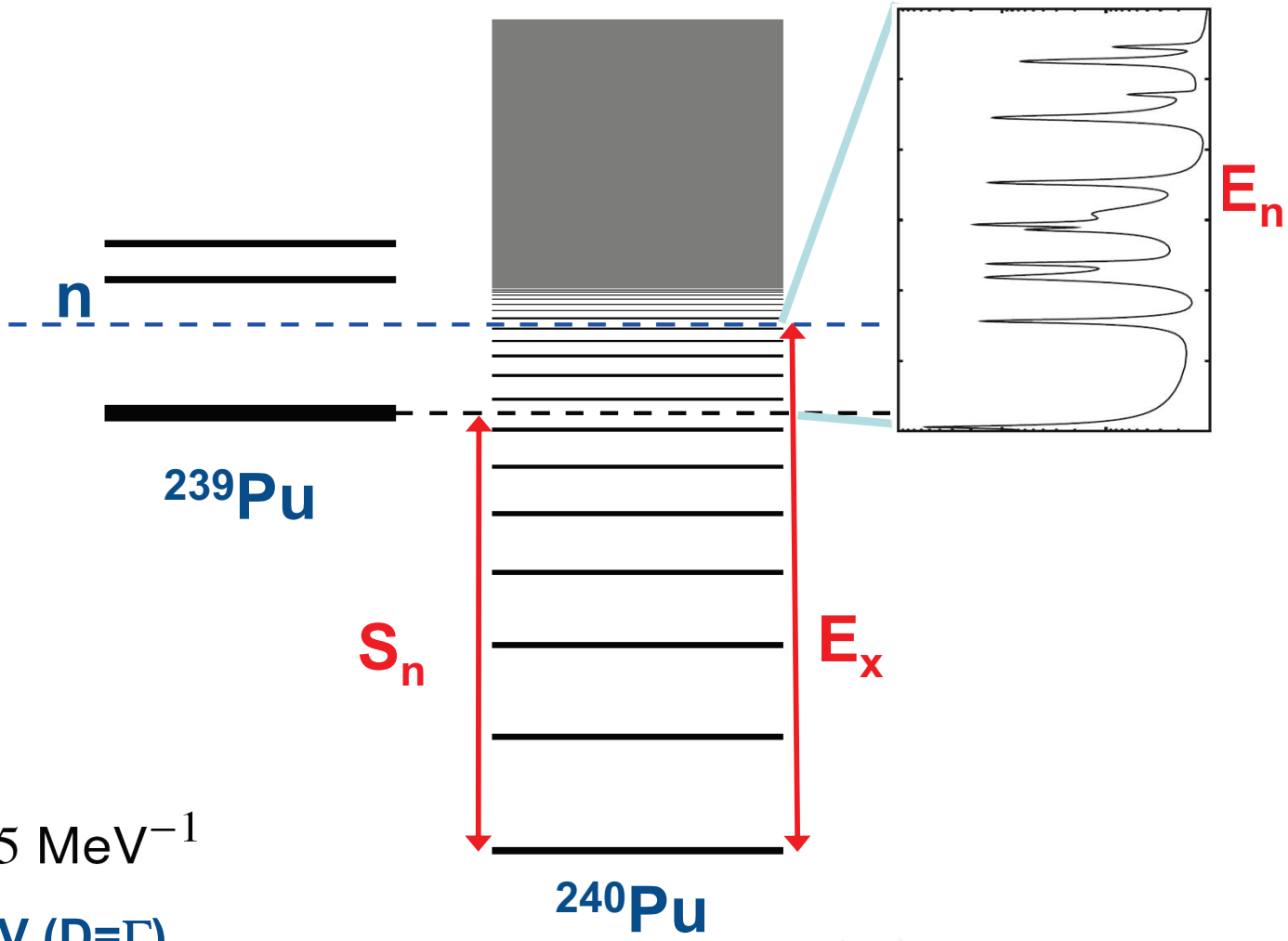
Typical $E_x = S_n + E_0$

$S_n = 6.53\ 10^6$ eV

Typical spacing D_0=2.07 eV

$$D \sim E^{5/4} e^{-2\sqrt{aE}} \qquad a \approx 23.55\ \mathrm{MeV}^{-1}$$

s-wave overlap at $E_x \approx 2.3$ MeV ($D=\Gamma$)



Measurements of nuclear reaction data

The resolved resonance range: resonance parameters

Excitation and decay of an intermediate metastable state

Channels, i=initial, f=final

Excitation: $P_e=\Gamma_i/\Gamma$

Decay: $P_d=\Gamma_f/\Gamma$

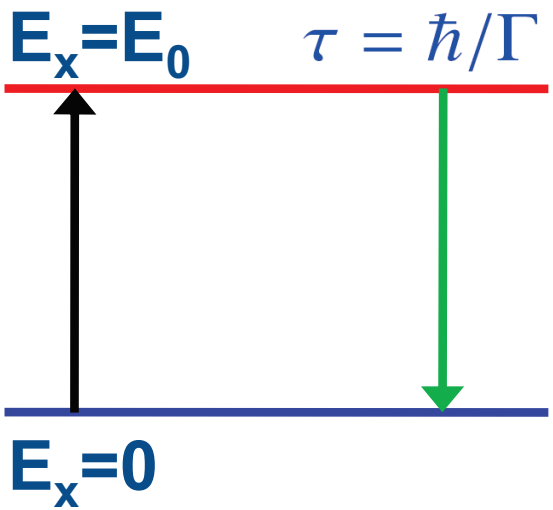
$$\sigma_a(E) = \frac{\pi}{k^2} g_J \frac{\Gamma_i \Gamma_f}{(E-E_0)^2 + \Gamma^2/4}$$

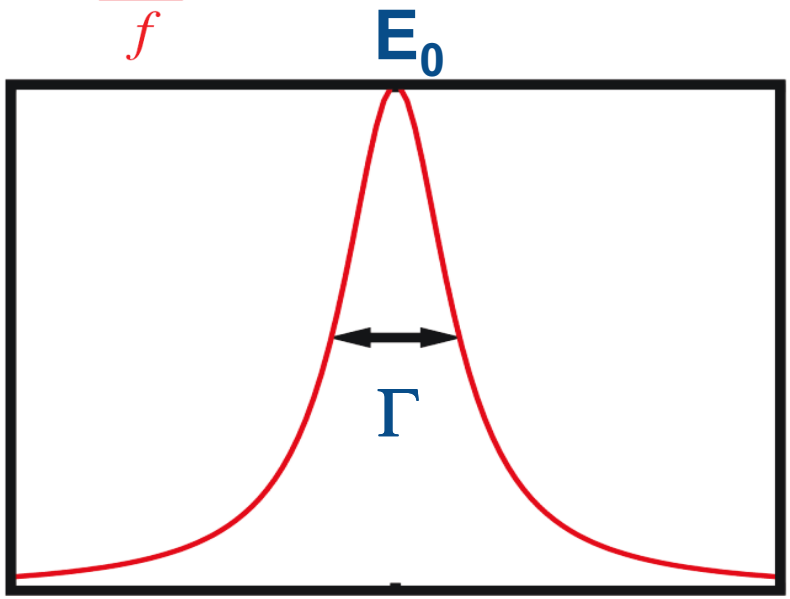
$$\Gamma = \sum_f \Gamma_f$$

Mean life time τ

Natural line width Γ

$$\tau = \hbar/\Gamma$$





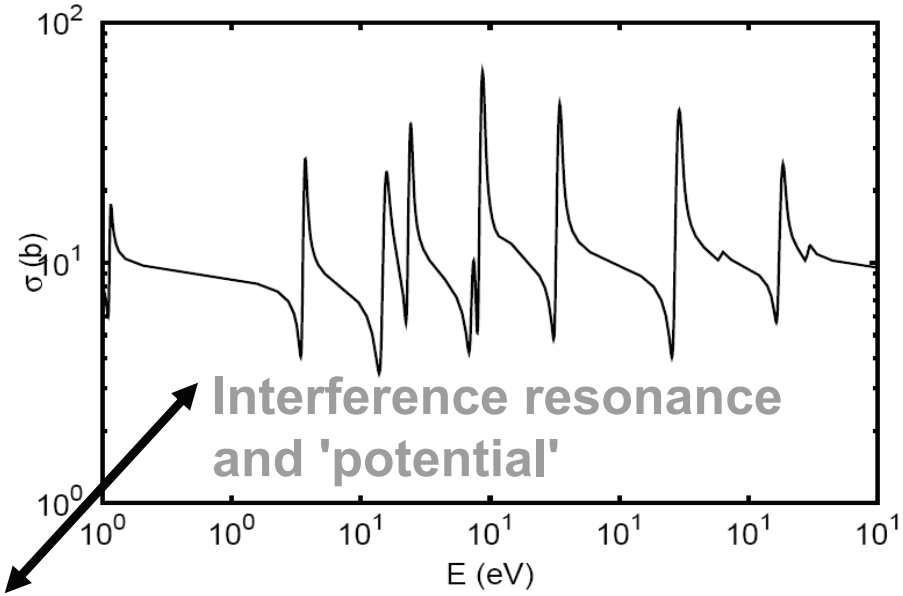
Measurements of nuclear reaction data

$$\sigma_a(E) = \frac{\pi}{k^2} g_J \frac{\Gamma_i \Gamma_f}{(E - E_0)^2 + \Gamma^2/4}$$

in

out

Spin factor



$$\sigma_T(E) = g_J \frac{4\pi}{k^2} \left\{ \frac{\Gamma_n \Gamma/4}{(E - E_0)^2 + \Gamma^2/4} + \frac{\Gamma_n (E - E_0) k R'}{(E - E_0)^2 + \Gamma^2/4} + (kR')^2 \right\}$$

Radius

Many parameters

E_0, J^π, Γ, Γ_n, Γ_γ, Γ_f, R', g_J

R-matrix: sophisticated model

Advanced analysis codes:

REFIT, SAMMY, CONRAD

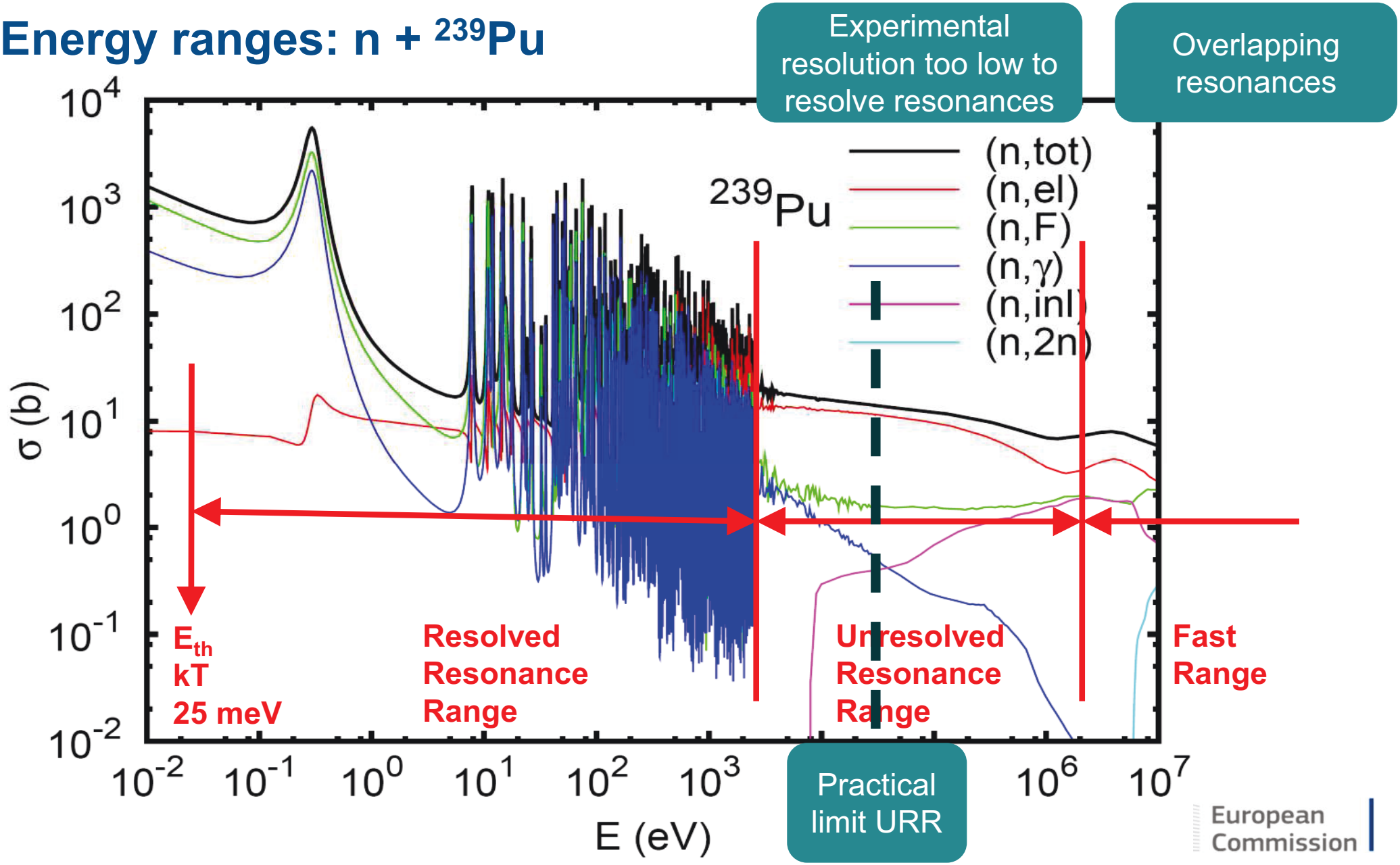
Characterization of resonances requires measurements with good energy resolution

Good understanding of broadening mechanisms (Doppler, moderator, sample & detector)

European Commission

Measurements of nuclear reaction data

Energy ranges: n + ^{239}Pu



Measurements of nuclear reaction data

Summary part 1

Interest in nuclear data

Use of uncertainties

Need for measurements

Cross sections

total, fission, elastic

inelastic, residual or ejectile yields

Differential cross section

Angular distribution

Emission spectrum

Double differential

Experimental parameters

Physical (resonance) parameters

Influence quantities

Doppler broadening

Instrumental broadening

Sample broadening

Temperature

Pressure

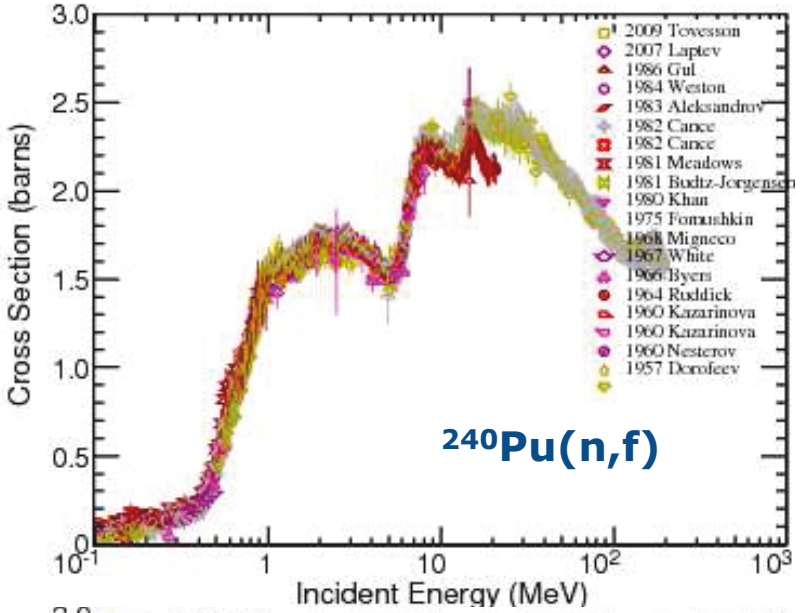
Sample composition, impurities, dimensions, roughness,…

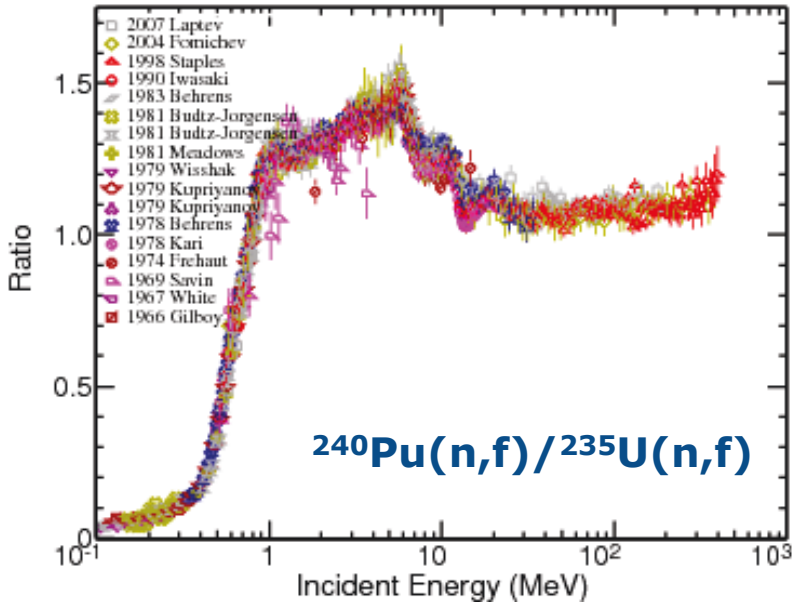
Room return

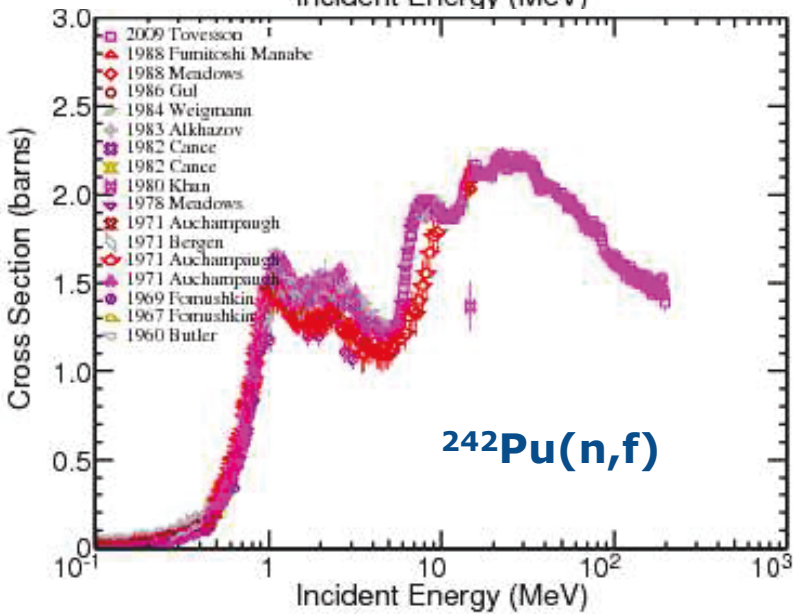
Collimation

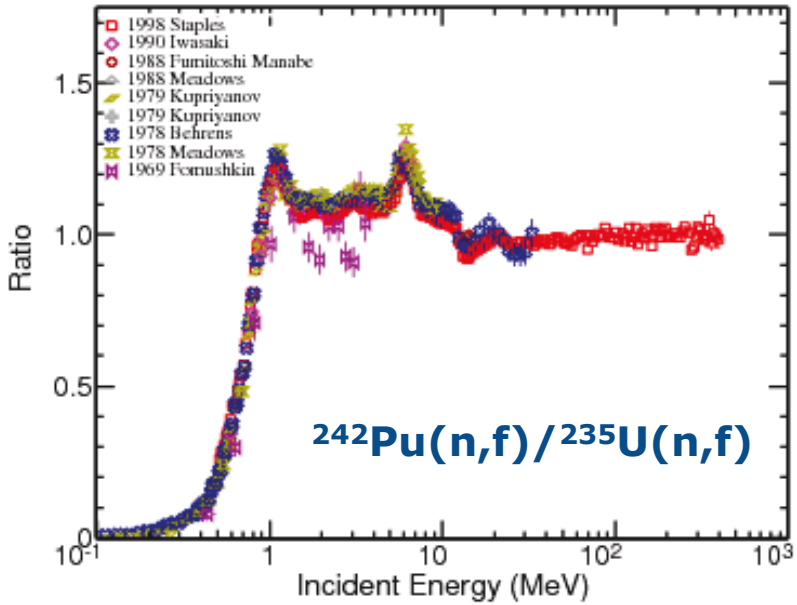
Neutron sources

Example: ^{240}Pu(n,f) and ^{242}Pu(n,f) status









Despite considerable effort
10% spread

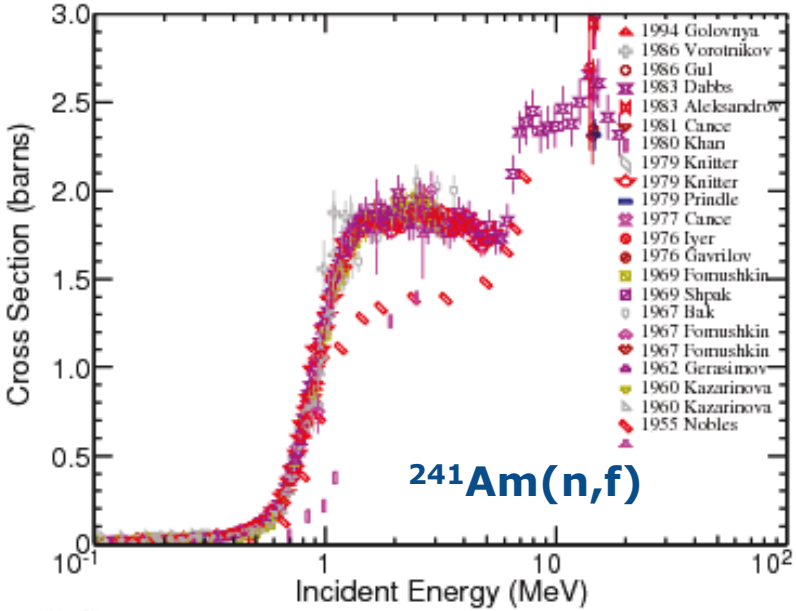
Many measurements claim 2% or better for the ratio

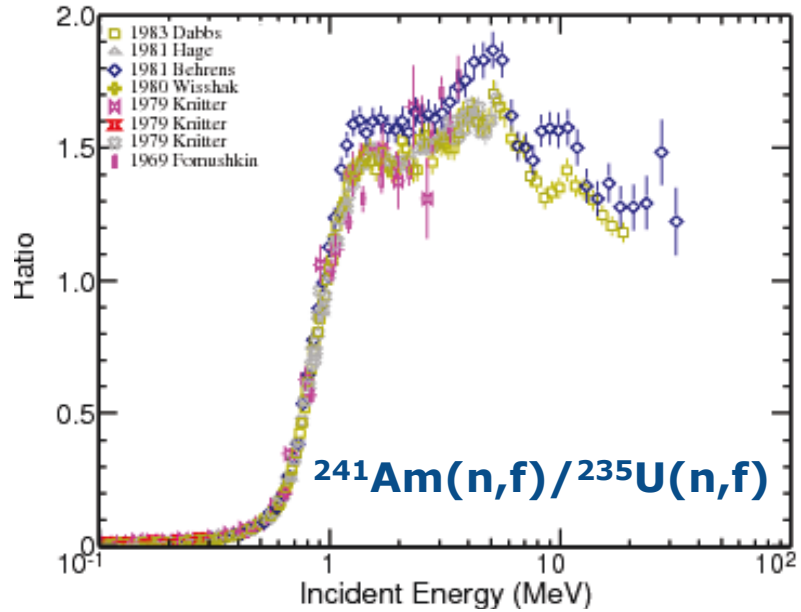
Many ratio data

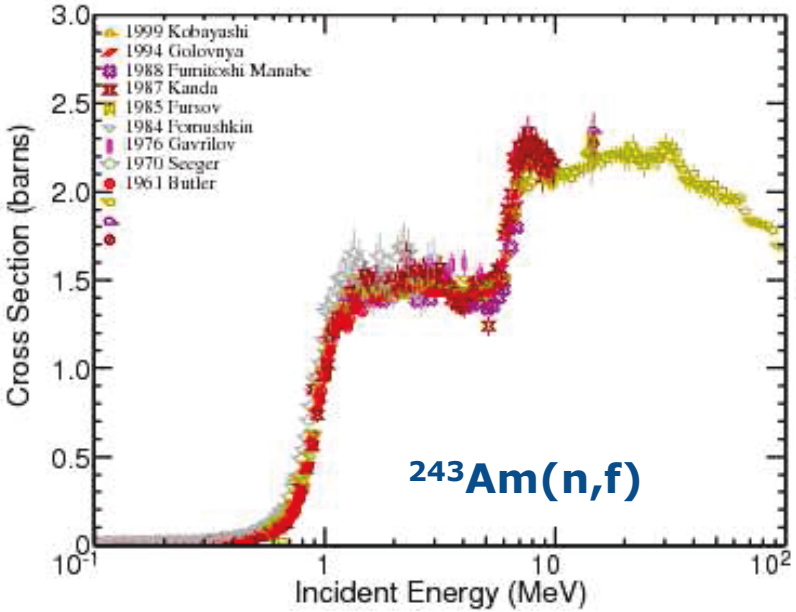
Almost all relative to ^{235}U(n,f)

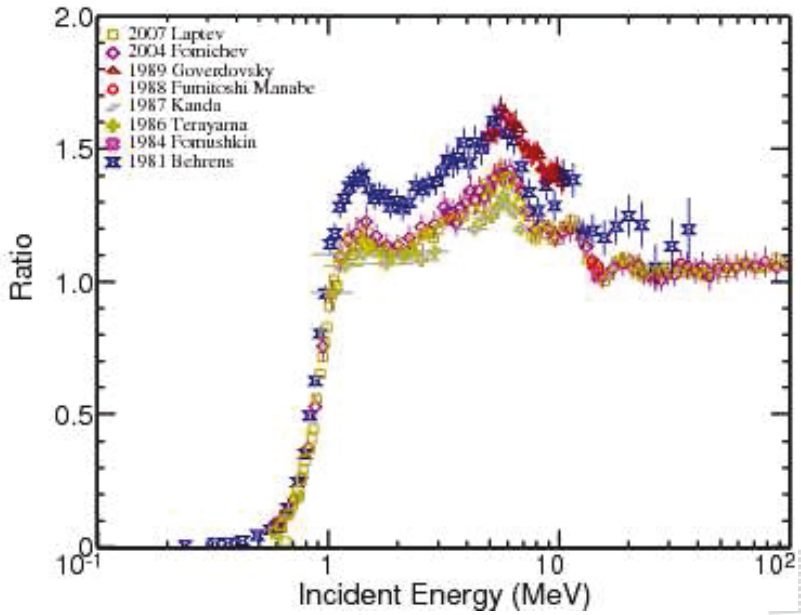
Lessons learned?
What can we add?

Example: ^{241}Am (n,f) and ^{243}Am(n,f) status









Larger spread
Discrepancies
Fewer ratios to 235U for 241Am

European Commission

Experiments

- Ingredients
  - Neutron source
  - Detectors for the process
  - Charactising flux or normalization
  - Sample material
- Characteristics differ strongly on the quantity studied
- % level cross sections require a lot of care for detail
- Important to know your experiment
- Important to learn from earlier experience
- Look for new technological developments

- Examples
  - Neutron sources
  - Cross sections
  - Neutron multiplicity
  - Neutron spectrum
  - Fission fragment yields
  - Kinetic energy, angular distributions
  - Prompt fission gammas
  - Delayed neutrons and gammas

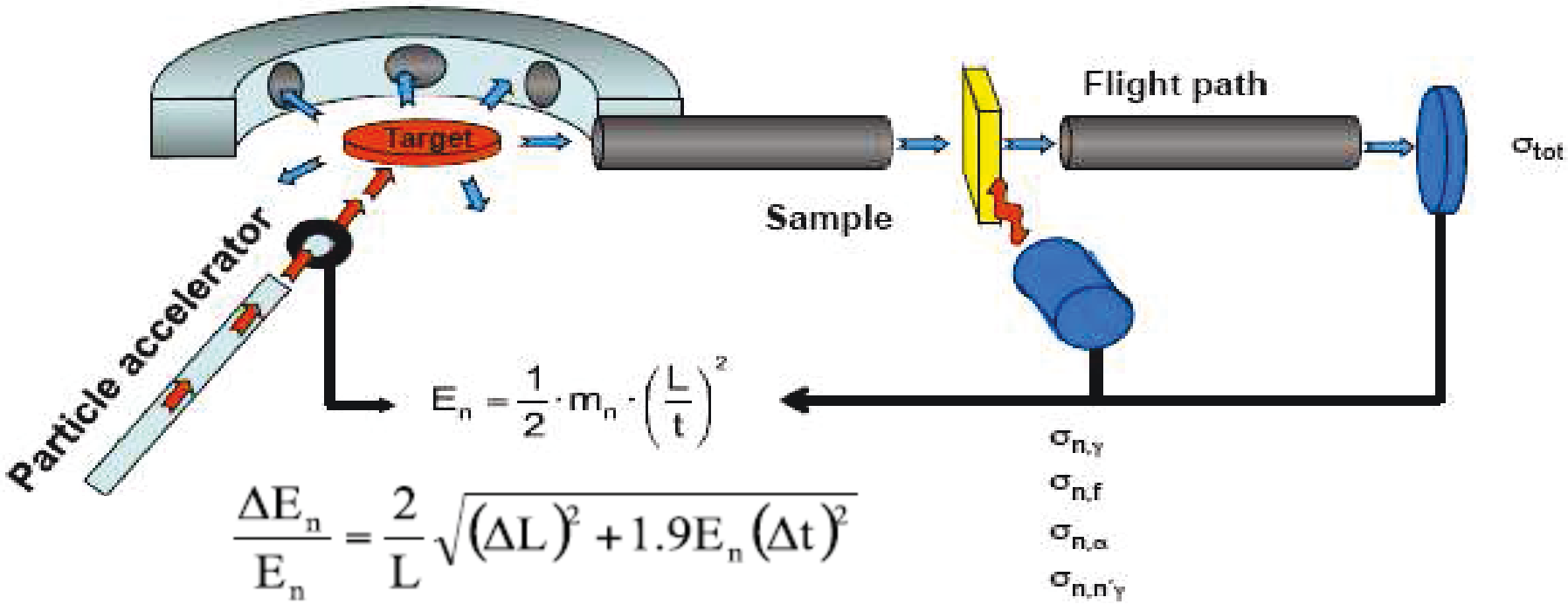
Neutron sources

- **Time-of-flight**
  - **White neutron source**
  - **Pulsed**
  - **Flight path length and time determine energy**
  - **Photo neutrons**
  - **Spallation neutrons**
  - **Low and intermediate energy nuclear reactions (quasi monoenergetic or white spectra)**

- **Continuous field/beam**

  (Presentation Nolte)
  - **Quasi mono-energetic**
  - **DC**
  - **Binary nuclear reactions**
  - **Spectrum from**
    - **Reaction kinematics**
    - **Target energy loss**
    - **Angular distribution**
    - **Number of open channels**

Time-of-flight



$$E_n = \frac{1}{2} \cdot m_n \cdot \left(\frac{L}{t}\right)^2$$

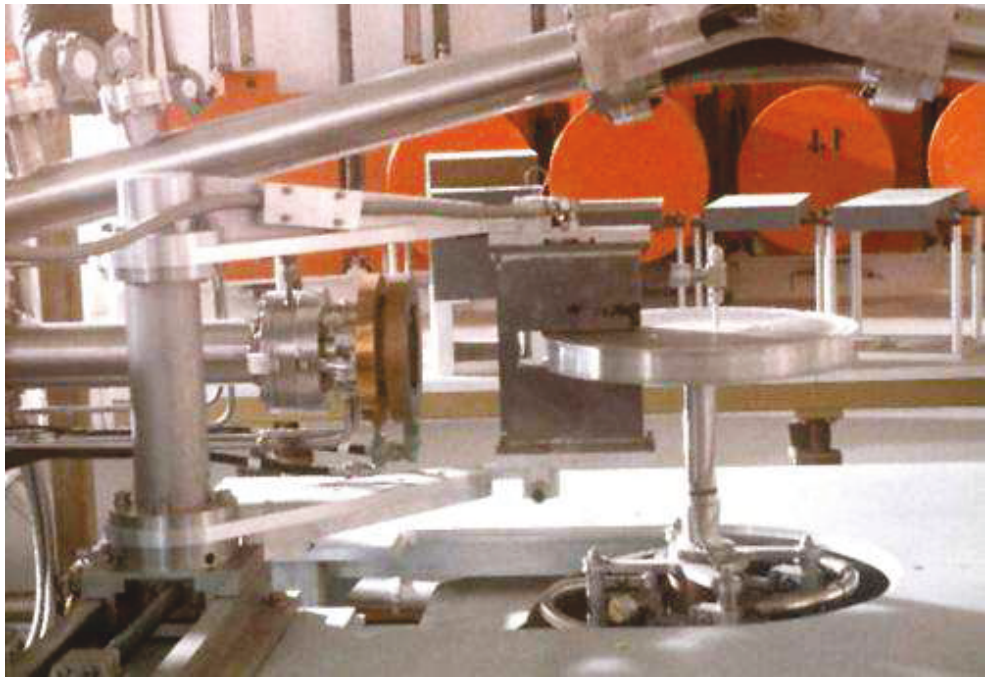
$$\frac{\Delta E_n}{E_n} = \frac{2}{L}\sqrt{(\Delta L)^2 + 1.9E_n(\Delta t)^2}$$

Note that the relativistic expression must be used for accurate work on energies and certainly above a few tens of MeV

GELINA, electron linear accelerator

Others: nELBE, RPI, Kyoto, Pohang, KAERI, ... (Markus Nyman)

Neutron conversion target

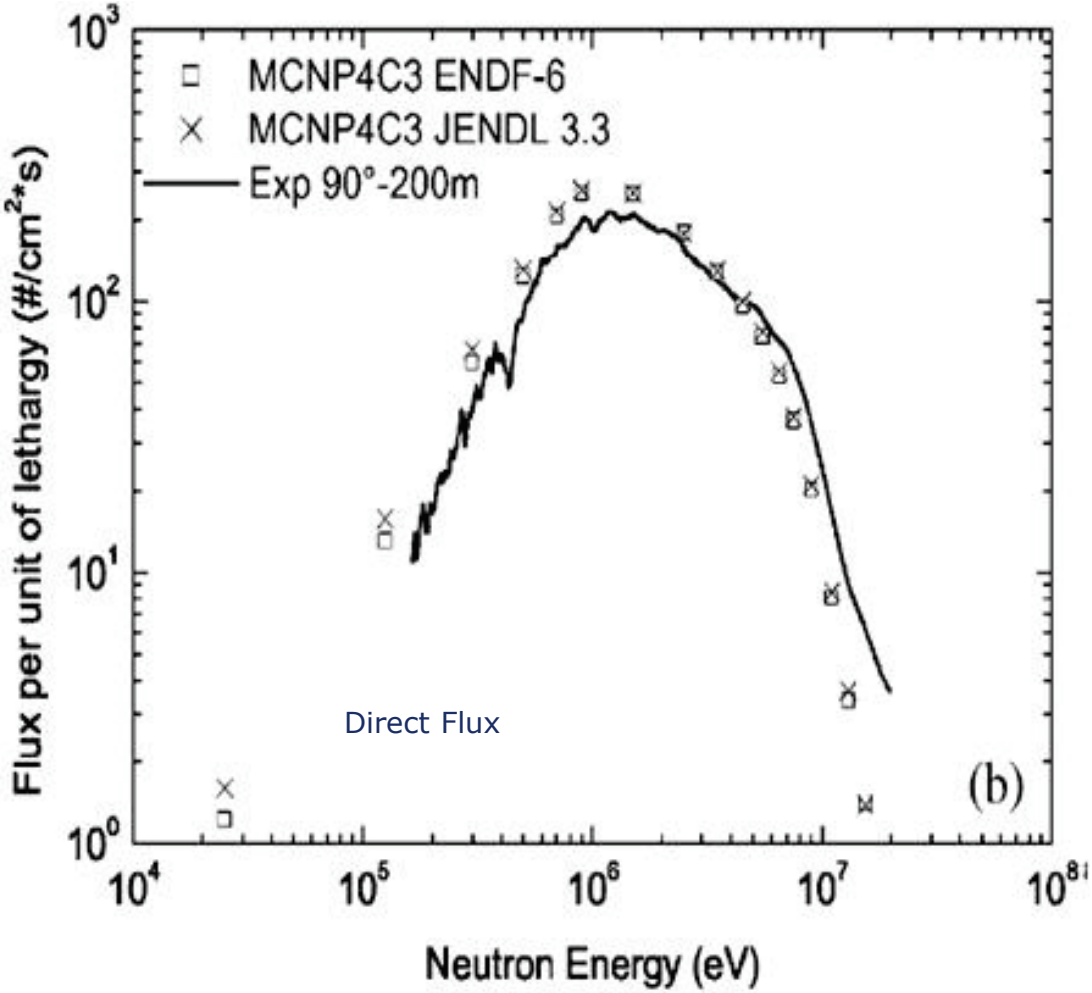


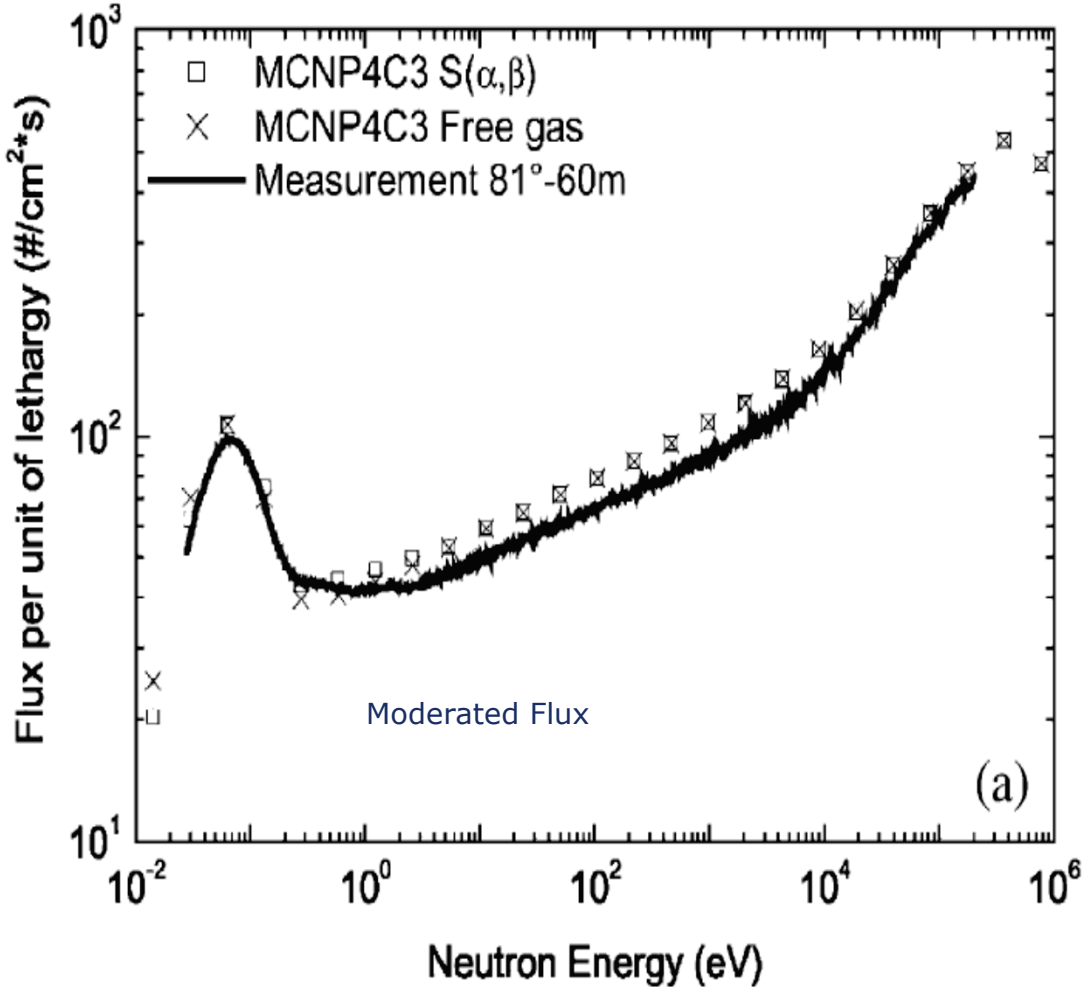
Uranium target ($e^- \Rightarrow \gamma \Rightarrow n$)
rotating, mercury cooled
Moderated or fast neutron spectrum
24 h/d, 100h/w, 12 parallel FPs

12 Flight paths, 8 to 400 m

Flaska et al., NIM , A531, 394 (2004)

GELINA neutron flux

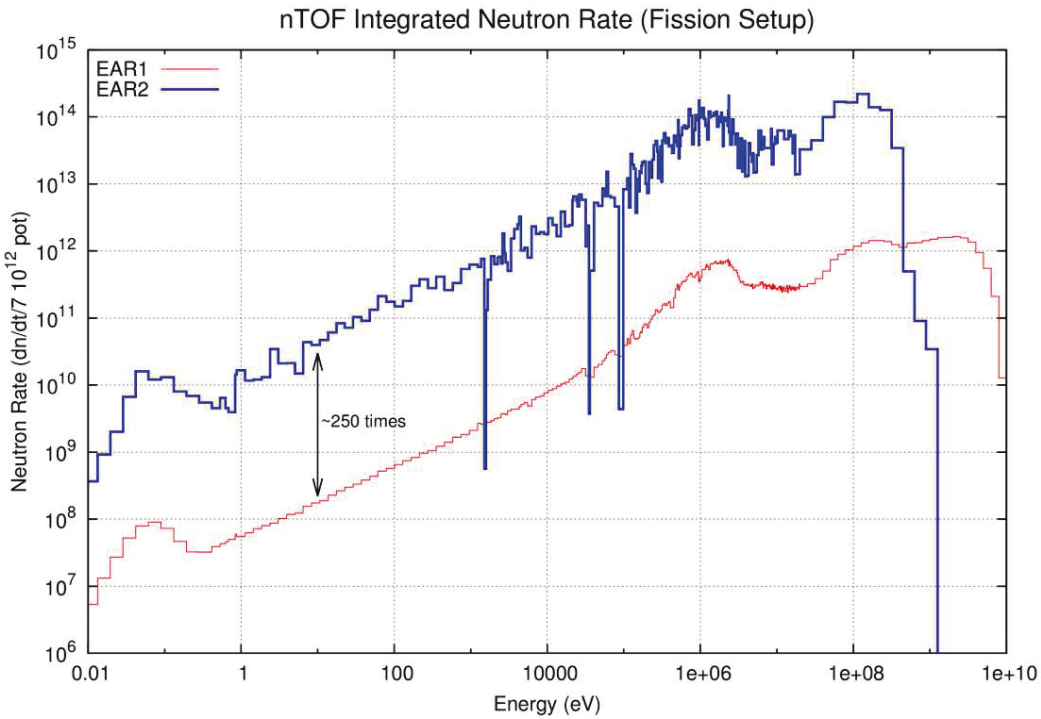


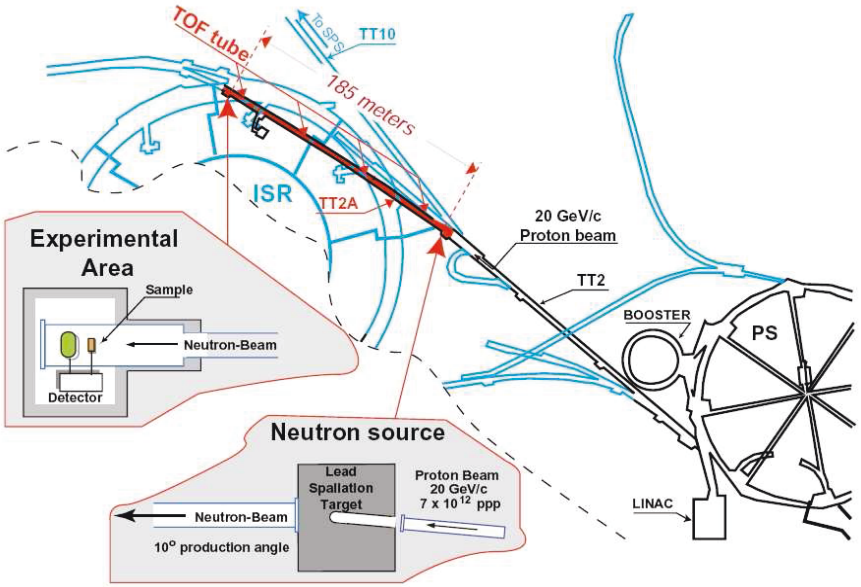


- **Neutrons/electron: 0.06**
- **neutrons / burst: $3.3\ 10^{10}$**
- **neutrons/second: $2.6\ 10^{13}$**

CERN, LANL, JAEA, SNS, ISIS, Nevis

Neutrons from spallation reactions (400 – 20 GeV)





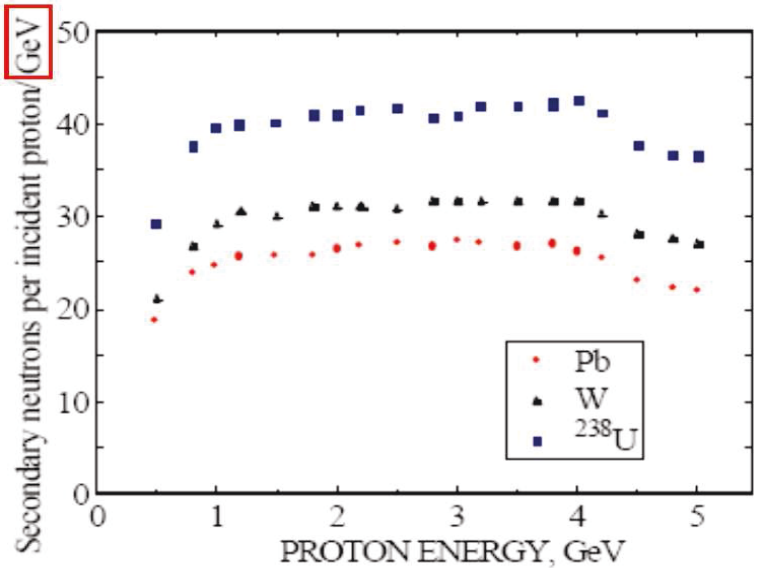
Neutron energies up to the proton energy

Neutrons/proton/GeV 25

Neutrons/pulse (nTOF) 2 10^{14}

Neutrons/second (nTOF) 7 10^{13}

Near future: EAR-2 at n_TOF, NFS @ SPIRAL2/GANIL

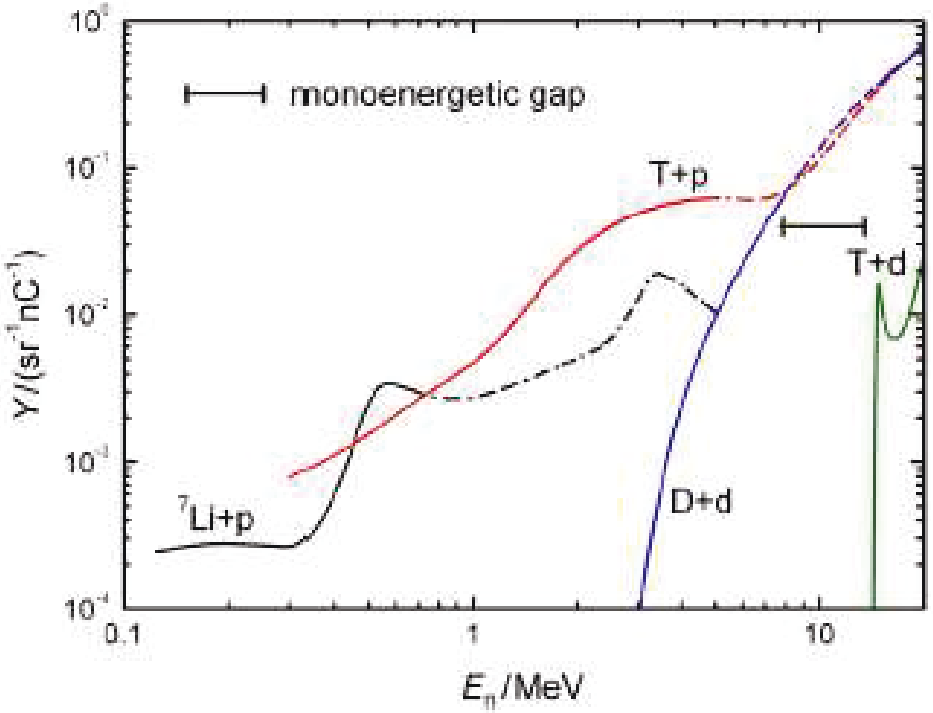


Quasi mono-energetic sources

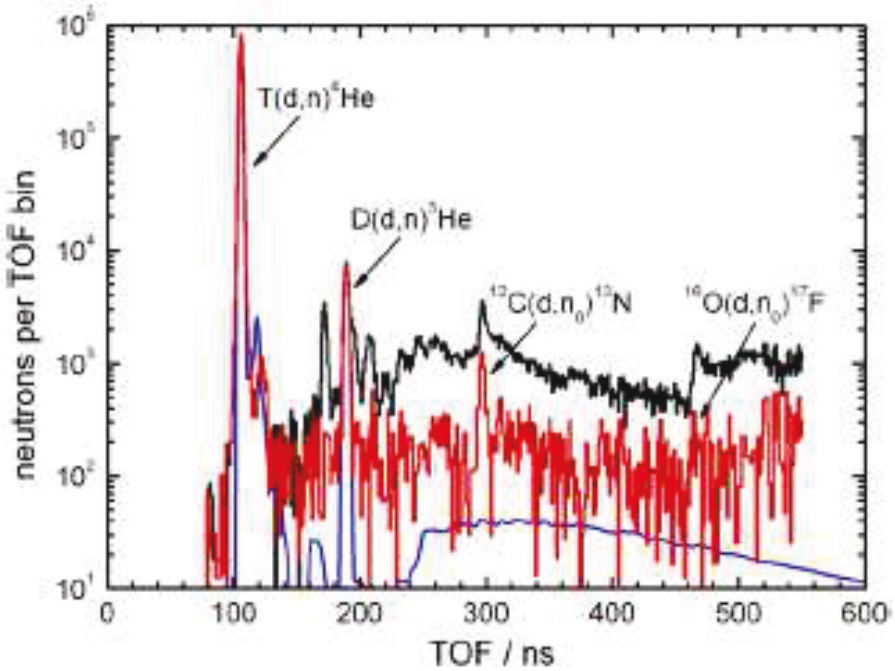
See presentation Nolte

- All flux at one energy
- Smaller cross sections
- Smaller samples

  E.g. Radioactive samples



- Charactised by reaction, energy loss, reaction kinematics, differential cross section
  - Primary neutrons, e.g. NeuSDesc
  - Background neutrons by TOF



Nolte and Thomas, Metrologia 48 (2011) S263
Birgersson and Lövestam, NeuSDesc, EUR 23794 EN (2009)

Cross sections

- Dominated by fission ionization chambers (FIC)
- Dominated by ratios to $^{235}U(n,f)$
- Important to know what is involved (FIC, ratios)
- Important to provide a good uncertainty analysis

- Other options?
  - Frisch-grid
  - PPAC
  - Solid state detectors
  - Normalization to hydrogen
  - Normalization to other fission

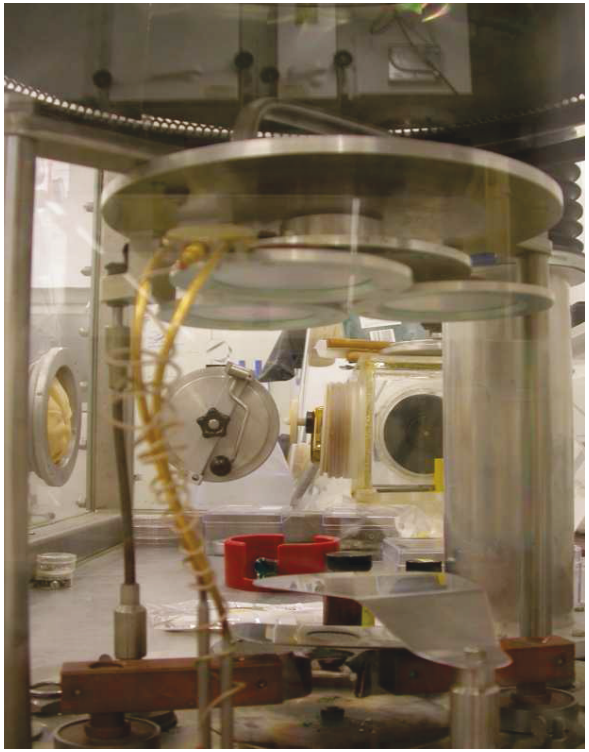
$$\sigma \equiv \frac{\text{Reaction rate}}{\text{flux}}(\text{per target nucleus}) = \frac{\dot{R}}{\Phi}$$

$$\sigma = \frac{\text{\# reactions}}{\text{fluence}}(\text{per target nucleus}) = \frac{R}{F}$$

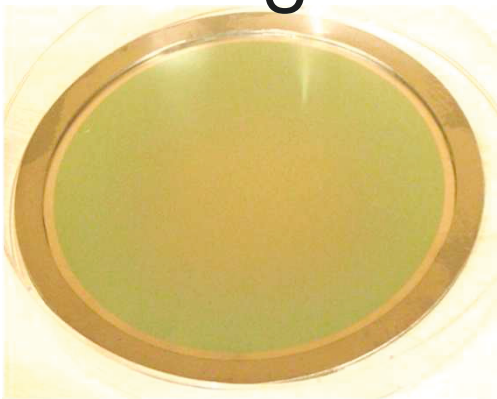
$$F = \Phi t,\ R = \dot{R}t,\ t = \text{measurement time}$$

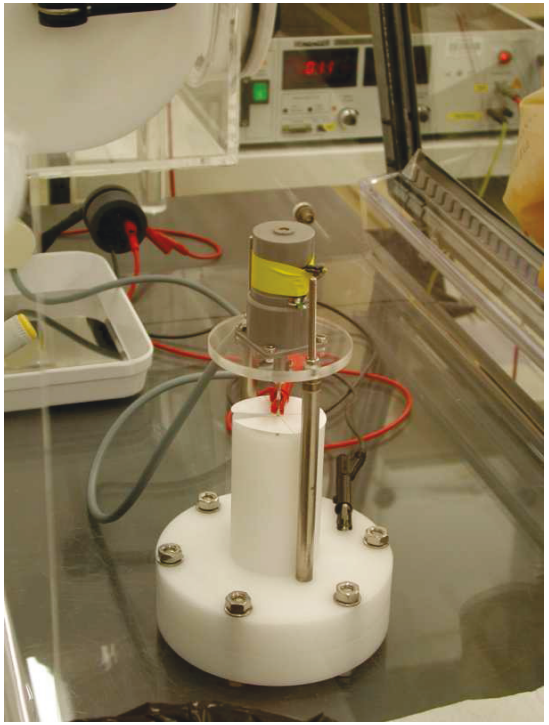
- Effects to consider
  - Sample quality
  - Selectivity
  - Detection efficiency
  - Background
  - Attenuation and scatter
  - Geometry
  - Source characteristics
  - Time resolution
  - …

Cross sections
Sample preparation

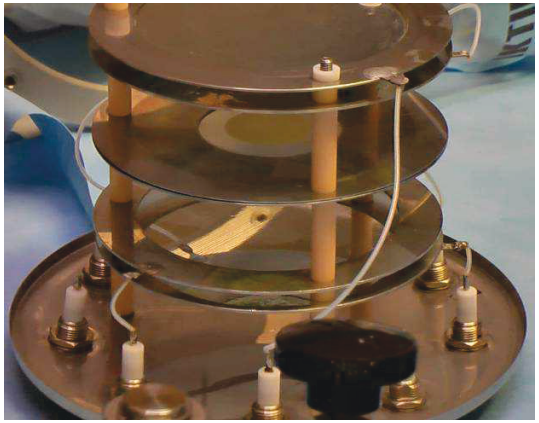


^{235}U





- **Evaporation**
  - **Best (^{235}U)**
  - **Inefficient**
- **Electrodeposition**
  - **Quality is less**
  - **Efficient**
  - **$^{240,242}Pu$**



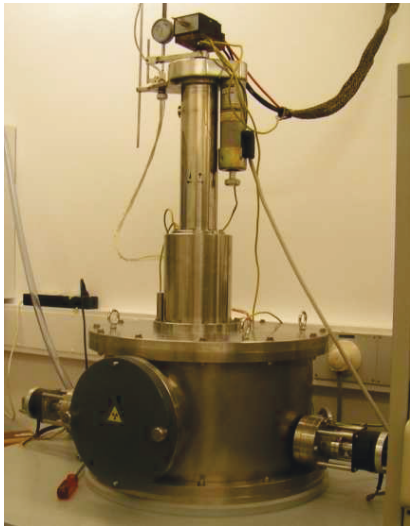
^{242}Pu

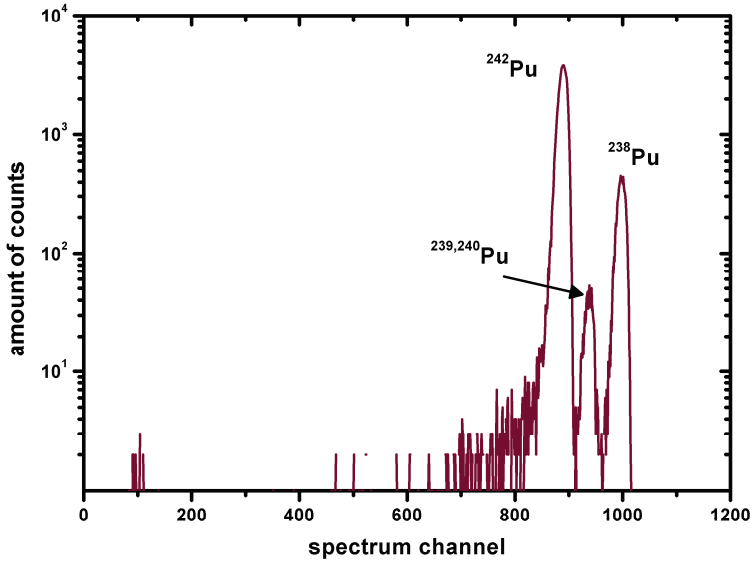
^{240}Pu

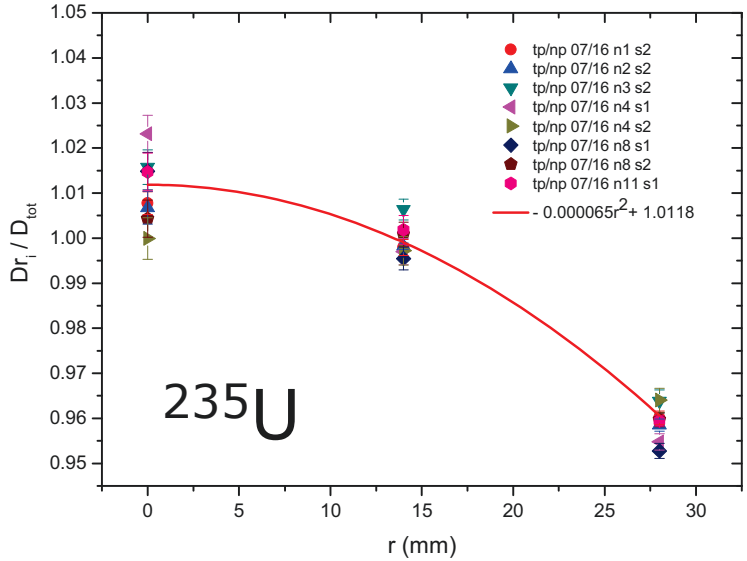
Cross sections

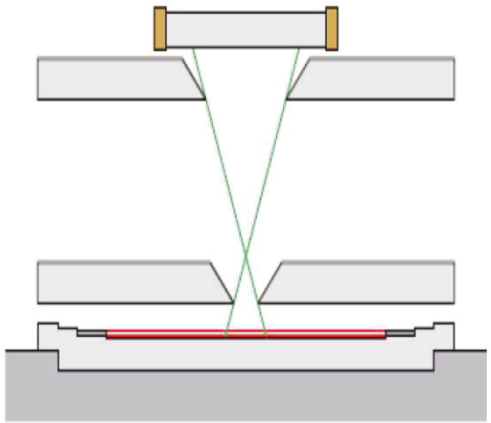
Sample Characterisation, activity and homogeneity

Inhomogeneity: +2% areal mass density
61 mm out of 70 mm









- **Defined solid angle counting (absolute)**
- **Homogeneity survey with alpha counting**
- **Note new findings by Vascon et al. (Mainz) for lanthanide molecular plating; bearing on actinides? See presentation Eberhardt.**

INTDS 2012, Heyse et al. Sibbens et al.

Cross sections

Characterisation, purity, isotopes, specific activity

Callet& De Bièvre 15 November 1985	Atom%	Acc (2s)
U-234	0.0626	0.0025
U-235	99.8266	0.0044
U-236	0.0365	0.0027
U-238	0.0739	0.0025

Activity to atoms
Mass spectrometry
65% activity: U-234

Quantity	Value (1s)
Decay constant	8.78(10) 10^{-17} U/s

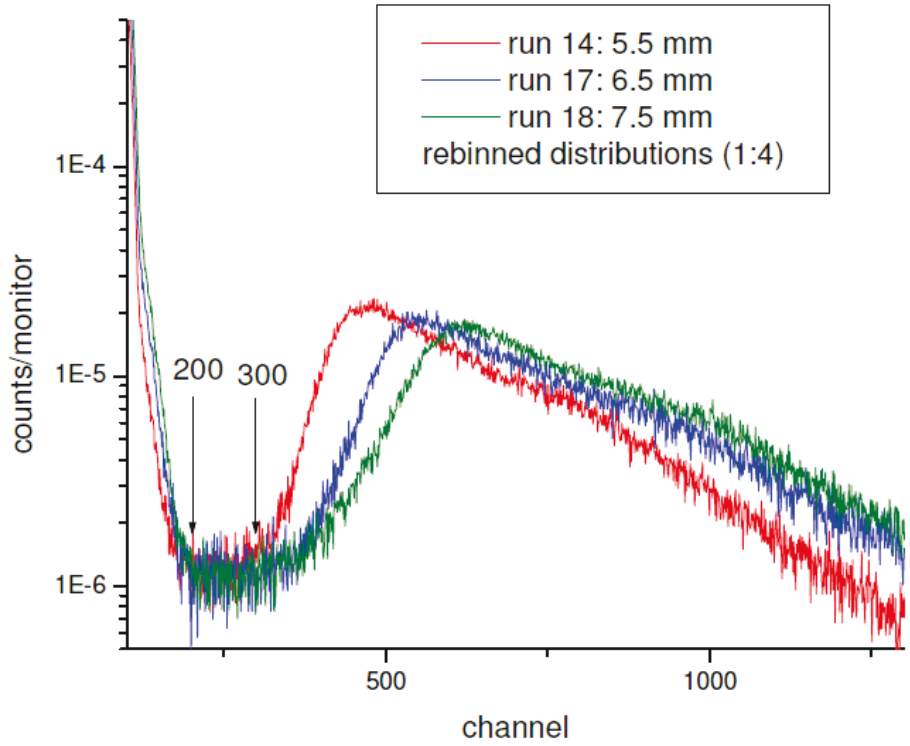
Richter 23 March 2009	Atom%	Acc (2s)
U-234	0.06389	0.00014
U-235	99.82275	0.00020
U-236	0.03768	0.00007
U-238	0.07568	0.00013

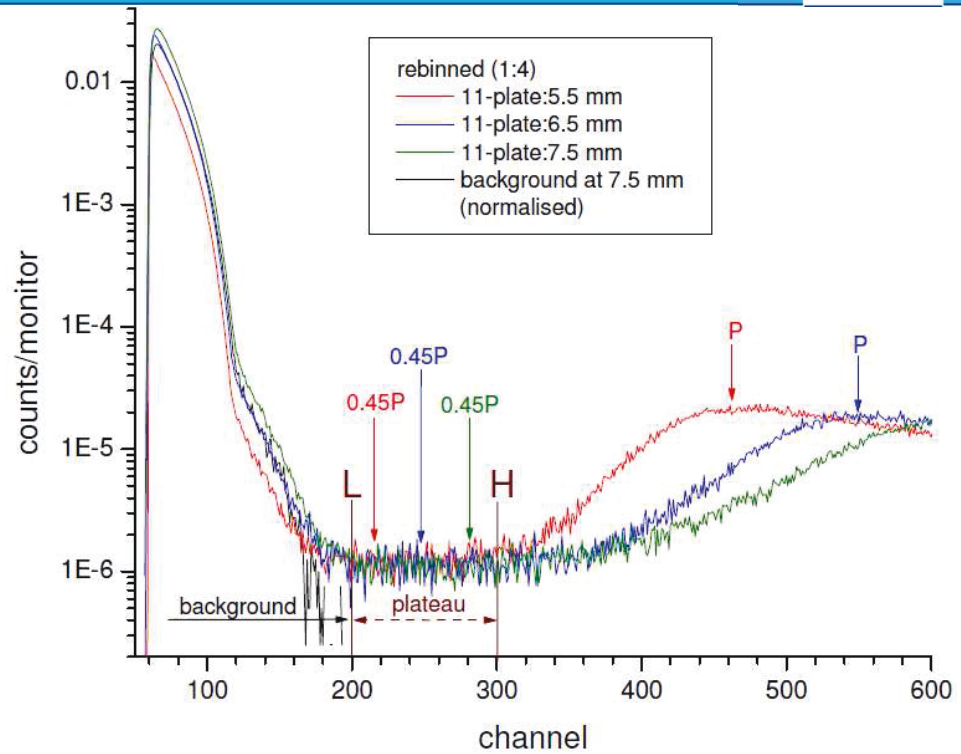
Quantity	Value (1s)
Decay constant	8.88(2) 10^{-17} U/s

More accurate new value: +1% and 0.3% uncertainty

Cross sections

Fission ionization chambers, pulse heights, selectivity, efficiency





Separation of alpha-particle+noise from fission fragments

Threshold criterium:

1) negligible/small alphas
2) small nr. of FF below threshold
3) calculable

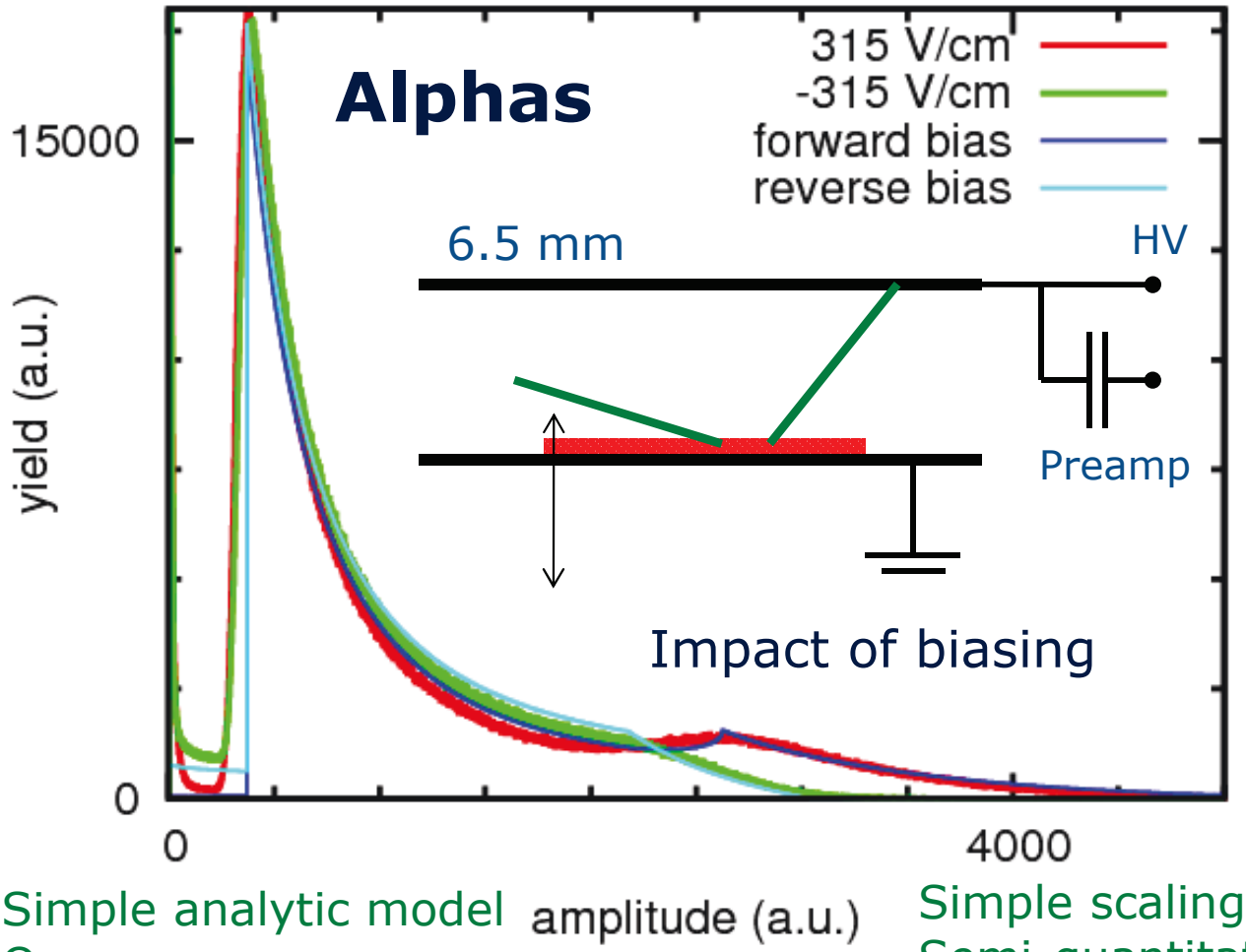
gap	below-threshold	below+above
mm	%	1000*counts/monitor
5.5	3.4(1)	8.36(2)
6.5	3.7(1)	8.35(2)
7.5	4.1(1)	8.35(2)

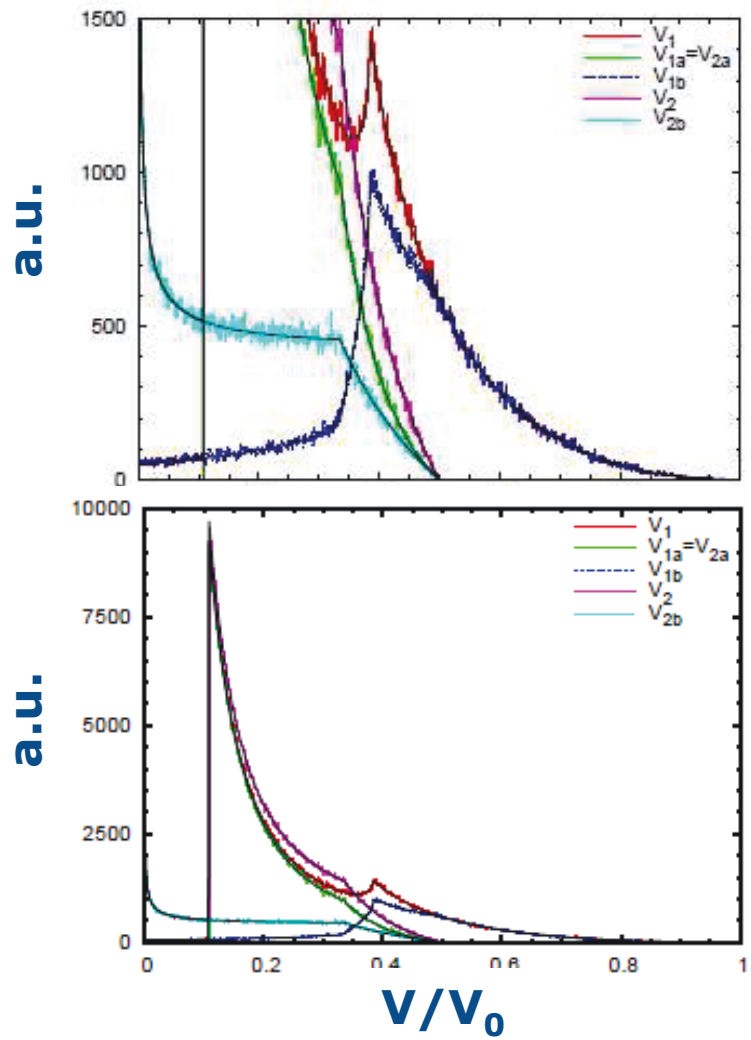
- A larger gap facilitates 1).
- The fraction lost is small (475 μg/cm2 ^{235}U; form UF_4)
- The fraction lost is very calulable (to 0.25%).

Cross sections

Fission ionization chambers, expected behaviour at low energy

Parallel plate measured activitiy: 26.6(2) kBq (2009)
Defined opening angle counting: 26.88(5) kBq (2001)





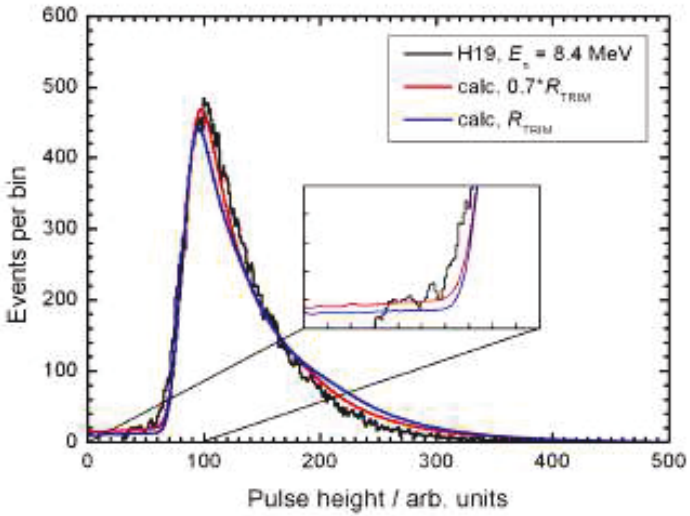
Simple analytic model
One energy, one range
Uniform charge deposition

Simple scaling
Semi-quantitative agreement

Cross sections

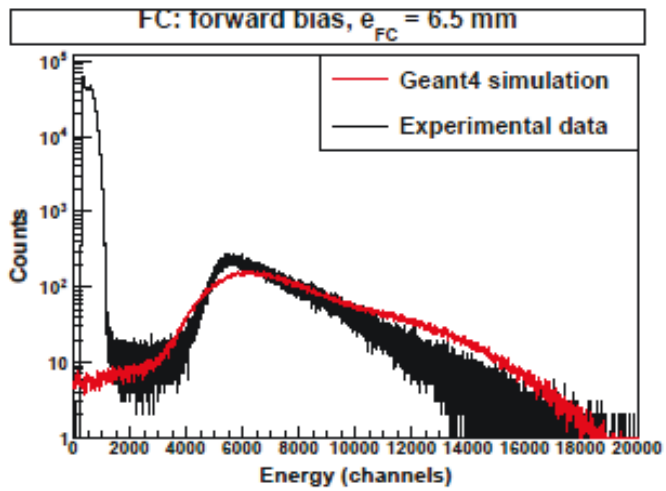
Ionization chambers: modeling the PH distribution

- **FIC U-235**



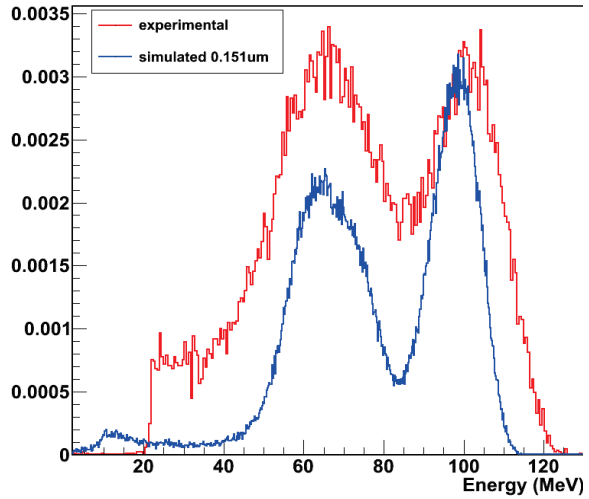
Mosconi et al. CERN EFNUDAT workshop 2010

FIC U-235



Thiry, PhD thesis, Strasbourg 2010

Frisch-grid

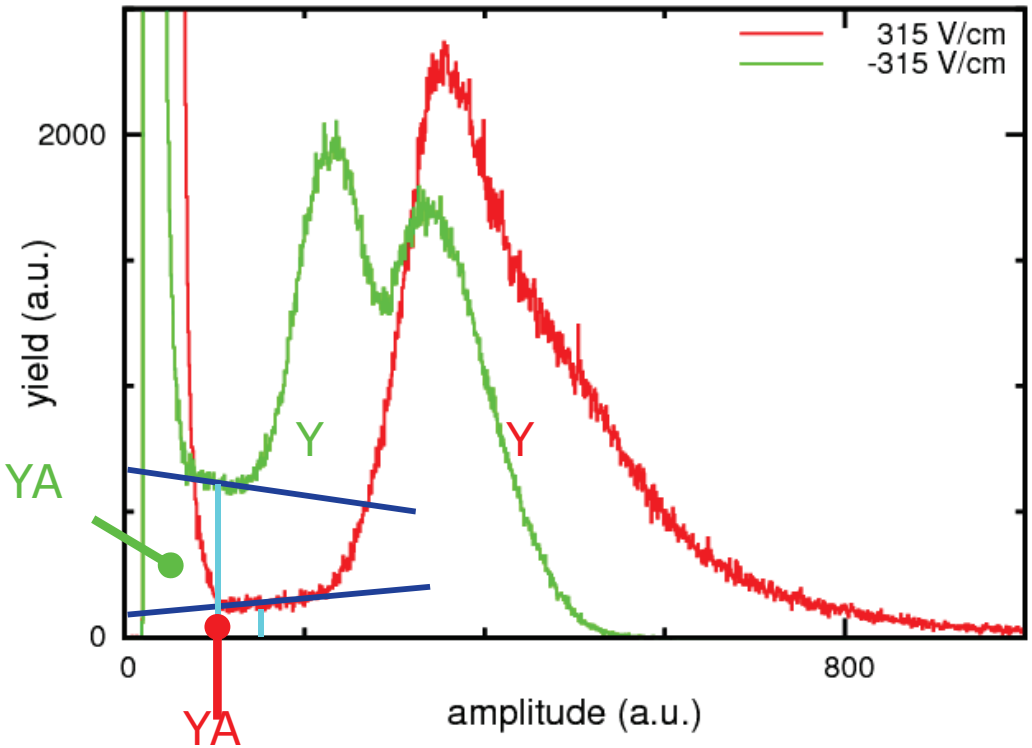


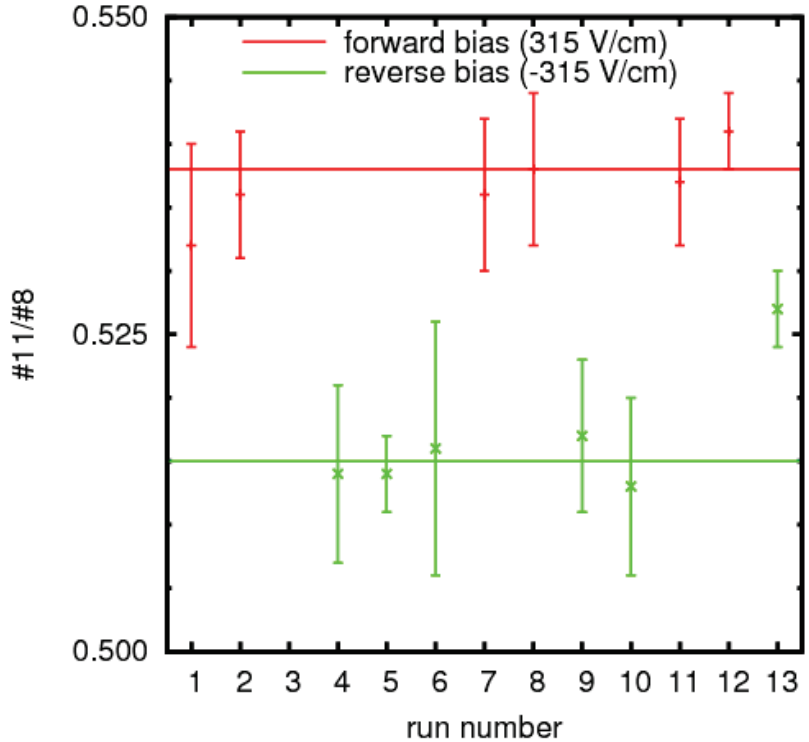
Salvador-Castineira, Theory-2, 2012

Here is where the impact of surface roughness and elemental composition need further investigation

Cross sections

Fission ionization chambers, forward and reverse bias





Efficiency = Y / ($Y+Y_A+Y_B$)

$Y+Y_A$ forward versus backward bias

4.4% effect for 0.475 mg/cm^2 ^{235}U in the form of evaporated UF_4

Y: yield above threshold, Y_A: yield below threshold (linear extrapolation)

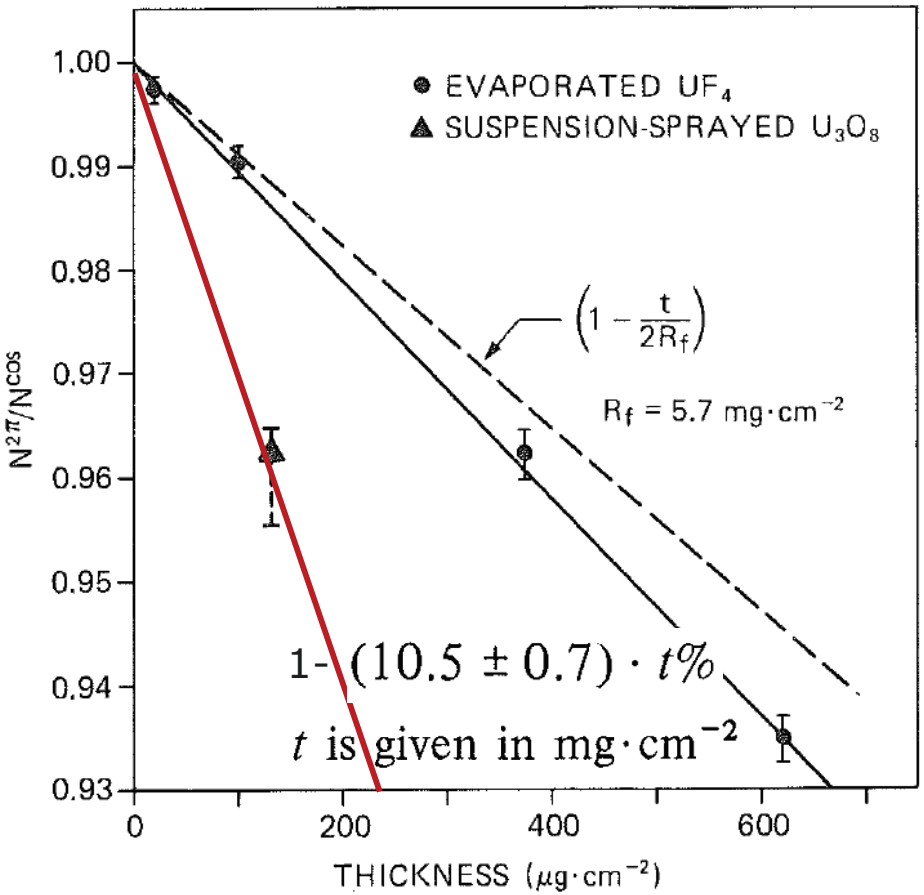
Y_B: fragments stopped in the deposit (not shown)

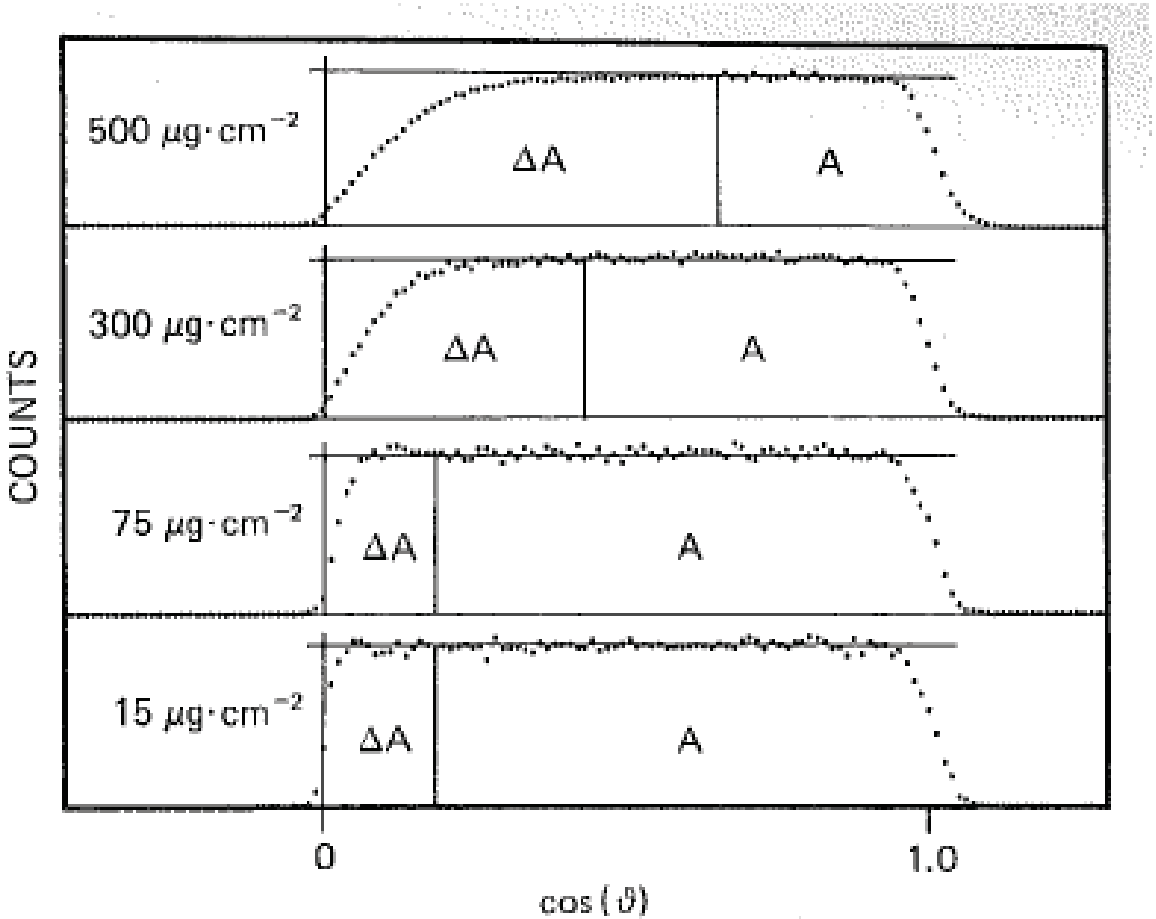
$Y_B/(Y+Y_A+Y_B)$ = 0.105(7) t/(mg/cm2)

Y_B: measured by Budtz-Jörgensen Nucl.Instrum.Meth. 236(1985)630

Cross sections

Loss in the deposit; FIC, Frisch-grids, PPAC, μ-pattern

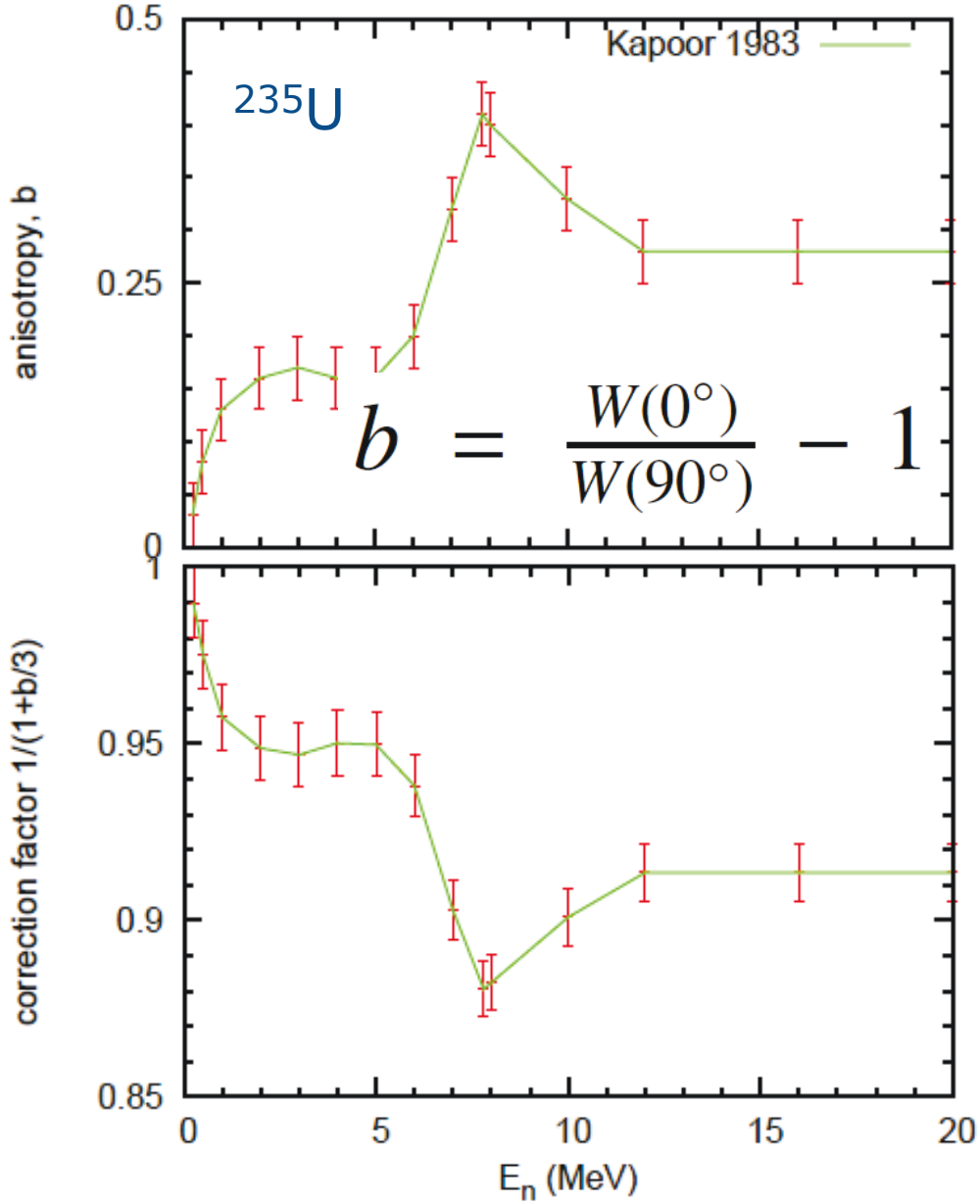




Angular distribution measurements with isotropic fission (thermal neutrons, ^{235}U)
Ranges from SRIM2008 are too large! Too little loss in deposit by a 20%.
Situation appears much worse for U_3O_8 suspension spraying
What about other methods of preparation?

Budtz-Joergensen et al., NSE86(1984)10

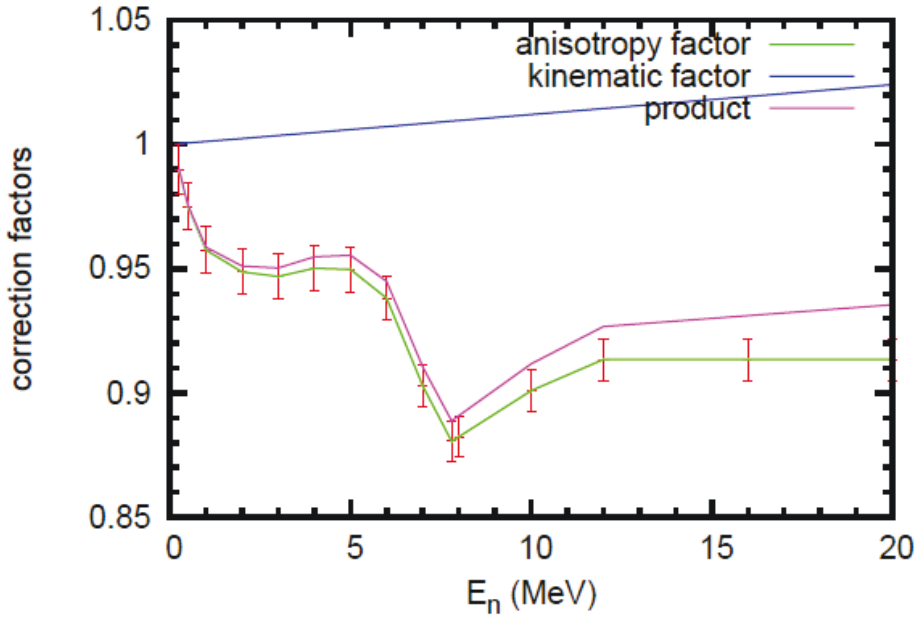
Cross sections
Role of anisotropy

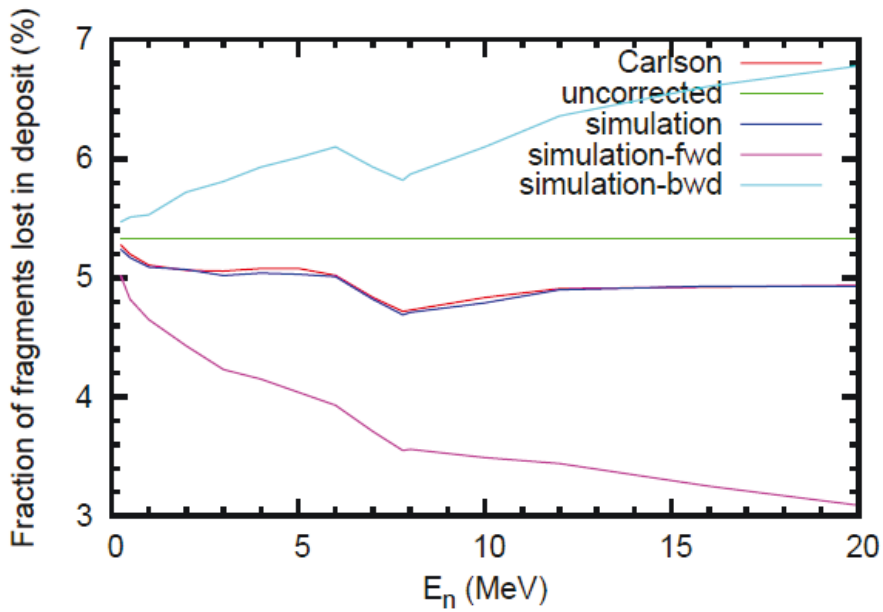


- **Reduced solid angle measurements need to account for anisotropy**
- **Already true for Ionization chambers**
  - **Depends on target thickness**

Cross sections

Role of kinematics





- **Chamber orientation dependent**
- **Orientations averaged: progressively important above 8 MeV**
- **Only one orientation: larger than 1% near 5 MeV**

Plompen et al. J. Kor.Phys.Soc. 59 (2011)1581; EUR 25208 EN (2011)

[1] D. B. Gayther, International intercomparison of fast neutron fluence-rate measurements using fission chamber transfer instruments, Metrologia 27 (1990) 221.

[2] G. W. Carlson, The effect of fission fragment anisotropy on fission-chamber efficiency, Nucl. Instrum. Methods Phys. Res. 119 (1974) 97.

[3] C. Straede, C. Budtz-Jörgensen, H. Knitter, ^{235}U(n,f) fragment mass-, kinetic energy- and angular distributions for incident neutron energies between thermal and 6 MeV, Nucl. Phys. A 462 (1987) 85.

[4] S. S. Kapoor, The ^{235}U fission fragment anisotropies, Nuclear Data Standards for Nuclear Measurements, Technical reports series nr. 227, International Atomic Energy Agency, Vienna, ISBN 92-0-135083-X (1983).

[5] J. F. Ziegler, J. Biersack, M. Ziegler, SRIM The stopping and range of ions in matter, www.srim.org, SRIM Co., Chester, MD 21619, USA, ISBN 0-9654207-1-X (2008).

[6] Budtz-Jörgensen, H. Knitter, Assaying targets for nuclear measurements with a gridded ionization chamber, Nucl. Instrum. Methods Phys. Res. 236 (1985) 630.

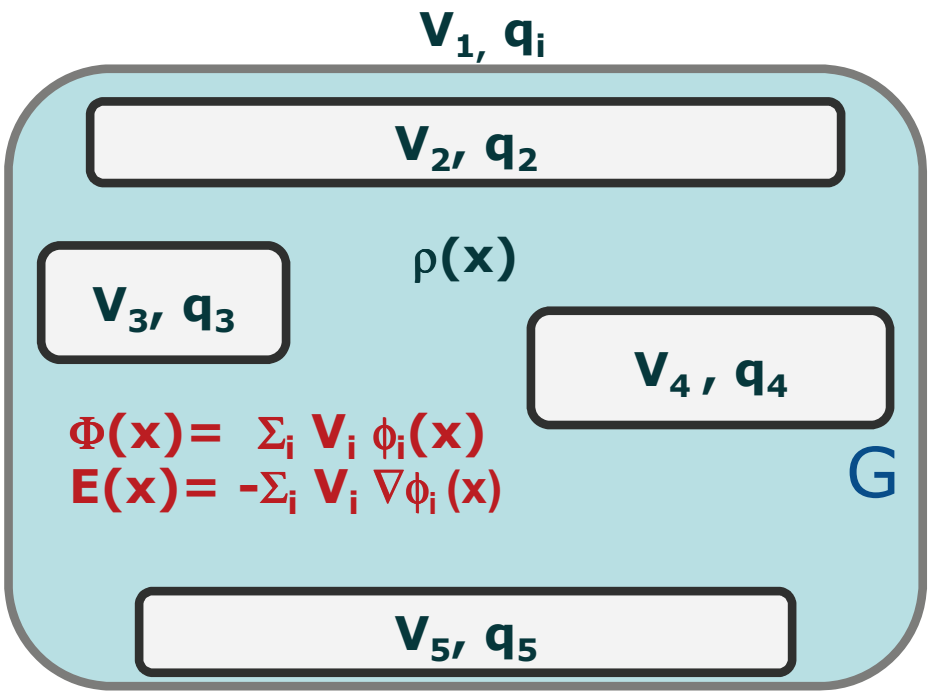
Induced charge & current

ionization chambers, Si, Ge, diamond detectors

- Bodies with perfectly conducting surfaces, maintained at fixed voltage V_i
- Standard solution

  Take $V_i \neq 0$, $\rho=0$, $V_{j\neq i}=0$.

This gives standard solution: $f_i(x)$;
normalized $\phi_i(x)=f_i(x)/V_i$



The induced charge on S_i due to a charge in the intermediate area G ?

Green: $$q_i = -\int_G \phi_i \rho \, dv$$

Point charge q created at p

$\rho(x) = q\,\delta(x-p)$: $q_i = -q\,\phi_i(p)$

If charge moves to S_i: $\Delta q_i = -q(1-\phi_i(p))$

Sum = –q: q ariving at S_i annihilates the charge it induced.

Charge moves → current flows from S_i: integrated charge q observed.

Charge is conserved.

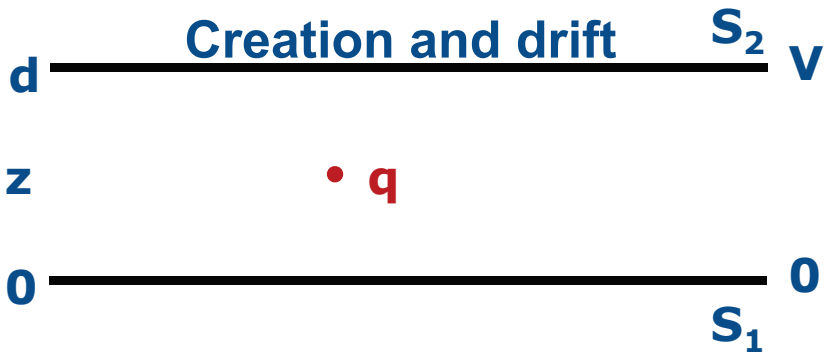
Current observed during drift

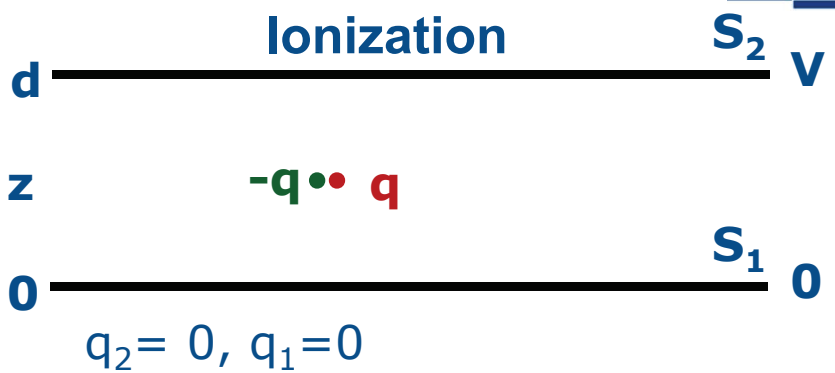
$I_i = -dq_i/dt = q\,v.\nabla\phi_i = -q\,v.E_i$

S_j, $j \neq i$: $\Delta q_j = q\phi_j(p)$ and then, sum = 0

Induced charge & current

parallel plate





Standard solutions

$\phi_2 = z/d$,
$\phi_1 = 1-z/d$

Actual field

$\phi = Vz/d$,

Creation

$q_2 = - q\, z/d$
$q_1 = - q\, (1-z/d)$

Drift

$\Delta q_2 = -q\, (1-z/d)$ for q collected on S_2
$\Delta q_1 = -q\, z/d$ for q collected on S_1

$\Delta q_2 = q\, z/d$ for q collected on S_1
$\Delta q_1 = q\, (1-z/d)$ for q collected on S_2

Case 1: –q collected on S_2; q immobile

$\Delta q_2 = q\, (1-z/d)$ and $\Delta q_1 = q\, (1-z/d)$

the integrated current depends on z because q did not move

Case of electron-ion pairs: gases

Ionization chambers

bad resolution

Case 2: –q collected on S_2, q on S_1

$\Delta q_2 = q\, (1-z/d) + qz/d = q$ and $\Delta q_1 = -q$

the integrated current is the charge

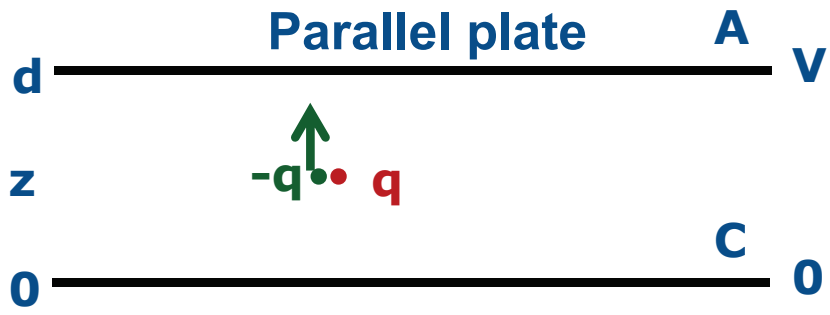
Case of electron-hole pairs, nearly the same mobility

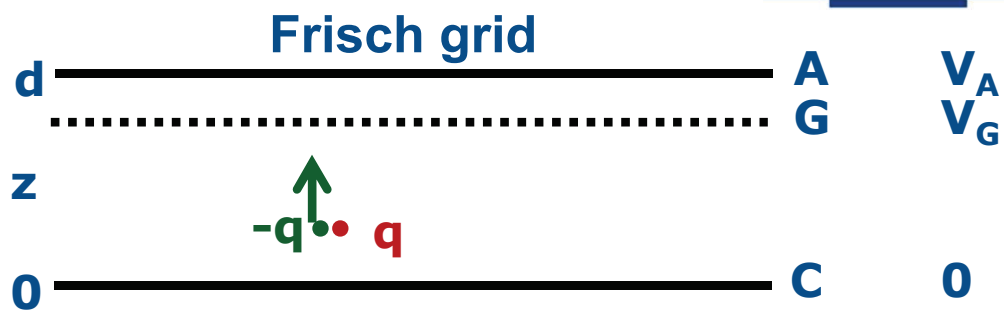
silicon, germanium, diamond

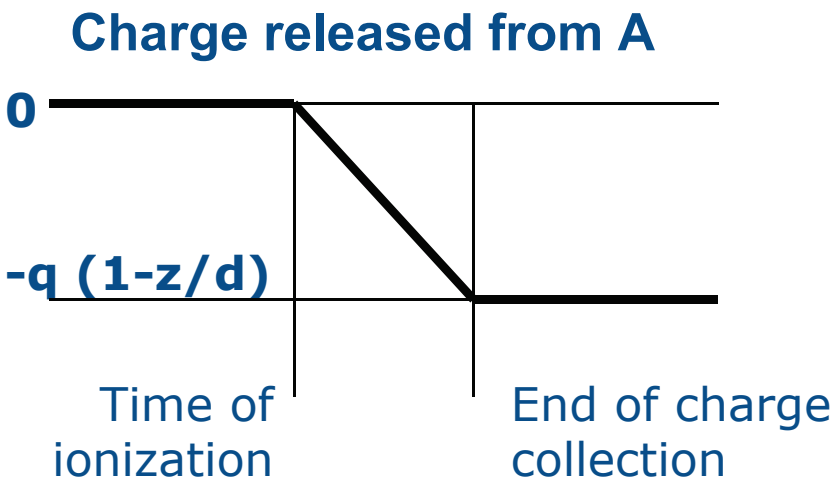
good resolution

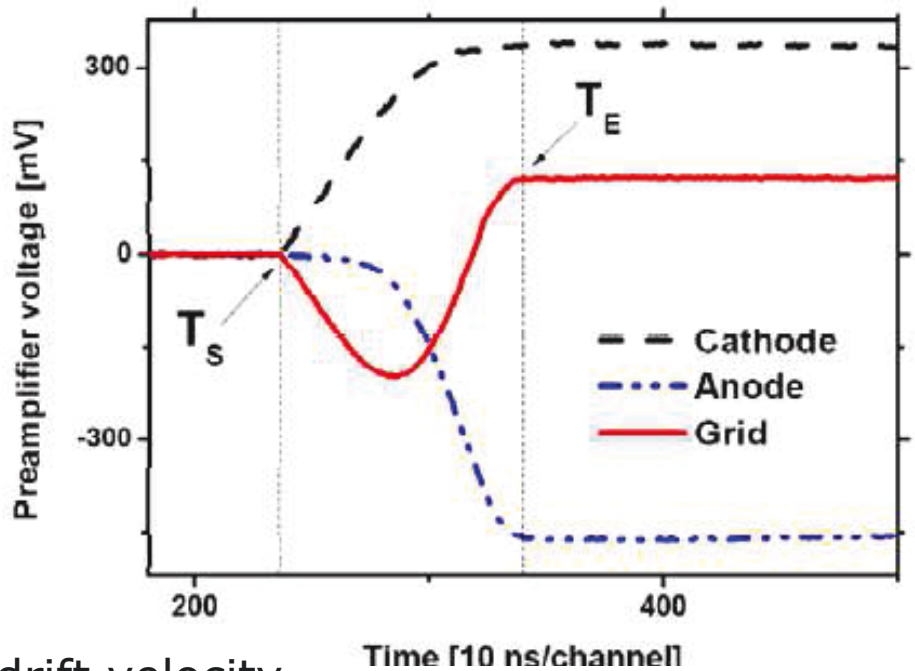
Induced charge & current

signals; perfect charge integrating preamplifier





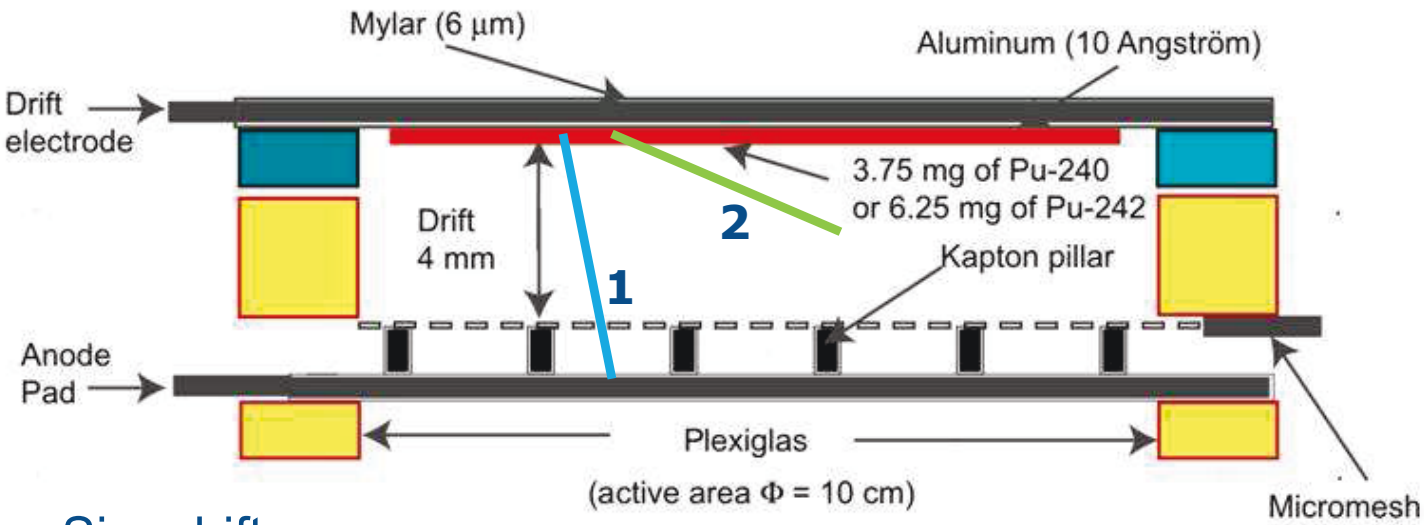


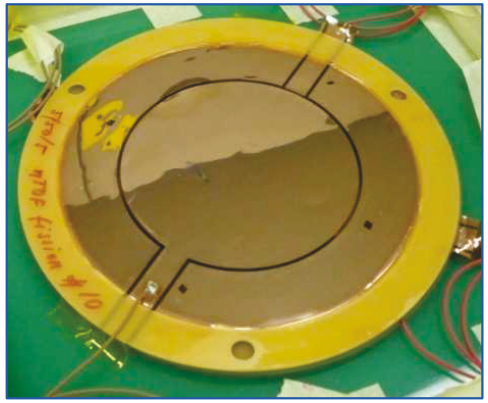


P10-gas: 4 10^4 m/s drift velocity
25 ns/mm drift time
5 mm: 125 ns, 30 mm: 750 ns
Time-resolution: 1-5 ns fwhm

Detectors based on proportional amplification

PPAC, Micromegas, GEM

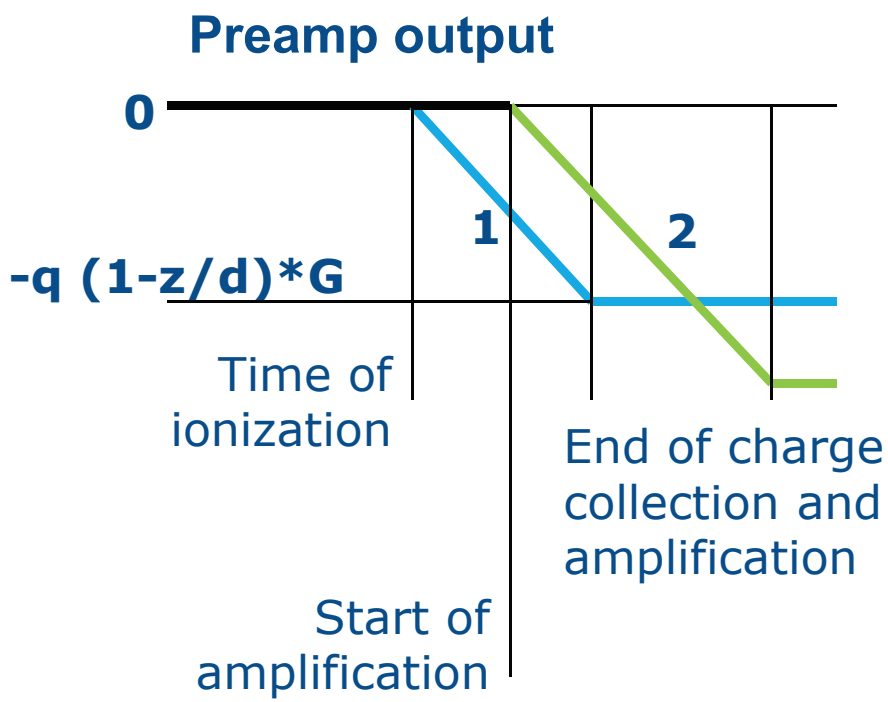




Size drift zone determines minimum charge deposited

High field zone
Charge is amplified between mesh and anode; gain G

Induced charge is negligible (below electronics threshold)



For good timing the drift zone must be as small as possible

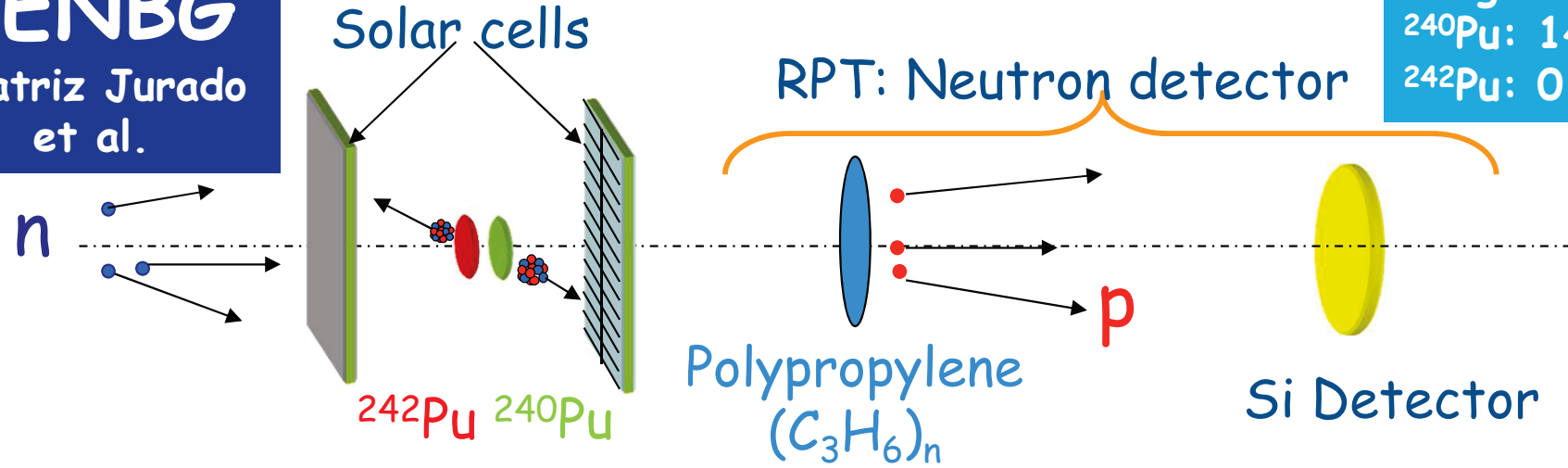
Pictures: A. Tzinganis
ERINDA workshop JYU 2013

New approaches to fission cross sections

Solid state detectors and normalization to H(n,n)H

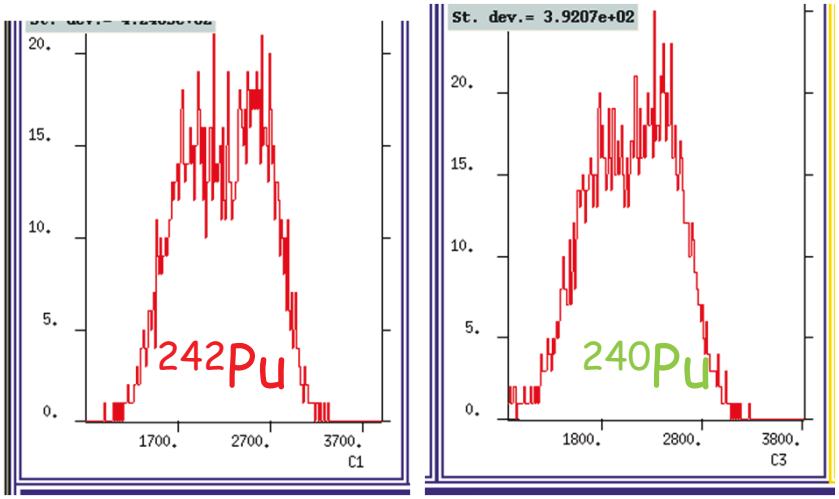
CENBG
Beatriz Jurado et al.

Targets from IRMM
^{240}Pu: 14 Mbq (1.7 mg)
^{242}Pu: 0.2 Mbq (1.7 mg)

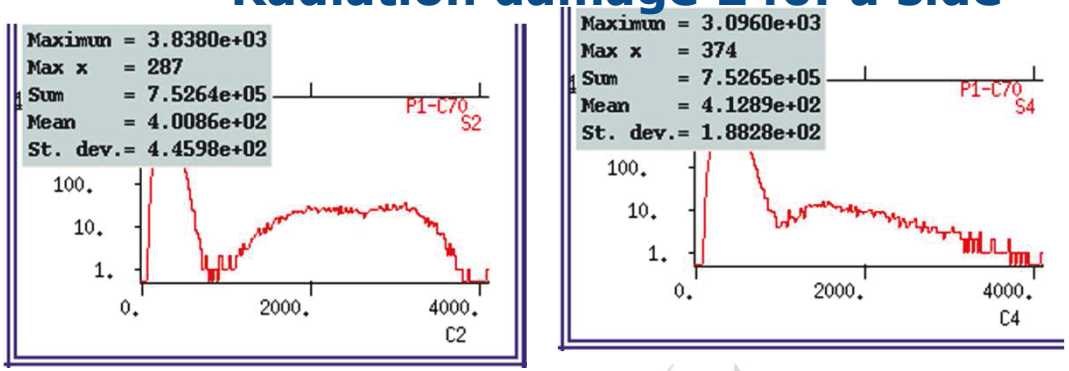


First run 6-14 December 2012 at Bruyeres le Chatel

Start of experiment
Very good α-FF separation



After experiment
Radiation damage 240Pu side



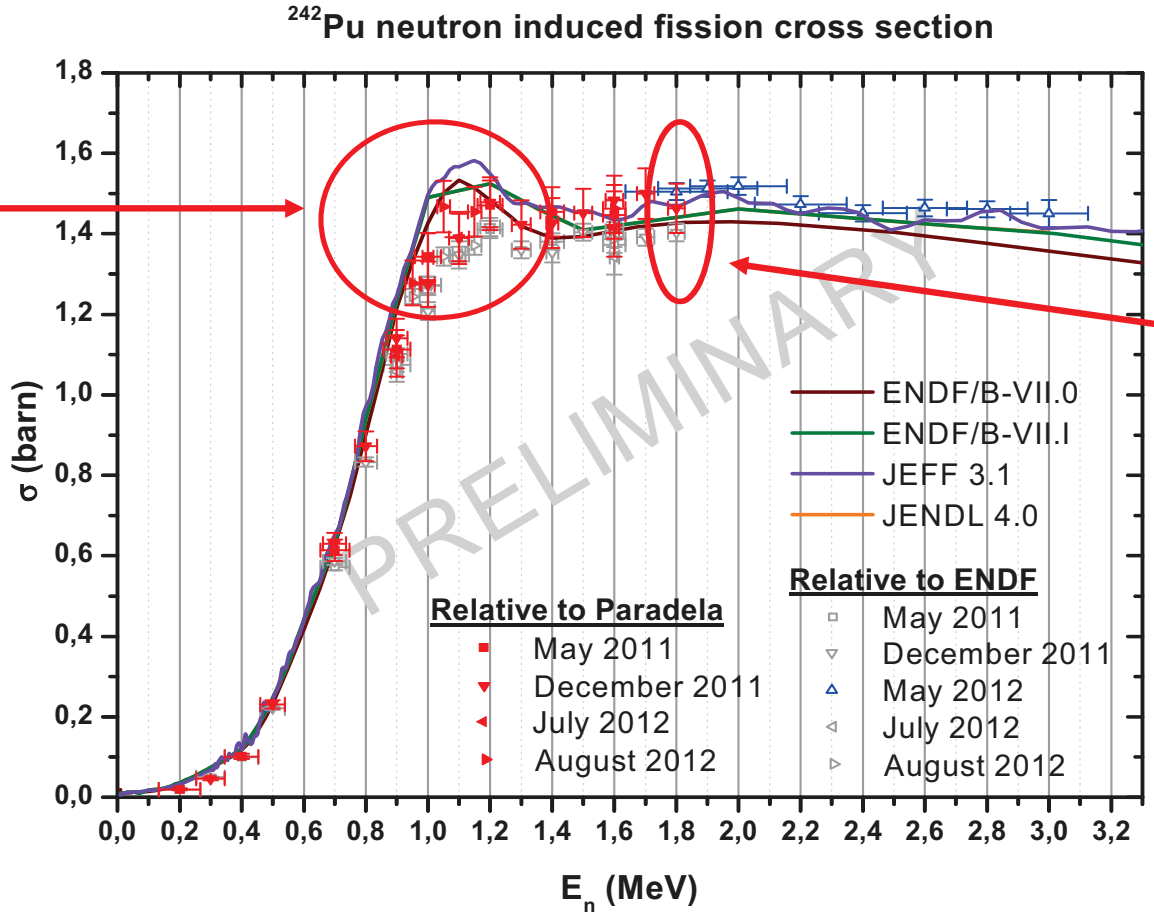
New approaches to fission cross sections

Frisch-grid and ^{237}Np and ^{238}U as reference

Poster session: Paula Salvador Castiñeira et al.

Neutron induced fission cross section ^{242}Pu

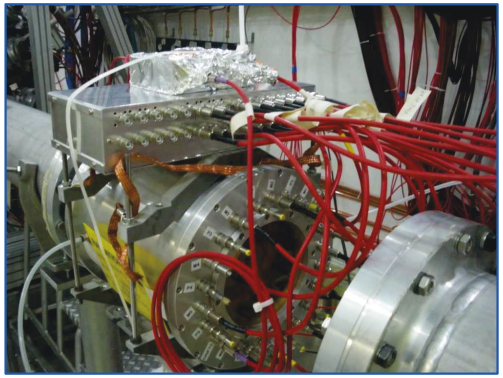
~6%
(12%)

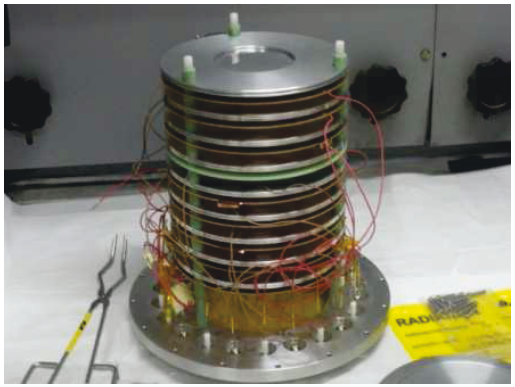


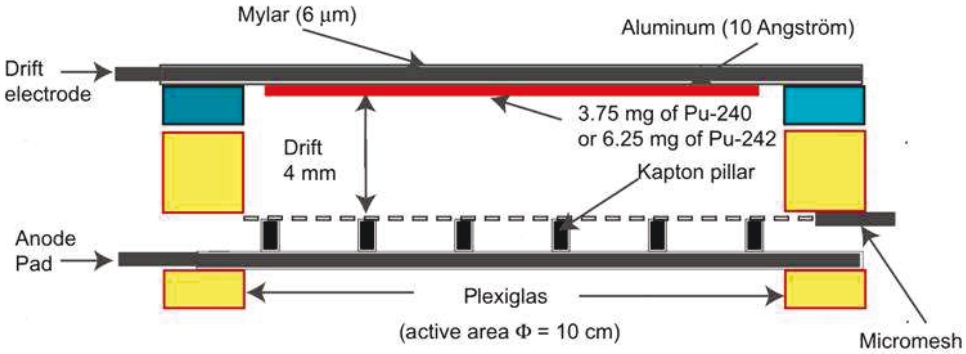
~ 3%
(7%)

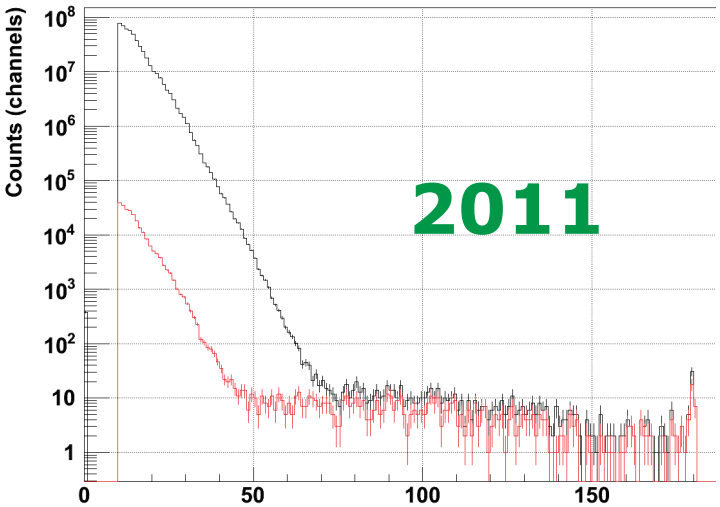
New approaches to fission cross sections

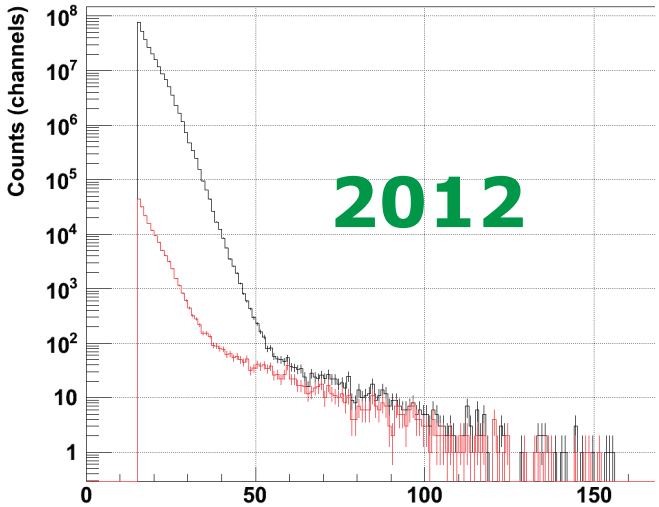
Micromegas detectors, relative to $^{235}U(n,f)$

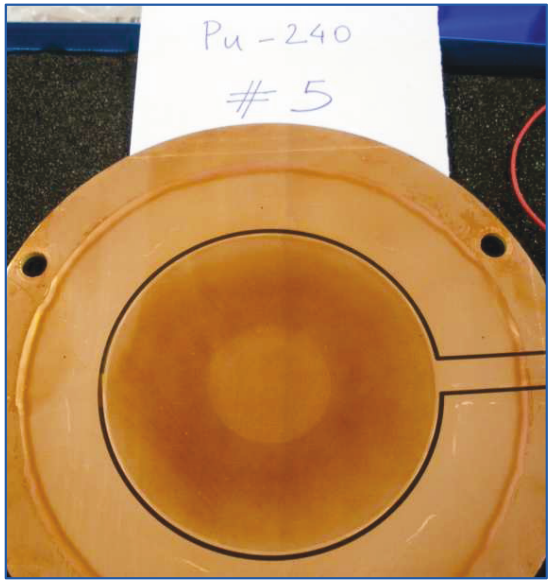








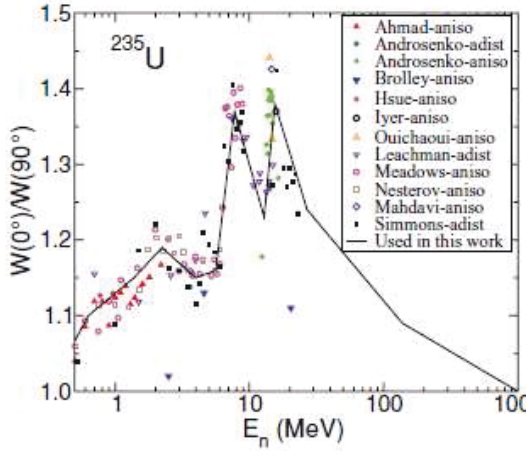


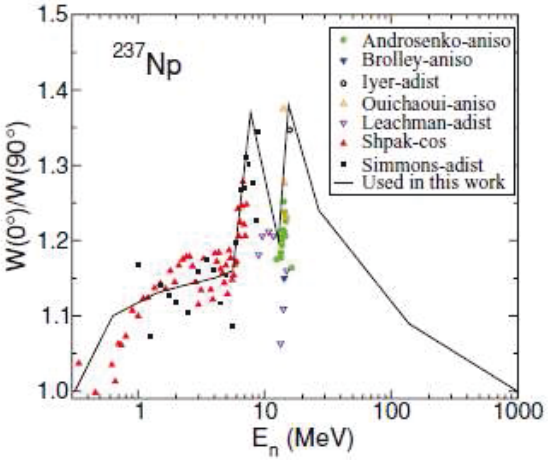


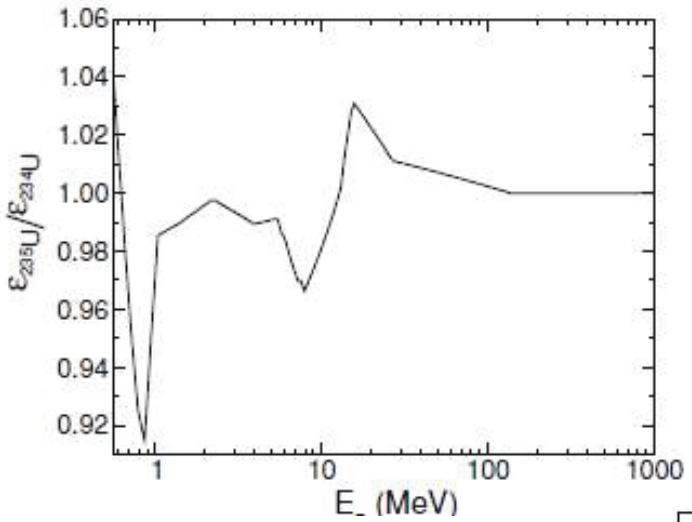
A. Tsinganis (NTUA), et al., 2nd ERINDA Progress Meeting
Jyvaskyla, January 8-11, 2013

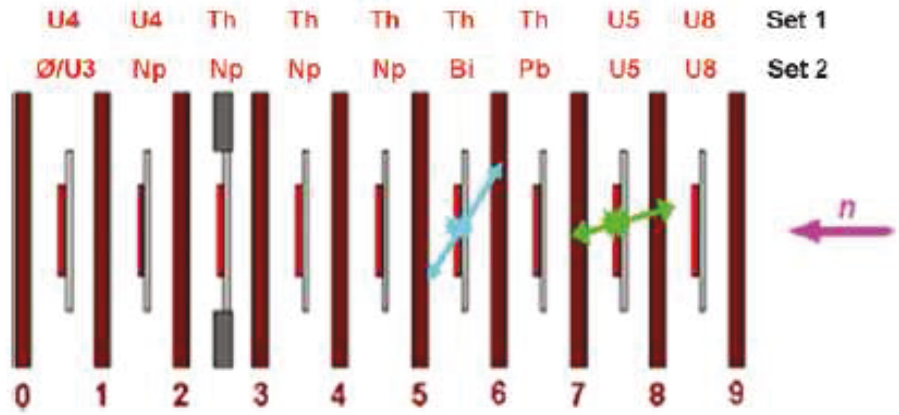
New approaches to fission cross sections

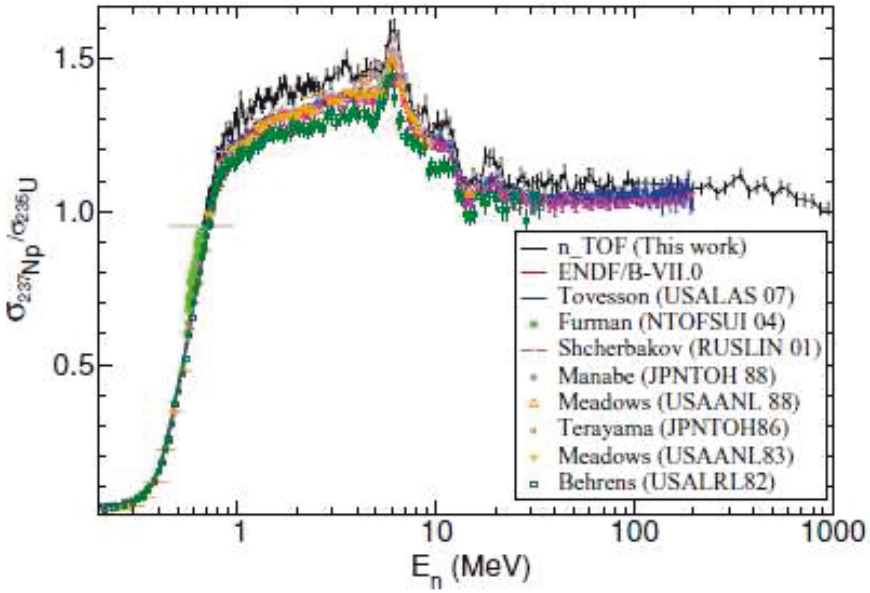
PPAC relative to $^{235}U(n,f)$; See Audouin and Leong









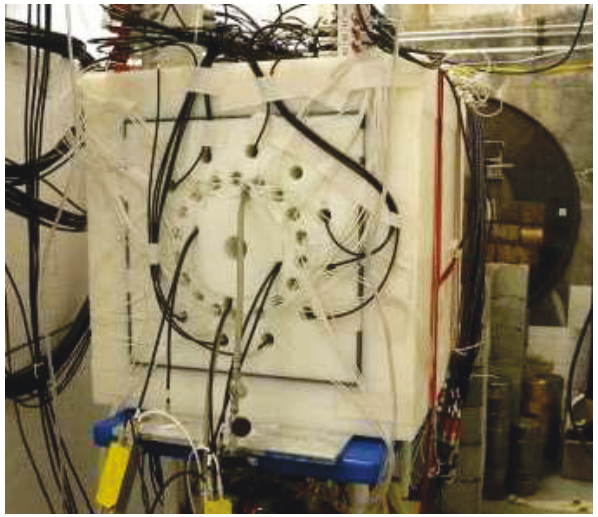


Paradela et al. PRC82(2010)034601

Neutron multiplicity

- **Number of neutrons per fission event**
- **Fission trigger**
- **Emitted neutron number**
  - Low efficiency detector
  - **High efficiency detector (CEA@LANL)**

    T. Granier, JEFF-GEDEPEON workshop 2011



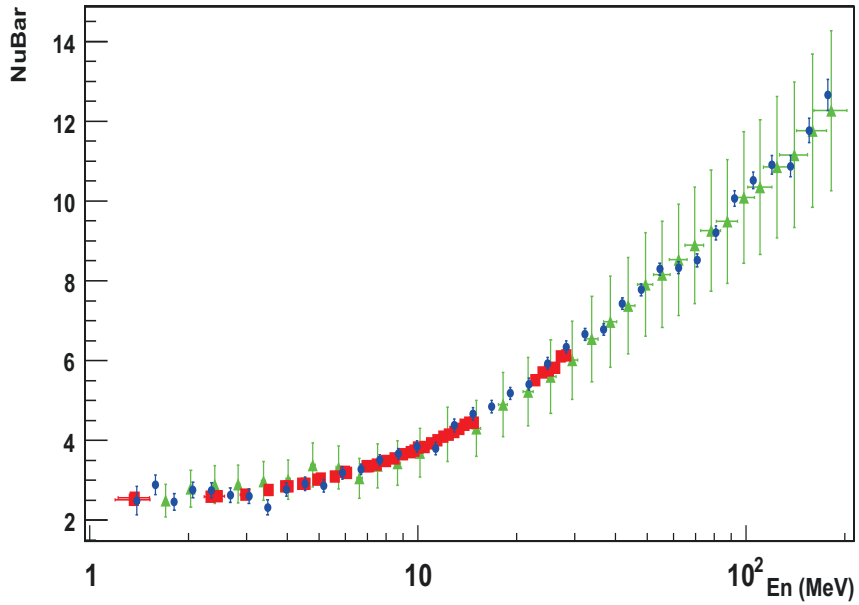
FC 1 mg ^{238}U

30 ^{3}He counters in PE moderator

PE+^{10}B shield block room return

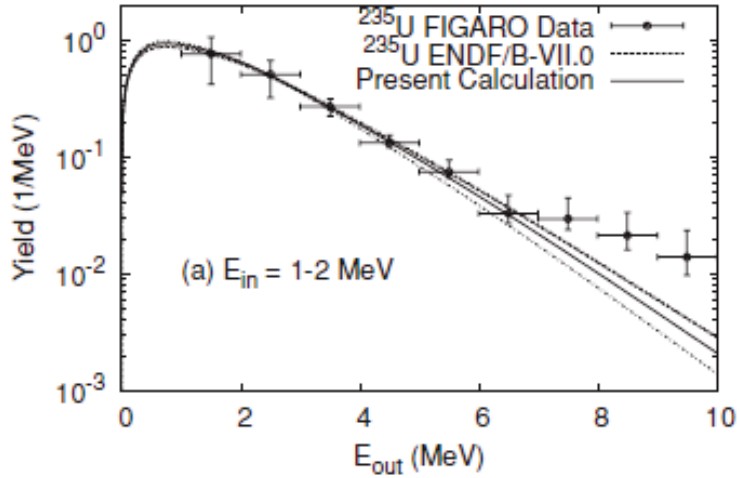
Neutron pulses up to 150 μs

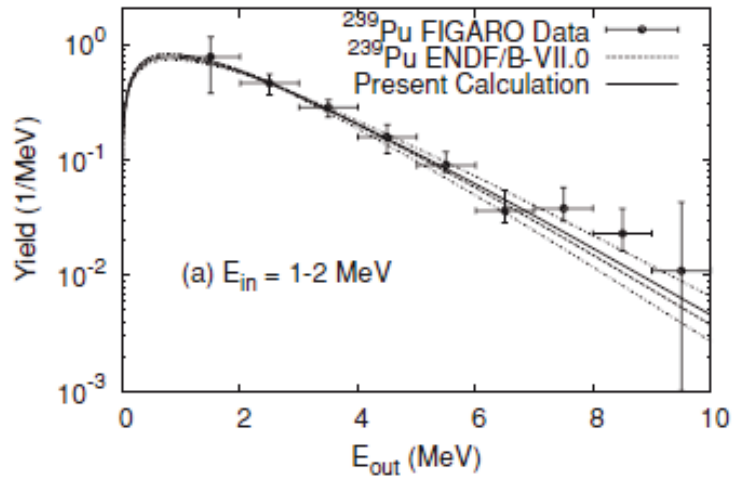
Calibration by ^{252}Cf(sf) (eff ≈ 25%)



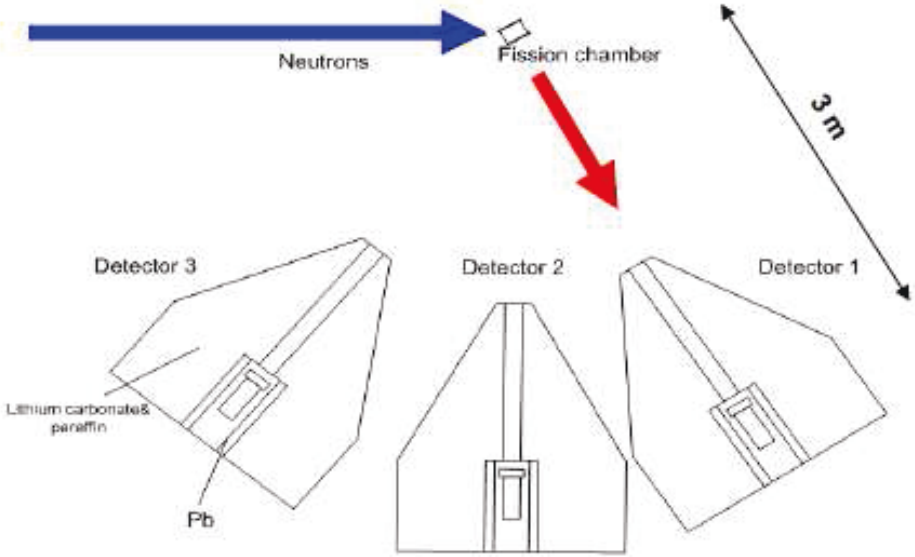
Prompt fission neutron spectrum

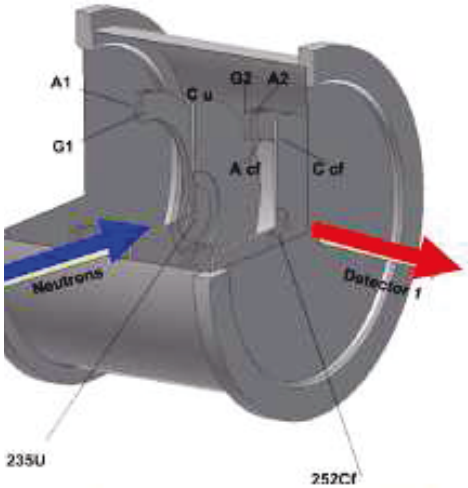
- FC: ^{235}U (100 mg), ^{239}Pu (80 mg), 11+11 deposits on 0.125 mm Pt
- LANL 800 MeV p + W, pulsed 200 ps
- E_n 1-8 MeV, 22.74 m FP, Pb+PE filters
- Double TOF: E_n and E_n'
- FC – 20 liq.scintillators 12.5x5 cm

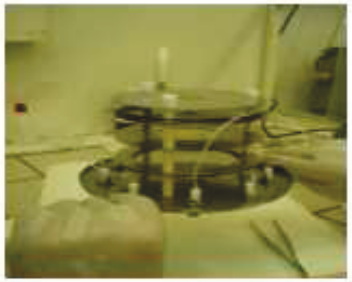


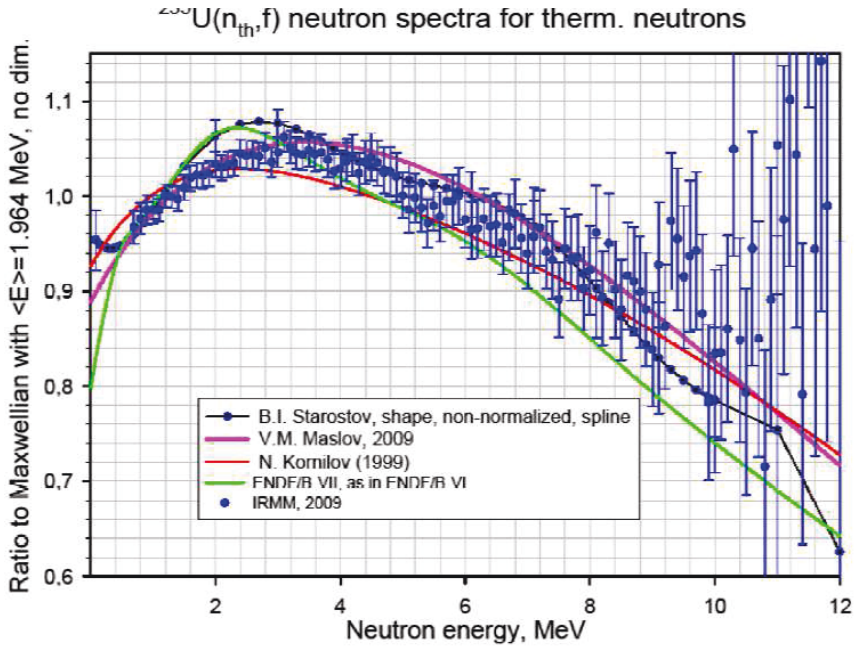


Prompt fission neutron spectrum









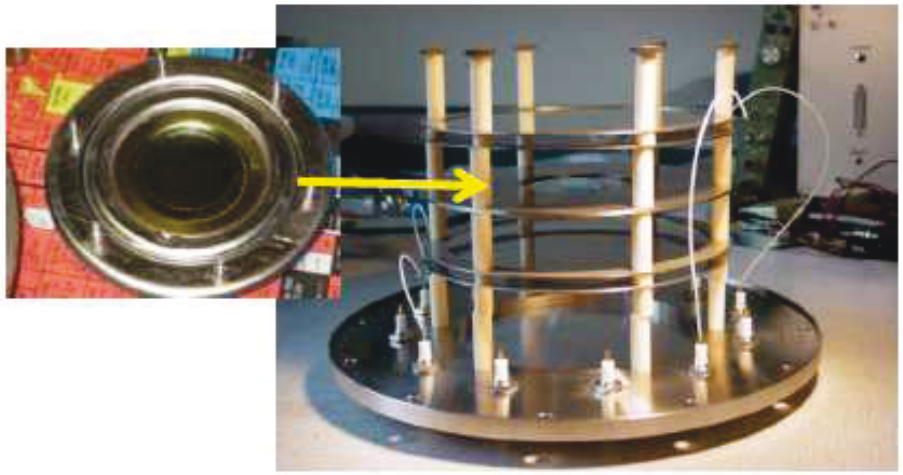
Jefdoc-1388 Hambsch et al. (2011)

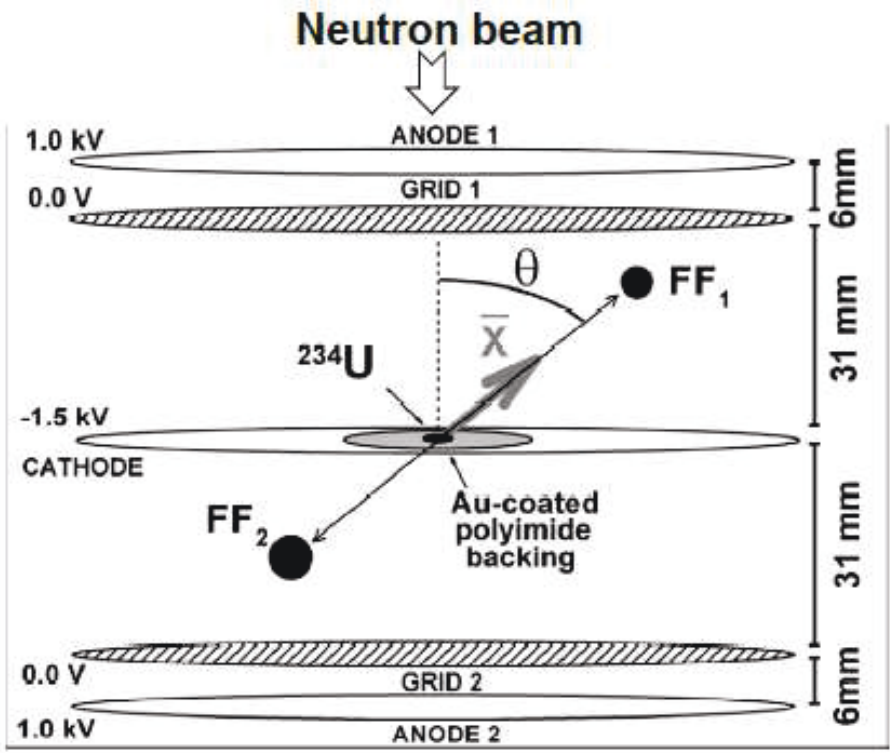
Hambsch et al.
Budapest
reactor beam
Liquid scintillator
LS301, 4”x2”
Frisch-grids, TOF
^{235}U, 112 μg/cm^2
^{252}Cf(sf) efficiency
97.7% enr
FF eff. 98%

Changes imply significant reactivity impacts: -300 to 800 pcm

FF mass, kinetic energy and angle

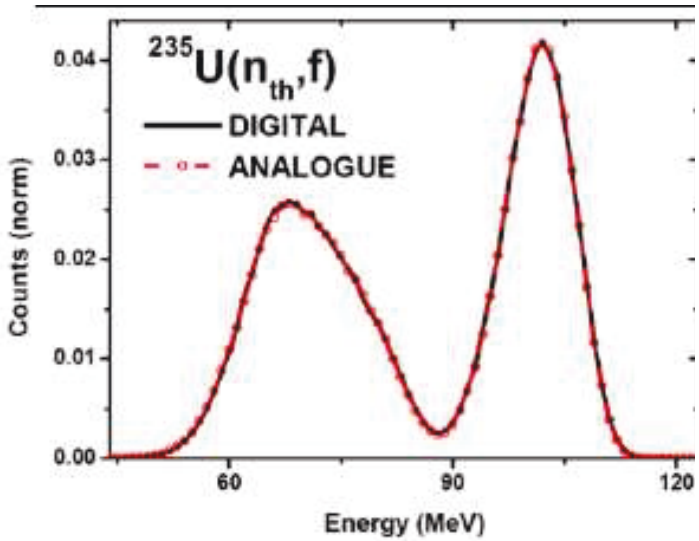
- Energy and angle are measured for both FF (summing and drift-time methods).
- Double E method used for fragment mass calculations (energy and momentum conservation).
- Precision pulse generator used for signal-drift monitoring.
- Counting gas: P-10 (90%Ar+10% CH_4).
- 1.05 bar gas pressure.
- 0.1 l/min gas flow.

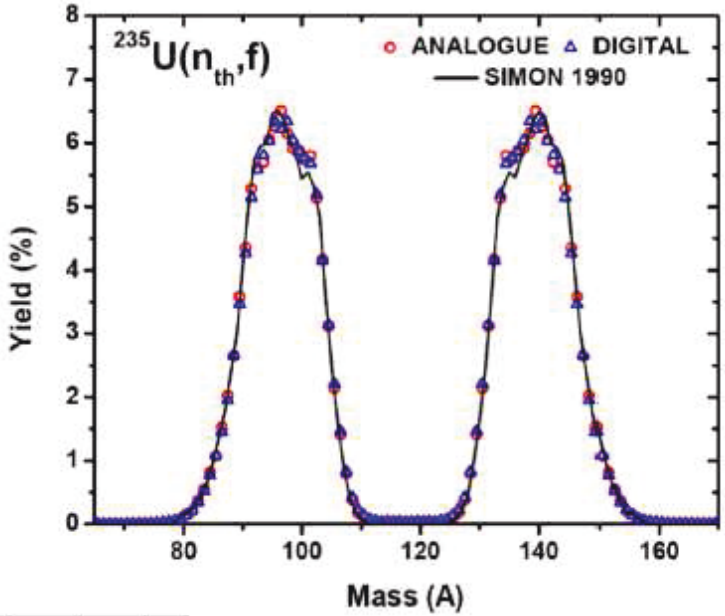


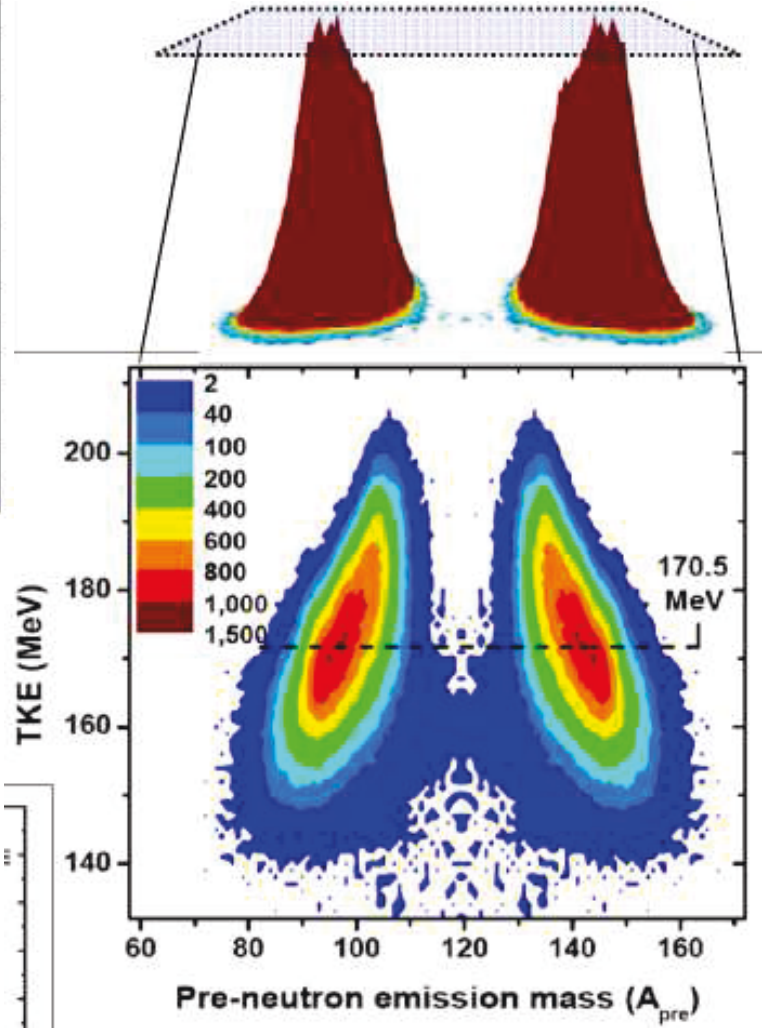


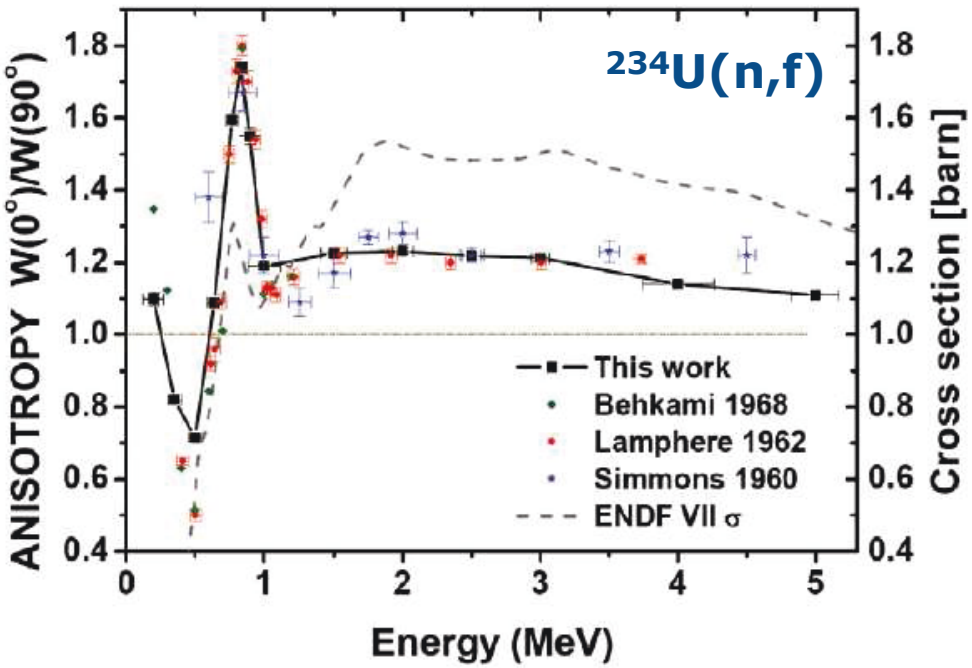
Budtz-Joergensen et al., NIMA258(1987)209
Buneman et al., Can.J.Res.A27(1949)191

FF mass, kinetic energy and angle







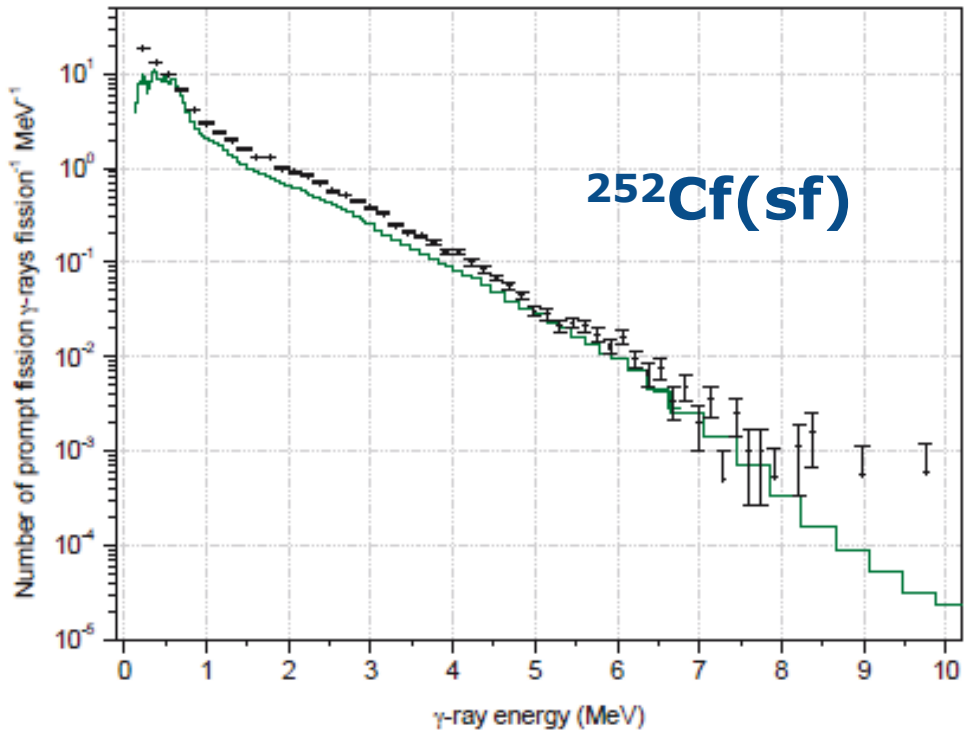


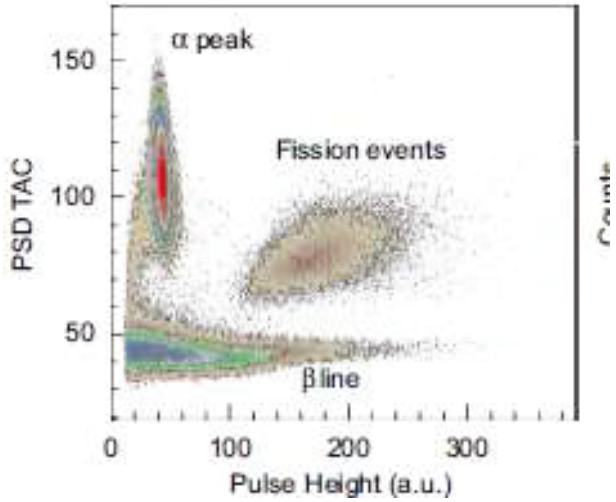
Prompt fission gammas

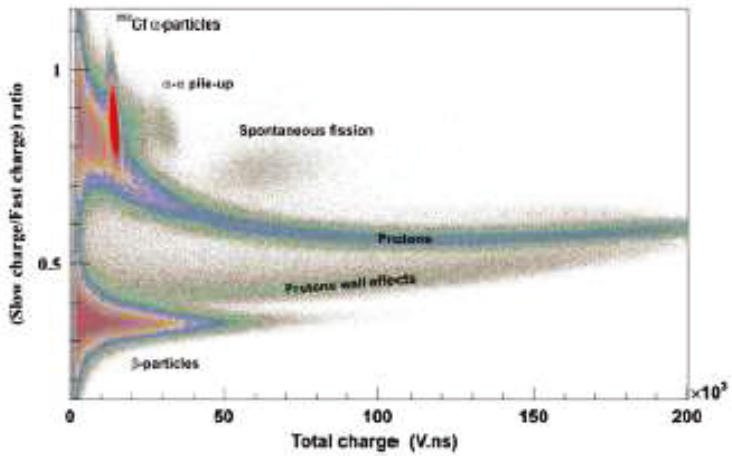
CEA DAM DIF (BRC); van de Graaff (right)

TOF for neutron gamma discrimination

Active-target (FC/LS) and BGO gamma-det.







Liquid scintillator
With target disolved in it

Laborie et al., Phys.Proc.31(2012)13

Bélier et al., Nucl.Instrum.Meth. A664(2012)341

Prompt fission gammas

New gamma-ray detectors: $LaBr_3$, $LaCl_3$, $CeBr_3$

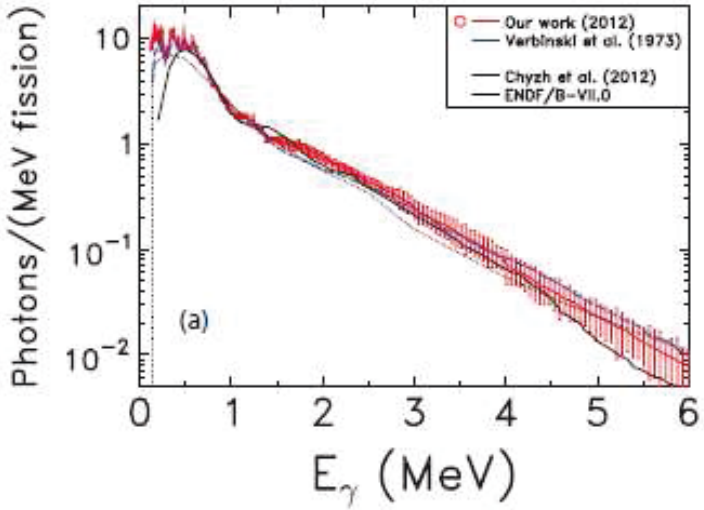
Testing and characterisation

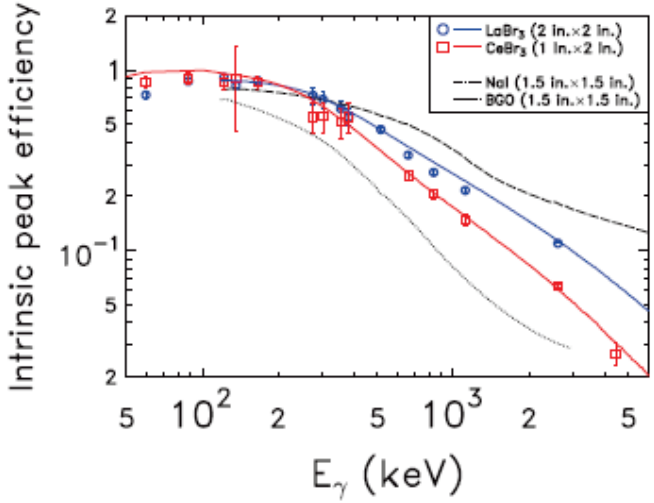
First demonstration ^{252}Cf

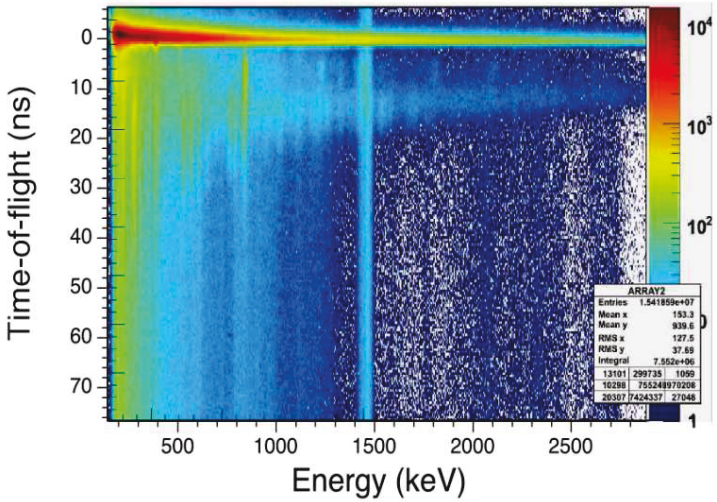
Ongoing/nearly completed ^{235}U

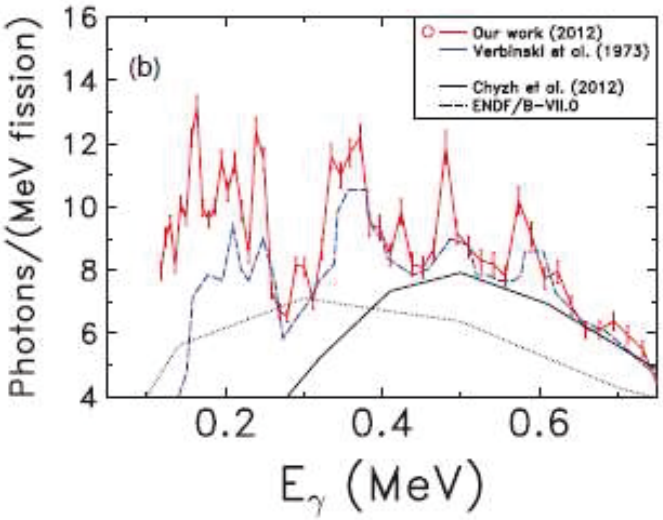
TOF, FIC vs gamma detector

Neutron-gamma separation









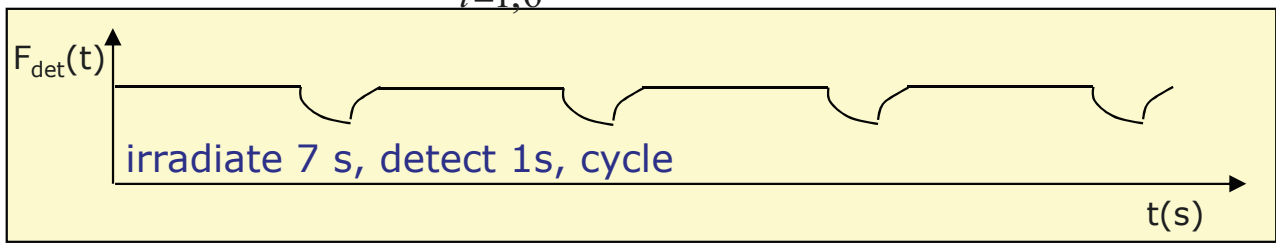
PRC87(2013)024601 Billnert et al.

Delayed neutrons

- **232Th**
- **PTB VdG**

$$F_{\det}(t) = n_{fissions}\ \varepsilon\ Y_d(t)$$

$$Y_d(t) = \upsilon_d \sum_{i=1,6} a_i \exp(-\lambda_i t)(1-\exp(-\lambda_i t_{irr}))$$



Neutron detector :

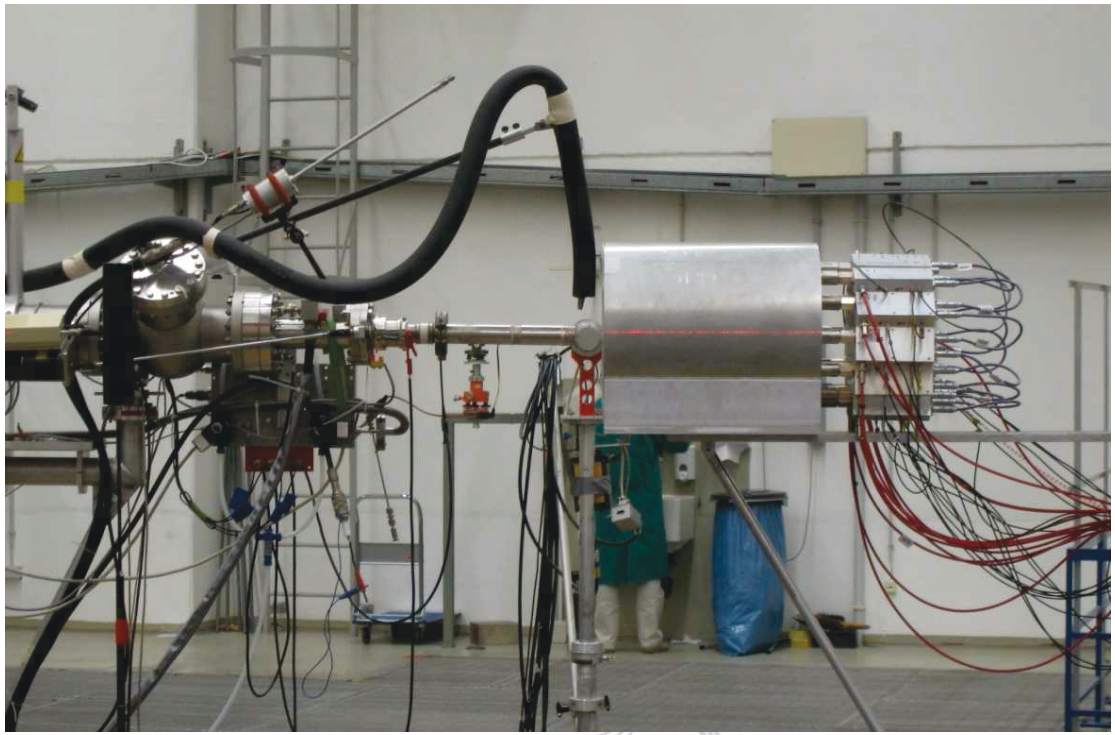
- Cylinder of CH2
  Φin=6 cm, Φout=16 cm, L=37cm)
- 12 tubes 3He
- efficiency ε > 20% (sample in centre)
- constant efficiency between 0.1 and 1 MeV
- not sensitive to gamma
- Also used for photofission studies

Thorium sample :

- Cylinder (r=1.275 cm, h=3 cm)
- m=182 g

Efficiency :

- MCNPX simulations
- Measurements with Cf-252 sources

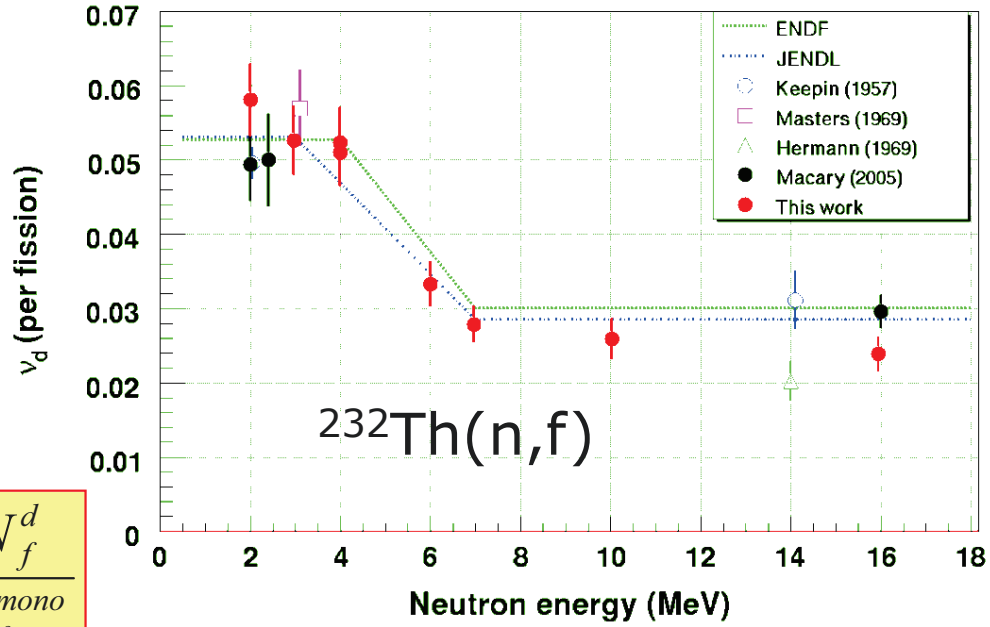


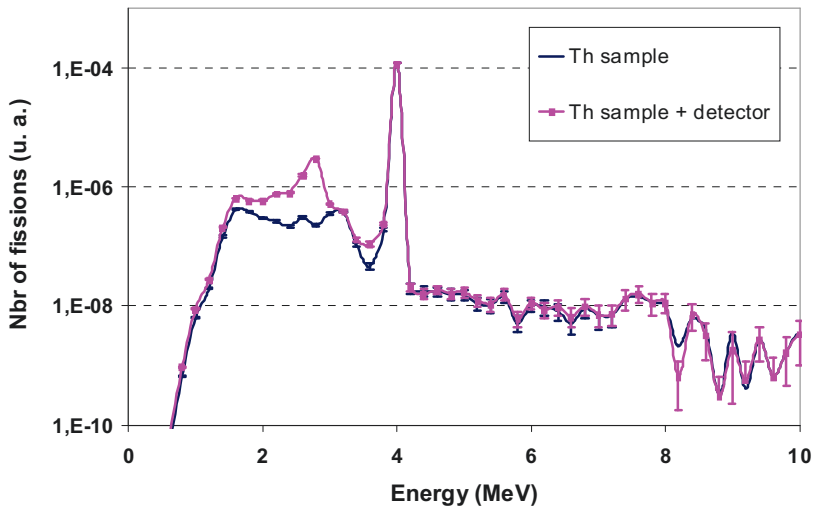
X. Ledoux et al. JEFF-GEDEPEON 2011

Delayed neutrons (Ledoux et al.)

- **Effective spectrum**
  - Neutron source
  - Scattering in sample
  - Fission neutrons
  - Two background zones
  - to subtract

$$\upsilon_d^{mono} = \frac{F_{\det}(0)}{\varepsilon\, m\, N_f^{mono}\, Y_{\theta=0^\circ}\, K} - \upsilon^u \frac{N_f^u}{N_f^{mono}} - \upsilon^d \frac{N_f^d}{N_f^{mono}}$$





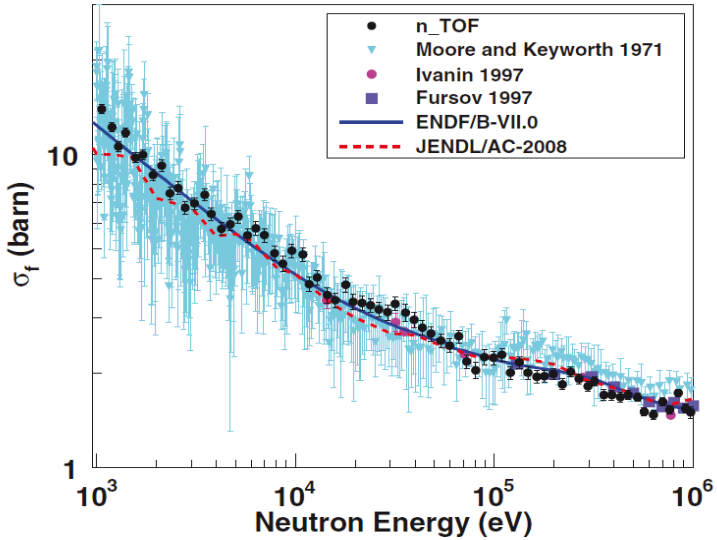
International collaboration

European projects acting on HPRL

ANDES
ERINDA
EUFRAT
GEDEPEON (NEEDS…)
TRAKULA
Subgroup-31
Subgroup-33

New: CHANDA
Broader: file projects, WPEC, IAEA

ANDES Example: ^{245}Cm(n,f), required: 3%
Calviani et al.: 5% PRC85(2012)034616



Belloni et al., ^{241}Am(n,f) EPJA49(2013)2
Belloni et al., ^{243}Am(n,f) EPJA47(2011)160
Belloni et al., ^{233}U(n,f), EPJA47(2011)2

Summary

- Fission is the process for energy production, safety, waste
- Many different aspects, all needed for a certain application
- Target uncertainty for cross sections and nubar are very tight
- For cross sections there is a remarkable bias for technique and normalization (FIC, 235U(n,f))
- Investigations in new technical options should be promoted
- There is considerable work ongoing that adds diversity with clear benefits (and also some learning points)
- Learn from past lessons
- International collaboration, in and beyond value is Europe, is a must

- Good new work is needed with new technology and enthusiastic new people