# Joint Research Centre

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*Stimulating innovation*
*Supporting legislation*


# The nuclear fission process

**S. Oberstedt**

**Joint ICTP-IAEA School, Trieste, Oct. 19 – 30, 2015**

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# Joint Research Centre IRMM


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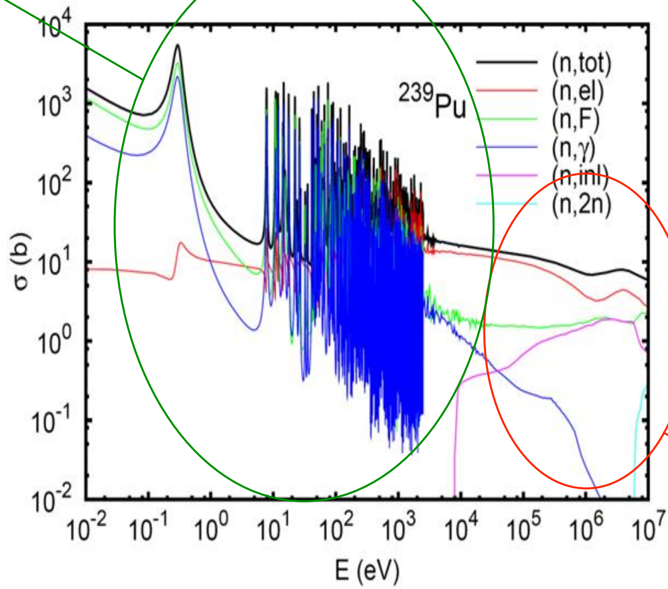
# The JRC Nuclear Facilities

# The JRC Nuclear Facilities

**Time-of-flight measurements**

GELINA




MONNET (from 2017)

**Mono-energetic neutron beams**

**Neutron reference data measurements for safety assessments of nuclear energy systems**

**CIELO project towards world-wide nuclear data standardisation**

**Measurements of nuclear data standards**

**Investigations for a better understanding of the nuclear fission process**

**Open Access program EUFRAT https://ec.europa.eu/jrc/eufrat**

# Table of content

- Introduction to the fission process
- Fission-fragment characteristics
- Fission observables
- "How to measure fission fragment properties?"

2nd course: "Fission-fragment de-excitation: ..."

- Prompt fission neutrons
- Prompt $\gamma$-ray emissions

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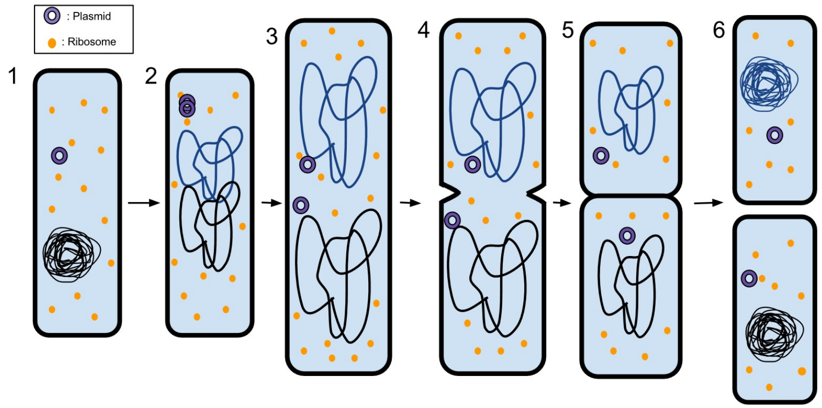
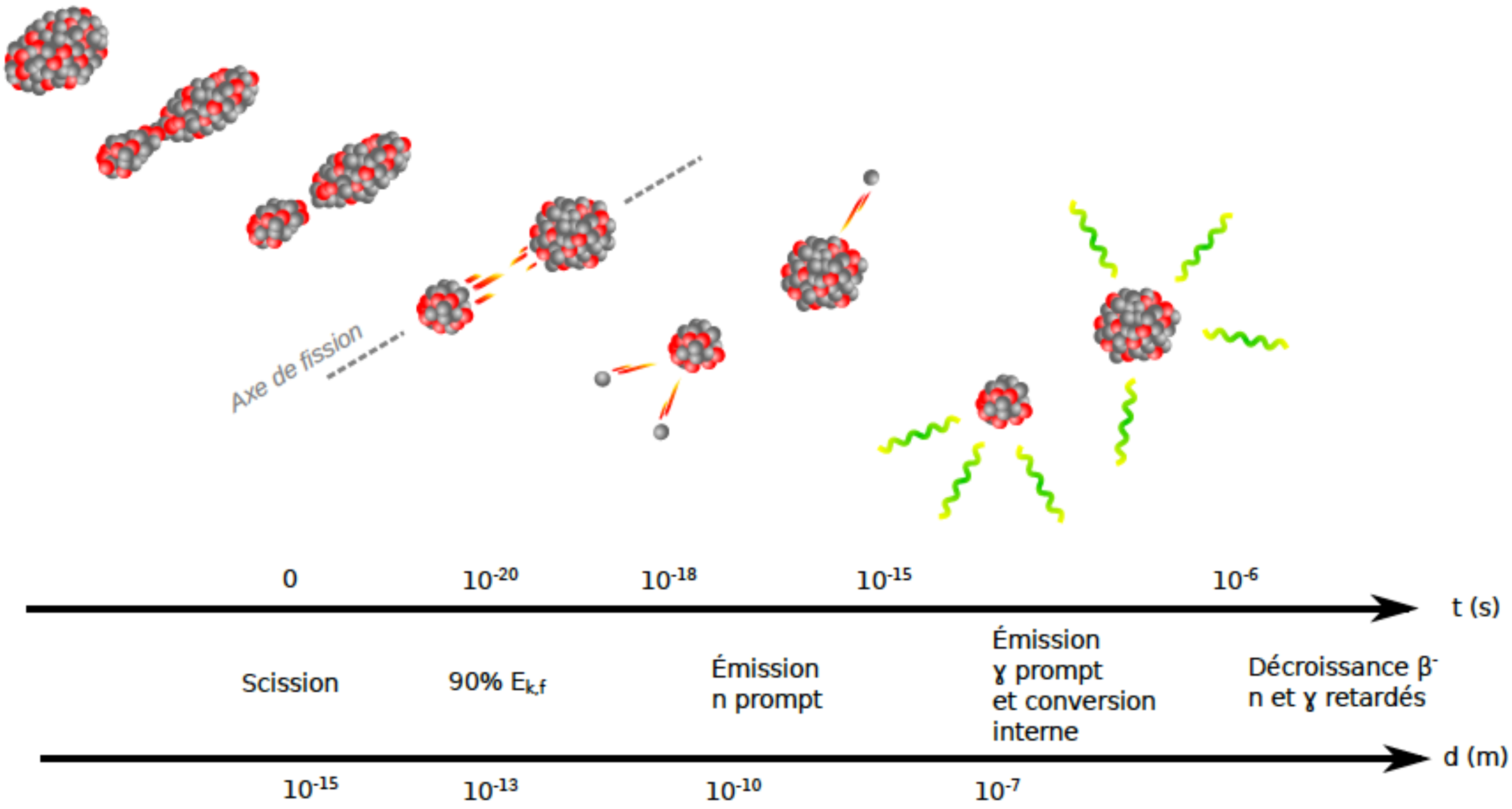
# The definition of "fission"




***Fission*** **is the division of a cell (or body, population, or *species*) into *two or more parts* and the *regeneration* of those parts into *separate* cells (bodies, populations, or *species*).**

***Binary fission*** **produces *two separate* cells, populations, *species* etc., whereas multiple fission produces more than two cells, populations, species etc.**

# The fission process

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# The fission process

**prompt neutrons ($10^{-18}$ s)**

**fission fragments ($10^{-21}$ s)**


**ternary α, t, d, $^{10}$Be…**

**prompt γ-rays ($10^{-16}$ s)**

| | |
|---|---|
| kinetic energy<br>prompt γ-rays | heat |
| prompt neutrons<br>(delayed neutrons) | chain reaction |
| ternary α, t, d | gas production in the fuel (waste) |
| fission fragments | decay heat, toxicity (waste) |

# The fission process

prompt neutrons ($10^{-18}$ s)

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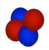

ternary $\alpha$, t, d, $^{10}$Be…

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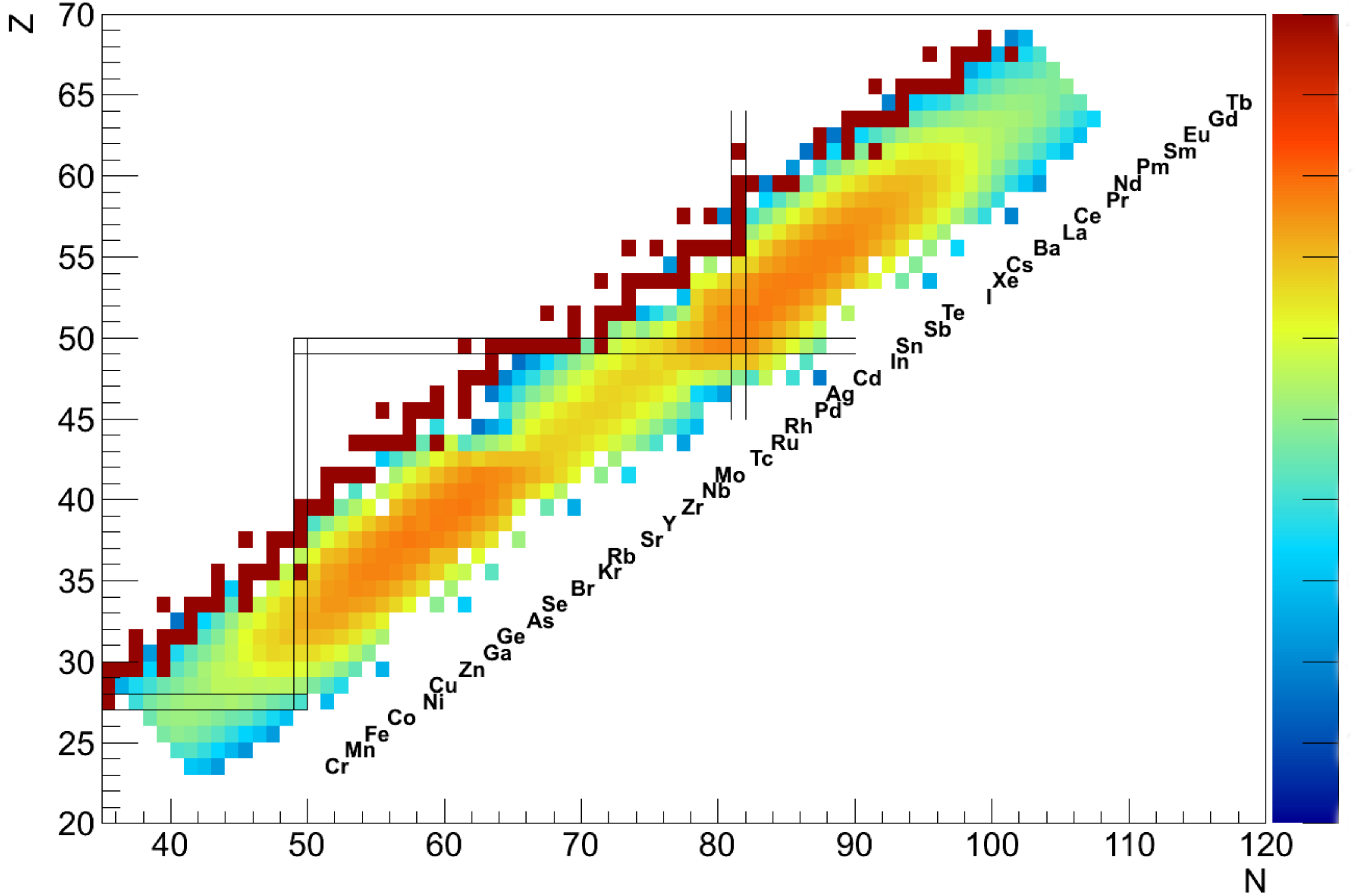
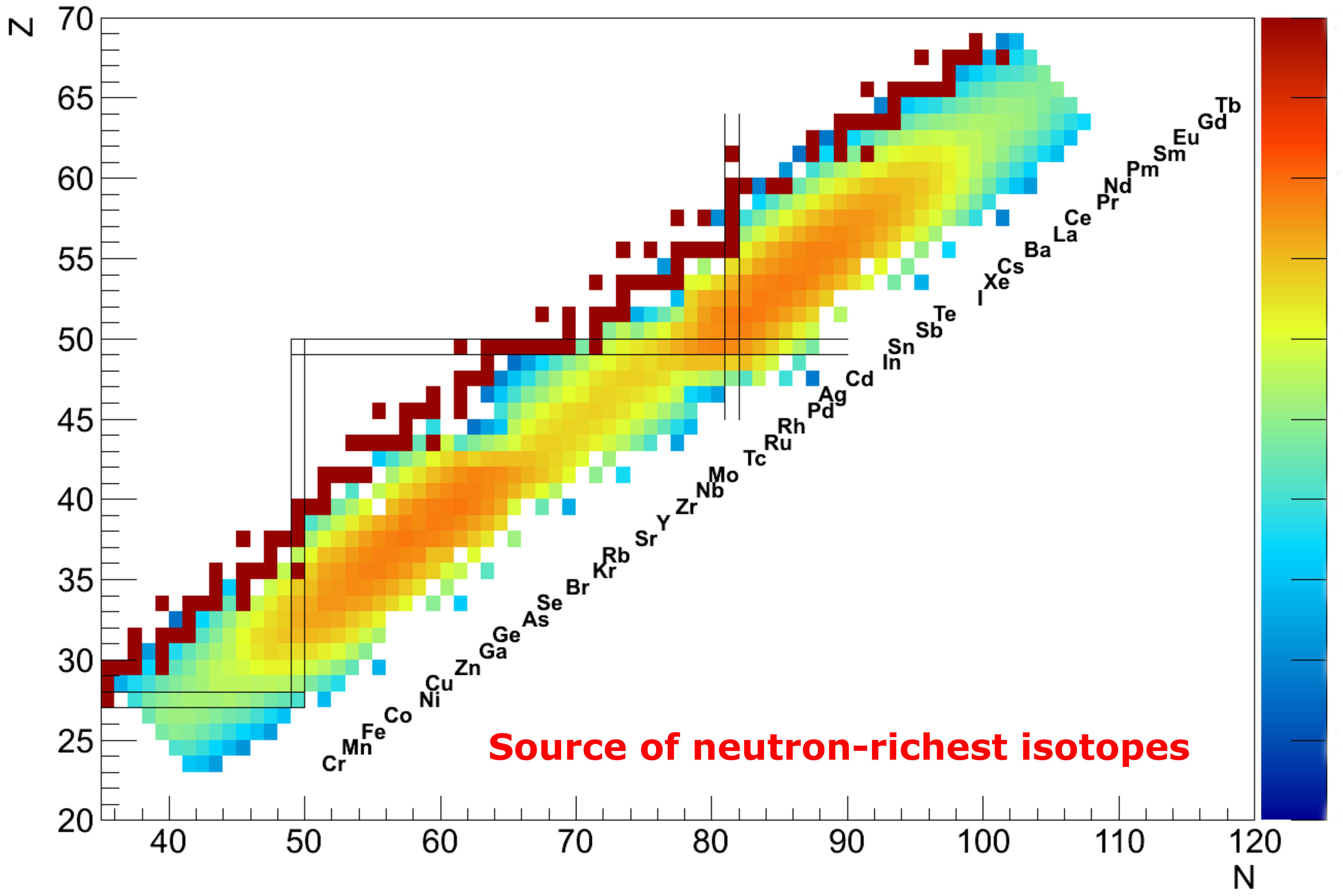
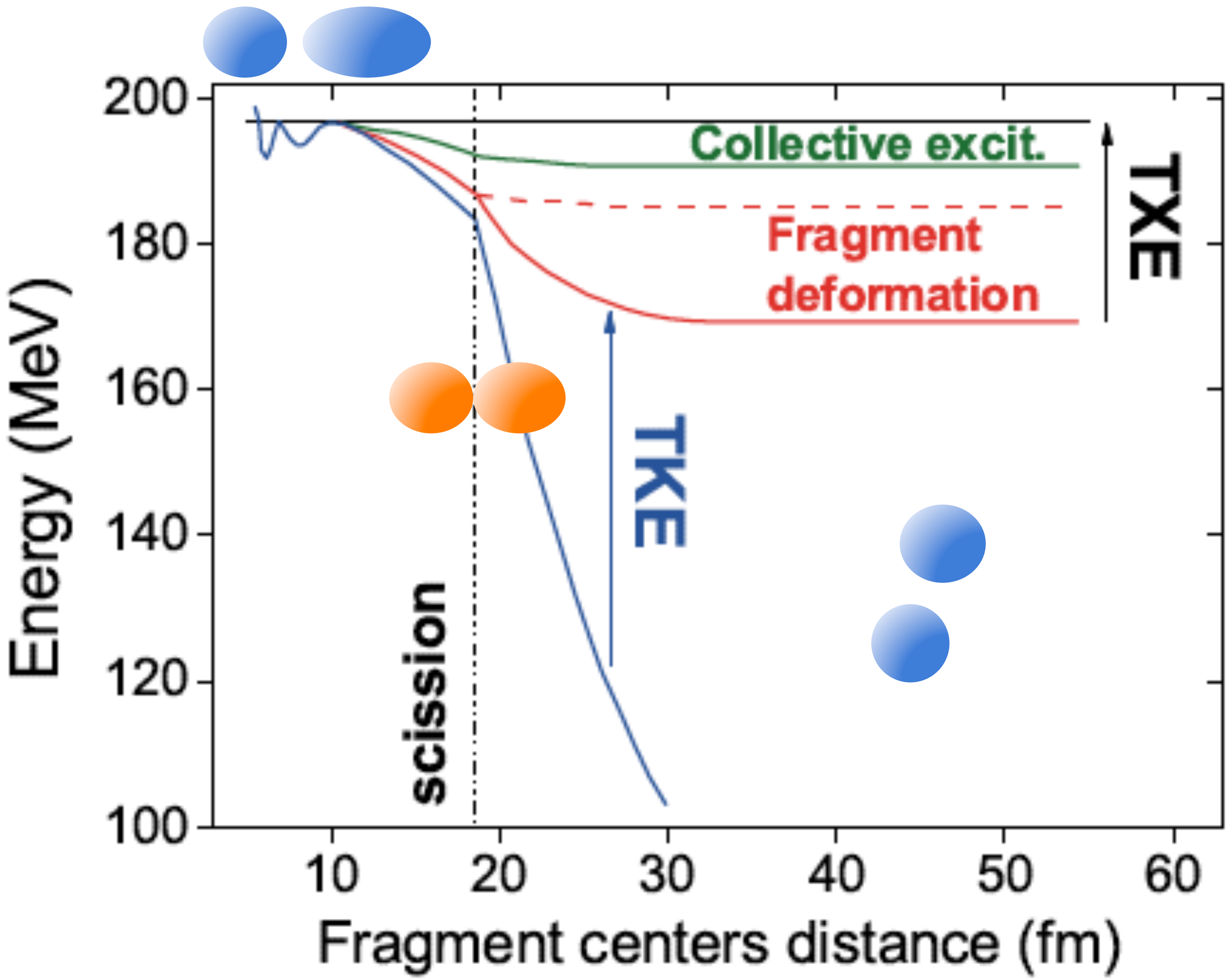


# The fission process



# The fission process

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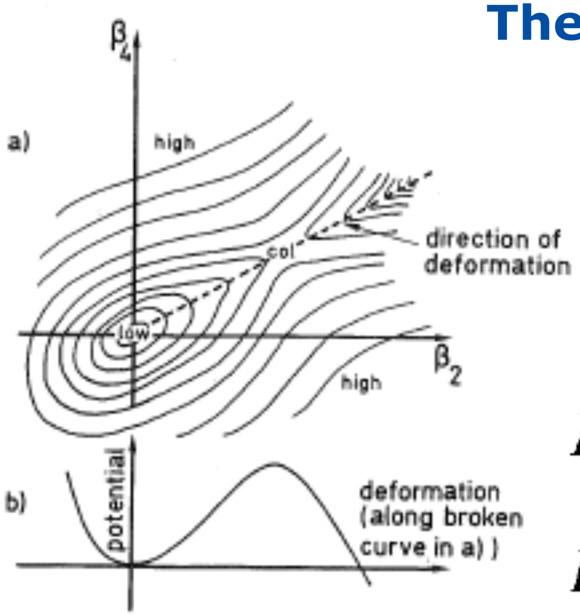
# The fission process

## The Liquid-Drop Model (LDM)




$$R(\vartheta,\varphi) = R_o\left[1 + \sum_{\lambda,\mu} a_{\lambda\mu} Y_{\lambda\mu}(\vartheta,\varphi)\right]$$

$$E = E_v + E_s + E_c + E_p = E_{LDM} + E_p$$

$$E_{def}(\epsilon) = E_s(\epsilon) + E_c(\epsilon) - E_s(0) - E_c(0)$$

$$E_c(\epsilon) = E_c(0)(1 - 2/5\ a_{20}^2)$$

$$E_s(\epsilon) = E_s(0)(1 + 2/5\ a_{20}^2)$$

**Fissility parameter:** $x = E_c(0)/2E_s(0)$; **Bohr and Wheeler**

# The fission process

**With:**

$$E_c(0) = 0.71 Z^2/A^{1/3}$$

$$E_s(0) = 17.8 A^{2/3}$$

**It follows:** $X \sim Z^2/A$

$X = 1 \Longleftrightarrow Z^2/A = 50$

**Consequences:**

- **For *X > 1* nucleus is unstable against fission**
- **Multipole expansion ($\lambda = 16$):** $E_B \approx 0.83\, E_S(0)\, (1 - X)^3$
- **…**

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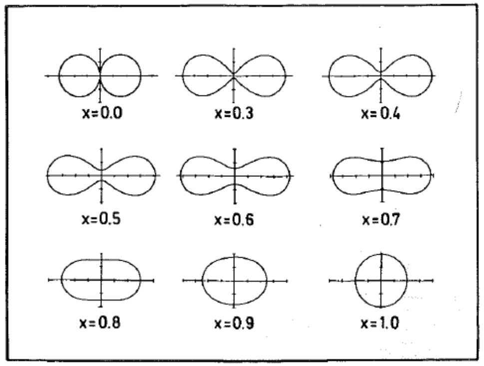


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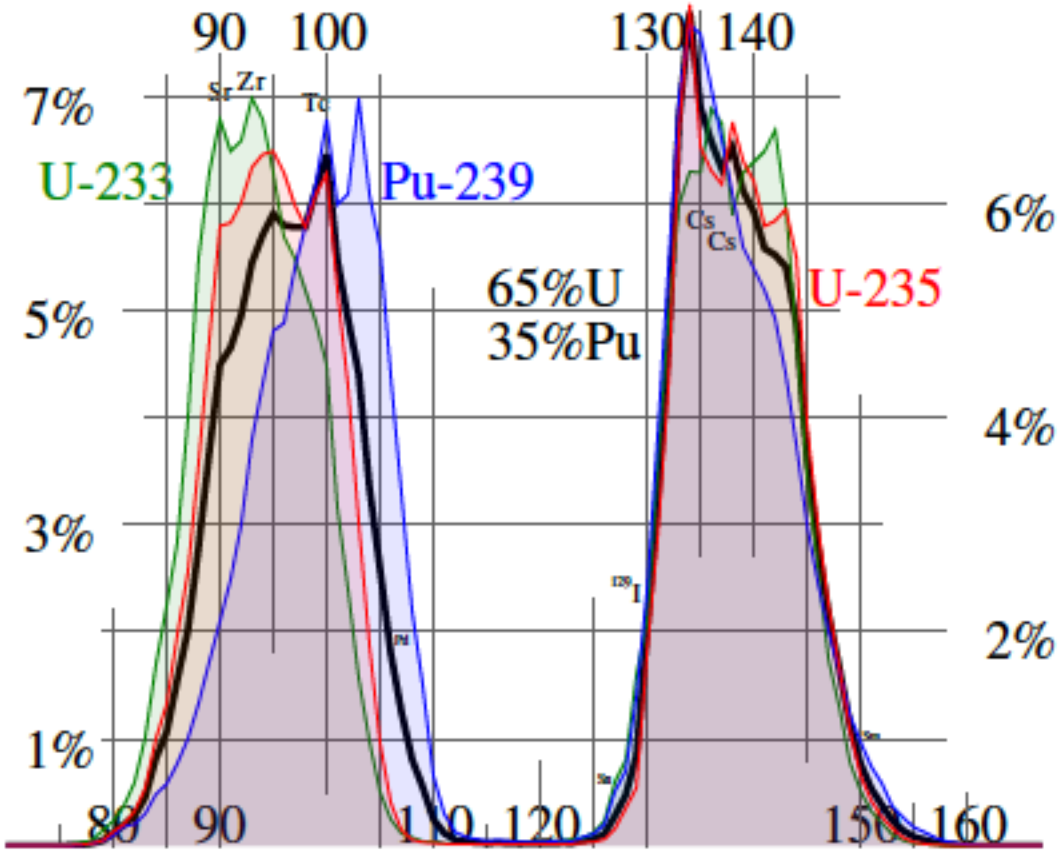
- **Multipole expansion (λ = 16):** $E_B \approx 0.83\, E_S(0)\, (1 - X)^3$
- **Ground-state is spherical, symmetric fission**

# The fission process




Fragment mass number

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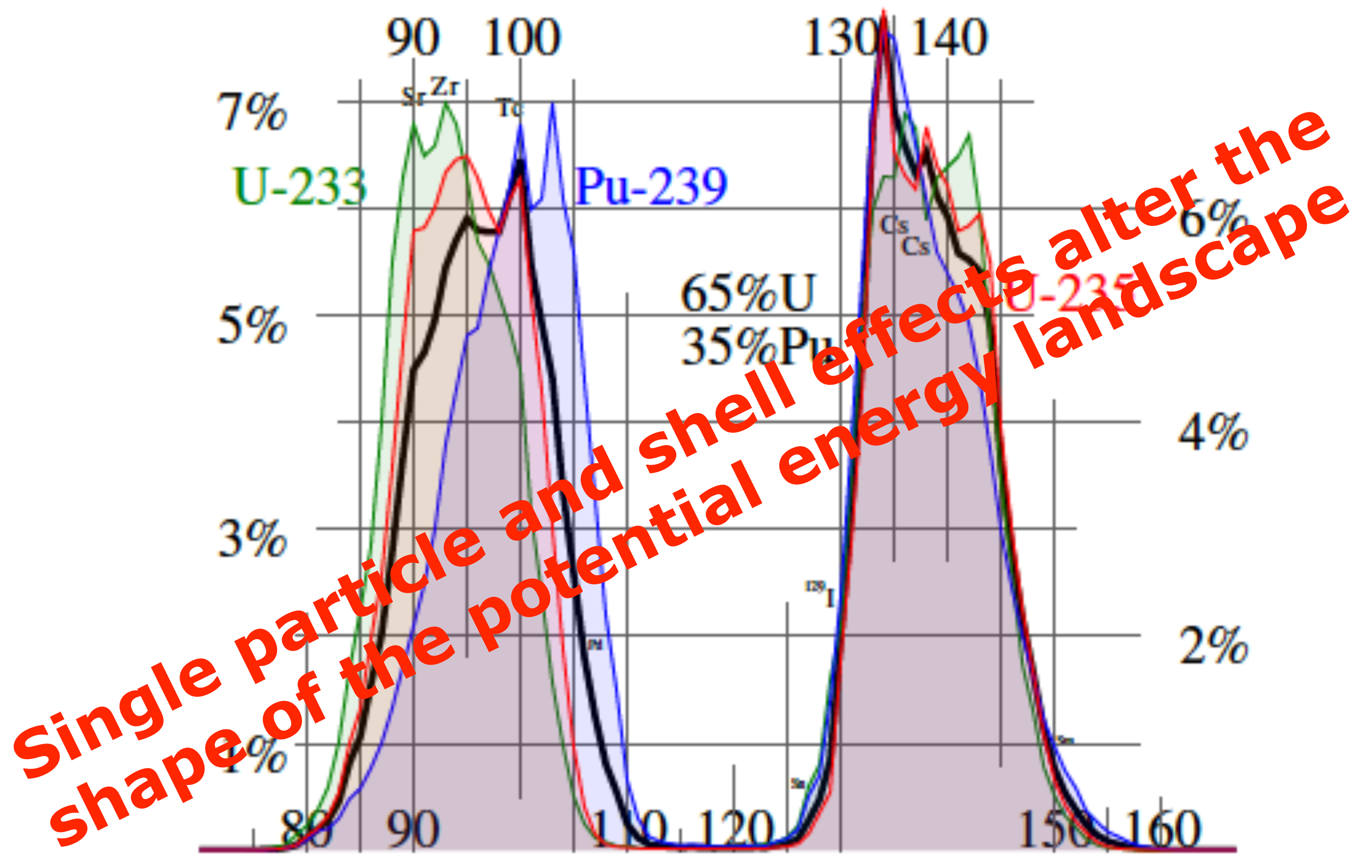
# The fission process




**Fragment mass number**

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# The fission process

**"Macroscopic-microscopic" or "shell correction" (SCM)**

$$U = \sum_{\nu} 2 n_\nu \epsilon_\nu$$

$$E = U - \widetilde{U} + E_{LDM} = E_{LDM} + \delta U$$

$$\widetilde{U} = 2 \int_{-\infty}^{\widetilde{\lambda}} \epsilon \widetilde{g}(\epsilon) d\epsilon$$

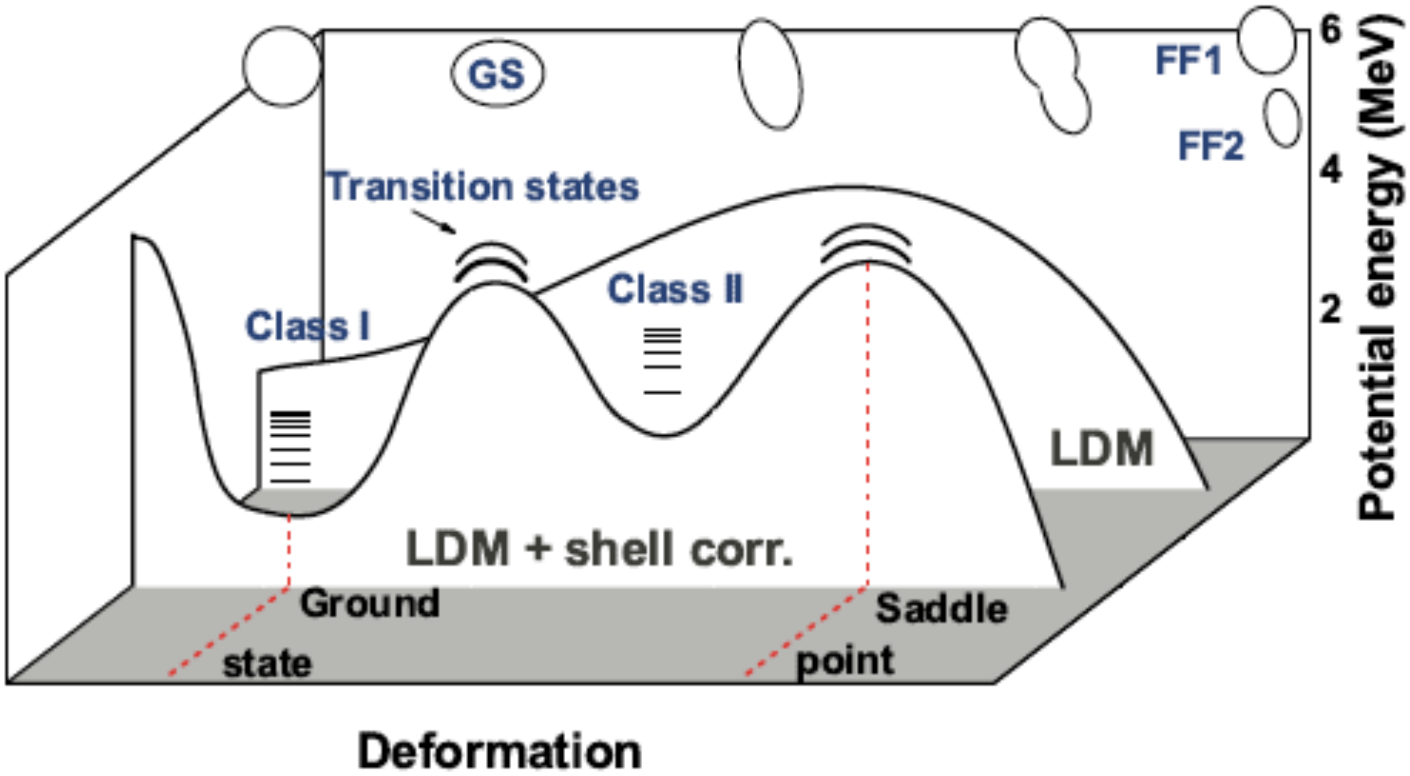
$$N = 2 \int_{-\infty}^{\widetilde{\lambda}} \widetilde{g}(\epsilon) d\epsilon$$

**N : particle number**

$$\widetilde{g}(\epsilon) = \frac{1}{\sqrt{\pi}\gamma} \sum_{\nu} \exp[(\epsilon - \epsilon_\nu)^2/\gamma^2];$$ **$\gamma$ = 10 MeV**

# The fission process

## "Macroscopic-microscopic" or "shell correction" (SCM)




A.A. Adili, PhD thesis

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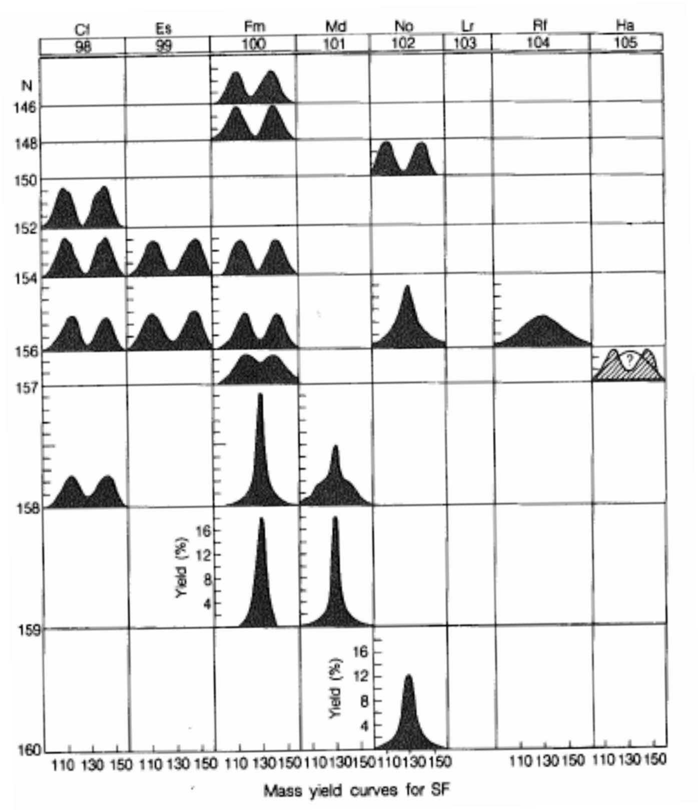
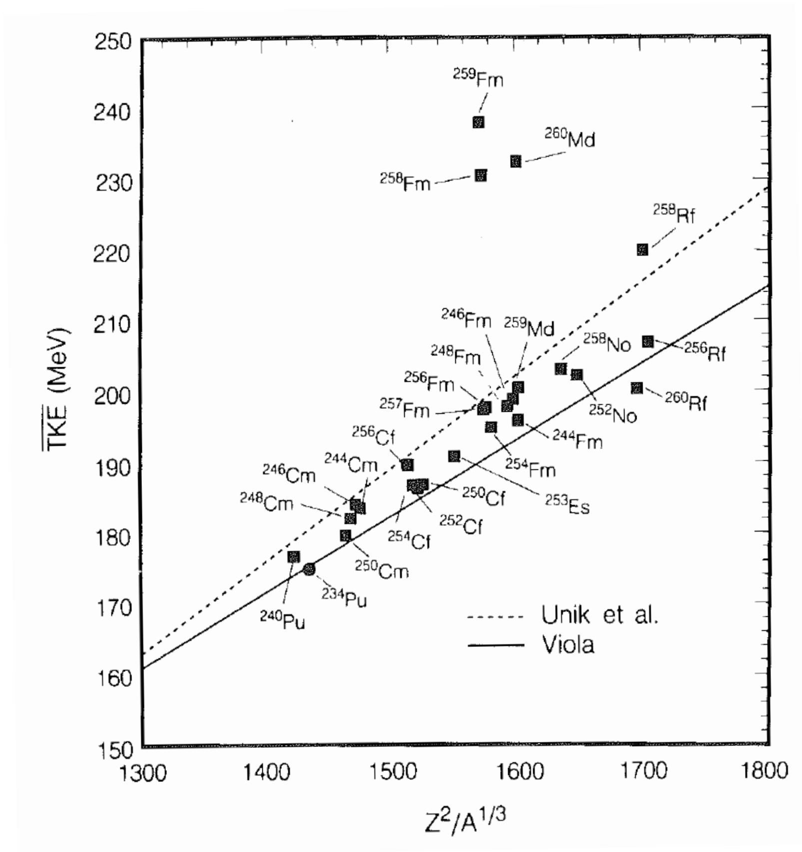
# The fission process

## SCM – consequences:




**D.C. Hoffman, Nucl. Phys. A502 (1989) 21c**

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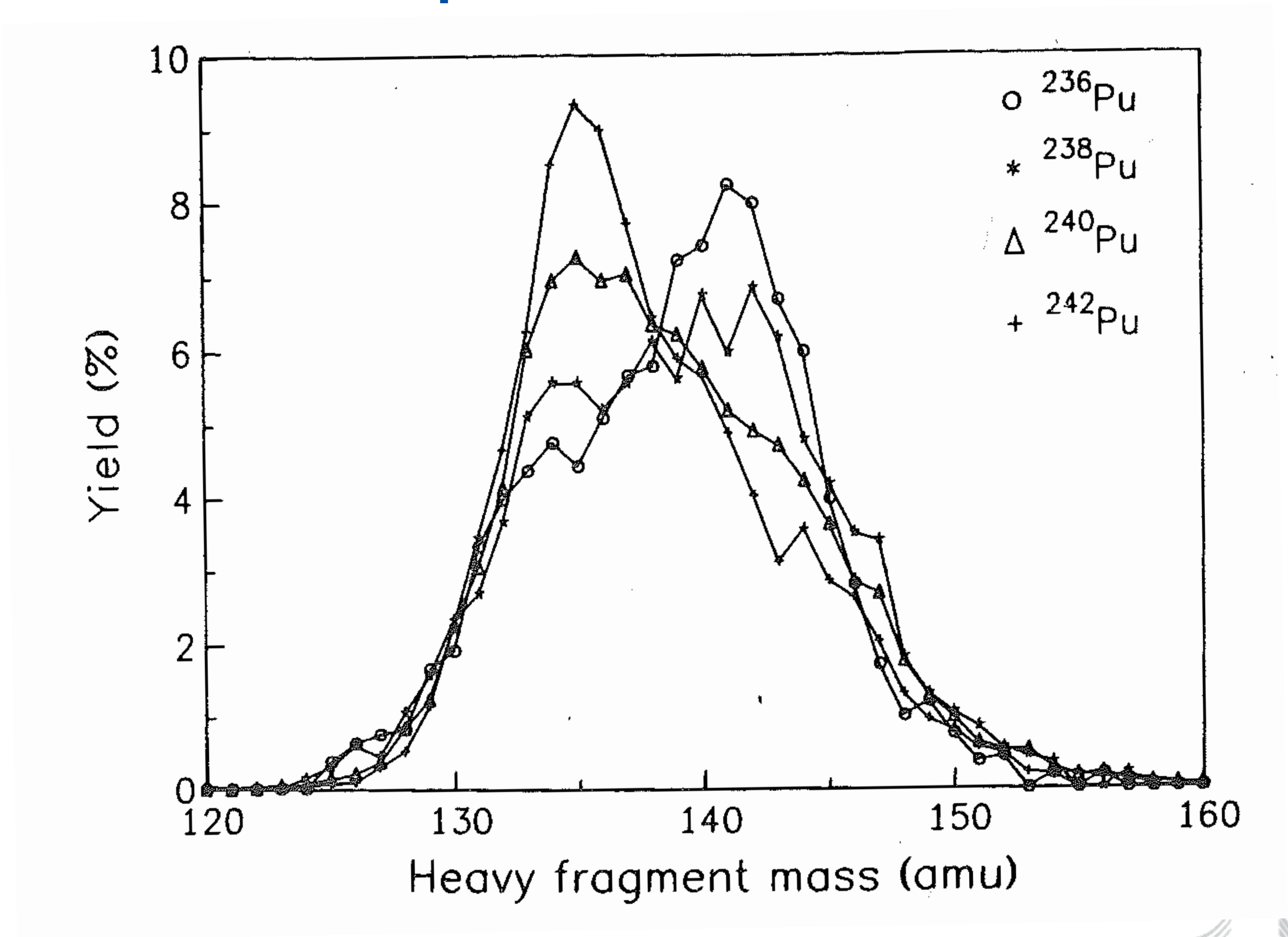
# The fission process

## SCM – consequences:



# The fission process

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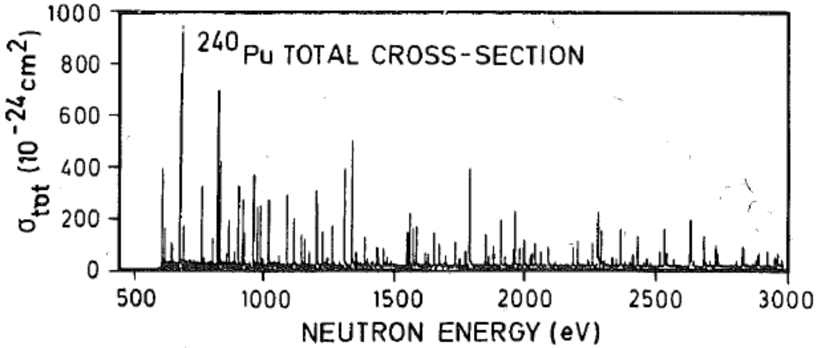
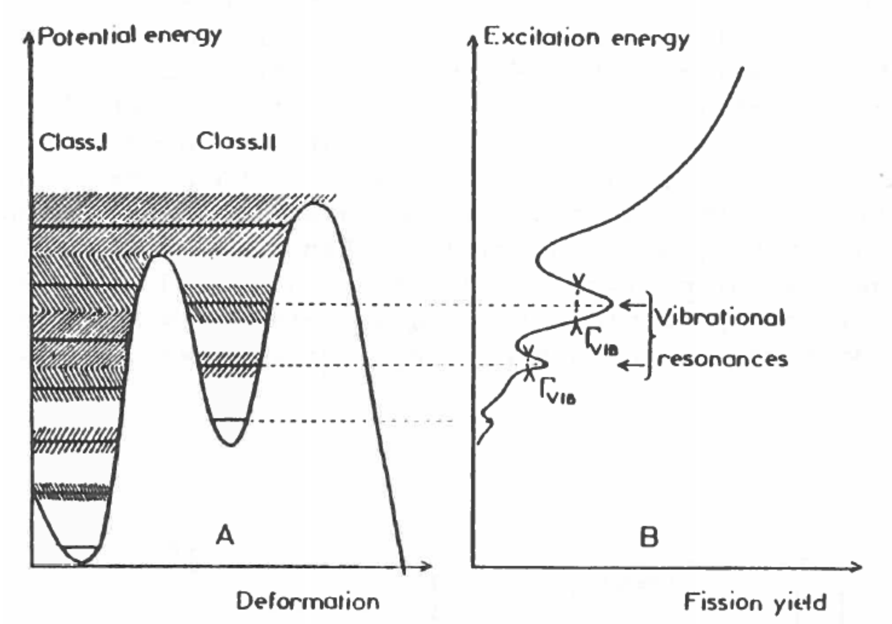
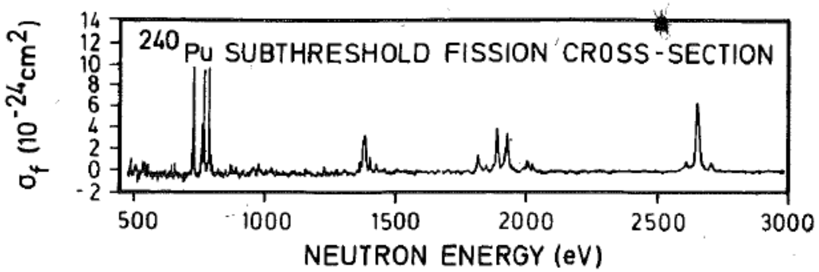
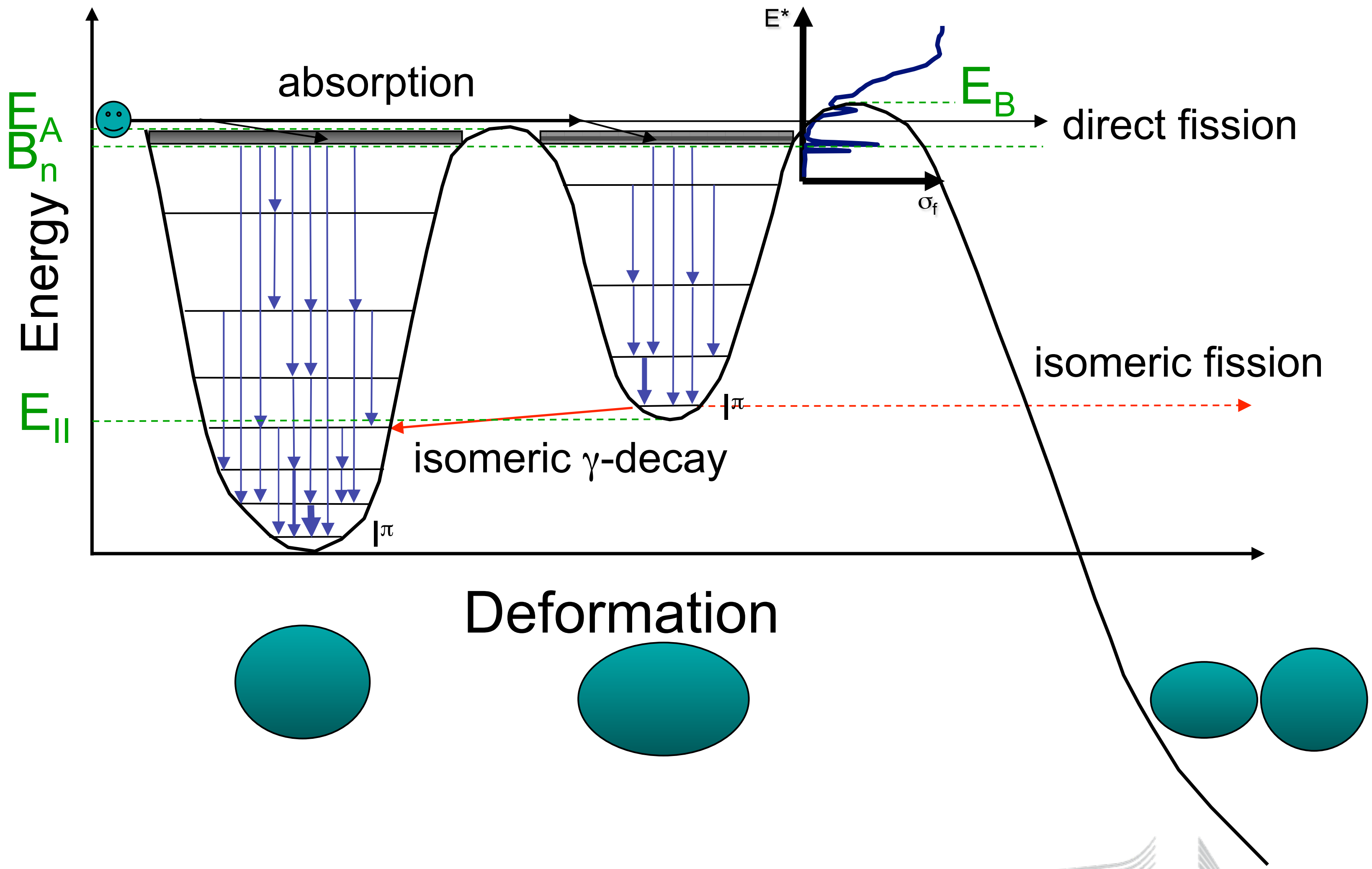


# The fission process

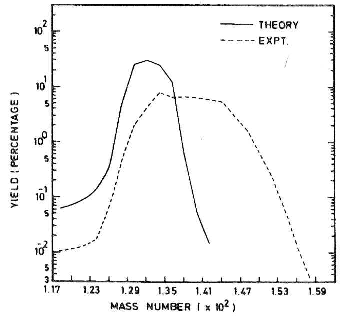


# The fission process

**No theory here!!!**

**…**

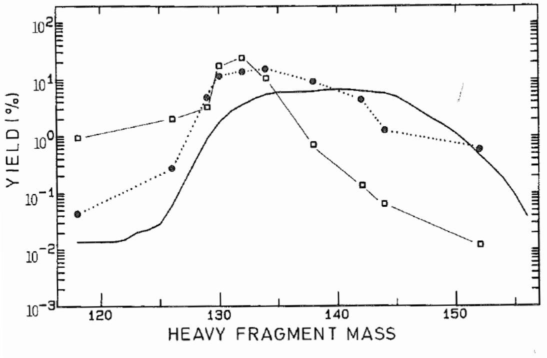
# The fission process




No theory here!!!

But look at:

"The Nuclear Fission Process", Ed. C. Wagemans
Chapter VII, p. 227ff (1991)




Recent papers:

GEF, K.-H. Schmidt, B. Jurado
FREYA, R. Vogt, J. Randrup
...

M. Prakash, V.S. Ramaurthy et al., IAEA (1980)
J. Moreau, K. Heyde et al., "IX[e] Journée d'Etudes sur la Fission Nucléaire"(1980)

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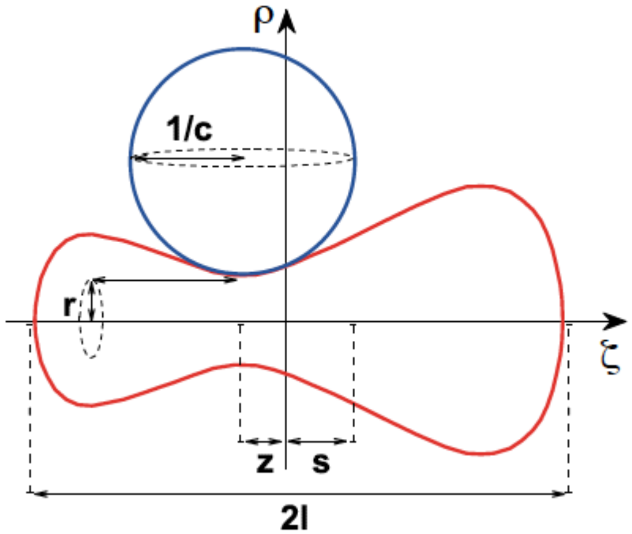
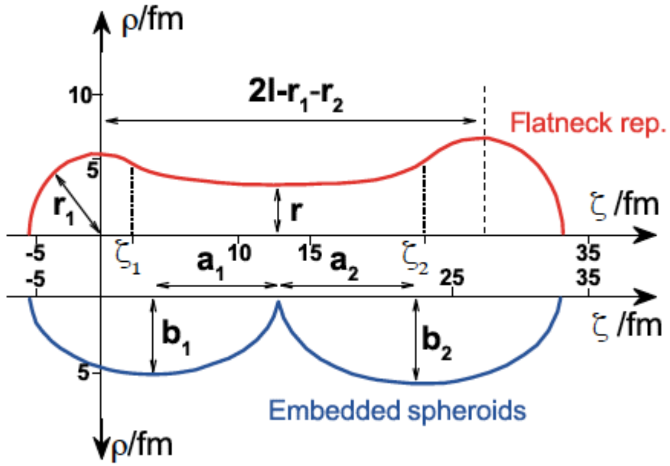
# Fission within the MM-RNR model

## (Multi-Modal Random Neck-Rupture)




$$\rho^2(\zeta) = (l^2 - \zeta^2) \sum_{n=0}^{N} a_n (\zeta - z)^2 .$$

$$l = \frac{11}{2}\left(r - \frac{\zeta}{2}\right) - \zeta, \zeta = -2, \ldots, 3.$$

- number of fission modes
- inner barrier height
- individual outer barrier heights

- mode-specific scission configurations
- fission-fragment deformation
- fission-fragment intrinsic excitation


U. Brosa, S. Grossmann and A. Müller, Physics Report 197 (1990) 167-262
SO, F.-J. Hambsch and F. Vives, NP A644 (1998) 289-305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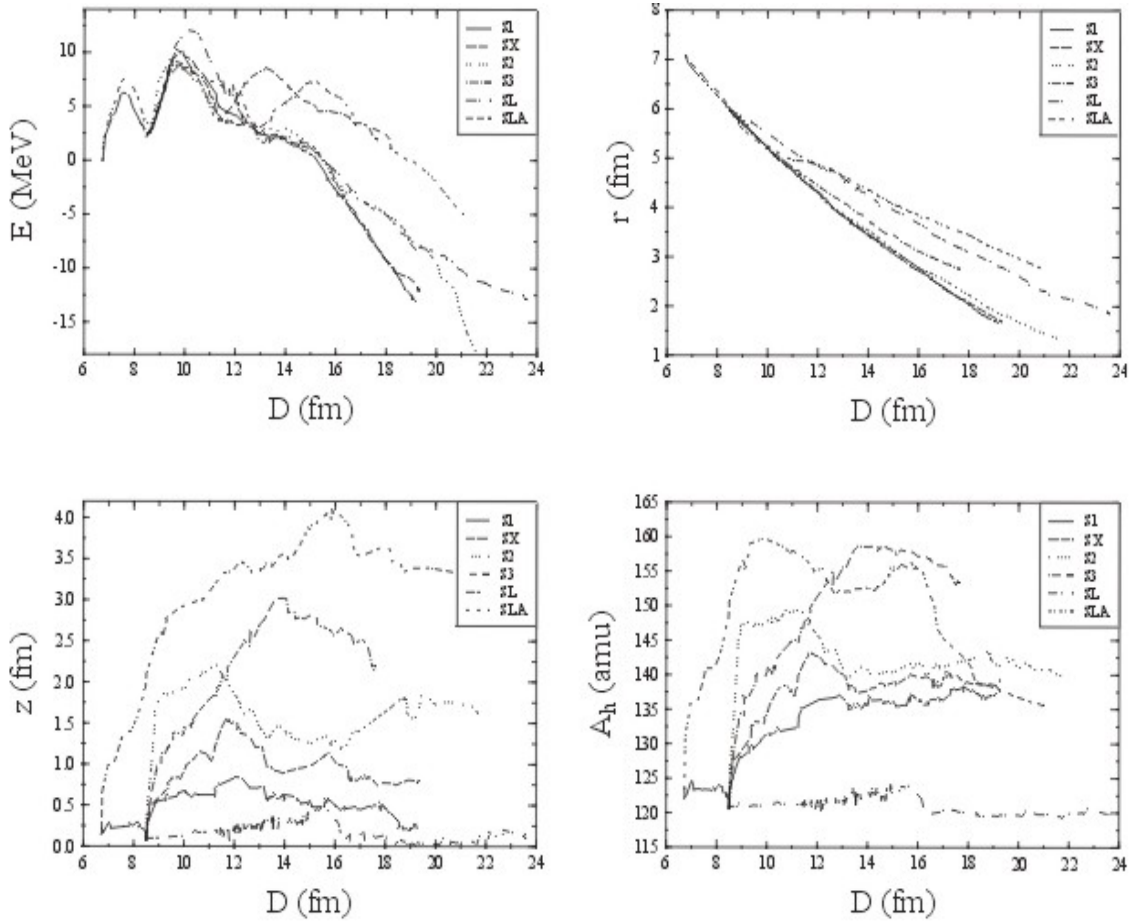
# Fission within the MM-RNR model
## (Multi-Modal Random Neck-Rupture)

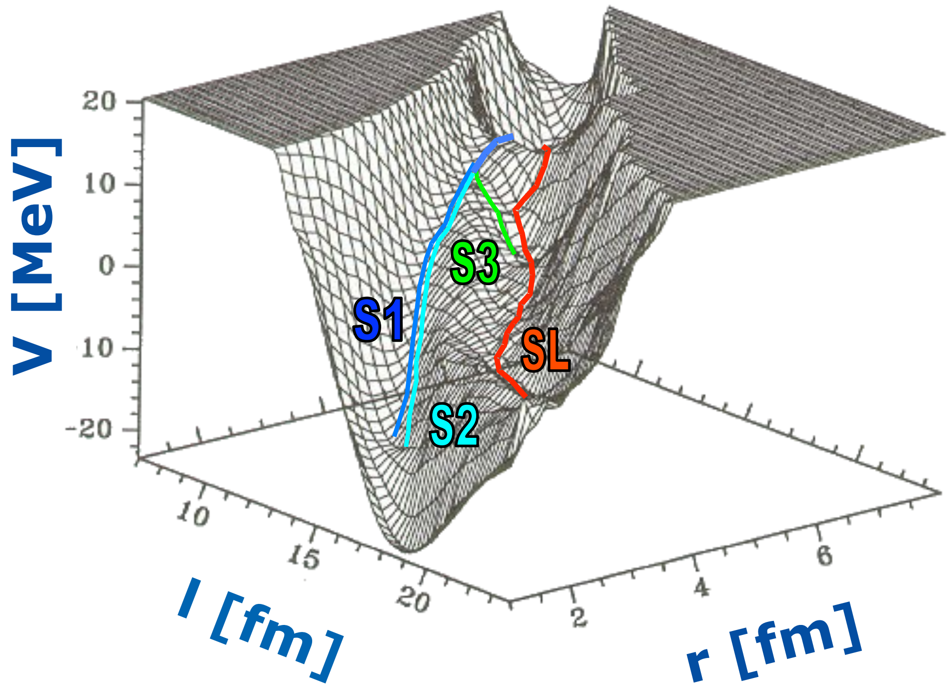
### Calculated fission modes for $^{239}U$




SO, F.-J. Hambsch , F. Vives, NP A644 (1998) 289-305

# Fission within the MM-RNR model
## (Multi-Modal Random Neck-Rupture)

**S1 – standard I**
**S2 – standard II**
**S3 – standard III**
**SL – super long**



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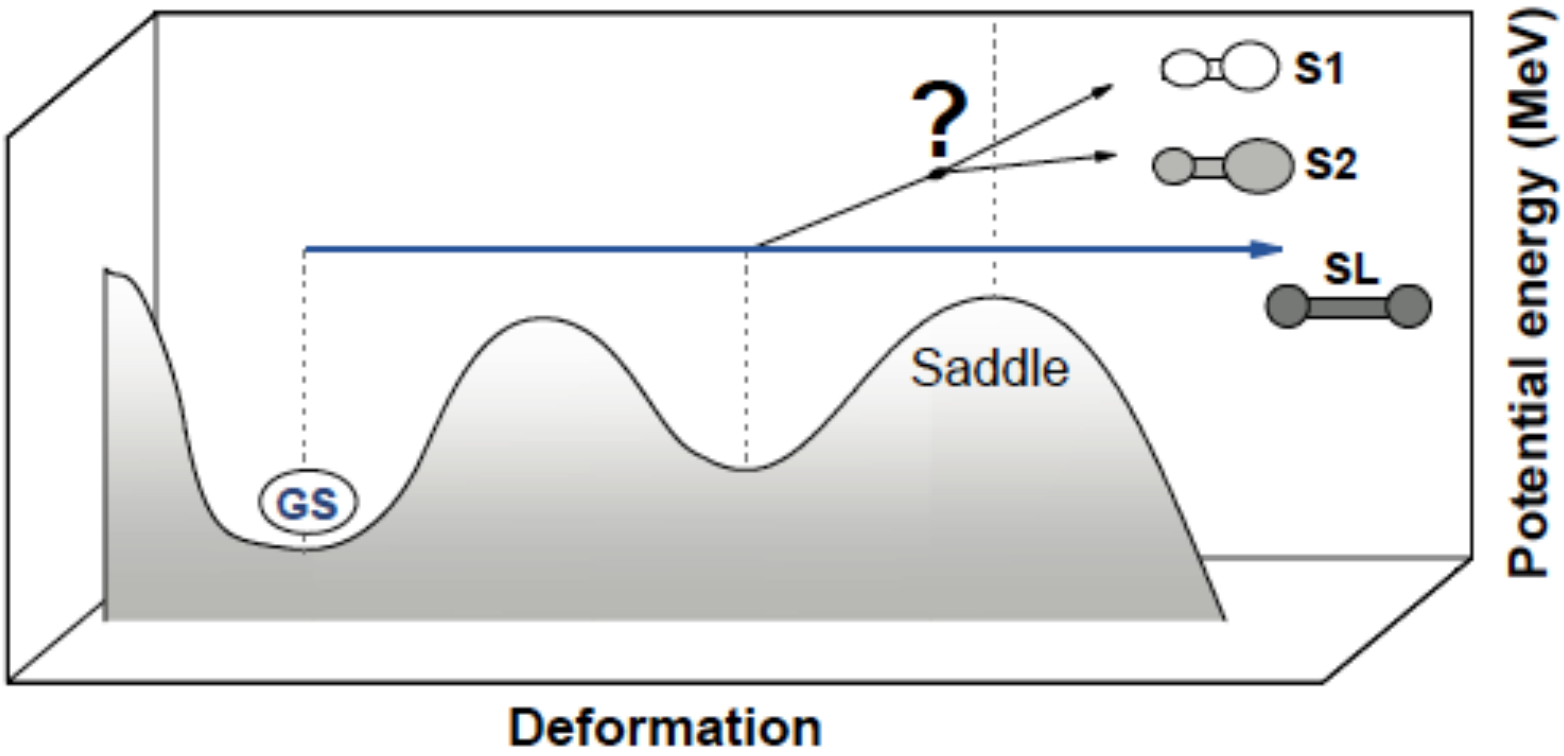


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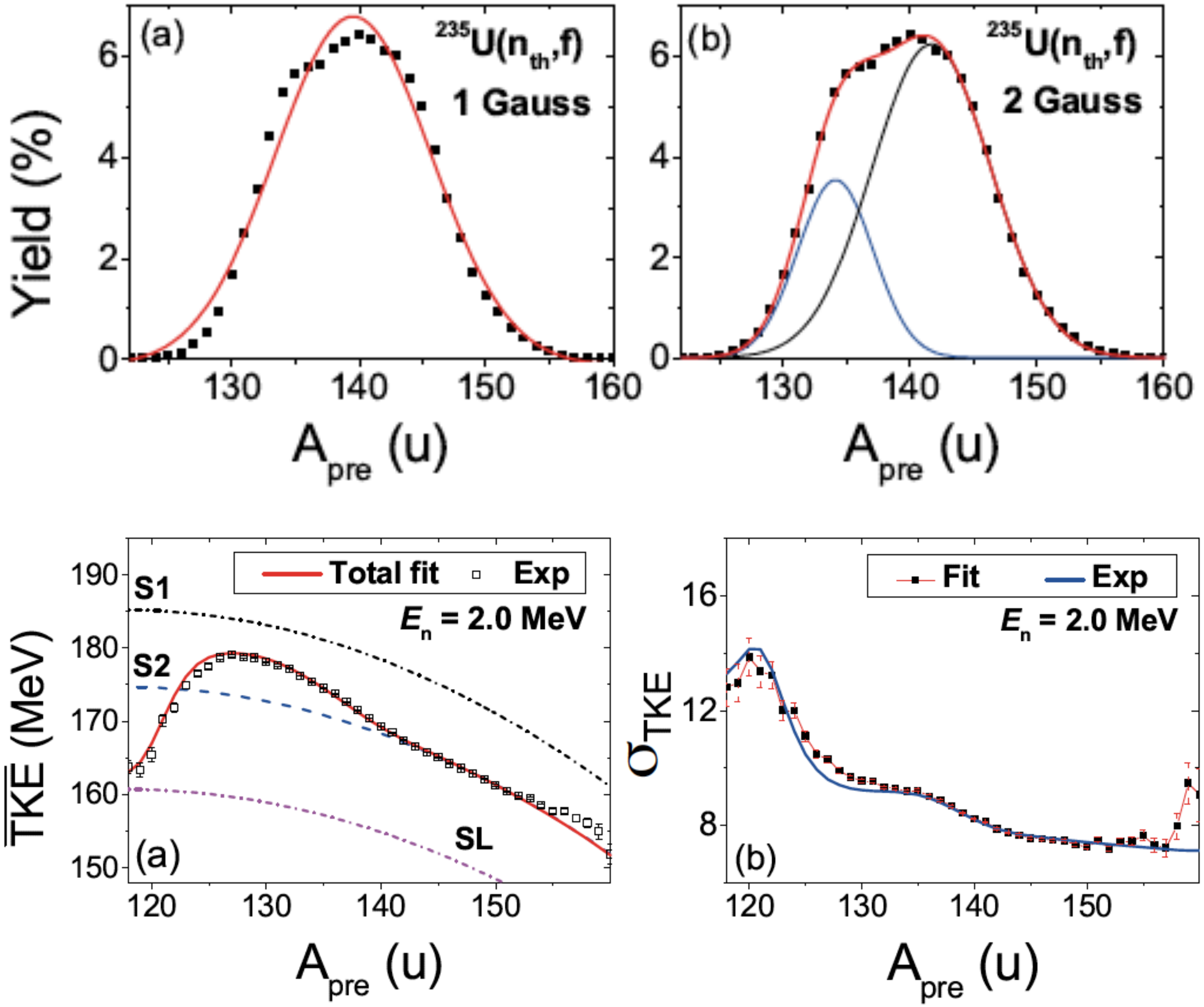


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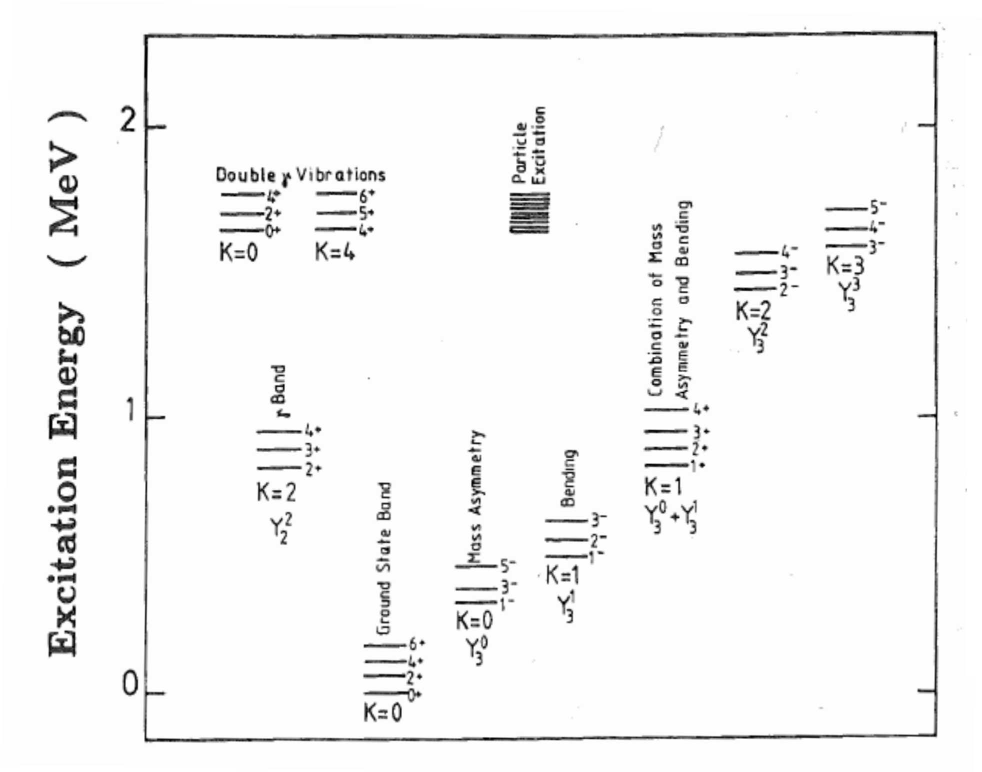
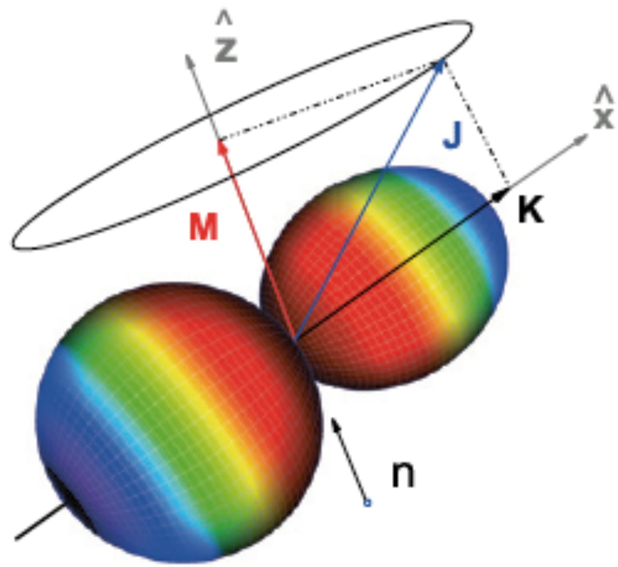
# Fission "geometry"

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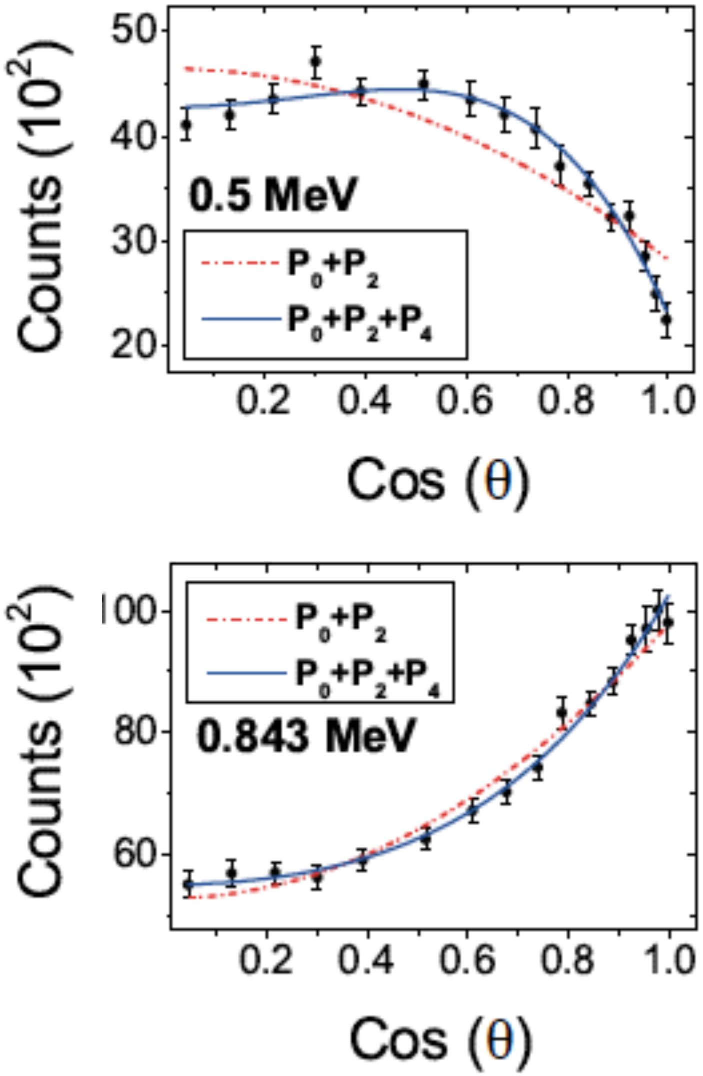


$$W_L(\theta) = A_0\left[1 + \sum_{L=2}^{L=max} A_L P_L(\cos(\theta))\right]$$

$$W_2(\theta) = A_0\left(1 + A_2\left(1.5\cos^2(\theta) - 0.5\right)\right)$$

$$\frac{W(0^o)}{W(90^o)} = \frac{1 + A_2 + A_4 + A_6 \ldots}{1 - \frac{1}{2}A_2 + \frac{3}{8}A_4 - \frac{5}{16}A_6 \ldots}$$

$$W_4(\theta) = W_2(\theta) + A_0 A_4\left(4.375\cos^4(\theta) - 3.75\cos^2(\theta) + 0.375\right)$$

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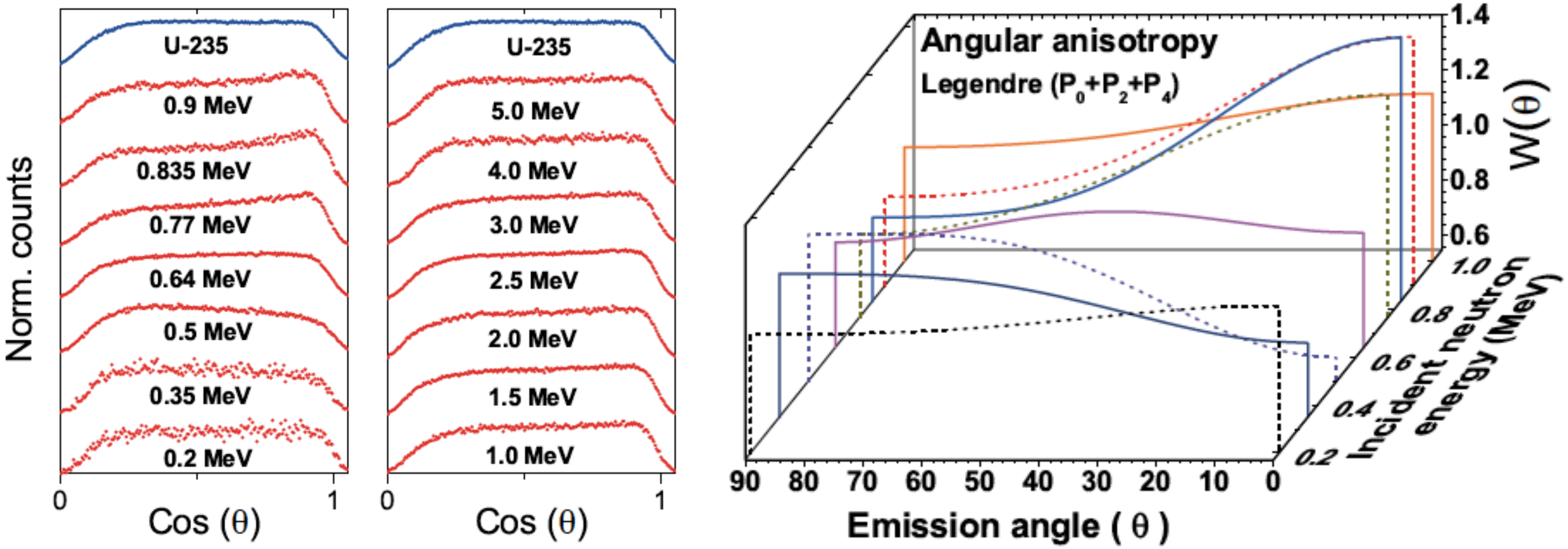


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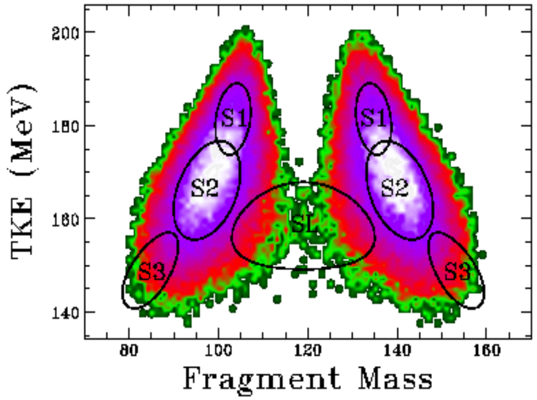
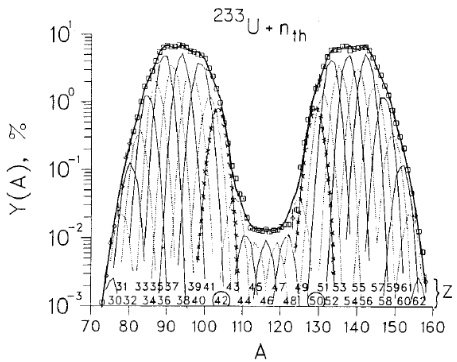
# Fission observables

- **Fission cross-section or fission probability**
- **Mass yield distribution**
  - Pre-neutron emission
  - Post-neutron emission
  - Cumulative yields, mass chain yields




- **(Total) kinetic energy distribution**
- **Element yields**
- **Angular distributions**
- **Fission modes ?**

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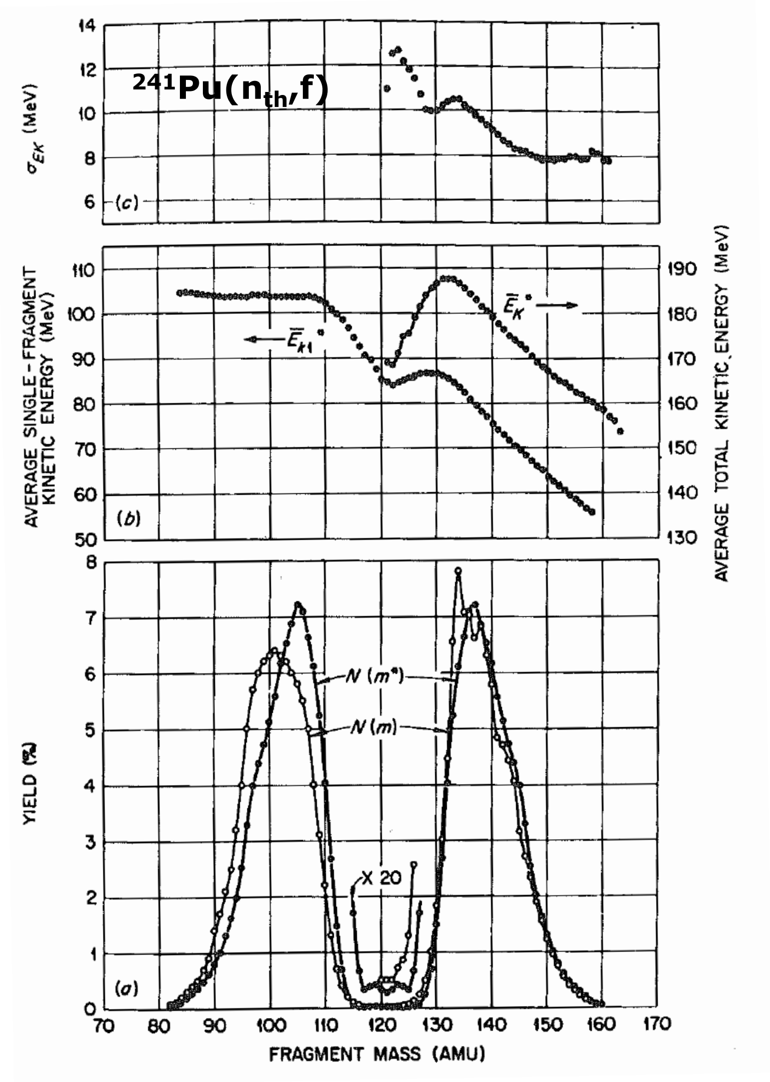
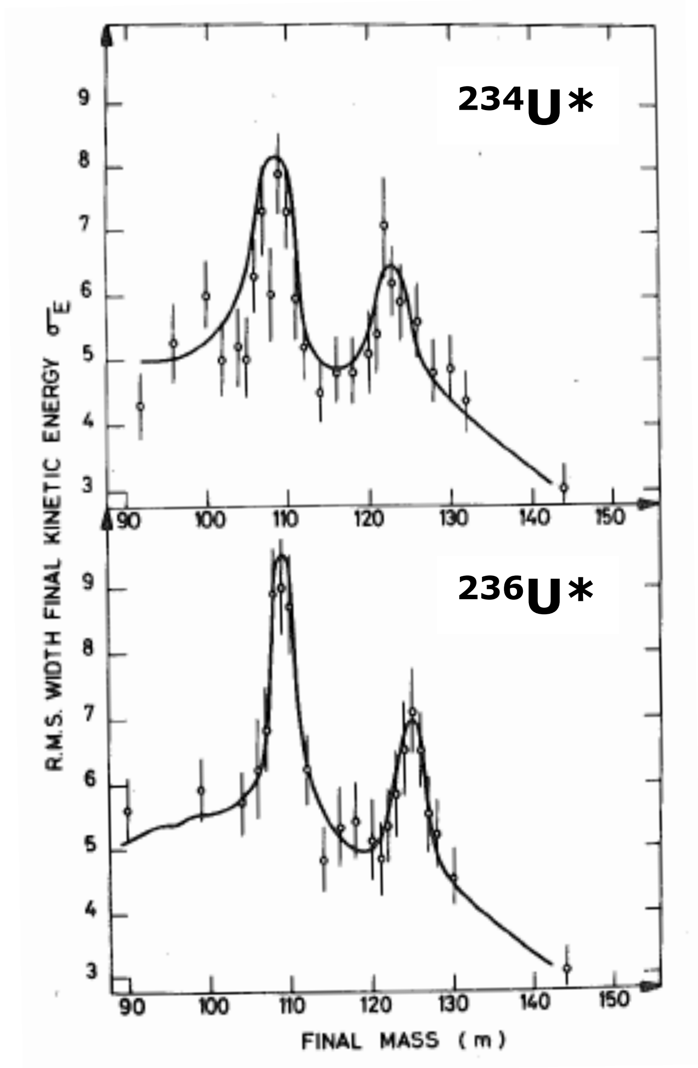
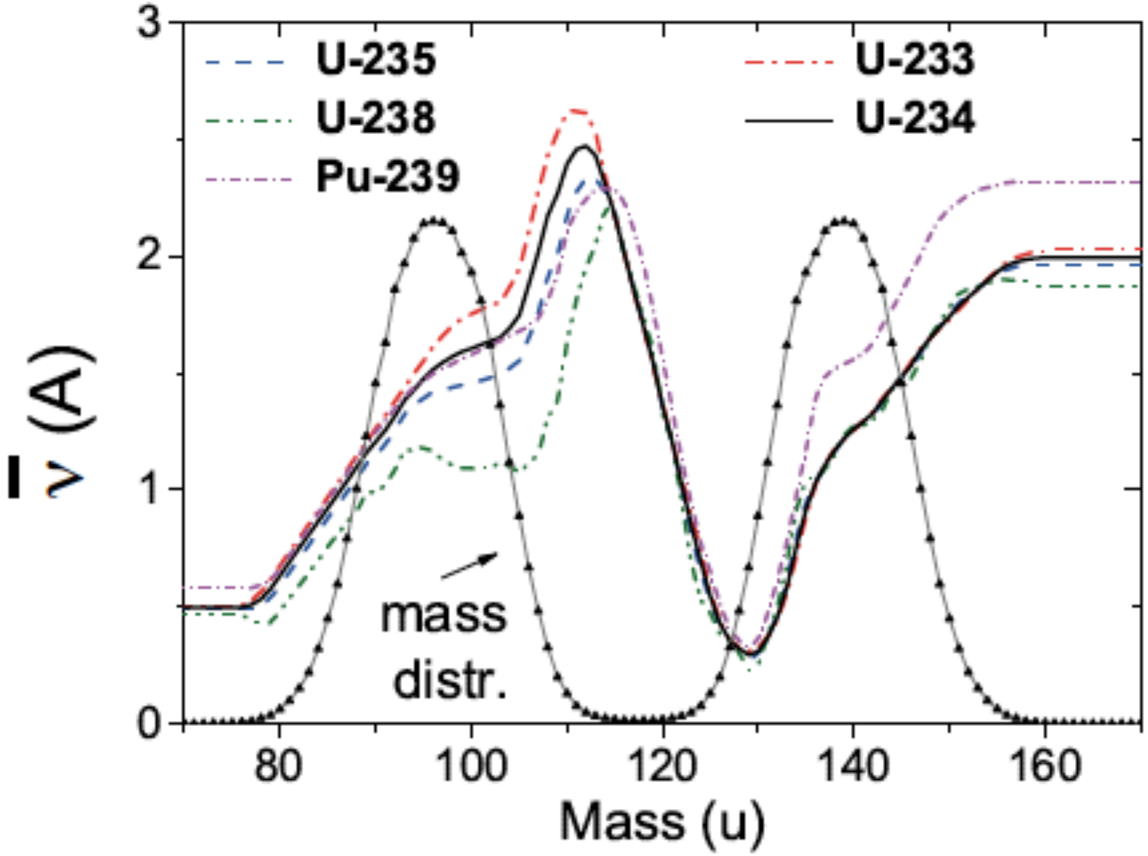
# The fission process




J.N. Neiler, F.J. Walker, and H.W. Schmitt, Phys. Rev. 149 (1966) 894
D. Belhafhaf, J.P. Brissot, Ch. Ristori et al. Z. Phys. A309 (1983) 253

# The fission process

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# Fission observables

## Fission isomers

- Half-life
- Partial half-lives: isomeric fission, back-decay to $1^{st}$ minimum
- Branching ratio

## Fission barrier parameters:

- Barrier height: $E_A$, $E_B$, … $E_B(S1)$, $E_B(S2)$, $E_B(SL)$…
- Transmission (curvature parameter): $h\varpi_A$, $h\varpi_B$
- Super-deformed ground-state energy…
- Isomeric fission fragment characteristics

# Fission reactions

- **Spontaneous fission**
  - In general even-even isotopes ($J^{\pi} = 0^{+}$)
  - Isotropic angular distributions
  - No beam time at accelerator or reactor required

- **Photon-induced (or electromagnetic fission)**
  - Few transition states
  - even-even target ($J^{\pi} = 0^{+}$)
  - E1, E2(M1) -> $J^{\pi} = 1^{-}$, K = 0,1

    -> $J^{\pi} = 2^{+}(1^{+})$, K = 0,1,2
  - Transverse character of real photons: M = ±1

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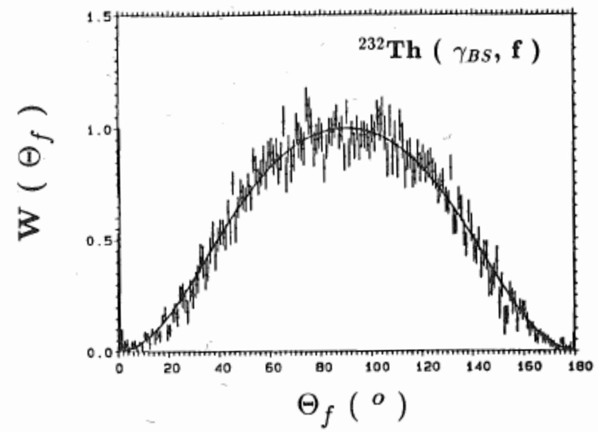
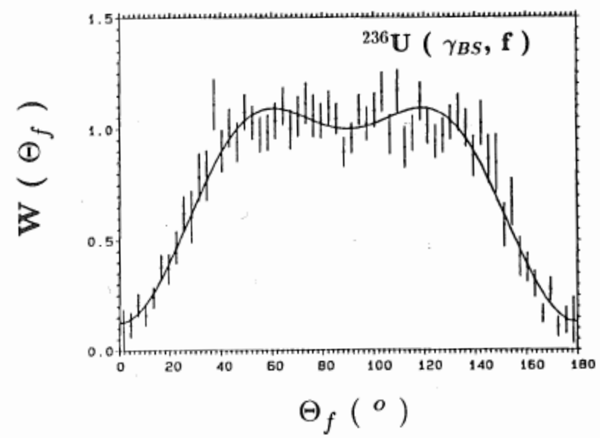
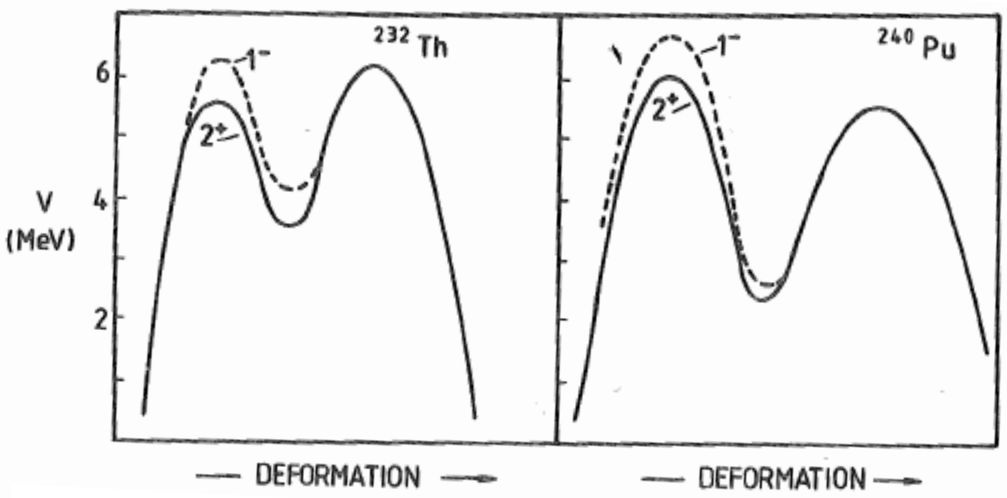


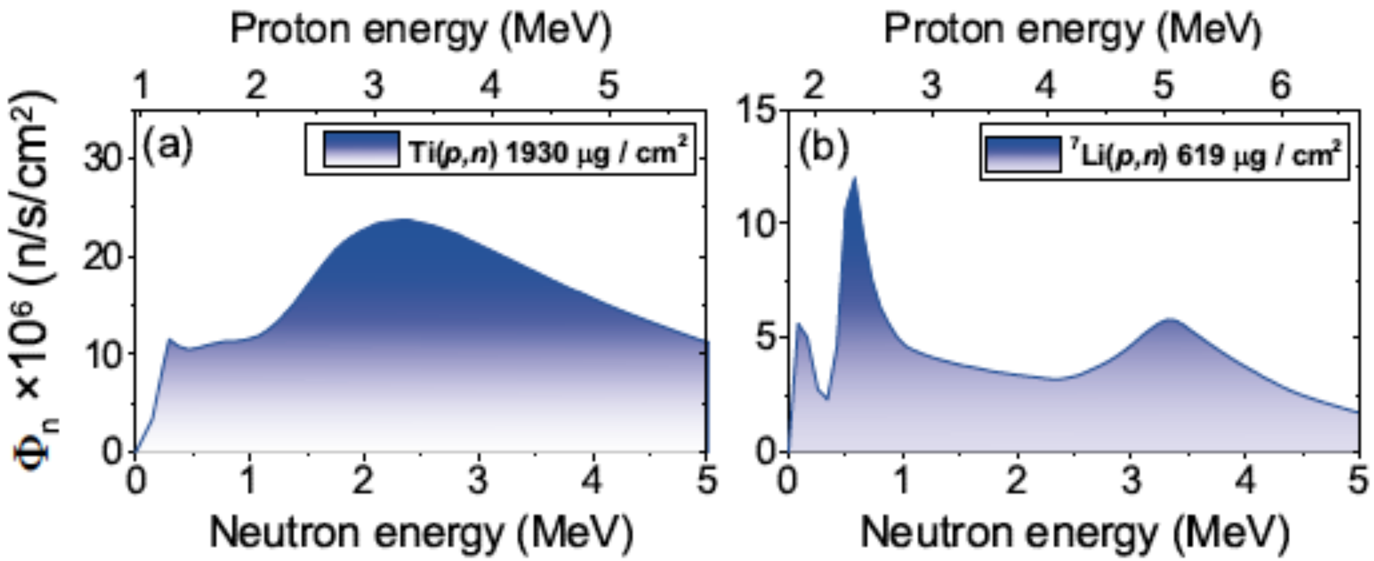

$$W^J_{M=\pm 1,K}(\theta) = a + b \cdot \sin^2\theta + c \cdot \sin^2 2\theta$$



# Fission reactions

- **Neutron-induced fission**
  - Thermal energy ($E_n$ = 0.025 eV)
  - Resolved resonance region (0.3 eV < $E_n$ < 2 keV)
  - Fast-neutron energies ($E_n$ > 0.1 MeV)

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# Fission reactions

- **Charged-particle induced fission**
  - Surrogate reactions to investigate fission of highly-active isotopes
  - Population of isomeric states in the second (super-deformed) well
  - Investigation at energies below the neutron separation energy

# How to "measure" fission properties

- **Fission fragment properties:**
  - ✓ **Fragment mass and charge yields**
    - Radio-chemical methods
    - Neutron activation with sub-sequent $\gamma$-spectrometry

- **Cumulative yields (fragments produced after $\beta$-decay has set in)**
- **Mass chain yields (essentially stable fission products)**
- **Not all elements chemically assessable**
- **Permits use of massive targets**

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# How to "measure" fission properties

- **Fission fragment properties:**
  - ✓ **Fragment mass and charge yields**
    - Radio-chemical methods
    - Neutron activation with sub-sequent $\gamma$-spectrometry

- **(neutron) activation of a target pellet, $\mathcal{O}$(g)**
- **$\gamma$-spectrometry during cooling periods, $\{\Delta t_j\}$**
- **From known $\gamma$-rays and decay probabilities ($\beta$, $\lambda_i$)**

  **→ cumulative and mass chain yield**
- **Radio-chemistry for $\Delta t \rightarrow \infty$**

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# How to "measure" fission properties

- **Fission fragment properties:**
  - **Energy measurements**
  - **Post-neutron mass and kinetic energy (before β-decay)**
  - **Pre-neutron fragment characteristics (@scission)**
    - Double energy technique
    - Time-of-flight spectrometers

- **Targets with thin actinide layers**
- **Deposits on thin support backings**
- **Minimize energy-loss and straggling**

# Fission targets

**Spectroscopic backings:**

- **Polyimide foil (≈ 30 μg/cm$^2$)**
- **Nickel (self-supporting, 250 nm)**
- **Vacuum evaporation**
- **Diameter up to 70 mm possible**
- **$^{234,236,238}$U, $^{239}$Pu (JRC D.4 SN3S)**

**Non-spectroscopic backings**

- **Thick backing (> 25 μm)**
- **Al, Ni, Ta,...**
- **Molecular plating**
- **$^{232}$Th, $^{233-238}$U, $^{237}$Np, $^{239,241}$Pu (JRC D.4 SN3S)**

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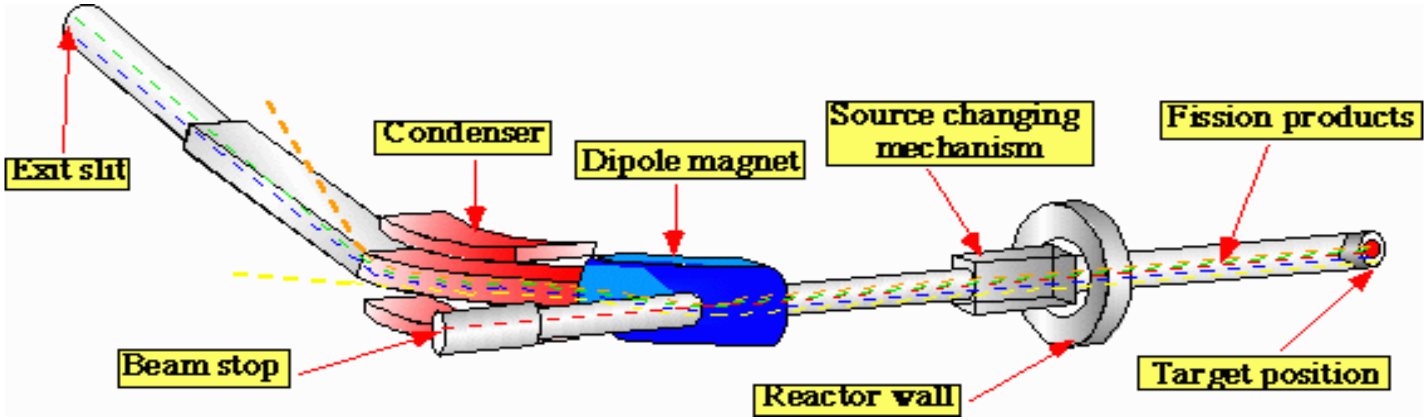
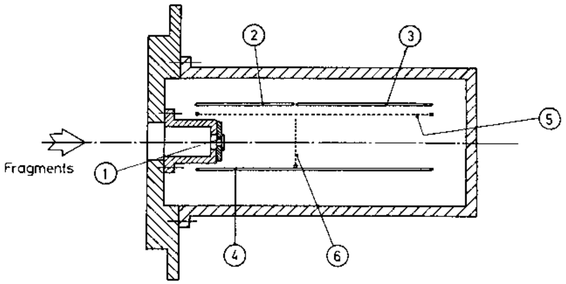
# Mass and kinetic energy distributions

## LOHENGRIN (*NPP-PN1*)




$\Phi_n$ = 5 ·10$^{14}$ /cm$^2$/s
L = 23 m
$\Omega_L$ = 3.5·10$^{-5}$ sr
A/ΔA = 400 - 1500
E/ΔE = 100 - 1000
Z/ΔZ < 40
$E_{kin}$ ≤ 5.5 MeV·q/e

✓ **Recoil mass-separation: post-neutron characteristics**

# Separator equations

- Magnetic field deflection is given by

$$\frac{mv^2}{r_{mag}} = q(\vec{v} \times \vec{B})$$

- Electric field deflection is given by

$$\frac{mv^2}{r_{el}} = q \cdot E$$

- Together the A/q and $E_{kin}$/q separation is given by

$$\frac{m}{q} = \frac{B^2 r_{mag}^2}{r_{el} E} \qquad \frac{E_{kin}}{q} = \frac{E r_{el} q}{2}$$

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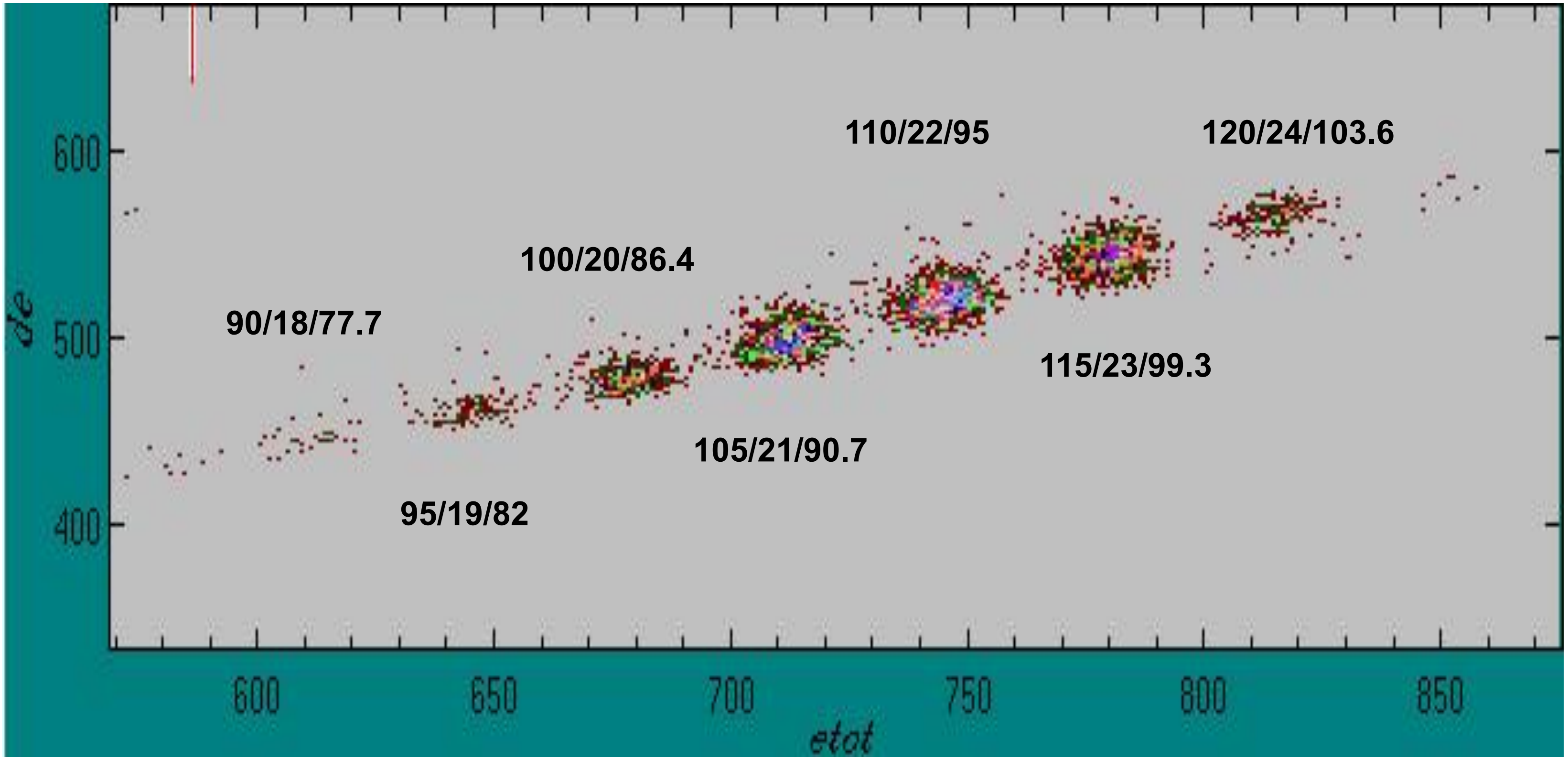
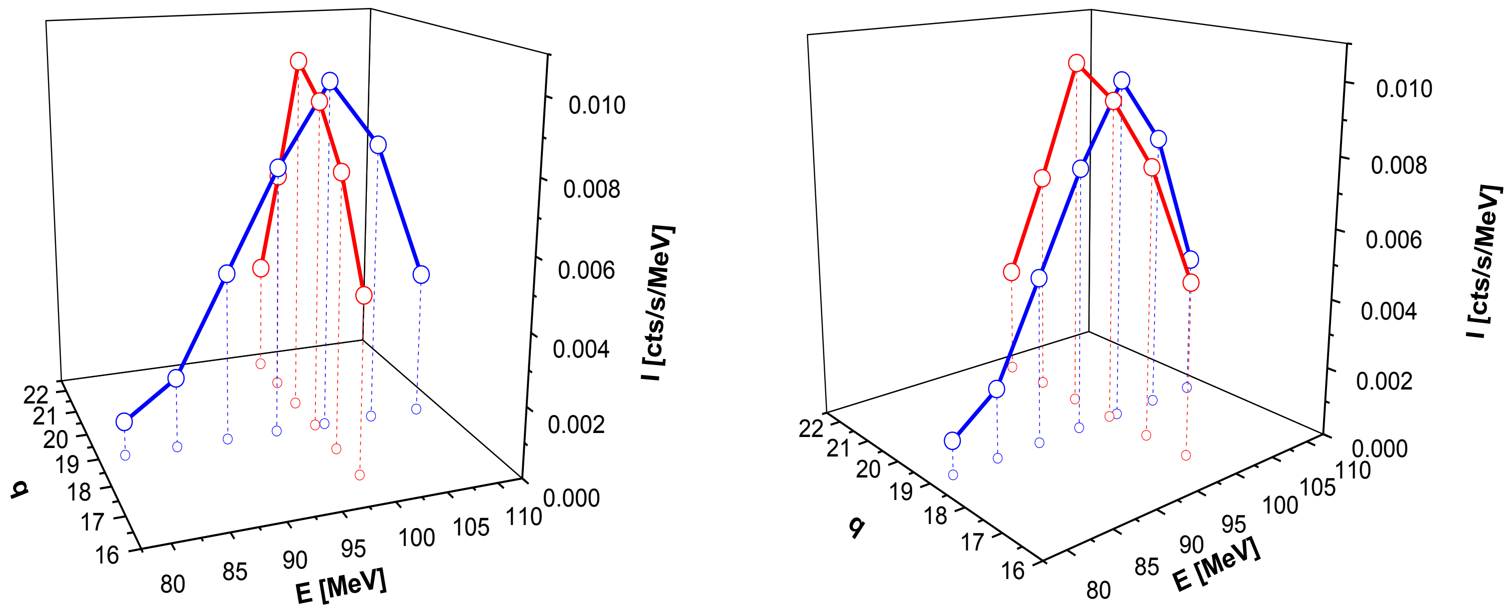
# Characteristic spectrum

**A=110 q=22 E=95 MeV**



# Scan to obtain a single mass yield

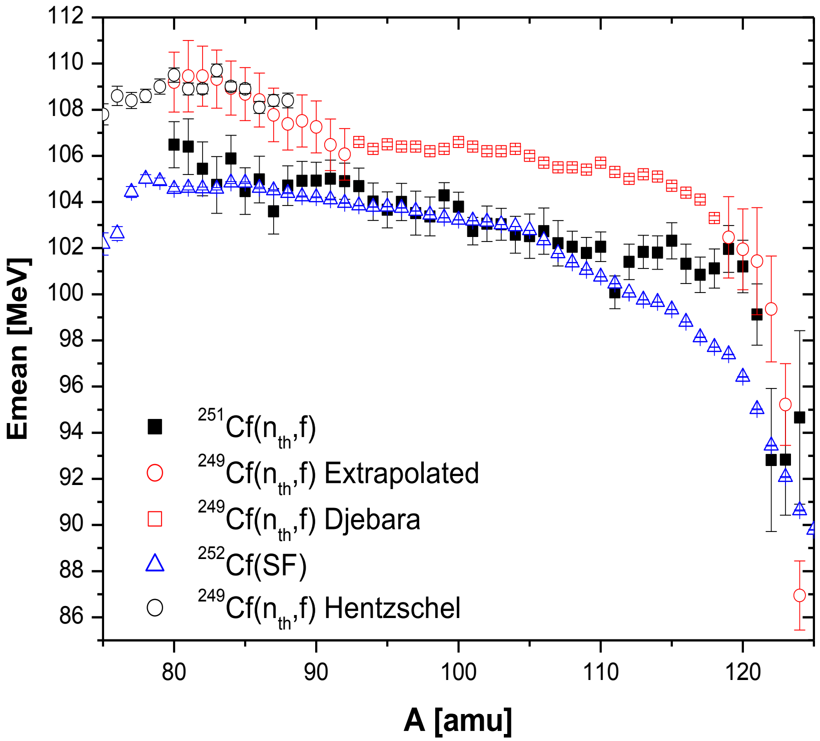
- Ionic charge distribution at about mean energy
- Energy distribution at about mean ionic charge

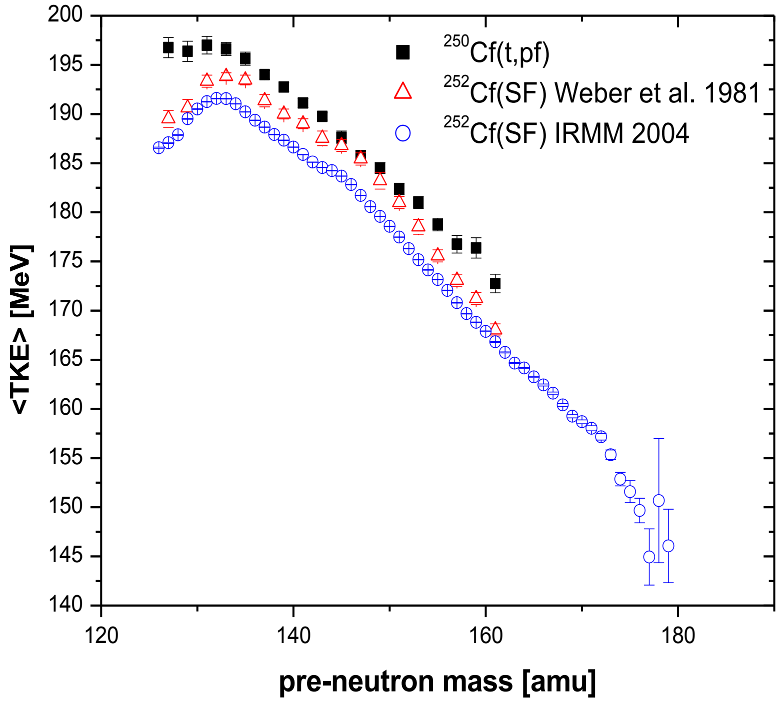


# Needed corrections

- Energy loss of the fragments in the target layer
- Target loss through burn-up and sputtering during heating
- Minimization of sputtering by covering the target with a 250 nm thick Ni-foil; creates additional energy loss
- Average total energy loss $\Delta E \approx 7$ MeV

# Mean fragment mass and kinetic energy




**<TKE> from the reaction $^{250}$Cf(t,pf), Weber, Britt and Wilhelmy , Phys Rev. C 23 (1981) 2100-2103**

E. Birgersson, SO, A. Oberstedt et al., NP A791 (2007) 1-23

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# Mass and kinetic energy distributions

- **Double energy technique:**
  - ✓ Based on the conservation of momentum

$$A_1 v_1 + A_2 v_2 = 0$$
$$A_1 + A_2 = A_{CN}$$

$$E_1 / E_2 = A_2 / A_1$$

- **Measured quantities are post-neutron emission kinetic energies!**

- **In the following: $A_1$*, $A_2$*, $E_1$*, … denote pre-neutron emission quantities.**

- **Silicon detectors, ionization chambers, PPACs, …**

# Mass and kinetic energy distributions

- **Double energy technique:**
  - Based on the conservation of momentum

$$E_i = A_i/A_i^* \, E_i^* + A_n/A_i \, E_n - (2\, E_i^*/A_i^*)^{1/2} \, A_n v_n \, \langle \cos\theta \rangle$$

# Mass and kinetic energy distributions

- **Double energy technique:**
  - Based on the conservation of momentum
  - Prompt neutron emission

$$E_i = A_i/A_i^* \; E_i^* + A_n/A_i \; E_n - (2 \; E_i^*/A_i^*)^{1/2} \; A_n v_n \; <\cos\theta>$$

$$E_i = A_i/A_i^* \; E_i^* + A_n/A_i \; E_n$$

**And if $\nu$ neutrons emitted:**

$$E_i = A_i/A_i^* \; E_i^* + \nu \; A_n/A_i \; E_n$$

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# Mass and kinetic energy distributions

- **Double energy technique:**
  - ✓ Based on the conservation of momentum

$$E_i = A_i/A_i^* \ E_i^* + A_n/A_i \ E_n - (2\,E_i^*/A_i^*)^{1/2} A_n v_n <\cos\theta>$$

$$E_i = A_i/A_i^* \ E_i^* + A_n/A_i \ E_n$$

**And if $\nu$ neutrons emitted:**

$$E_i = A_i/A_i^* \ E_i^* + \nu \ A_n/A_i \ E_n$$

**≈ 20 keV**

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# Mass and kinetic energy distributions

- **Double energy technique:**
  - ✓ Based on the conservation of momentum

$$E_i = A_i/A_i^* \, E_i^* + A_n/A_i \, E_n - (2 \, E_i^*/A_i^*)^{1/2} A_n v_n \langle\cos\theta\rangle$$

$$E_i = A_i/A_i^* \, E_i^* + A_n/A_i \, E_n$$

**And if $\nu$ neutrons emitted:**

$$E_i = A_i/A_i^* \, E_i^* + \nu \, A_n/A_i \, E_n$$

**≈ 20 keV**

**< 0.05 %**

**50 MeV < $A_i/A_i^* \, E_i^*$ < 100 MeV**

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# Mass and kinetic energy distributions

- **Double energy technique:**

$$E_i = A_i/A_i^* \, E_i^* \qquad \text{with } i = 1,2$$

$$A_i^* = A_{CN} \, E_j^*/(E_i^* + E_j^*) \qquad \text{with } i,j = 1,2$$

$$A_i^* = A_{CN} \, A_j^*/A_j \, E_j/(A_i^*/A_i \, E_i^* + A_j^*/A_j \, E_j^*)$$

$$= A_{CN} \, E_j/((A_i^*/A_j^* \, A_j/A_i) \, E_i^* + E_j^*)$$

$$A_1^* = A_{CN} \, E_2/((1 + \xi_{12}) \, E_1 + E_2) \qquad \text{with: } A_1^*/A_1 \, A_2/A_2$$

$$A_2^* = A_{CN} \, E_1/(E_1 + E_2/(1 + \xi_{12})) \qquad = 1 + \xi$$

# Mass and kinetic energy distributions

- **Double energy technique:**

0th approximation: $E_1 = E_1^*$ and $E_2 = E_2^*$

determine $A_1^*$ and $A_2^*$ → $\mu_1$ and $\mu_2$ : provisional masses

neglecting prompt neutron emission

determination of energy loss $\Delta E_i(A_i, Z_i, E_i)$, i =1,2

pulse height defect $PHD(A_i, Z_i, E_i)$, i =1,2

Gives now new values for $E_1^*$ and $E_2^*$ → next iteration

# Mass and kinetic energy distributions

- **Double energy technique:**

**1st approximation:** $E_1^* = E_1 + PHD_1 + \Delta E_1$

**and** $E_2^* = E_2 + PHD_2 + \Delta E_2$

**determine** $\nu_1$ **and** $\nu_2$ → $\nu_i\ (A_i, TKE_i)$

**determination of energy loss and pulse height defect PHD**

**Gives now new values for** $E_1^*, A_1^*\ E_2^*, A_2^*$**…** → **next iteration**

# Mass and kinetic energy distributions

- **Double energy technique:**

**Prompt neutron emission**

$$\bar{\nu}_{234}(A) = \bar{\nu}_{233}(A)\left(1-\frac{1}{2}\beta\right) = \bar{\nu}_{233}(A)\left(1-\frac{1}{2}\left(1-\frac{\bar{\nu}_{235}(A)}{\bar{\nu}_{233}(A)}\right)\right) = \frac{1}{2}\left(\bar{\nu}_{235}(A)+\bar{\nu}_{233}(A)\right) \quad ,$$

$$\nu_{234}(A,\mathrm{TKE}) = \bar{\nu}_{234}(A) + \frac{\bar{\nu}_{234}(A)}{\bar{\nu}_{234}(A)+\bar{\nu}_{234}(A_{\mathrm{CN}}-A)} \cdot \frac{\langle \mathrm{TKE}(A)\rangle - \mathrm{TKE}}{E_{\mathrm{sep}}}$$

**Momentum transfer from incident neutron**

$$\cos\left(\theta^{\mathrm{CM}}\right) = \sqrt{1-\frac{E_{\mathrm{pre}}^{\mathrm{LAB}}}{E_{\mathrm{pre}}^{\mathrm{CM}}}\left(1-\cos^2\left(\theta^{\mathrm{LAB}}\right)\right)}$$

$$E_{\mathrm{pre}}^{\mathrm{CM}} = E_{\mathrm{pre}}^{\mathrm{LAB}} \pm 2A_{\mathrm{CN}}^{-1}\sqrt{A_{\mathrm{pre}}A_{\mathrm{n}}E_{\mathrm{pre}}^{\mathrm{LAB}}E_{\mathrm{n}}^{\mathrm{LAB}}}\cos\left(\theta^{\mathrm{LAB}}\right) + A_{\mathrm{CN}}^{-2}A_{\mathrm{n}}A_{\mathrm{pre}}E_{\mathrm{n}}^{\mathrm{LAB}}$$

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# Mass and kinetic energy distributions

- **Double energy technique:**

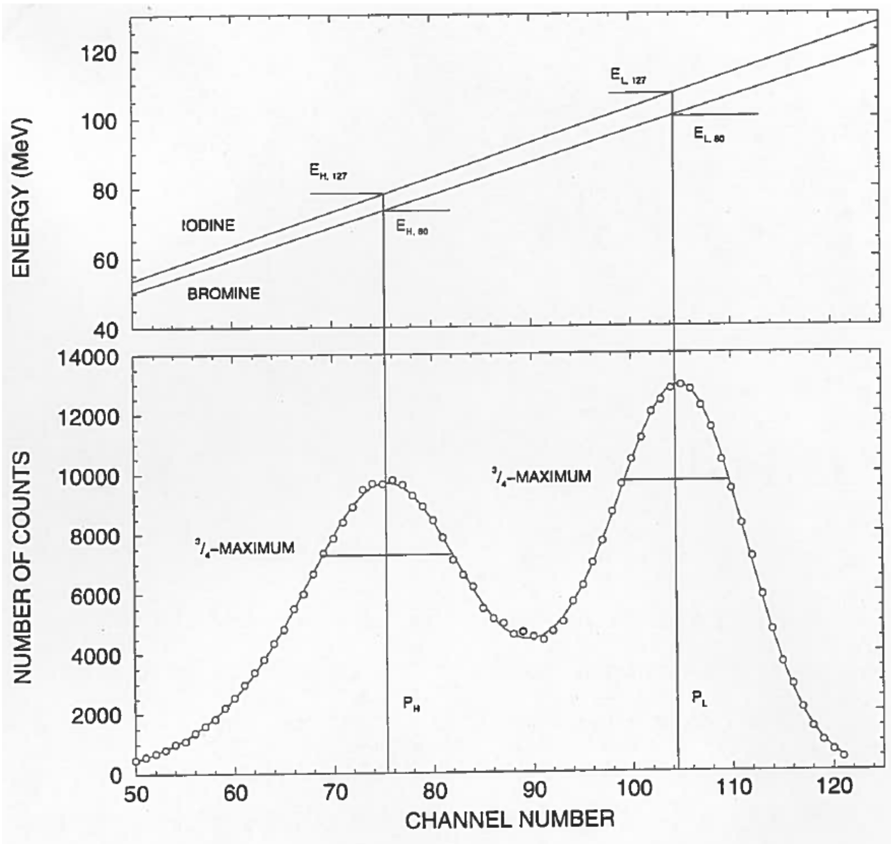
**Energy measurements with silicon detectors**

- ✓ Typical sizes (area): 50 – 900 $mm^2$
- ✓ Thickness typically 100 – 300 mm
- ✓ Very good energy resolution

- ✓ Large detectors normally not segmented

# Pulse-height defect in Si-detectors

$E = a\ Ph + b \rightarrow E = (a + a'\ A)\ Ph + b + b'\ A$




$a = A / (P_L - P_H)$

$a' = A' / (P_L - P_H)$

$b = B - a\ P_L$

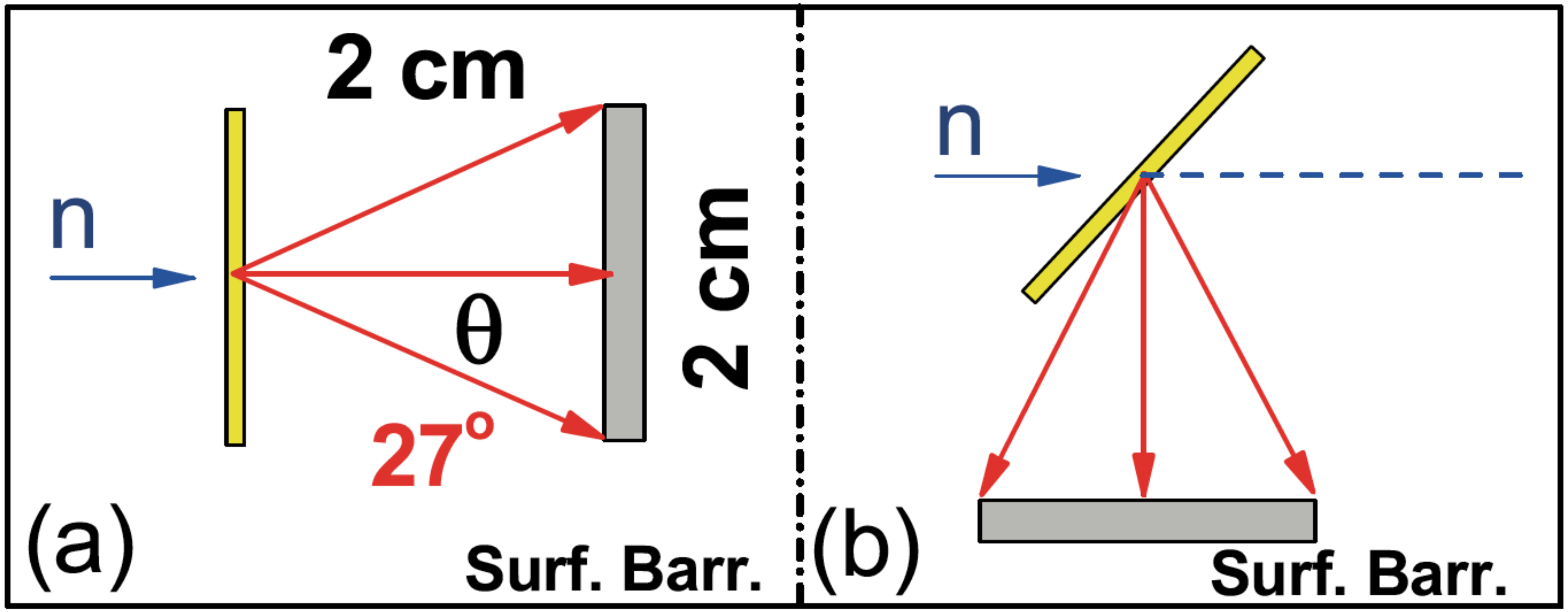
$b' = B' - a'\ P_L$

**A, A′, B, B′**

are characteristic quantities of a specific silicon detector

# Double-E with silicon detectors

➢ **Double energy technique:**

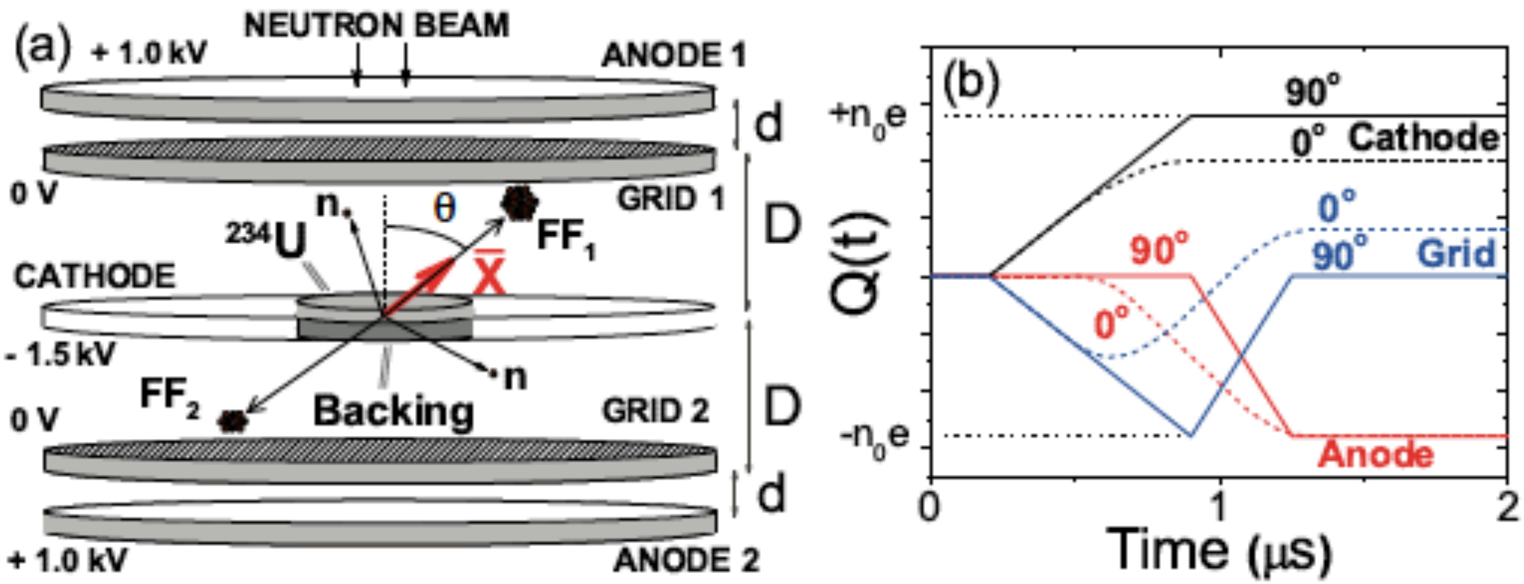



- ✧ **Energy loss variation in dead layer 12%**
- ✧ **Energy loss variation in target layer 12%**

- ✧ **Geometrical efficiency: $\varepsilon < 7\%$**

# Mass and kinetic energy distributions

- **Double energy technique:**




✓ **Geometrical efficiency: $\varepsilon < 100\%$**

✓ **Emission angle θ measured**

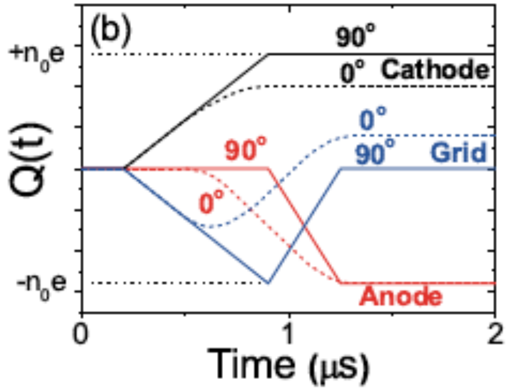
✓ **Angular dependent ΔE in target layer can be corrected**

# Ionization chambers

$$Q_C = n_0 e \left(1 - \frac{\overline{X}}{D}\cos(\theta)\right)$$

$$Q_A = -n_0 e$$

$$Q_A = (Q_A^* + \sigma Q_C)(1-\sigma)^{-1}$$




$$Q_G = n_0 e \frac{\overline{X}}{D}\cos(\theta)$$

$$Q_G^* = n_0 e (1-\sigma)\frac{\overline{X}}{D}\cos(\theta)$$

$$Q_\Sigma = -Q_C = Q_A + Q_G$$

**A. A. Adili, F.-J. Hambsch, R. Bencardino, SO et al., NIM A671 (2012) 103**
**A. Göök, F.-J. Hambsch, A. Oberstedt, SO, NIM A664 (2012) 289**

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- **Determination of the emission angle:**

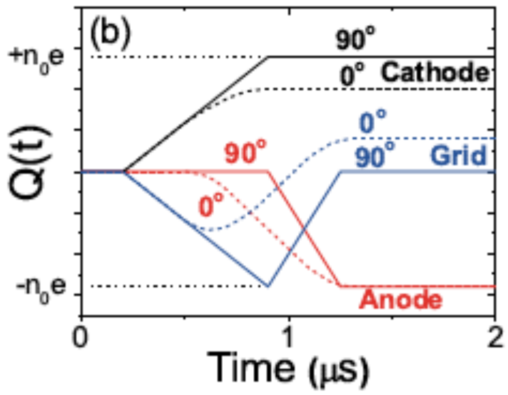
$$\cos(\theta) = \frac{P_A - P_\Sigma}{(\overline{X}/D)\,P_A}$$

**Analogue DAQ**

$$\cos(\theta) = \frac{P_G}{n_0 e\,(\overline{X}/D)}$$

**Digital DAQ**

$$\cos(\theta) = \frac{T_{90^\circ} - T}{T_{90^\circ} - T_{0^\circ}}$$

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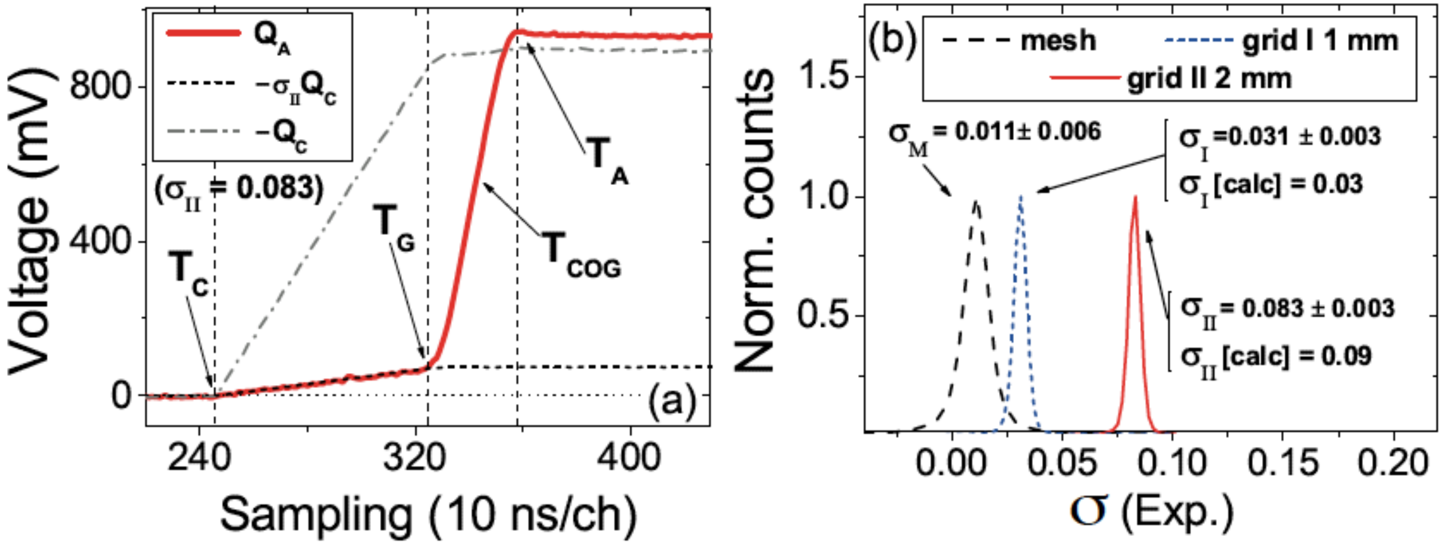
## ➢ The Frisch-grid inefficiency:




$$\sigma(d,r,a) = \left(1 + \frac{d}{a/2\pi\left(\left(\pi^2 r^2 \cdot a^{-2}\right) - \ln\left(2\pi r \cdot a^{-1}\right)\right)}\right)^{-1}$$

$$\frac{V_A - V_G}{V_G - V_C} \geq \frac{p + p\rho + 0.5 \cdot r\left(\rho^2 - 4 \cdot \ln\rho\right)}{a - a\rho - 0.5 \cdot r\left(\rho^2 - 4 \cdot \ln\rho\right)}$$

| Parameter | Value (mm) |
|---|---|
| Grid-cathode distance (*D*) | 31 |
| Anode-grid distance (*d*) | 6 |
| Grid wire spacing (*a*) | 1 |
| Grid wire radius (*r*) | 0.05 |

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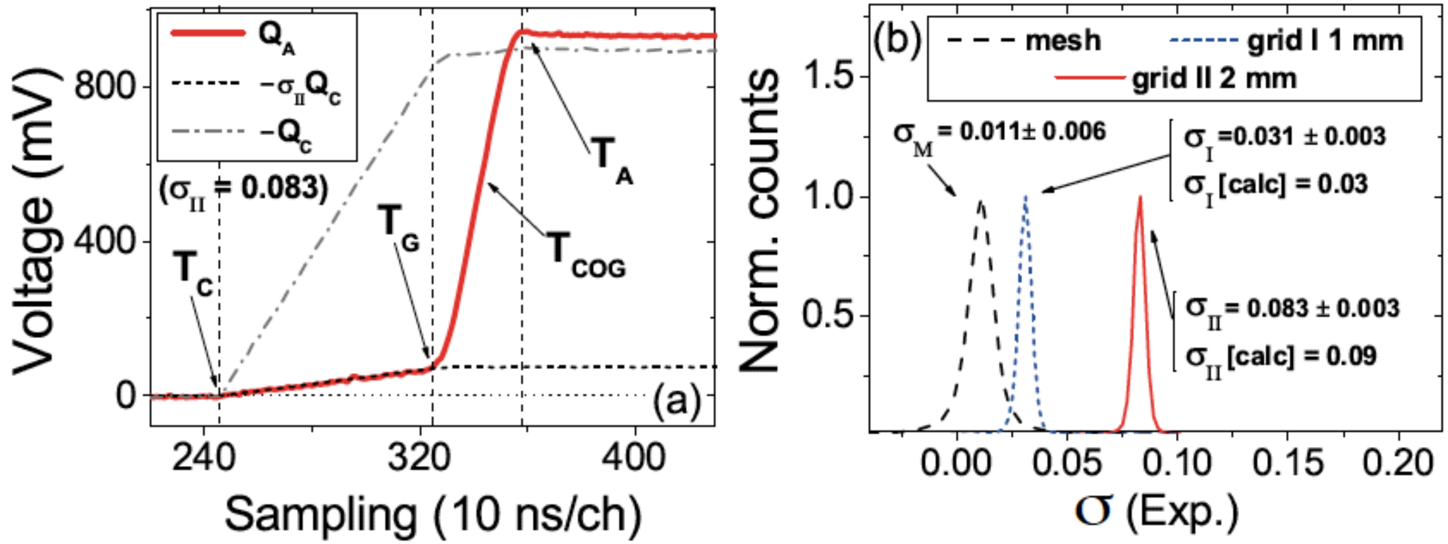
## ➢ The Frisch-grid inefficiency:




$$\sigma(d,r,a) = \left(1 + \frac{d}{a/2\pi\left(\left(\pi^2 r^2 \cdot a^{-2}\right) - \ln\left(2\pi r \cdot a^{-1}\right)\right)}\right)^{-1}$$

**2 < ξ < 4**

$$\frac{V_A - V_G}{V_G - V_C} \geq \frac{p + p\rho + 0.5 \cdot r\left(\rho^2 - 4 \cdot \ln\rho\right)}{a - a\rho - 0.5 \cdot r\left(\rho^2 - 4 \cdot \ln\rho\right)}$$

| Parameter | Value (mm) |
|---|---|
| Grid-cathode distance (*D*) | 31 |
| Anode-grid distance (*d*) | 6 |
| Grid wire spacing (*a*) | 1 |
| Grid wire radius (*r*) | 0.05 |

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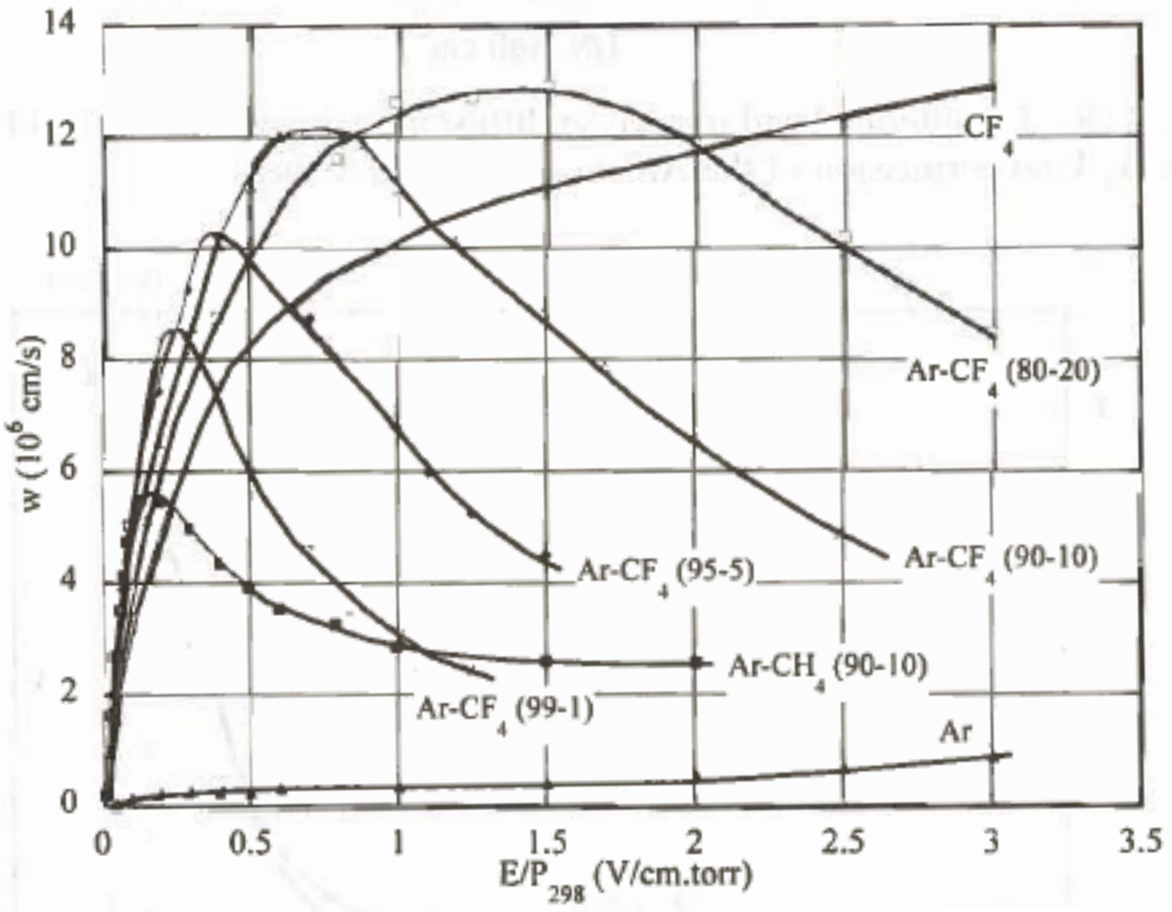
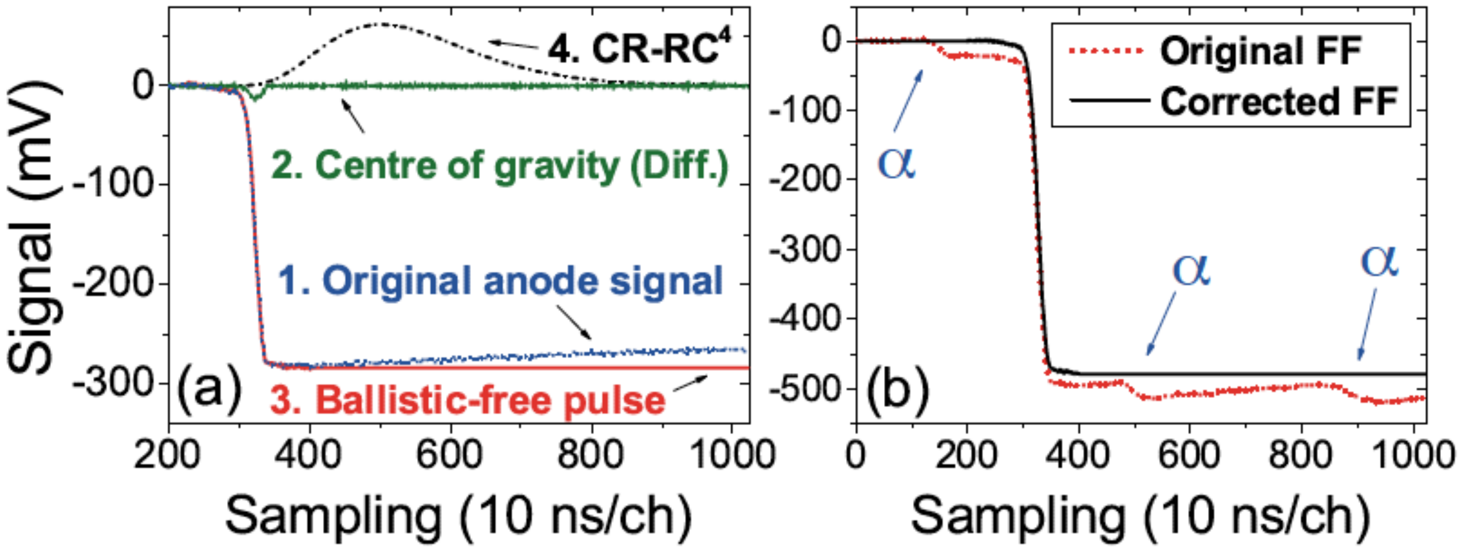
# Ionization chambers

- Selection of counting gas and electric field strength:



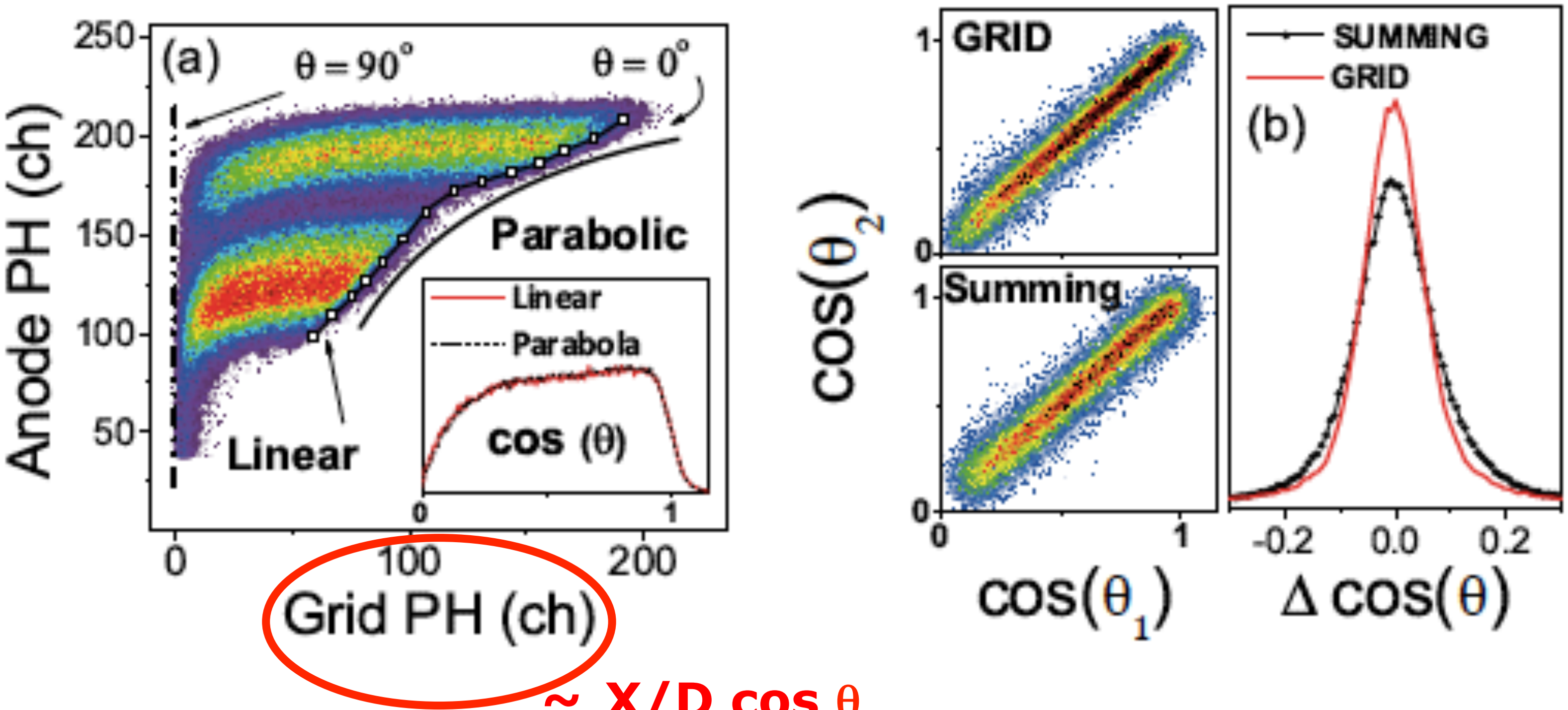
# Measurement with a FGIC

➢ **Signal treatment:**



# Measurement with a FGIC

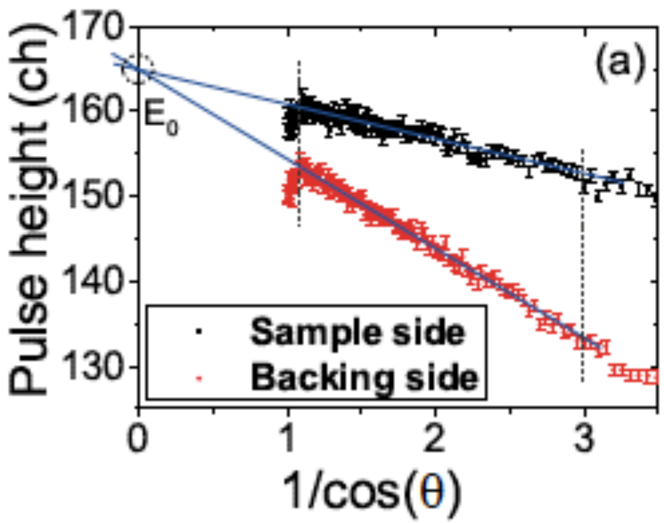
➢ **Fragment range (X/D) correction:**

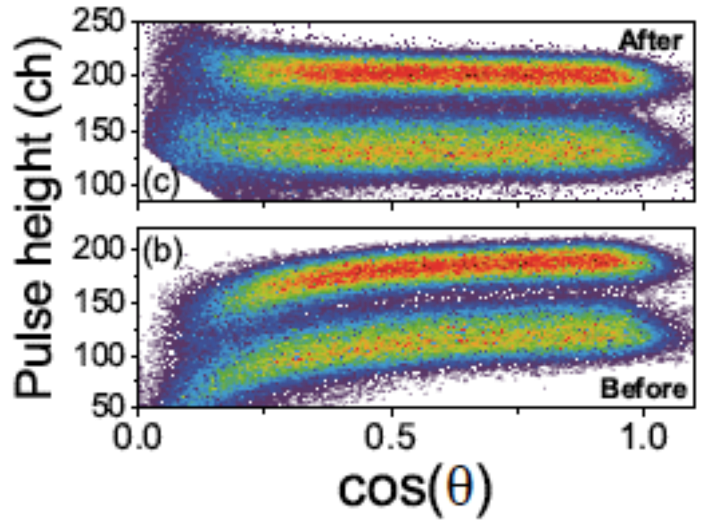


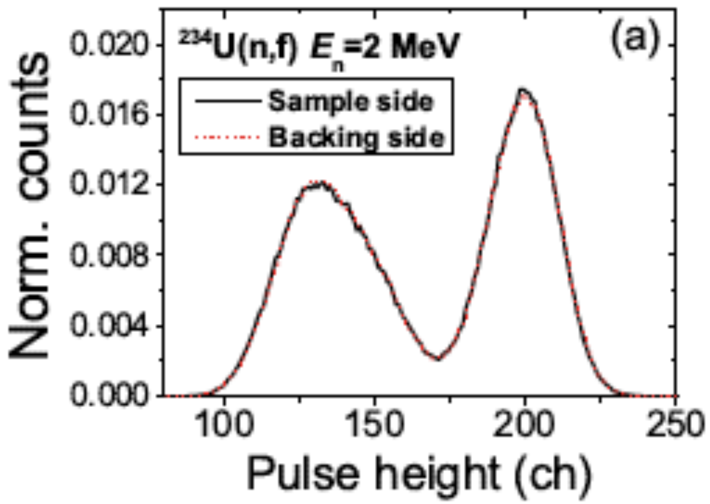

**~ X/D cos θ**

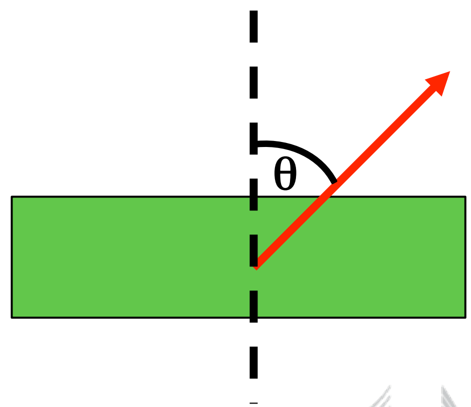
# Measurement with a FGIC

- **Energy loss correction in the target:**

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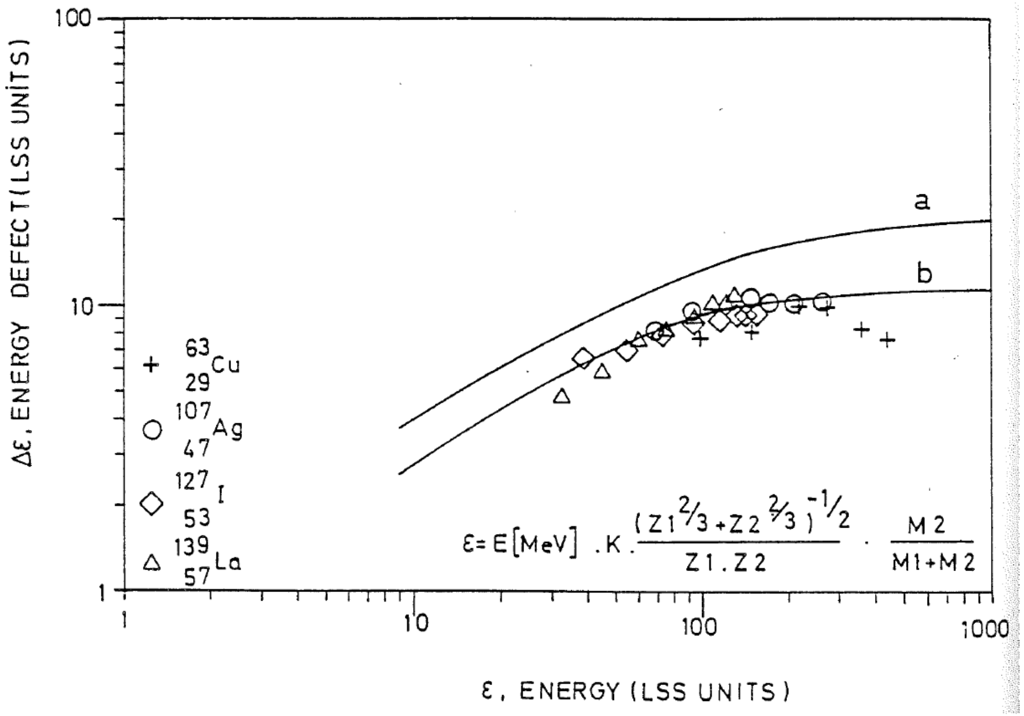
# Measurement with a FGIC

➢ **Pulse-height defect correction:**

$$\mathrm{PHD}\left(A_{\mathrm{post}},E_{\mathrm{post}}^{\mathrm{LAB}}\right)=\frac{A_{\mathrm{post}}E_{\mathrm{post}}^{\mathrm{LAB}}}{\alpha}+\frac{A_{\mathrm{post}}}{\beta}$$

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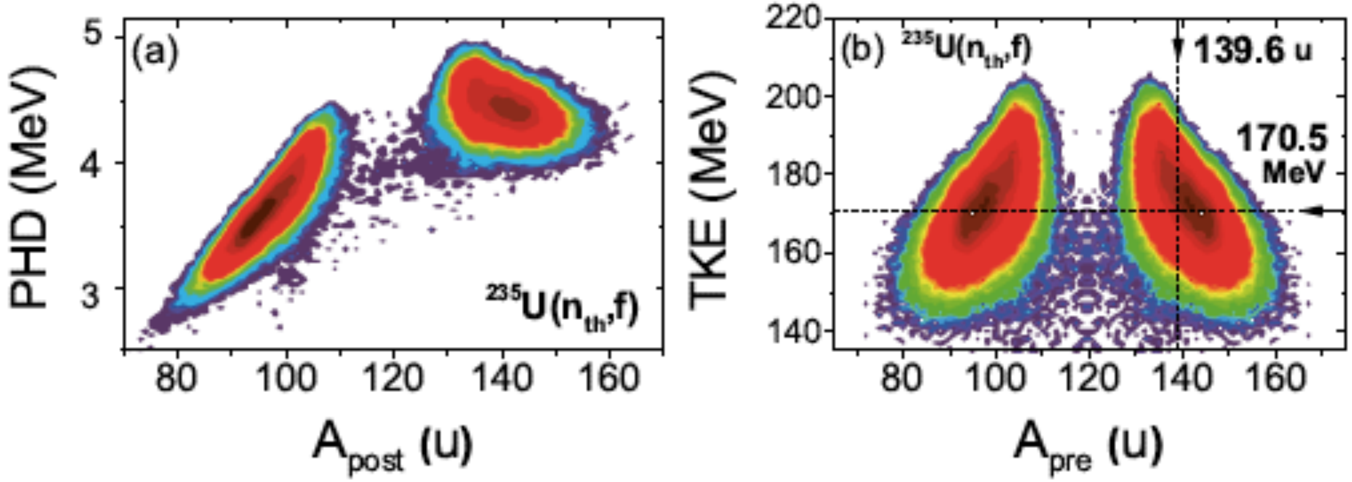
# Measurement with a FGIC

- **Pulse-height defect correction:**

$$\mathrm{PHD}\left(A_{\mathrm{post}}, E_{\mathrm{post}}^{\mathrm{LAB}}\right) = \frac{A_{\mathrm{post}} E_{\mathrm{post}}^{\mathrm{LAB}}}{\alpha} + \frac{A_{\mathrm{post}}}{\beta}$$




- **From reference measurement on $^{235}U(n_{th},f)$**

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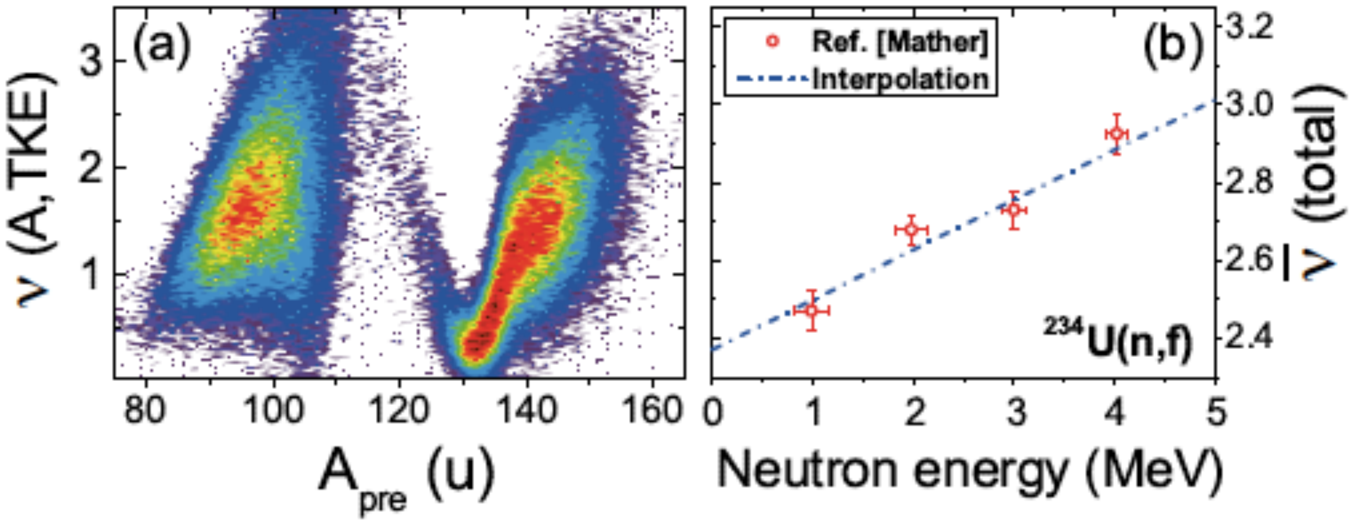
# Measurement with a FGIC

- **Prompt neutron correction:**

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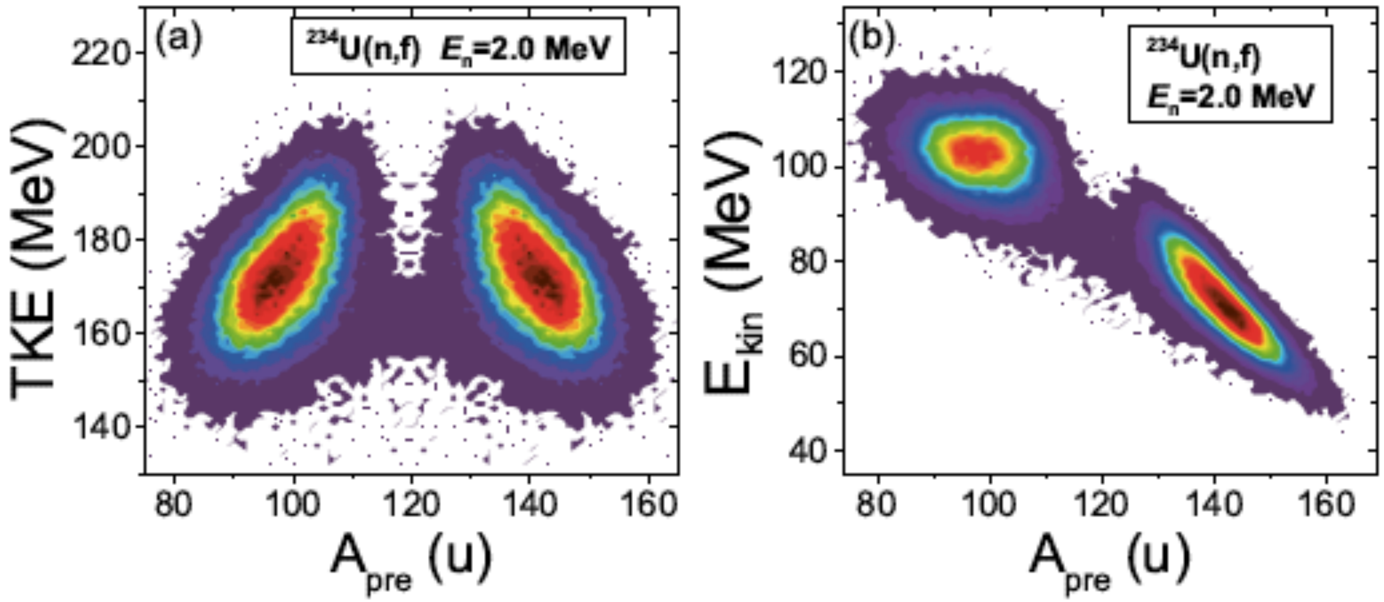
# Measurement with a FGIC

➢ **FINAL mass and energy distributions:**

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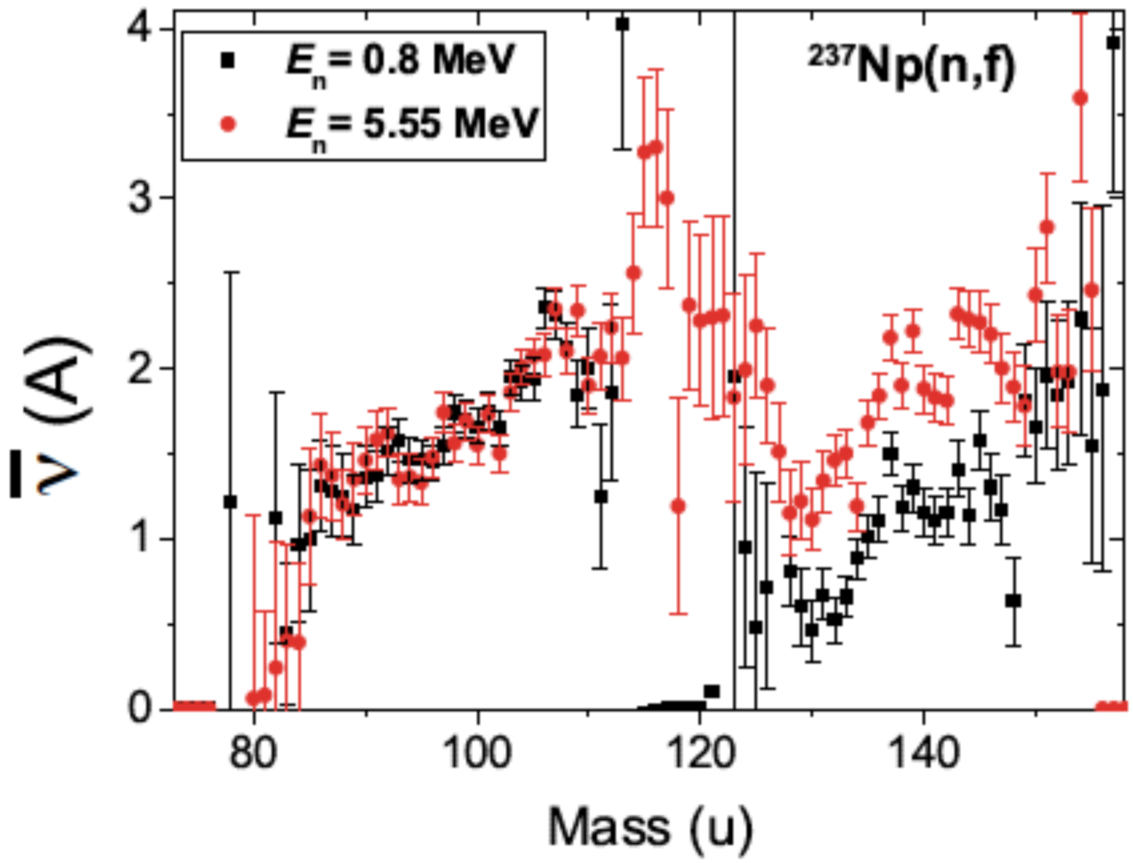
# Measurement with a FGIC

- **Prompt neutron correction (IMPORTANT):**

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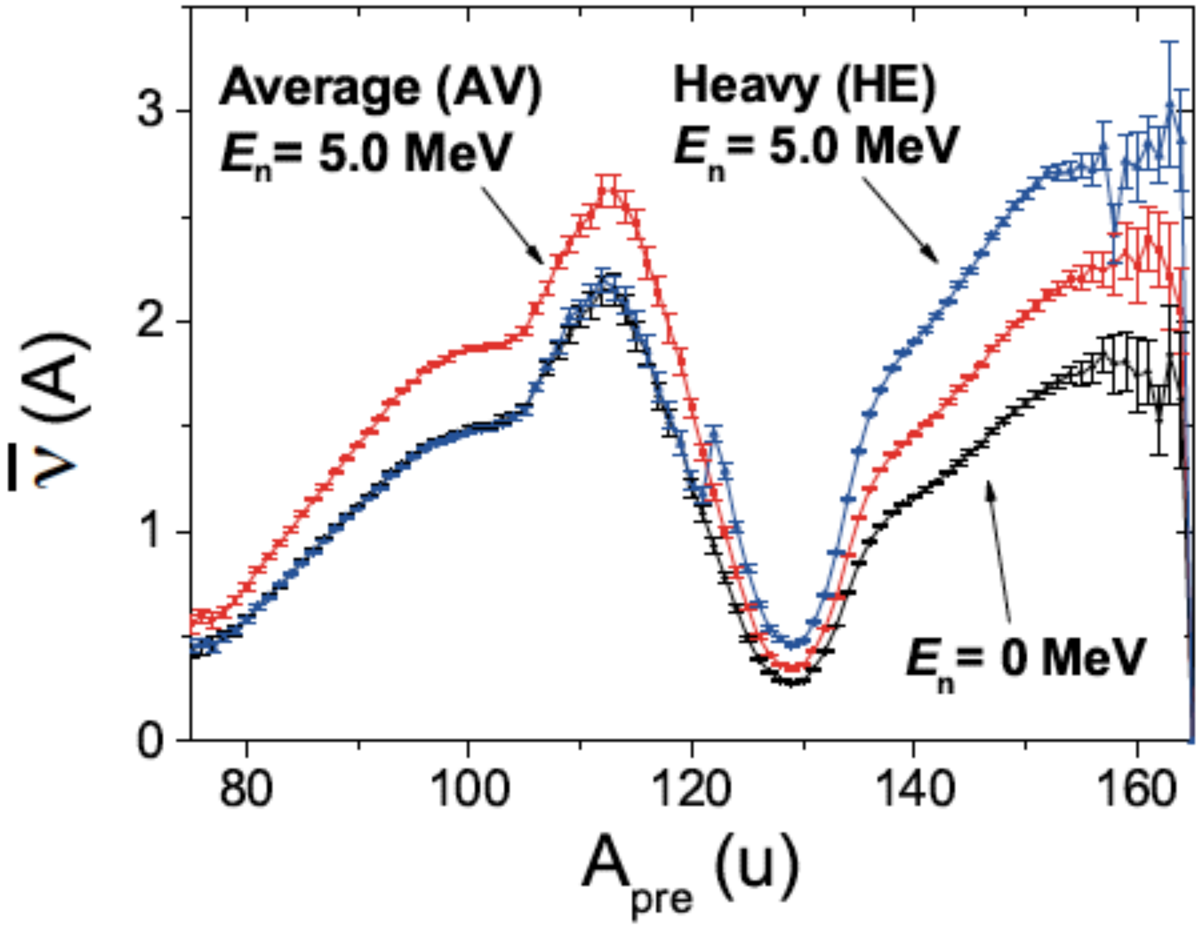
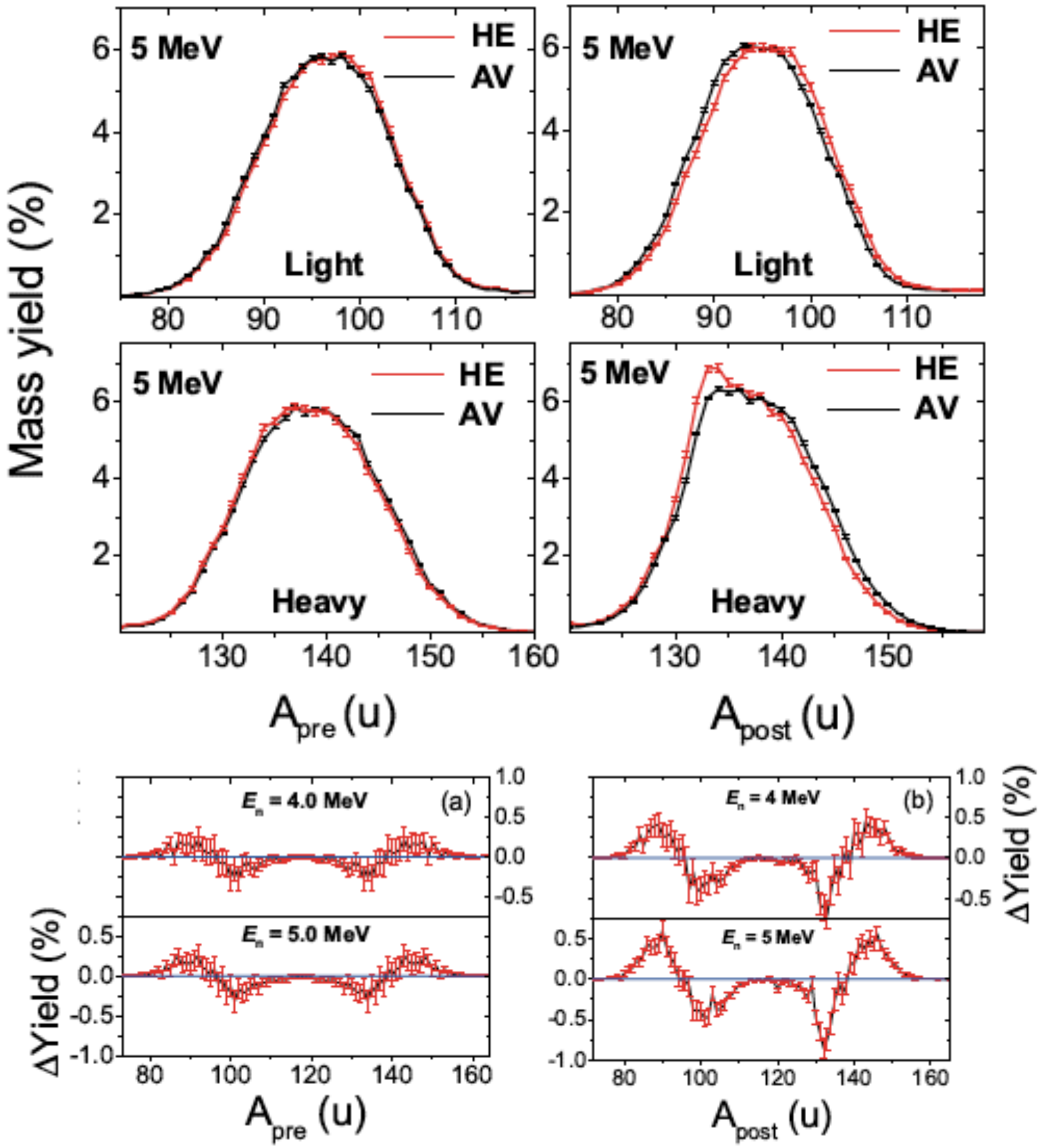
# Measurement with a FGIC

- **Prompt neutron correction (IMPORTANT):**




5 MeV
HE
AV
Light
Heavy
Mass yield (%)
A_pre (u)
A_post (u)
E_n = 4.0 MeV
E_n = 5.0 MeV
E_n = 4 MeV
E_n = 5 MeV
(a)
(b)
ΔYield (%)

# Mass and kinetic energy distributions

✓ Double-energy technique well developed

✓ Use of Frisch-grid ionization chambers best for fragment spectrometry

✓ High geometrical efficiency

✓ Good grip on energy-loss corrections

∇ Depend on prompt fission neutron data!!!

∇ Mass resolution $\Delta A > 3$, depends also on target properties

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# Mass and kinetic energy distributions

- Double velocity technique:

- Direct access to pre-neutron characteristics
- Assumption: $v_i^* = v_i$ (isotropic PFN emission)

$$A_i^* = v_j/(v_1 + v_2)\, A_{CN}$$

- → Pre-neutron kinetic energies and TKE
- Mass resolution limited because of PFN emission
- $\Delta A \approx 1.3$ u

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# Mass and kinetic energy distributions

- Double velocity – double energy technique:

- Direct access to pre-neutron characteristics
- Assumption: $v_i^* = v_i$ (isotropic PFN emission)

$$A_i^* = v_j/(v_1 + v_2)\, A_{CN}$$

- Post-neutron characteristics simultaneously
- Event-wise $A_i = 2E_i/v_i^2$

# Mass and kinetic energy distributions

- Double velocity – double energy technique:

- $\{A_i^*, A_i\} \rightarrow \nu(A^*, TKE)$

- Indirect measurement of PFN multiplicity
- Independent method

- All correlations with fragment characteristics assessable

# Mass and kinetic energy distributions

- Double velocity – double energy technique:
- realized 2v-2E spectrometers:

  - ✓ COSI FAN TUTTE (ILL, Grenoble)

    $D_{TOF}$ = 1070 mm, 2 MCP as time pick-off

    energy measurement with IC (thin entrance)

    highest mass resolution $\Delta A < 0.7$ u

    very low geometrical efficiency, $\mathcal{O}(10^{-5})$

    *only used in a single v-E version*

    nuclear charge yields, Y(Z)

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# Mass and kinetic energy distributions

- **Double velocity – double energy technique:**
- **Realized 2v-2E spectrometers:**

  - ✓ **SPIDER (LANL)**

    **$D_{TOF}$ = 750 mm, 2 MCP as time pick-off**

    **energy measurement with IC (SiN window)**

    **post-neutron mass resolution $\Delta A < 2$ u**

    **geometrical efficiency, $\mathcal{O}(10^{-3})$**

    **Y(A) results from single v-E measurement**

# Mass and kinetic energy distributions

- Double velocity – double energy technique:
- realized 2v-2E spectrometers:

- ✓ VERDI(JRC IRMM)

  $D_{TOF}$ = 500 mm, MCP + PIPS as time pick-off

  energy measurement with PIPS (NTD-Si)

  full 2v-2E version operational

  pre-neutron mass resolution $\Delta A \approx 2$ u

  geometrical efficiency, $\mathcal{O}(10^{-2})$

  Y(A*,A; $\nu$) results

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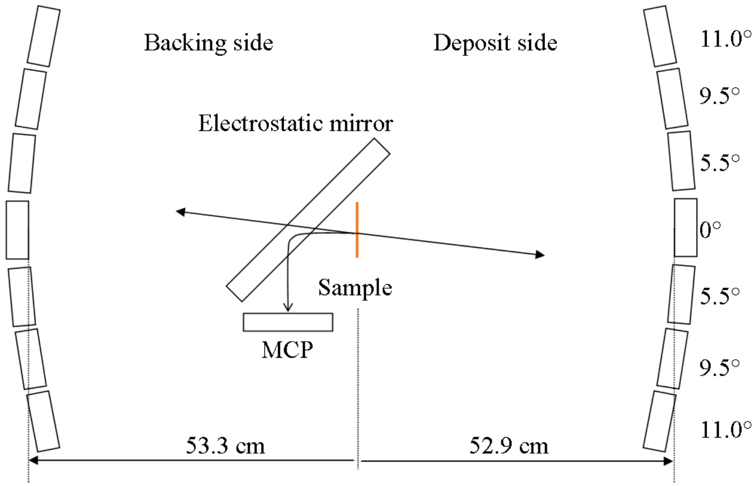
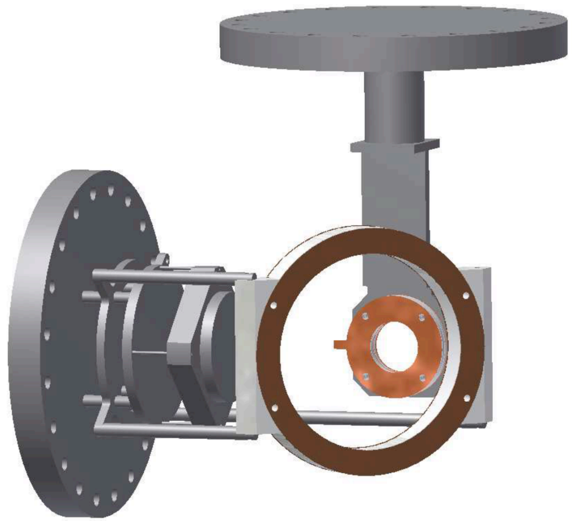
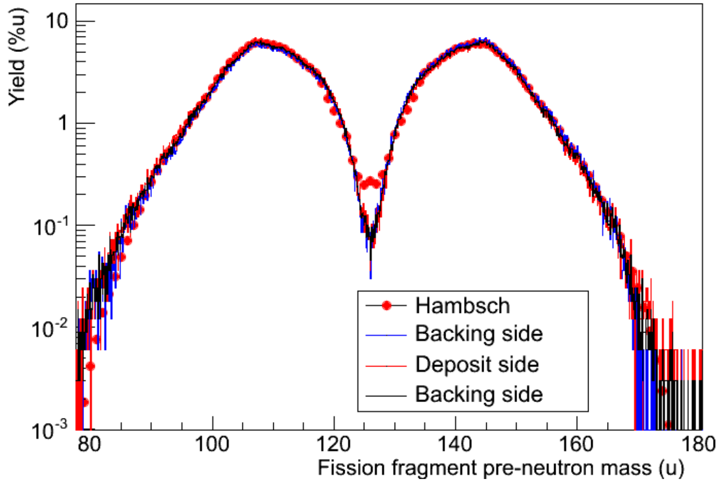
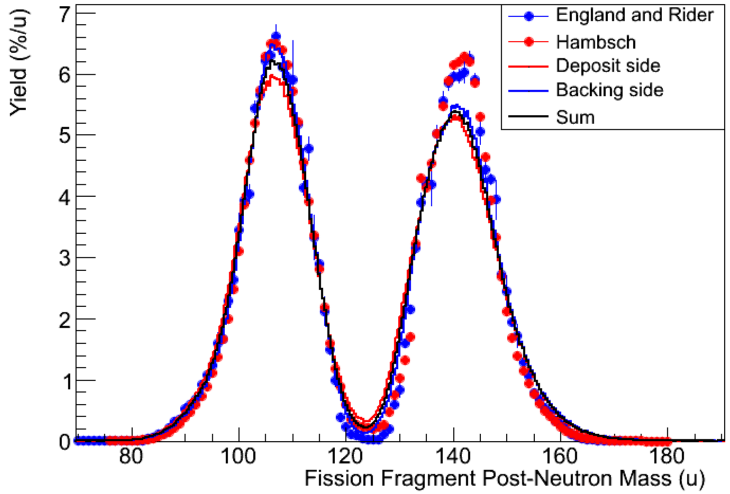
- **Double velocity – double energy technique:**
- **VERDI (JRC IRMM)**



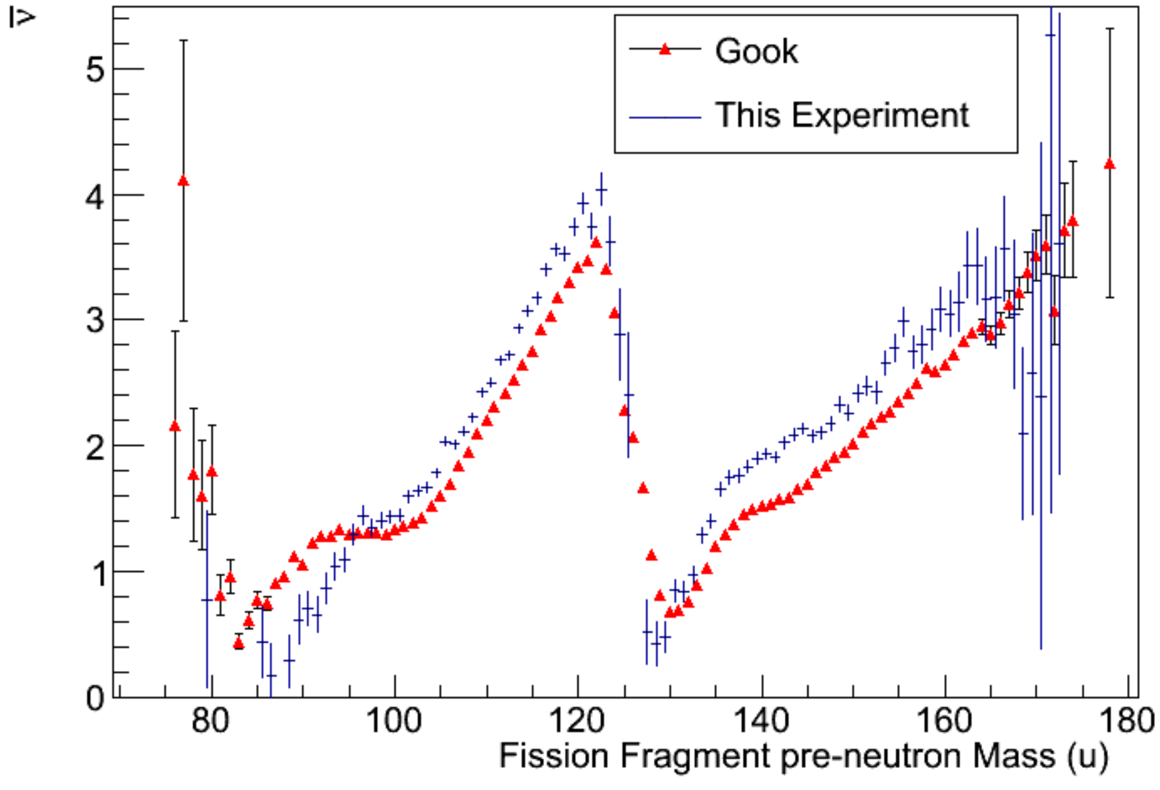



- **Double velocity – double energy technique:**
- **VERDI (JRC IRMM)**



- **Double velocity – double energy technique:**
- **VERDI (JRC IRMM)**

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# Mass and kinetic energy distributions

- **Double velocity – double energy technique:**

  - ✓ **Superior mass resolution**
  - ✓ **No a-priory knowledge about prompt neutron emission required**
  - ✓ **Independent method to obtain prompt neutron multiplicity data**

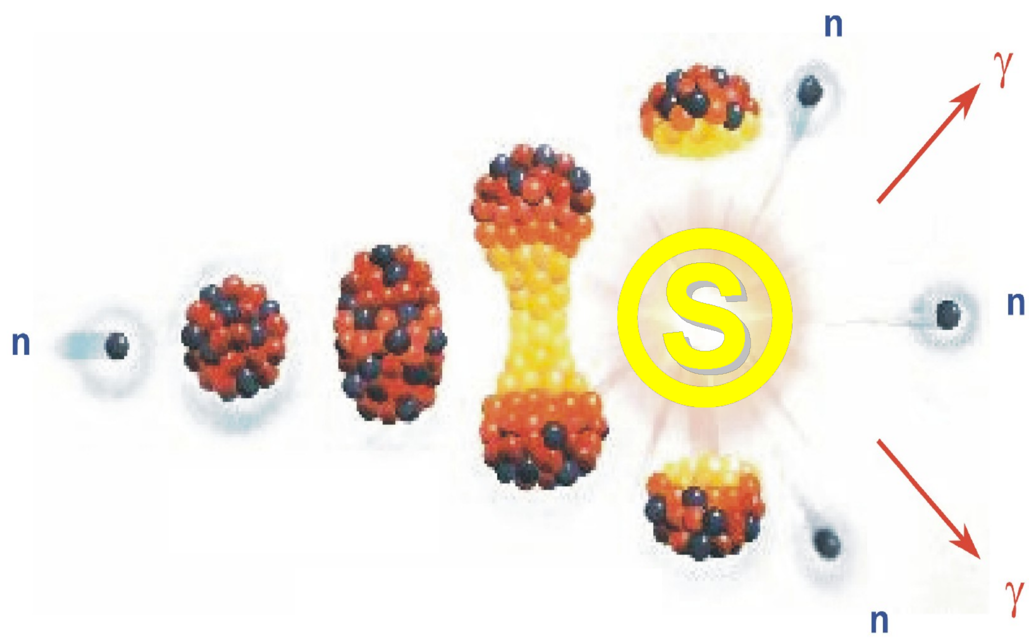
- **Low geometrical efficiency**

# How to "measure" fission properties

- **Different measurement techniques**
  - Recoil mass separation
  - Double energy technique
  - Double velocity + double energy measurement
  - Activation analysis by means of $\gamma$-spectrometry
  - Radio-chemical methods

- **Choice of silicon detectors or Frisch-grid ionization chambers depends on the particular measurement environment**

# Thank you very much for Your attention

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# Literature

**Experimental data, measurement techniques**


- "The Nuclear Fission Process", C. Wageman (ed.), CRC Press (1991), ISBN 0-8493-5434-X
- "Nuclear Fission and Neutron-Induced Fission Cross-Sections", A. Michaudon (ed.), Pergamon Press (1981), ISBN 0-08-026125-6
- H.J. Krappe, K. Pomorski, Lecture Notes in Physics 838, Springer (2012), ISBN 978-3-642-23514-6
- H. Nifenecker, C. Signarbieux, R. Babinet, J. Poitou, Phys. and Chem. of Fission 1973, Vol. II, Proc. of a Symp., Rochester, New York, 13 - 17 August 1973, IAEA, Vienna, STI/PUB/347 (1974) 117
- IAEA, 2000, Compilation and Evaluation of Fission Yield Nuclear Data, Report: IAEA-TECDOC-1168, available through INIS Clearinghouse, IAEA, Box 100, A-1400 Vienna, Austria

- Migneco, E., Theobald, J.P., 1968, Nucl. Phys. A, 112, 603
- Bjornholm, S., Lynn, J.E., 1980, Rev. Mod. Phys., 52, 725
- Oed, A., Geltenbort, P., Brissot, R., Gönnenwein, F., Perrin, P., Aker, E., Engelhardt, D., 1984, Nucl. Instr. Methods in Phys. Res., 219, 569
- Oed, A., Geltenbort, P., Gönnenwein, F., 1983, Nucl. Instr. Methods, 205, 451
- E. Moll et al., NIM 123 (1975) 615
- H. G. Clerc et al., Nucl. Phys. A247 (1975) 74
- M. Ashgar et al., Nucl. Phys. A311 (1978) 205
- W. Lang et al., Nucl. Phys. A345 (1980) 15
- M. Djebara et al., Nucl. Phys. A425 (1984) 120
- C. Schmitt et al., Nucl. Phys. A430 (1984) 21
- H.G. Clerc et al., Nucl. Phys. A452 (1986) 277
- A. Göök et al., Nucl. Phys. A851 (2011) 1


European Commission

# Literature

## Experimental data, measurement techniques


- Knitter, H.-H., Hambsch, F.-J., Butz-Jörgensen, C., 1992, Nucl. Phys. A, 536, 221
- Butz-Jörgensen, C., Knitter, H.-H., Straede, CH., Hambsch, F.-J., Vogt, R.A., 1987, Nucl. Instr. Methods in Phys. Res. A, 258, 209
- F.-J. Hambsch, H. H. Knitter, C. Budtz-Jørgensen, and J. P. Theobald, Nucl. Phys. A491, 56 (1989)
- F.-J. Hambsch, I. Ruskov, and L. Dematte, in Proc. Scientific Workshop on Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gamma Rays (Theory-1), EUR 24802 (Sinaia, Romania, 2011) 41
- A. Göök, F.-J. Hambsch, A. Oberstedt, S. Oberstedt , NIM A 664 (2012) 289
- A. Al-Adili, F.-J. Hambsch, R. Bencardino, S. Pomp, S. Oberstedt, Sh. Zeynalov, NIM A 671 (2012) 103
- A. Al-Adili, F.-J. Hambsch, R.Bencardino, S.Oberstedt, S.Pomp, NIM A 673 (2012) 116
- S. Oberstedt, F. Gunsing, Nucl. Phys. A589 (1995) 435
- S. Oberstedt, F. Gunsing, Nucl. Phys. A636 (1998) 129
- F.-J. Hambsch, S. Oberstedt, Nucl. Phys. A617 (1997) 347
- Thirolf, P.G., Habs, D., Prog. in Part. and Nucl. Phys., 49 (2002) 245
- S. Oberstedt et al., Nucl. Phys. A761 (2005) 173
- A. Oberstedt, S. Oberstedt, NIM A570 (2007) 51
- E. Birgersson et al., Nucl. Phys. A570 (2007) 51
- A. Oberstedt, S. Oberstedt, M. Gawrys, N. Kornilov, Phys. Rev. Lett. 99, 042502 (2007)
- M. Lebois, J.N. Wilson, P. Halipre, B. Leniau, I. Matea, A. Oberstedt, S. Oberstedt, D. Verney, Nucl. Instr. Meth. A735 (2014) 145
- K. Meierbachtol et al., NIM A788 (2015) 59
- M. O. Fregeau et al., NIMA (2016) submitted


European Commission

# Literature

**Theory and Modelling:**


- Myers, W.D., Swiatecki, W.J., 1966, Nucl. Phys., 81, 1
- Strutinsky, V.M., 1967, Nucl. Phys. A, 95, 420
- Brosa, U., Großmann, S., Müller, A., 1990, Physics Reports, 197, 167
- S. Oberstedt, F.-J. Hambsch, F. Vivès, Nucl. Phys. A617 (1997) 347
- R. Vogt, J. Randrup, Phys. Proc. 47 (2013) 3 (Refs. in there!)
- R. Vogt, J. Randrup, Nucl. Dt. Sheets 118 (2014) 220 (Refs. In there!)
- K.-H. Schmidt, OECD/NEA, JEF/DOC 1398 (2012)
- K.-H. Schmidt and B. Jurado, OECD/NEA, JEF/DOC 1423 (2012).
- K.-H. Schmidt, B. Jurado, Ch. Amouroux, JEFF-Report Data Bank, Nuclear-Energy Agency, OECD (2015).