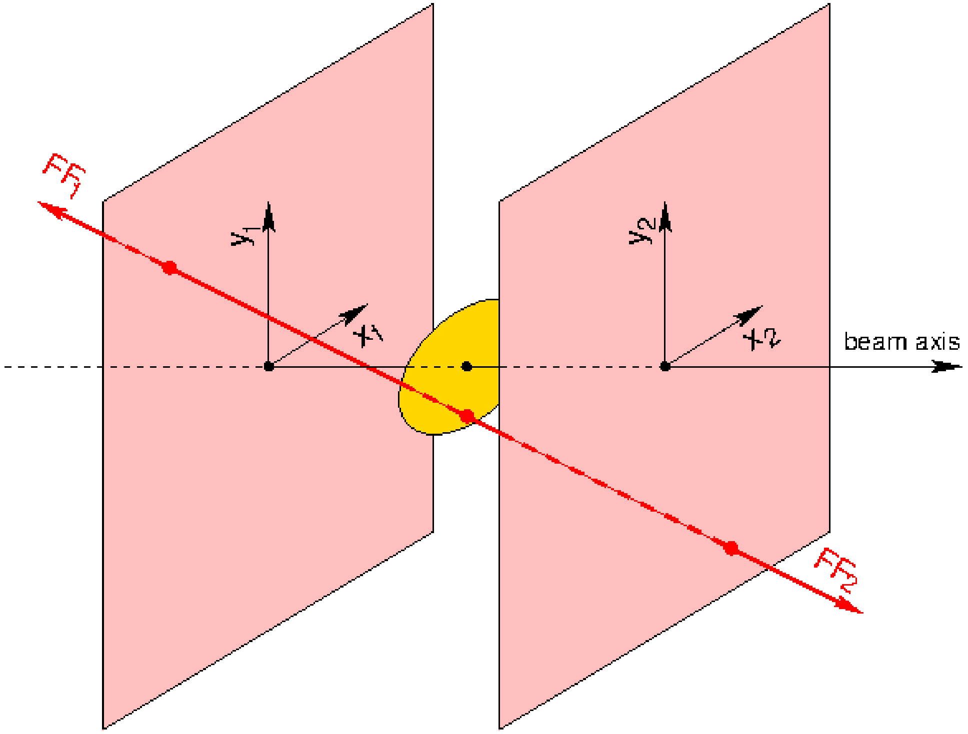
Fission fragment angular distributions and physique mechanism

Lou Sai Leong

Principle of FFAD detection

- Reconstruction of fission angle respect to the beam axis so need of fission fragment tracking
- Discrimination of light particles from fission fragments

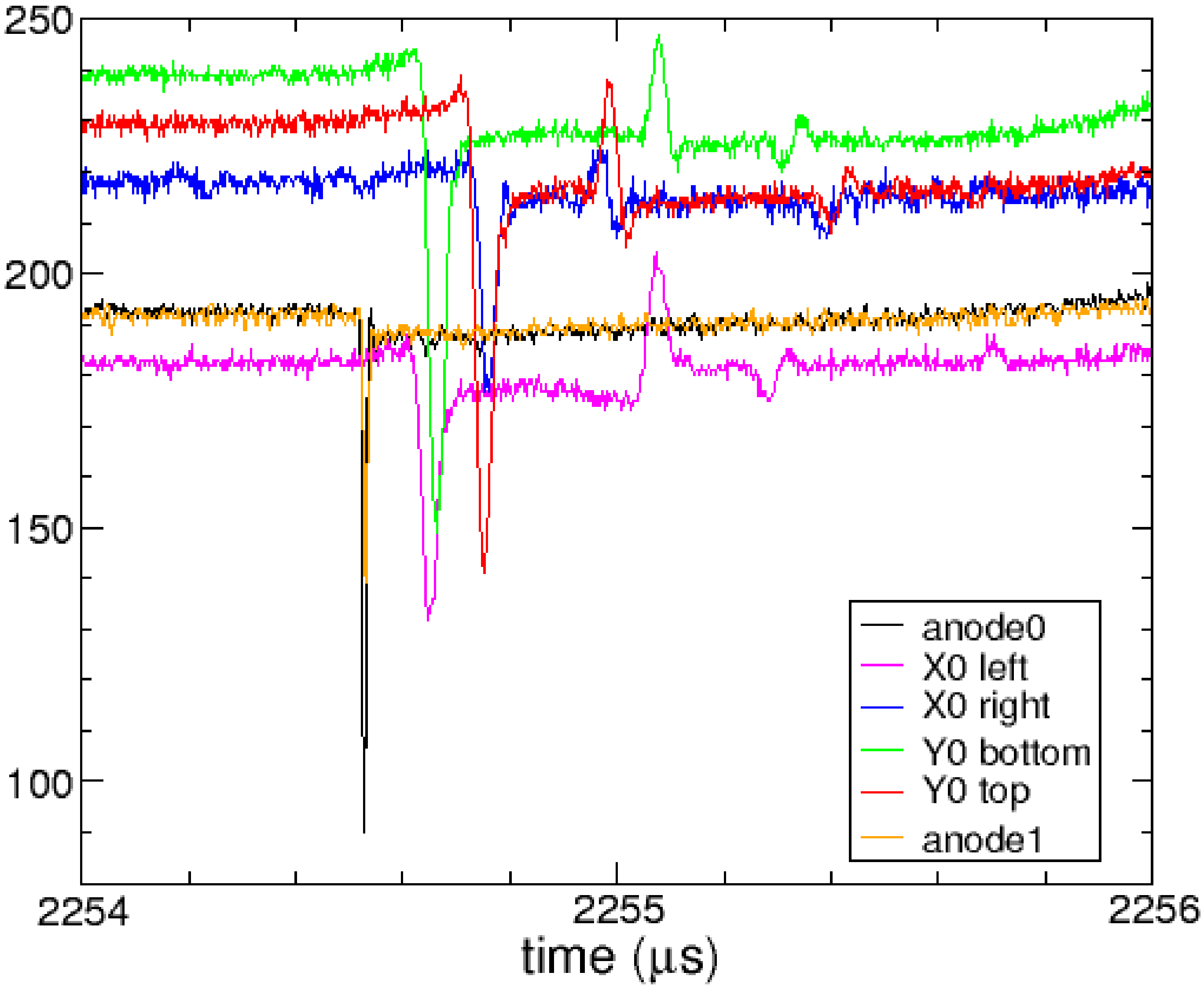


- Coincidence method:
one detector on each side of the target

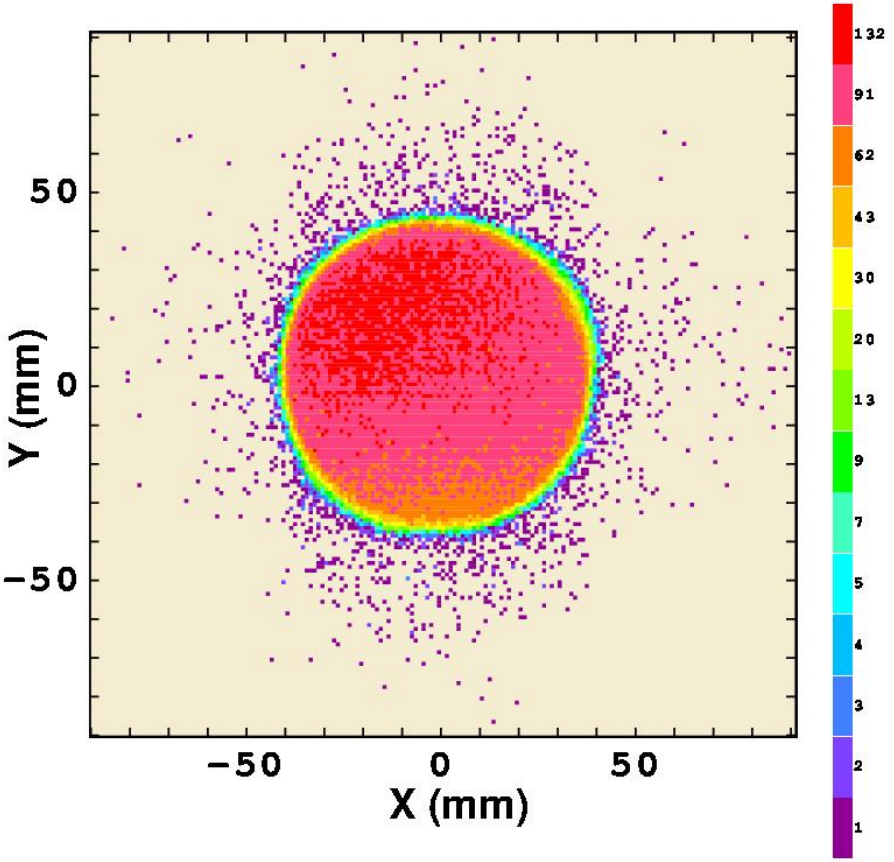
- Choice of PPAC.

- Recoil effect is negligible
(simulation).

Fission event identification

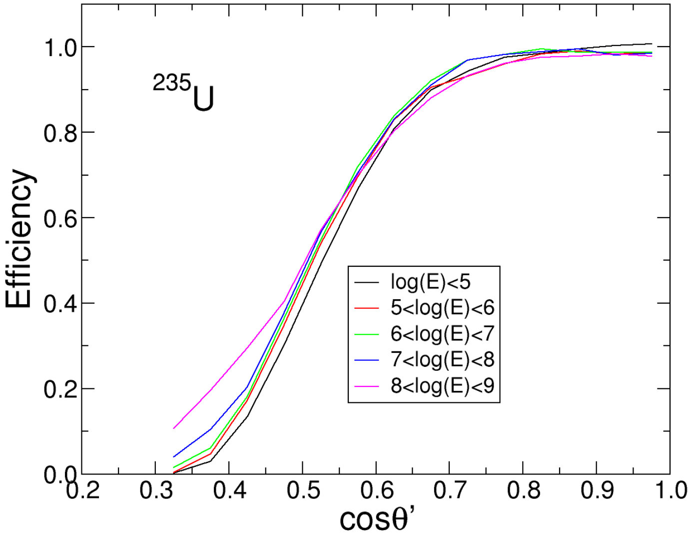


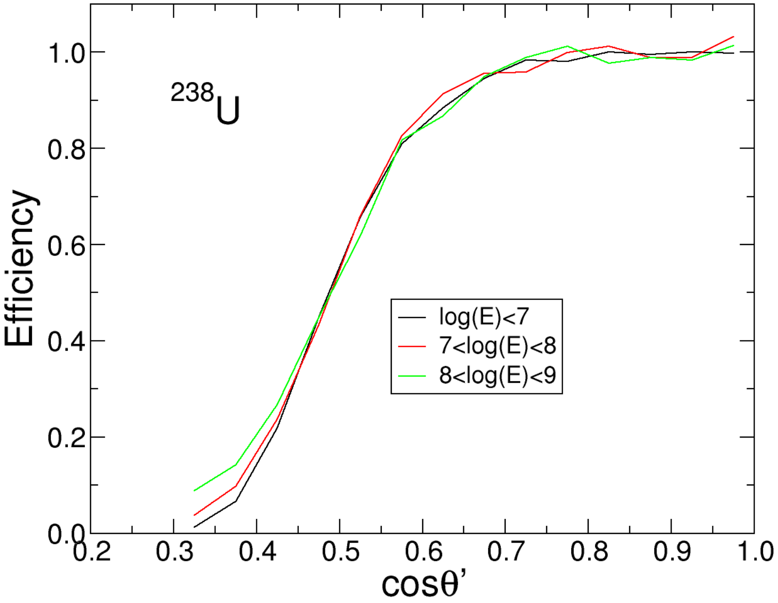
Power of the tracking method
Reconstruction of target shape

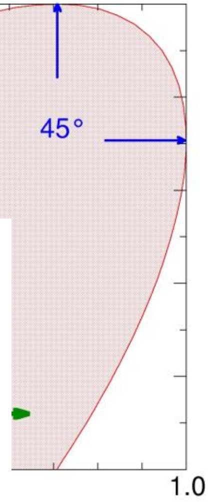


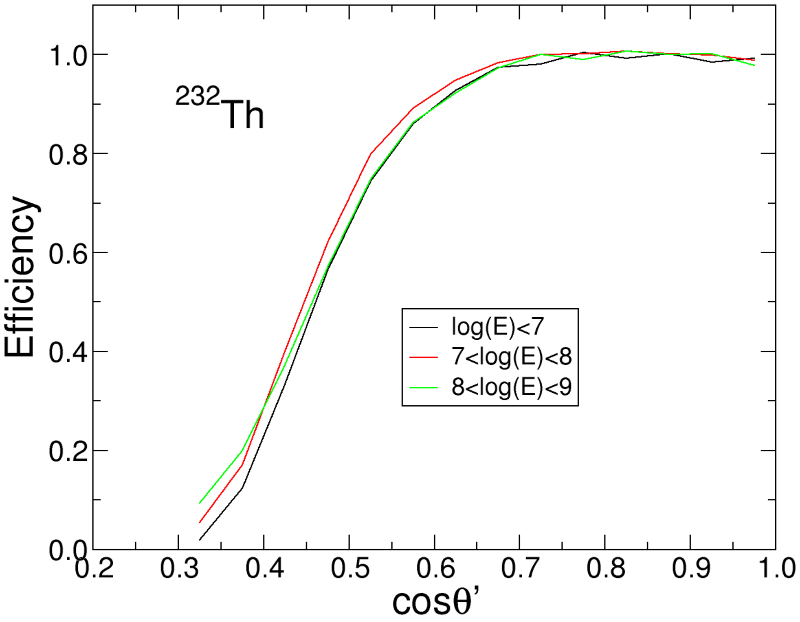
Self-determi cy

The angular distribution depend ed in.
But the detection efficiency depe



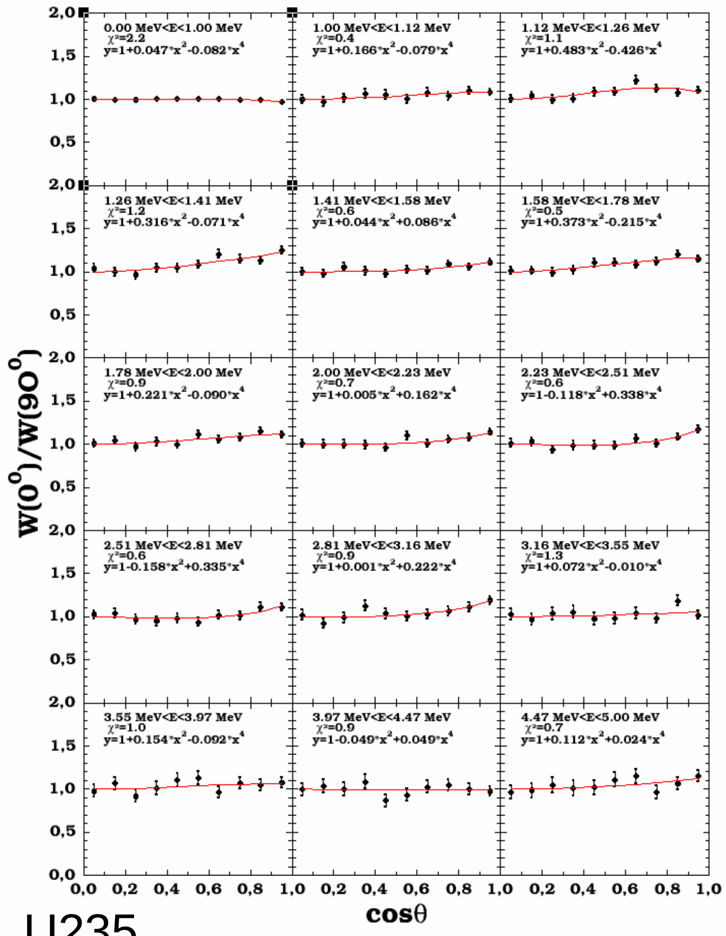




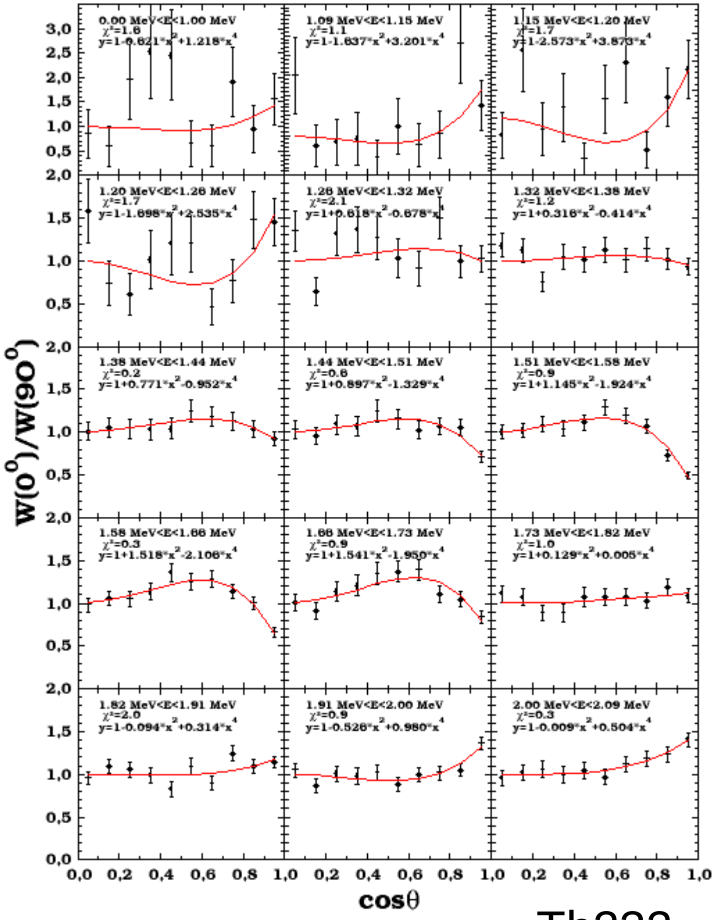


efficiency
FAD.

^{235}U and ^{232}Th FFAD for each energy bin, fitted by Legendre polynomials



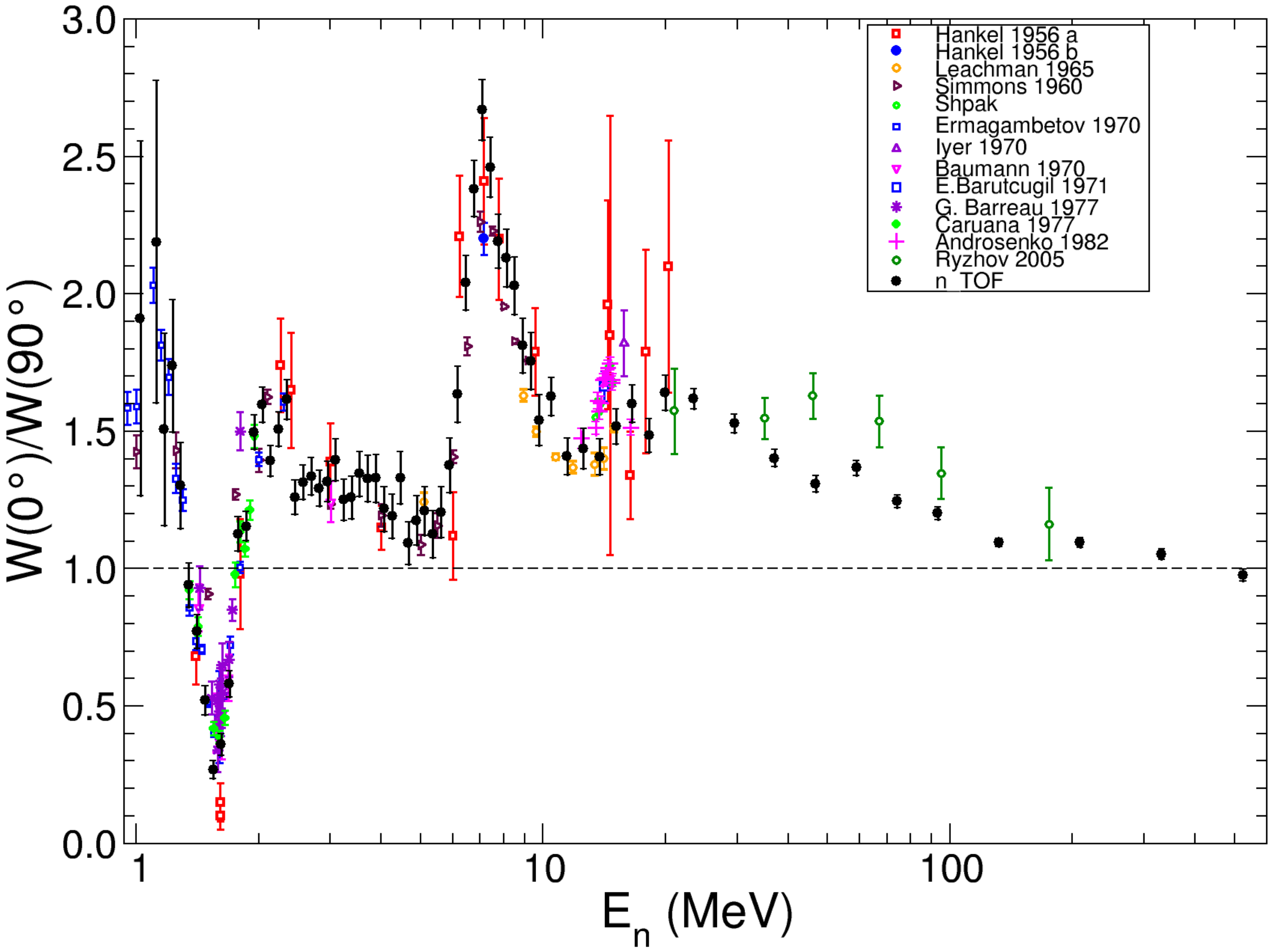
U235



Th232

$$W(\cos\theta)=\sum_{L_{even}}^{L_{\max}} A_L P_L(\cos\theta)\quad L_{\max}=2,4,6.$$

Result and Discussions: ^{232}Th



FFAD theory: low E*

$\overrightarrow{l}$: Orbital angular momentum.

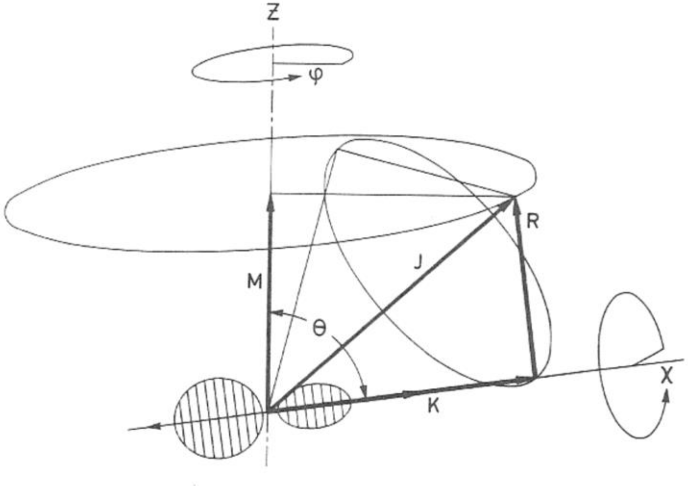
$\overrightarrow{S}$: Sum of target and projectile spin.

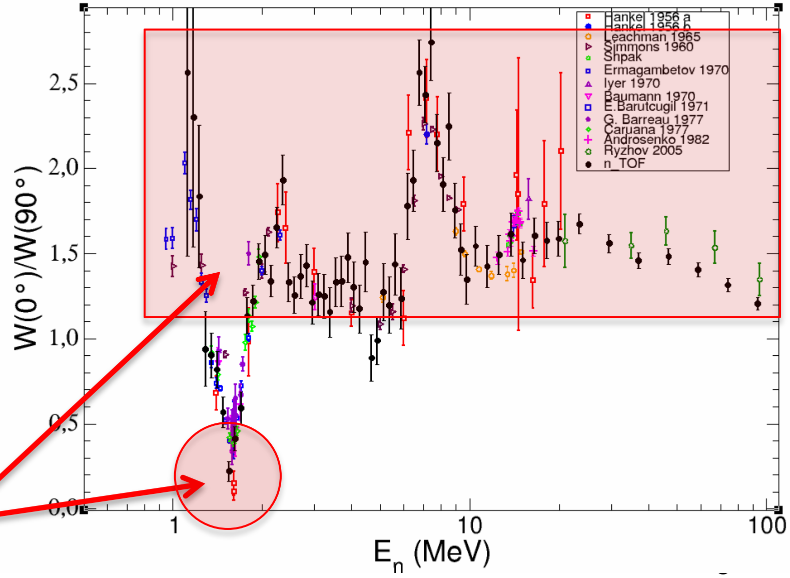
$\overrightarrow{J}$: Angular momentum: $\overrightarrow{J} = \overrightarrow{l} + \overrightarrow{S}$

$\overrightarrow{M}$: Projection of $\overrightarrow{J}$ on the neutron beam direction.

$\overrightarrow{K}$: Projection of $\overrightarrow{J}$ on the fissioning symmetric axis.

The angular distribution $W(J, K, M) \approx |d^J_{K,M}|^2$





If $K \ll J \longrightarrow$: angular distribution is forward-backward peaked.

$K \approx J \longrightarrow$: angular distribution side-ward peaked.

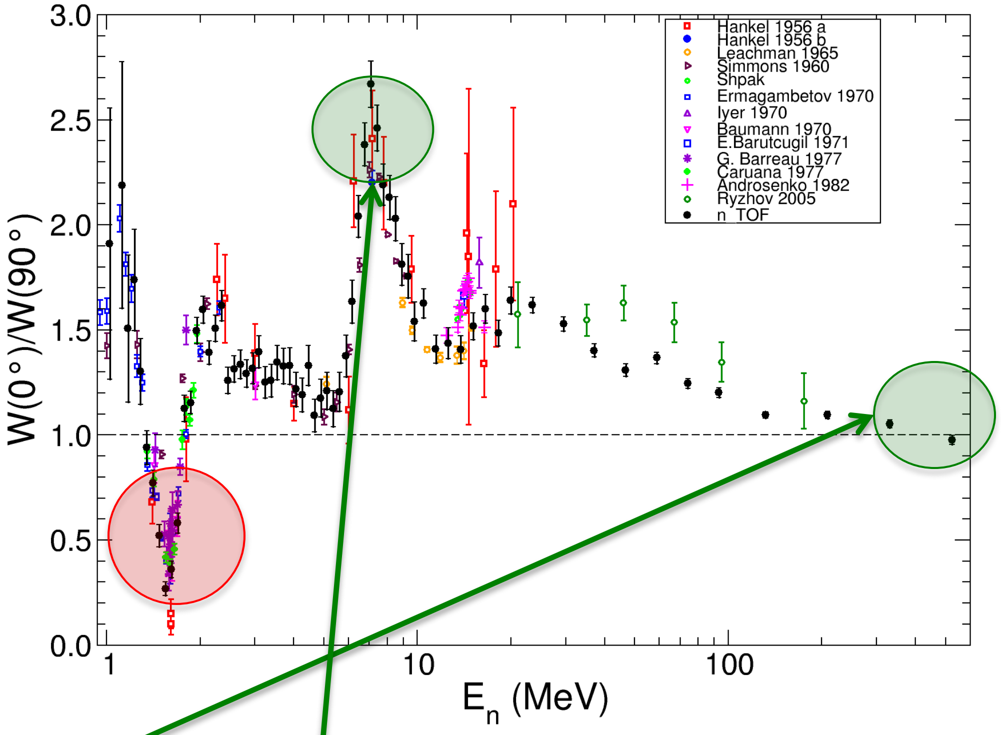
FFAD theory: higher E*

$$W^J_{M,U}(\theta) \approx \sum_{K=-J}^{K=J} |d^J_{M,K}|^2 exp(-K^2/2K_0^2(U))$$

U is the thermal excitation energy: $U = E^* - B_f = a_f T^2$.

$$J_{eff} = J_\wedge J_\| / (J_\wedge - J_\|)$$

$$K_0 \gg J_{eff} T$$

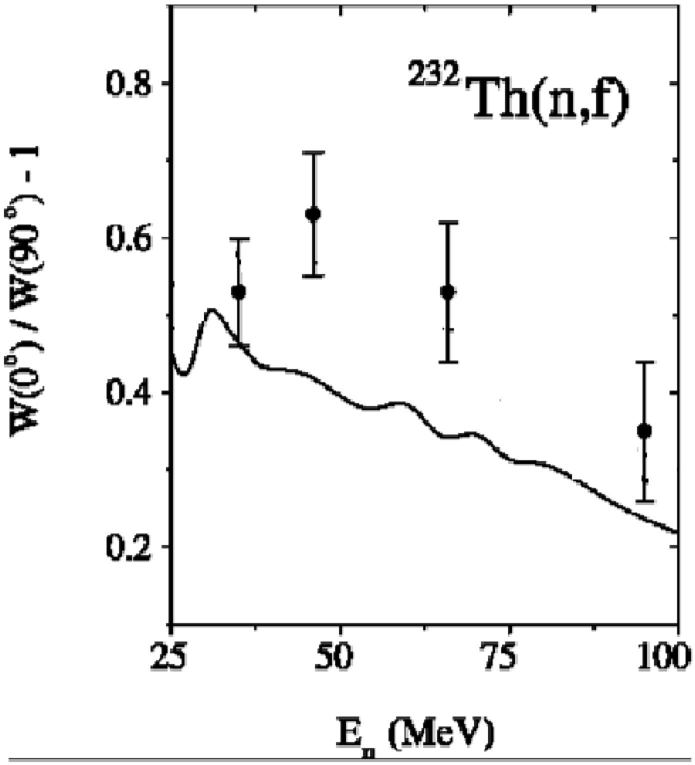


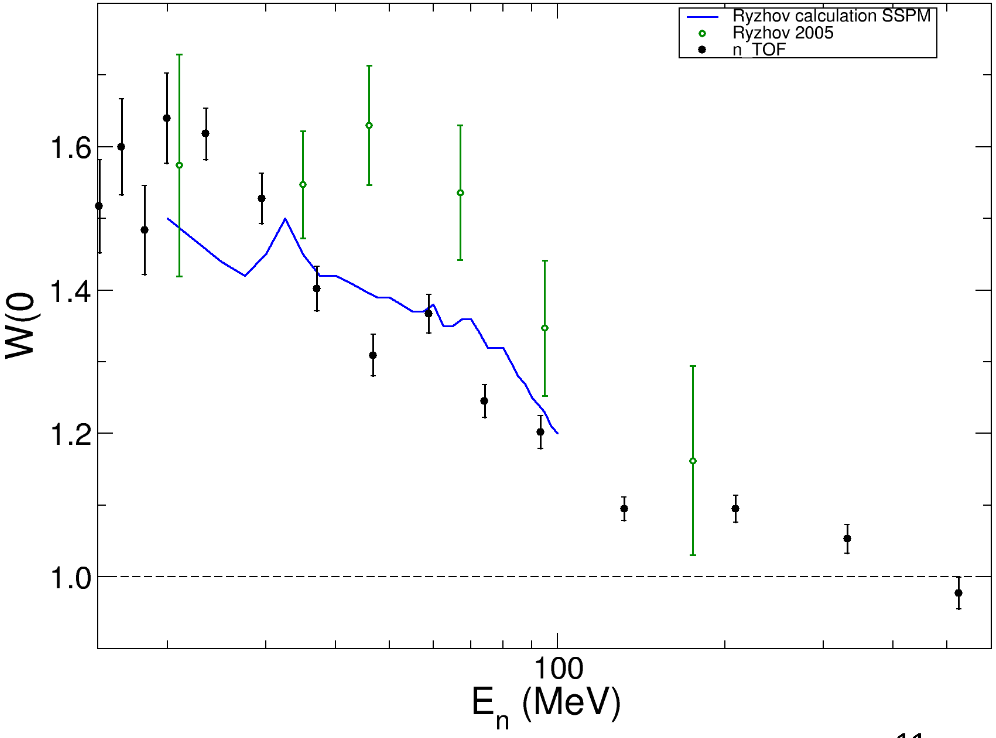
if K_0^2 is high: angular distribution is isotropic.

if K_0^2 is low: angular distribution is forward-backward peaked.

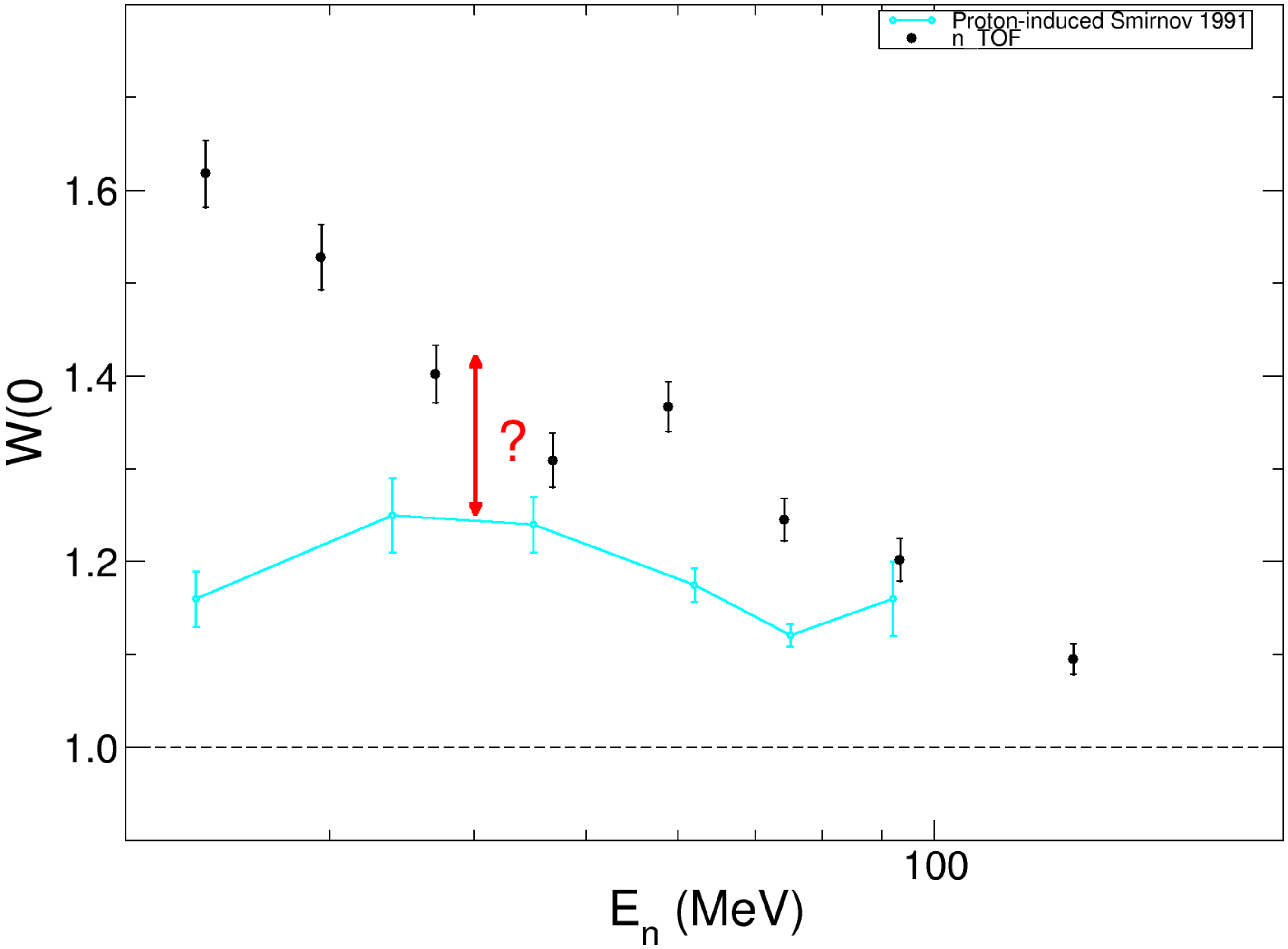
Comparison to Ryzhov calculation

Calculation with statistical saddle-point model combined with pre-equilibrium (pre-compound emission of nucleons followed by fission of the heated nucleus)



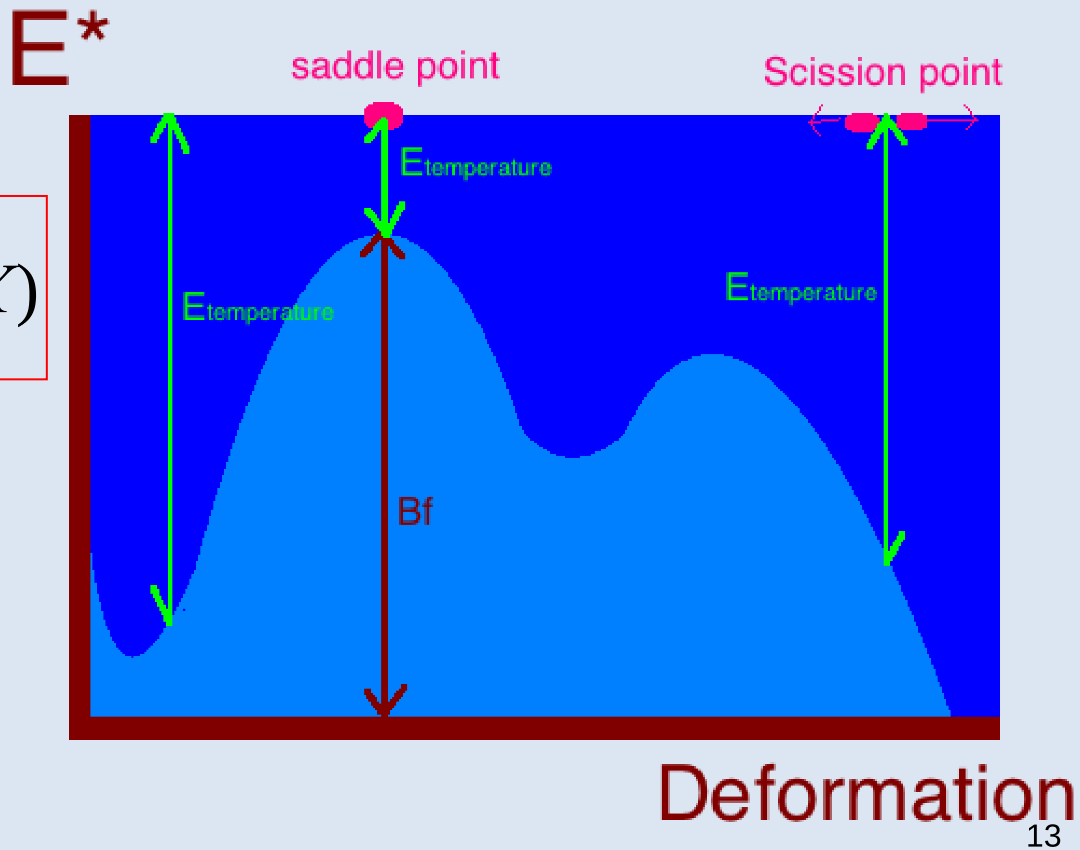


Comparison with proton-induced FFAD



FFAD is related to Z^2/A fissility parameter

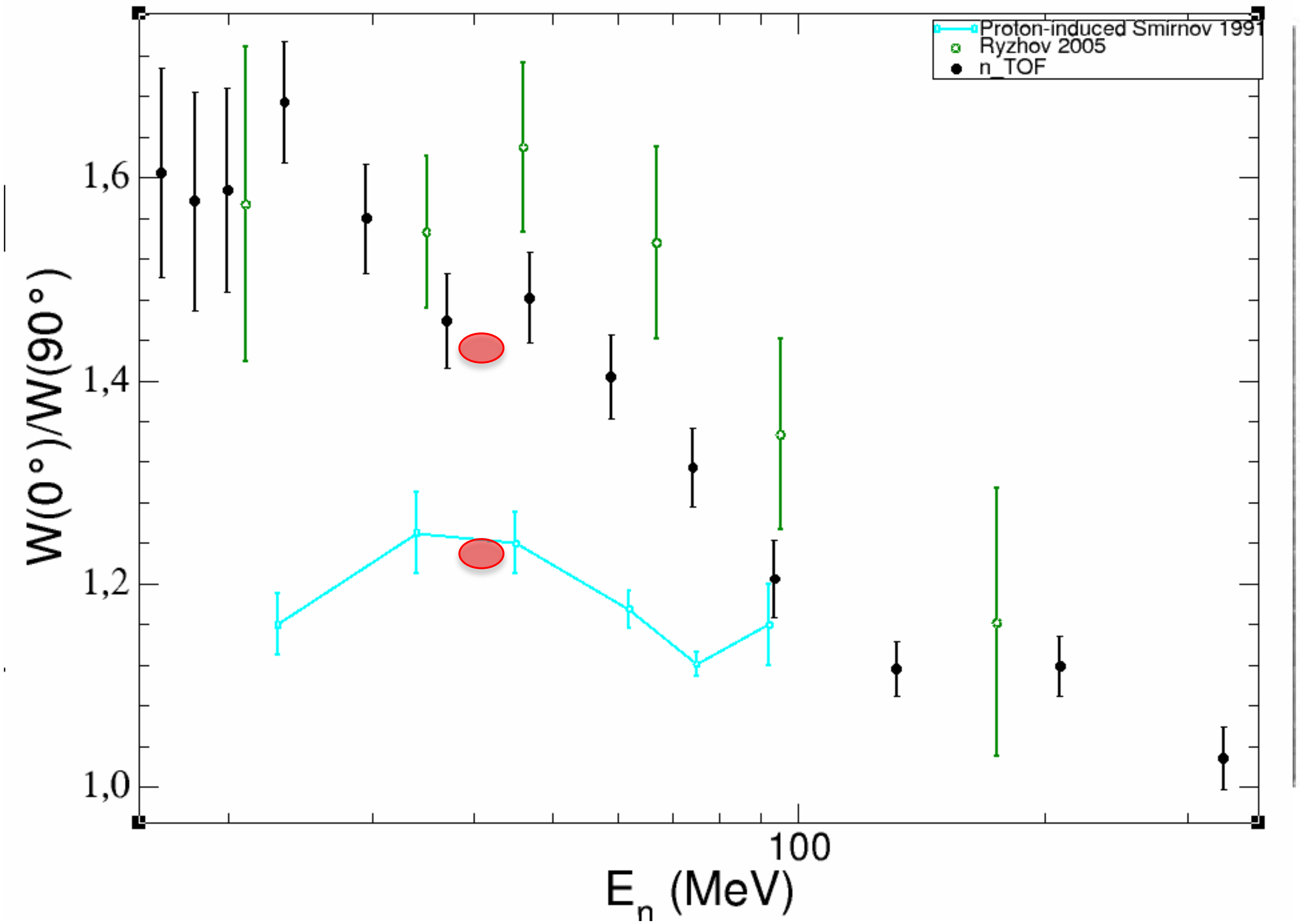
$$(\frac{Z^2}{A} -) \mapsto (B_f \,\bar{}\,) \mapsto (U - = E^* - B_f) \mapsto (K_0 -) \mapsto FFAD_{isotropic}$$



$$\boxed{\frac{Z^2}{A}(n+{}^{A}X) < \frac{Z^2}{A}(p+{}^{A}X)}$$

Proton-induced anisotropy is always lower than the neutron-induced anisotropy

^{232}Th FFAD is related to Z^2/A



nTOF data: in agreement with Ryzhov calculation
Disagreement with Tutin+Ryzhov measurement
Follow the fissility systematics: at 40MeV, most of the incident particles are captured.

Conclusion

- We have measured the fission fragment angular distribution of ^{232}Th from threshold to 600 MeV

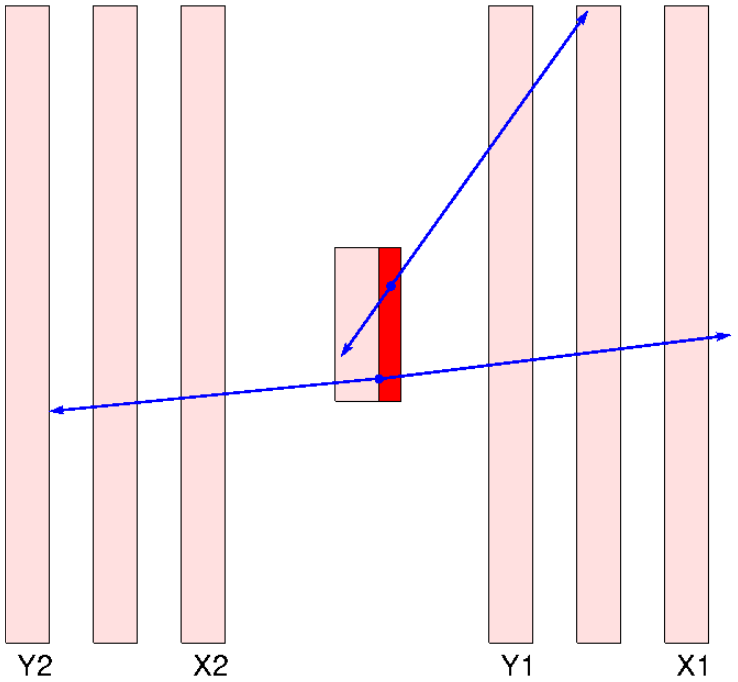
- Below 10 MeV we are in agreement with previous data and around 14 MeV a better accuracy is achieved

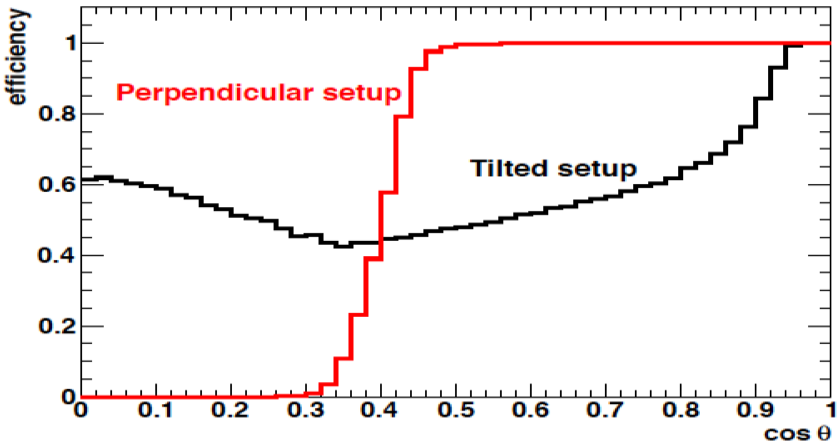
- Between 20 and 100 MeV we find a steeper drop of the anisotropy, compared to Ryzhov data and we are in agreement with his calculation

- The agreement with the fissility systematics indicates that the incoming neutron is captured at 40 MeV

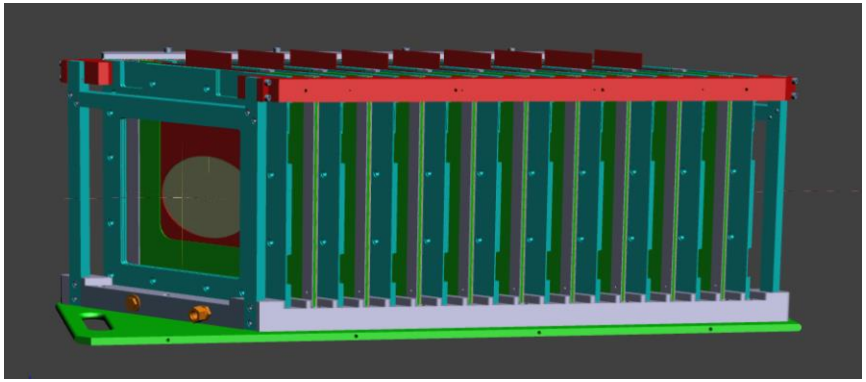
ARIGATOU

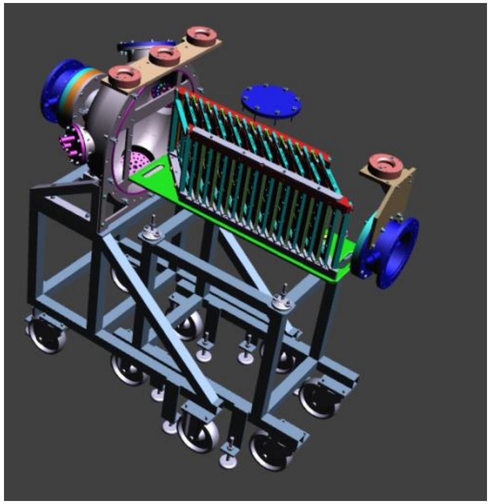
Detector Efficiency



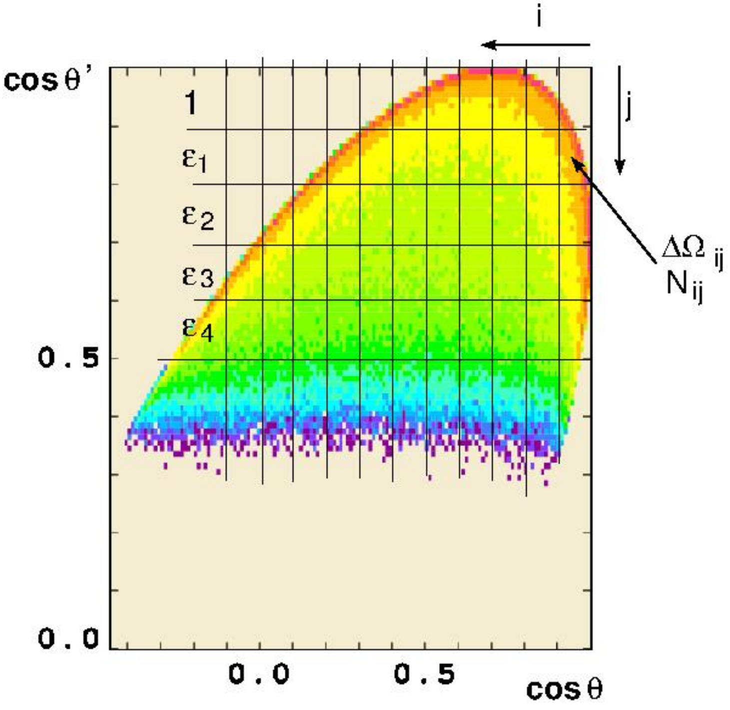


Tilted geometry → cover all angles.





Efficiency Calculation

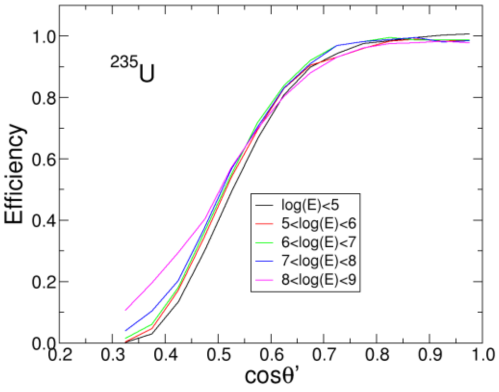


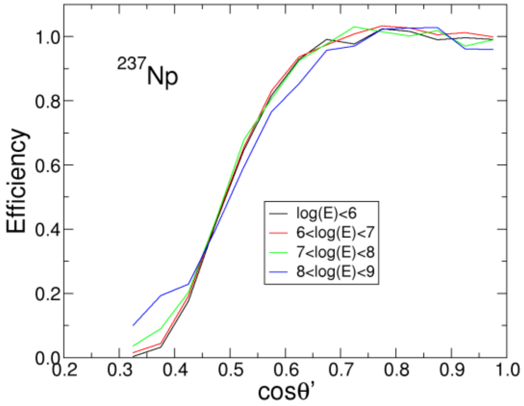
$$N_{ij} = M \times \Delta\Omega_{ij} \times \varepsilon_j \times W(\cos\theta)$$

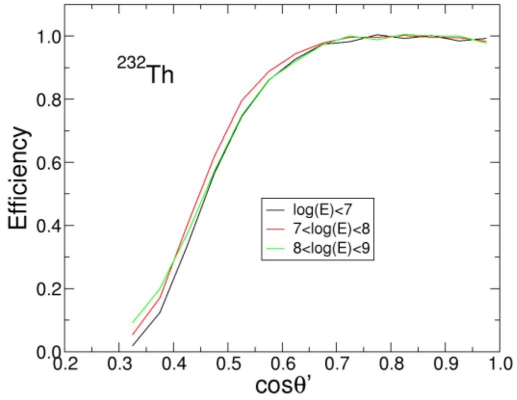
Minimization (least square fitting) of

$$\sum_{i,j}\left(\frac{M \times \Delta\Omega_{ij} \times \varepsilon_j \times \left(1 + a_2 \cos^2\theta + a_4 \cos^4\theta\right) - N_{ij}}{\sqrt{N_{ij}}}\right)^2$$

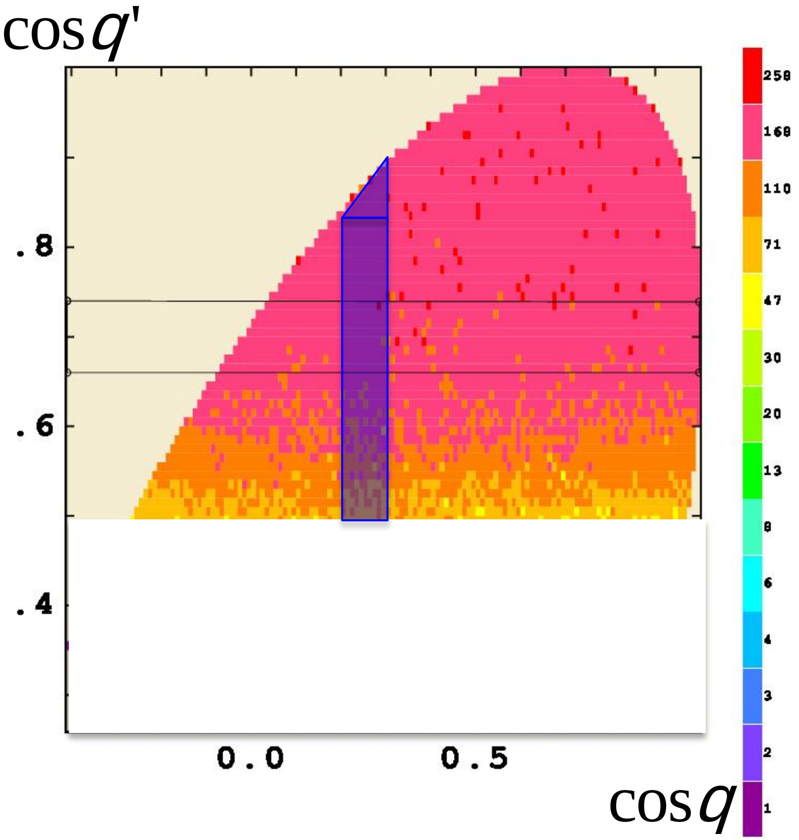
Over $\mathbf{M}, a_2, a_4, \varepsilon_1, \varepsilon_2, \ldots, \varepsilon_n$







Construction of angular distribution

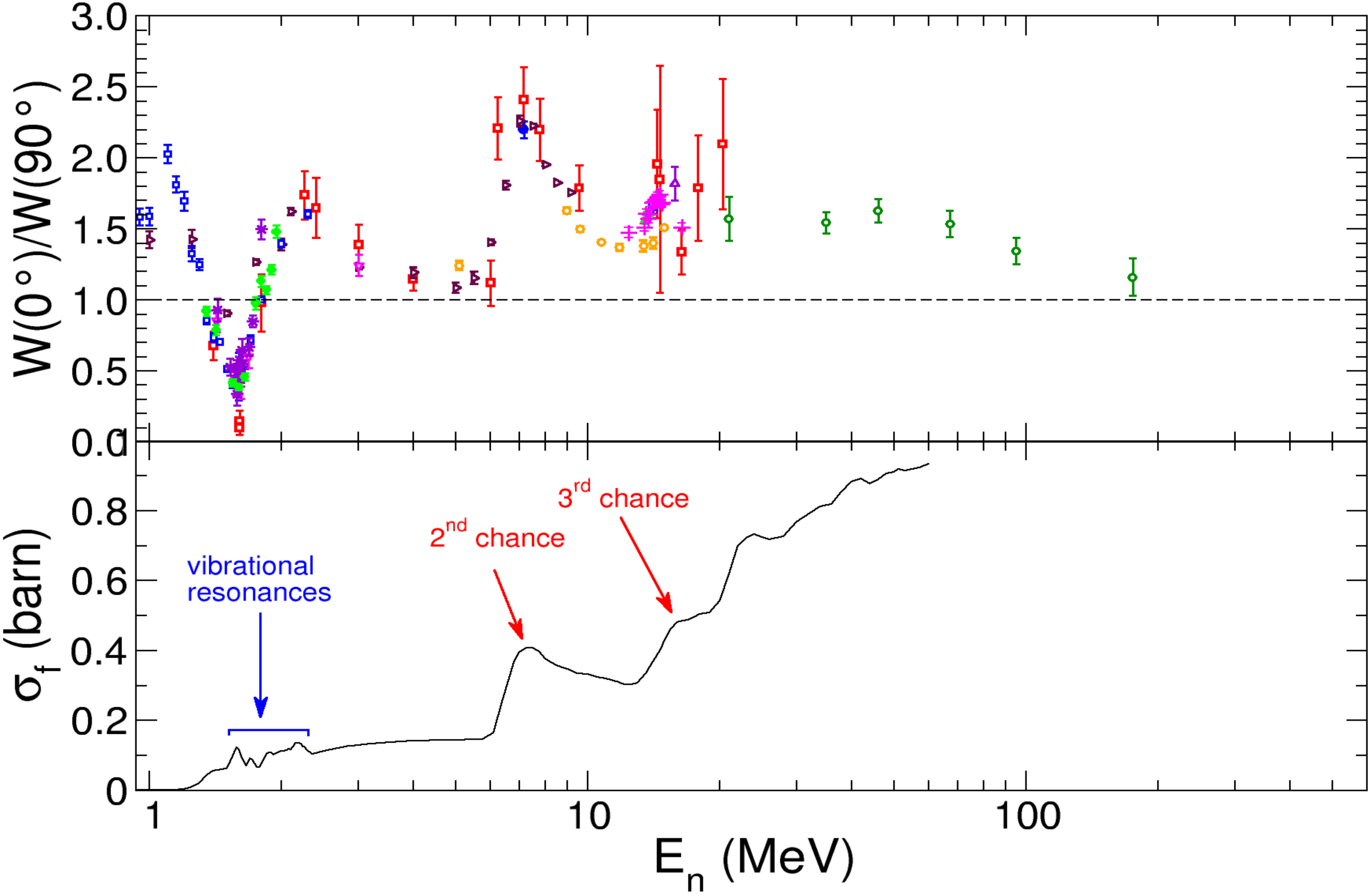


$$dN = W(\cos\theta)\times\varepsilon(\cos\theta')\times d\Omega$$

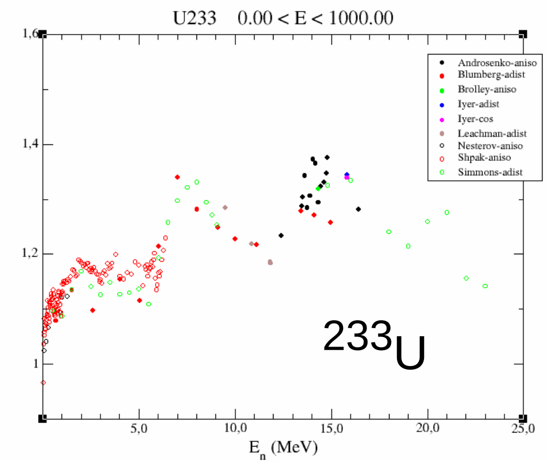
$$W(\cos\theta) = \frac{N(\cos\theta)}{S}$$

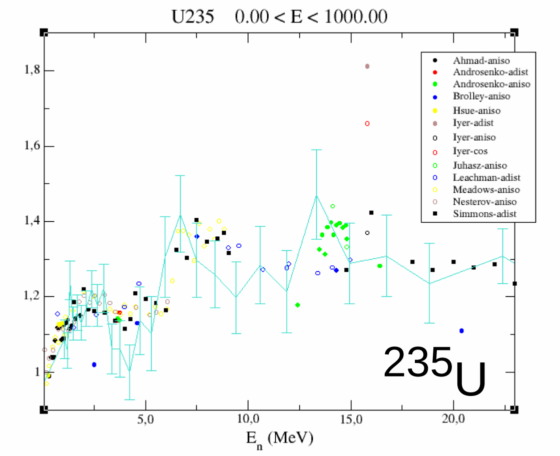
$$N(\cos\theta) = \sum_{i,\cos\theta'>0.5} N_i$$

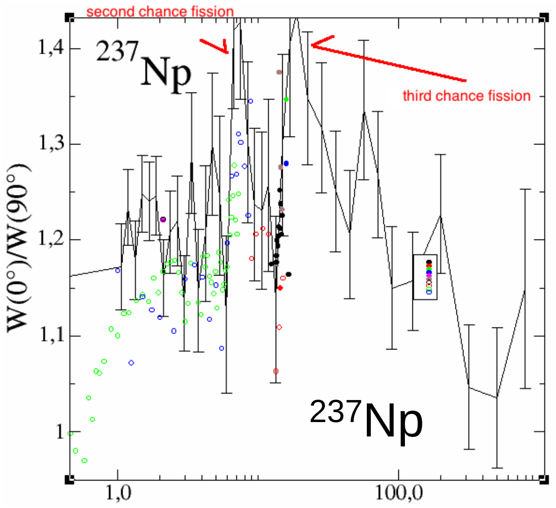
$$S = \sum_{i,\cos\theta'>0.5} \Delta\Omega_i \times \varepsilon_i$$

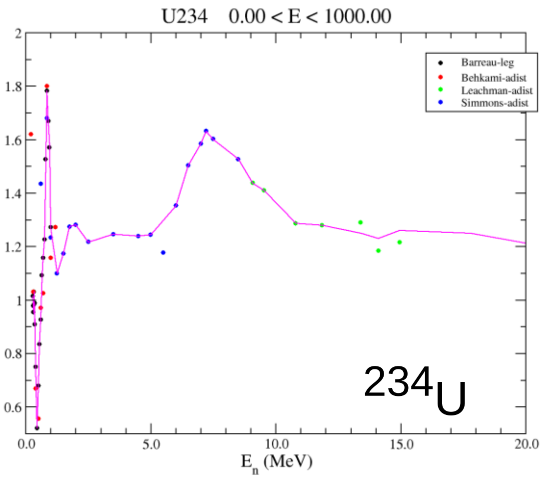

W(0°)/W(90°)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
0.8
0.6
0.4
0.2
0
σ_f (barn)
vibrational resonances
2nd chance
3rd chance
1
10
100
E_n (MeV)

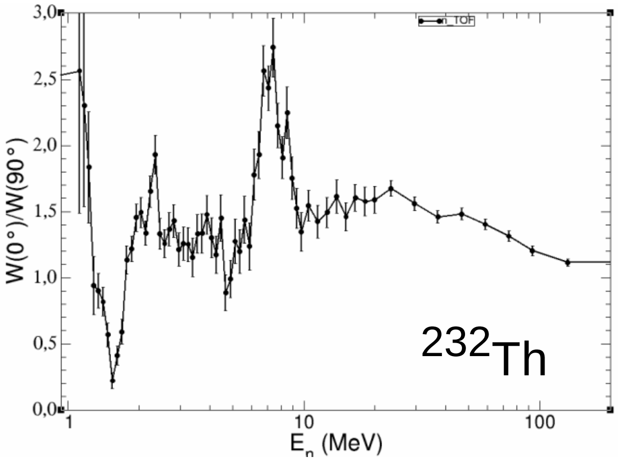
Interesting remarks

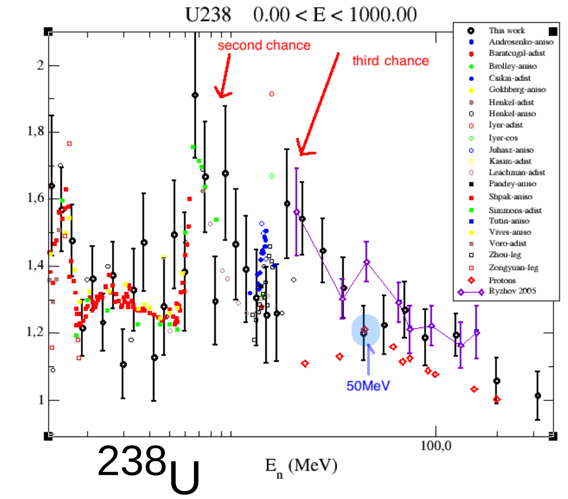






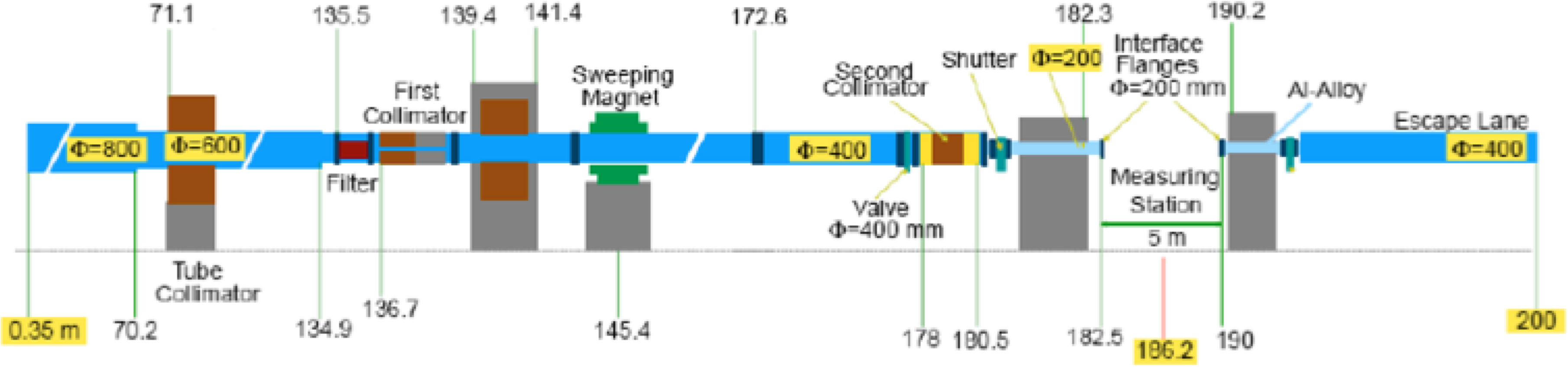


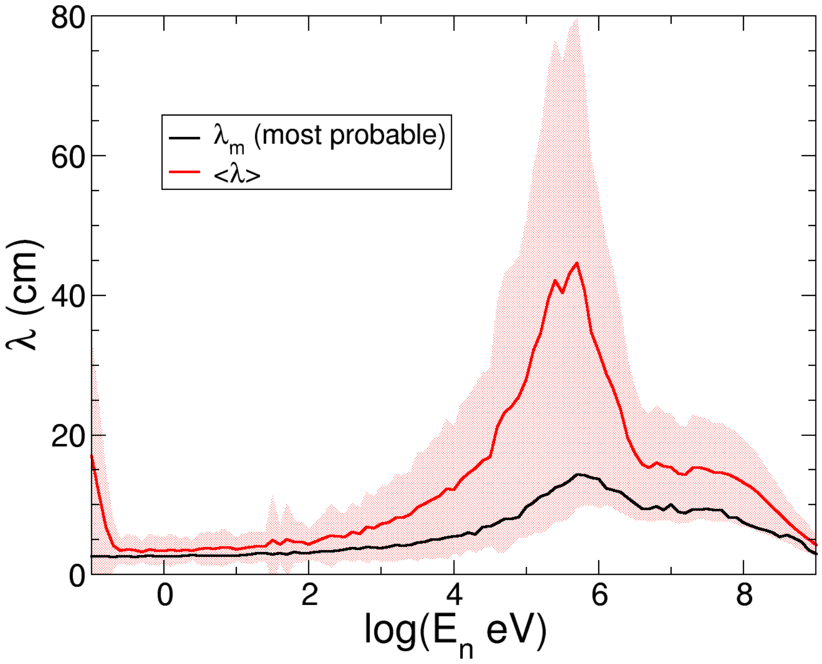


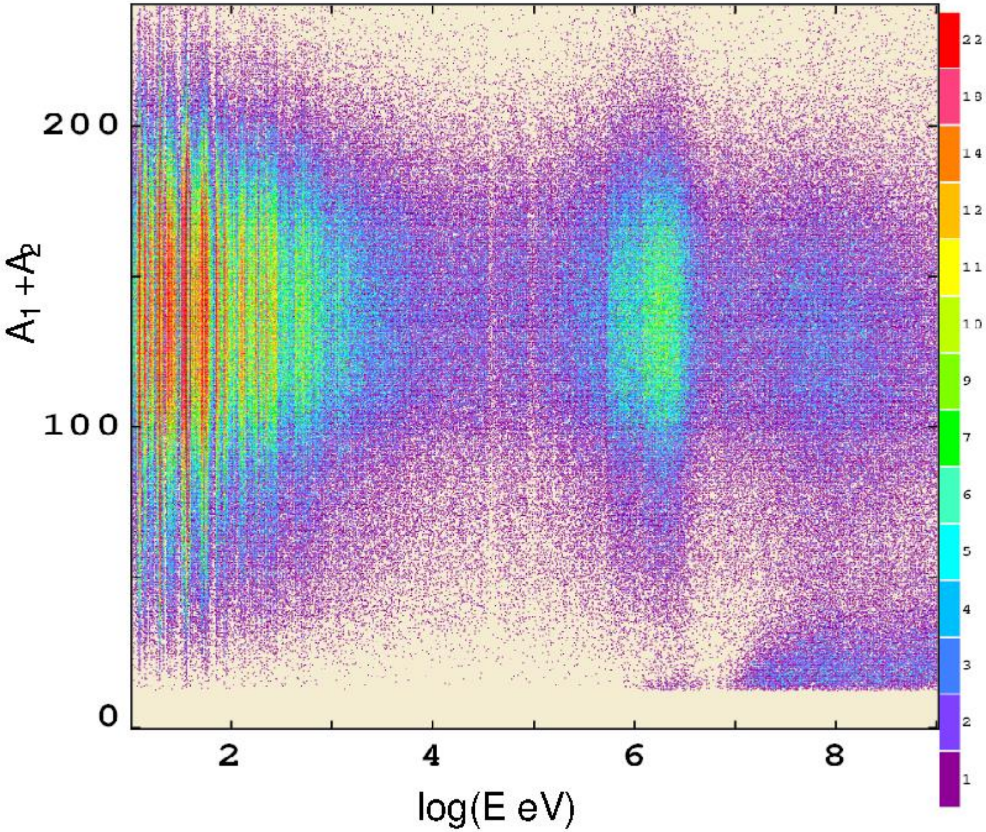


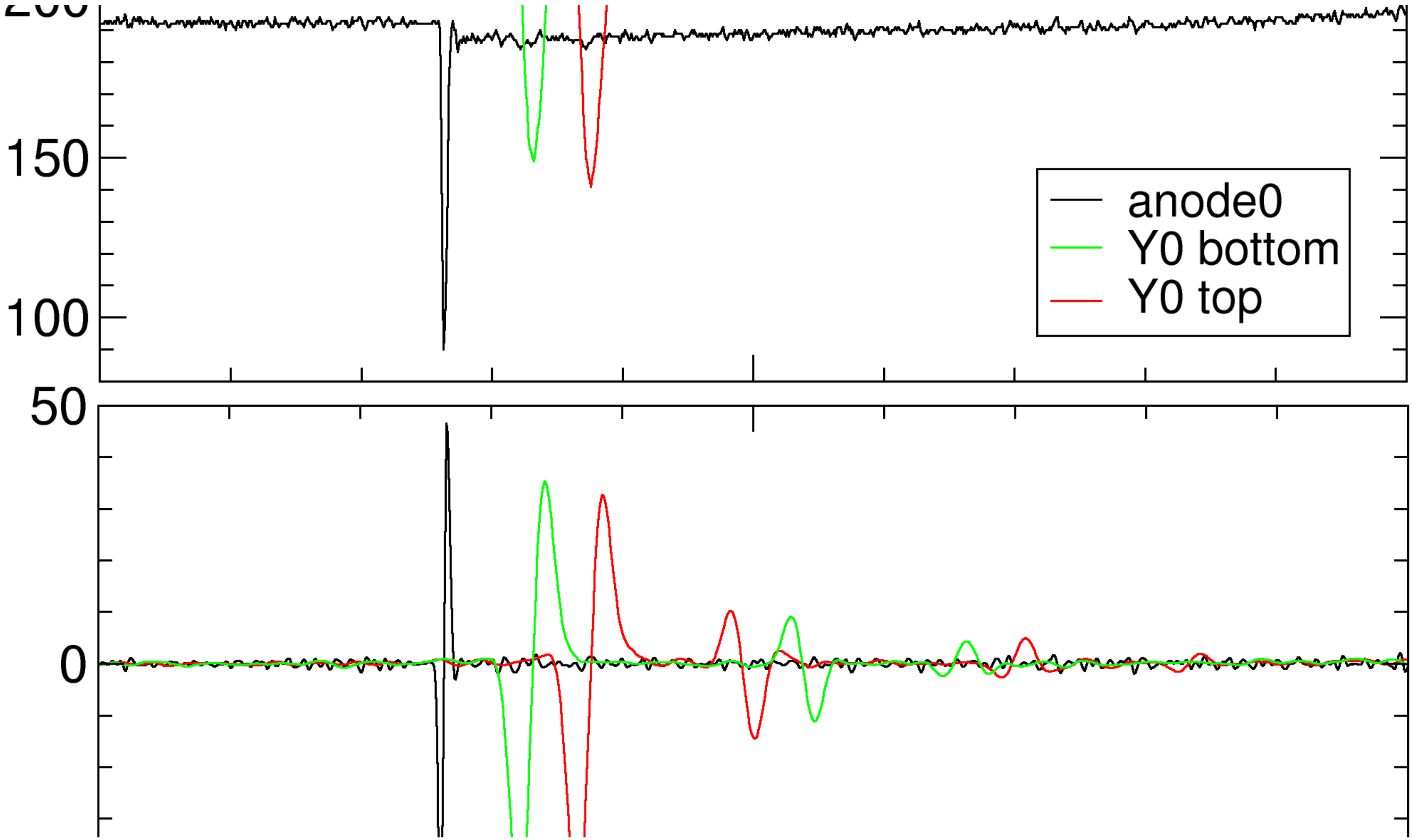
For the even-even target, the anisotropy in the second opening chance fission is always higher than the third opening chances.

For the odd-mass target, both anisotropy in second and third opening chance fission are very similar


71.1
135.5
139.4
141.4
172.6
182.3
190.2
Interface Flanges Φ=200 mm
Shutter
Φ=200
Second Collimator
First Collimator
Sweeping Magnet
Al-Alloy
Escape Lane
Φ=800
Φ=600
Φ=400
Φ=400
Filter
Valve Φ=400 mm
Measuring Station
5 m
Tube Collimator
0.35 m
70.2
134.9
136.7
145.4
178
180.5
182.5
186.2
190
200


80
60
40
20
0
λ (cm)
0
2
4
6
8
log(E$_n$ eV)
λ$_m$ (most probable)
<λ>


200
100
0
$A_1 + A_2$
2
4
6
8
log(E eV)
22
18
14
12
11
10
9
7
6
5
4
3
2
1


200
150
100
50
0
anode0
Y0 bottom
Y0 top

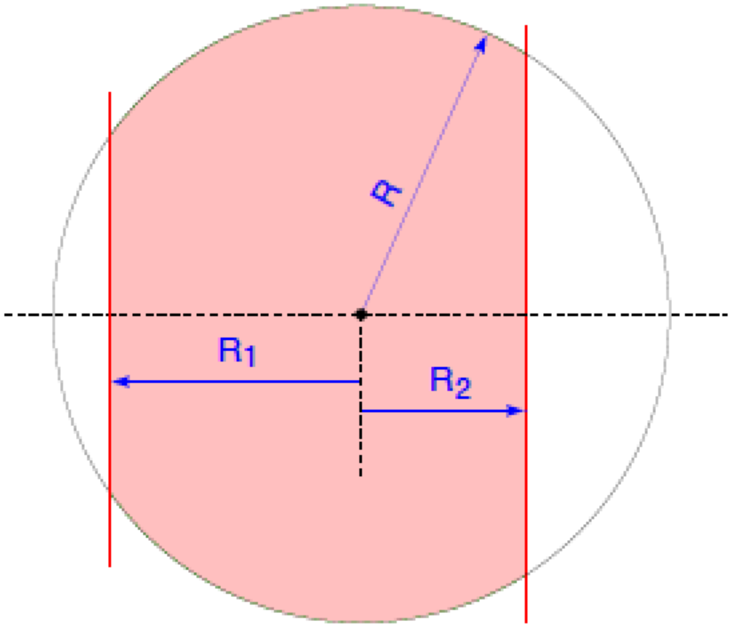


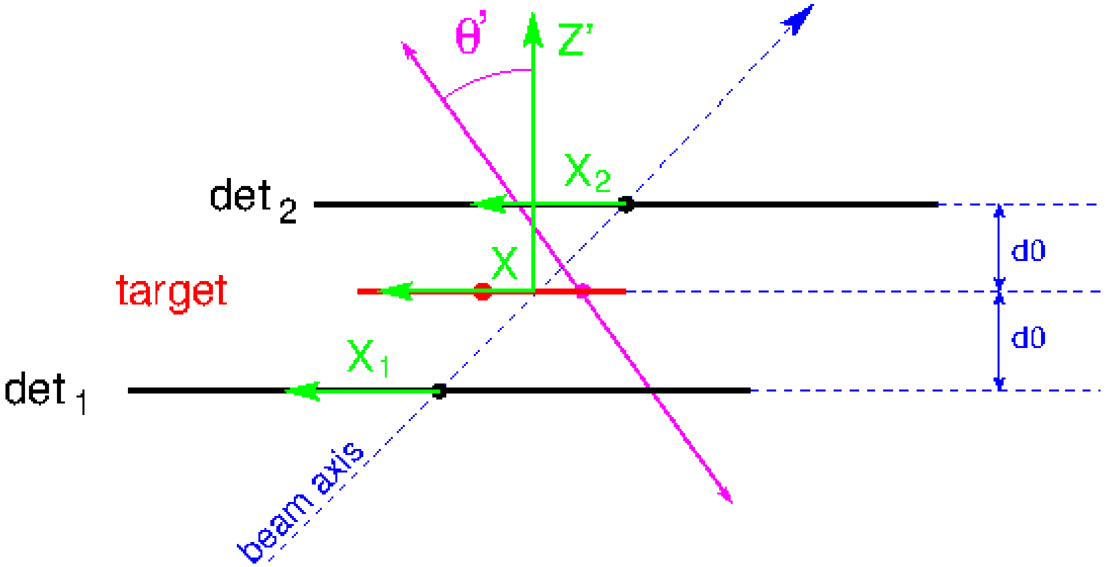
Figure 2

Correction of target Limit.

F(x1,x2)

x1=R1/R

x2= R2/R



Separation energy, so-called binding energy (Nucleus-neutron strong interaction)

Excitation energy

Outgoing neutron kinetic energy by (n,n'): evaporation, pre-equilibrium, reaction direct.

Incident neutron energy

$$E^* = S_n + E_{n^{in-kinetic}} > B_f$$

First chance fission

$$E^* = S_n + E_{n^{in-kinetic}} > B_f + S_n + E_{n^{out-kinetic}}$$

Second chance fission

Ex:U235 $E^* = \underset{U236*}{S_n} + E_{n^{in-kinetic}} > B_f + \underset{U236*}{S_n} + E_{n^{out-kinetic}} + \underset{U235*}{S^l_n} + E^l_{n^{out-kinetic}}$

Third chance fission

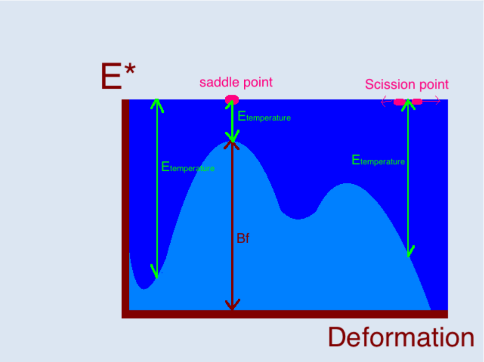
Fission barrier (Nucleus Deformation energy)

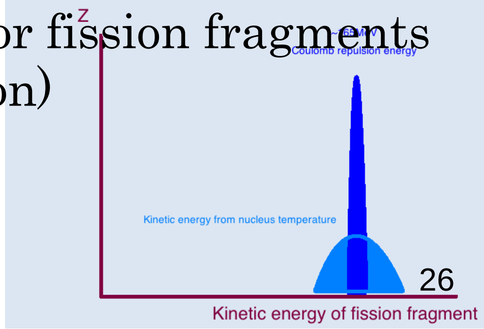
Nucleus heating

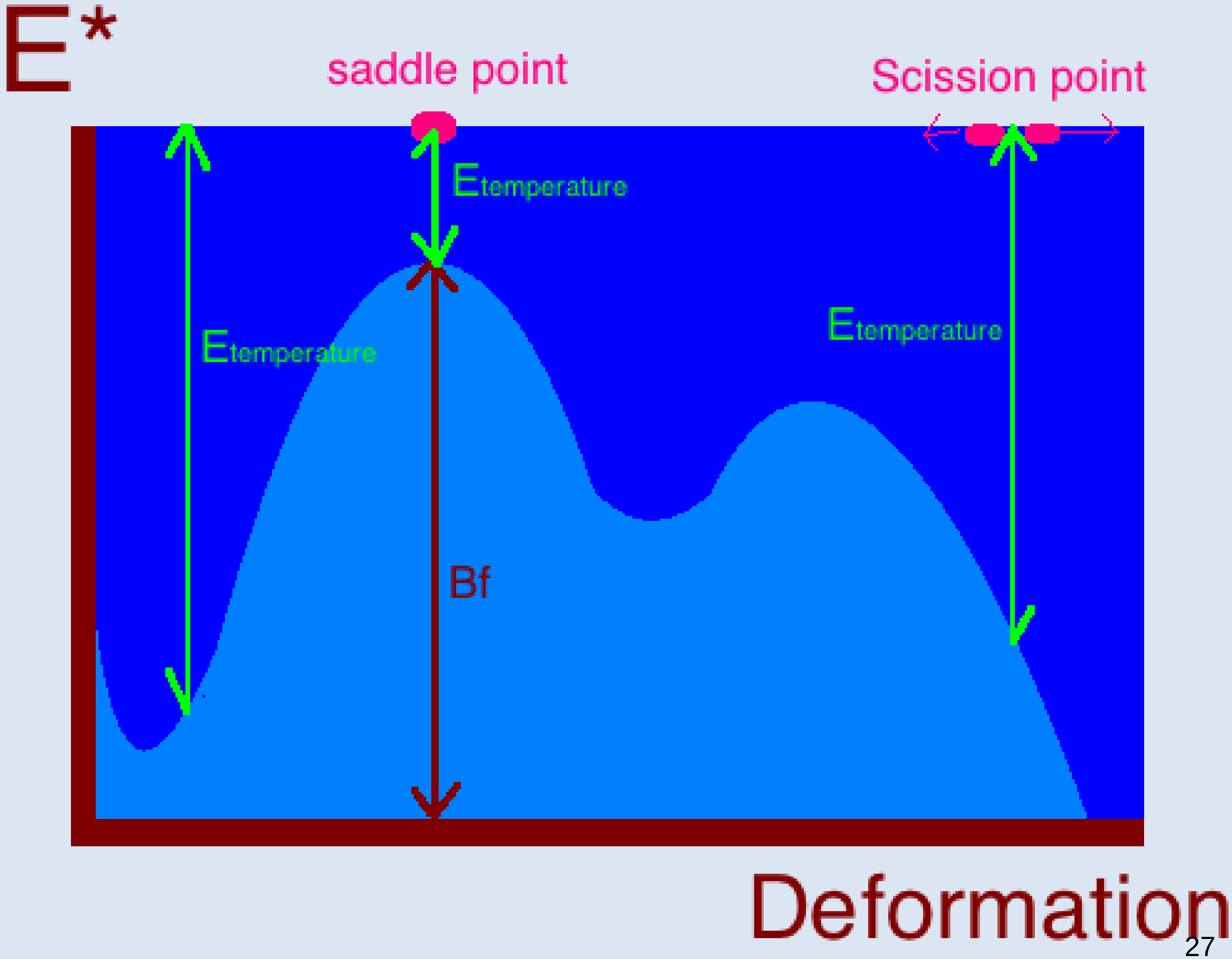
$$E^* - B_f = a_f T^2$$

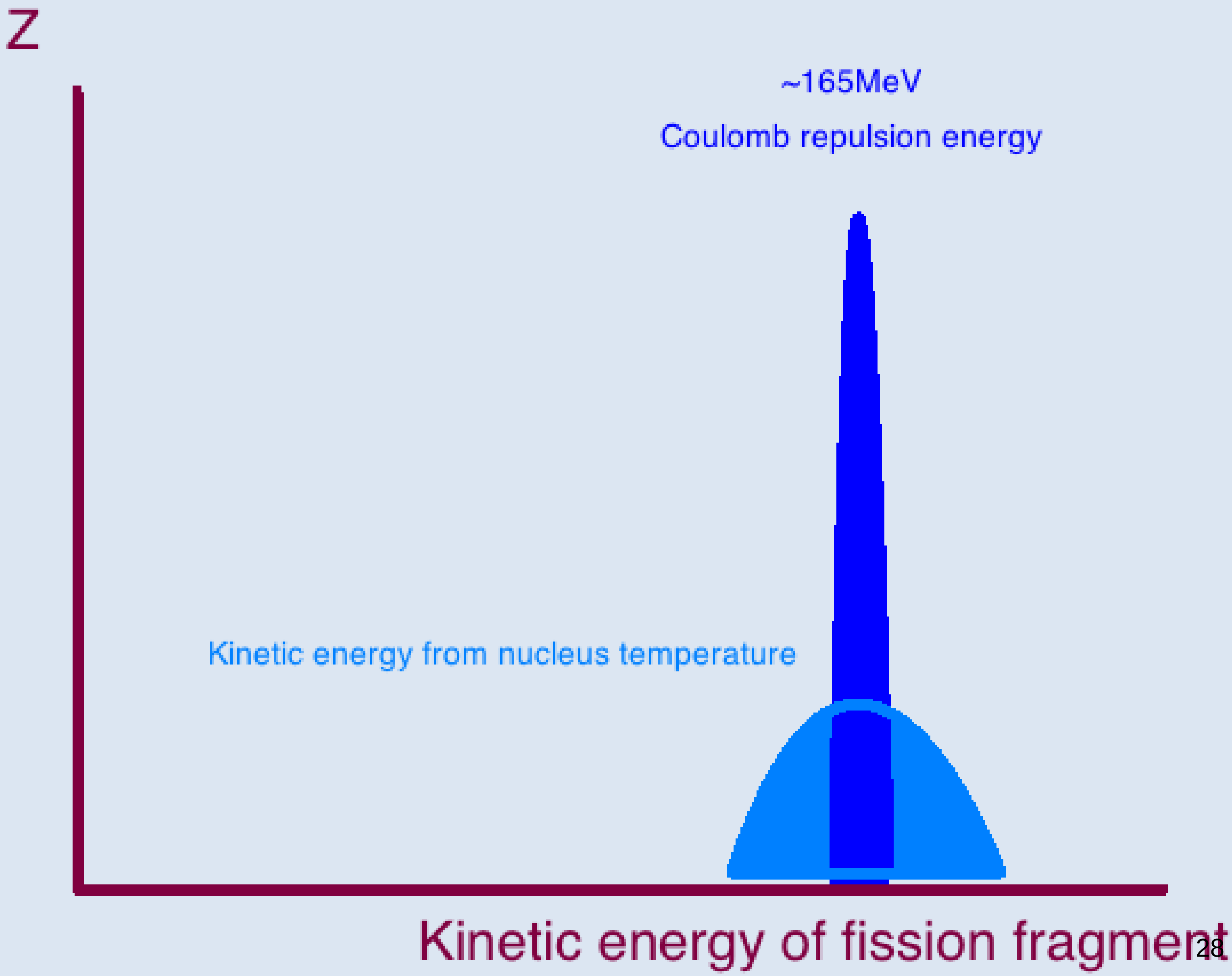
Stochastic heating->Agitation to nucleus ->thermal energy (Eth) -> -> nucleus vibrate ->Transfer temperature to kinetic energy for fission fragments (Energy Fluctuation)

Level density parameter (no constant)






E*
saddle point
Scission point
$E_{temperature}$
$E_{temperature}$
$E_{temperature}$
Bf
Deformation



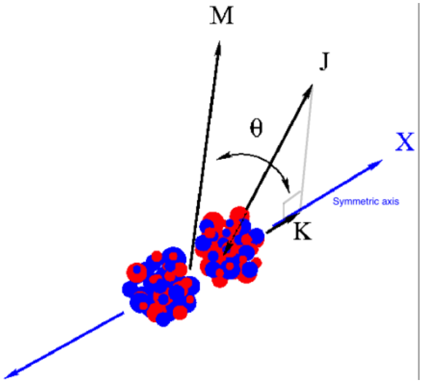
~165MeV

Coulomb repulsion energy

Kinetic energy from nucleus temperature

In a given neutron incident energy: entire fission process

J: Total angular momentum (conserved)
M: Projection J to space-fixed axis, always beam axis (Z) (conserved)
K: Projection J to symmetric axis, FF direction, (no conserved)->Give information of fission process
l: orbital momentum, direction always confused with plan perpendicular to beam(plan XY) (conserved)
S: Target spin, direction isotropic.
s: Neutron spin, direction isotropic.



$$\vec{J} = \vec{S} + \vec{s} + \vec{l}$$

$$|\vec{J}| \leq K \leq \vec{J}$$

$$J_{eff} = J_{\perp} J_{\parallel} / (J_{\perp} - J_{\parallel})$$

$$K_0^2 = 4\pi J_{eff} T / h^2$$

$$W^J_{M,K}(\theta) \propto \exp(-K^2 / 2K_0^2)$$

Ekinetic little (l little), target even-even (or odd-odd), S=0 or target even-odd but less S (ex: 3/2) and J=l+s -> l little -> J little -> K little -> isotropic

Ekinetic high, target even-even, S=0 and J=l+s -> l high direction on plan(XY) -> J high -> Distribution K (0->J) in Jeff -> anisotropic

While K little, J high, M high, anisotropie forward-backward

While K grand, J high, J direction tend to the symmetric axis -> anisotropie sideward

Ekinetic very high, target even-even, S=0 and J=l+s -> l high direction on plan(XY) -> J high satured -> Distribution K (0->J) in Jeff -> isotropic ?? Compare to Proton

Ekinetic little (l little), target even-odd, S high and J=s+S -> J but no privilege cause target spin is isotropic except polarized -> J all direction-> K all direction -> isotropic

Ekinetic high (l high), target even-odd, S high and J=s+S+J -> same effect than second one-> anisotropic

Summary

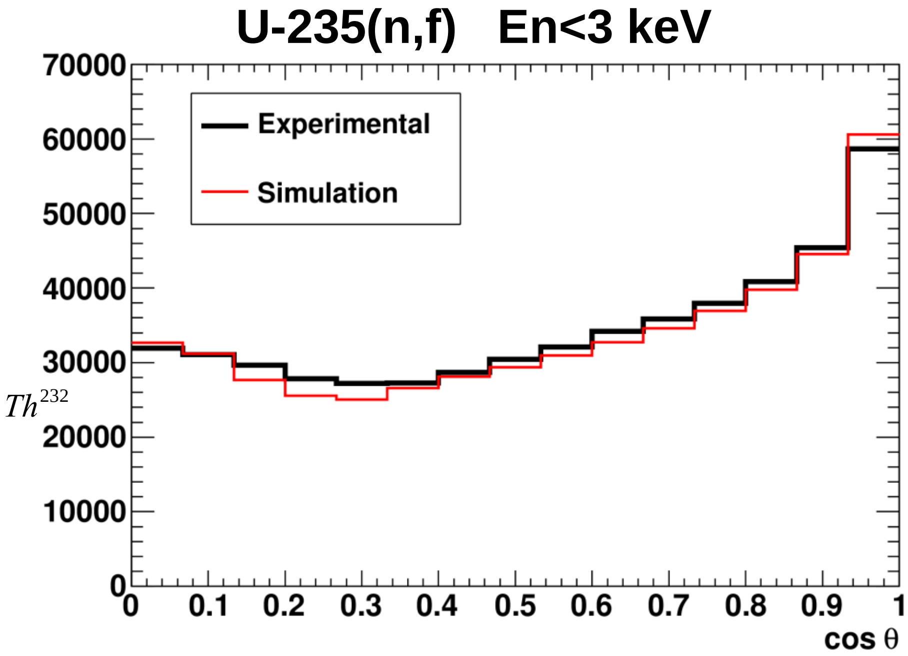
- Introduction
  - Nuclear data
  - Fission fragment angular distribution (FFAD)
- Instrumentation
  - nTOF
  - PPAC
- Analysis
- Detector efficiency
  - Simulation method
  - New method (self-determination of efficiency)
- Results and discussions
  - Comparison to FFAD calculation
  - Comparison to proton induced (^{232}Th)
- ^{237}Np cross section validation

Analysis-First Method Simulation (Diego Tarrio)

- Detected FFAD in ^{235}U = efficiency because emitted FFAD isotropic.
- Build the geometry of two PPAC interleaving a target ^{235}U.
- Compare the FFAD simulation with experiment distribution.
- Correct the efficiency basing on this simulation for the other actinides.

Simulation-Geant4

- Geometry: Detectors, targets at 5mbar.
- Isotropic Fission Fragment into the detectors
- Process: Fellow the Fission Fragment tracking slow down in all the layers
- Record energy deposition in each layer for all angles.

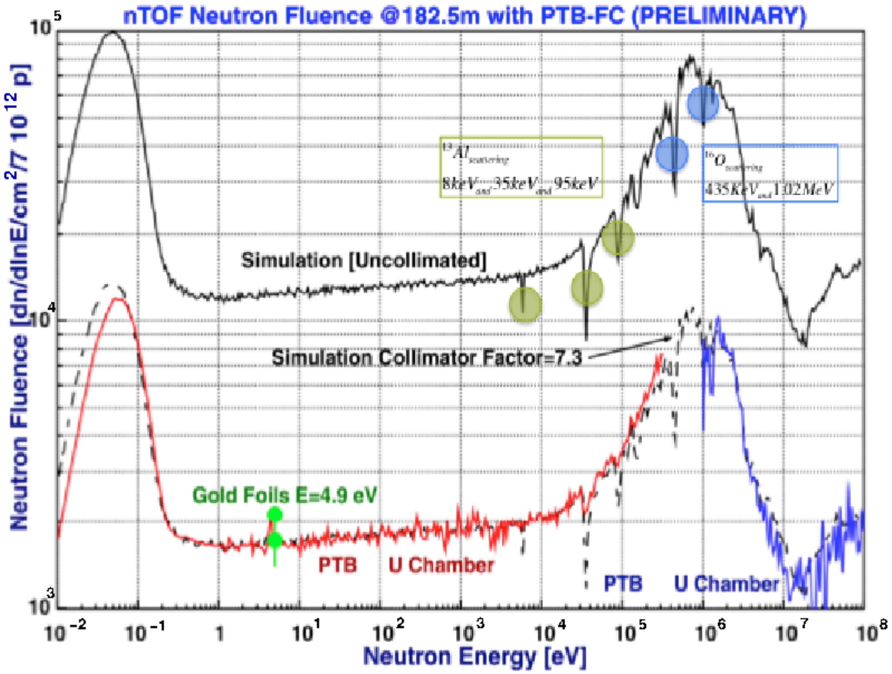


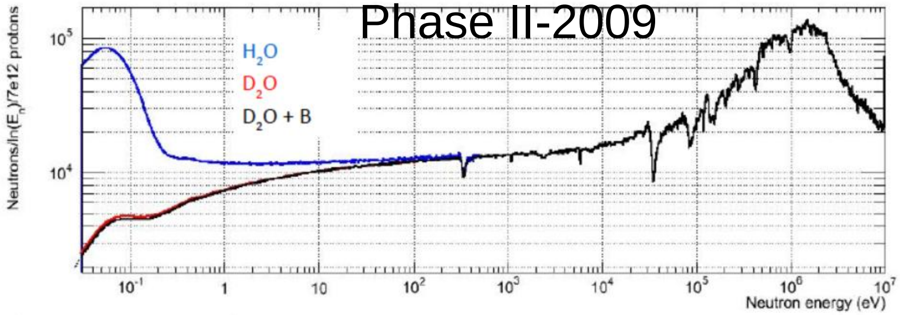
The method of simulation seems to save to estimate the efficiency:

$$\varepsilon_{target}(\cos\theta) = \varepsilon_{235U}(\cos\theta) \times \frac{\varepsilon_{target/simul}(\cos\theta)}{\varepsilon_{U235/simul}(\cos\theta)}$$

Problems of this method:

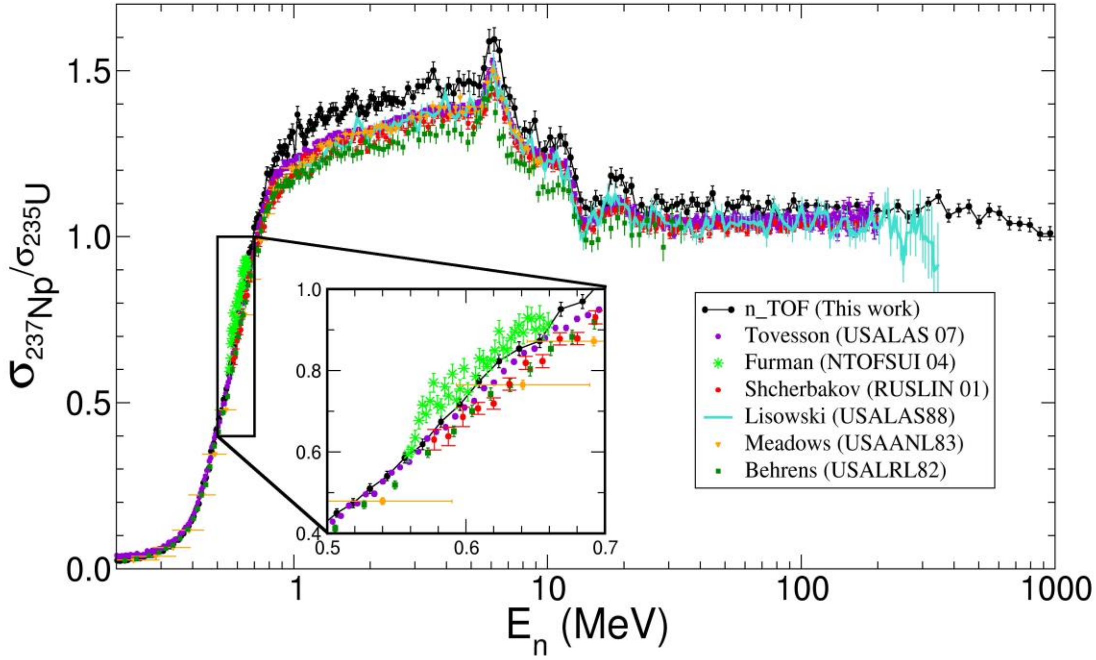
- Dependence of simulation
- Target backing thickness uncertainties.





Phase II-2009

nTOF Np fission cross section compared to previous measurements

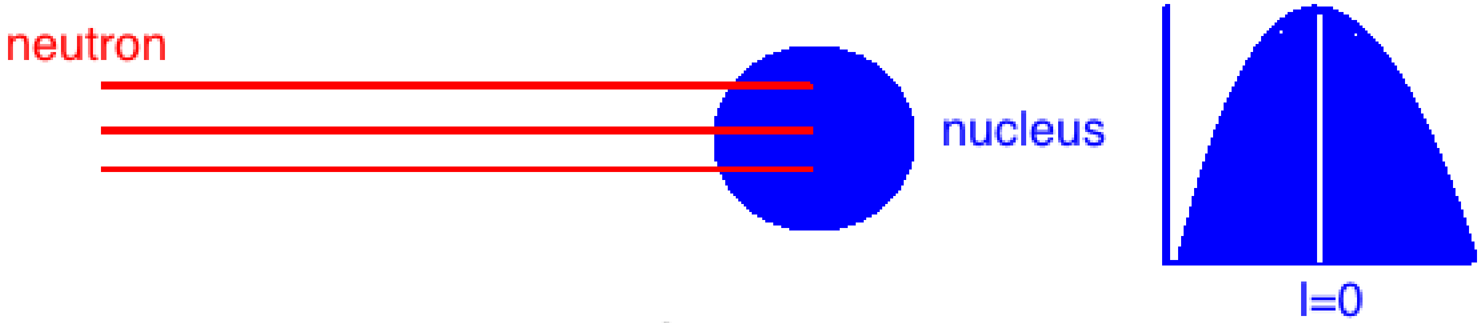


- ENDF-B7.0 based on Tovesson measurement(2008).
- Tovesson's one normalised to ENDF-B6.8 at 14 MeV.
- ENDF-B6.8 based on Lisowski's measurement(1988).
- Lisowski normalized to Meadows (1983) between 1 and 10 MeV
- n TOF measurement consistent with data at 14 MeV within the experimental uncertainty of 4%

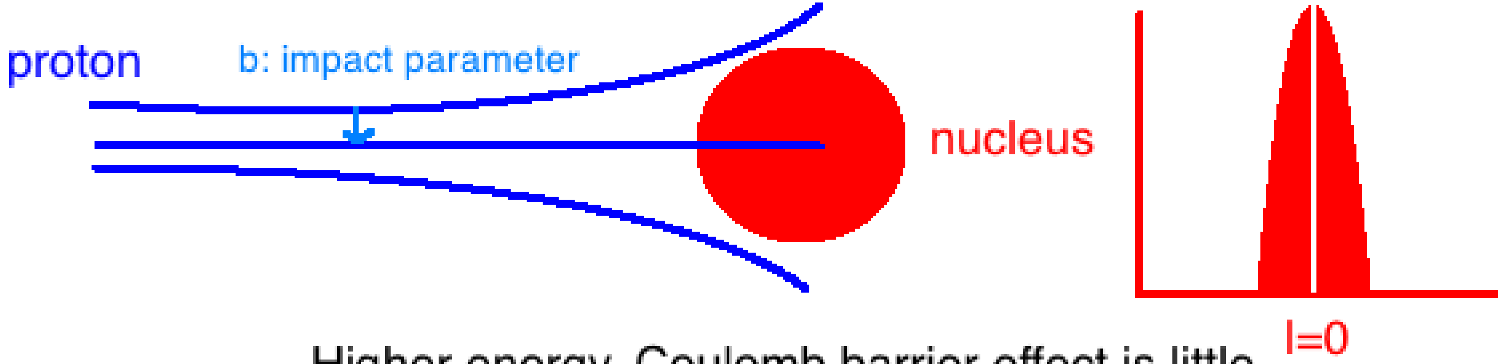
Verification of 237Np cross section is necessary

Nucleus depends on fissibility parameter

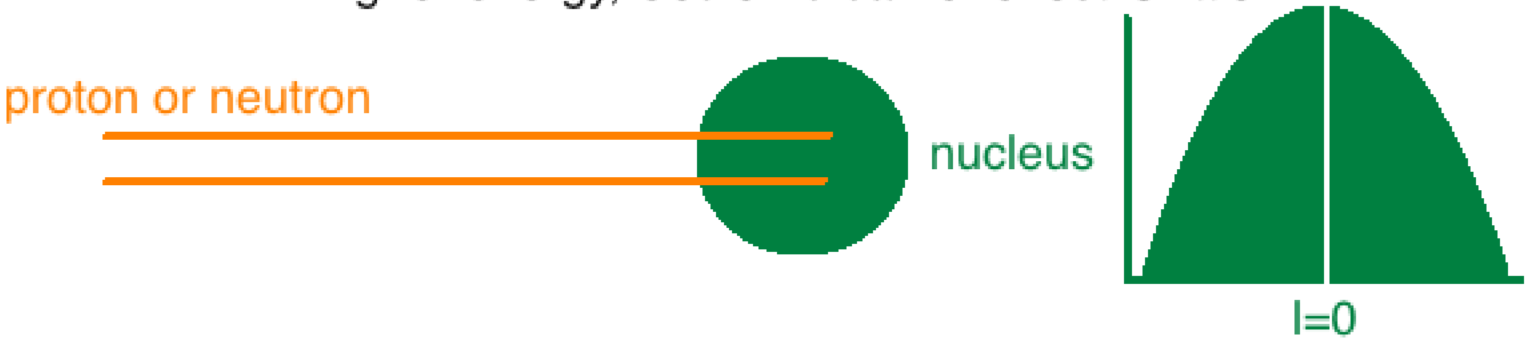
direct reaction

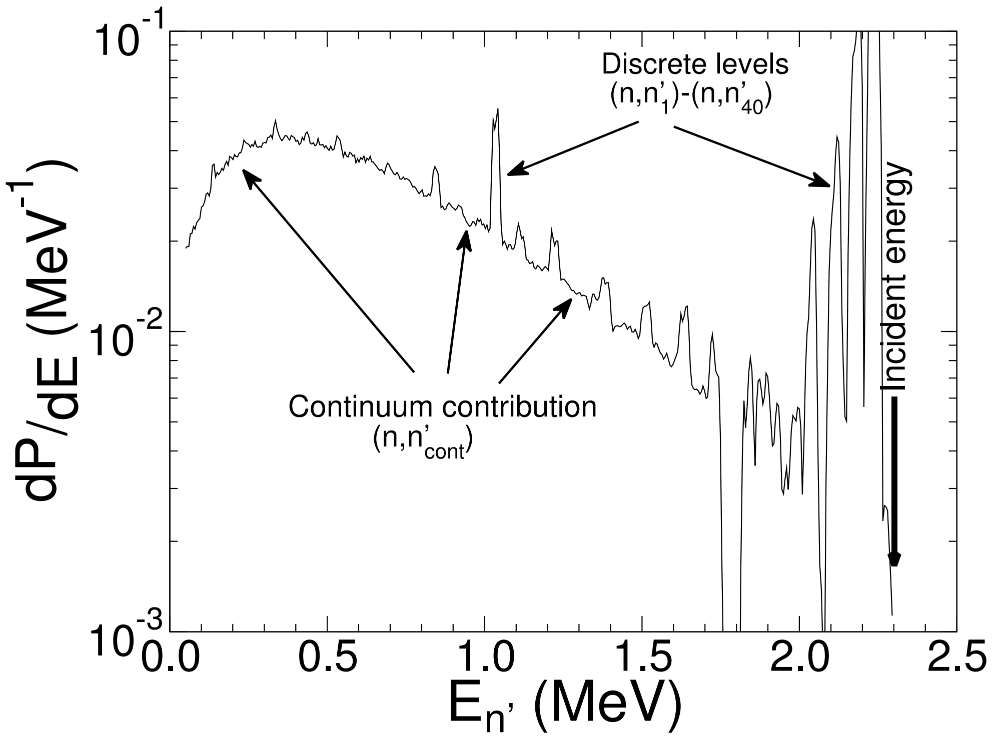


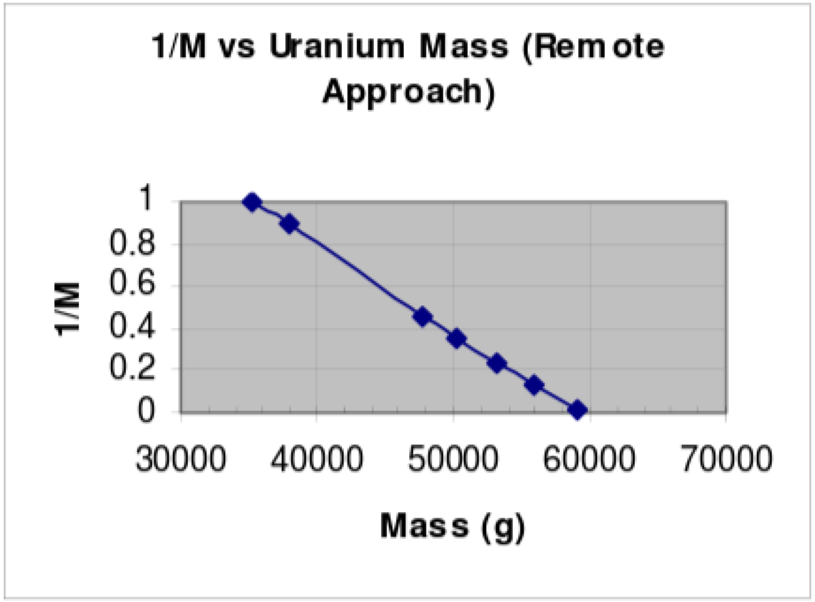
Coulomb repulsion



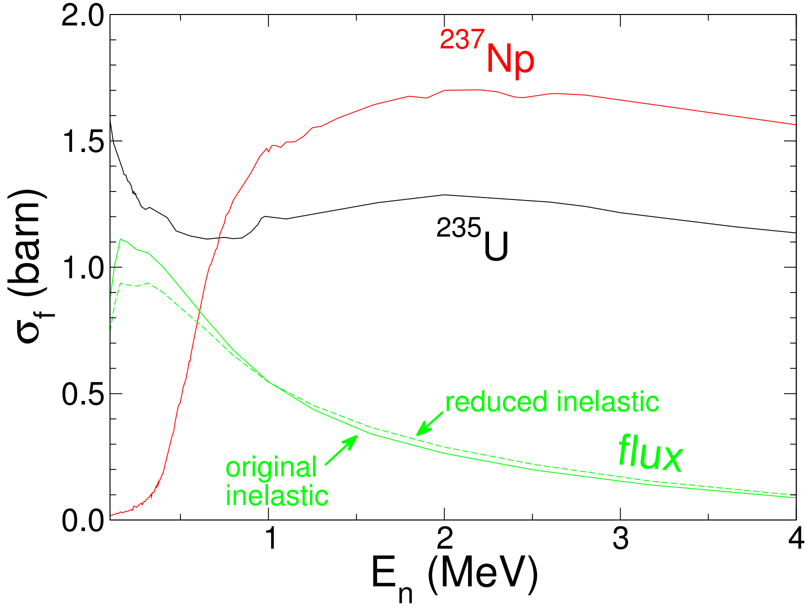
Higher energy, Coulomb barrier effect is little



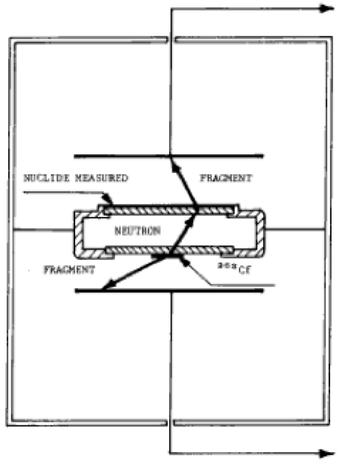


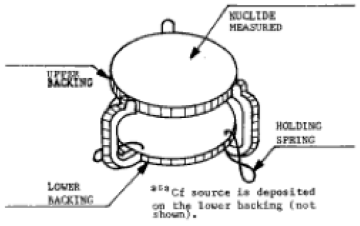


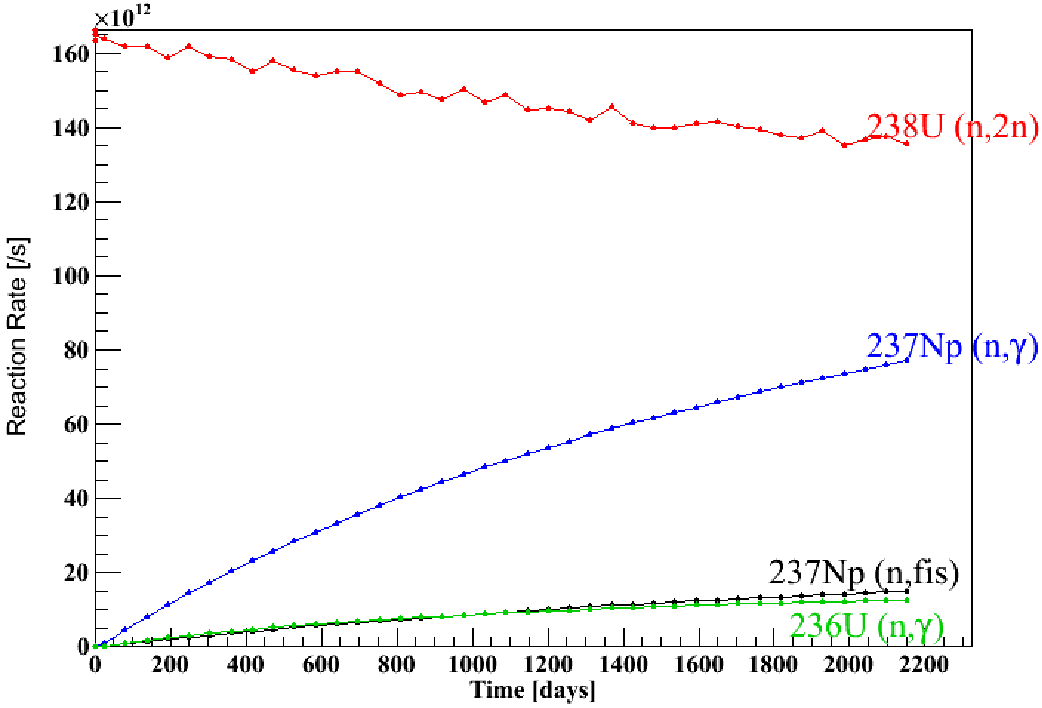
1/M vs Uranium Mass (Remote Approach)



Adamov experiment with ^{252}Cf source






×10^12
Reaction Rate [/s]
0
20
40
60
80
100
120
140
160
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
Time [days]
238U (n,2n)
237Np (n,γ)
237Np (n,fis)
236U (n,γ)