Angular Distributions and Anisotropy of Fission Fragments from Neutron-Induced Fission of ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, ^{nat}Pb and ^{209}Bi in Intermediate Energy Range 1- 200 MeV

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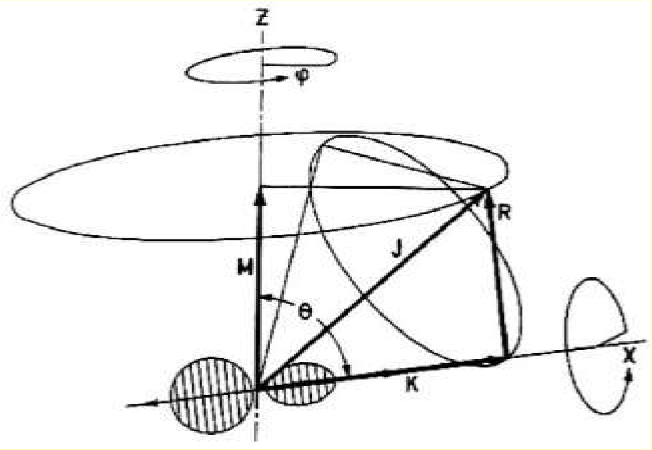
Angular distributions of fission fragments

Transition states at the saddle point of highly deformed fissioning nuclei:

[redacted] (wave function of axial top)



For low excitation energies we need a proper sum over non-uniform M distribution, and few [redacted]annels) and finally:

At high excitations with many opened fission channels one can use statistical model for the K projection distribution – $\rho(K)$:

[redacted]

$\rho(K) \sim \exp\left(-\frac{K^2}{2K_0^2}\right)$, where [redacted] and [redacted]

In statistical model:

[redacted]

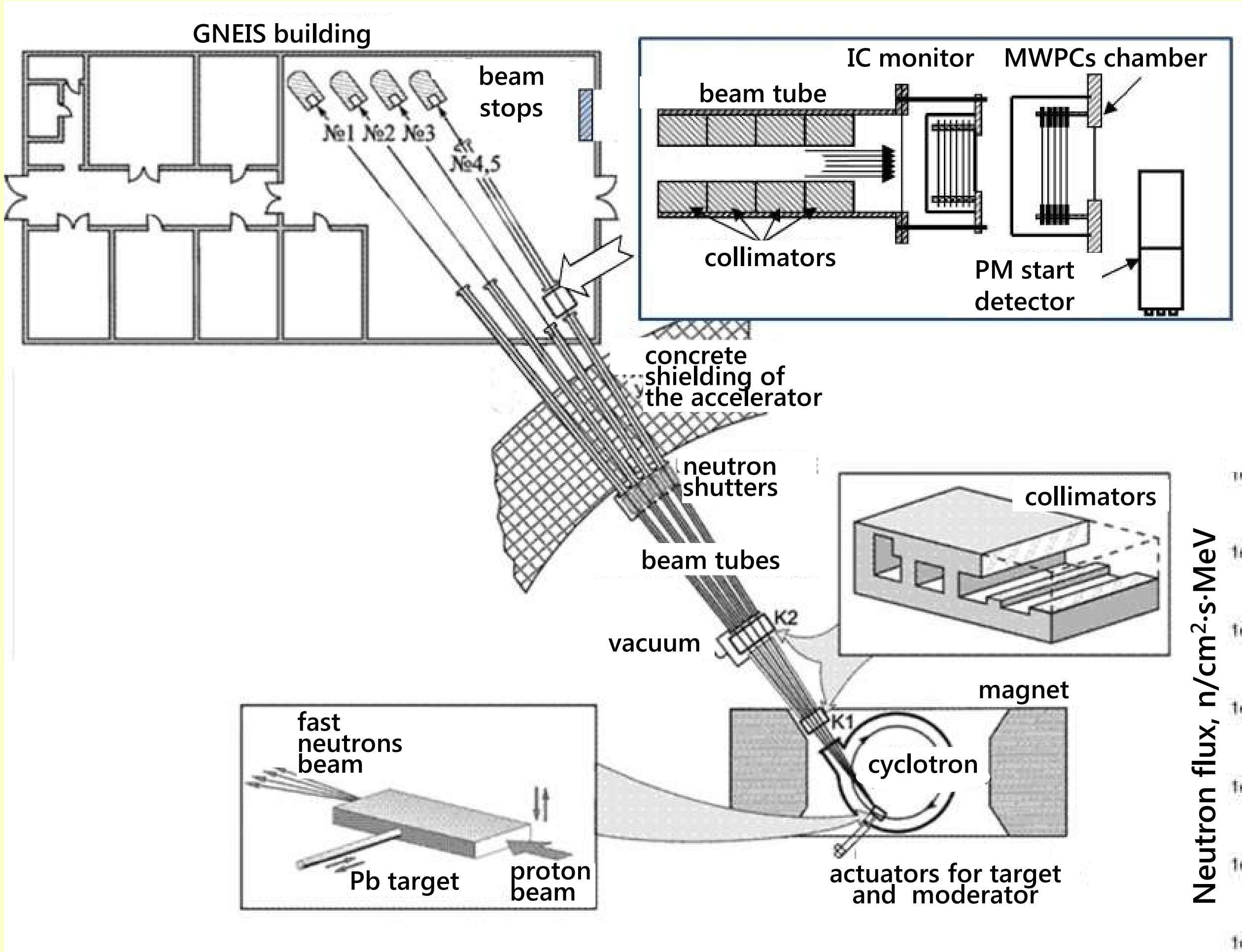
Motivation

- Information on fission barriers and transition state spectra on barriers. (states of highly deformed fissioning nucleus at the fission saddle point)
- Verification and developing of models for adequate description of processes in nuclei at high excitations (relative contribution of equilibrium and non-equilibrium processes into the dynamics of highly excited nuclei)
- The angular distributions data are important for precise measurements of the fission cross-sections, because it should be taken into account as efficiency correction for non 4π detectors.
- Such an information for highly excited nuclei is important for development of new technologies, such as Accelerator-Driven Systems for nuclear power, nuclear waste transmutation, radiation testing of materials, nuclear medicine and etc.
- Existing data about fission fragment anisotropy have sometimes big discrepancies even for incoming neutron energies below 20 MeV, they are very scarce above 20 MeV and are practically absent for neutron energy range above 100 MeV.
- Therefore, there is a need to have data for a number of actinides as well as for Pb and Bi nuclei because Pb-Bi eutectic is one of the primary coolant candidates for advanced nuclear reactors and Accelerator-Driven System.

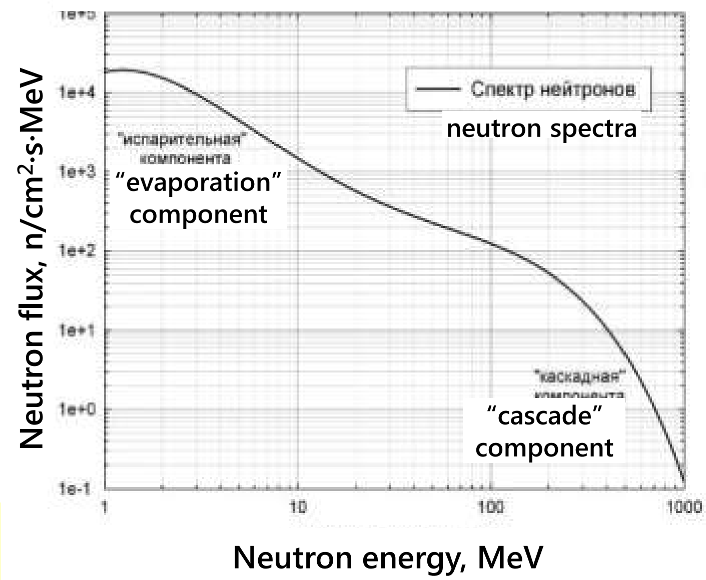
Current status

	GNEIS, PNPI	n-TOF, CERN	WNR, LANSCE
^{232}Th	2014-2015 JETP Letters, 102, 203 (2015)	2013, 2014 Nucl. Data Sheets, 119, 35 (2014). EXFOR)	
^{233}U	2016 JETP Letters, 104, 365 (2016)		
^{235}U	2014-2015 JETP Letters, 102, 203 (2015)	2013, 2015 EPJ Web of Conf. 111, 10002 (2016); E. Leal-Cidoncha, FIESTA2017. Santa Fe, September 2017	2015 V. Kleinrath PHD Thesis 2016; V. Geppert-Kleinrath arXiv:1710.00973v1 [nucl-ex] Oct 2017, subm to PRC
^{238}U	2014-2015 JETP Letters, 102, 203 (2015)	2013, 2015 EPJ Web of Conf. 111, 10002 (2016)	
^{209}Bi	2016 JETP Letters, 104, 365 (2016)		
nat-Pb	2017 Pisma v JETF, 107, 547 (10.05.2018) (in Russian) The English version in JETP Letters will appear ~1.5 months later		
^{239}Pu	2017 Pisma v JETF, 107, 547 (10.05.2018) (in Russian) The English version in JETP Letters will appear ~1.5 months later		

Neutron TOF-spectrometer GNEIS



Neutron spectrum of GNEIS: from thermal to 1GeV

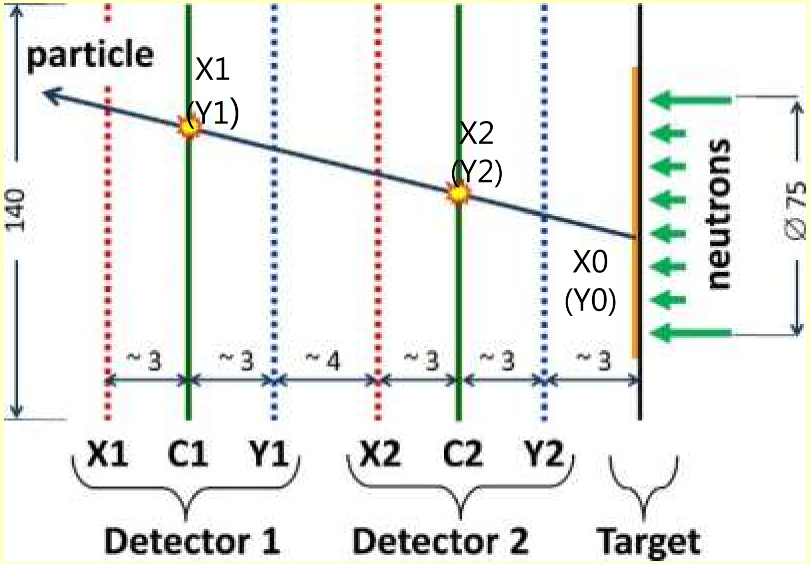


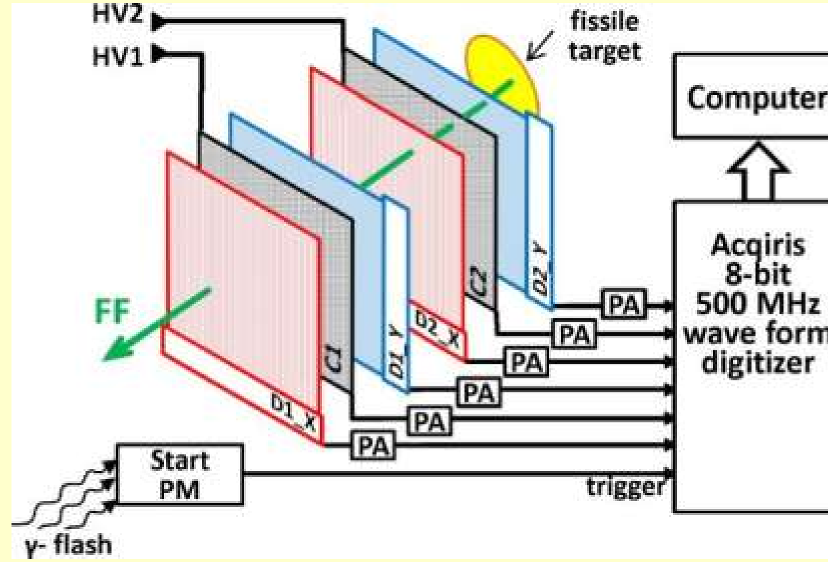
Main parameters:

[redacted]

[redacted]

Experimental setup





$$\cos(\theta) = \frac{d}{\sqrt{(x1 - x2)^2 + (y1 - y2)^2 + d^2}}$$

$$L / (T_{cathode} - T_{trigger}) \rightarrow E_n$$

Position sensitive low pressure multi-wire proportional counters (MWPCs):

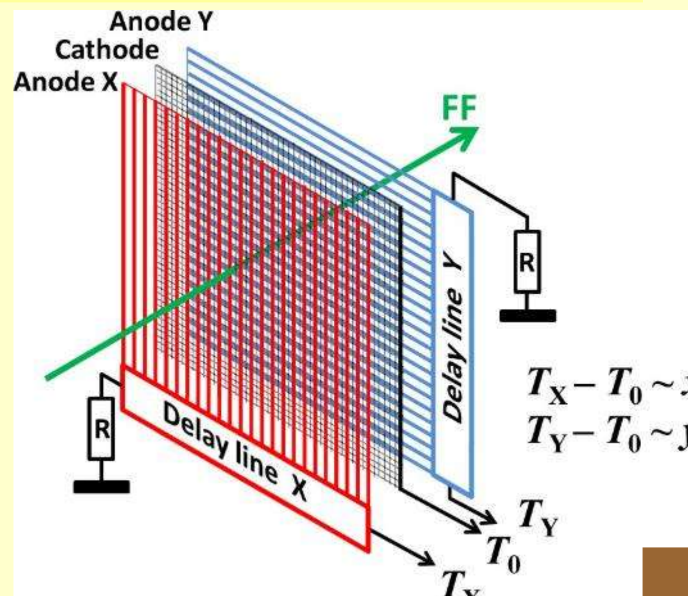
Sizes 140×140 mm;

Gaps between electrodes planes ~3 mm ;

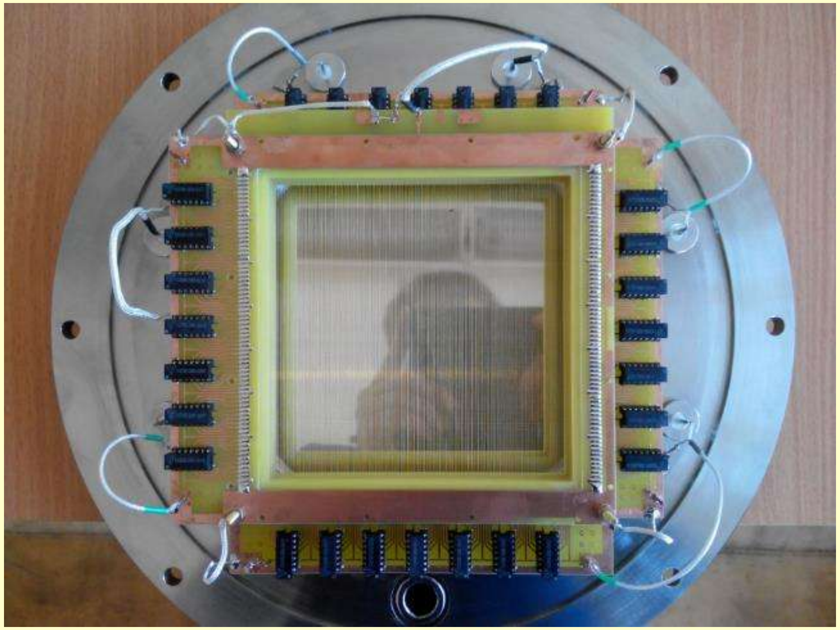
Grids – ∅ 25 μm ***Au*** plated ***W*** wire, 1 mm spacing

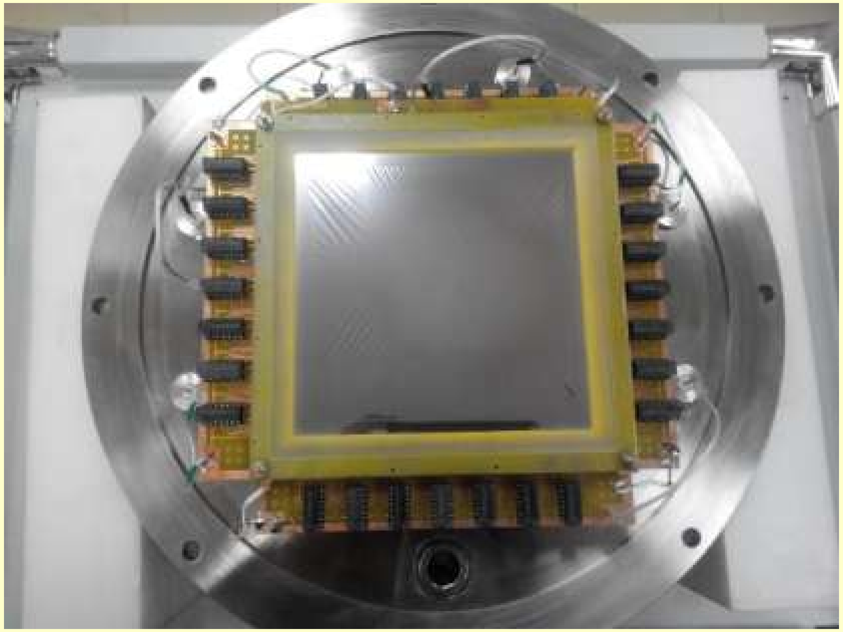
Actinide targets – ~ 150-300 μg/cm^2 "painted" on 0.1 mm ***Al*** foil

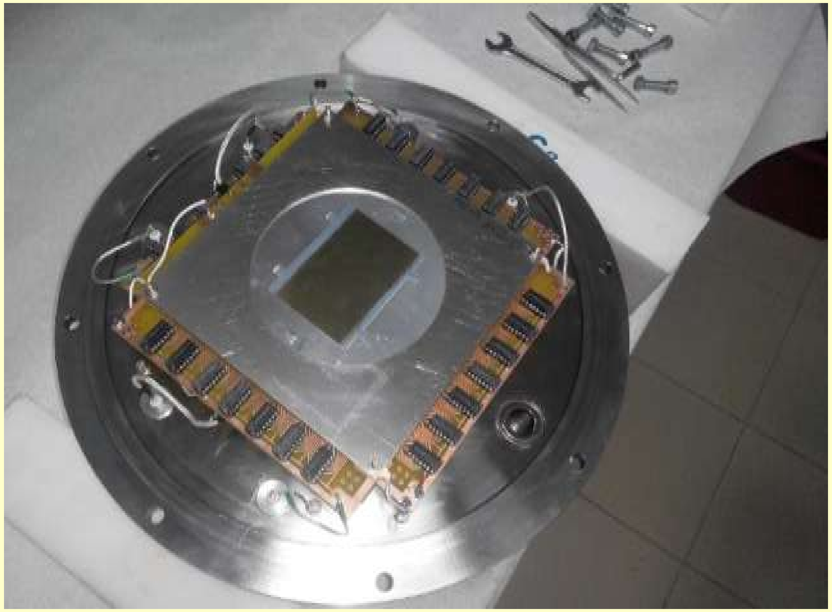
Bi and Pb targets – ~1000 μg/cm^2 evaporated on 2 μm Mylar films



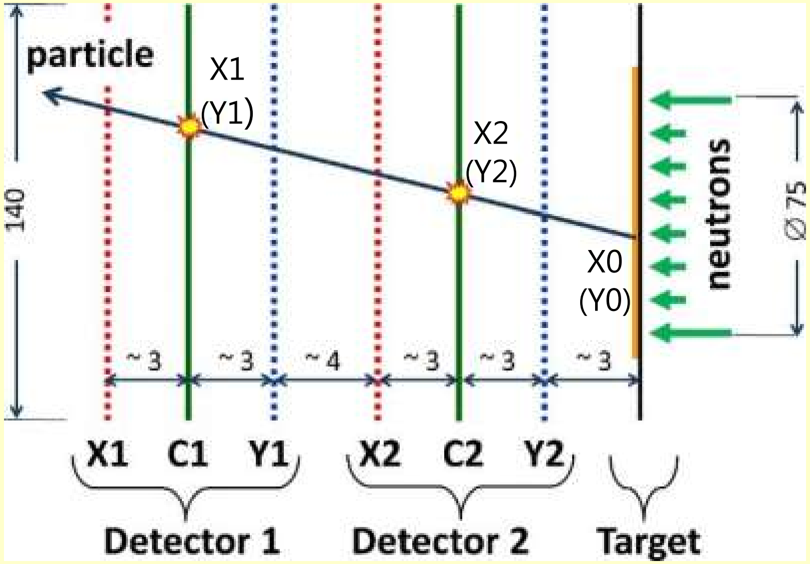
Experimental setup

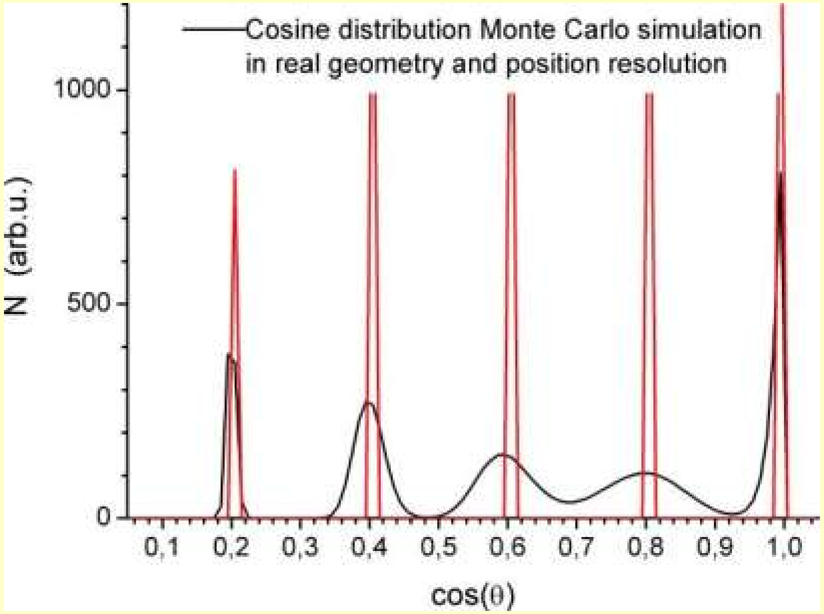




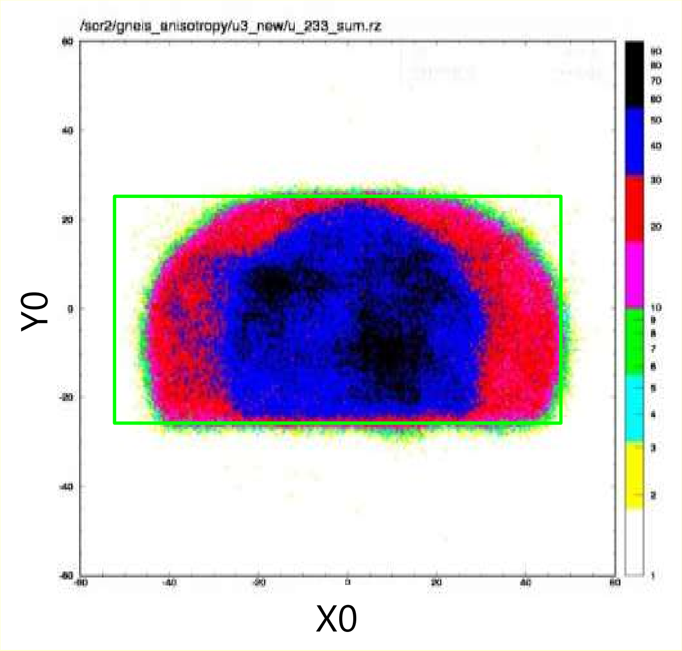


Experimental setup

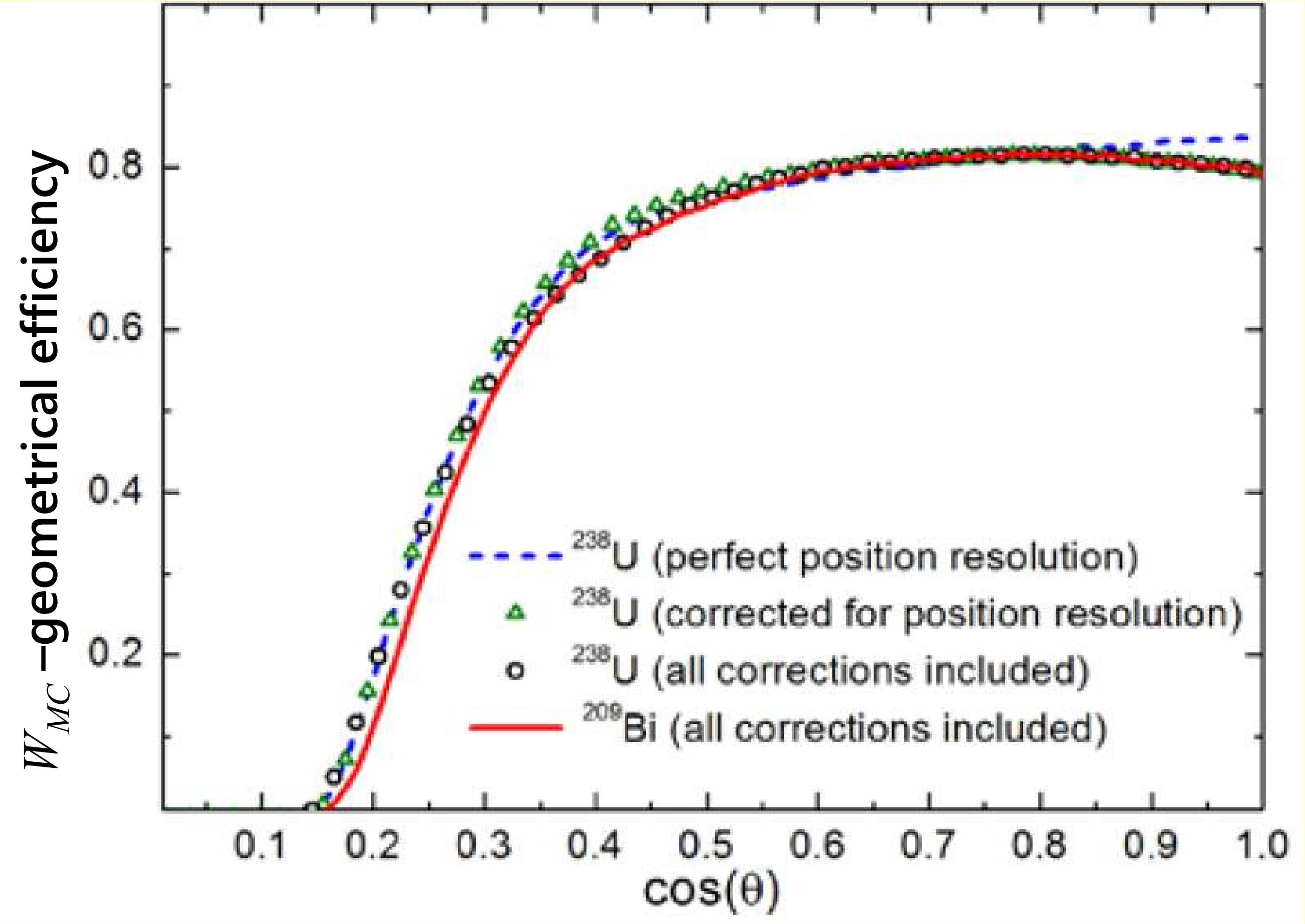




Reconstructed target image



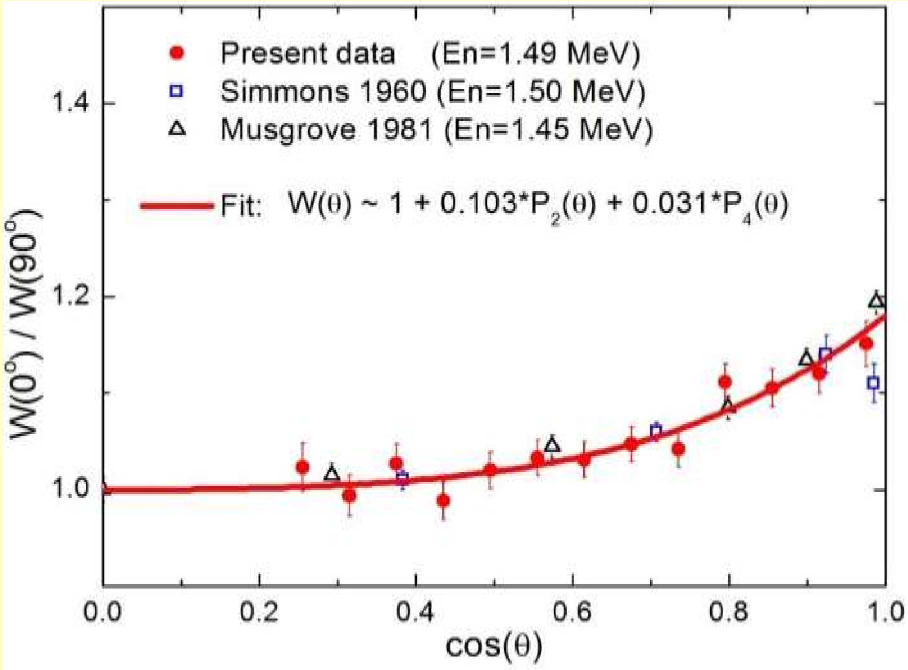
Cos θ Monte-Carlo simulation with real geometry

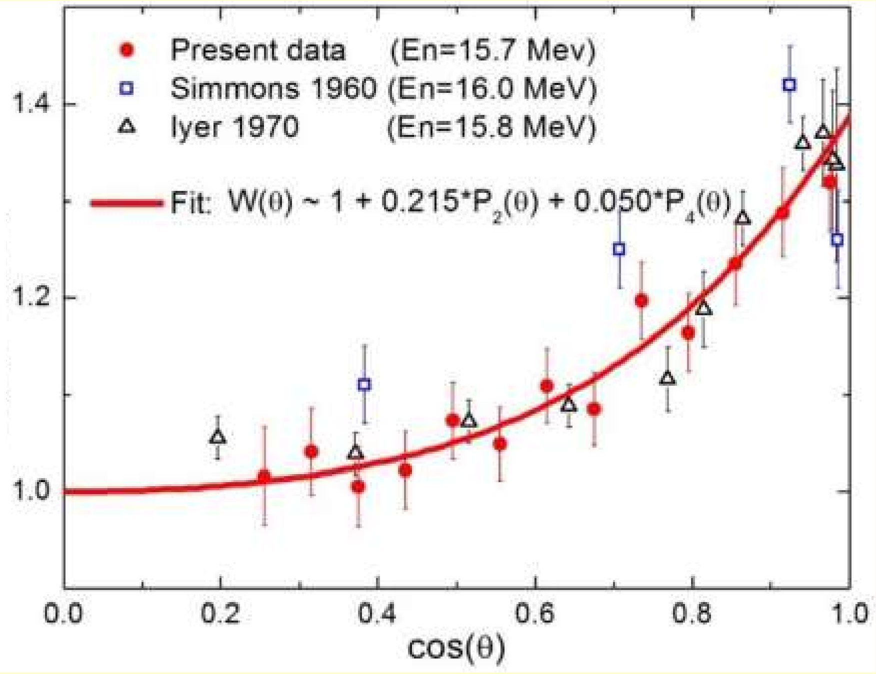


$$k_{geom} \sim \frac{1}{W_{MC}(\theta)}$$

$$W_{correct}(\theta) = k_d \cdot k_{geom} \cdot W_{exp}(\theta)$$

Results: angular distributions of ^{233}U



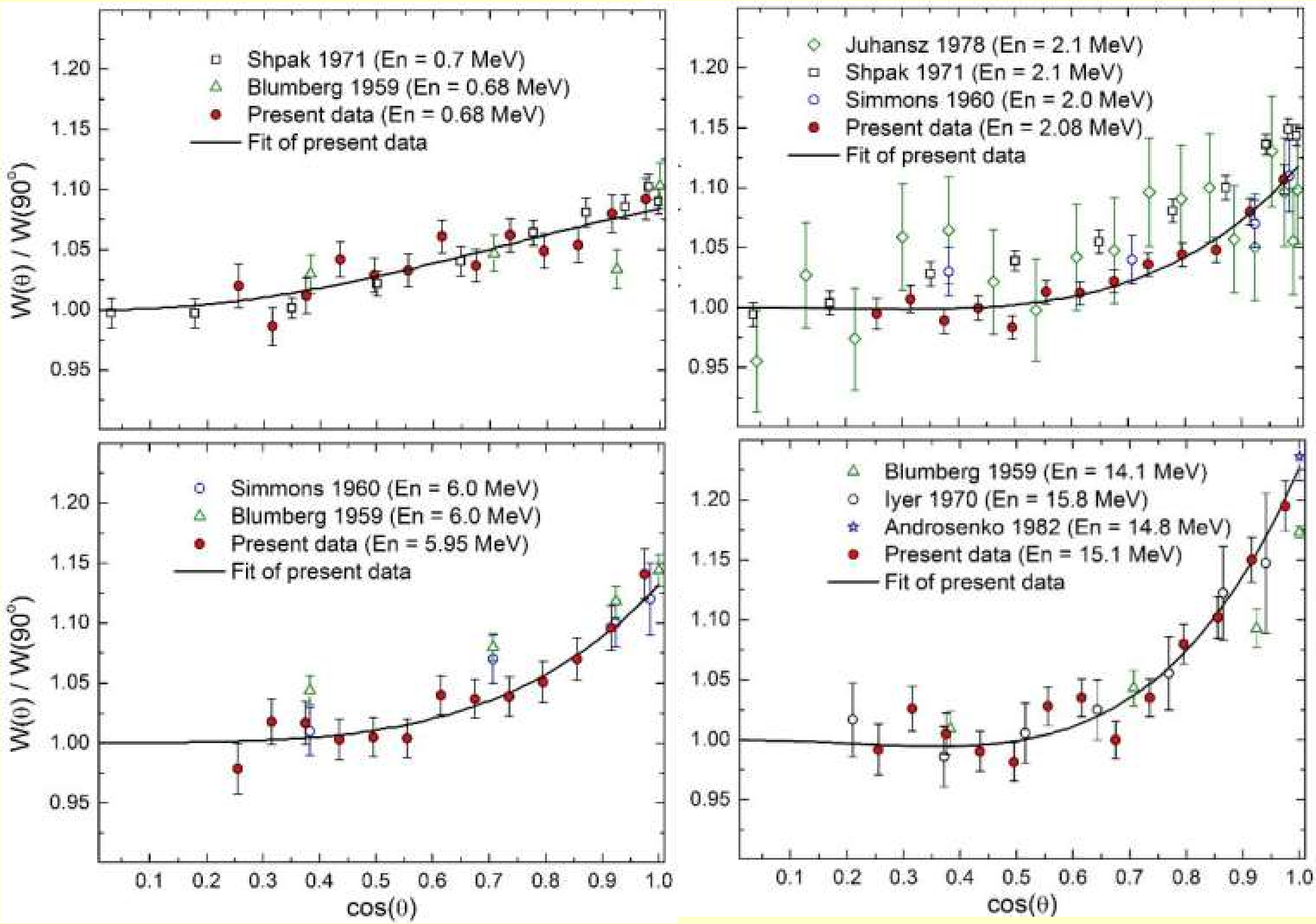


$$W(\theta) = A_0 \left[1 + \sum_{n=1}^{2} A_{2n} P_{2n}(\cos(\theta)) \right]$$

$$W(0^\circ)/W(90^\circ) = \frac{1 + A_2 + A_4}{1 - \frac{1}{2}A_2 + \frac{3}{8}A_4}$$

Cos θ fitting range was 0.24– 1.0

Results: angular distributions of ^{239}Pu

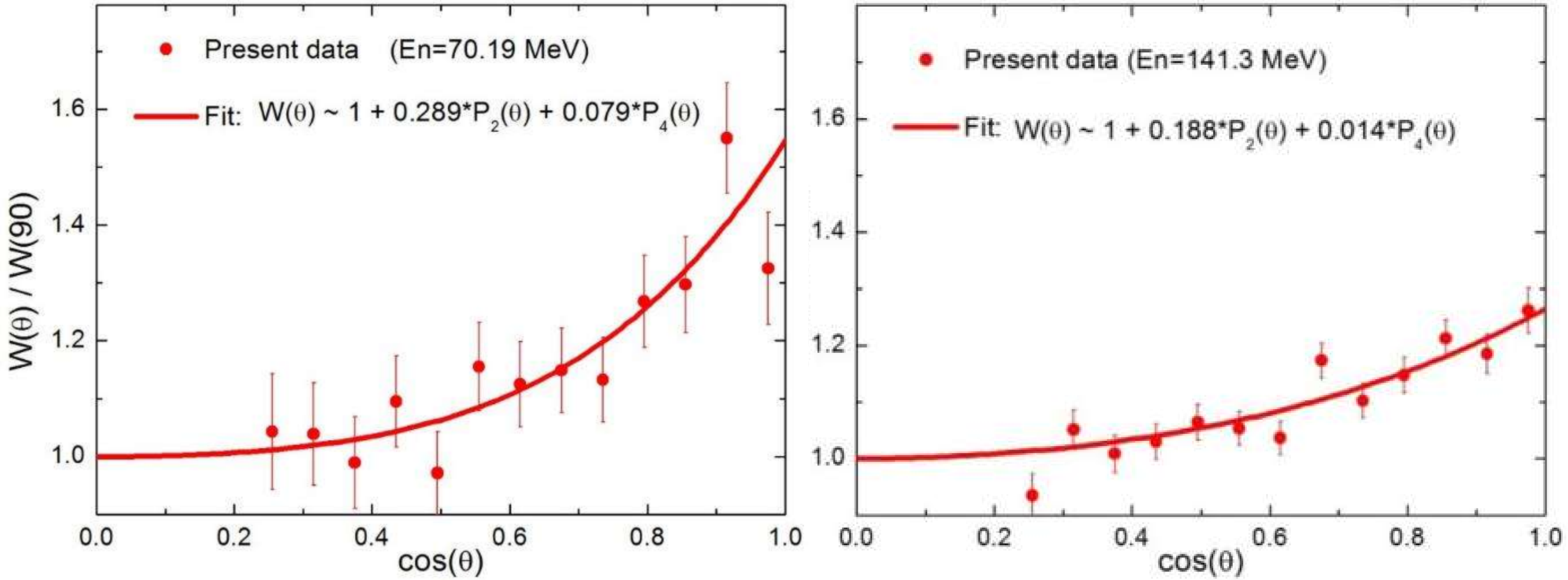


$$W(\theta) = A_0\left[1 + \sum_{n=1}^{2} A_{2n}P_{2n}(\cos(\theta))\right]$$

$$W(0^\circ)/W(90^\circ) = \frac{1 + A_2 + A_4}{1 - \frac{1}{2}A_2 + \frac{3}{8}A_4}$$

Cos θ fitting range was 0.24– 1.0

Results: angular distributions of 209Bi

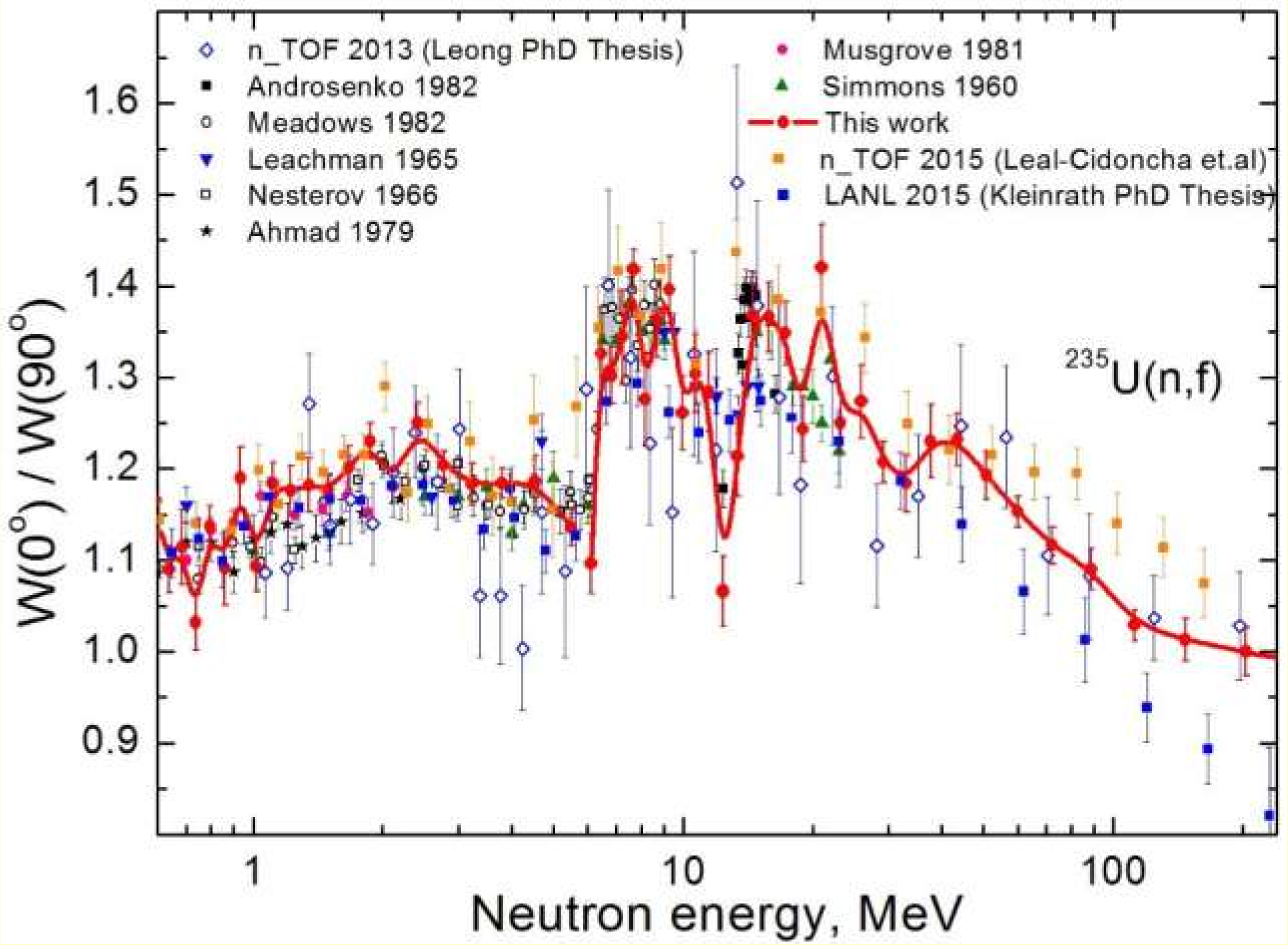


- ✓ In presented examples our results are in a good agreement with the other data (if there are available ones).
- ✓ Since experimental techniques used by referred authors are different from ours, this agreement may be treated as a convincing proof of accuracy and reliability of our measurement technique and data processing, at least in the neutron energy range below 20 MeV.
- ✓ It can be seen, that experimental data are well fitted by the sum of even Legendre polynomials up to 4-th order.
- ✓ Above 100 MeV, the angular distributions of fission fragments can be describe with good accuracy by following equations:

$$W(\theta) \sim (1 + b\, cos^2(\theta))$$

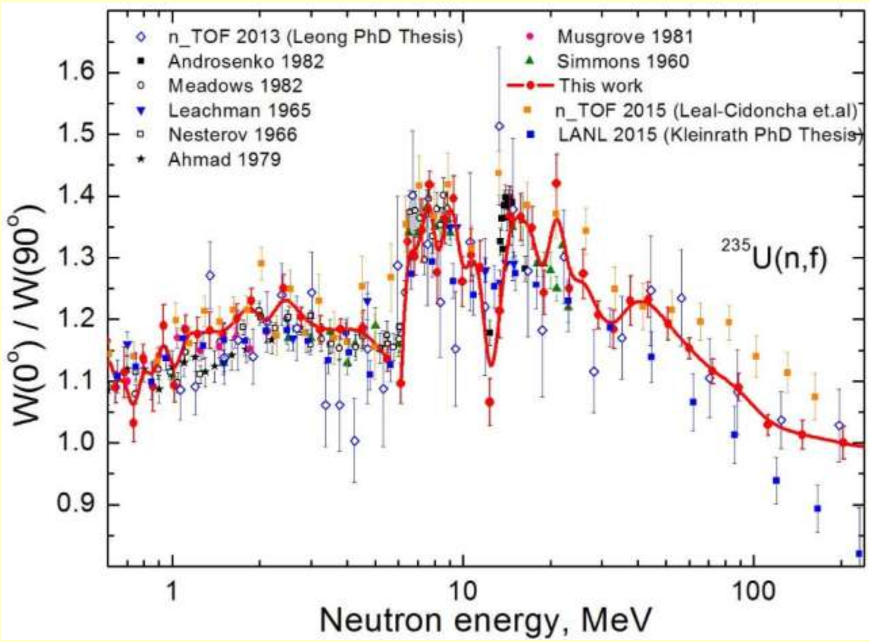
$$b = \frac{W(0°)}{W(90°)} - 1$$

Results: anisotropy in 235U

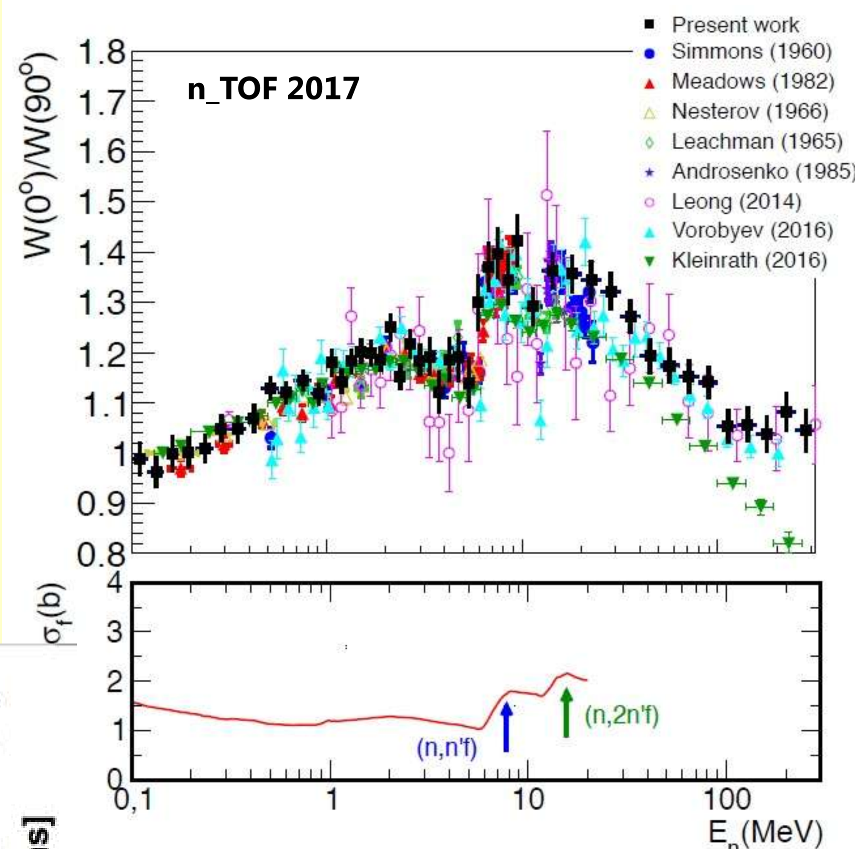


- ✓ There is a general agreement between data obtained in this work and by other experimental groups in neutron energy range 1-200 MeV.
- ✓ Above 50 MeV there is disagreement between these results and those obtained in 2015 by Kleinrath (WNR, LANSCE) and Leal-Cidoncha et.al (n_TOF, CERN).

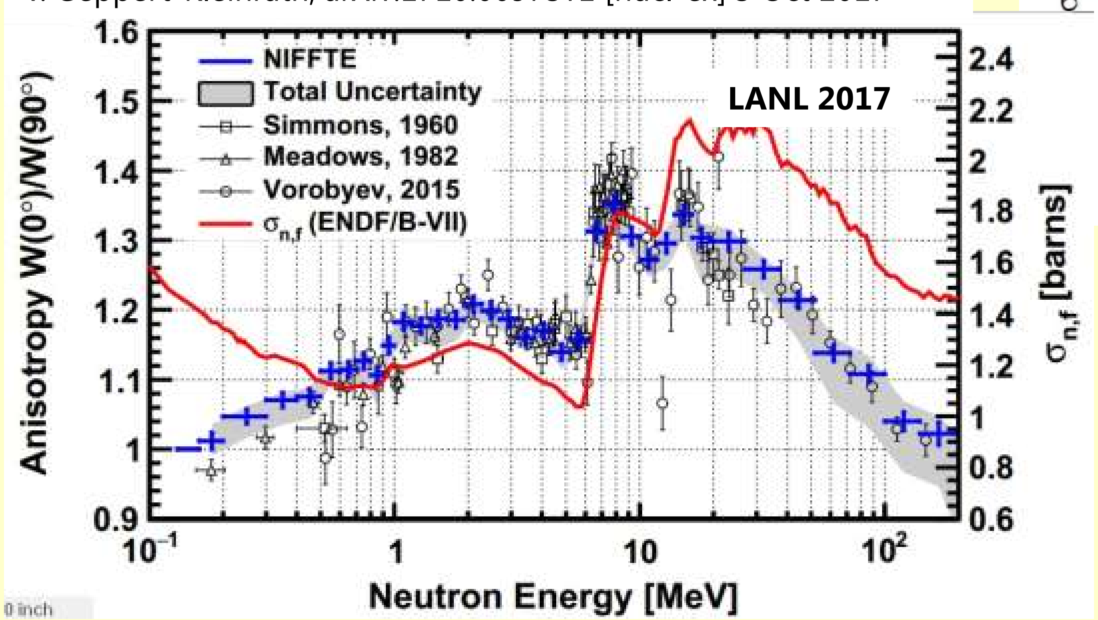
Results: anisotropy in 235U – comparison with new data



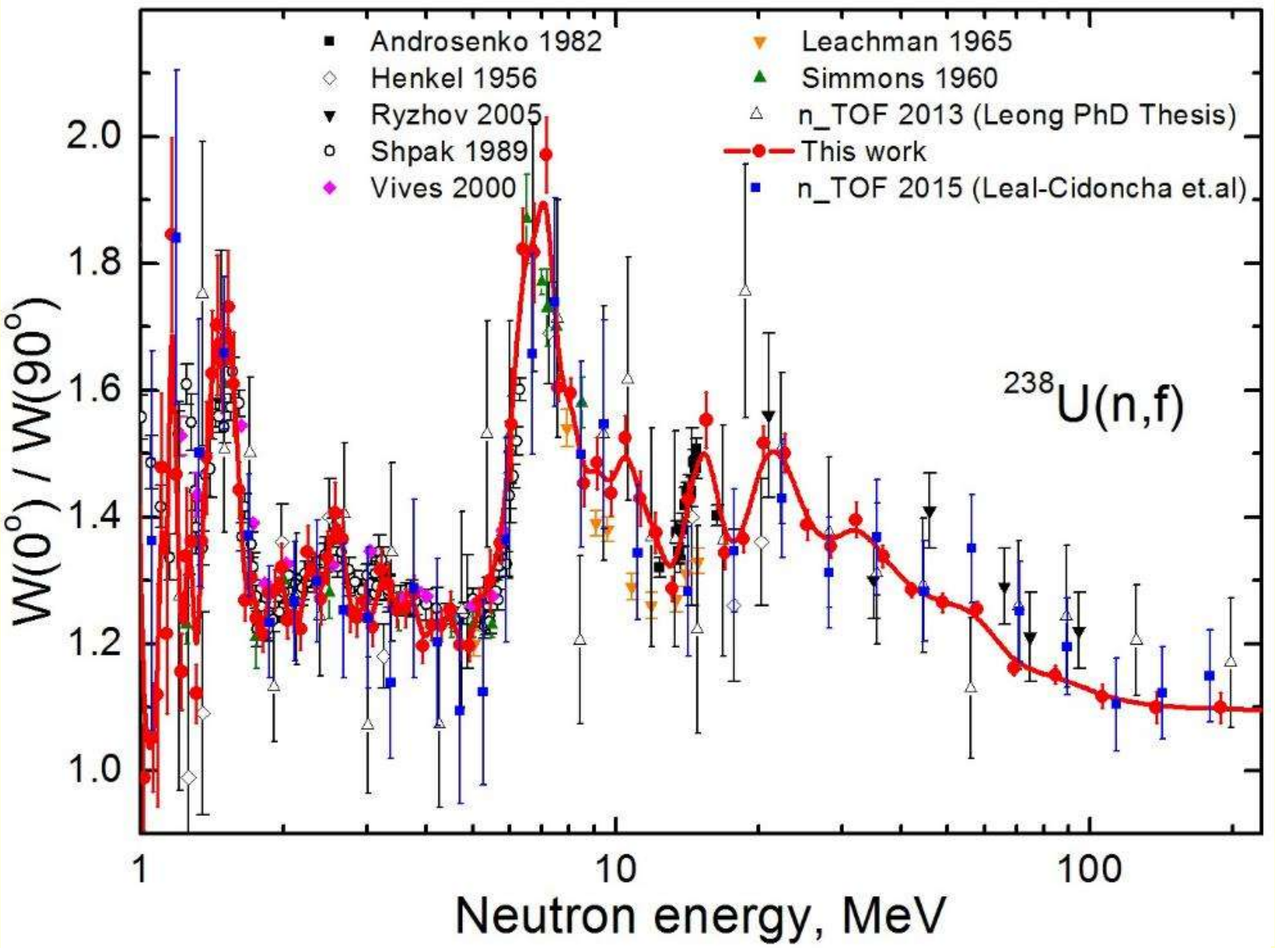
E. Leal-Cidoncha, FIESTA2017. Santa Fe, Sept 2017



V. Geppert-Kleinrath, arXiv:1710.00973v1 [nucl-ex] 3 Oct 2017

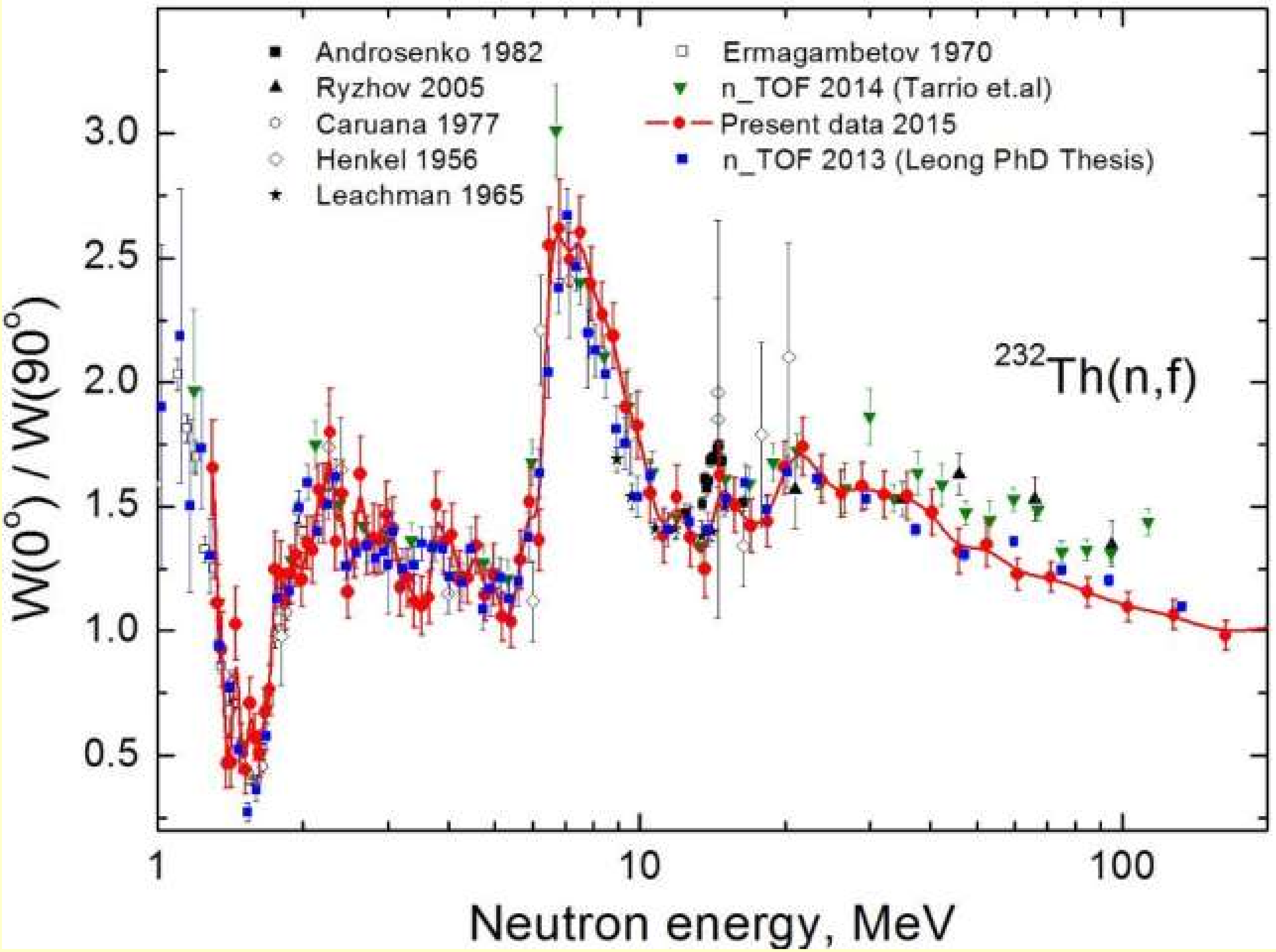


Results: anisotropy in 238U



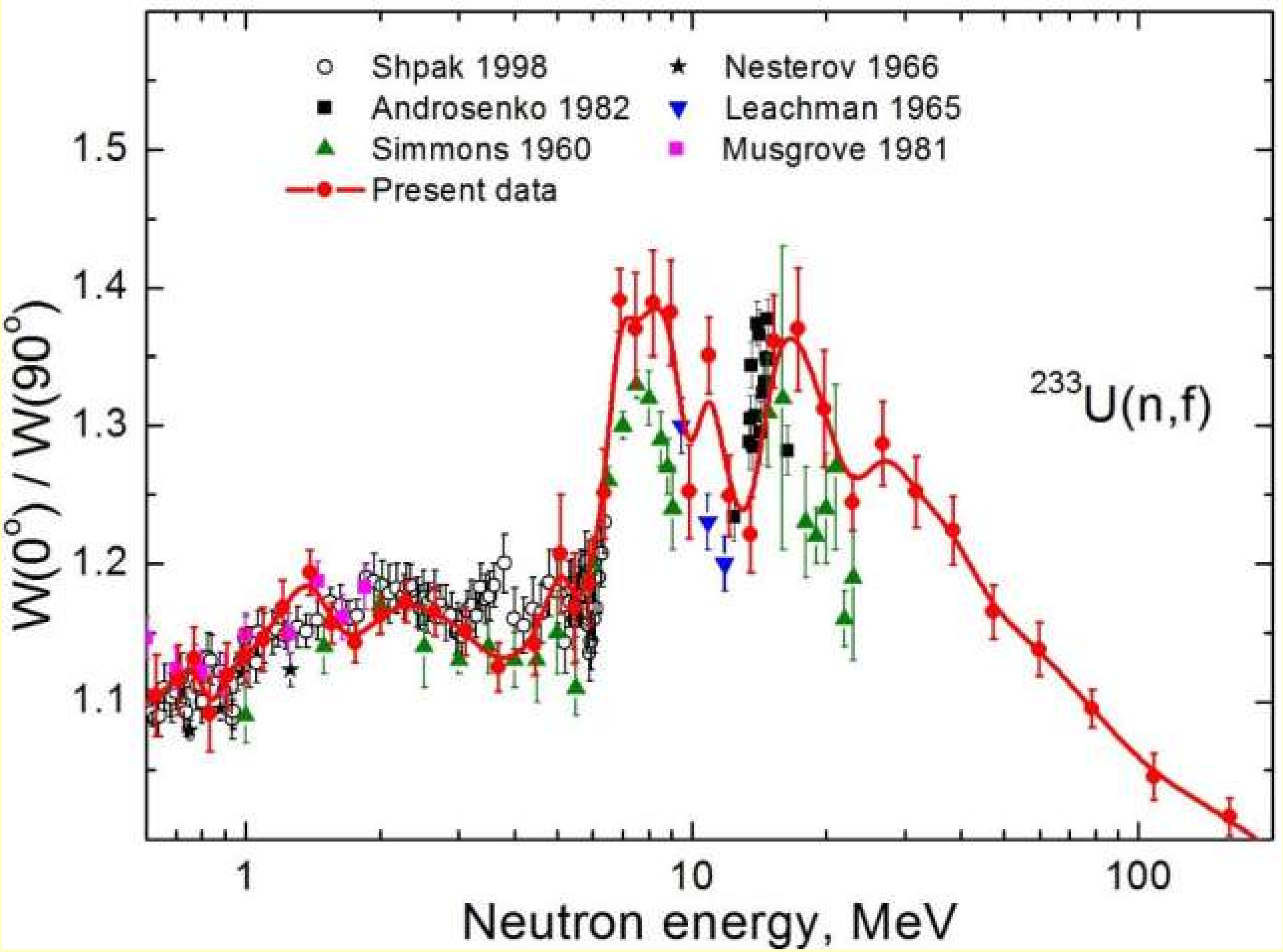
- ✓ There is a general agreement between data obtained in this work and by other experimental groups in neutron energy range 1-200 MeV.
- ✓ Above 20 MeV the uncertainties of our data are much smaller than those presented by Ryzhov et.al (TSL, Uppsala) and Leong, Leal-Cidoncha et.al (n_TOF, CERN).

Results: anisotropy in 232Th



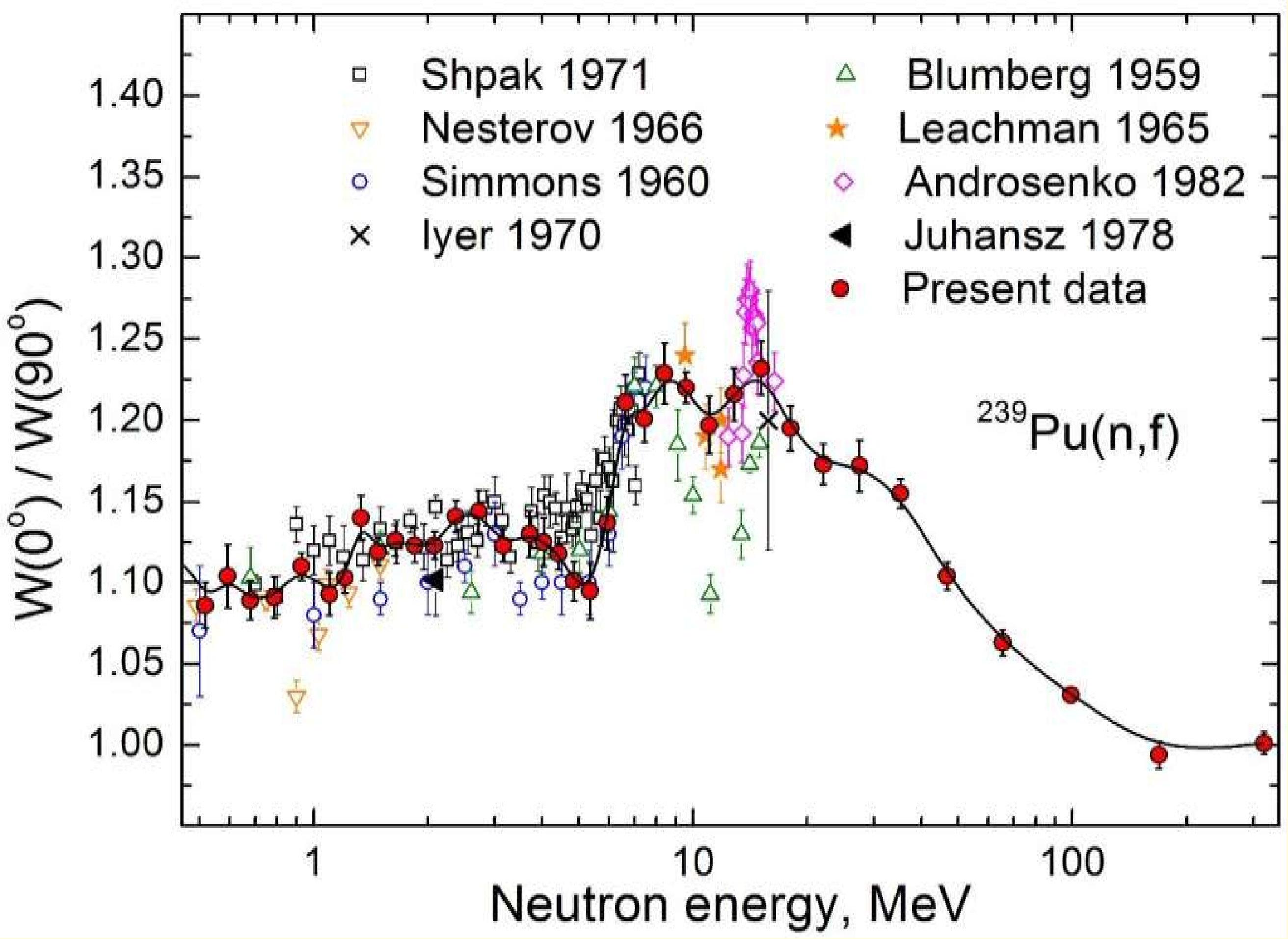
- ✓ There is a general agreement between data obtained in this work and by other experimental groups in neutron energy range below 40 MeV.
- ✓ Above 40 MeV our data agree with results given by Leong (n_TOF, CERN) and differ substantially from the data presented by Ryzhov et.al (TSL, Uppsala) and Tarrio et.al (n_TOF, CERN).

Results: anisotropy in 233U



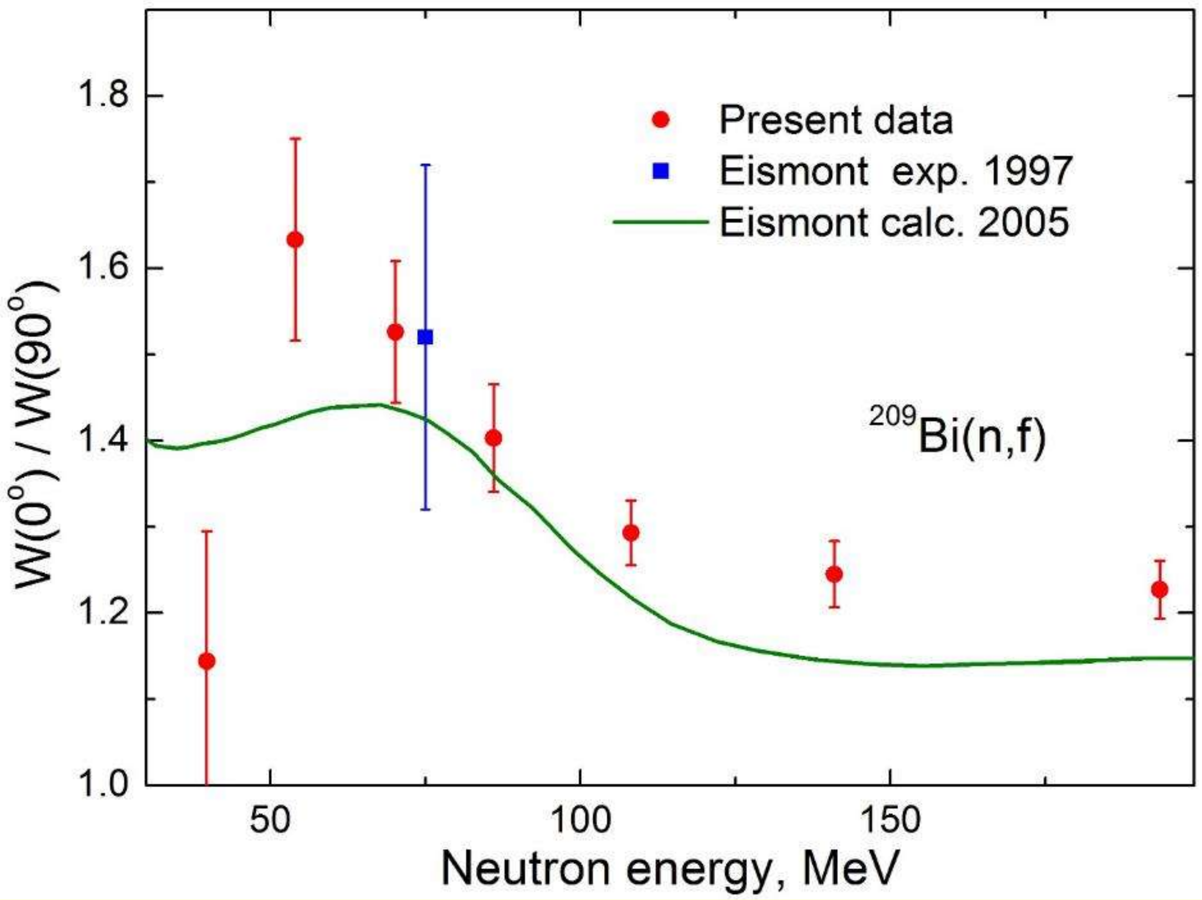
- ✓ In the neutron energy range below 20 MeV, our results agree within experimental uncertainties with the most full data sets. The exception are the Simmons data, in the neutron energy range 7-24 MeV, which are 4÷7% below than our data.
- ✓ There is no data besides ours in the neutron energy range above 24 MeV.

Results: anisotropy in 239Pu



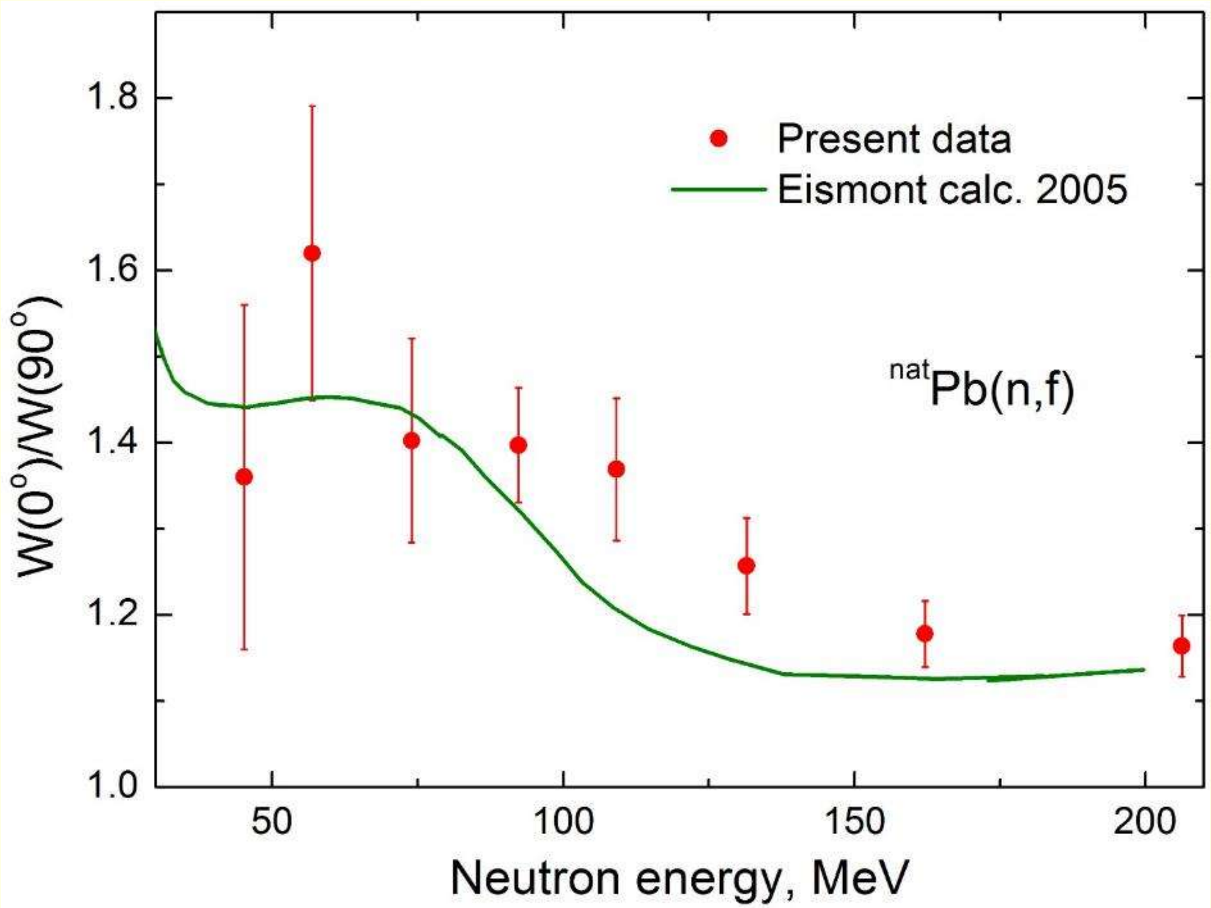
- ✓ There is no other data except our data above 16 MeV .
- ✓ Below 16 MeV our data coincide reasonably well with existing datasets.

Results: anisotropy in 209Bi



- ✓ Our data agree with the only ONE existing point at 75 MeV of Eismont et.al. And also they reasonably agreed with calculations made by Eismont, except the fact that above 75 MeV the model gives some underestimation.
- ✓ There is a maximum of the anisotropy at ~50 MeV equal to ~1.6 followed by descend with increasing neutron energy. At 200 MeV the anisotropy is about 1.2.

Results: anisotropy in nat-Pb



- ✓ There is no other data except our data. Again, they reasonably agreed with calculation of Eismont, except the fact that «plato» lasts somewhat longer above 75 MeV .
- ✓ There is some similarity between nat-Pb and 209-Bi. The maximum anisotropy near the threshold seems to be ~1.6

Conclusions

- The fission fragment angular distributions have been measured for ^{233}U, ^{235}U, ^{238}U, ^{232}Th, ^{239}Pu, ^{209}Bi and ^{nat}Pb in neutron energy range 1-200 MeV using the same data processing and the same experimental setup.

- The reliability is confirmed by an agreement between obtained results and available literature data on fission fragments angular distributions for the fixed neutron energies and on anisotropies in the neutron energy range below 20 MeV, while the experimental techniques, fragment detectors, neutron sources and data processing were very different.

Conclusions

- Anisotropy of FFs emission has been obtained :

  for ^{235}U
  - achieved accuracy is 2÷5%;
  - above 50 MeV, our results are in agreement with the n_TOF data given by Leong, while the recent data by Leal-Cidoncha et.al (n_TOF, CERN) are higher than our results (~8% at 100 MeV) and by Kleinrath (WNR, LANSCE) are below present results (~10% at 100 MeV).

  for ^{238}U
  - achieved accuracy is 2÷5%;
  - obtained data are in agreement with literature data in all investigated neutron energy range (1-200 MeV);
  - in neutron energy range above 20 MeV uncertainties of obtained data are much smaller that those presented by Ryzhov et.al (KRI, St.-Petersburg + TSL, Uppsala) and Leal-Cidoncha et.al (n_TOF, CERN).

  for ^{232}Th
  - achieved accuracy is 5÷15%,
  - above 40 MeV, our results are in agreement with the n_TOF data given by Leong, while the data presented by Tarrio et.al (n_TOF, CERN) and Rizhov et.al (KRI, St-Petersburg + TSL, Uppsala) are higher than our results (~15% at 100 MeV).

Conclusions

for ^{233}U and ^{239}Pu

- achieved accuracy of obtained anisotropy is 2÷5%;
- presently, in neutron energy range above 20 MeV there are only our data.

for ^{209}Bi and ^{nat}Pb

- there are only our data;
- achieved accuracy is 3÷12%.

Conclusions

- Additional investigations are needed in neutron energy range above 20 MeV because:
  - there is a weak agreement not only between data obtained at different setups and TOF facilities, but also between data from the same set-up (at n_TOF -Leong, Tarrio, Leal-Cidoncha).
  - only 3 datasets are available in digital format (EXFOR database) except our results: Ryzov et al. (for ^{238}U and ^{232}Th) and Tarrio et al. (only for ^{232}Th);
- Development of theoretical model for adequate description of nuclear dynamics at high excitation energies is very important (contribution of pre-equilibrium processes, evolution of nuclear spin alignment ...), and such work is now in progress.

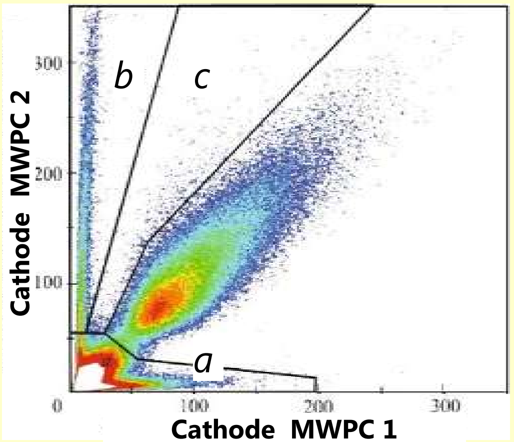
Thank you for attention

Further plans

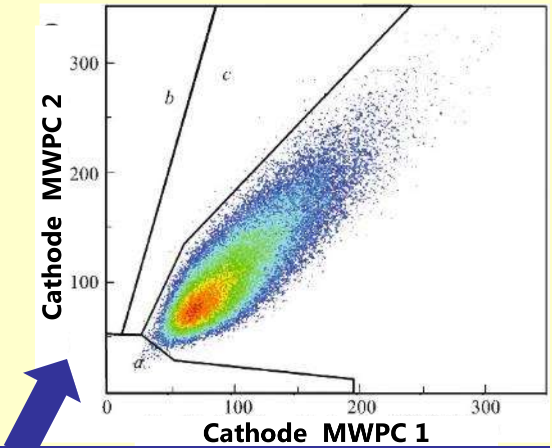
	$T_{1/2}$ (year)	A (Bq/mg)
Np-237	2.14 E+6	2,59 E+04
Pu-240	6 561	8,37 E+06
Am-243	7 370	7,36 E+06
U-236	2.34 E+7	2,38 E+03
Pu-242	375000	1,45 E+05
Pu-241	14.35 (бета)	3,81 E+09
Th-230	75 400	7,60 E+05
U-234	245 500	2,29 E+05

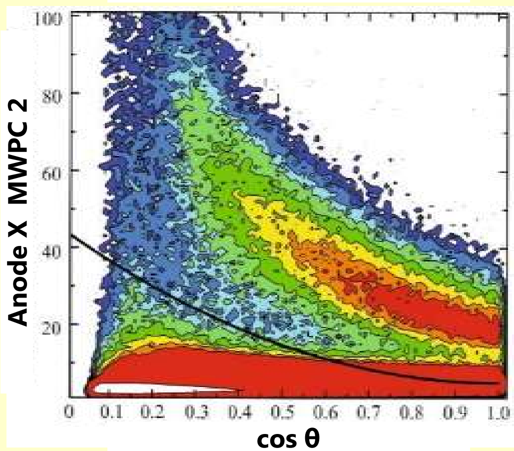
237Np, 240Pu, 243Am - supported by RFBR

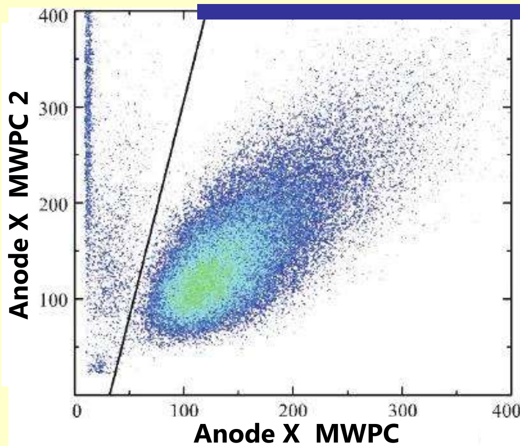
Fission events selection: 209-Bi example

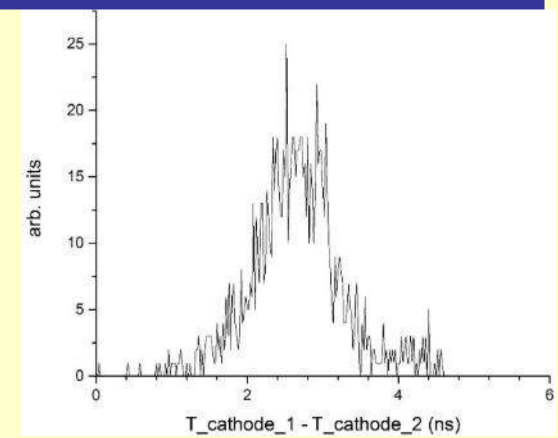


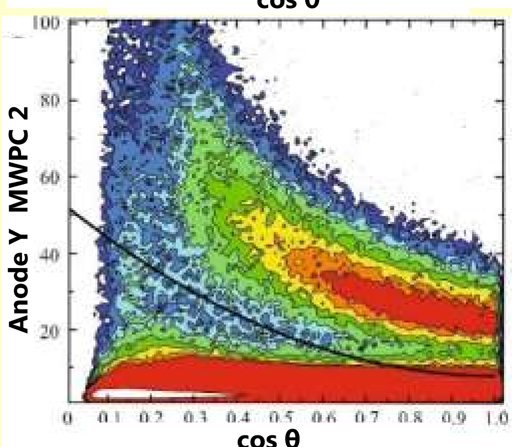
a. non-fission reactions in backing and alphas and noises
b. FFs “died” in MWPC 2 (first from the target)
c. FFs “died” on the cathode of MWPC 1 (second from the target)

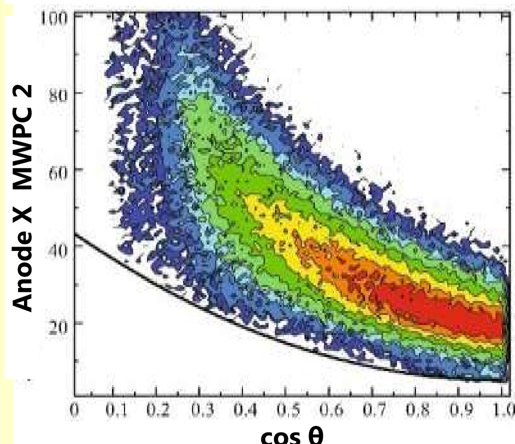




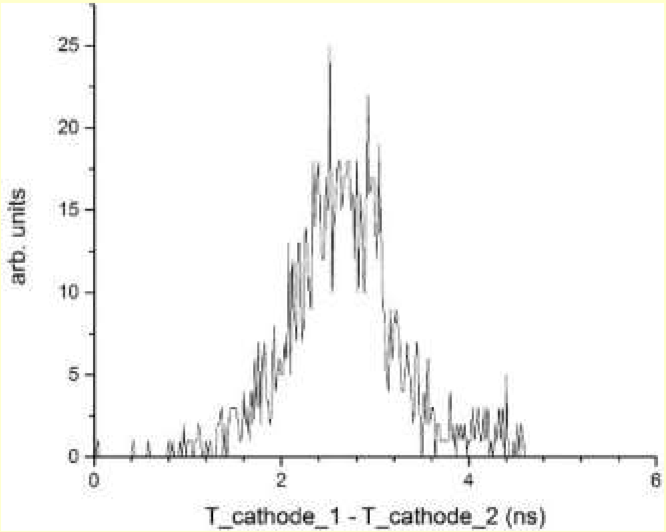


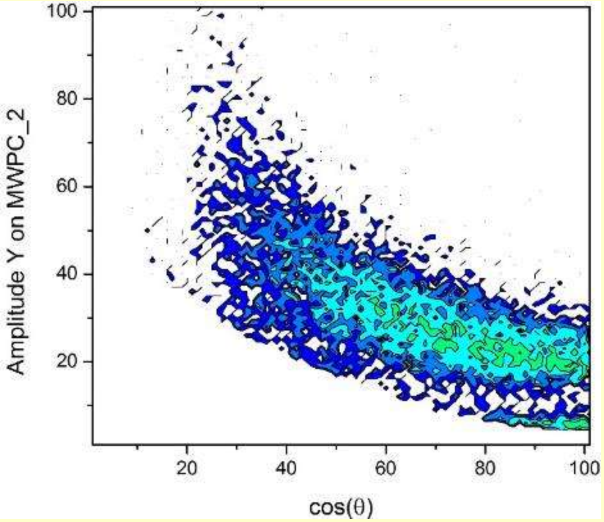


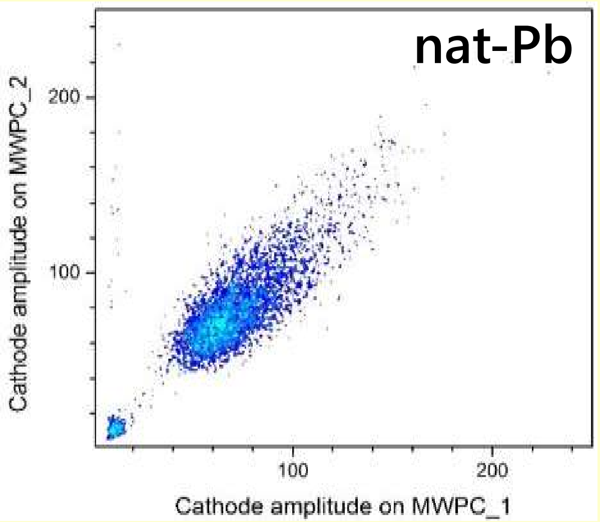


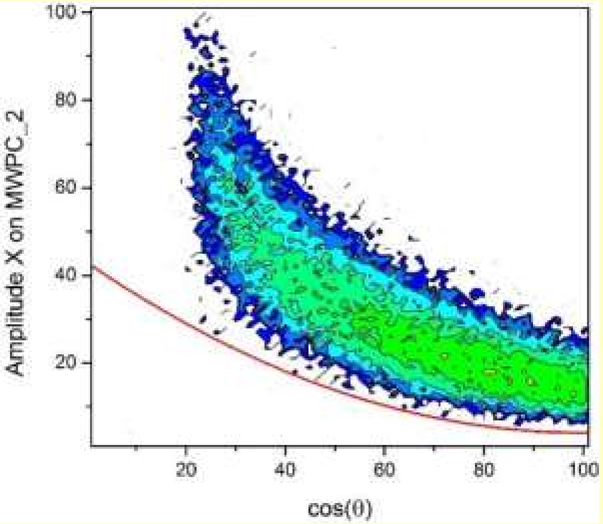


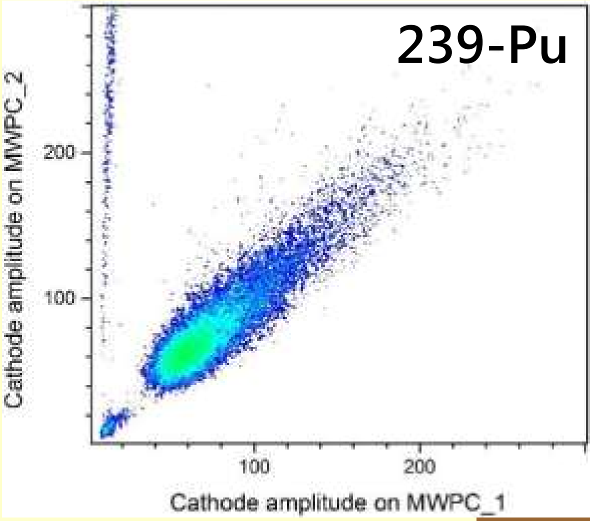
Fission events selection: nat-Pb and 239-Pu



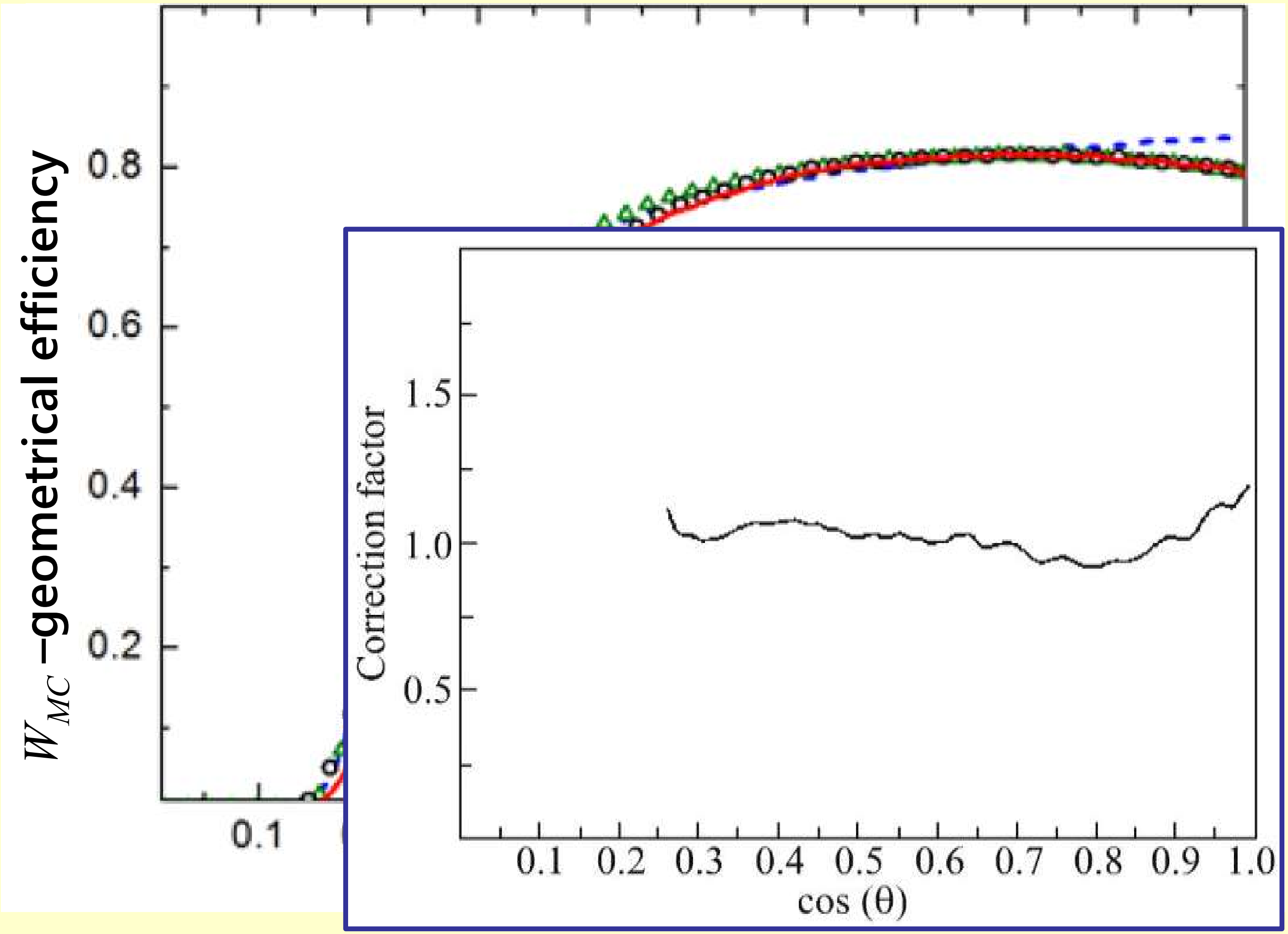








Cos θ Monte-Carlo simulation with real geometry



$$k_{geom} \sim \frac{1}{W_{MC}(\theta)}$$

$$W_{correct}(\theta) = k_d \cdot k_{geom} \cdot W_{exp}(\theta)$$

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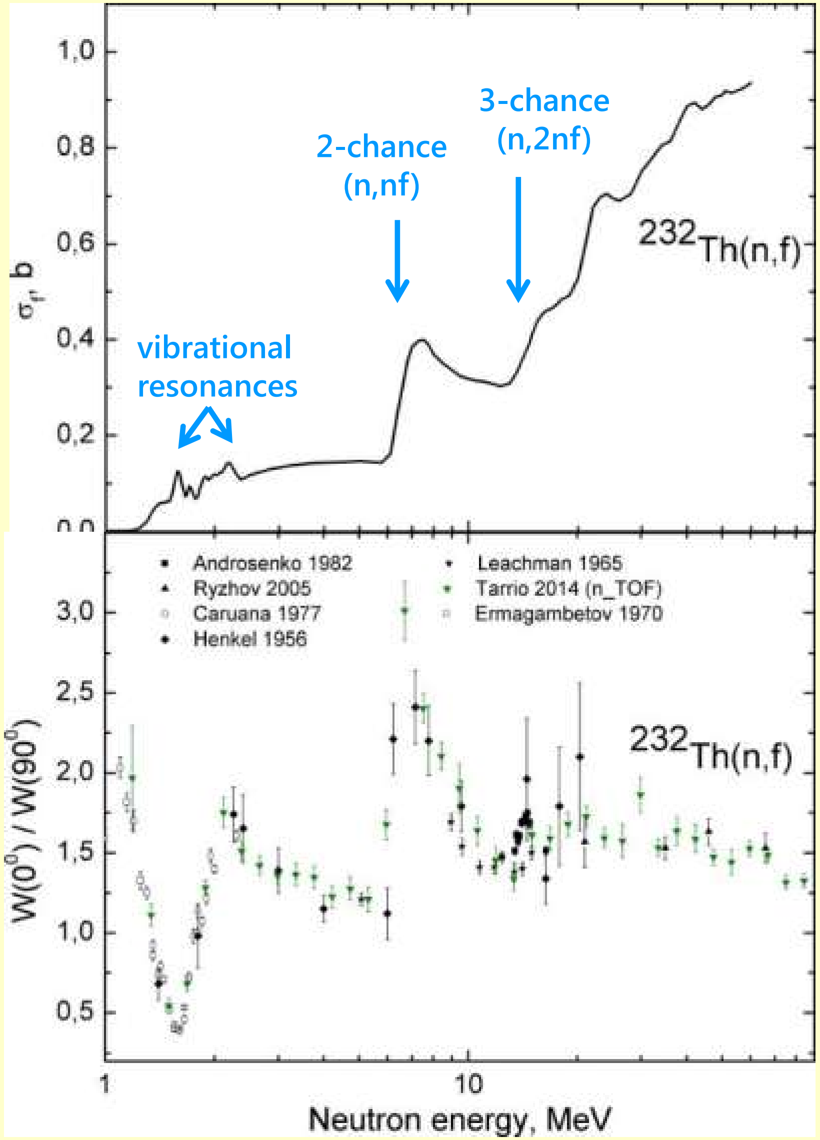
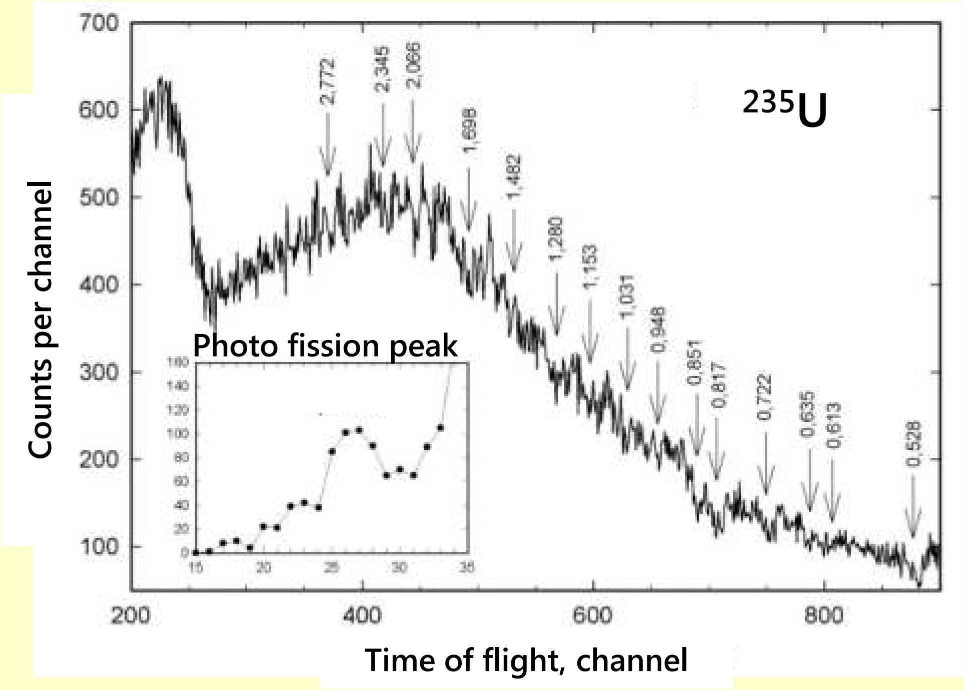
Angular distributions of fission fragments



Neutron TOF-spectrometer GNEIS



Energy /time-of-flight calibration:
Pb – neutron resonance dips and γ-flash peak