Anisotropy in the Fragments Emission from Fission Induced by Intermediate Energy Neutrons (1- 200 MeV)

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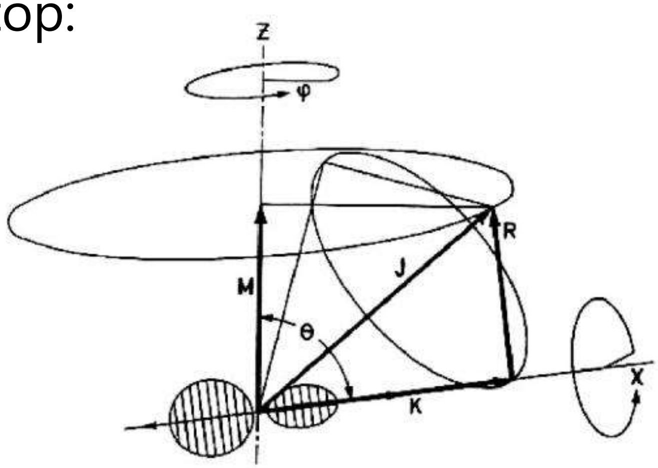
Angular distributions of fission fragments

Axially symmetric transition states at the saddle of fissioning nucleus are describing by wave functions of axially symmetric top:

[redacted]



For low excitation energies we need a proper sum over M distribution, and few available J, K (fission chann[redacted]

At high excitations with many opened fission channels one can use statistical model for the K projection distribution:

[redacted]

$$\rho(K) \sim \exp\left(-\frac{K^2}{2K_0^2}\right)$$

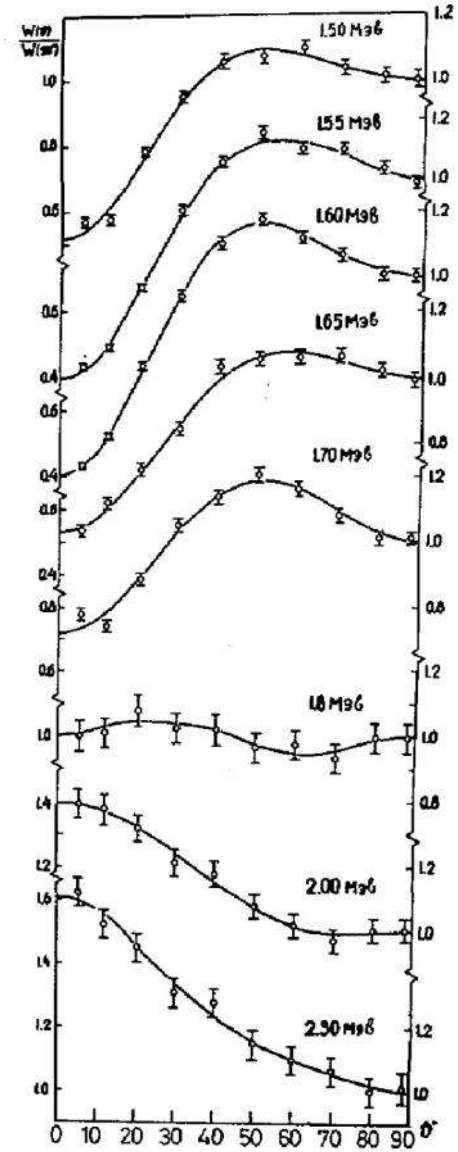
[redacted]

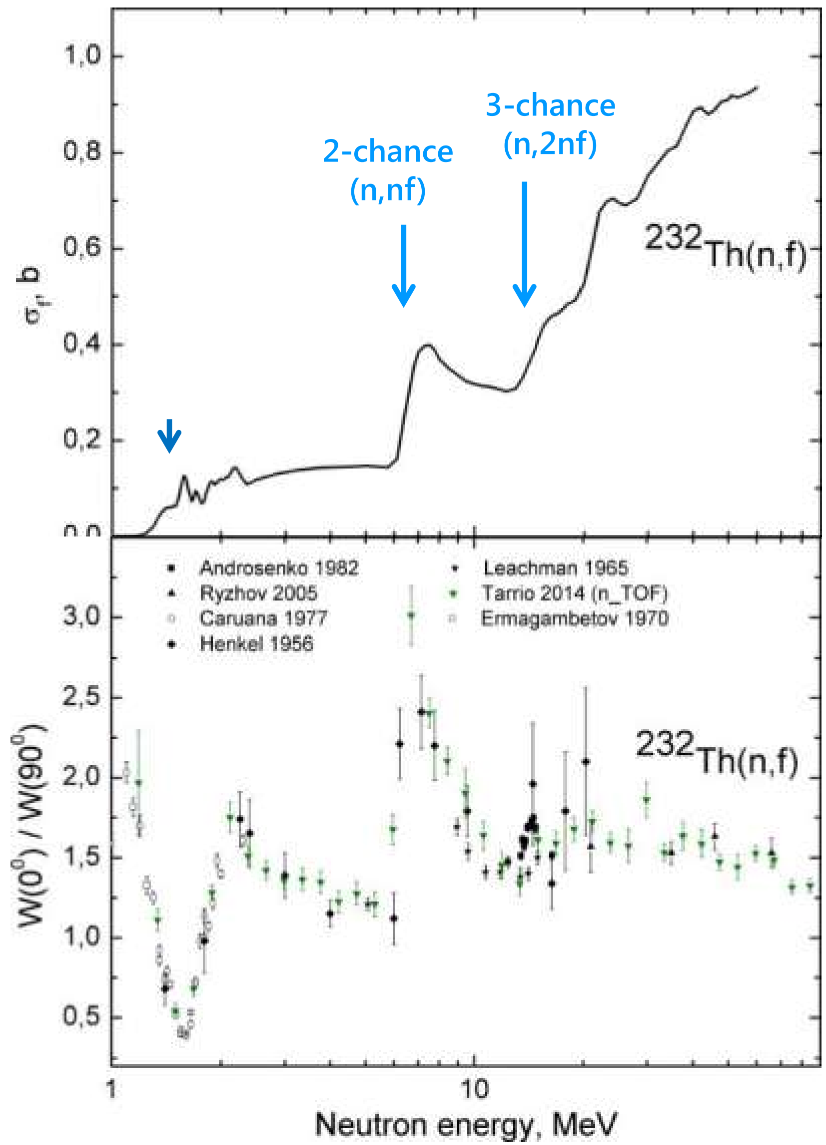
In the transition state statistical model:

[redacted]

Angular distributions of fission fragments

$^{232}Th(n,f)$
Androsenko et al. (1969)





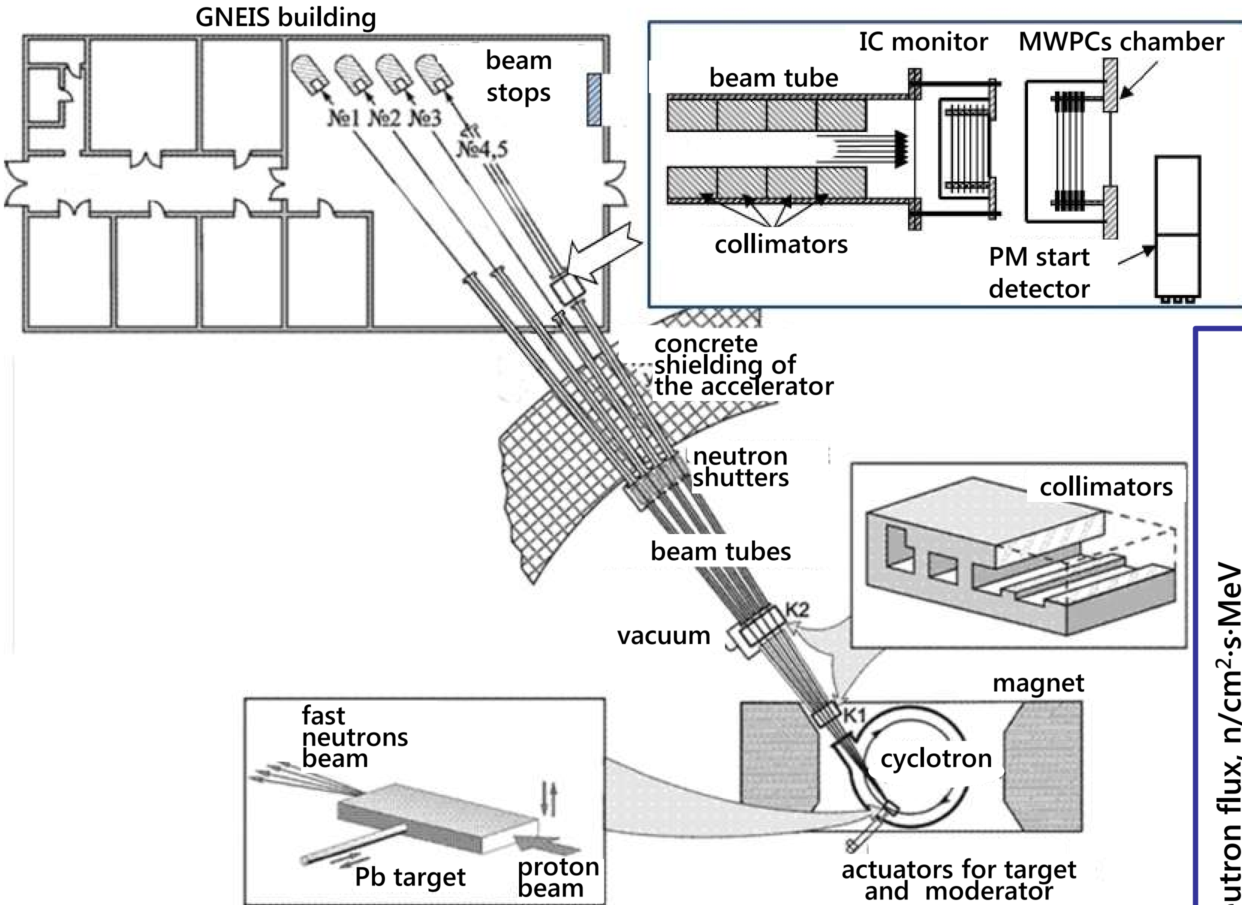
Motivation

- The experimental study of angular distributions of fission fragments near the threshold and low chance fission is a way to determine the properties of transition states of fissioning nucleus at the saddle point.
- The information about angular distribution of fission fragment is very important to verify parameters of models using for adequate fission process description in neutron energy range above 20 MeV.
- The data on nuclear fission in intermediate energy range 1-200 MeV are of prime importance for the advanced nuclear technologies such as Accelerator-Driven Systems (for nuclear power generation and nuclear transmutation).
- 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.
- The data about fission fragment anisotropy are very scarce in neutron energy range above 20 MeV and are practically absent for neutron energy range above 100 MeV.
- Therefore, in neutron energy range above 20 MeV, 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.

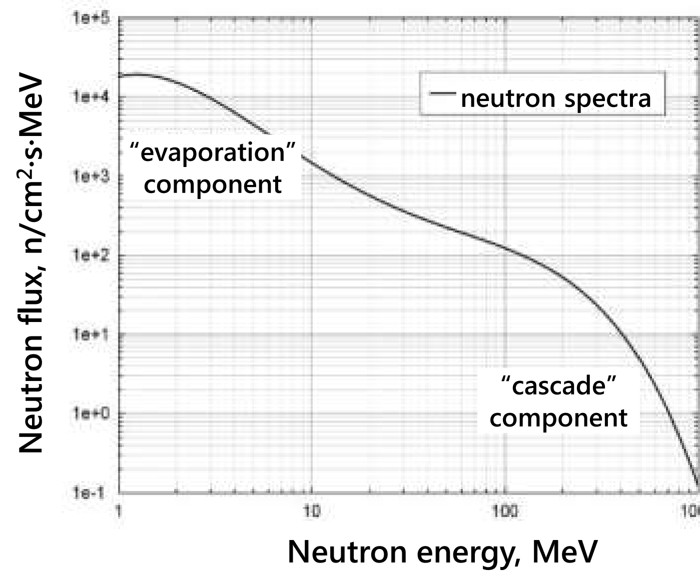
Current status

	PNPI GNEIS	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)	2015 V. Kleinrath PhD Thesis
^{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	2016-2017		
^{239}Pu	In progress		

Neutron TOF-spectrometer GNEIS



Neutron spectrum of GNEIS: from thermal to 1GeV

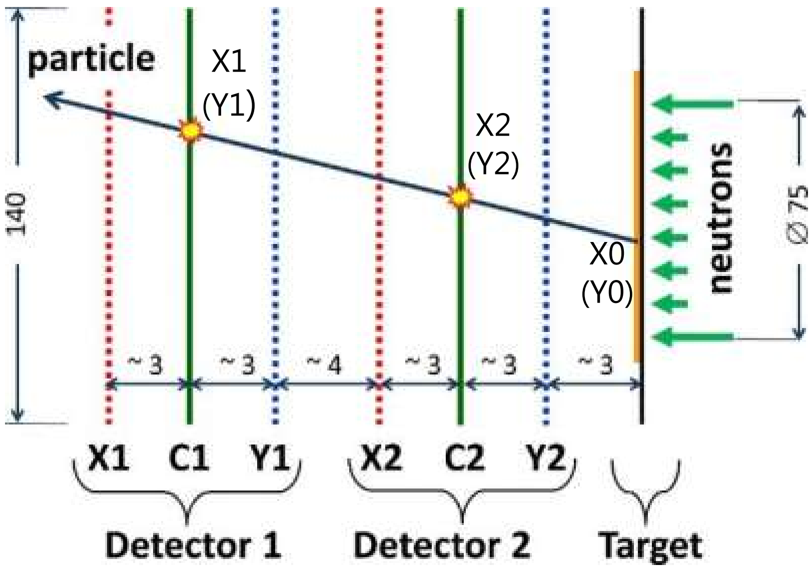


Main parameters:

[redacted]

[redacted]

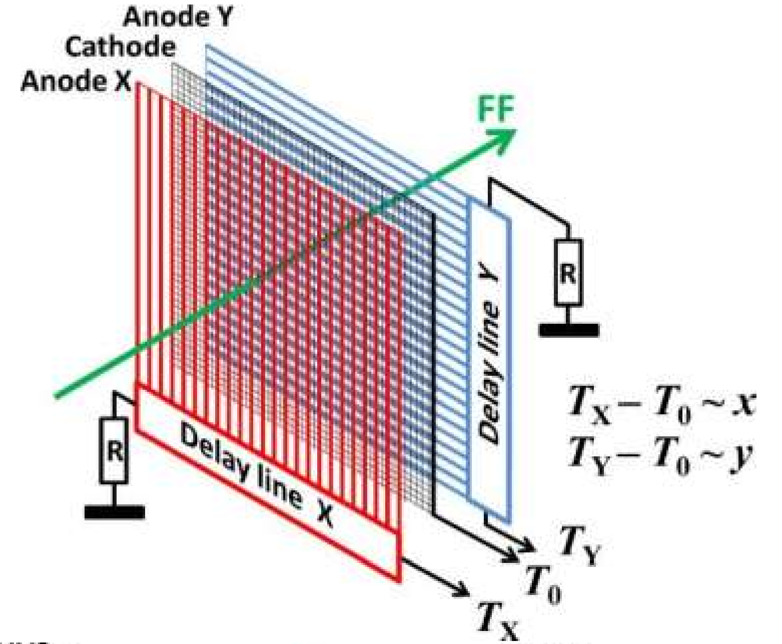
Experimental setup

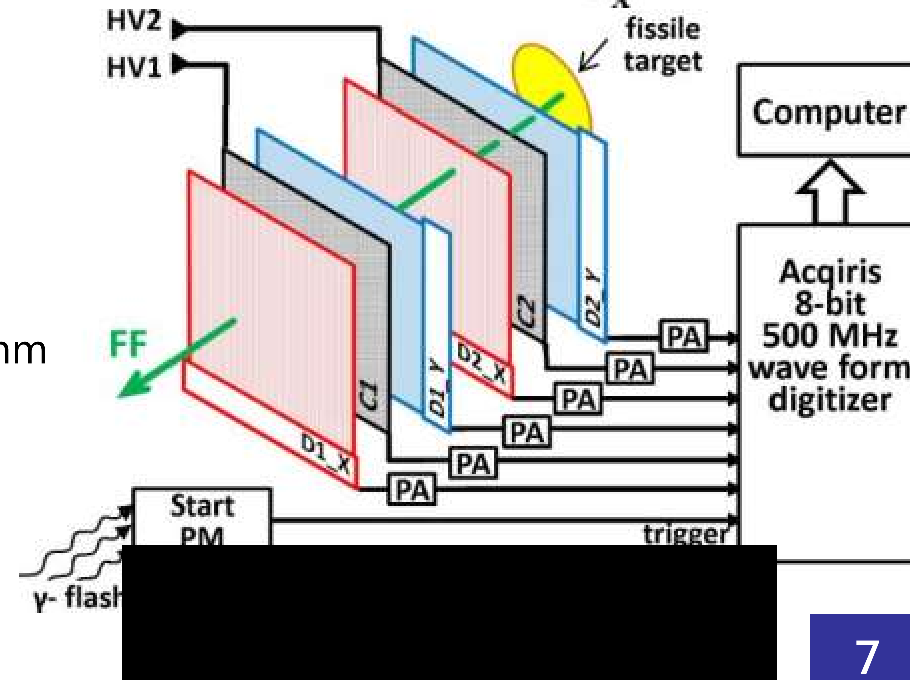


$$\cos(\theta) = \frac{d}{\sqrt{(x1 - x2)^2 + (y1 - y2)^2 + d^2}}$$

2 position sensitive low pressure
multi-wire proportional counters (MWPCs):
Sizes 140×140 mm;
Distances between electrodes ~3 mm ;
Grids made of 25 μm gold plated tungsten wire, 1 mm spacing

Actinide targets - ~ 100-150 μg/cm^2
Bi and Pb targets - ~1000 μg/cm^2
Th, Bi, Pb made by vacuum deposition
on 2 μm Mylar films
Uraniums were “painted” on ~100 μm Alu foil





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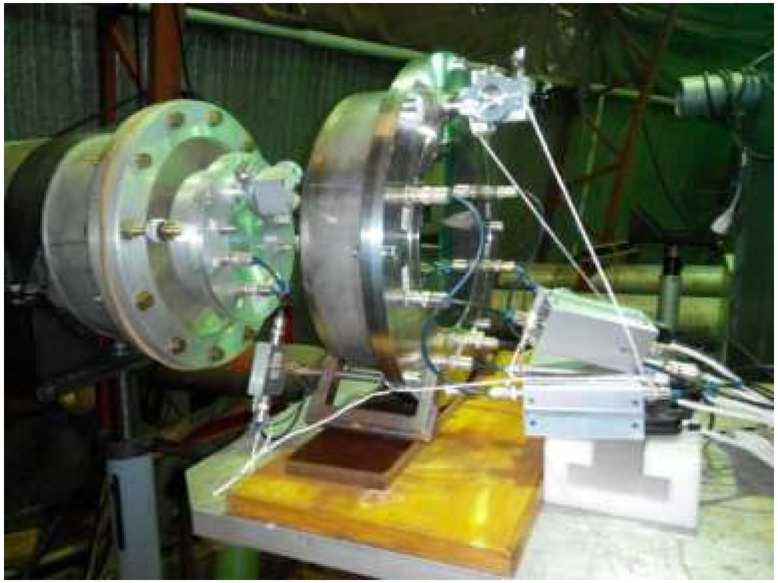
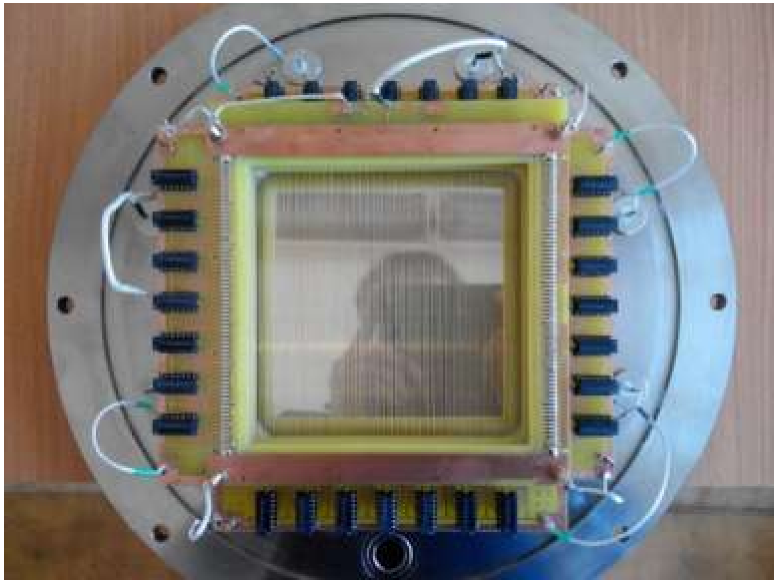
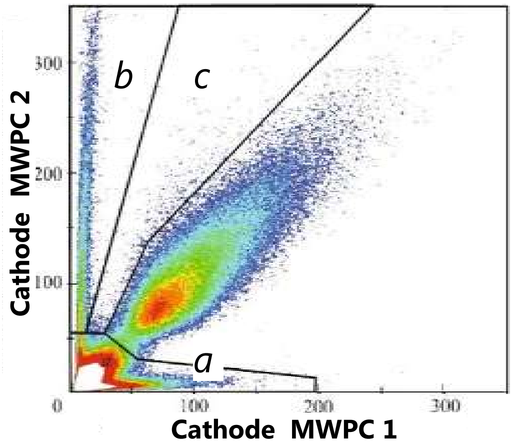
Experimental setup

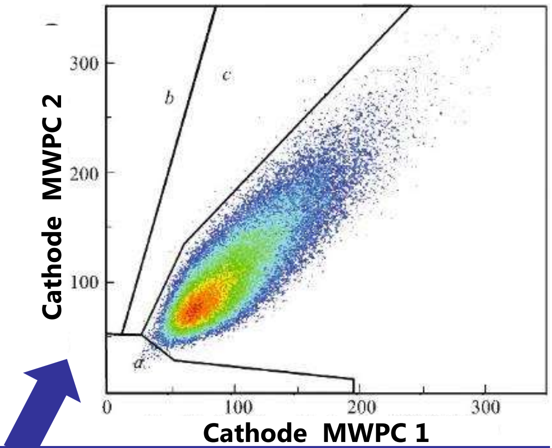


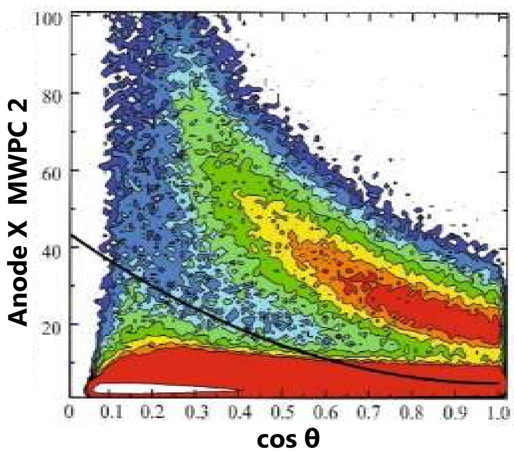


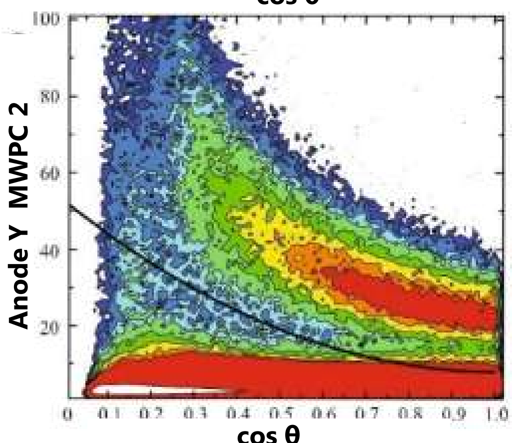
Fission events selection: 209-Bi example

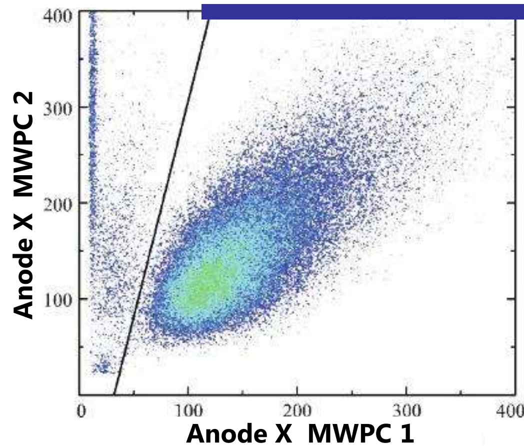


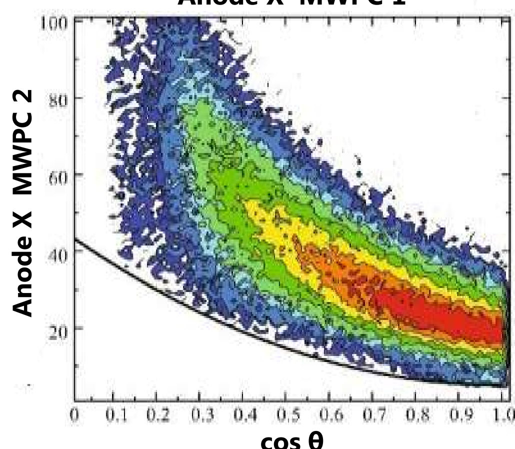
a. non-fission reactions in backing and alphas and noises
b. FFs "died" in MWPC 2 (first from the target)
c. FFs "died" on the cathode of MWPC 1 (second from the target)

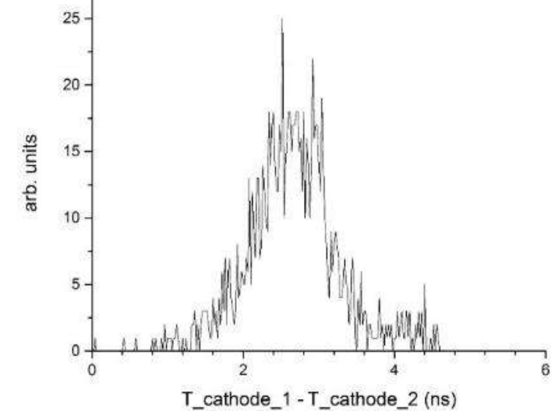




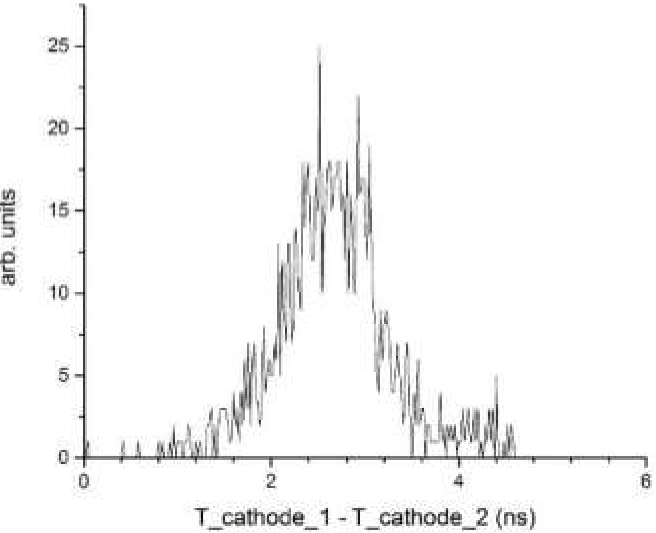


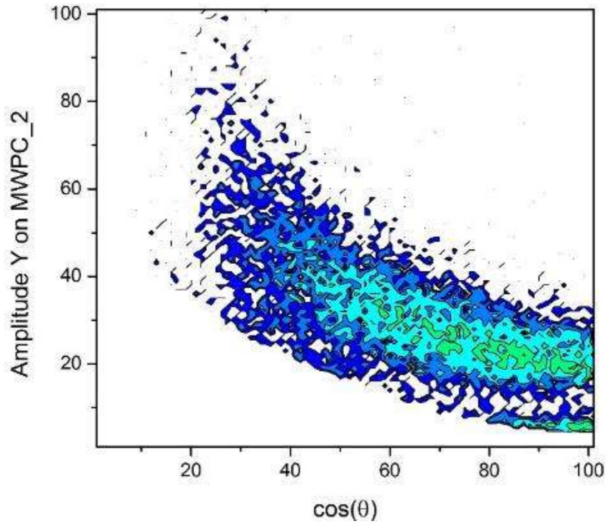


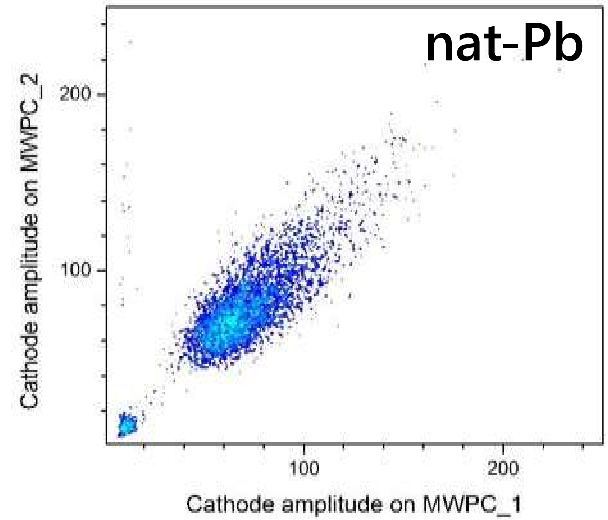


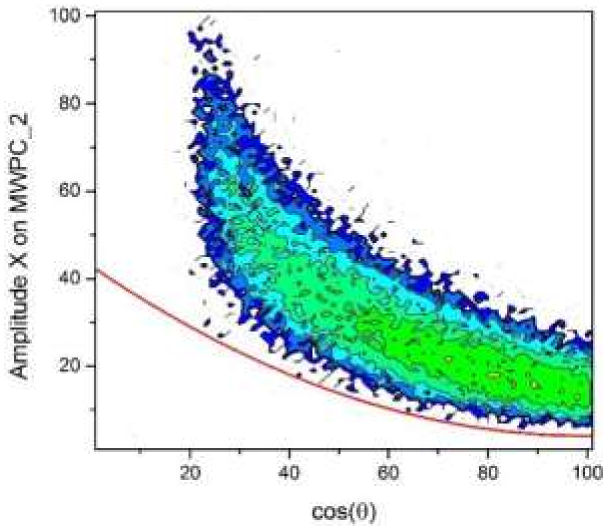


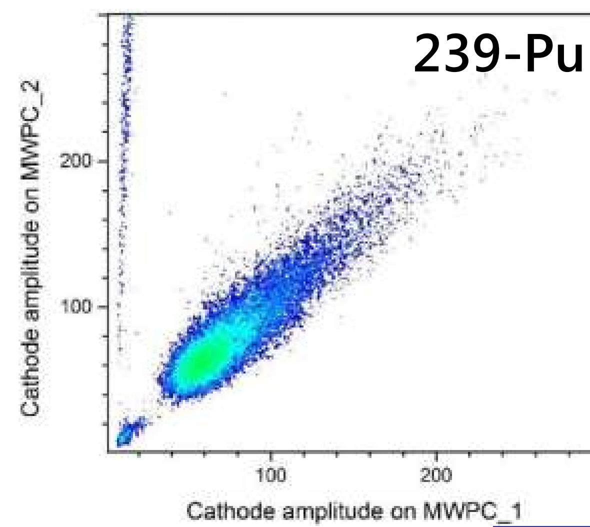
Fission events selection: nat-Pb and 239-Pu



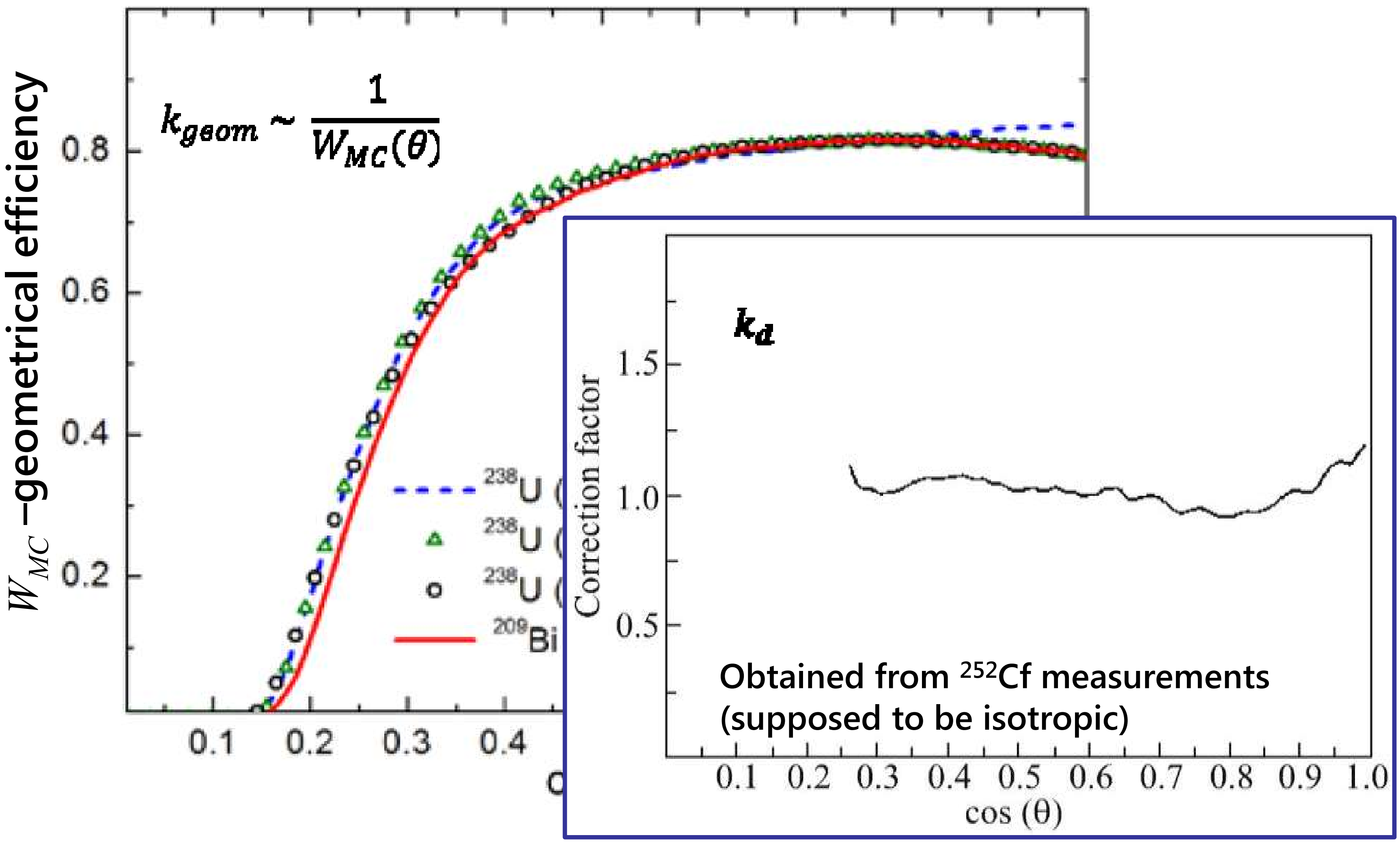






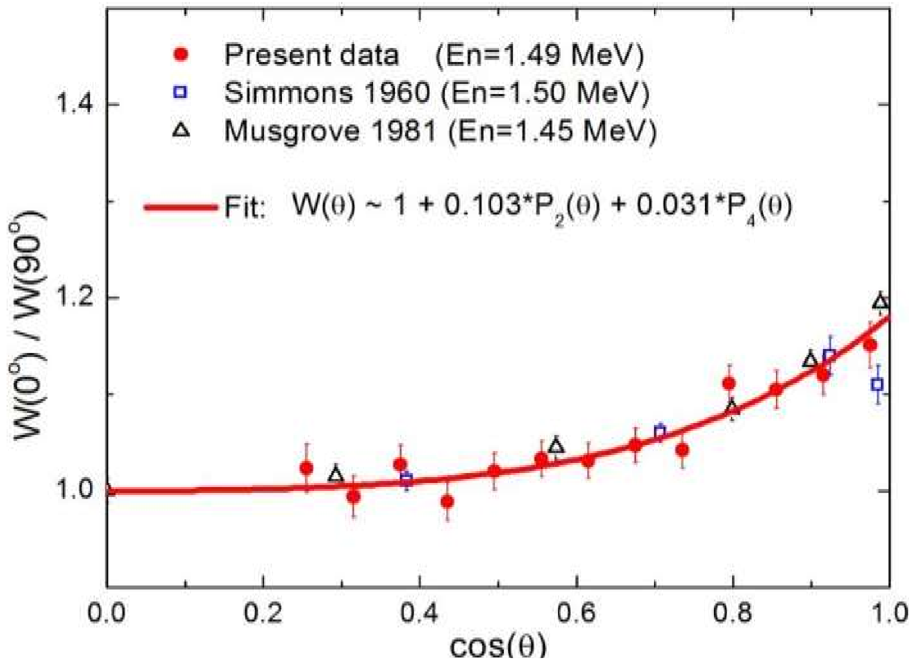


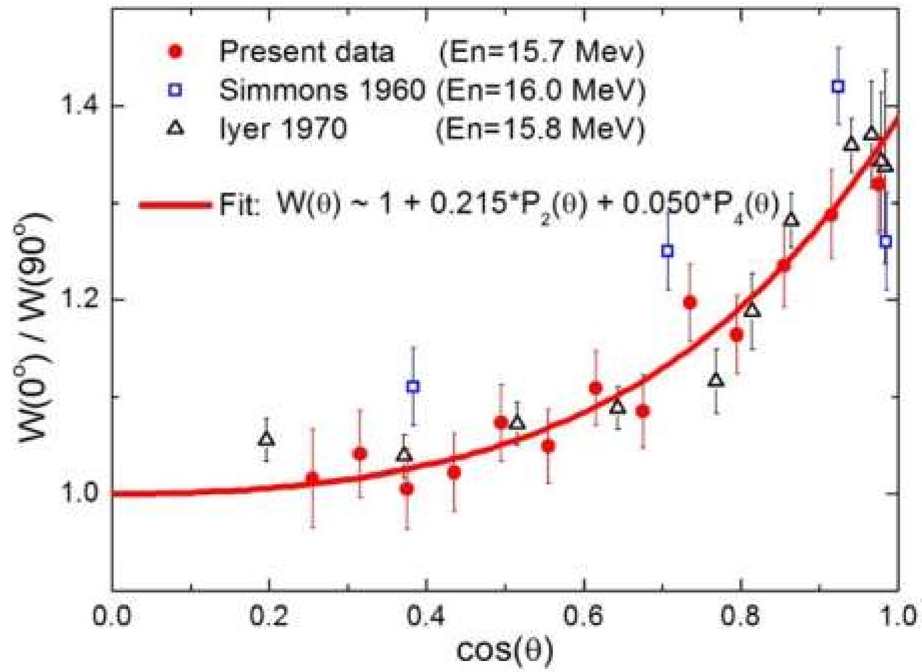
Cos θ Monte-Carlo simulation with real geometry



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

Results: angular distributions of ^{233}U





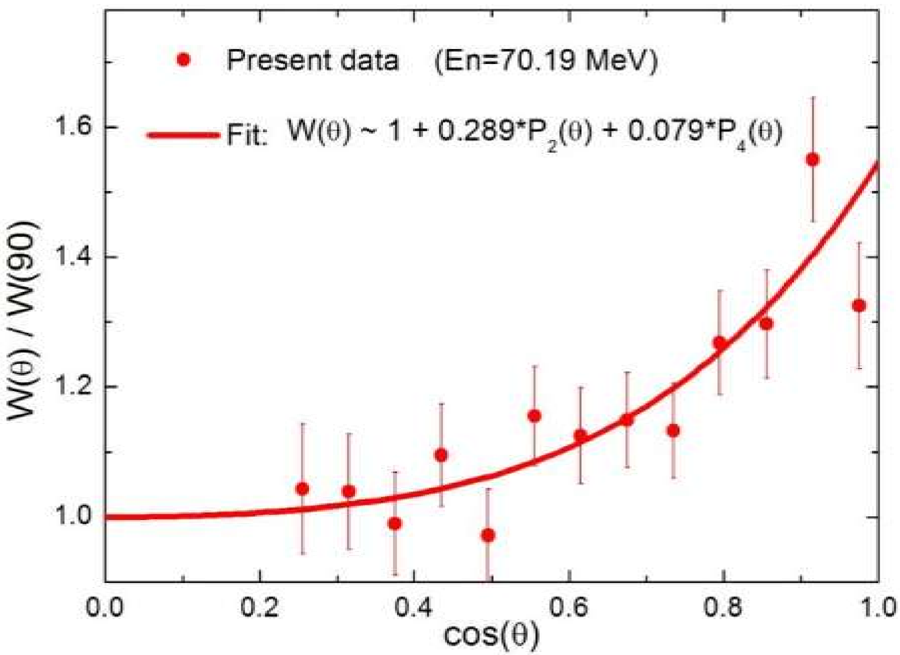
$$W(\theta) = A_0\left[1 + \sum_{n=1}^{2} A_{2n}P_{2n}(\cos(\theta))\right]$$

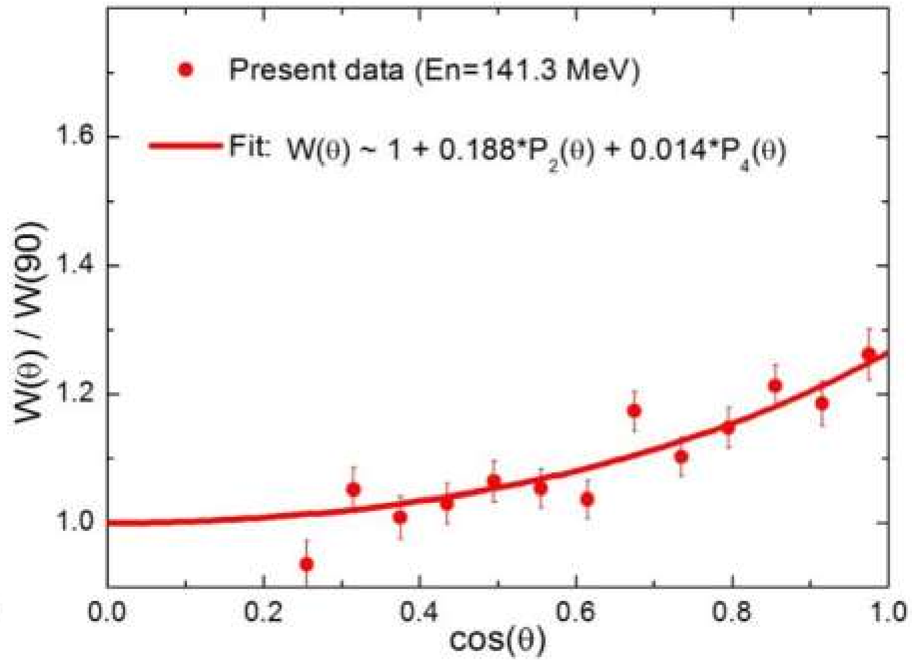
$$W(0°)/W(90°) = \frac{1 + A_2 + A_4}{1 - \frac{1}{2}A_2 + \frac{3}{8}A_4}$$

- ✓ In presented examples our results are in a good agreement with the other data.
- ✓ Since experimental techniques used by referred authors differ both in fragment detectors and in neutron sources, 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.

Cos θ fitting range was 0.24– 1.0

Results: angular distributions of 209Bi

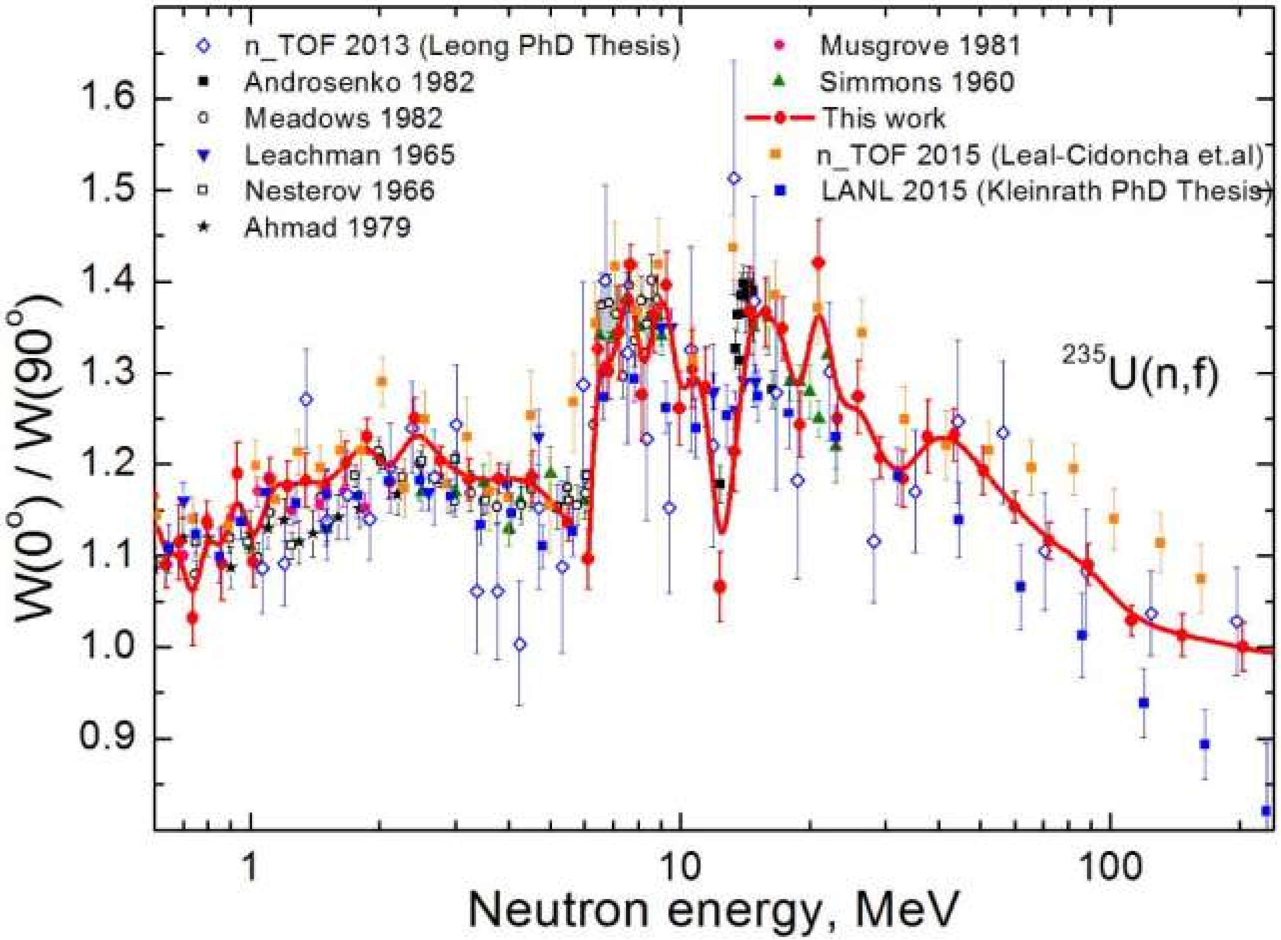




- ✓ Above 100 MeV, the angular distributions of fission fragments can be describe with good accuracy by following equations:

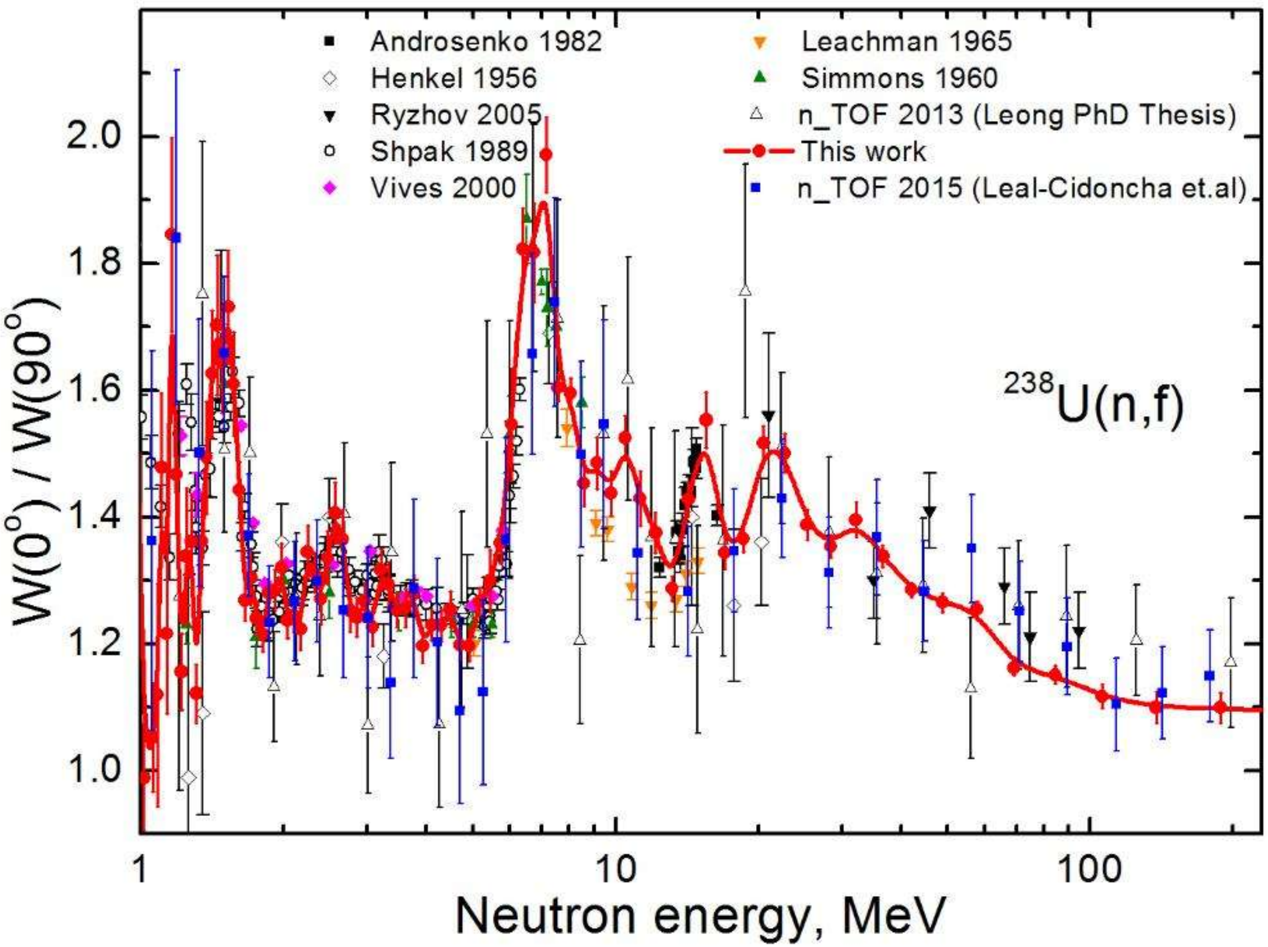
$$W(\theta) \sim (1 + b\,cos^2(\theta)) \qquad b = \frac{W(0^\circ)}{W(90^\circ)} - 1$$

Results: anisotropy in 235U



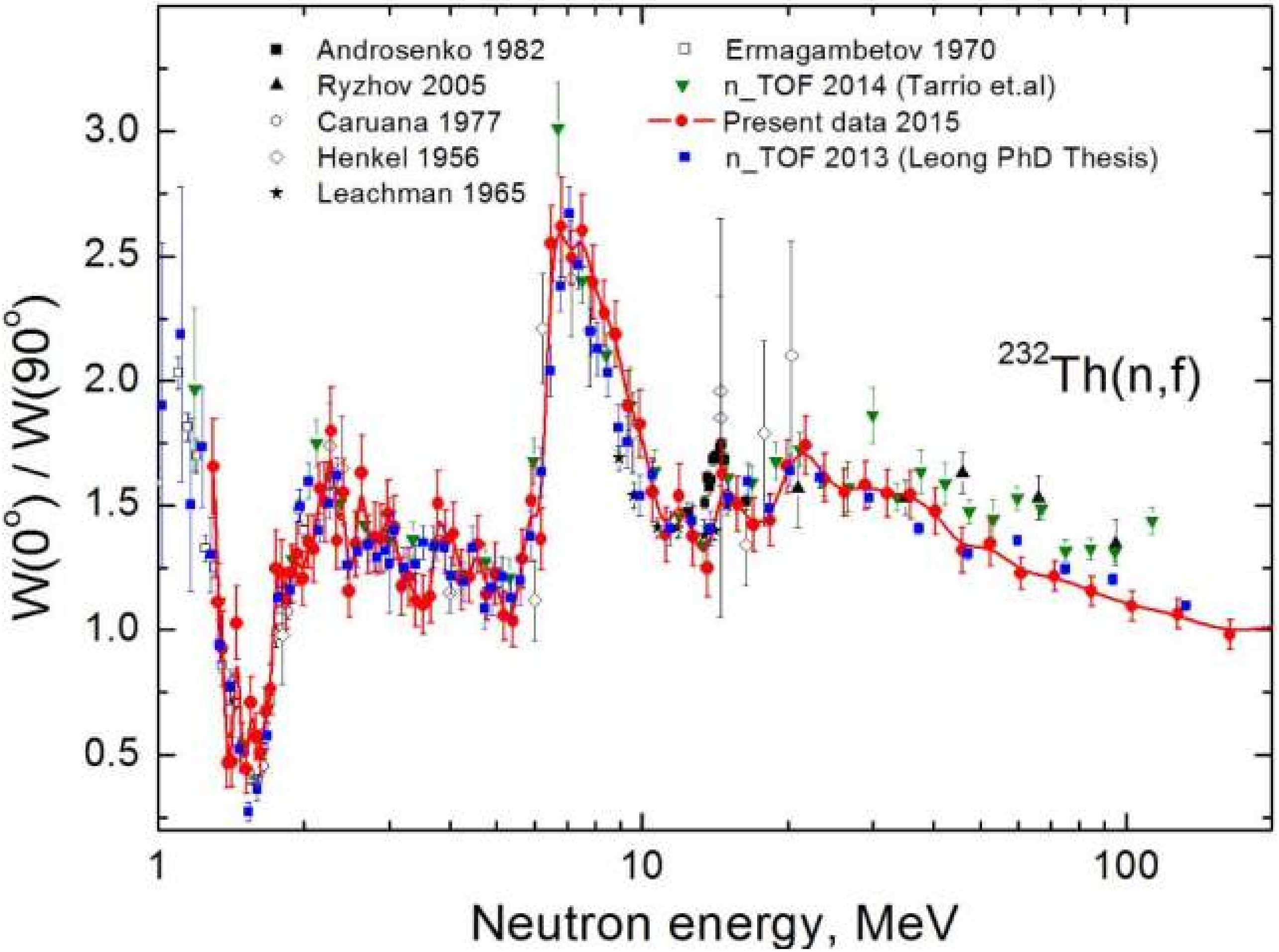
- ✓ There is a general agreement between data obtained in this work and by other experimental groups in neutron energy range 1-200 MeV.
- ✓ Above 50 MeV there is disagreement between these results and those recently obtained by Kleinrath (WNR, LANSCE) and Leal-Cidoncha et.al (n_TOF, CERN).

Results: anisotropy in 238U



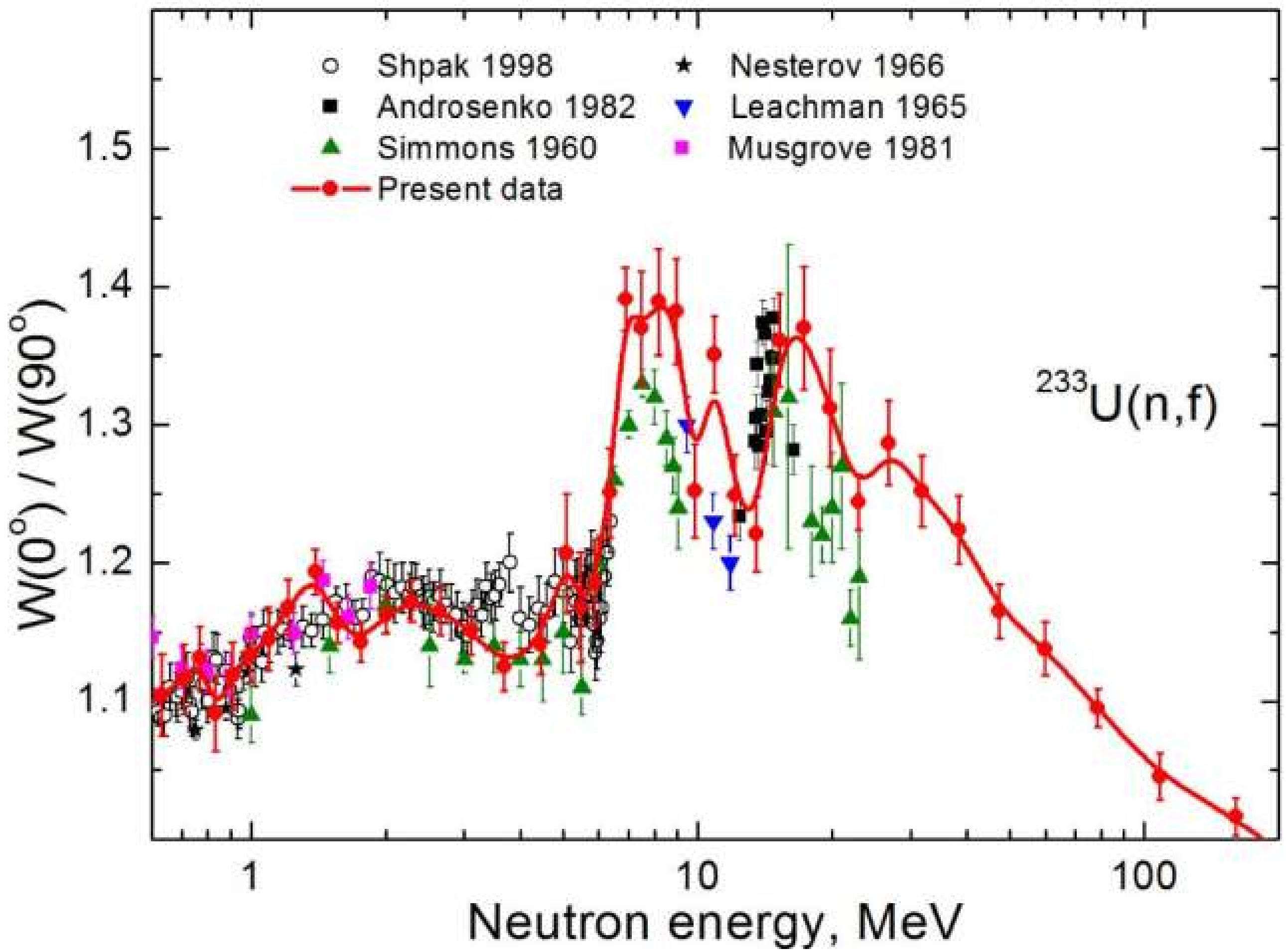
- ✓ There is a general agreement between data obtained in this work and by other experimental groups in neutron energy range 1-200 MeV.
- ✓ Above 20 MeV the uncertainties of our data are much smaller than those presented by Ryzhov et.al (TSL, Uppsala) and Leong, Leal-Cidoncha et.al (n_TOF, CERN).

Results: anisotropy in 232Th



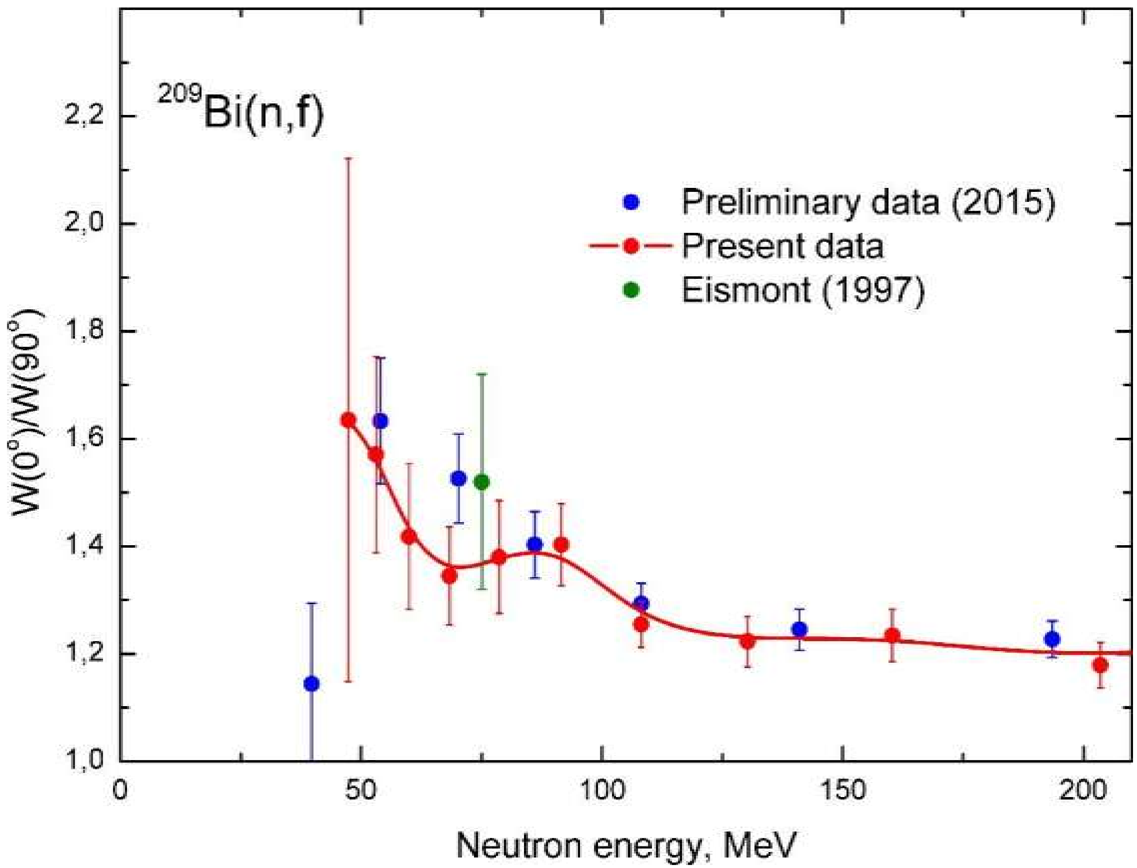
- ✓ There is a general agreement between data obtained in this work and by other experimental groups in neutron energy range below 40 MeV.
- ✓ Above 40 MeV our data agree with results given by Leong (n_TOF, CERN) and differ substantially from the data presented by Ryzhov et.al (TSL, Uppsala) and Tarrio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

Results: anisotropy in 233U



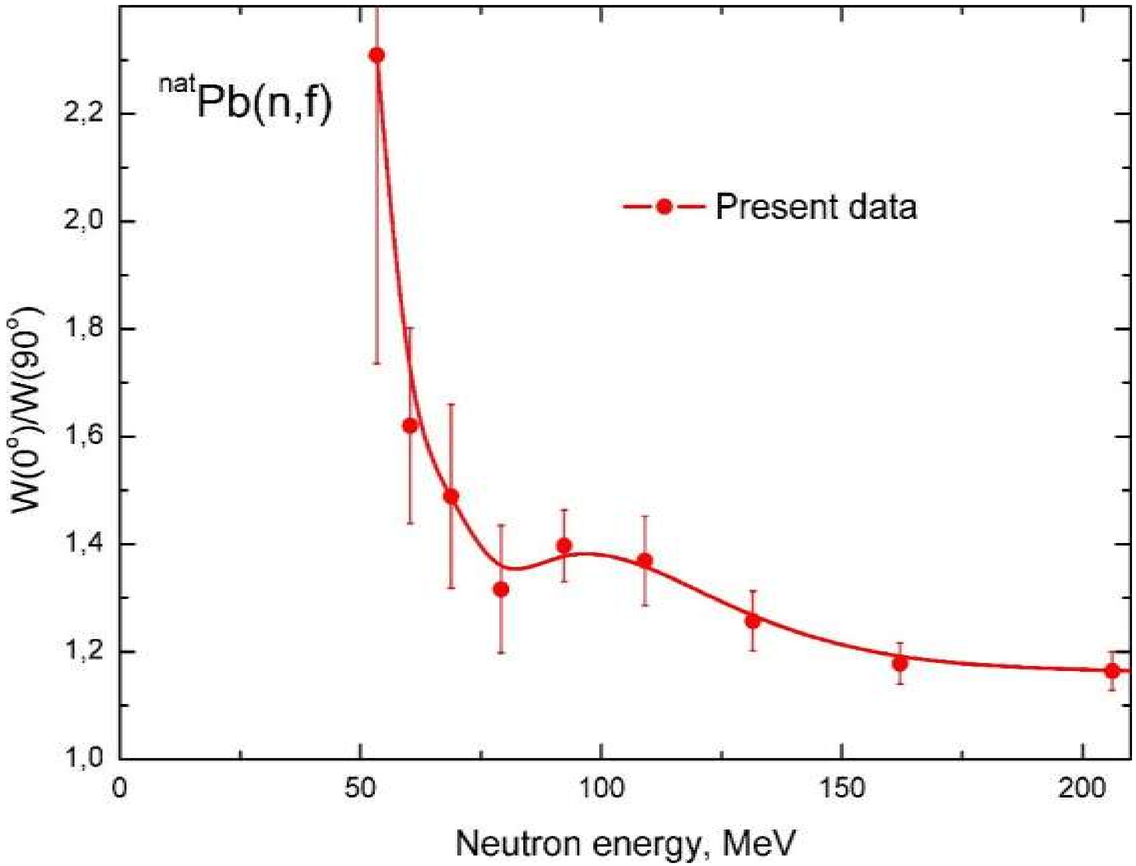
- ✓ In the neutron energy range below 20 MeV, our results agree within experimental uncertainties with the most full data sets. The exception are the Simmons data, in the neutron energy range 7-24 MeV, which are 4÷7% below than our data.
- ✓ Presently, there is only present results in the neutron energy range above 24 MeV.

Results: anisotropy in 209Bi



- ✓ There is no other data except our data. Our data agree with previous result Eismont et.al at 75 MeV.
- ✓ 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.
- ✓ There is some similarity between Pb and 209-Bi. The maximum anisotropy near the threshold seems to be even higher ~2.0

Conclusions

- The fission fragment angular distributions have been measured for ^{233}U, ^{235}U, ^{238}U, ^{232}Th, ^{209}Bi and ^{nat}Pb in neutron energy range 1-200 MeV using the same data processing and position sensitive multiwire proportional counters for fission fragments registration.
- The reliability of the used set-up and data processing are confirmed by an agreement between obtained results and available literature data within experimental errors (while the experimental techniques, fragment detectors, neutron sources and data processing are different):
  - For all investigated nuclei, in the neutron energy range below 20 MeV, the anisotropy of fission fragments emission obtained in this work is in a good agreement with other experimental works.
  - The angular distributions of fission fragments for the fixed neutron energy are consistent with available data.

Conclusions

- Anisotropy of the fission fragments emission has been measured :

  for ^{235}U
  - achieved accuracy of obtained anisotropy is 2÷5%;
  - above 50 MeV, our results are in agreement with the n_TOF data given by Leong, while the recent data presented 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 of obtained anisotropy 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 of obtained anisotropy 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

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

for ^{209}Bi

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

for ^{nat}Pb

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

for ^{239}Pu

- preliminary measurements have been performed ;
- the results will be obtained in this year.

- Additional investigations are needed in neutron energy range above 20 MeV because following:
  - 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 digit format (EXFOR database) except our results: Ryzov et al. (for ^{238}U and ^{232}Th) and Tarrio et al. (only for ^{232}Th);

Further plans

	$T_{1/2}$ (year)	A (Bq/mg)
Pu-239	24 110	2,29 E+06
Pu-240	6 561	8,37 E+06
Pu-241	14.35 (бета)	3,81 E+09
Pu-242	375000	1,45 E+05
Th-230	75 400	7,60 E+05
U-234	245 500	2,29 E+05
U-236	2.34 E+7	2,38 E+03
Np-237	2.14 E+6	2,59 E+04
Am-243	7 370	7,36 E+06

Thank you for attention

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Neutron beam profile

2D – image of neutron beam cross-section with ∅ 75 mm collimator