Investigation of the Prompt Neutron Emission Mechanism in Low Energy Fission of $^{233,\,235}$U(n_{th}, f) and ^{252}Cf(sf)

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Motivation

- To measure spectra of prompt fission neutrons at several angles relative to the light fragment direction to eliminate the absence of these data in literature.
- From previous experimental works:
  - The main source of prompt fission neutrons (PFNs) is accelerated fission fragments, the angular anisotropy of neutron emission is not established
  - The contribution of neutrons with other emission mechanism ("scission" neutrons) to the total yield of PFNs ranges from 1% to 20%
- To clarify the situation concerning the "scission" neutrons and angular anisotropy of neutron emission, the multi-parameter coincidence measurement of angular and energy distributions of neutrons and FFs is required.

Schematic view of the experimental set-up

Reaction Chamber:

^{235}U target (Ø15mm) – 280 μg/cm^2 UF_4 onto 70 μg/cm^2 Ti backing;

start MWPD (68 x 92 mm^2) located within 7 mm range from the target;

stop MWPD (72 x 38 mm^2) located at a distance of 140 mm from the chamber axis.

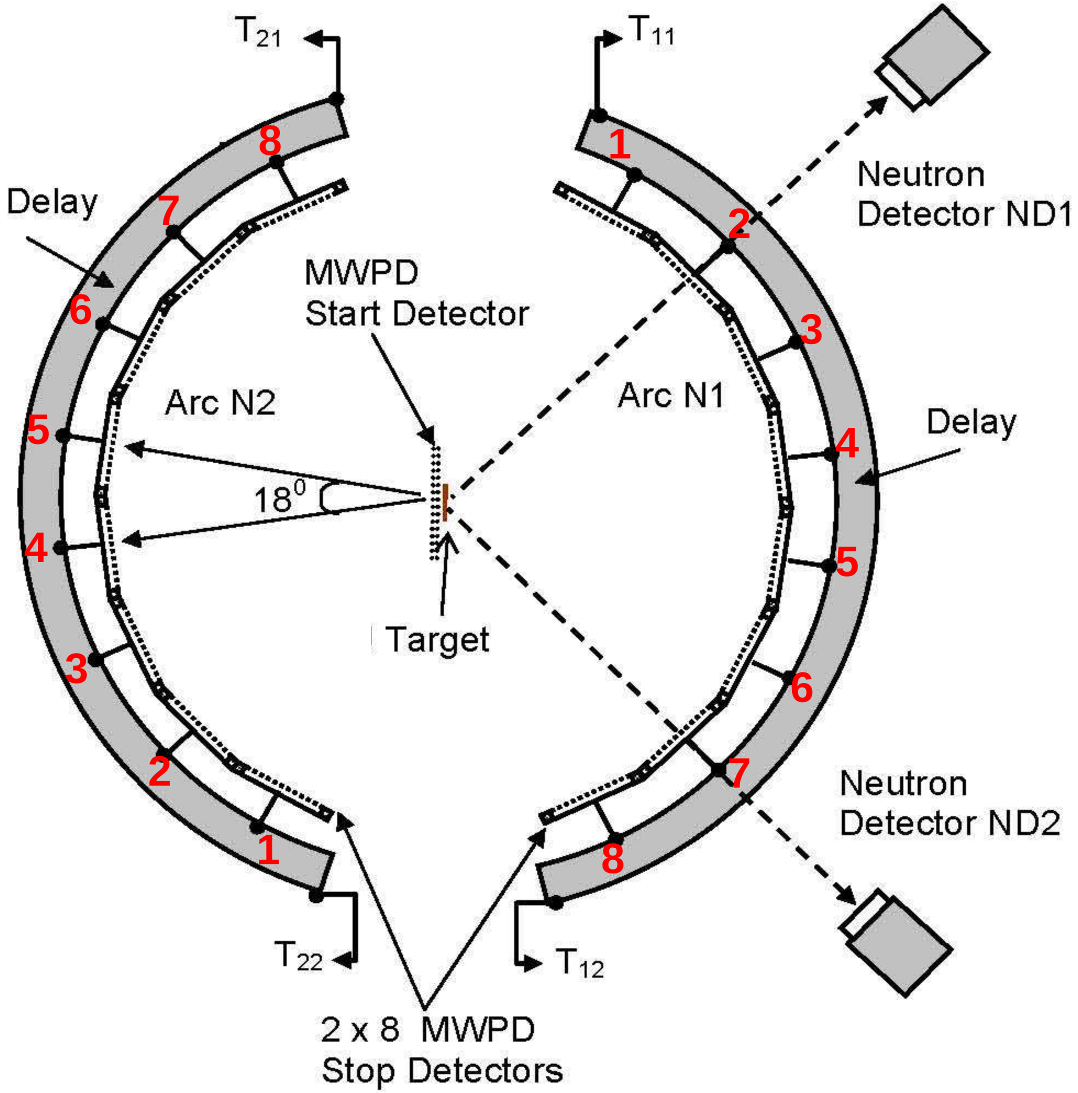
Neutron detectors:

stilbene crystals (50 x 50 mm^2 and 40 x 60 mm^2 mounted on the Hamamatsu - R6091)

neutron registration threshold – 150 ÷ 200 keV;

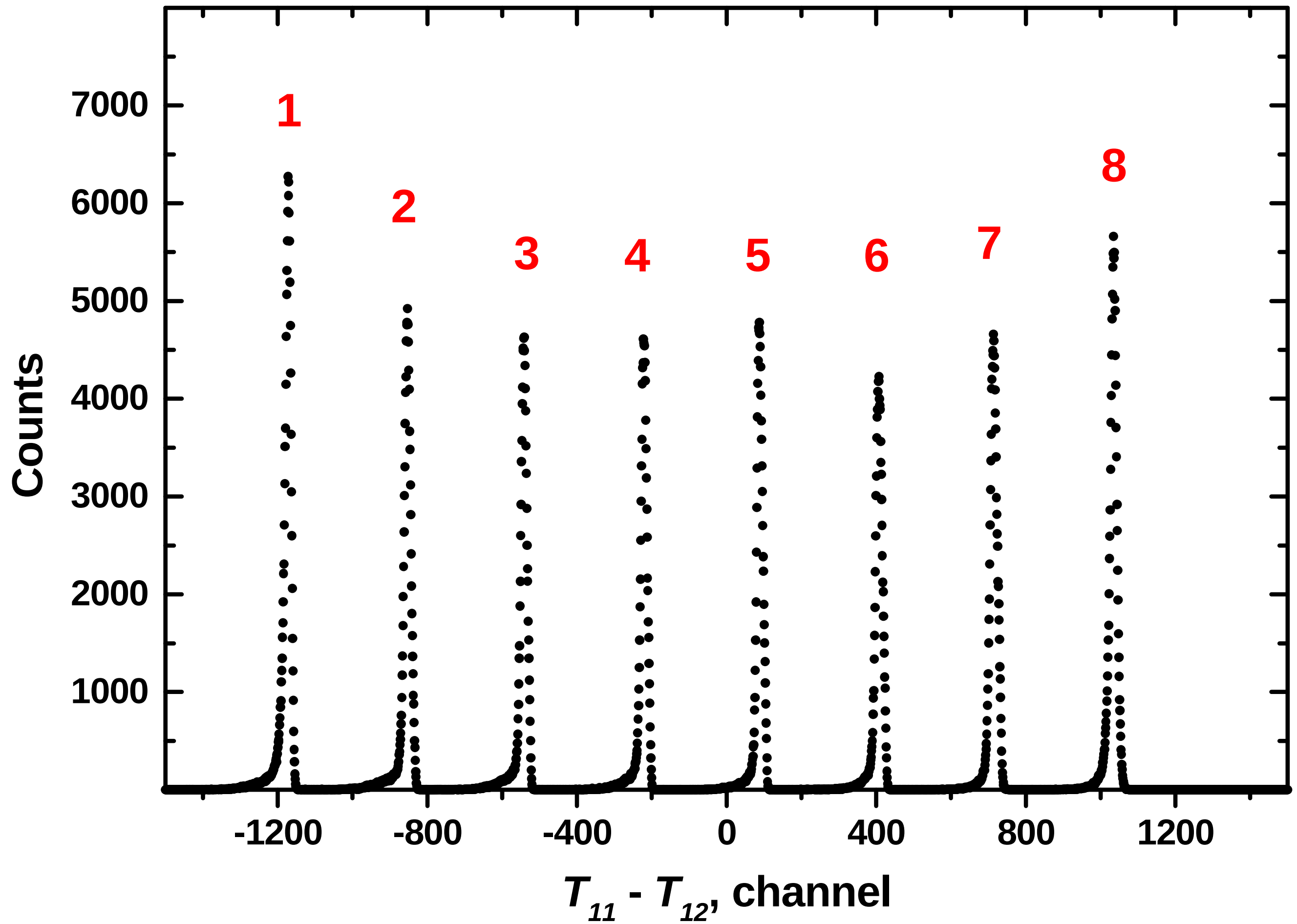
double-discrimination method – pulse shape and time-of-flight criteria

time-of-flight distance from target – ~ 50 cm



Raw experimental data:

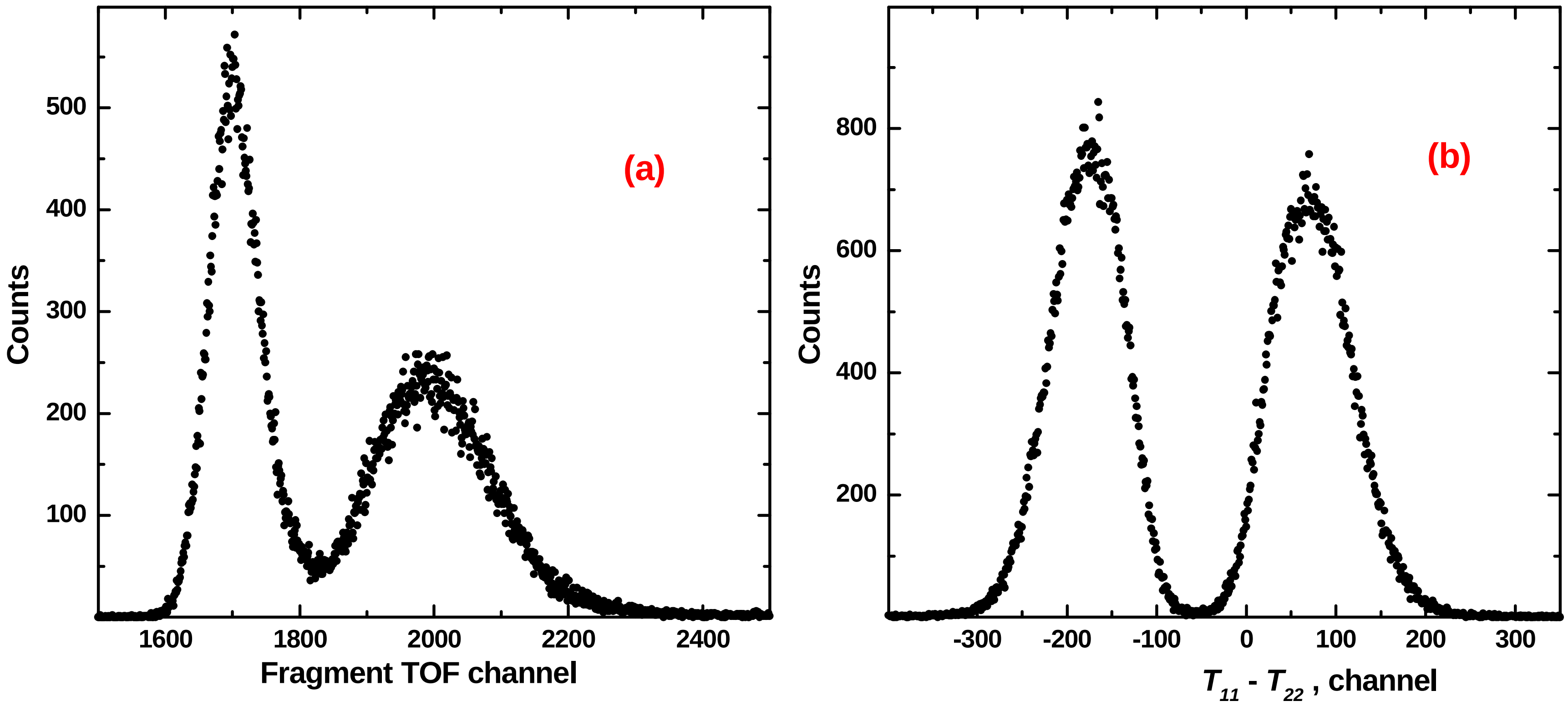
counts rate of fission fragments from different fragment detectors



Number of registered fission events as a function of MWPDs pulse timing delay from both ends of Arc N1

Raw experimental data:

fission fragments time-of-flight

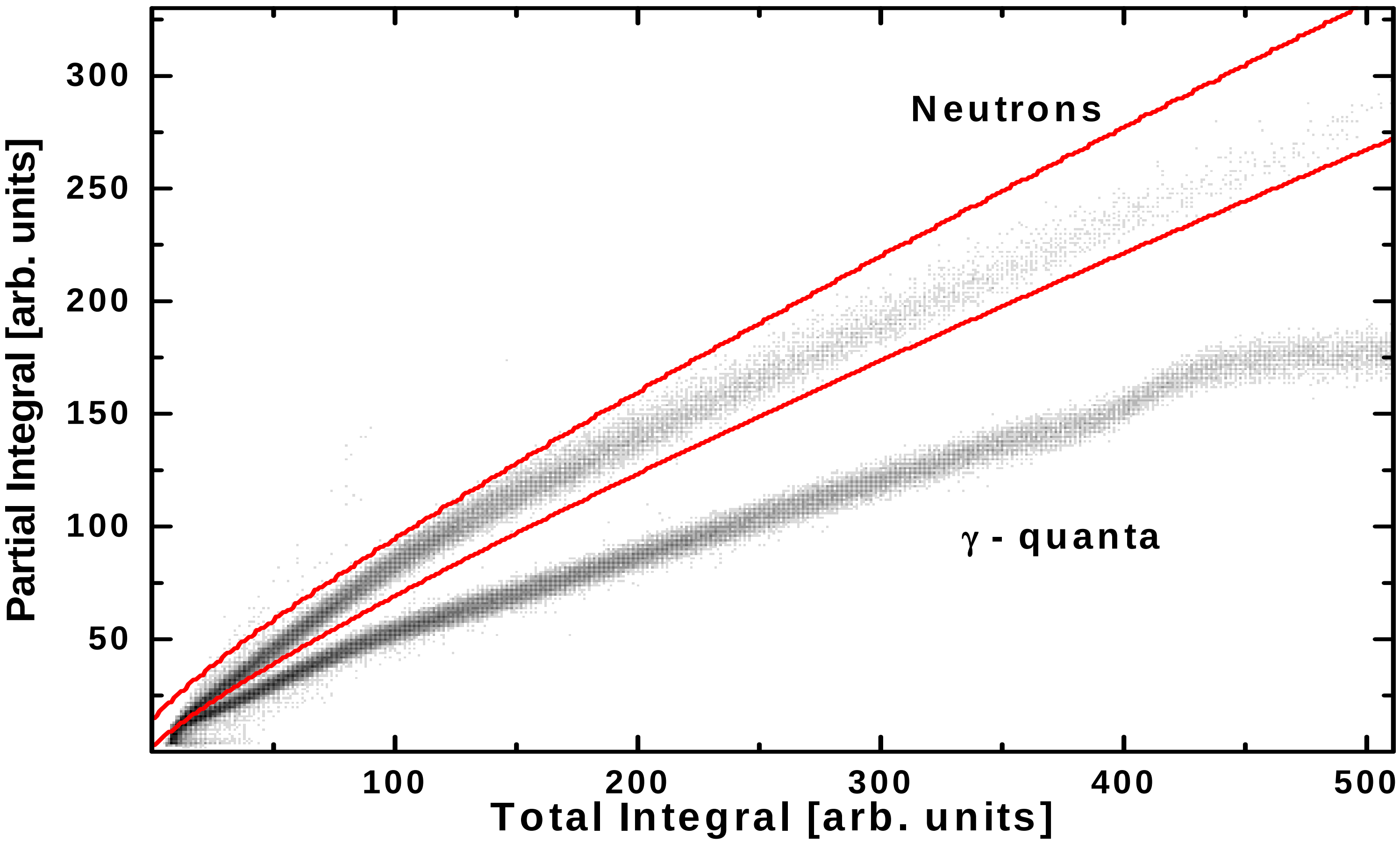


(a) fission fragments time-of-flight spectrum measured with second MWPD of Arc N1 (wasn't shaded by start MWPD)

(b) number of fragments as a function of TOF difference for fragments registered by two opposite detectors of Arc N1 and N2

Raw experimental data:

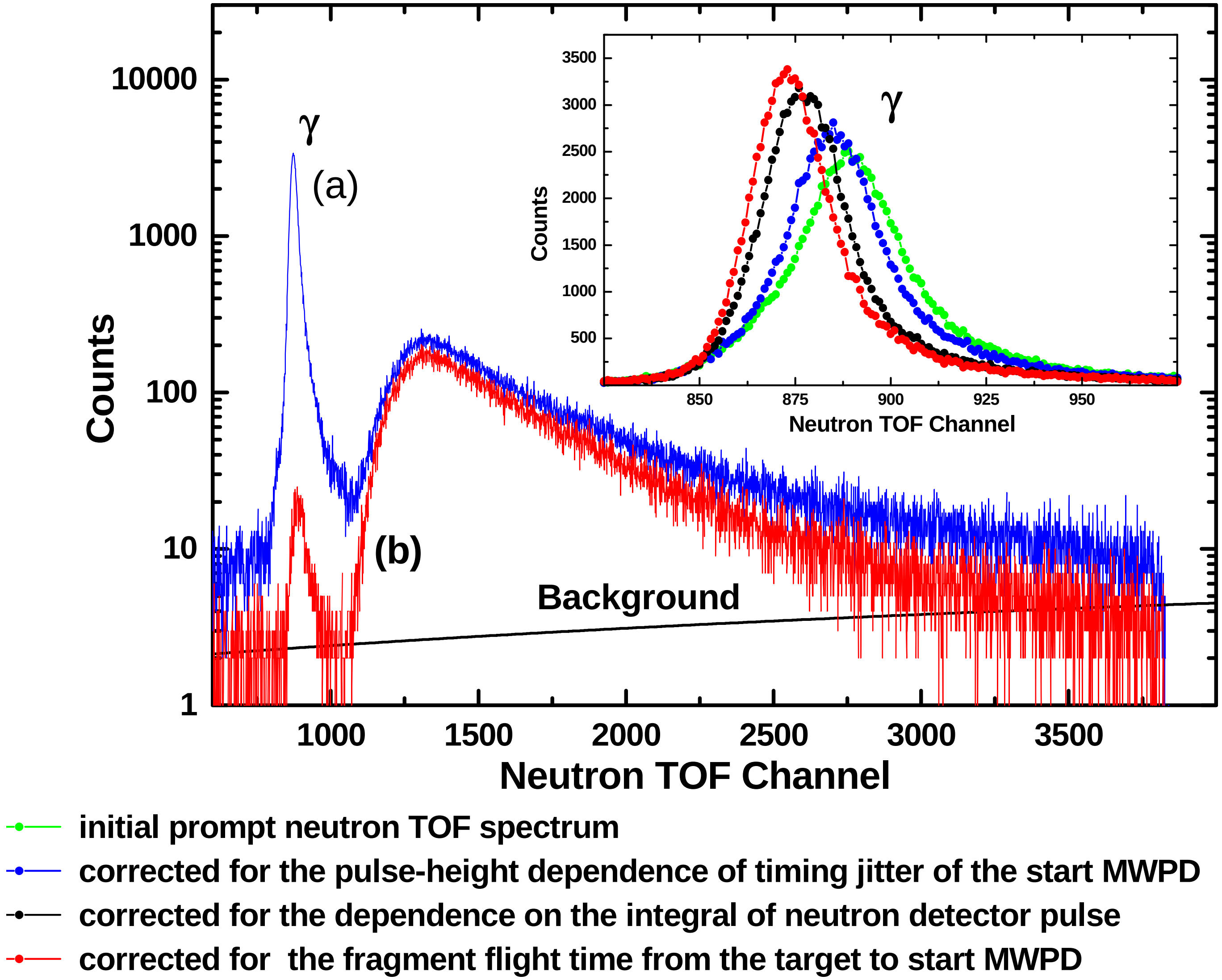
neutron - γ - quanta separation method



Both integrals (pulse-area) were measured for neutron detector in a time window of 300 nsec, while the partial integral window – with a delay ~30 nsec.

Raw experimental data:

total prompt neutron time-of flight spectrum



Analysis of the data

*Applied corrections for **:*

- time uncertainties in TOF measurements;
- neutron detector background (a double-discrimination method, true coincidence subtracted and the linear approximation of the remain part of background);
- fission fragment detector efficiency;
- complementary fission fragment contribution;
- angular and neutron energy resolution;
- neutron recoil correction;
- neutron detector efficiency determined as the ratio of the measured total neutron spectrum of ^{252}Cf(*sf*) to the reference standard spectrum;
- normalization to the average fission neutron multiplicity of ^{235}U recommended by ENDF/B-VII;

** - *Measurements of angular and energy distributions of prompt neutrons from thermal neutron-induced fission A.S. Vorobyev, O.A. Shcherbakov, Yu.S. Pleva, A.M. Gagarski, G.V. Val'ski, G.A. Petrov, V.I. Petrova, T.A. Zavarukhina, NIM A598 (2009) 795*

Analysis of the data

General features of the investigation of neutron emission mechanism:

- The contribution of "scission" neutrons is usually determined as difference between experimentally observable variables in the laboratory system and those calculated using known neutron spectra in the center-of-mass system.
- As the prompt neutron energy spectra in the center-of-mass system of light and heavy fragments the Maxwellian or Weisskopf spectra are usually used. The parameters of these spectra are adjusted so as to show the best fit of available experimental data.
- In our analysis the angular and energy spectra of the prompt fission neutrons emitted by accelerated fragments are calculated using experimental data for 0^0, 18^0 and 36^0 angles relative to the fission direction. Thus the calculated spectra are free of any parameters concerning the prompt neutron spectra in c.m.s.
- As a first step, the model of two fragments with average mass and kinetic energy is used for calculation of neutron spectra in the laboratory system instead of real mass and kinetic energy distributions.

Analysis of the data

Main features of our calculation

- Used equations (two fragments approximation):

The neutron spectra in the laboratory system:

$$n_{lab}(E_n, \theta_{lab}) = (E_n / E_{c.m.})^{1/2} \cdot \phi(E_{c.m.}, \Omega_{c.m.}) \cdot n_{c.m.}(E_{c.m})$$

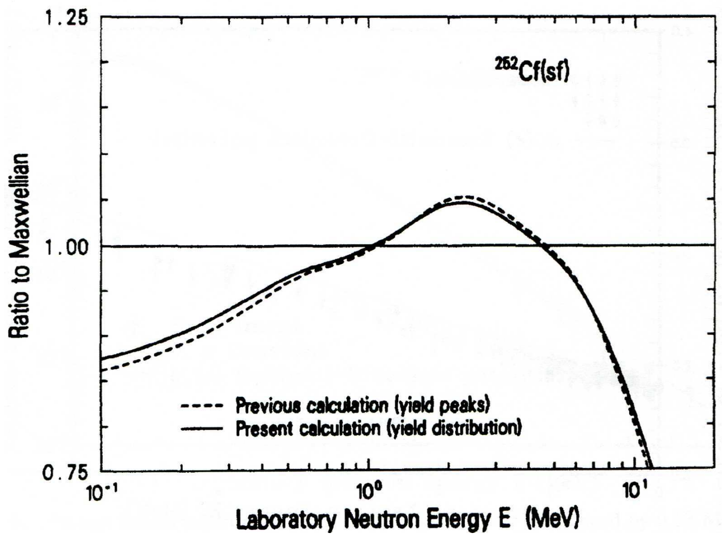
The neutron energy and spectra in the c.m.s of the fission fragments:

$$E_{c.m.} = E_n + E_f - 2 \cdot \cos(\theta_{lab}) \cdot (E_n \cdot E_f)^{1/2}$$

$$\phi(E_{c.m.}, \Omega_{c.m.}) = 1 + A_2 \cdot E_{c.m.} \cdot (3 \cdot \cos^2(\Omega_{c.m.}) - 1) / 2 ,$$

where anisotropy $A_2 = (1 - \phi(1,90^0) / \phi(1,0^0)) \geq 0.$

- Two fragments approximation gives a very good result, since, it was shown for ^{252}Cf(*sf*)** , it has a minor influence on the total neutron energy spectrum.



**D.G. Madland, IAEA Report INDC(NDS) – 251, Vienna, 1991, p. 201

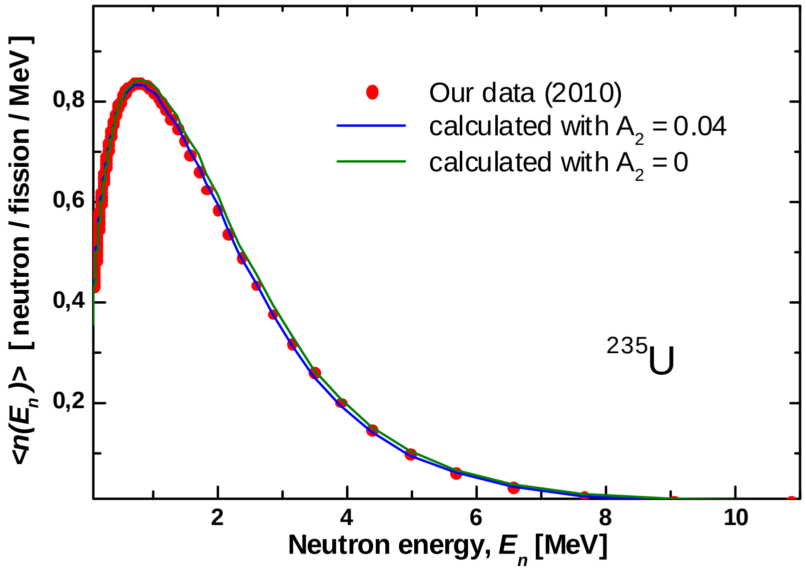
Analysis of the data

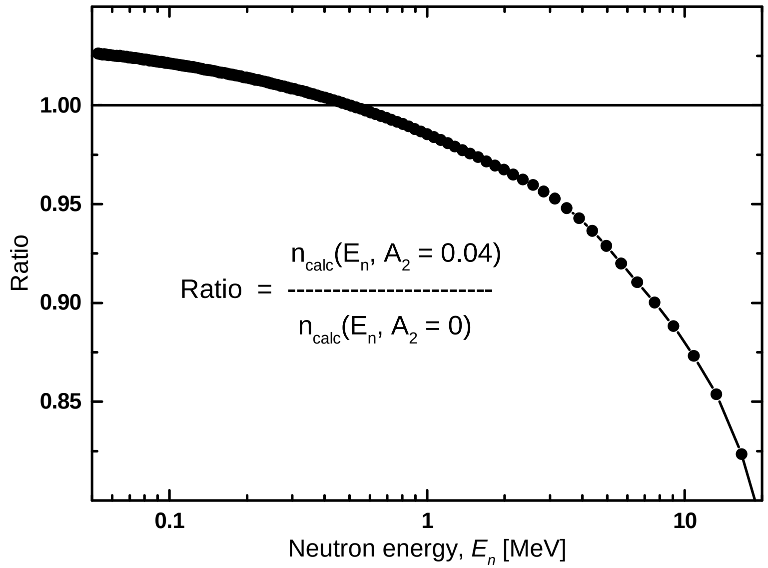
Calculation procedure

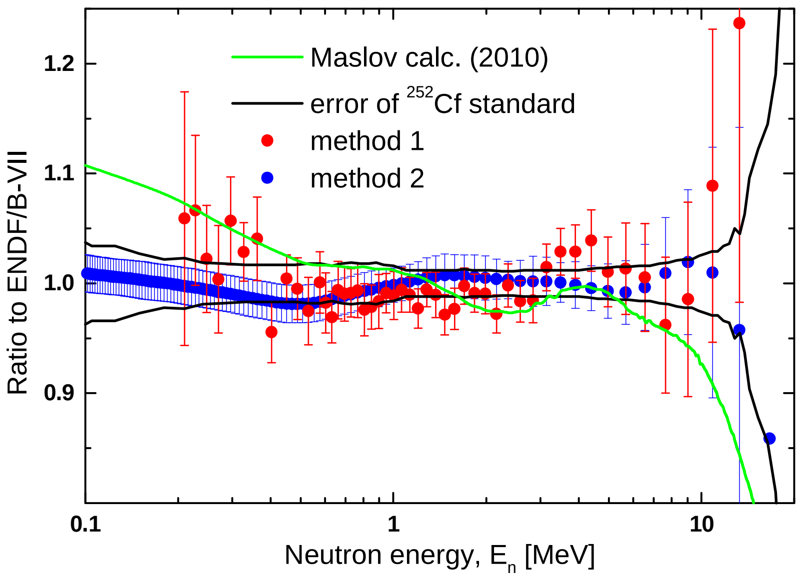
- *At the first step*, the neutron energy spectra in c.m.s are calculated under the assumption that neutrons registered at fixed angles relative to the light fragment direction were emitted solely by the light and heavy fragments, respectively;
- *At the second step*, the neutron contribution to the complementary fragment is subtracted and the energy spectra for these angles in the laboratory system are obtained;
- *Further*, using these energy spectra in the laboratory system, the neutron energy spectra for light and heavy fragments are obtained in the center-of-mass system;
- *Finally*, the spectra obtained in the center-of-mass system are used for calculation of neutron angular and energy distributions in the laboratory system.

Results:

total prompt neutron spectra in the lab. system







method 1 – summation over angles;

method 2 – calculated in a framework of neutron emission from accelerated fragments (A_2=0.04) using experimental spectra measured at small angles relative to fragment direction.

Results:

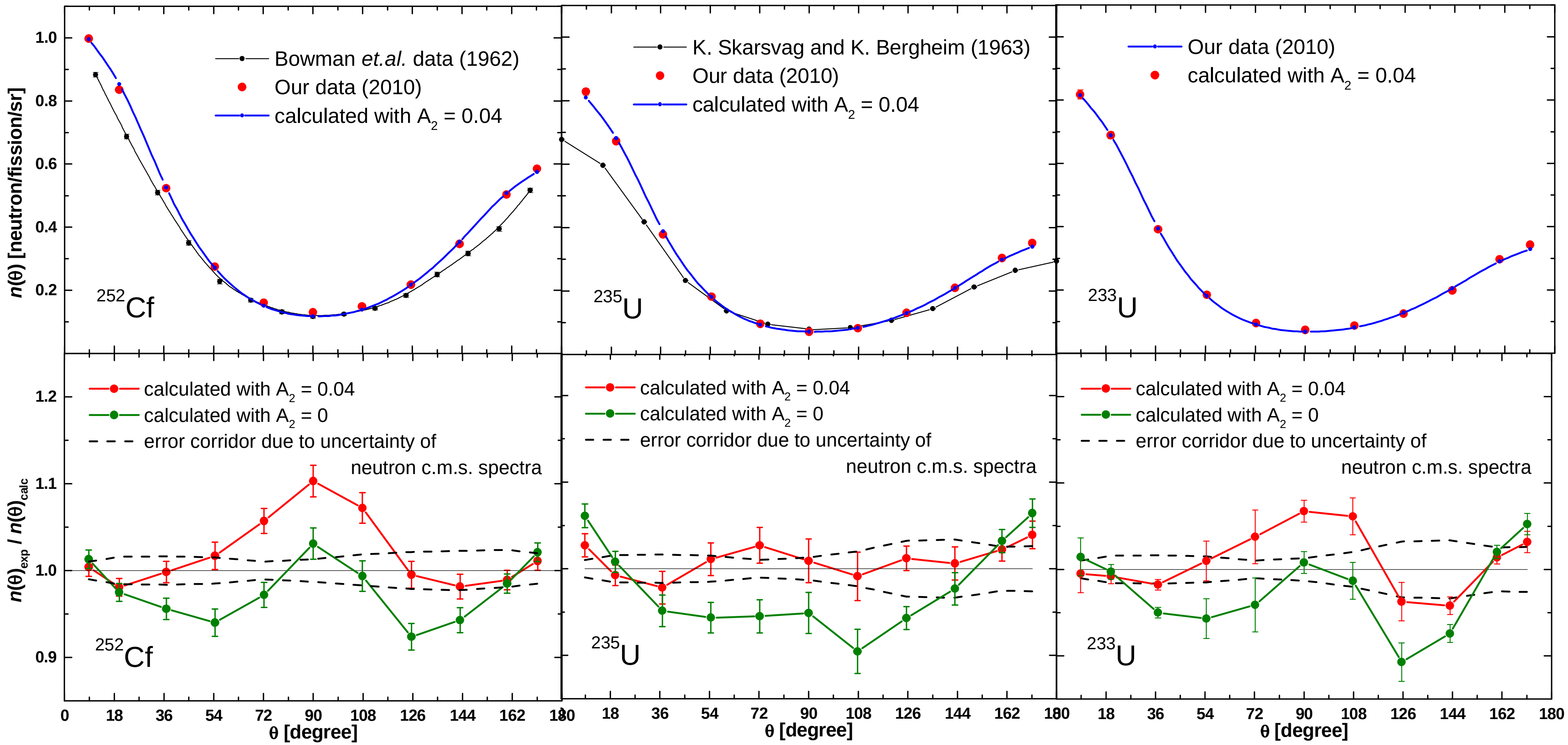
total prompt neutron spectra in the lab. system

Target	ν_{prompt} (Neutron / fission)			
	Calculated		Experiment	ENDF/B-VII
	$A_2 = 0$	$A_2 = 0.04$		
^{252}Cf(sf)	3.86	3.73	3.77 ± 0.02	3.7590
^{235}U(n_{th}, f)	2.56	2.45	2.44 ± 0.05	2.421
^{233}U(n_{th}, f)	2.60	2.48	2.54 ± 0.06	2.4894

- Both experimental and calculated prompt neutron spectra have been compared in 0.2-12 MeV energy range.
- The calculation performed using experimental data obtained for small angles relative to the fission fragment direction reproduces the total prompt neutron spectra both the shape and the average multiplicity .
- Also, the calculated energy spectra for fixed angles agree rather well with experimentally obtained ones.
- There is a minor distinction which is that the calculation ($A_2 = 0$) gives overestimated value of fission neutron yield as compared with experimental data.

Results:

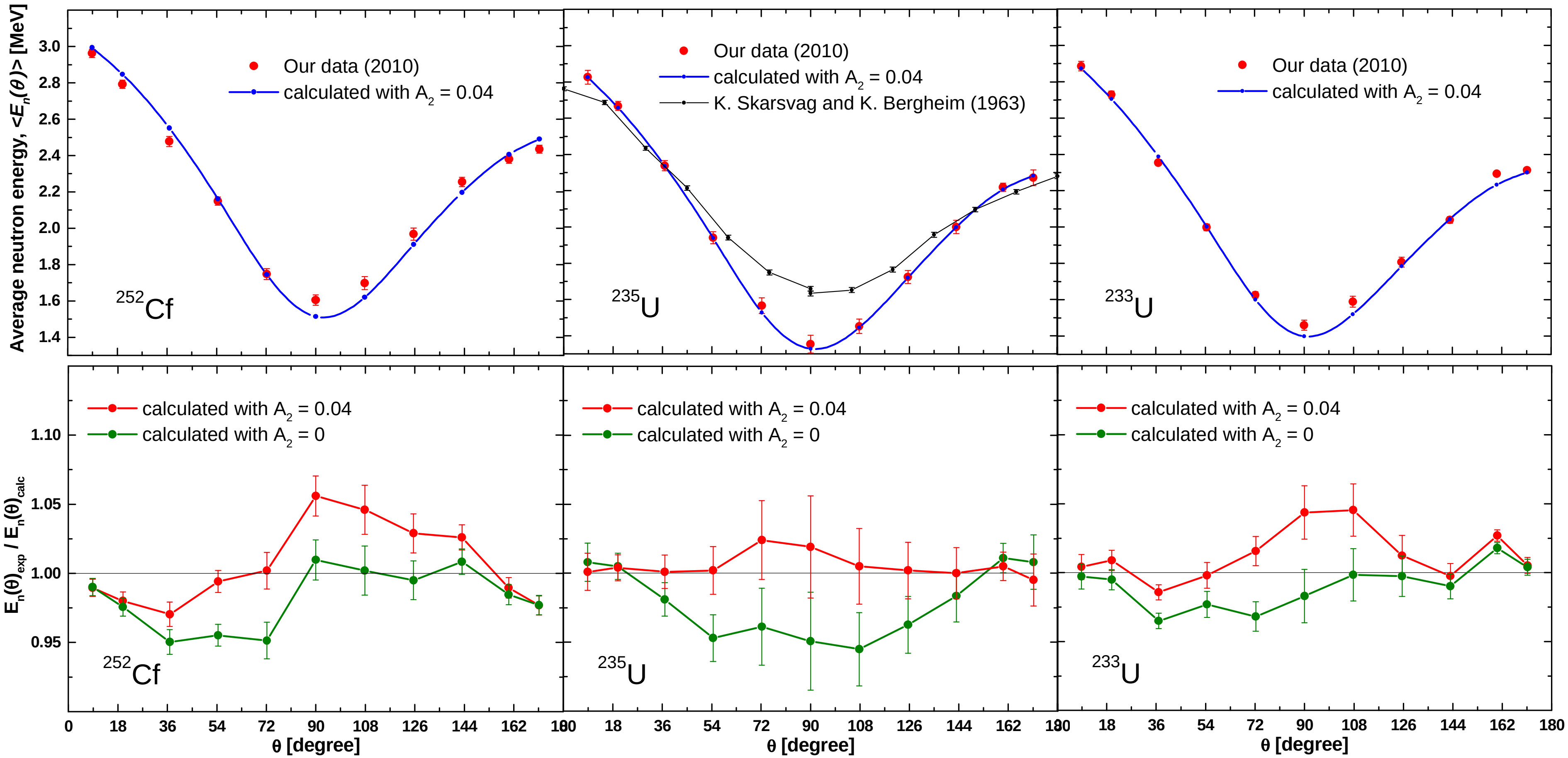
yield of prompt neutrons as a function of angle relative to the direction of light fission fragment in the lab. system



- Introduction of anisotropy with A_2 = 0.04 into the calculation improves agreement with obtained experimental data. At that, there is some surplus of measured yield over calculated at angles near 90^0.

Results:

angular distribution of the average prompt neutron emission energy

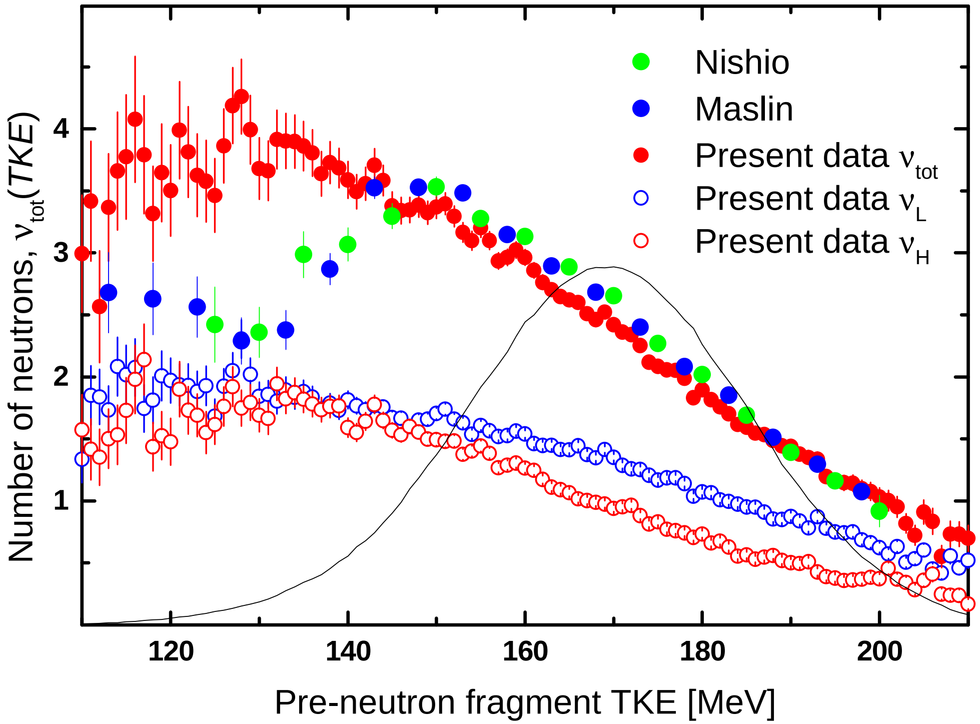


- Under the assumption that the "additional" neutrons are emitted isotropically in the laboratory system, their yield is deduced as about 5%, 4% and 3% of the total neutron yield for ^{252}Cf(*sf*), ^{233}U(n_{th}, *f*) and ^{235}U(n_{th}, *f*) respectively.

Results (correlation with FFs):

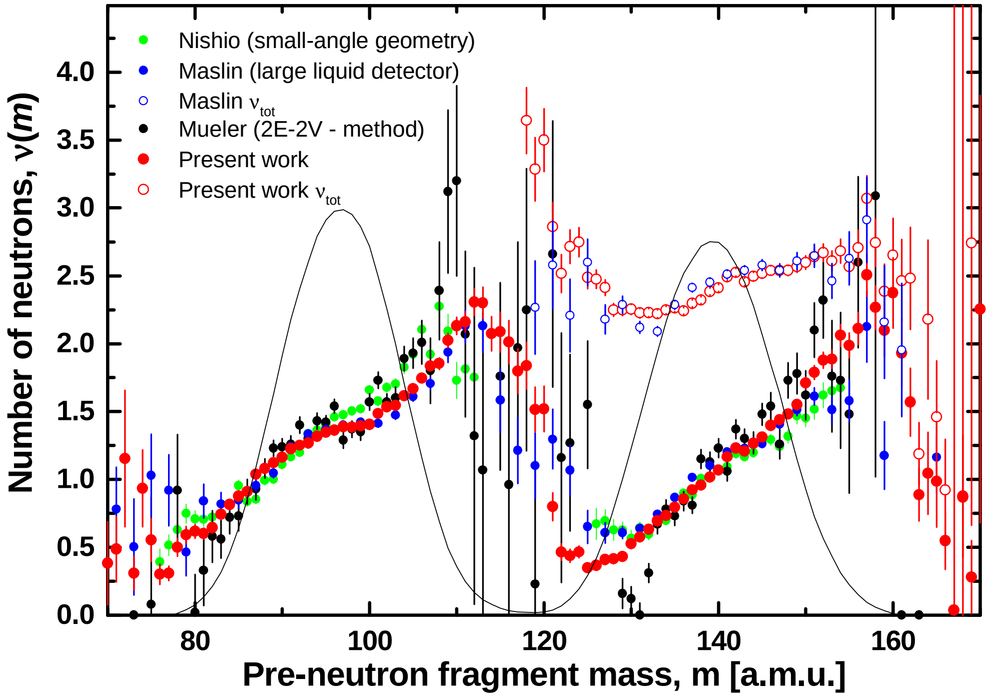
- The transformation of neutron spectra in the laboratory system (at small angles relative to fragments direction) to the center-of-mass system was performed for each fragment fixed mass and energy.
- A good agreement is observed between average number of prompt neutrons obtained by this experiment and other authors.

average prompt neutron multiplicity vs TKE



Results (correlation with FFs):

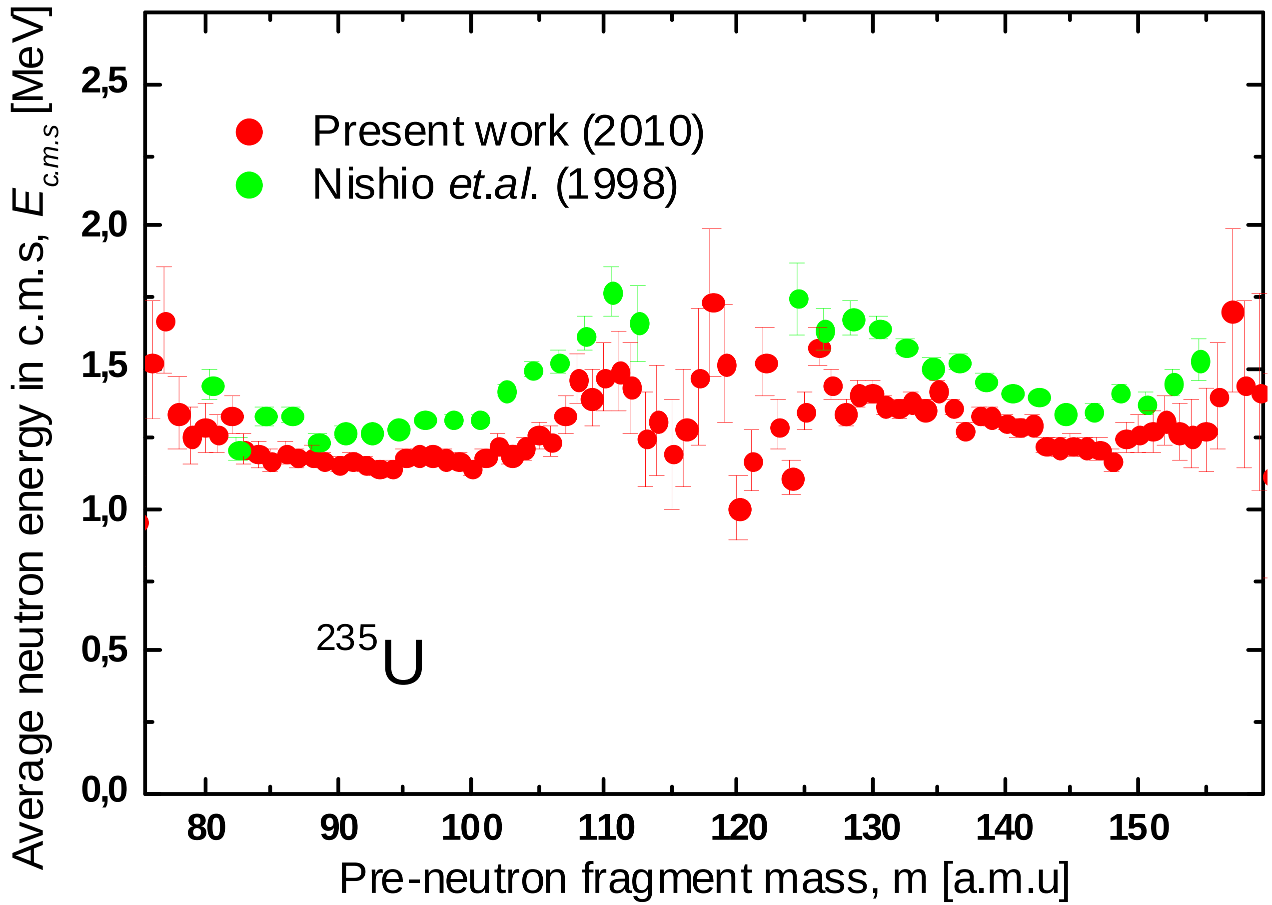
average prompt neutron multiplicity vs fragment mass



- The total number of prompt neutrons calculated from measured data at small angle is practically coincident with obtained from direct measurement of Maslin *et.al*. (large Gd-loaded liquid scintillation counter with efficiency about 85% - 4π-geometry). Probably, this means that a fraction of neutrons originating from sources other than accelerated fragments is small.

Results (correlation with FFs):

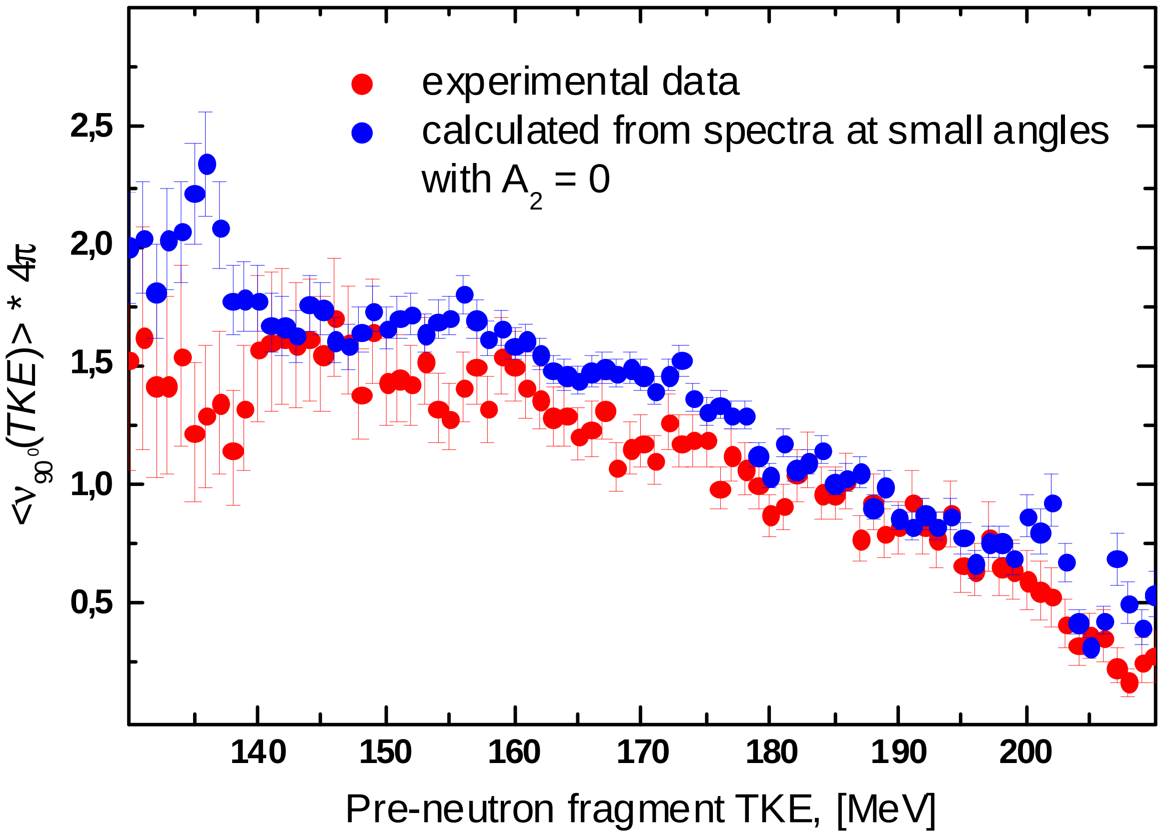
average neutron energy in the center-of-mass system vs fragment mass



- There is an overall agreement with Nishio *et.al*. data , but the Nishio's data is systematically higher then the present data (about 0.15 MeV).

Results ^{235}U (correlation with FFs):

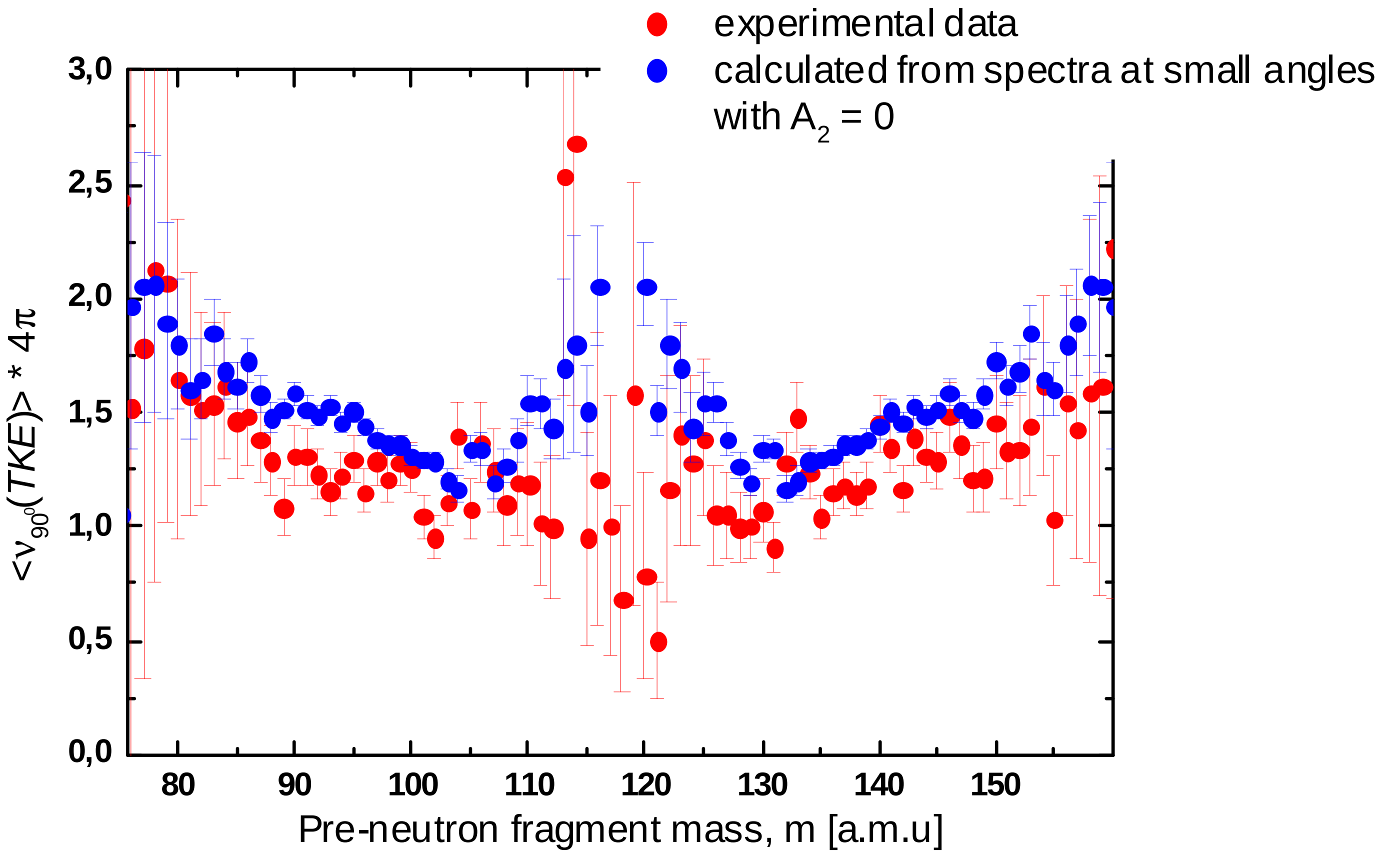
the average number of prompt neutrons emitted perpendicular to the fragment direction as a function of TKE



- The measured dependencies of prompt neutrons emitted at 90^0 relative to FFs direction on TKE and fragment mass are like to calculated ones. The inclusion of neutron anisotropy into calculation reduces the calculated prompt neutron yield by about 10%.

Results (correlation with FFs):

the average number of prompt neutrons emitted perpendicular to the fragment direction as a function of FFs mass



- Thus, the discrepancy between average number of prompt neutrons measured at 90^0 relative to FFs direction and calculated one is approximately constant and doesn't depend on fragment mass and the total kinetic energy (TKE).

Conclusion

- The prompt fission neutron energy spectra have been measured for $^{235,233}U(n_{th}, f)$ and $Cf(sf)$ at 11 fixed angles between the neutron and light fragment directions in the range from 0^0 to 180^0 in 18^0 interval.
- Comparison of experimentally obtained angular and energy distributions of prompt neutron and calculated one on the base of neutron evaporation from fully accelerated fragments enables:

  to estimate the contribution of "scission" neutrons as not to exceed 5% of total neutron yield in an assumption of isotropic evaporation in the laboratory system;

  to conclude that the angular anisotropy of the neutron emission in the fragment center-of –mass system, which is alike to $\sim 1 + 0.06 \cdot E_{c.m.} \cdot \cos^2(\Omega_{c.m.})$, should be included into any calculation of prompt neutron properties in the nuclear fission.
- Now we are doing more careful analysis of the obtained angle-energy distributions to determine the dependence of main characteristics of "scission" neutrons on fragment mass and kinetic energy.
- In future we are planning to carry out the same experiment for $^{239}Pu(n_{th}, f)$.

Thank you very much for your attention

Results $^{235}U(n_{tn},f)$:

ratio of the prompt neutron yields at 0^0 and 90^0 (180^0 and 90^0) as a function of energy in the lab. system