Prompt neutron emission in thermal neutron-induced fission of $^{235}U(n_{th}, f)$

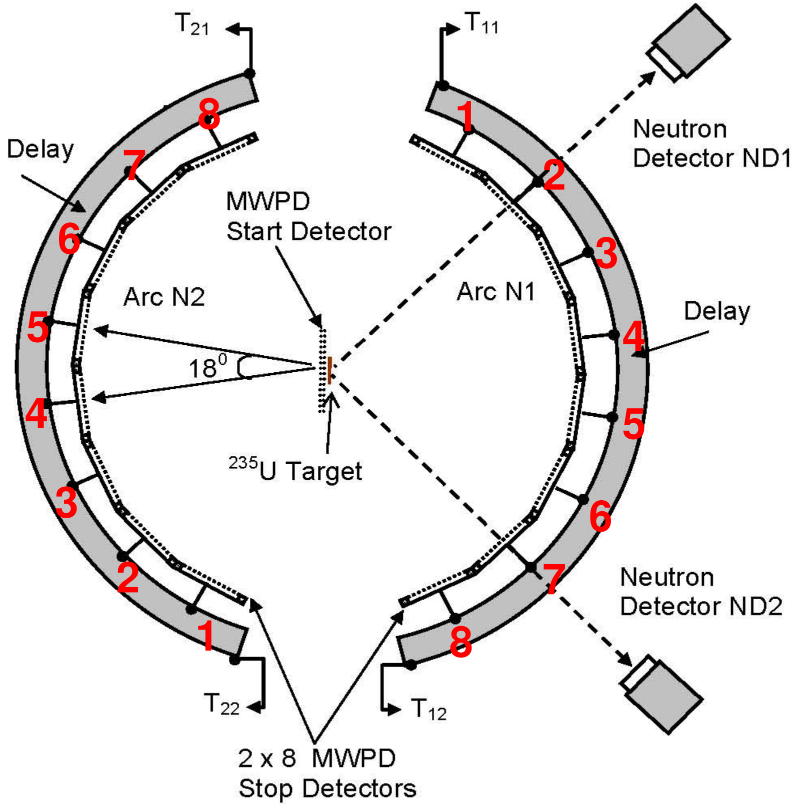
Vorobyev A.S., Shcherbakov O.A., Gagarski A.M.,
Val'ski G.V., Petrov G.A.

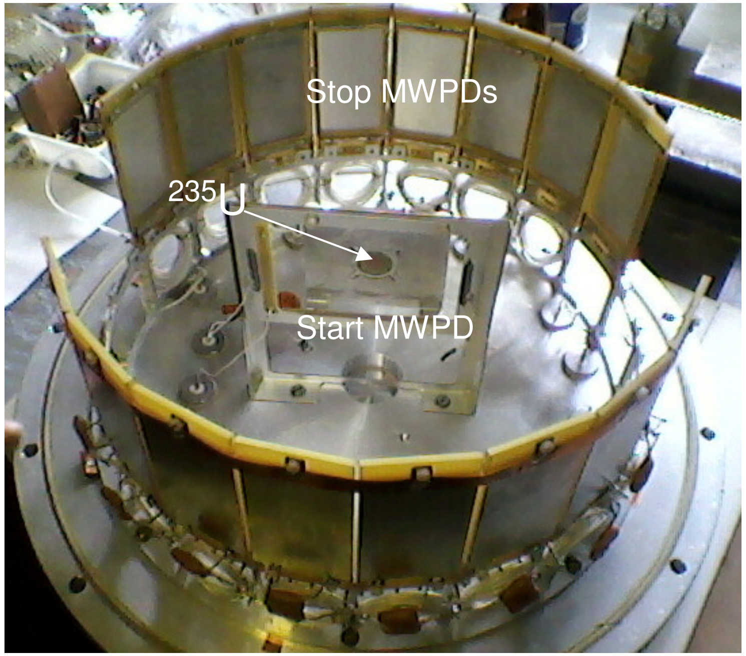
Petersburg Nuclear Physics Institute.
188300, Gatchina, Leningrad district, Russia
E-mail: alexander.vorobyev@pnpi.spb.ru

Motivation

- The main purpose is experimental investigation of the prompt neutron emission mechanism by the multi-parameter coincidence measurement of angular and energy distributions of neutrons and fission fragments.
- It is known 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 measure spectra of prompt fission neutrons at several angles relative to the light fragment direction to eliminate the absence of these data in literature.

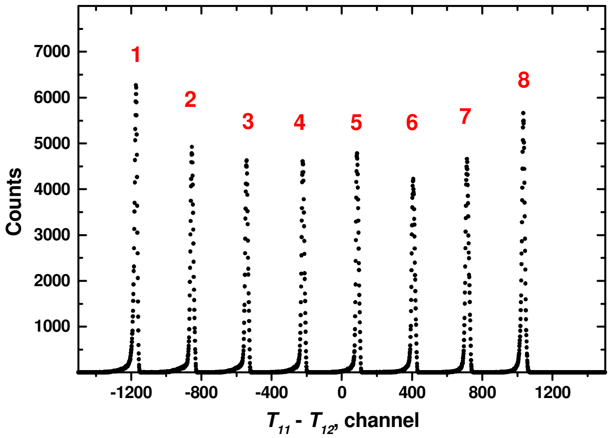
Schematic view of the experimental set-up

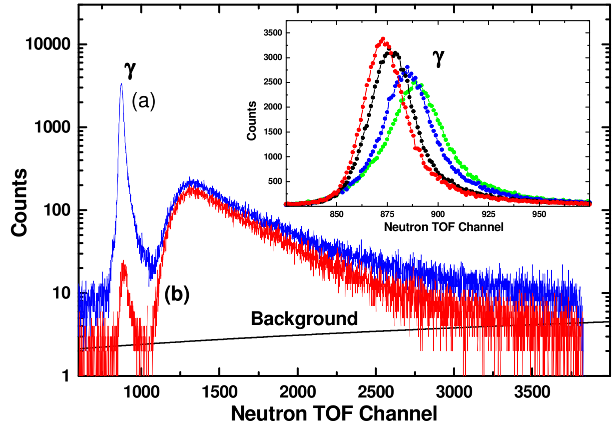


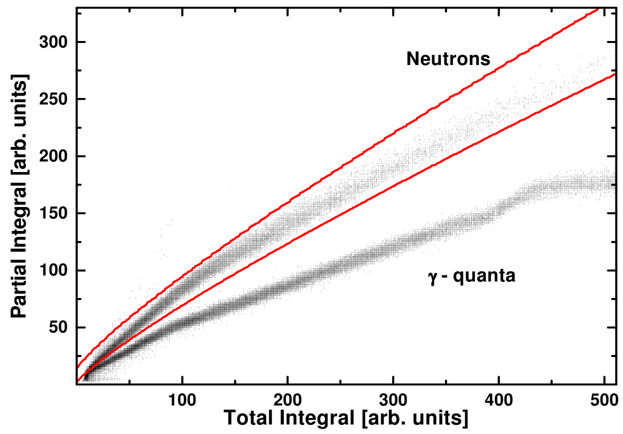


- **TOF measurement technique used for fission fragments (140 mm) and prompt neutrons registration (~50 cm)**
- **^{235}U target (99,9%, Ø15mm) - 280 μg/cm^2 UF_4 onto 70 μg/cm^2 Ti backing at centre of reaction chamber at the low operating gas pressure (4-6 Torr)**
- **Two neutron stilbene detectors (50 x 50 mm^2 and 40 x 60 mm^2 mounted on the Hamamatsu - R6091) in a cylindrical shielding (30 mm thick layer of lead and 40 mm polyethylene), neutron registration threshold ~200 keV**

Analysis of the data







Applied correction for:

- **Time uncertainties in TOF measurement:**
  - **Pulse-height dependent time walk in neutron and fission fragment channels**
  - **Different fission fragments TOF to start MWPD**
- **Neutron detector background :**
  - **a double-discrimination method (TOF and pulse shape with gamma suppression factor ~200)**
  - **true coincidence subtracted and the linear approximation of the remain part of background**
- **Fission fragment detector efficiency**
- **Complementary fission fragment contribution and neutron recoil correction**
- **Angular and neutron energy resolution (timing resolution : 1.0 - 1.2 ns)**
- **Neutron detector efficiency determined as the ratio of the measured total neutron spectrum of ^{252}Cf(*sf*) to the reference standard spectrum**

Analysis of the data:

Measurement of the total prompt neutron spectrum of $^{235}U(n_{th}, f)$ relative to $^{252}Cf(sf)$ (neutron detector efficiency determination)

^{252}Cf target placed into the experimental set-up in place of ^{235}U

$$\frac{N_U(E_n)}{N_{Cf}^{Std}(E_n)} = f_{res}^{A}(E_n)\cdot f_{res}^{E}(E_n)\cdot \frac{\int_0^{\pi} N_U^{\exp}(E_n,\theta)\sin(\theta)d\theta}{\int_0^{\pi} N_{Cf}^{\exp}(E_n,\theta)\sin(\theta)d\theta} = \overbrace{f_{res}^{A}(E_n)\cdot f_{res}^{E}(E_n)\cdot I(E_n)}^{F(E_n)}\cdot \frac{N_U^{\exp}(E_n)}{N_{Cf}^{\exp}(E_n)}$$

Where

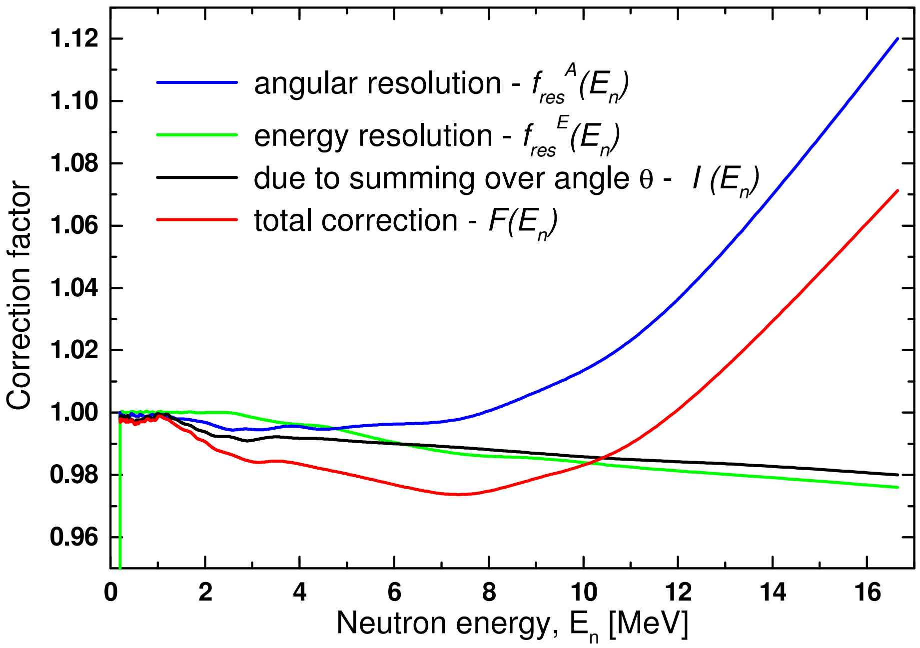
θ is the angle between the neutron direction and the direction of motion of the light fragments

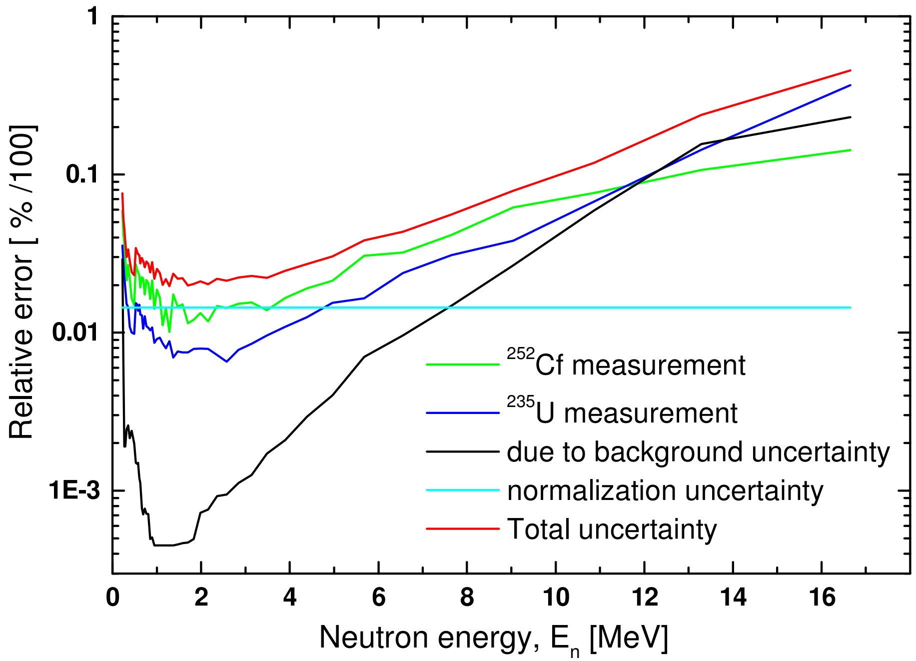
$N_{Cf}^{Std}(E_n)$ is linear interpolation of the ^{252}Cf prompt neutron spectrum evaluation (C.W.REICH, W MANNHART, T ENGLAD – ENDF-B/VII).

$$\frac{\int_0^{\pi} N_U^{\exp}(E_n,\theta)\cdot\sin(\theta)d\theta}{\int_0^{\pi} N_{Cf}^{\exp}(E_n,\theta)\cdot\sin(\theta)d\theta} = I(E_n)\cdot \frac{\sum_{\theta} N_U^{\exp}(E_n,\theta)\cdot\sin(\theta)\cdot\Delta\theta}{\sum_{\theta} N_{Cf}^{\exp}(E_n,\theta)\cdot\sin(\theta)\cdot\Delta\theta} = I(E_n)\cdot \frac{N_U^{\exp}(E_n)}{N_{Cf}^{\exp}(E_n)}$$

Analysis of the data:

Correction applied for ratio of neutron spectra $^{235}U(n_{th}, f)$ to $^{252}Cf(sf)$

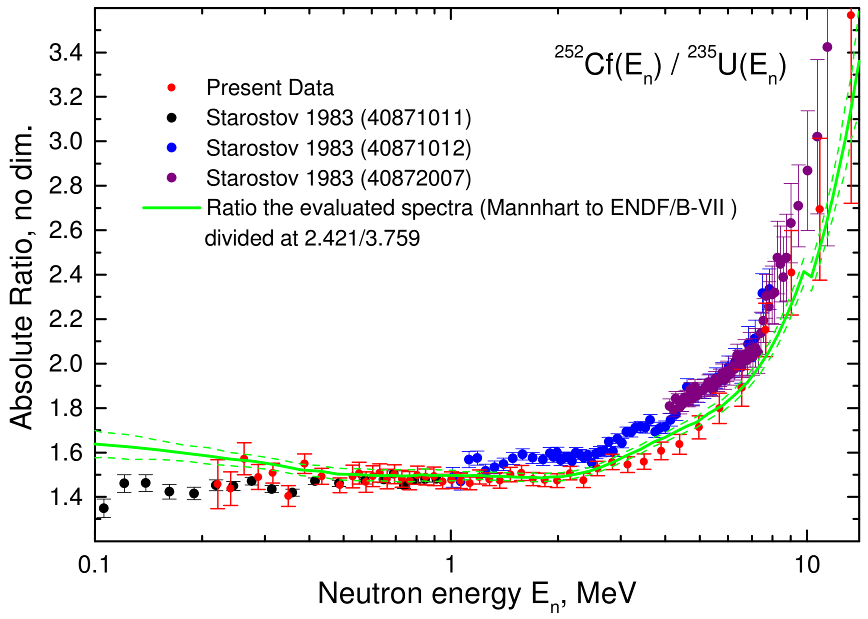


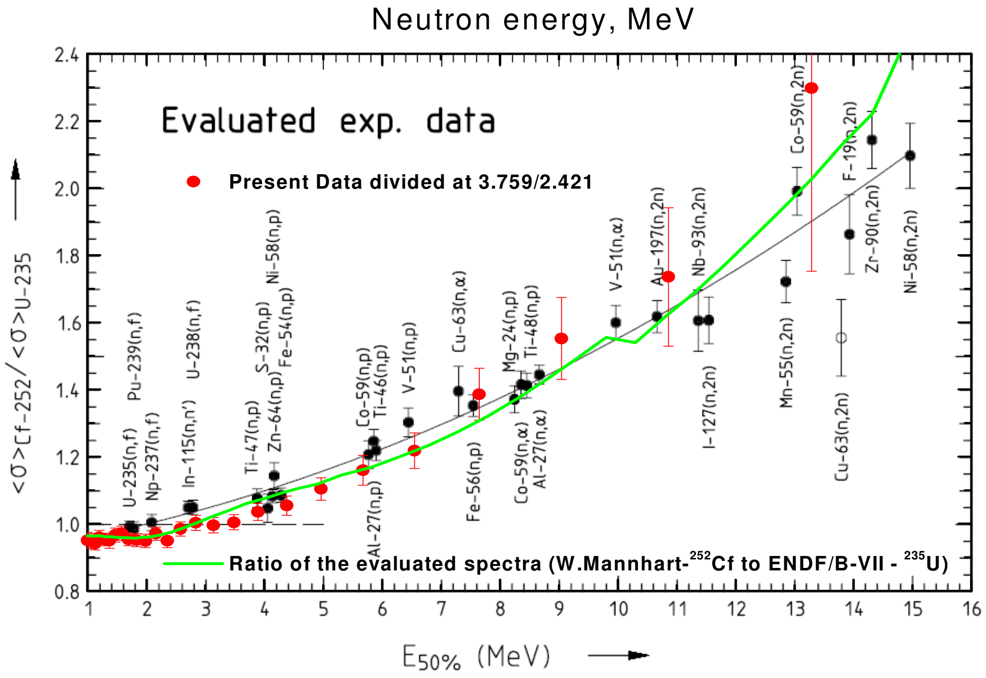


The angular and energy resolution correction are a minor influence on the total prompt neutron spectrum as well as correction due to summing over angle θ.

Result: Absolute ratio $^{252}Cf(sf)$ / $^{235}U(n_{th}, f)$

Comparison with evaluated data

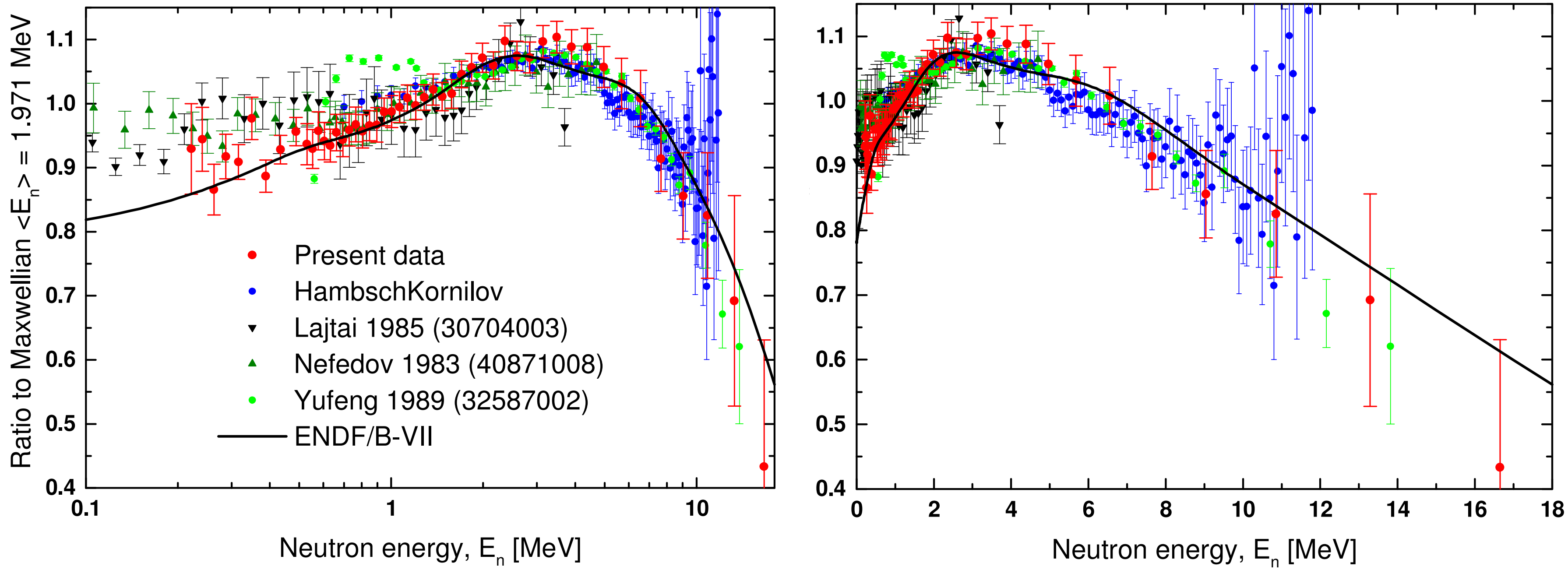




Within experimental errors the obtained ratio agrees with the evaluated data in 0.5 – 13.3 MeV energy range.

Result: PFNS of $^{235}U(n_{th}, f)$

Comparison with literature data



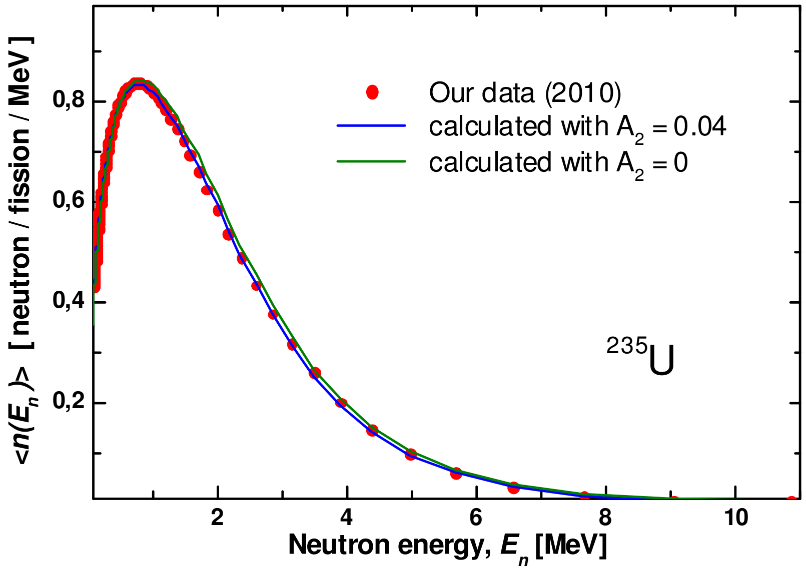
The PFNS were normalized to recommended value of ν_{tot} = 2.421 and obtained as:

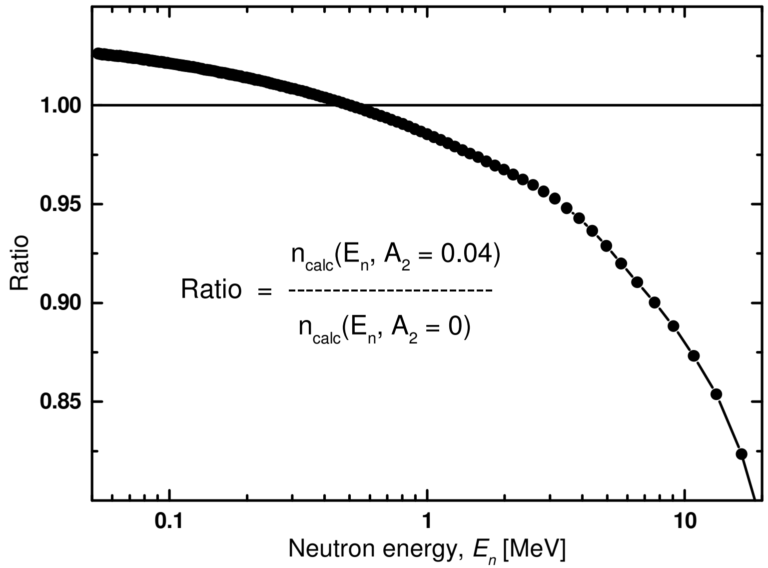
- Present data, Hambsch and Kornilov data, Lajtai data – absolute ratio $^{235}U(E_n)$/ $^{252}Cf(E_n)$ were multiplied by the Mannhart's evaluated spectrum of ^{252}Cf with ν_{tot} = 3.759
- Nefedov data – absolute value (the efficiency of neutron detector was calculated by Monte-Carlo method)
- Yufeng data – relative value

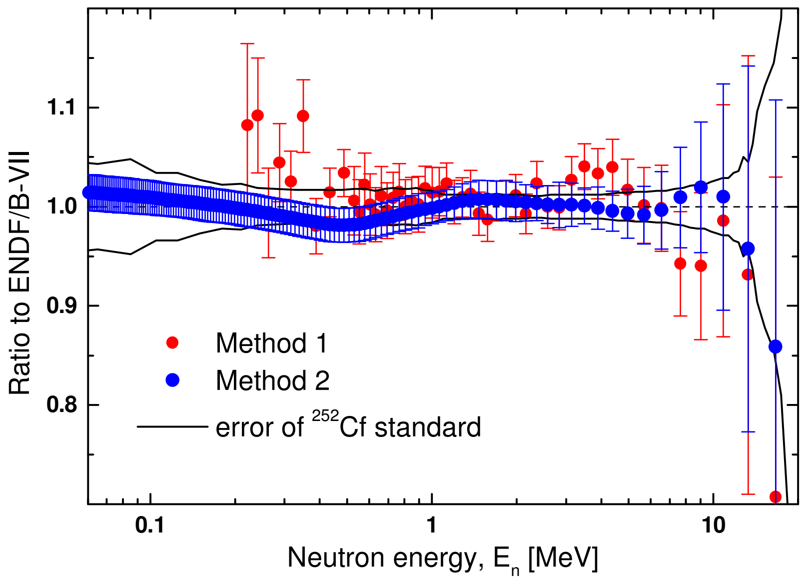
The obtained PFNS agrees with literature experimental data in full energy range

Result: PFNS of $^{235}U(n_{th}, f)$

Comparison with calculation







Method 1 – summation over angles;

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

Result:

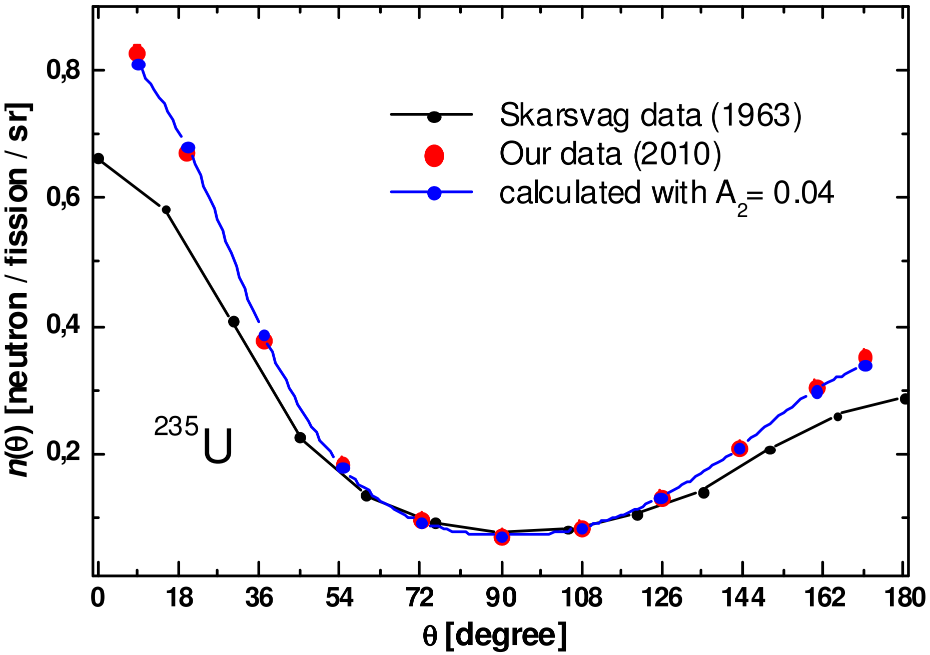
Comparison with calculation

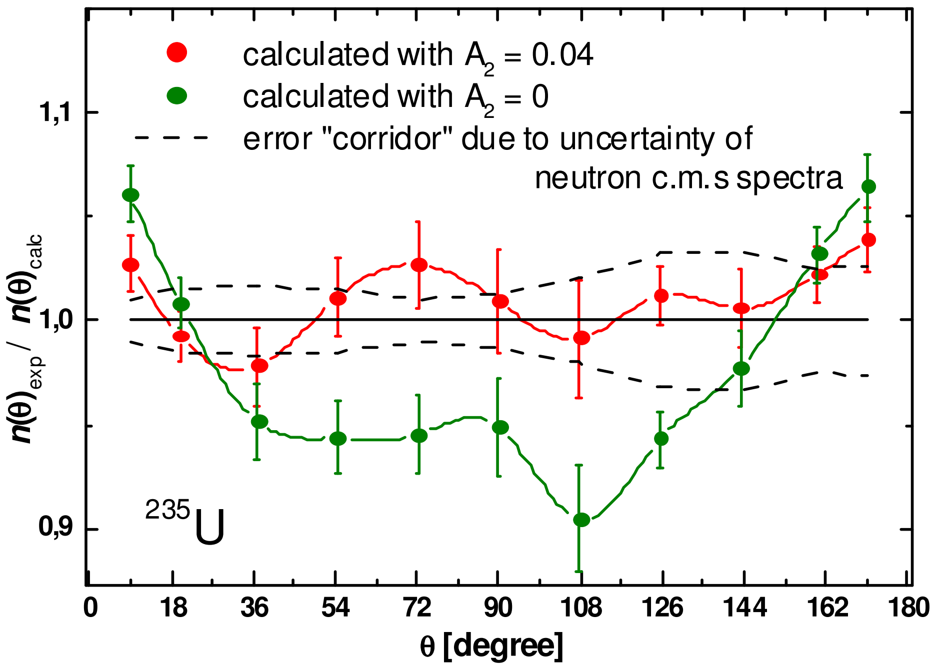
Target	ν_{prompt} (Neutron / fission)			
	Calculated		Experiment	ENDF/B-VII
	$A_2 = 0$	$A_2 = 0.04$		
^{252}Cf(sf)	3.86	3.73	3.77 ± 0.02	3.7590
^{235}U(n_{th}, f)	2.56	2.45	2.44 ± 0.05	2.421
^{233}U(n_{th}, f)	2.60	2.48	2.54 ± 0.06	2.4894

- 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

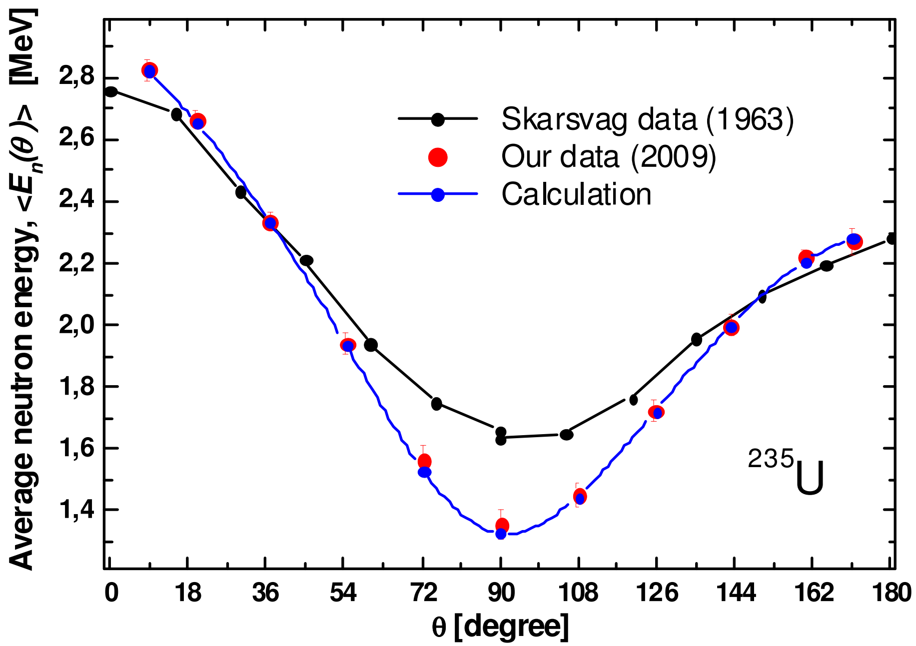


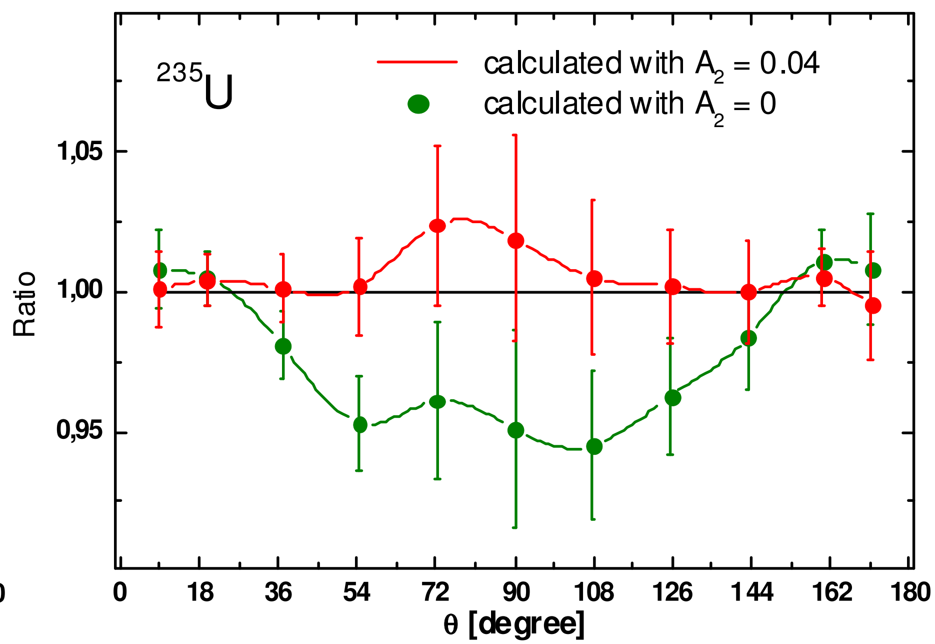


- Introduction of anisotropy with A_2 = 0.04 into the calculation improves agreement with obtained experimental data. At that, there is some surplus of measured yield over calculated at angles near 90^0.

Results:

angular distribution of the average prompt neutron emission energy



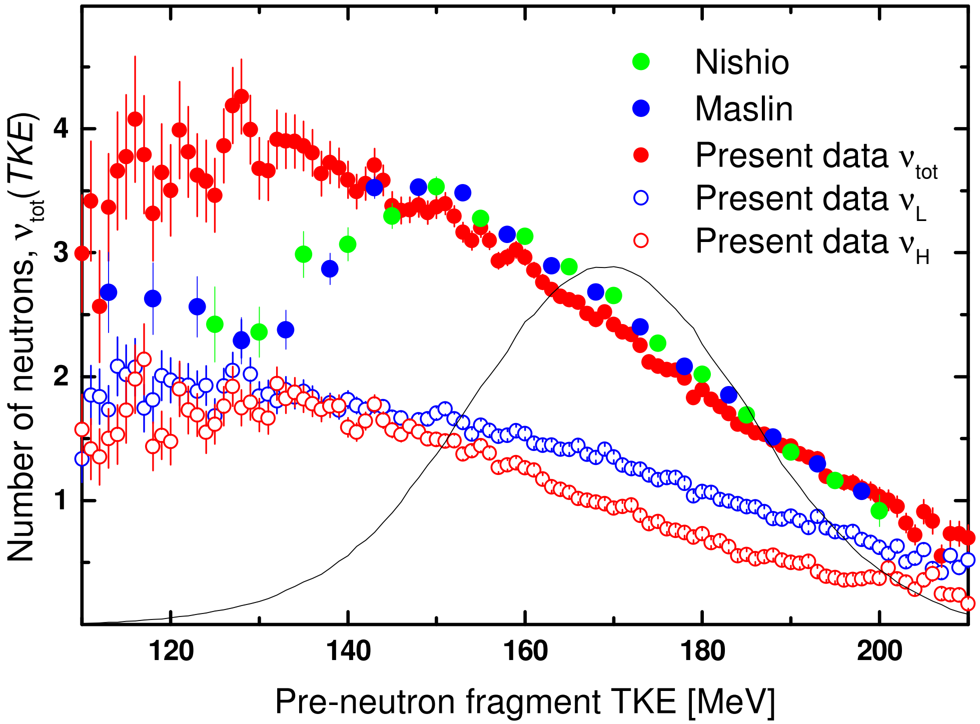


- Under the assumption that the "additional" neutrons are emitted isotropically in the laboratory system, their yield is deduced as about 3% of the total neutron yield for $^{235}U(n_{th}, f)$.

Results (correlation with FFs):

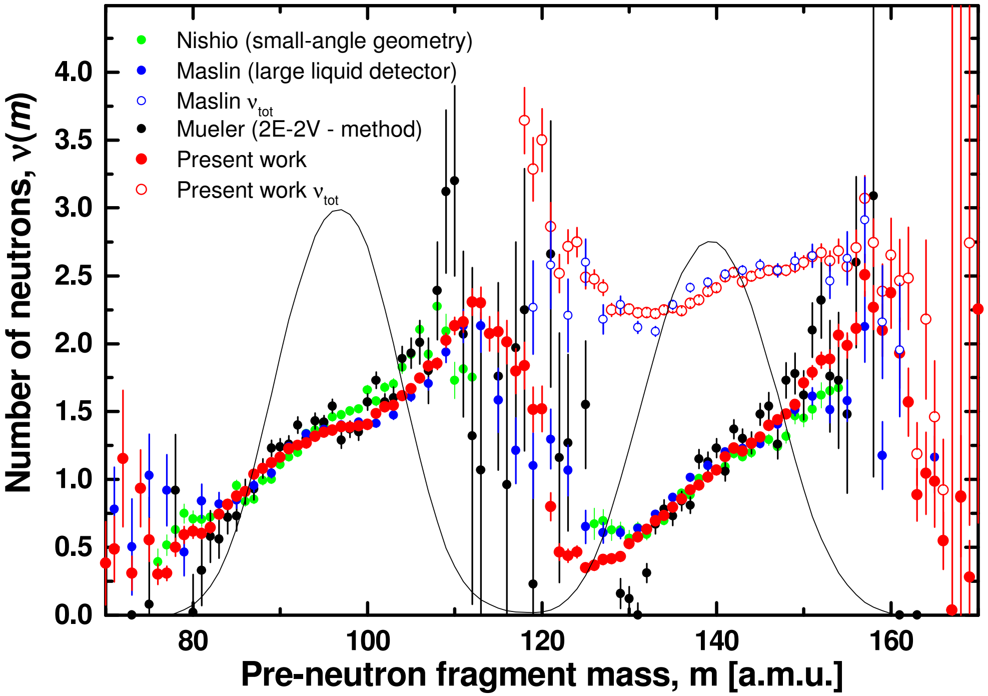
- The transformation of neutron spectra in the laboratory system (at small angles relative to fragments direction) to the center-of-mass system was performed for each fragment fixed mass and energy.
- A good agreement is observed between average number of prompt neutrons obtained by this experiment and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

average prompt neutron multiplicity vs TKE



Results (correlation with FFs):

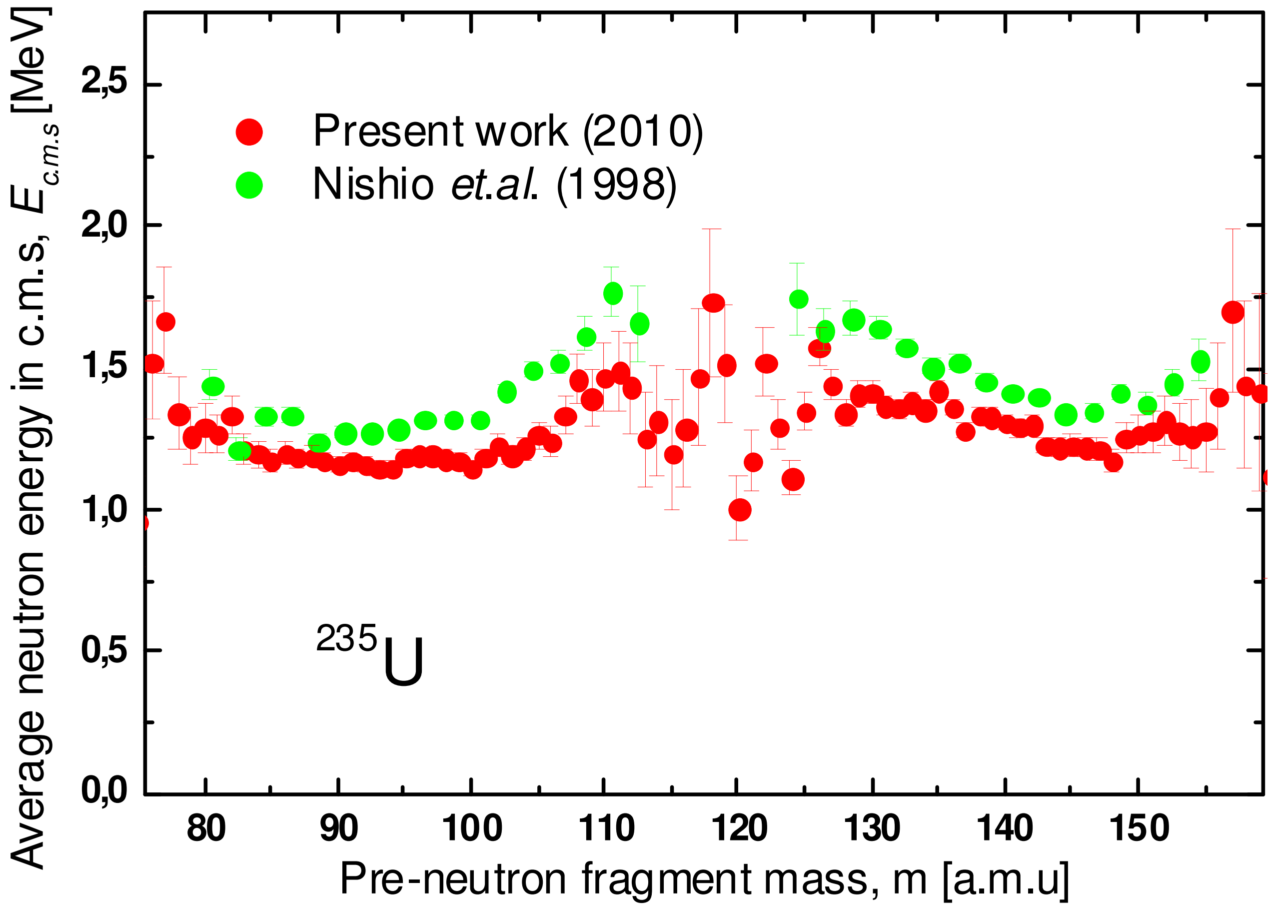
average prompt neutron multiplicity vs fragment mass



- 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):

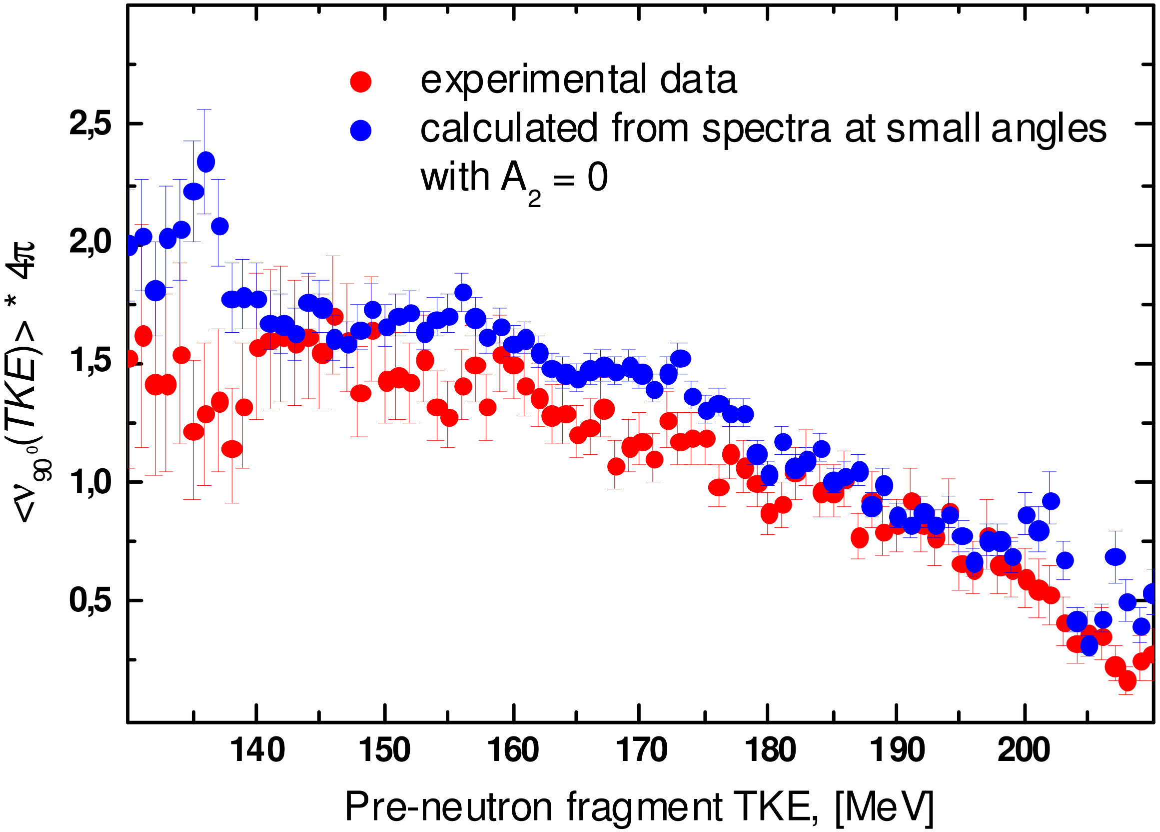
average neutron energy in the center-of-mass system vs fragment mass



- 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):

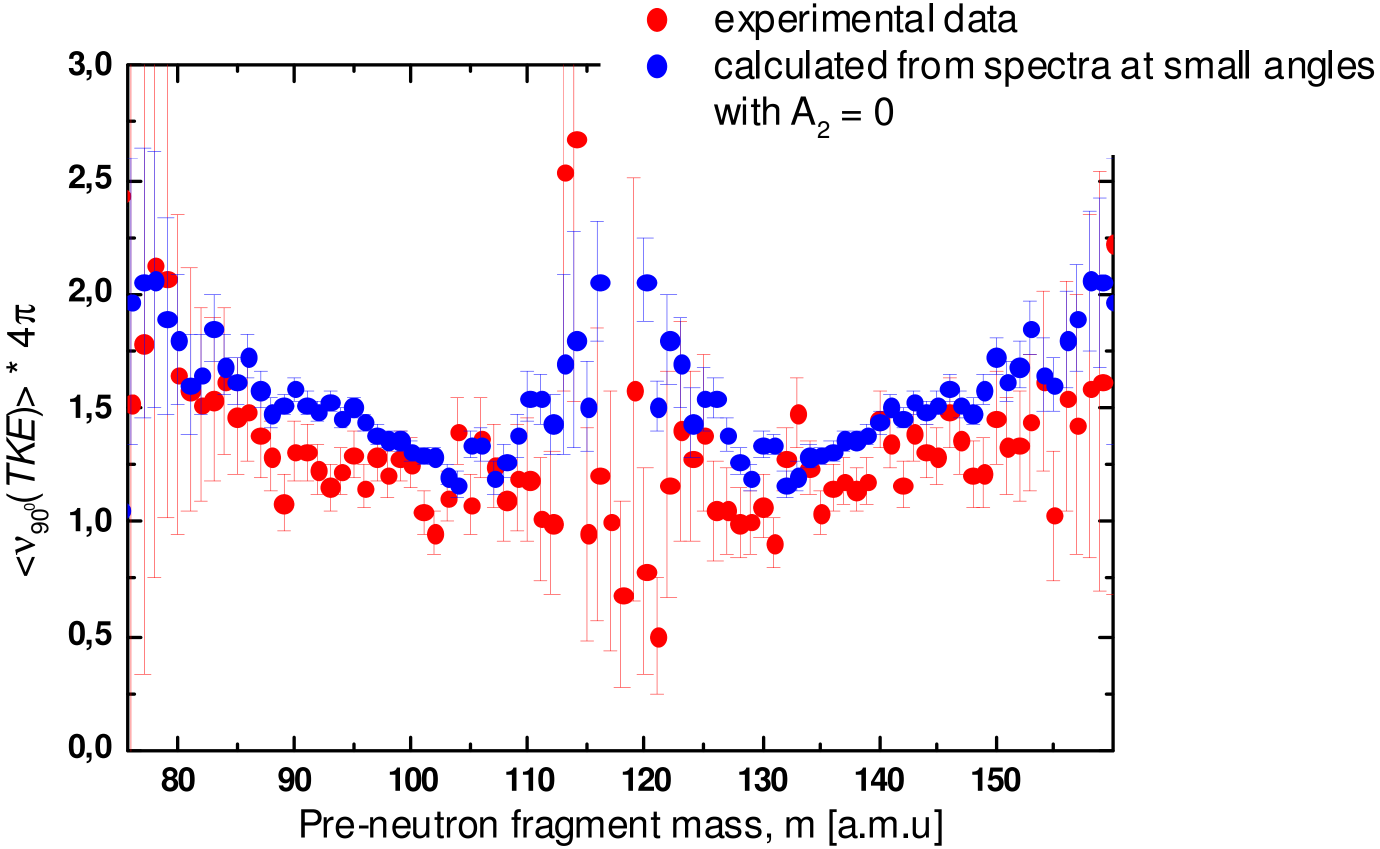
the average number of prompt neutrons emitted perpendicular to the fragment direction as a function of TKE



- 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

- Our PFNS agrees with literature experimental data in full energy range.
- Results of two our measurements ("efficiency" measurement and calculation performed using data obtained by us in previous experiment) are in a good agreement.
- The average of two measurements is in a good agreement with ENDF/B-VII in 0.5-16.6 MeV energy range.
- 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 (two fission fragment approximation);

  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.
- To obtain certain estimation of the emission mechanism other than emission from accelerated fragments 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.

Thank you very much for your attention