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Prompt fission neutron emission spectrum of ^{235}U(n,f) at thermal energies

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- Activation measurements with DONA
- Neutron emission in fission of $^{252}Cf(SF)$
- Conclusions

Introduction

- **Mono-energetic neutron source**
- 7 MV Van-de-Graaff accelerator
  - ^{7}LiF(p,n)^{7}Be, TiT(p,n)^{3}He, D_2(d,n)^{3}He, TiT(d,n)^{4}He
  - DC ($I_{p,d}$ < 50 μA), pulsed beam available
  - 4 + 1 non-T beam line
- $\Phi_n < 10^9$ /s/sr
- *NEPTUNE* isomer spectrometer
- ionisation chambers, NE213 neutron/gamma-ray detectors, BF_3 counters, HPGe detectors
- Bonner spheres
- fast rabbit systems ($T_{1/2}$ > 1s) for activation studies

- **GELINA neutron**
- **TOF spectrometer**

- 70 - 140 MeV electron accelerator
- repetition frequency: 40 - 800 Hz
- neutron pulse: 2 μs - 1 ns @ FWHM
- Φ_n = 3.4 10^{13}/s @ 800 Hz
- 12 different flight paths with a length between 8 and 400 m
- ionisation chambers, C_6D_6 detectors
- high-resolution γ-ray detectors
- fission chambers for flux monitoring

Motivation

- Nuclear energy production: ^{235}U most important isotope

→ Understanding the ^{235}U Prompt fission neutron spectrum (PFNS) essential for safe and economic use of nuclear power

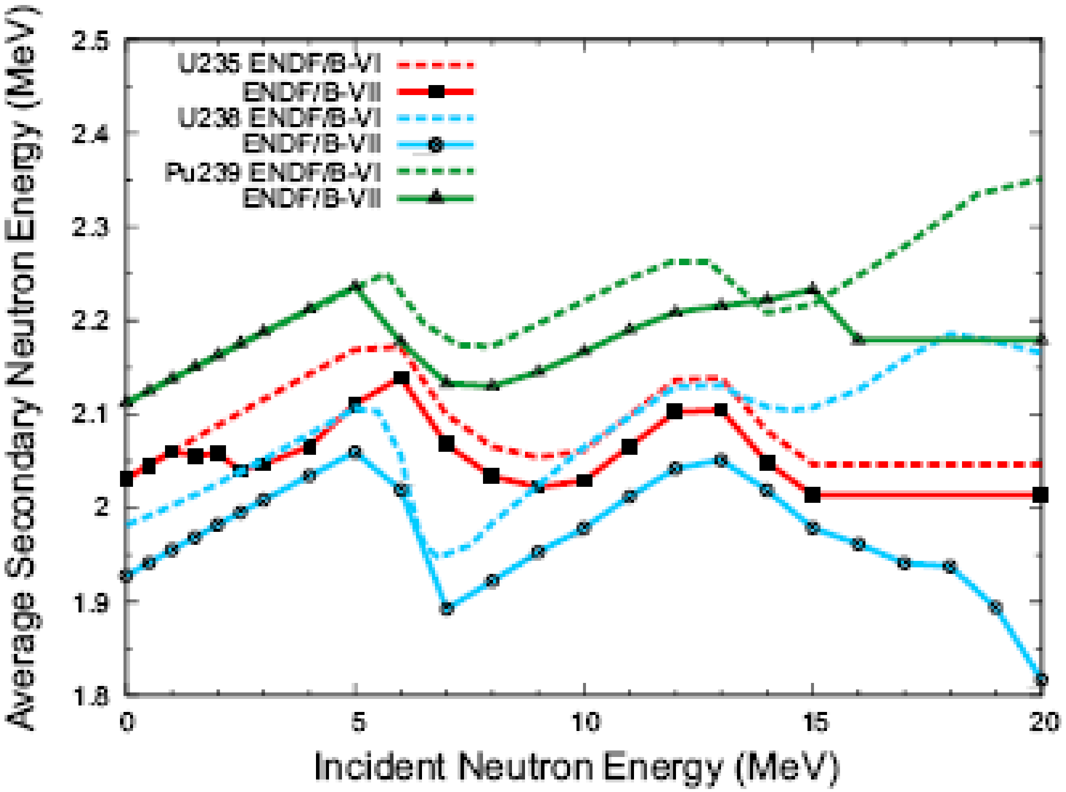
- 6 differential PFNS measurements since 1977 (E_0= thermal - 0.5 MeV)
- 30 integral cross-section measurements compiled by Mannhart et al.
  → Provide test of PFNS n(thermal) +^{235}U system

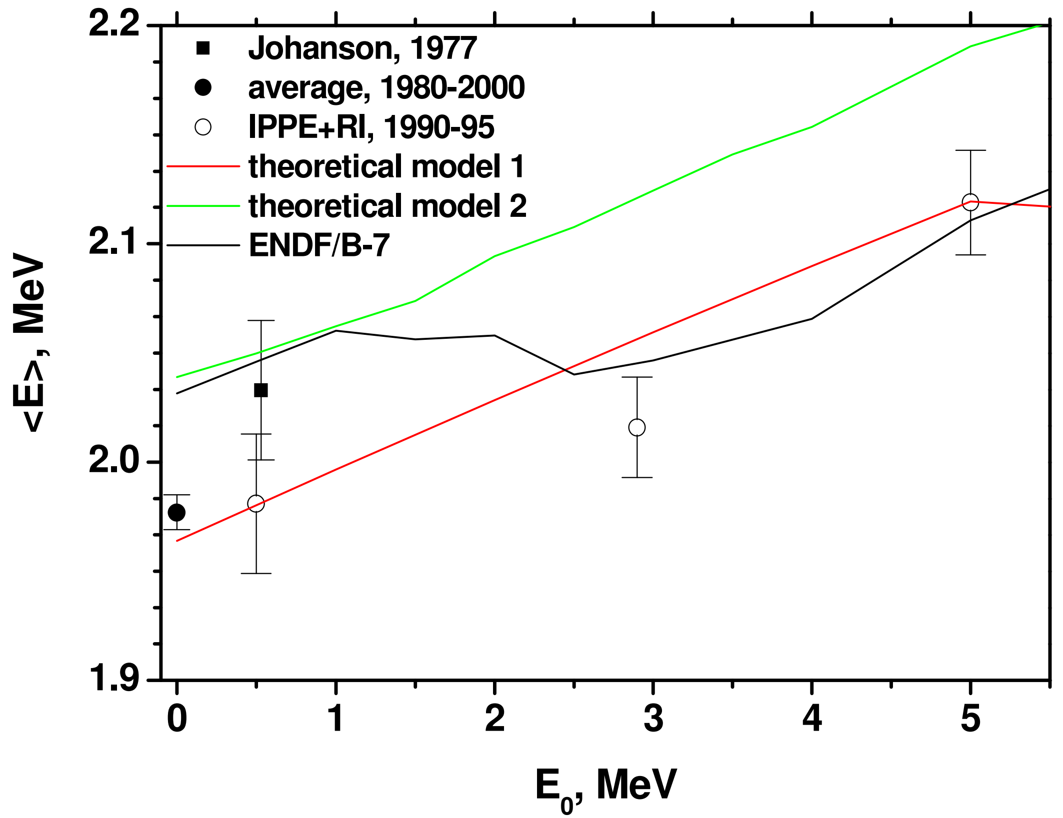
Persisting discrepancies between microscopic and macroscopic data

- Calculated spectra from differential measurements or based on a model don't reproduce the integral measurements and differential data simultaneously
  - Differential / integral measurements: **C/E** = $\langle\sigma_{CALCULATED}\rangle / \langle\sigma_{EXPERIMENT}\rangle$ = **0.9 … 0.6**
  - ENDF/B –VII (LA Model) reproduces integral cross sect. (10%), but not differential data

→ **Request from Nuclear Energy Agency OECD- NEA WPEC-9 to re-measure PFNS**

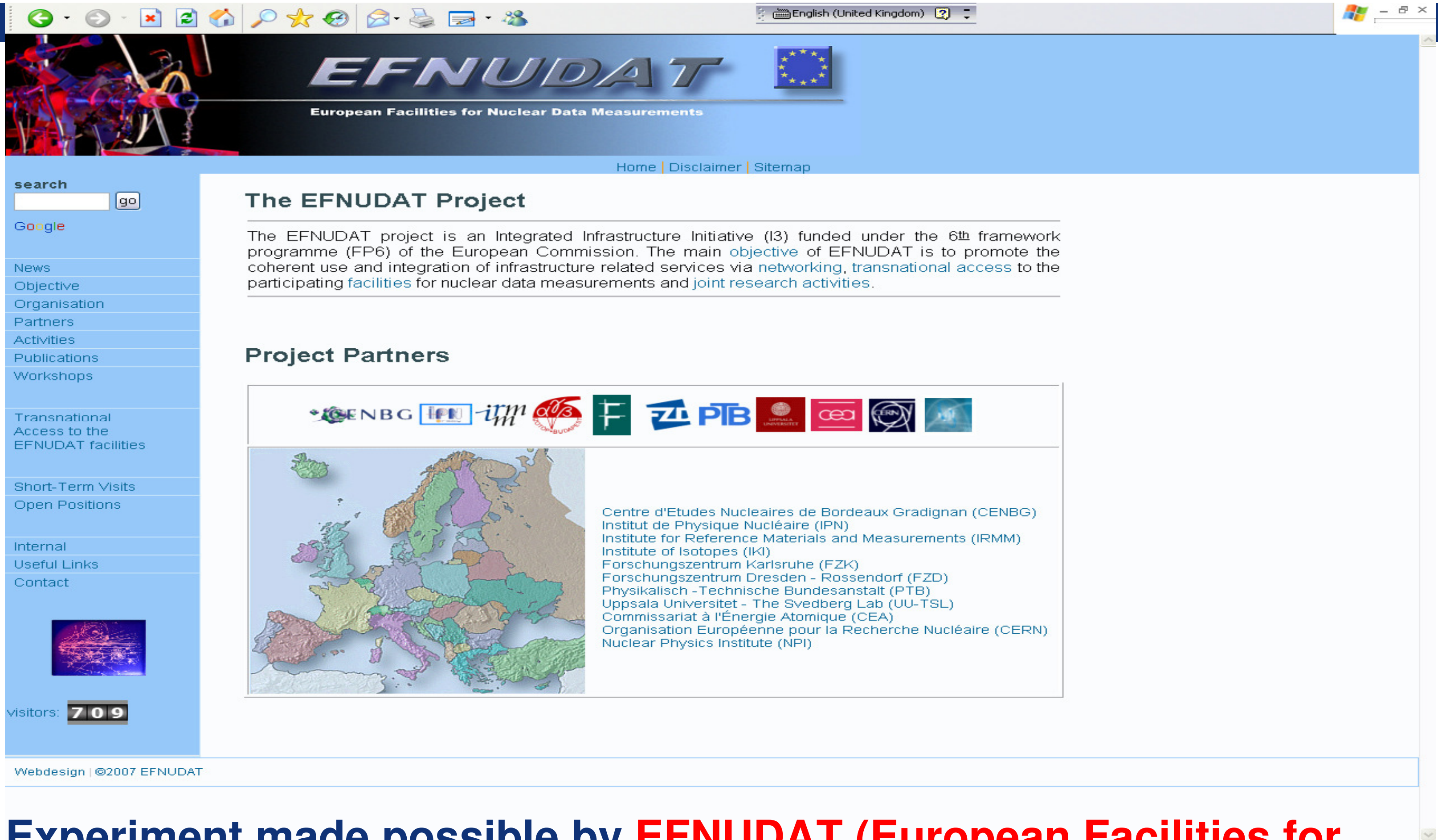
Motivation





M. Chadwick et al., Nuclear Data sheets 107 (2006) 2931

EFNUDAT



Experiment made possible by EFNUDAT (European Facilities for Nuclear Data Measurements) collaboration project , part of FP6 programme (ending Oct. 2010)

New project to continue in the spirit of EFNUDAT will be ERINDA (start date Dec. 1, 2010)

http:// www.efnudat.eu

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Experiment: Budapest Reactor

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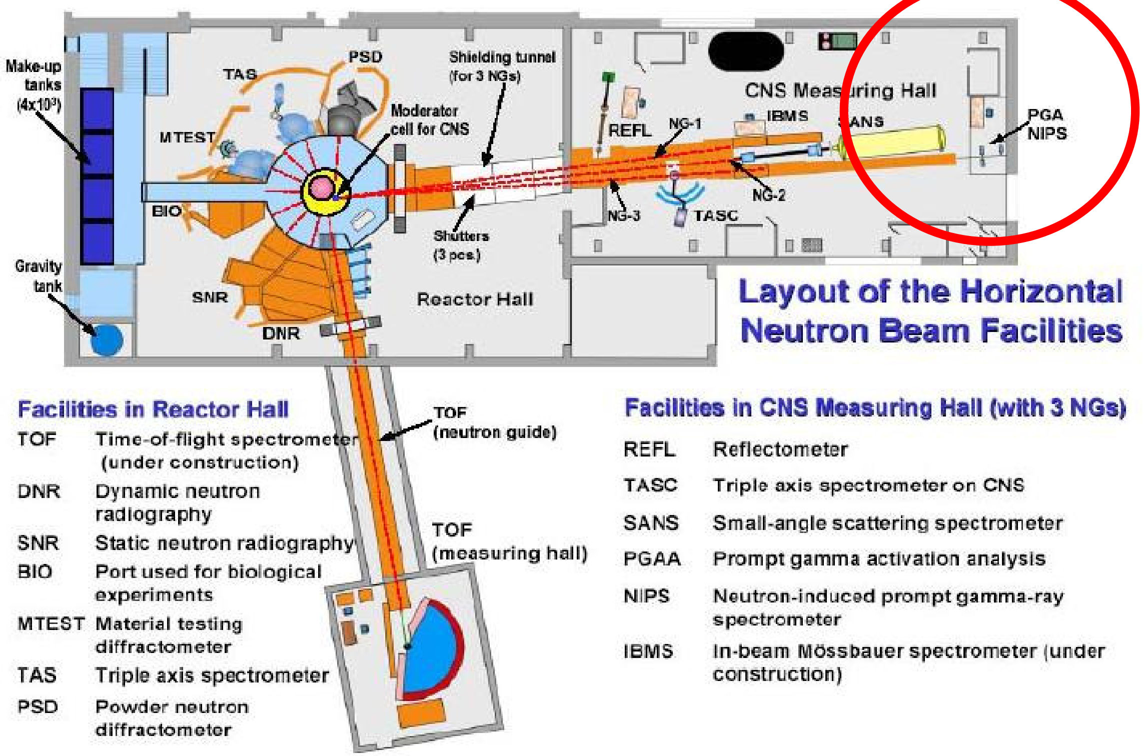
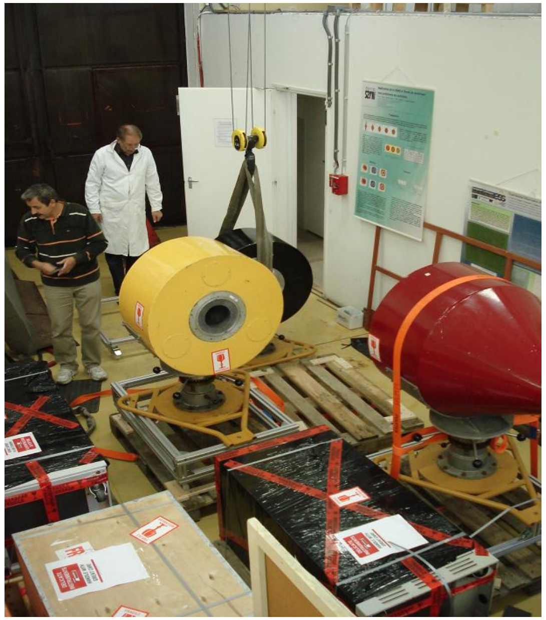


- Experiment performed at **Cold neutron PGAA facility** (T = 100 K, beamline 1) at 10 MW Budapest Research Reactor
- **10 days beam time** (200h) 2 weeks measurement,1st week setup & calibration, 15.09-3.10.2008
- **High flux:** 7 x 10^7 neutrons /cm^2/s at sample position
- **High stability**, well- characterised beam (geometry, spectrum)
- **Excellent support** from Hungarian colleagues

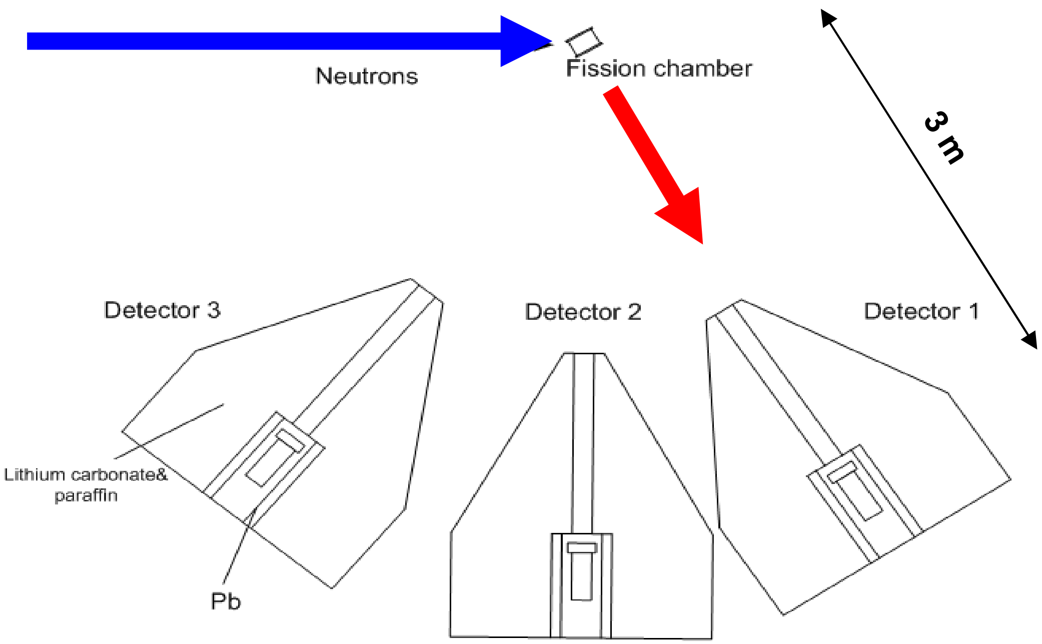
Experiment at Budapest Reactor

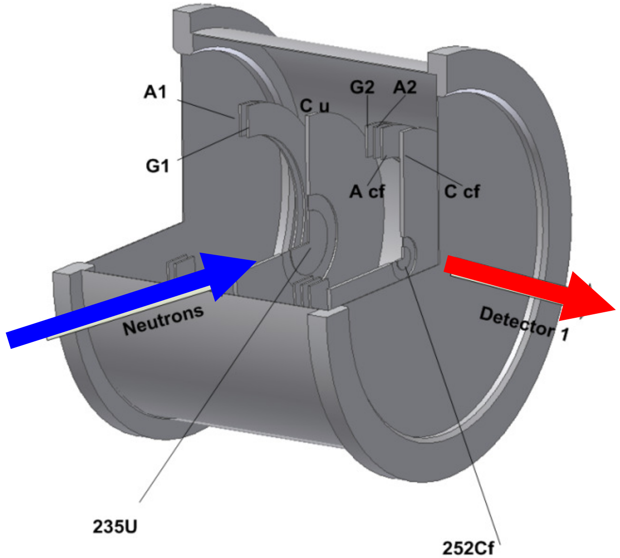


- Equipment:

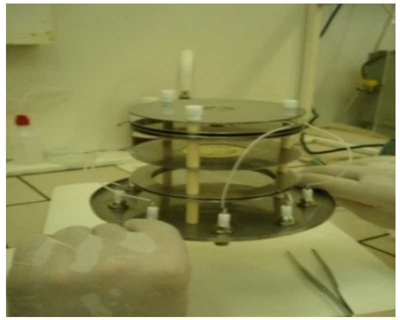
- Double Frisch grid ionisation chamber with thin ^{235}U target
- Parallel plate ionisation chamber with ^{252}Cf target for calibration
- NE213 equivalent neutron detectors in heavy shielding
- All electronic equipment needed
- Data acquisition system

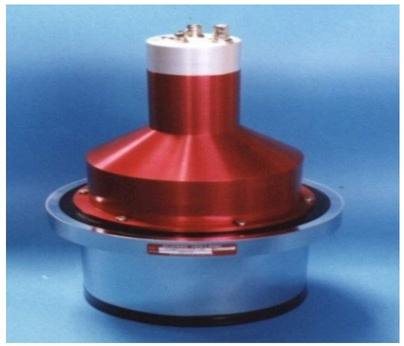
Experiment: Setup



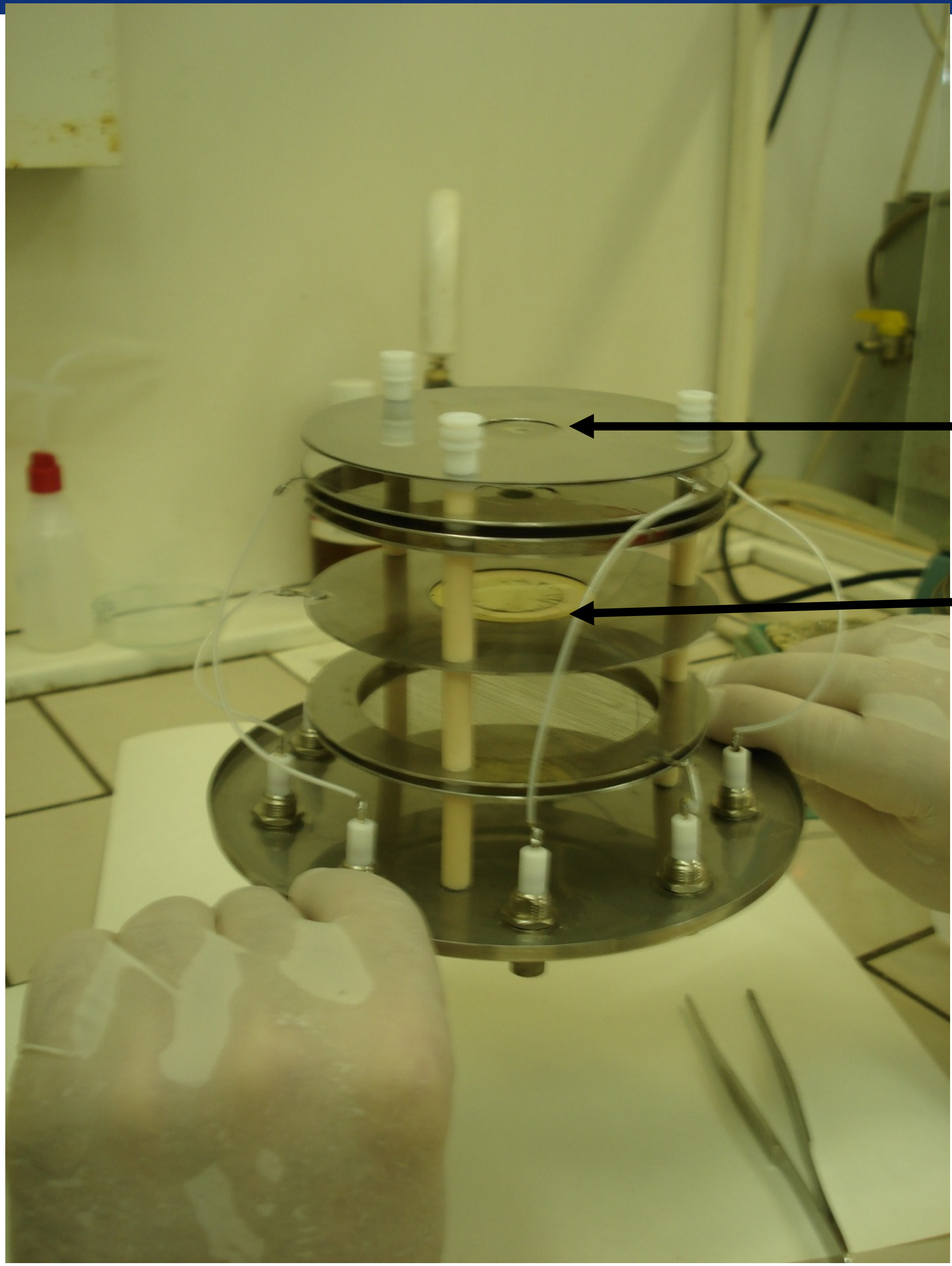


- **TOF measurement technique used (L = 3 m)**
- **3 neutron detectors LS301 (NE213 equivalent, size: 4'' x 2'' =10.16 x 3.08 cm) SCIONIX in heavy shielding**
- **Thin ^{235}U (97.7%) target 112 μg/cm^2 at centre of Ionisation chamber, fission count rate 50.000 /sec**
- **^{252}Cf target placed simultaneously into the same chamber shifted 5 cm relative to ^{235}U target (20.000 fissions/s)**
- **High Fission Fragment counting efficiency 98%**





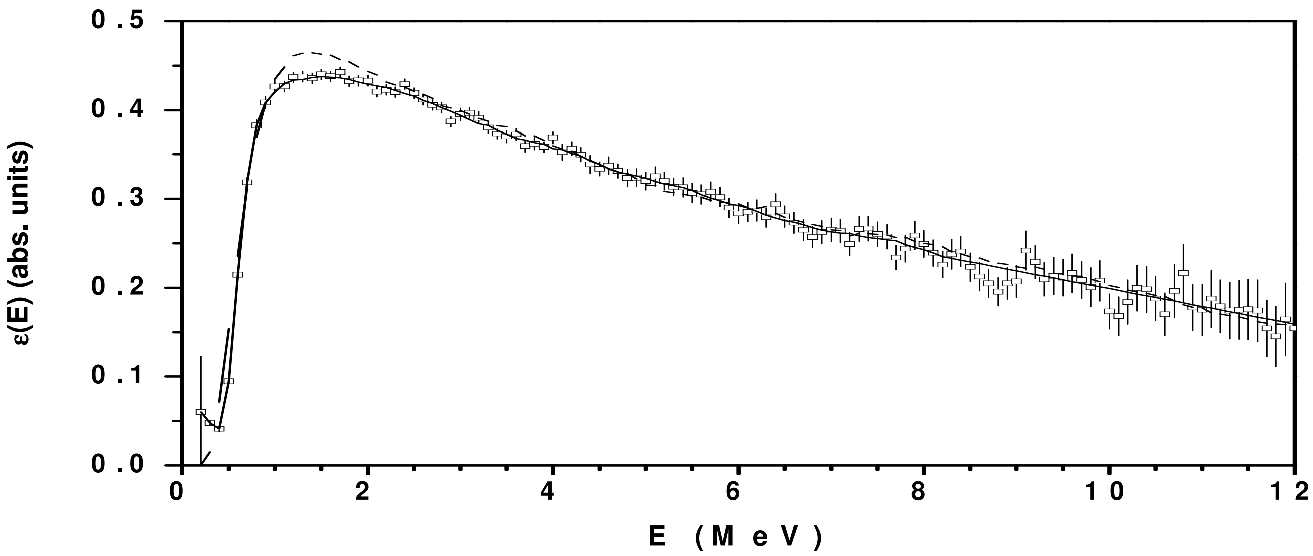
Ion chamber set-up at IKI



^{252}Cf reference sample

Thin ^{235}U sample

Test of measured Efficiency



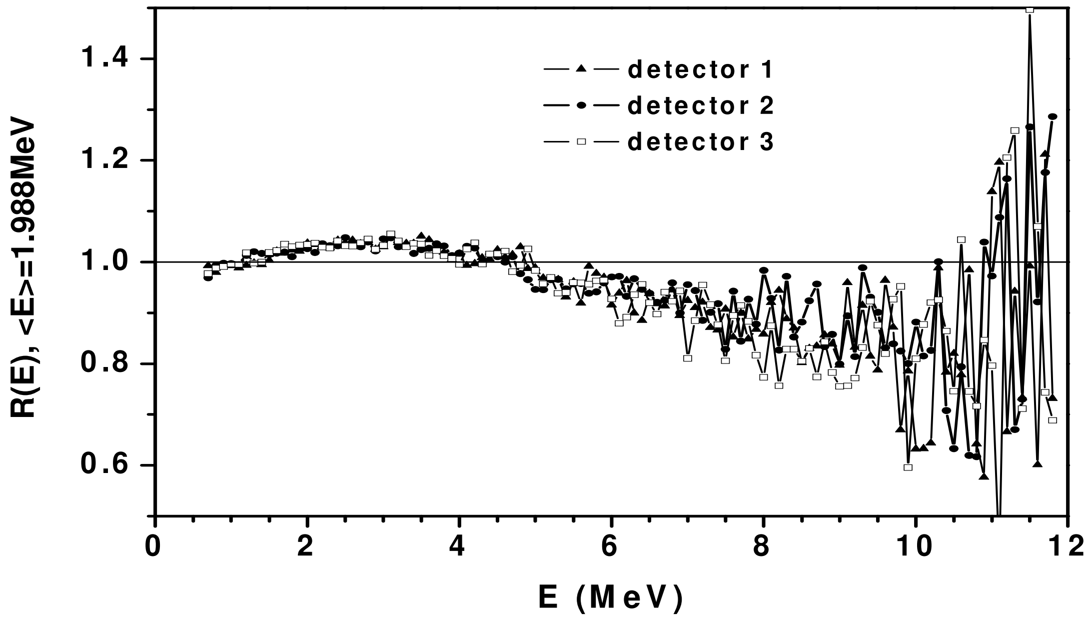
- To test measured efficiency, all experimentally determined parameters were included in the simulation
- Small difference at 8.7 MeV due to $^{12}C(n, 3\alpha)$, a reaction not well measured
- Small difference 5-6 % at the very low threshold (0.6 MeV)

➡ Measured and simulated intrinsic neutron detector efficiency agree very well over the energy range

➡ Measured efficiency used for PFNS determination

Neutron detector spectra

Ratio to Maxwellian



- Since 3 detectors were used, they can be cross-checked for reliability of results
- Each Run was analyzed separately to check for systematic errors
- No angular effect

→ Excellent agreement of 3 individual neutron detectors

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Individual detector results

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Average parameters of the PFNS for the reaction 235U(nth,f)			
Detector No.	Angle, degree	<E>, MeV	ν-prompt (Neutrons / fission)
1	72	1.987	2.491
2	102	1.990	2.548
3	132	1.987	2.378

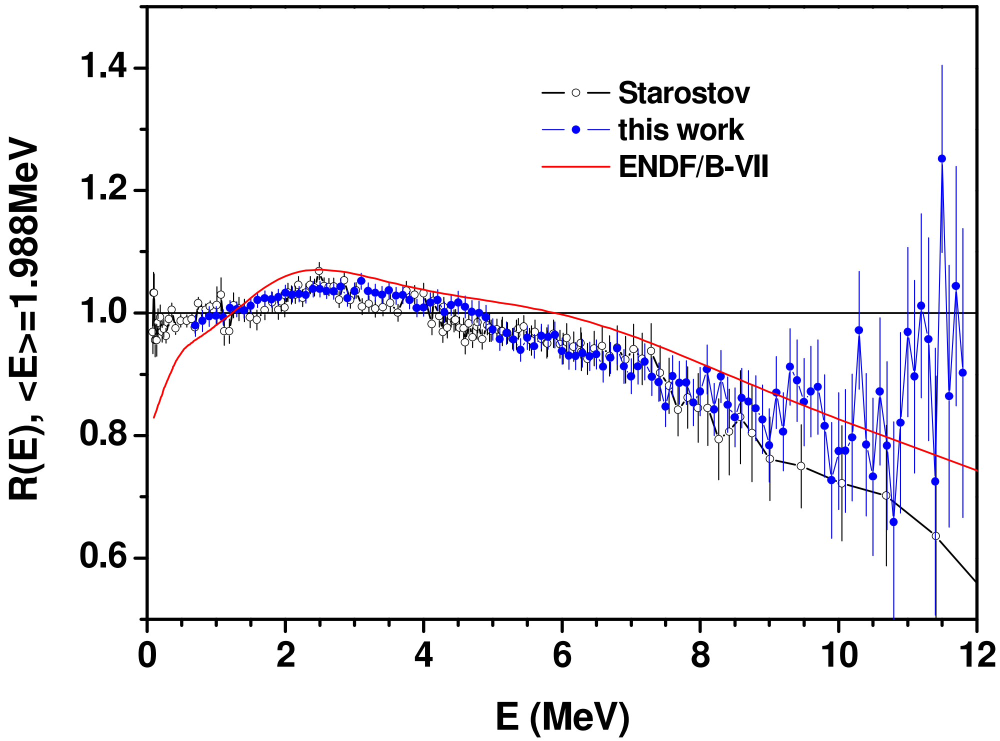
$\langle \nu \rangle = 2.47 \pm 0.08$ **ENDF/B-VII: $\langle \nu \rangle = 2.421$**

$\langle E \rangle = 1.988 \pm 0.010$ MeV **ENDF/B-VII: $\langle E \rangle = 2.03$ MeV**

- **Detectors agree well with each other**
- **< E> agrees with nearly all literature data**
- **Mean Energy in ENDF/B-VII is higher than all measurements**

Comparison to Literature Data

Ratio to Maxwellian



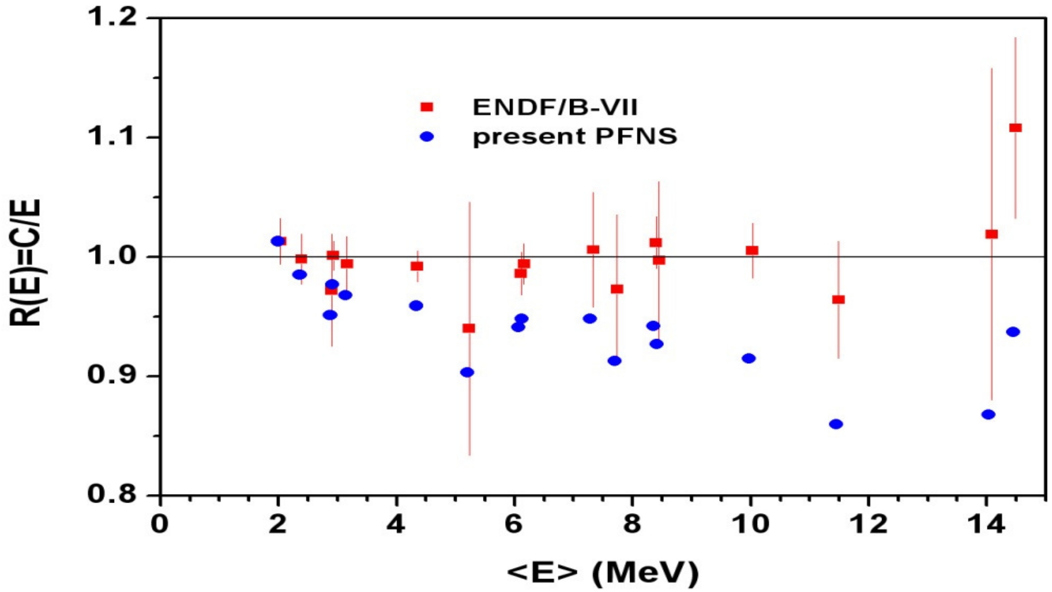
Our Data

Starostov et al. 1984 (EXFOR)

ENDF/B-VII

- Starostov et al.: Gas-scintillation-ionization detector + ^{235}U, IC, Reactor, relative to ^{252}Cf
- Excellent agreement with Starostov et al. over full energy range
- Our data and Starostov et. al. contradict ENDF/B-VII evaluation and the Los Alamos Model (Madland Nix)

Comparison to Literature Data



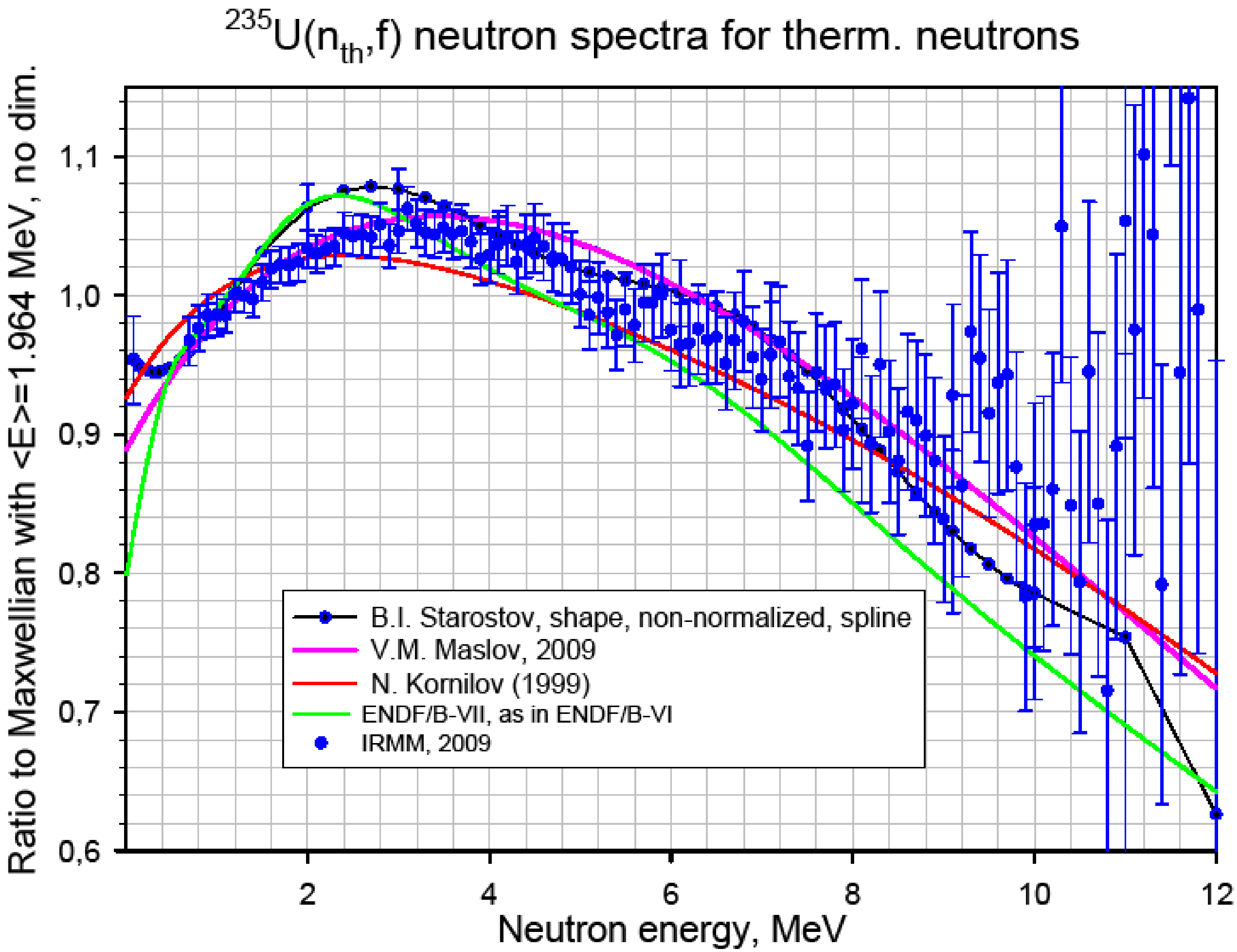
Source: IRDF-2002 International Reactor Dosimetry Files library

- Validation of the PFNS: Measured PFNS was used to calculate average integral cross sections and compared to set of integral measurements (activation reactions in reference neutron field)
- C/E = Calc. / Exp. spectrum-averaged cross sections $\int \sigma(E)\, N(E)\, dE / \int N(E)\, dE$
- Only reactions used with good C/E agreement for ^{252}Cf data.

C/E (our data) = 0.938±0.010   C/E (ENDF-B/VII) = 0.998±0.009

- Our ^{235}U PFNS agrees with all literature differential experimental data
- But no experimental data can describe the integral experiments

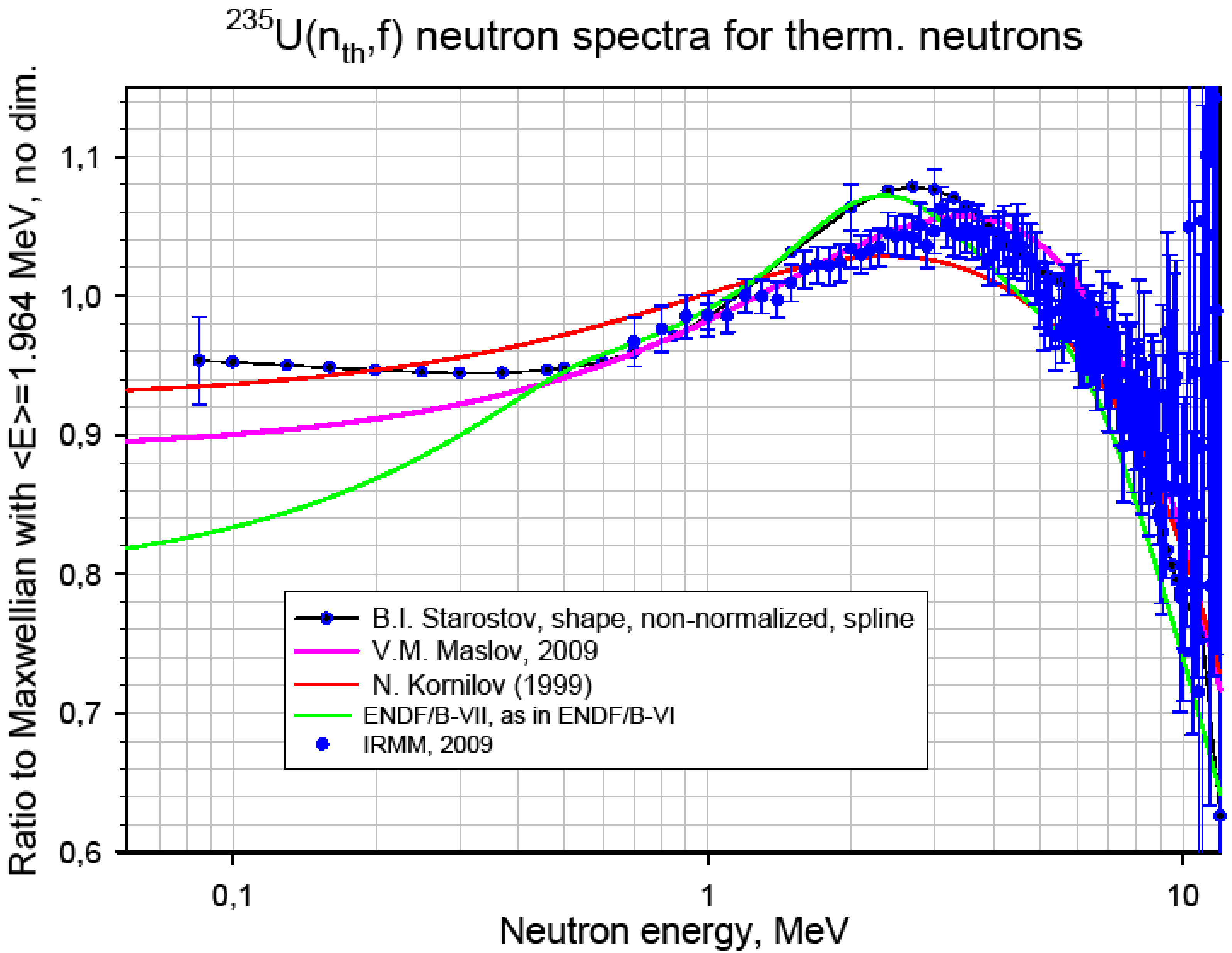
New spectrum calculation by V. Maslov



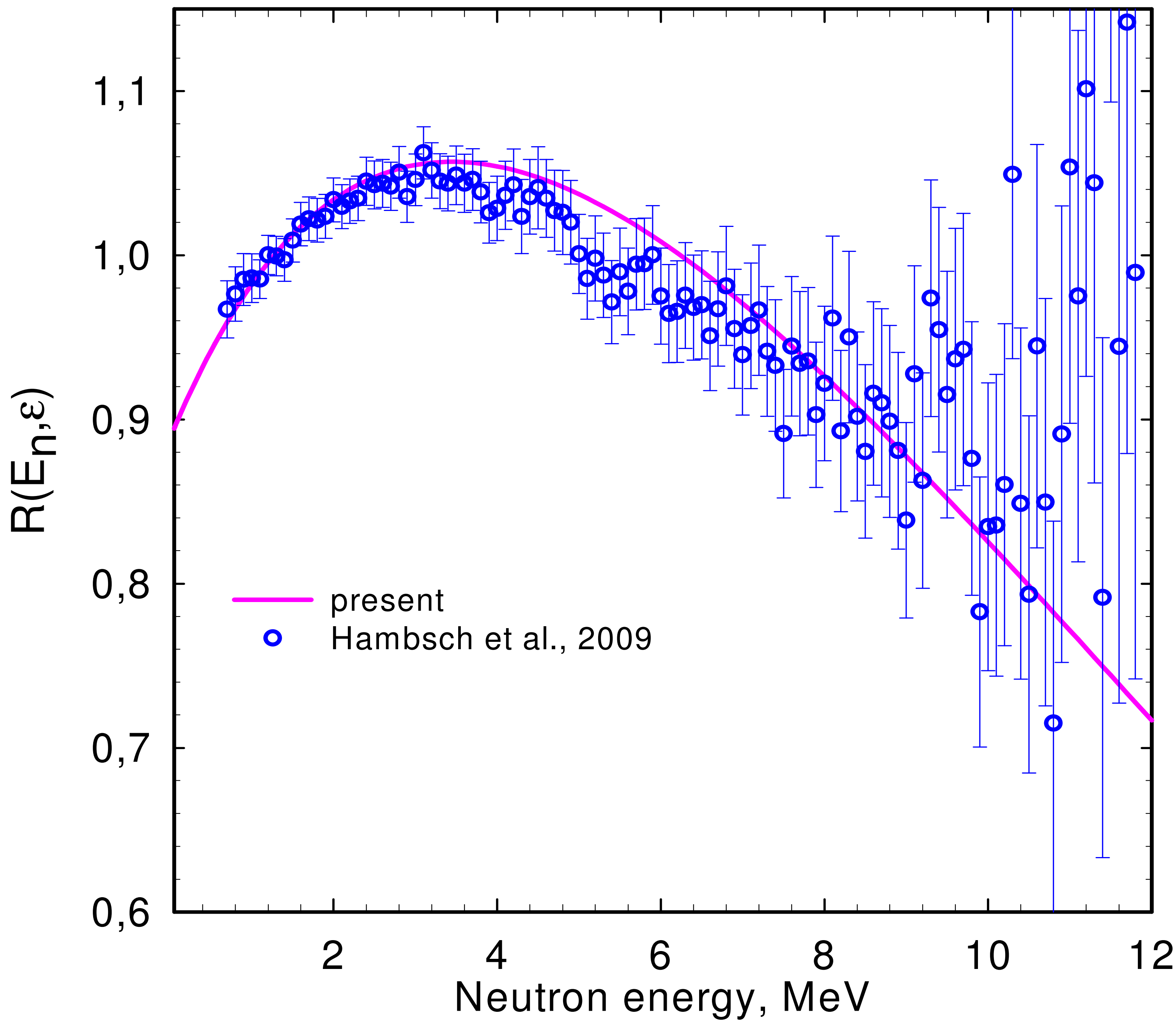
PFNS in Major Data Libraries

- **PFNS discrepancies in MDL are often quoted as PFNS uncertainty**
- **$^{235}U(n_{th}, f)$ PFNS of MDL essentially repeat each other**
- **$^{235}U(n_{th}, f)$ MDL' PFNS discrepant with measured PFNS laying well outside the biases of different data sets**
- **That may and had lead to arbitrary tweaking of neutron cross sections, neutron multiplicities to compensate ill-defined shapes of PFNS**

New spectrum calculation by V. Maslov

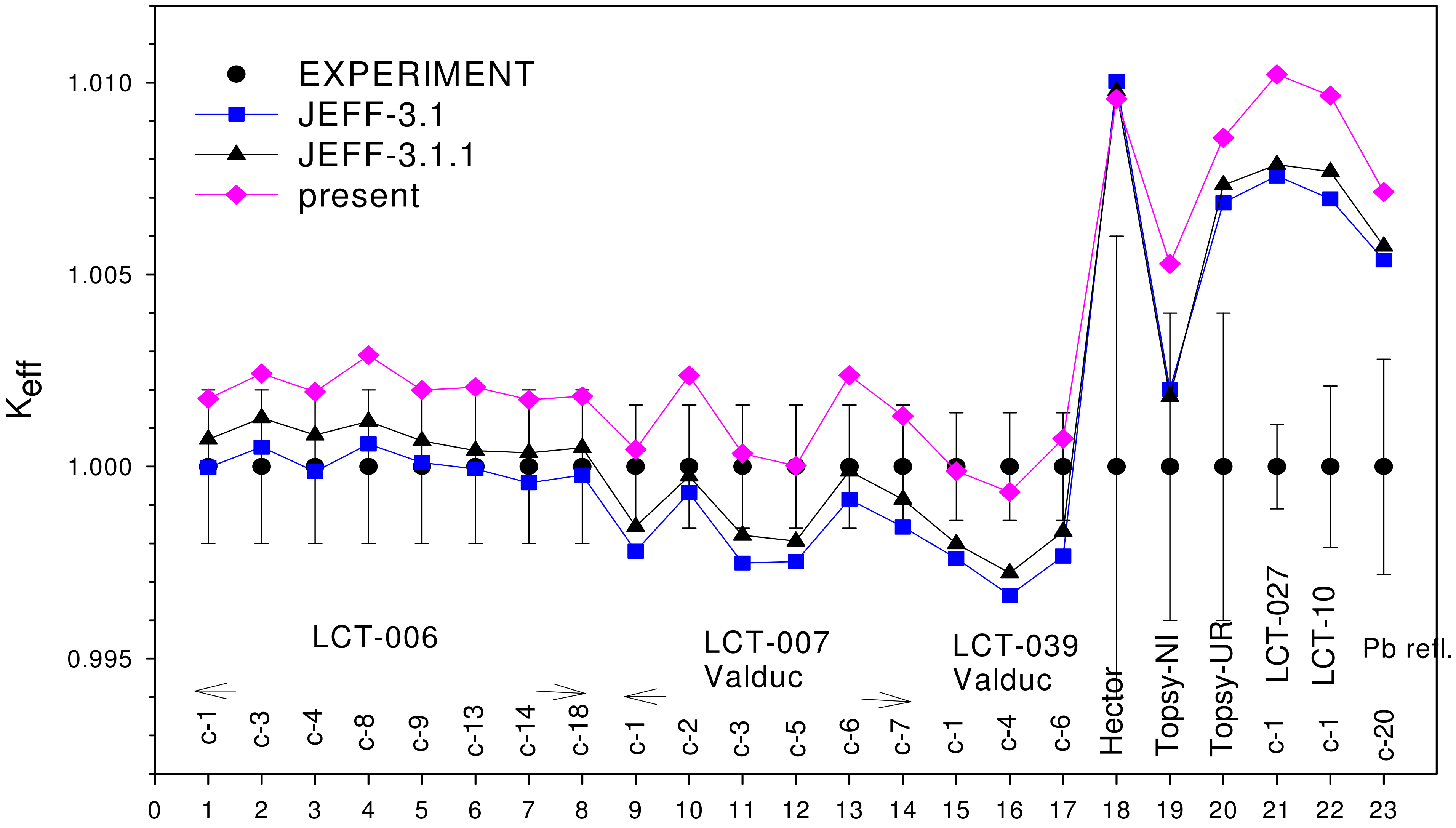


$^{235}U(n_{th},f)$ fission neutron spectrum



Critical assemblies

U - THERMAL REGION, TRIPOLI-4.4 calculations by J-C Sublet



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Critical assemblies

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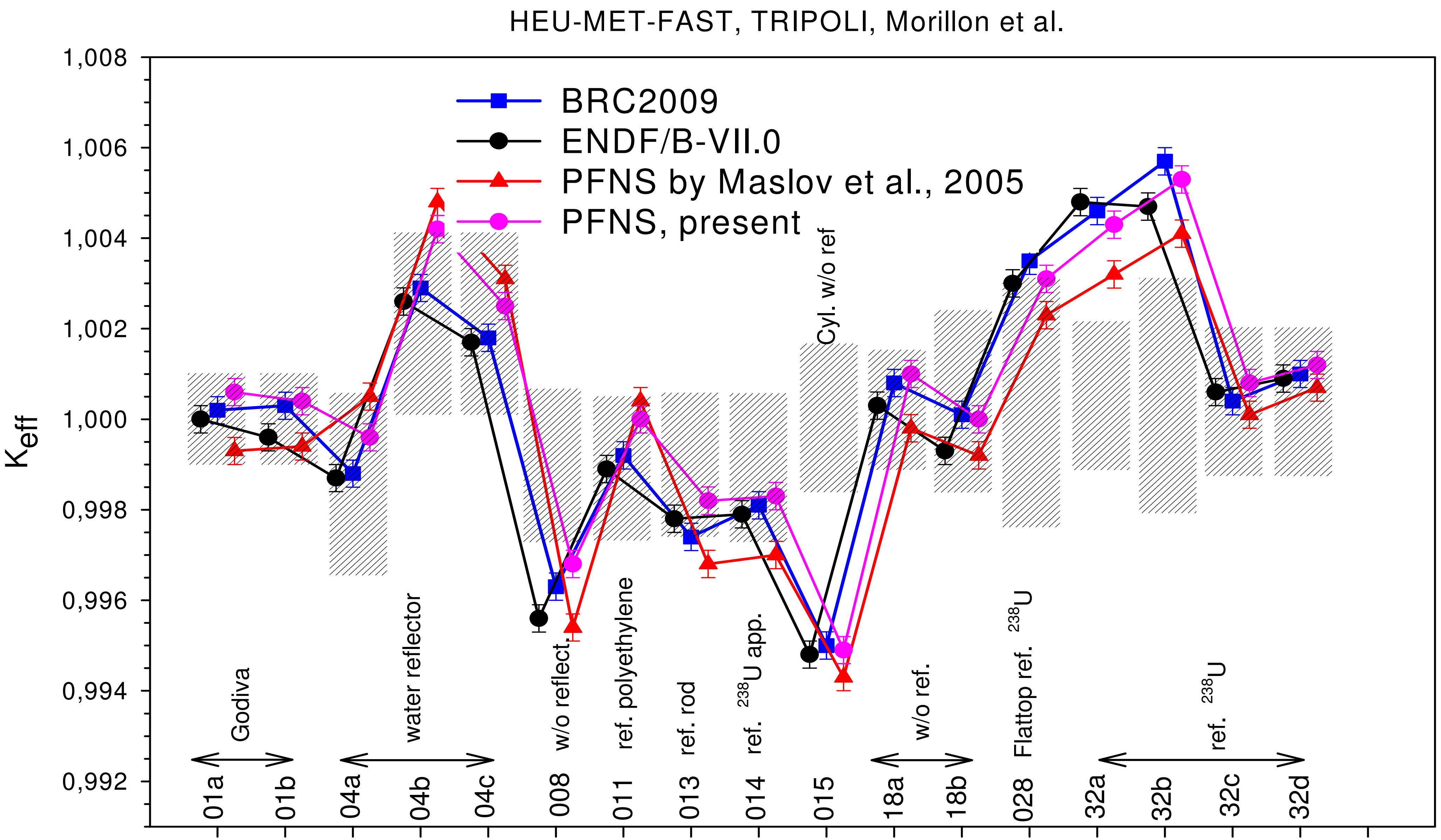
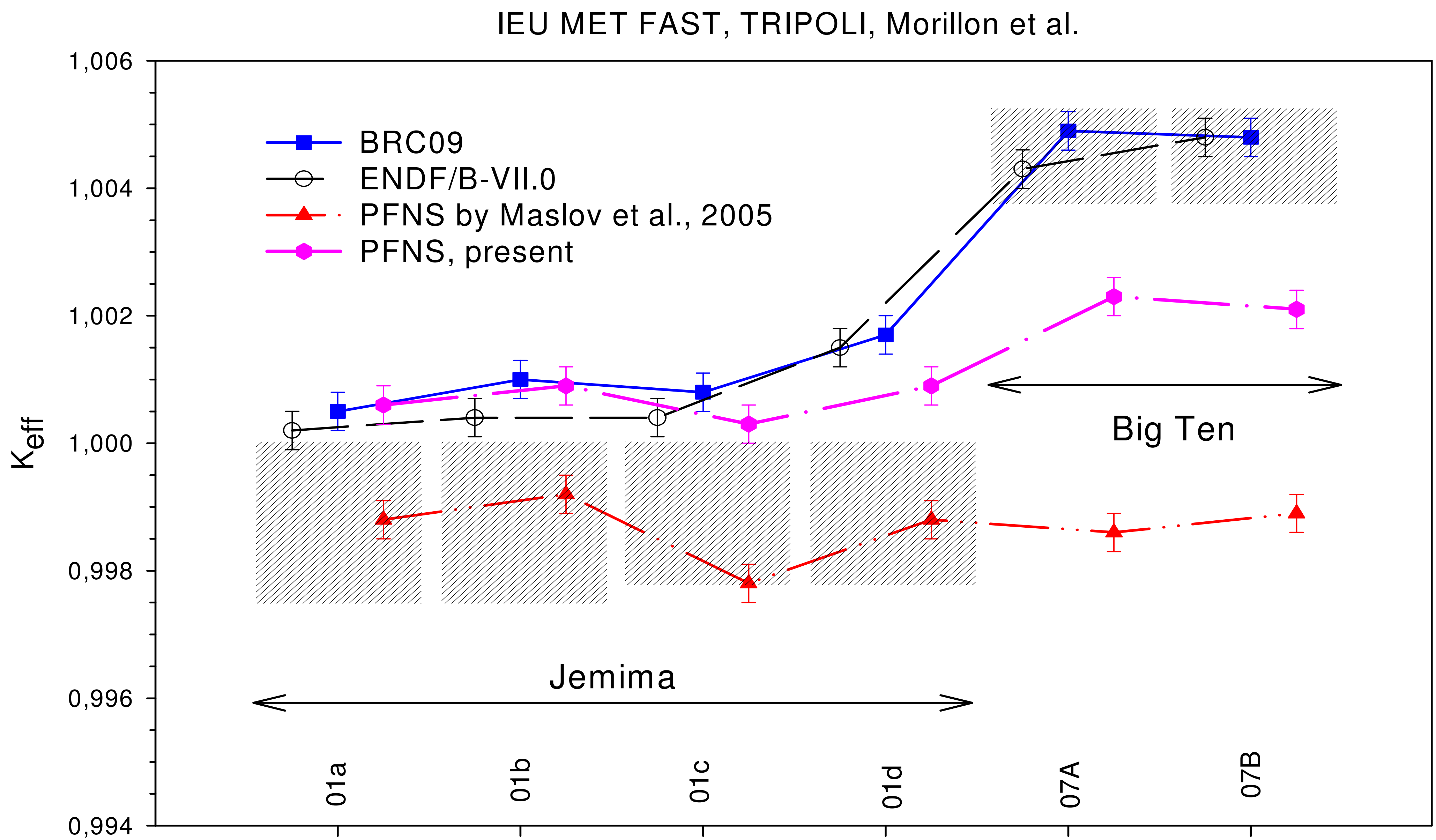
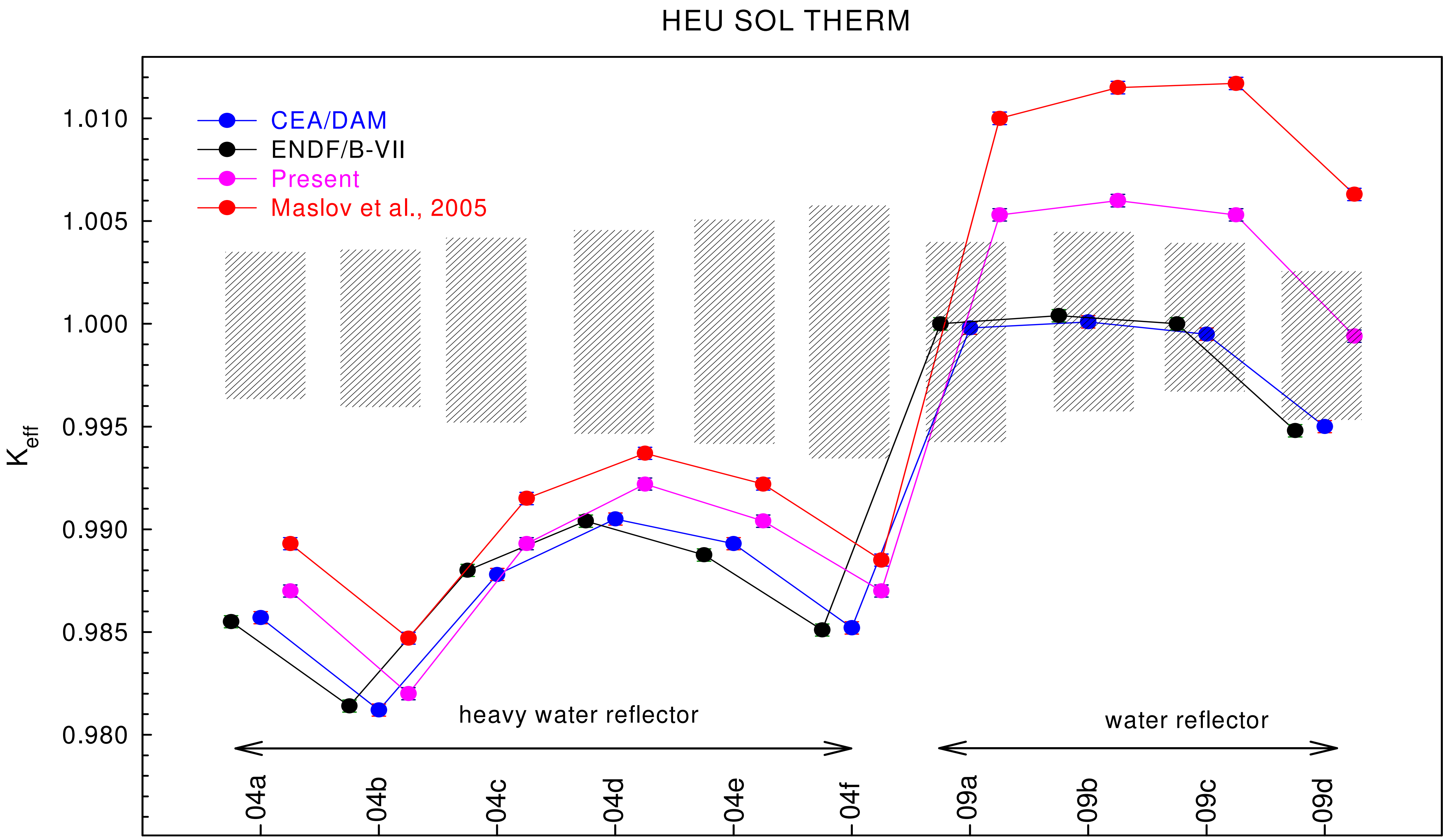


Critical assemblies



Critical assemblies



V. Maslov's conclusions

- Relative success of previous models' for LCT,HEU-MET-FAST was mainly due to

  Compensation of deficiency of soft neutrons with

excess of neutrons with ε=1~3 MeV.

Excess of hard-tail neutrons

was justified by some integral CSS, which are sensitive to ε=10~15 MeV

Present PFNS has no
deficiency of soft neutrons
has no
excess of neutrons with ε=1~3 MeV.
has no
excess of hard-tail neutrons.
That contradicts some integral CSS, which
are only sensitive to ε=10~15 MeV

Conclusions

1. GMA +phenomenological fit,
2. The energy balance model is validated for describing fission cross sections, nu_bar & PFNS.
3. K_{eff} sensitivity –SOL-LEU-IEU-HEU-(case')
   library' dependent, different weaks, PFNS'
4. K_{eff} sensitivity
   LEU- +Δ K_{eff} (200-300 pcm)

   IEU- over-tweaked $^{238}U(n,\gamma)$

   HEU- internal compensation effect

   PU-MET-FAST- -Δ K_{eff},(200pcm), over-tweaked

   HEU-SOL-THERM- +Δ K_{eff} (600 pcm)
   PU-SOL-THERM- +Δ K_{eff} (1000 pcm)

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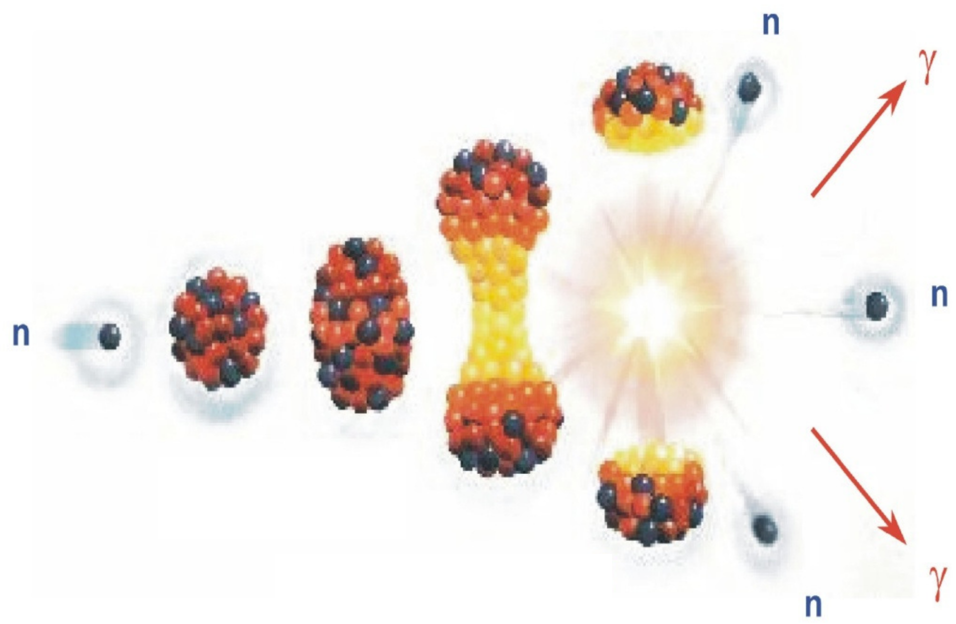
Conclusions and Outlook

- A new measurement of the $^{235}U(n,f)$ Prompt Fission Neutron Spectrum has been performed at the Budapest Reactor
- Simultaneous relative measurement to ^{252}Cf minimized systematic errors
- Excellent agreement of all 3 individual neutron detectors, no angular effect
- Very good - excellent agreement between our and literature data
- Our and literature data disagree with ENDF/B-VII and Los Alamos model
- All PFNS cannot predict integral data nor benchmark experiments
- Neutron emission before full acceleration is needed to describe the data



Thank you for your attention ☺