European Commission

Challenges in experiments and modelling of nuclear fission: prompt neutron and γ-ray emission

F.-J. Hambsch

IRMM, Belgium

Joint Research Centre

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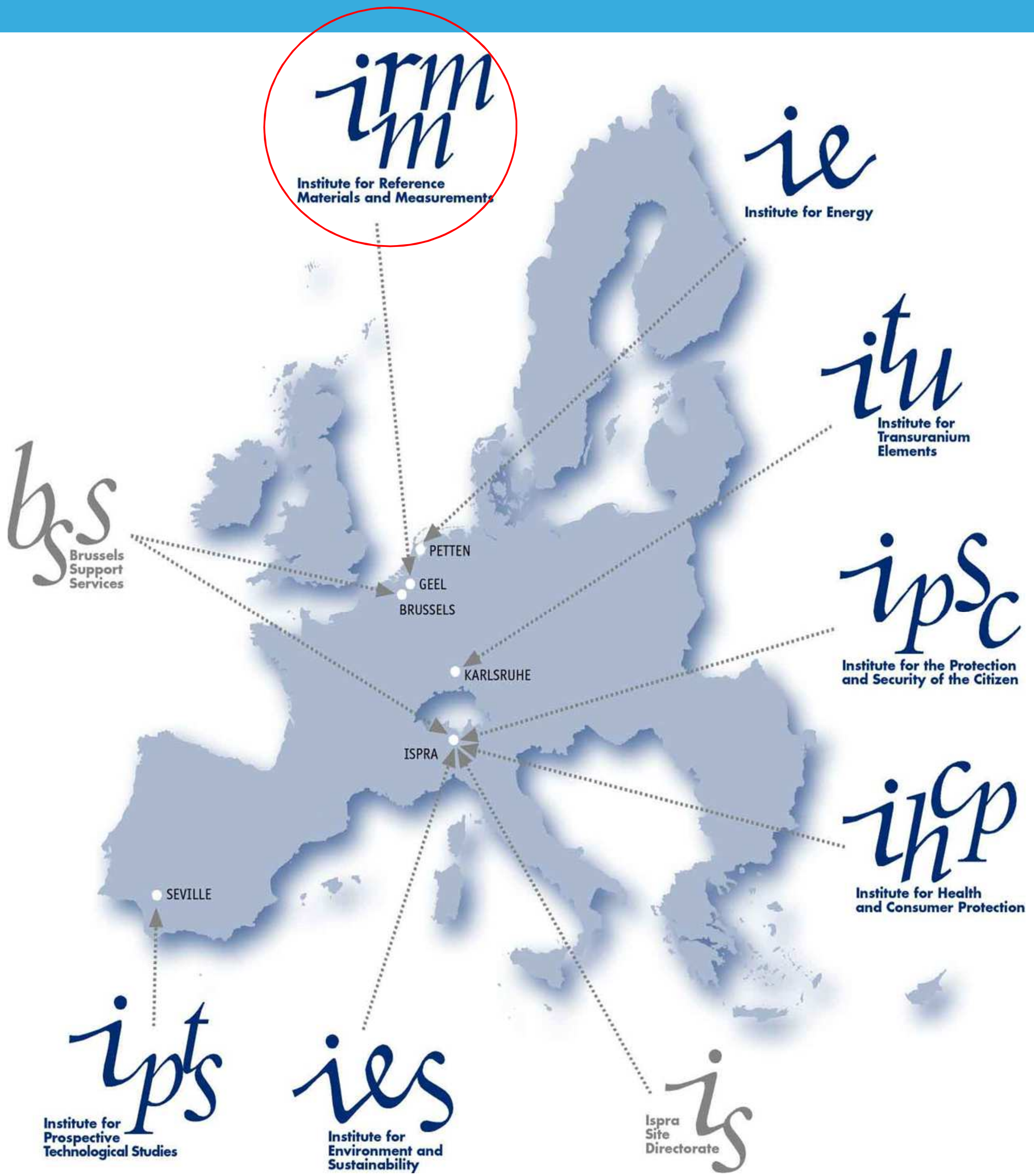
- Introduction
- Neutron multiplicities and
  Neutron-fission fragment correlations
- Prompt fission neutron spectrum
- Prompt fission γ-ray spectrum
- New detector developments
- Modelling
- Conclusions

Introduction



Accelerators for neutron data measurements

Van de Graaff

Geel linear accelerator

Introduction

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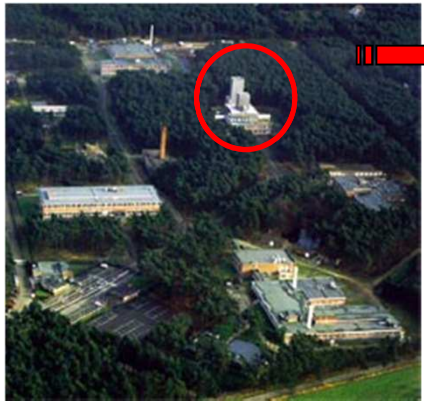

Mono-energetic neutron source

- **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**
- **$\Phi_n = 3.4\ 10^{13}$/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**

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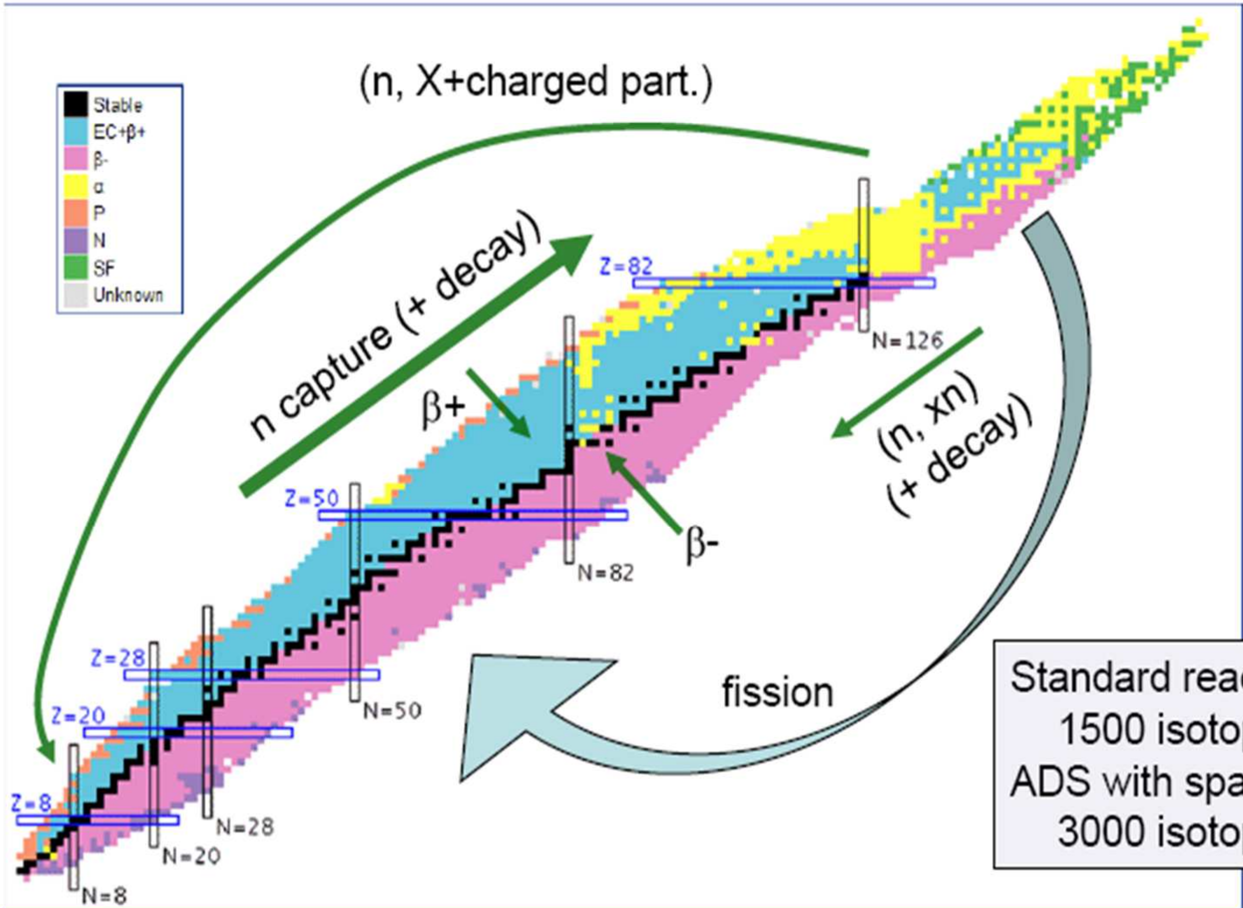
Complicated system

Main reactions in a nuclear reactor or transmutation device

- n- induced fission (energy + wastes)
- neutron capture (activation + breeding)
- elastic and inelastic neutron scattering
- radioactive decay
- (n,xn), (n, charged particle), …



Standard reactor
1500 isotopes
ADS with spallation
3000 isotopes

Nuclear data needs

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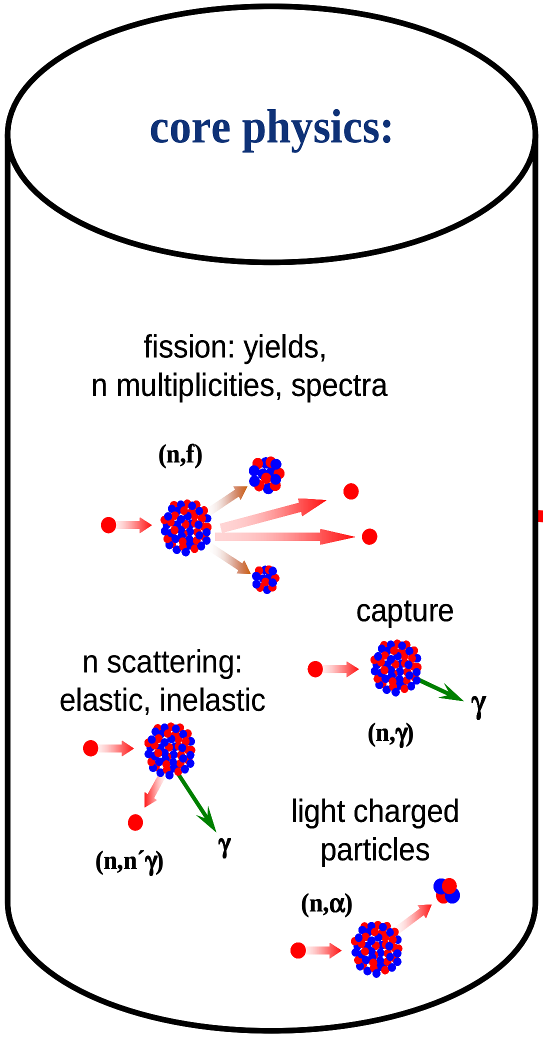

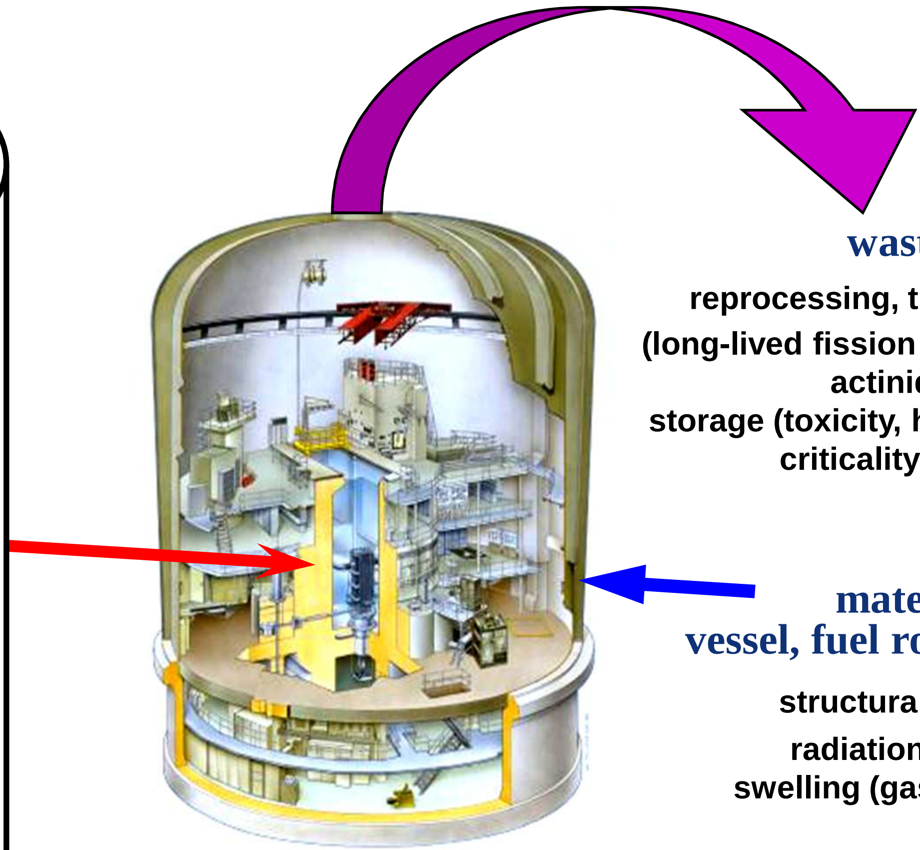

waste:

reprocessing, transmutation

(long-lived fission products, minor actinides)

storage (toxicity, heat production, criticality safety)

materials:
vessel, fuel rods, shielding:

structural materials

radiation damage,
swelling (gas production)

safe operation:

criticality (k_{eff} , self-shielding, Doppler broadening)
void coefficient , control rods
standards

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Nuclear Data Needs

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transmutation: MA (Am, Cm) (n,f), (n,γ)

closed fuel cycles, very high burnup:

Pu, MA (n,f), (n,γ)
FP (LLFP and stable) (n,γ)

advanced fuels, matrices: new materials ? (nitrides, ceramics, Zr, Mg, Ti,...?)

LFR, ADS: Pb, Bi, structural materials (n,γ), (n,n‘), (n,xn)

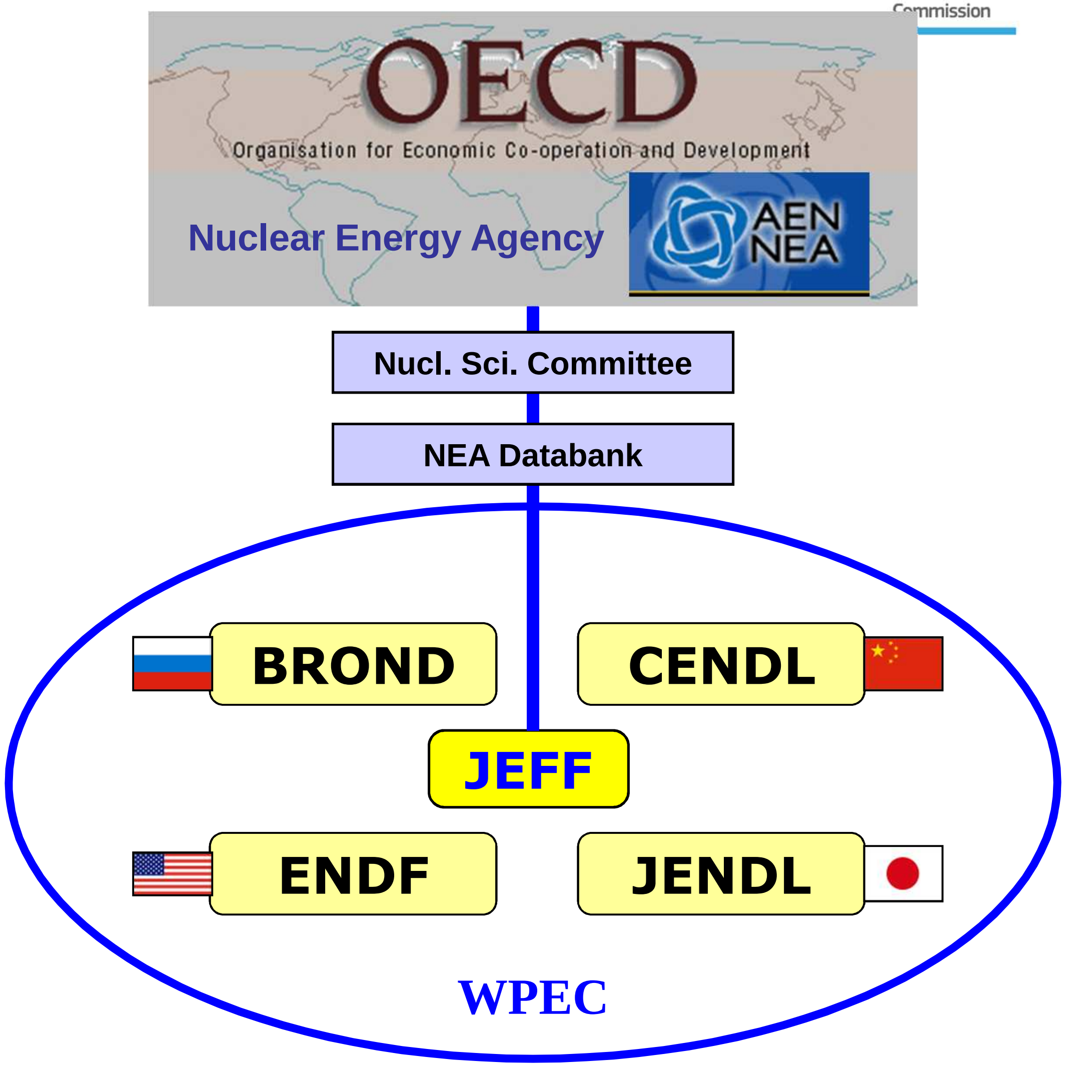
GFR, VHTR: Doppler broadening

radiation damage on structural materials: (n,α), (n,p), (n,xn)

→ sensitivity calculations
dedicated benchmark experiments

Coordination

IAEA - INDC



WPEC:
Working Party for
Evaluation Co-operation

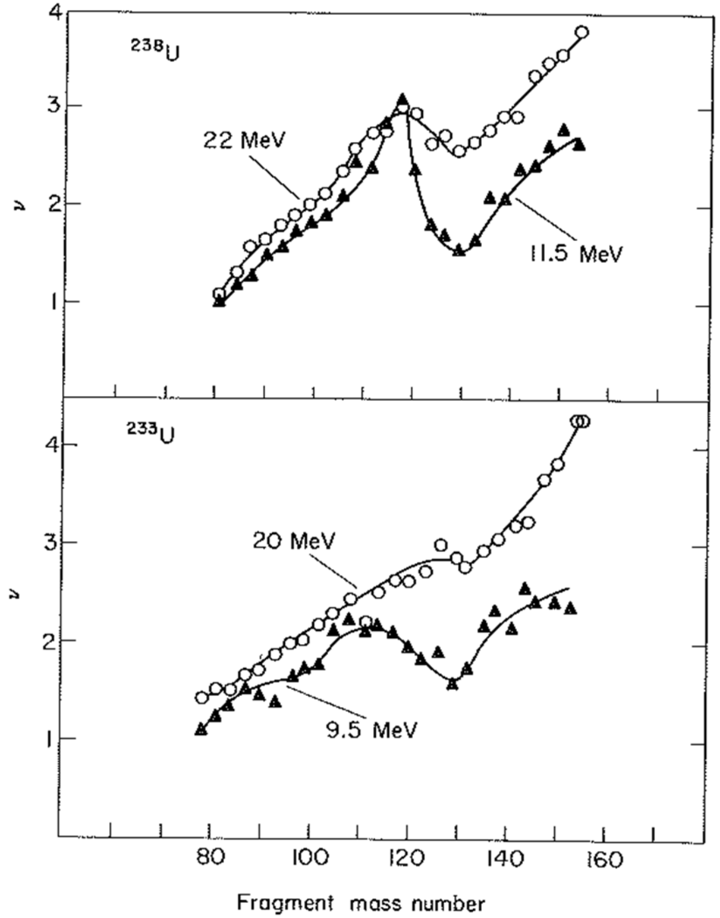
JEFF:
Joint European
Fission + Fusion datafile

Neutron multiplicities and
Neutron-fission fragment correlations

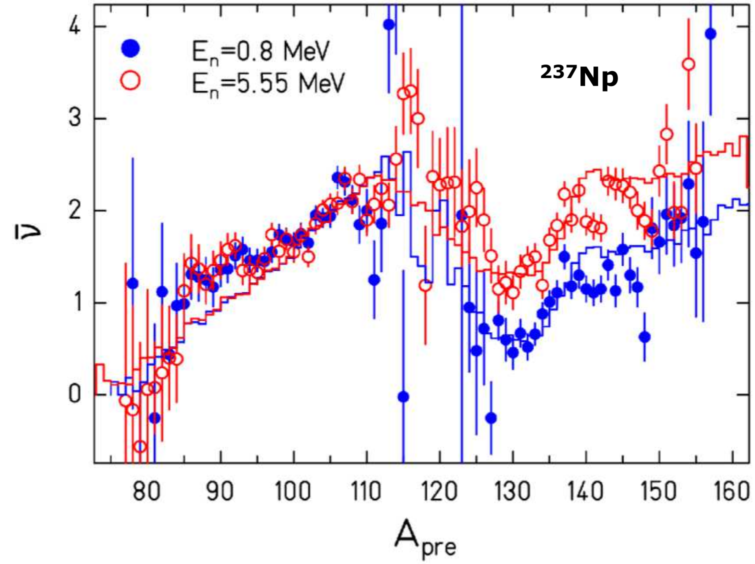
Motivation

- Experimental facts that the additional excitation energy at higher incident proton (neutron) energies does not change the neutron multiplicity for light and heavy fragments similarly (book Vandenbosch and Huizenga, 1973)
- Several models predict higher neutron multiplicities for heavy fragments at higher incident neutron energy
- Experiment on $^{234}U(n,f)$ up to En = 5 MeV used to test influence of different neutron multiplicity corrections

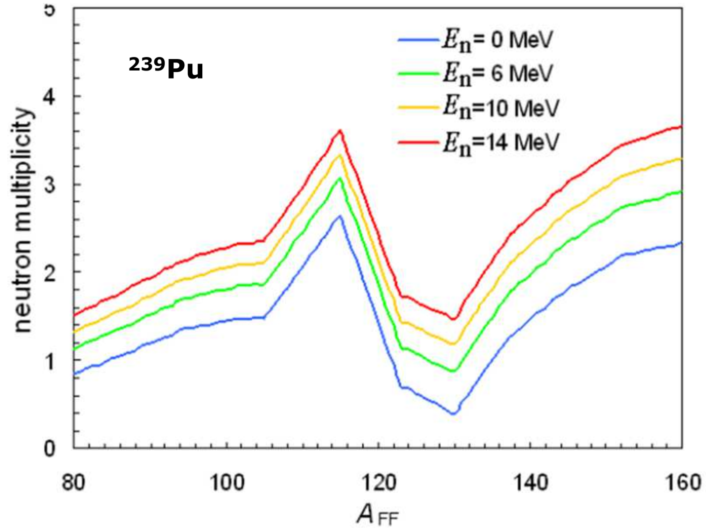
Neutron multiplicity as a fct of mass



Vandenbosch and Huizenga, Nuclear Fission, 1973



A.Naqvi, F. Kappeler, F. Dickmann, R. Müller, Phys. Rev. C 34 (1986) 21.



Lestone, Nucl. Data Sheets 112 (2011) 3120

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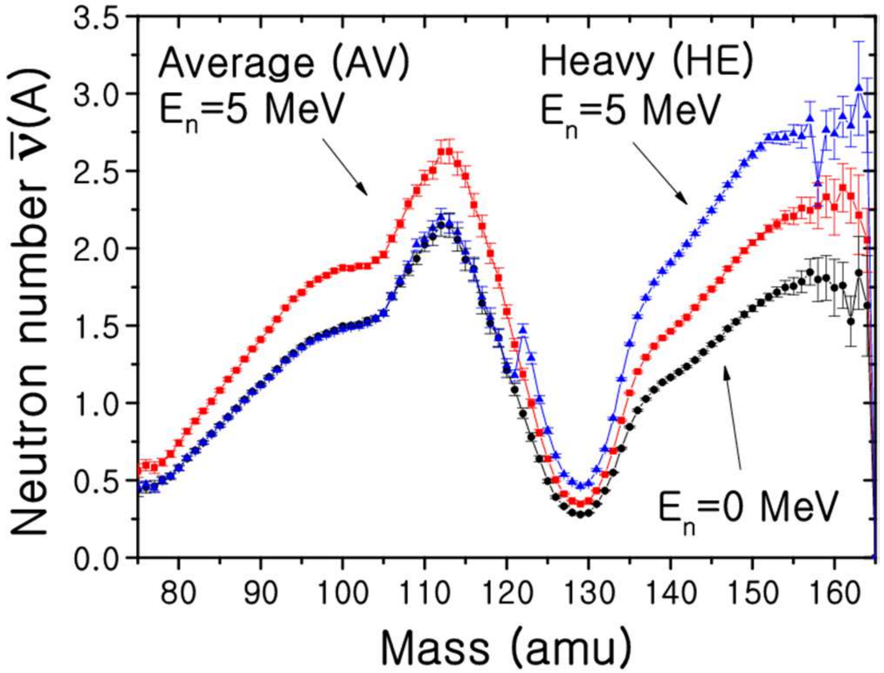
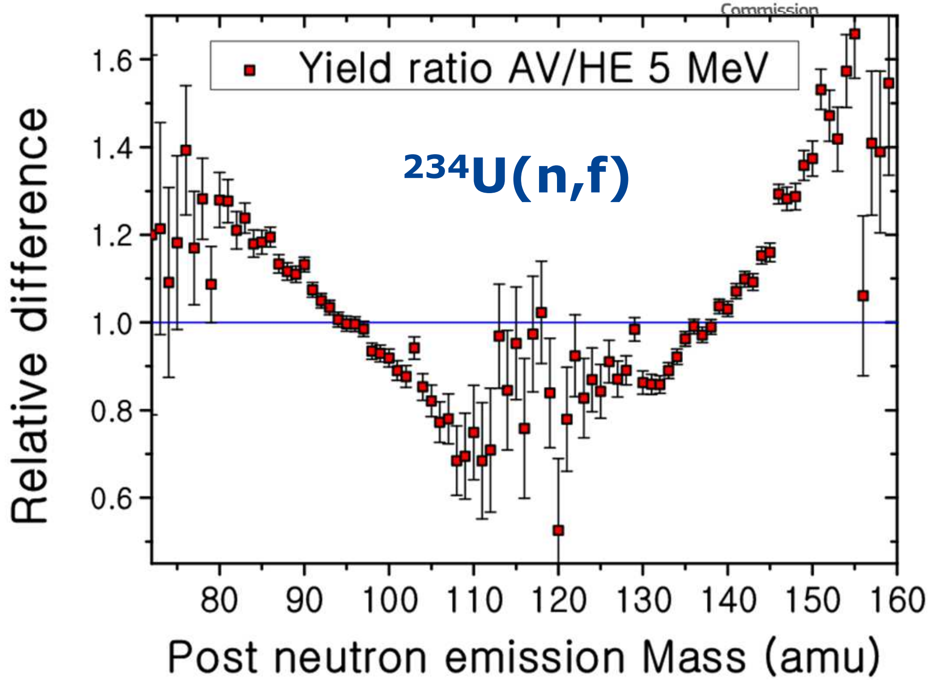
Impact of neutron multiplicity correction on fission fragment yield





Experimental evidence of higher neutron multiplicity for heavy fragments

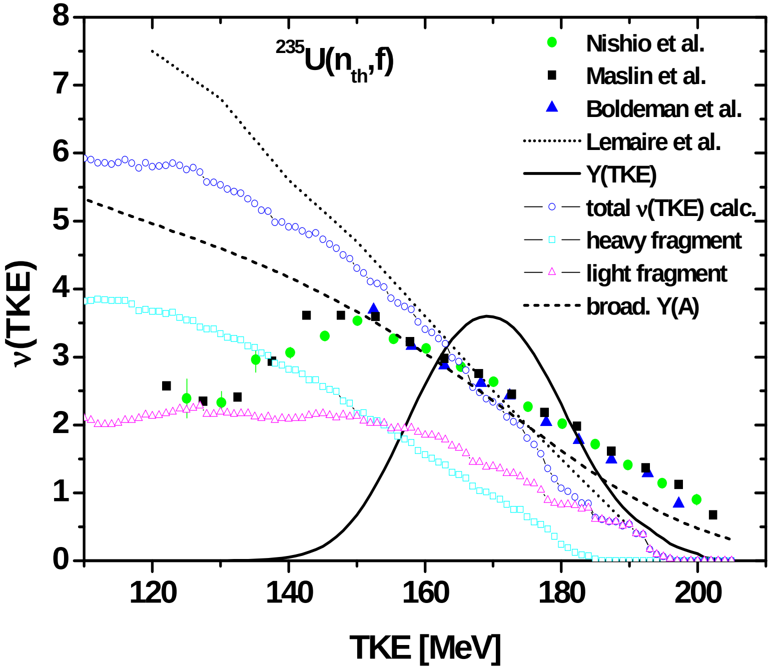
Theoretically understood by so-called energy sorting (light fragment hotter but in contact with heavy one) -> energy transfer to heavy one -> more neutron emission

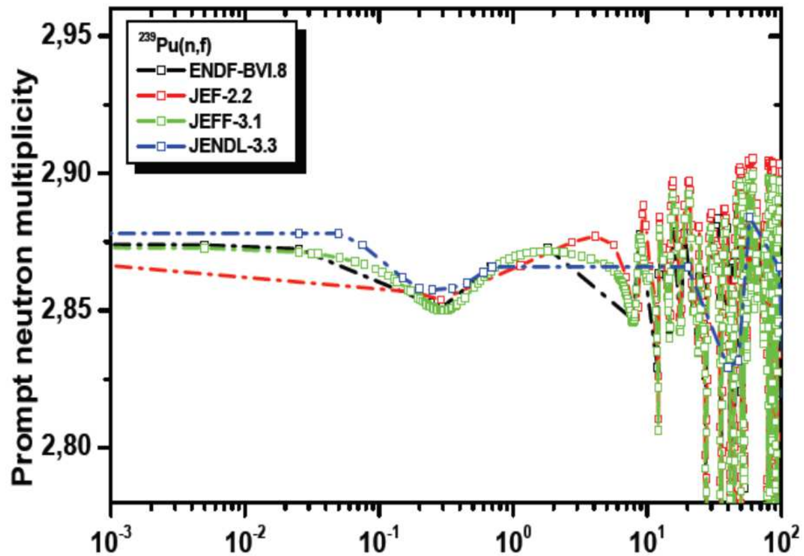
-> Impact on post neutron yields 20-30%

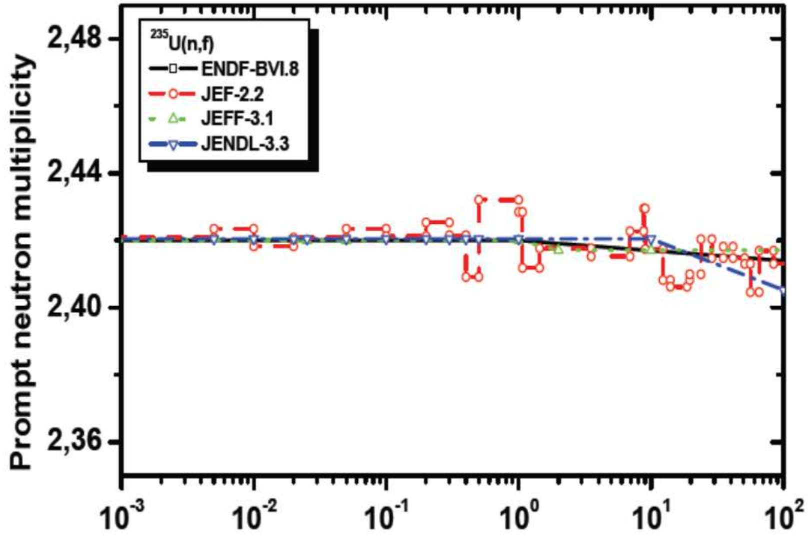
A. Al-Adili et al, Phys. Rev. C 86 (2012) 054601

Neutron emission in fission

- ^{235}U, ^{239}Pu fission yield fluctuations
- measure neutron multiplicity and neutron energy as a function of TKE
- need nuclear data for understanding of the fission process and for nuclear applications







Prompt neutron emission in $^{252}Cf(SF)$

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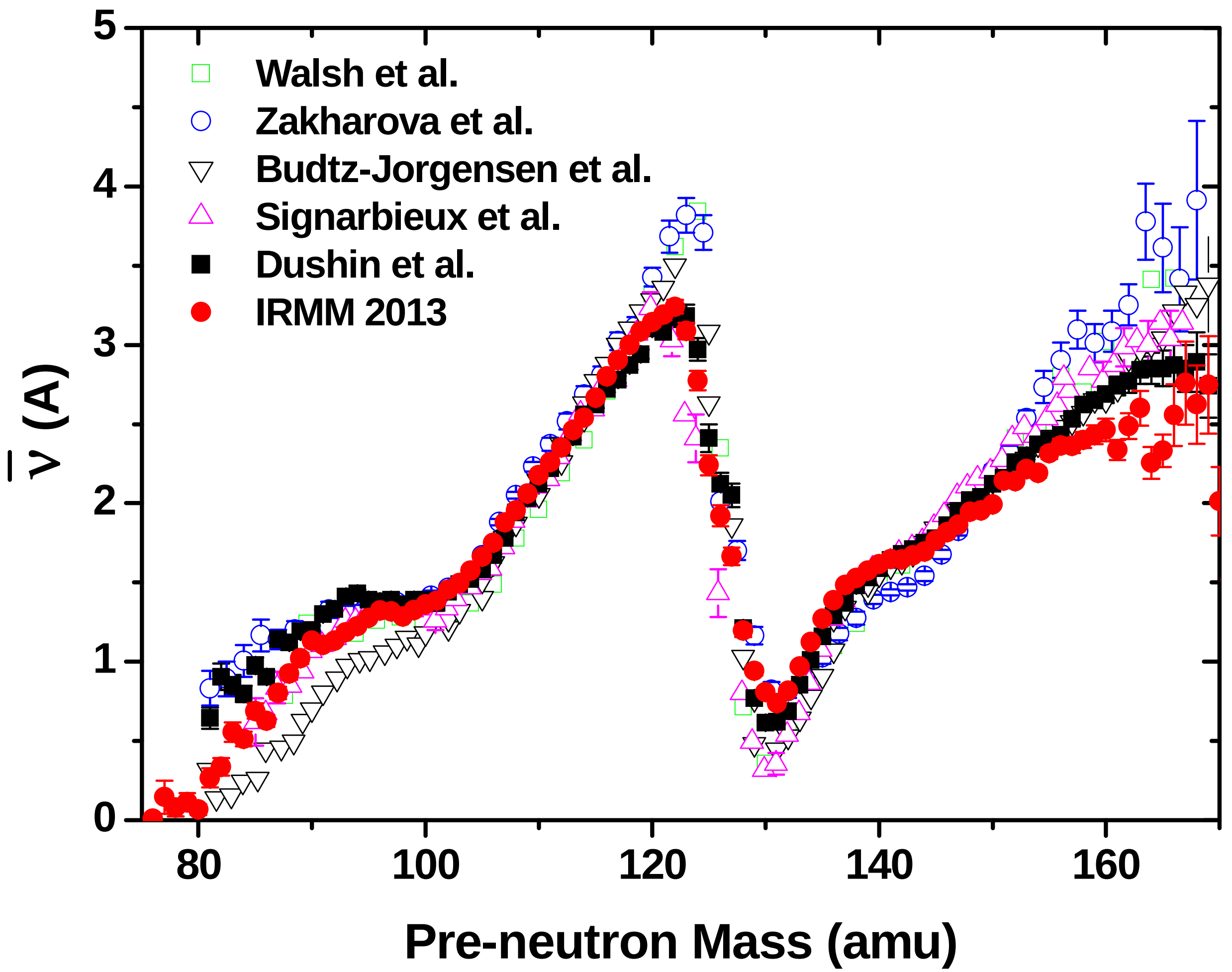

New IRMM data agree very well with literature values

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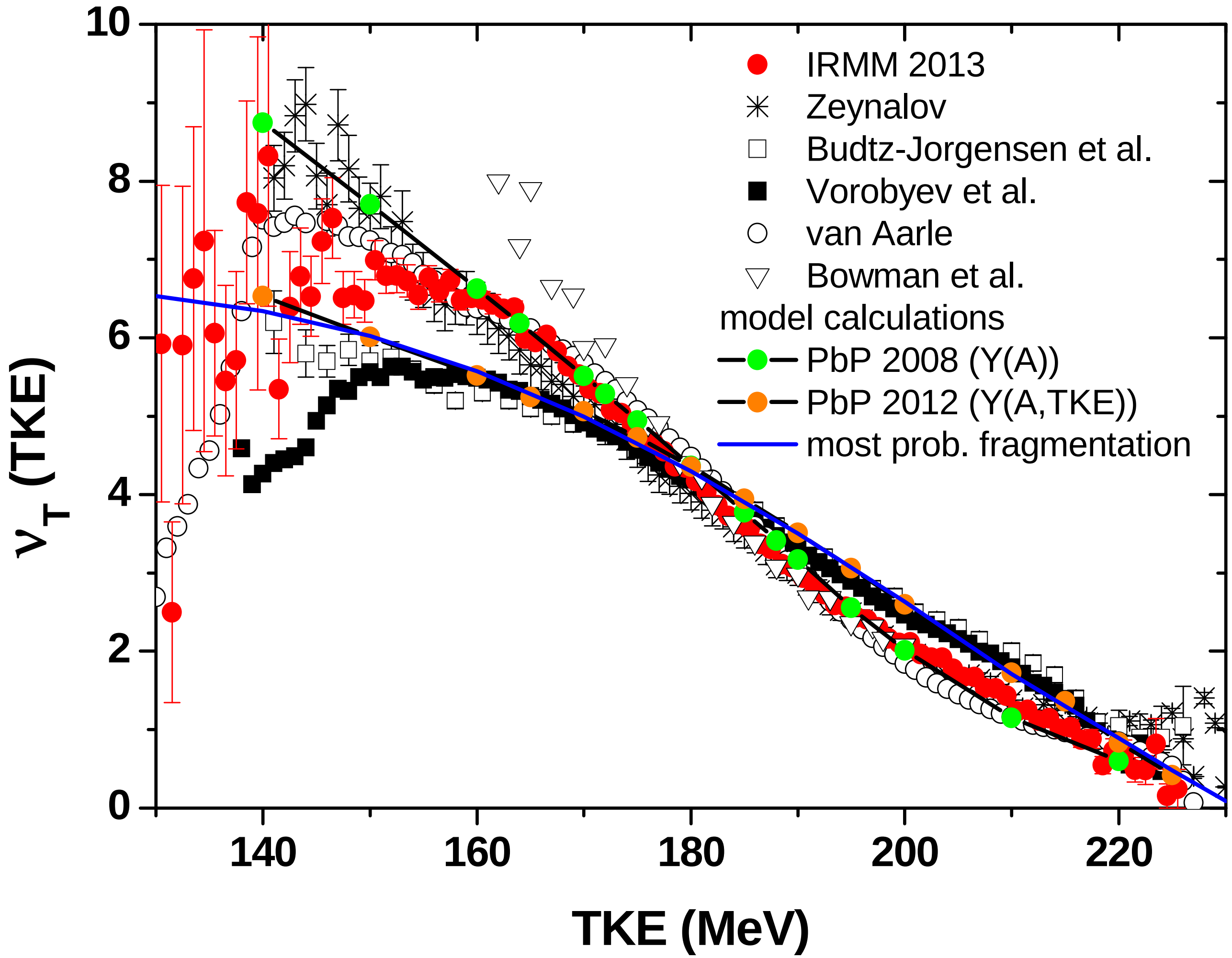
Prompt neutron emission in $^{252}Cf(SF)$



Still discrepancy between different experiments

Prompt fission neutron spectrum

Prompt fission neutron spectra

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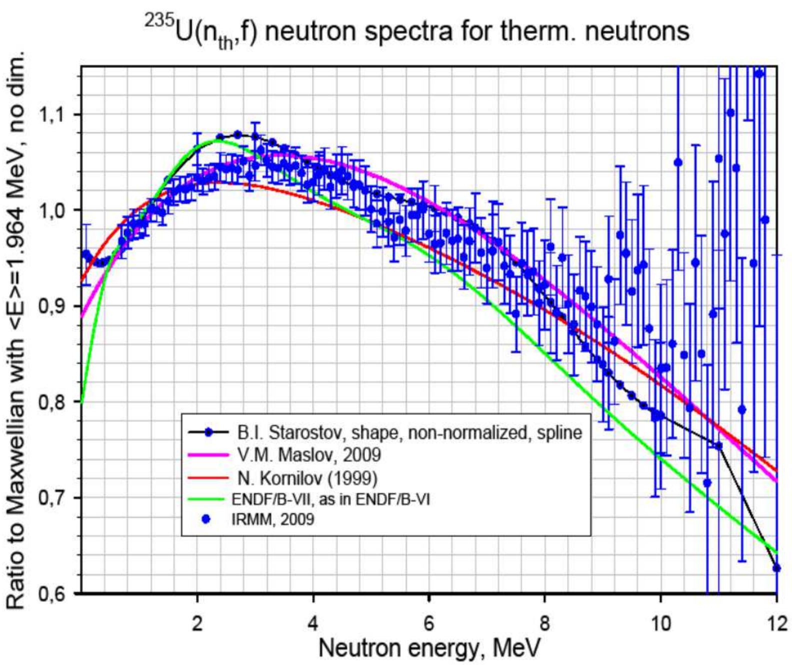
- **impact benchmarks k_{eff} as strong as cross sections:**
  - + *500 pcm* for solutions (unique amongst all libraries)
  - - *300 pcm* for thermal U but + *300 pcm* for fast U
  - + *800 pcm* for thermal Pu but - *300 pcm* for fast Pu

- **are as important as cross sections or angular distributions**

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



- ✓ Recent measurements performed by IRMM @ the research reactor in Budapest (EFNUDAT project)
- ✓ previous data from IPPE Obninsk confirmed
- ✓ Disagreement with the “Los Alamos” model (up to now still accepted reference)
- ✓ new data adopted in most recent ENDF/B-VII library
- ✓ New efforts for an improved theoretical description in collaboration with LANL and JINER, Minsk (ISTC project)

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SCINTIA array (IRMM)

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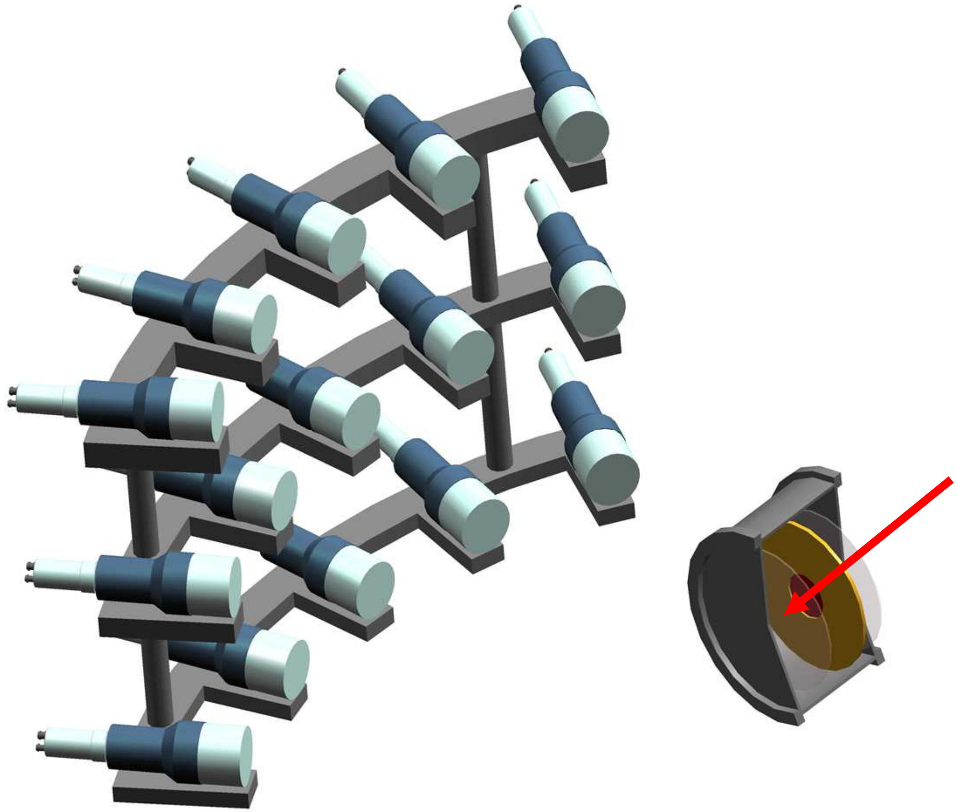

- Array of 15 neutron detectors
  - 10 SCIONIX LS301 (Φ=13 cm, h=7 cm)
  - 5 P-Therphenyl (Φ=8.5 cm, h=6.8 cm)
- Double Frisch grid ionisation chamber
- Double TOF setup
- Digital signal processing
- GELINA TOF 8m station
- Tests with $^{252}Cf(SF)$

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CHI NU array (LANL)

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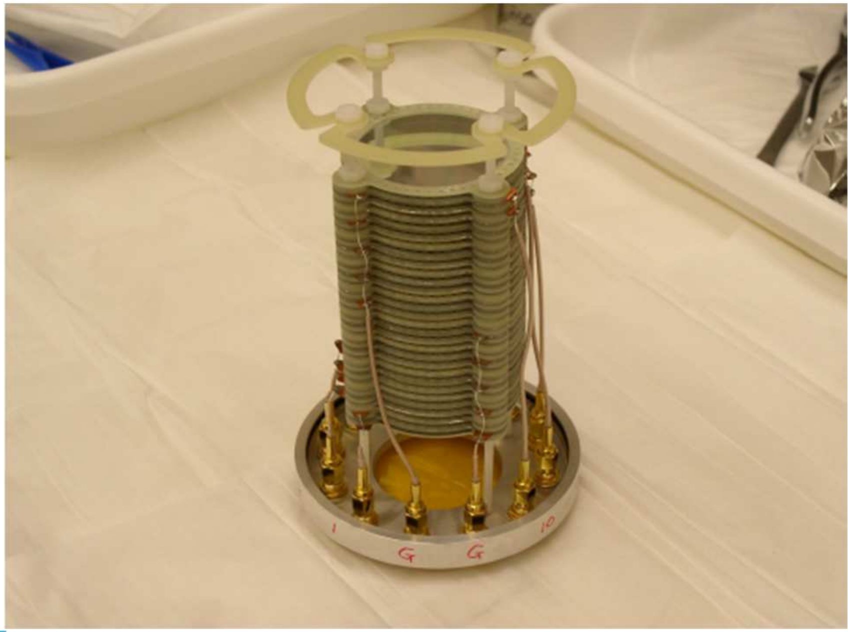
- Array of ~50 neutron detectors
- Parallel Plate Avalanche Detector (20 plates)
- Double TOF setup
- Digital signal processing
- LANL WNR facility



Prompt fission γ-ray spectrum

Prompt fission g-rays

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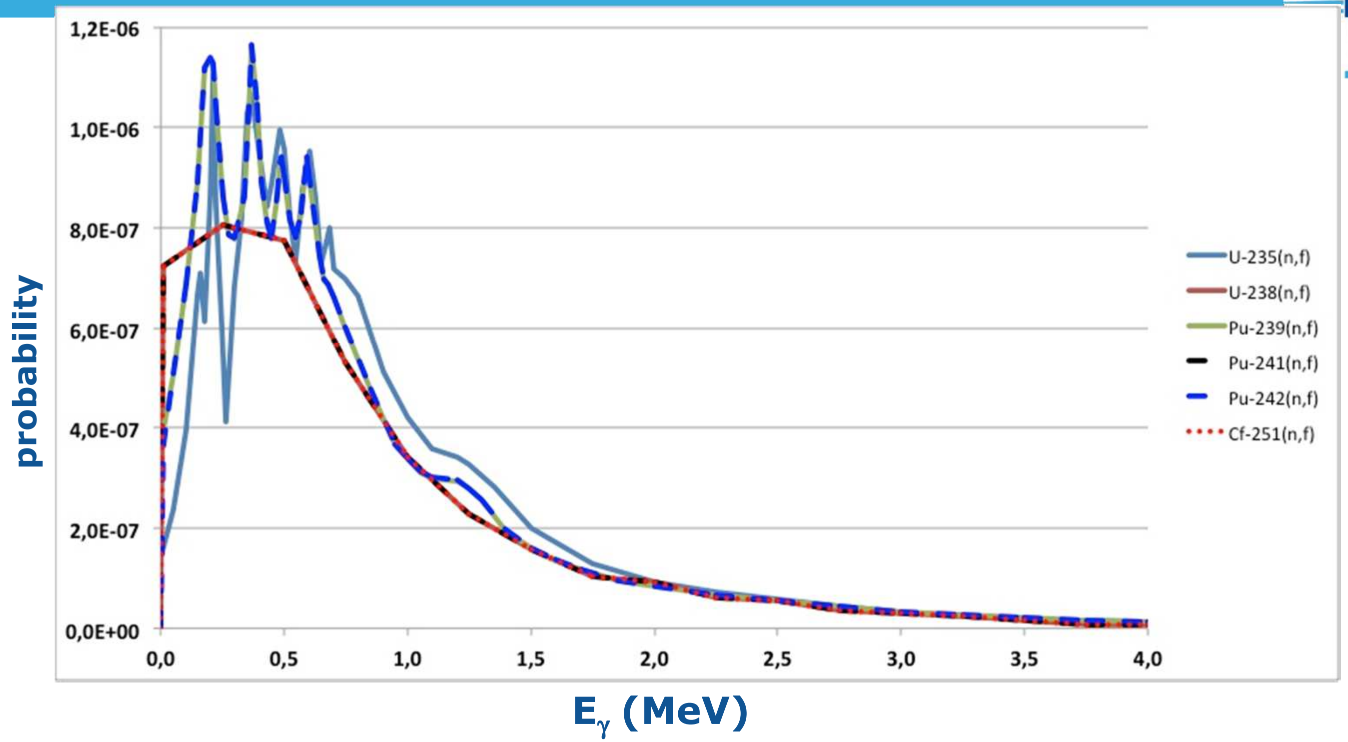
- Prediction of γ-heating for design of Gen-IV reactors
  - about 10 % of total energy released in the core of a standard nuclear reactor by fission γ-rays
  - about 40 % of those due to prompt γ-decay of fission products
- Modelling requires uncertainty not larger than 7.5 % (1σ)
  - but: present γ-ray emission data determined in early 1970's,
  - underestimating γ-heating with 10 - 28 % for ^{235}U and ^{239}Pu

⇨ **OECD/NEA Nuclear Data HPRL (H:3,H:4):**

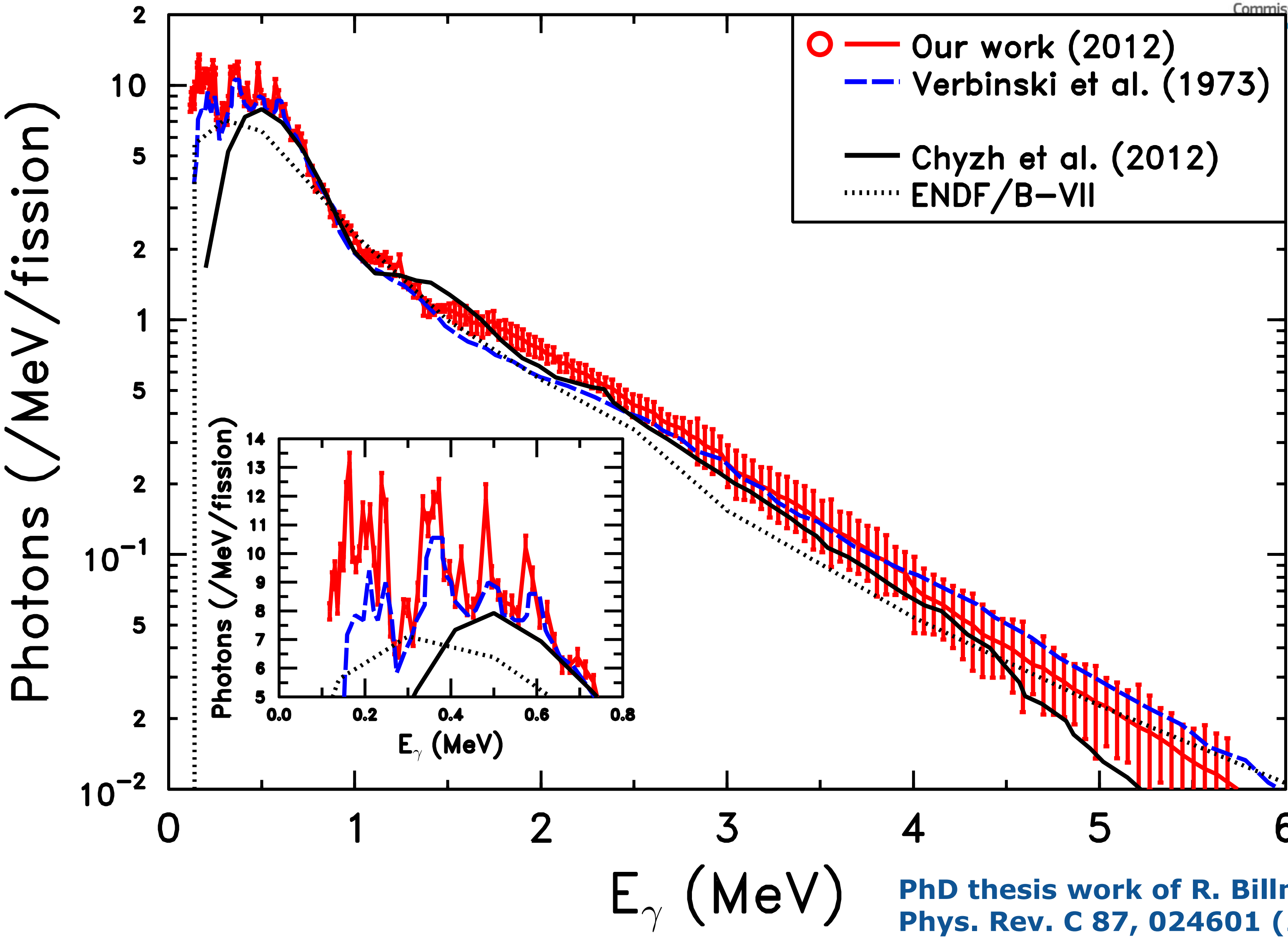
⇨ measurement of prompt γ-ray emission from ^{235}U(n,f) and ^{239}Pu(n,f)

Prompt fission γ-rays (status)



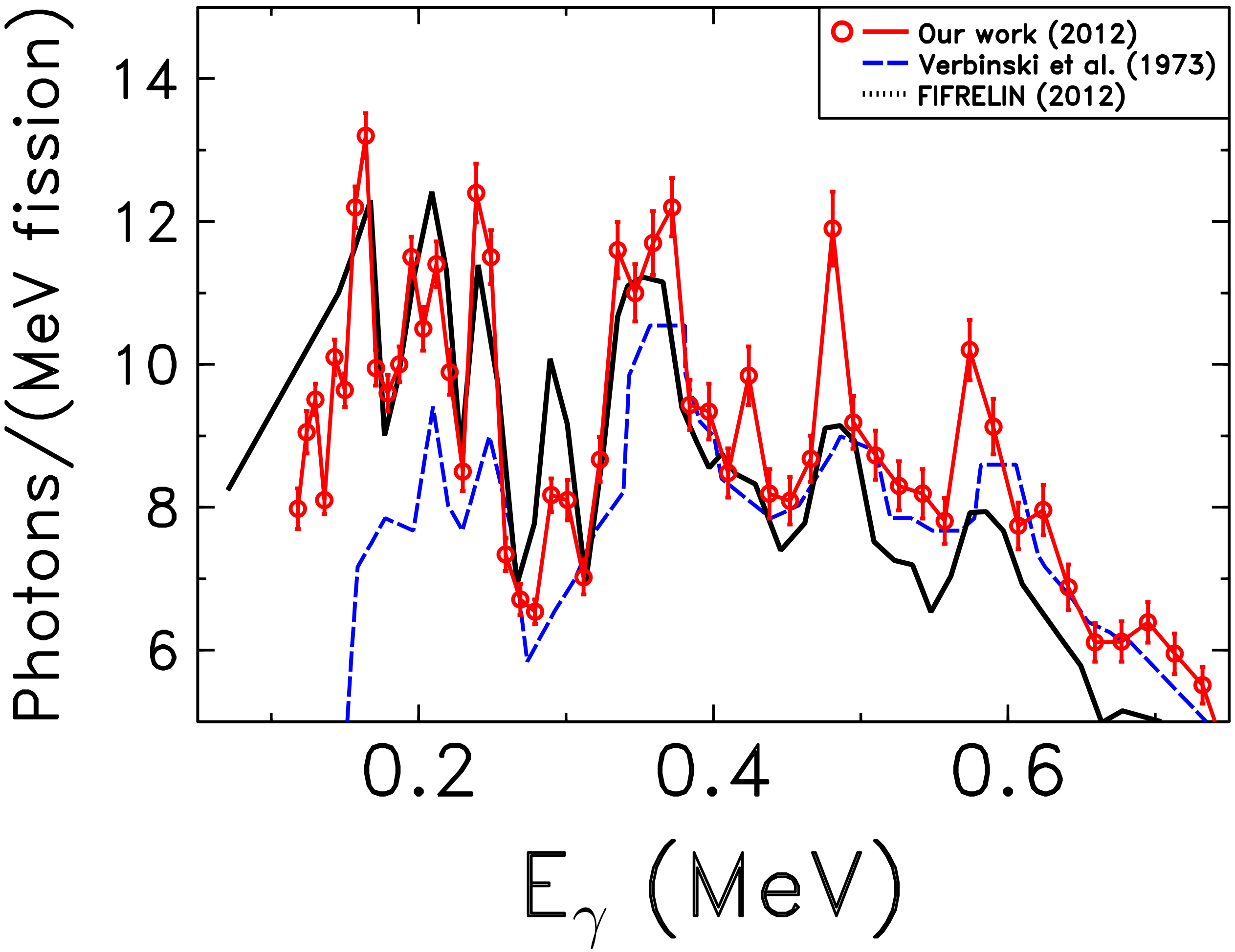
- **No (spectral) data submitted to the EXFOR library!**
- **Almost all evaluated data in ENDF/B-VII are based on evaluation exercises before 1990**
- **Evaluated data for ^{238}U, ^{241}Pu and ^{252}Cf identical**
- **The same is true for the spectra of $^{239,242}Pu$**

$^{252}Cf(SF)$: 2″× 2″ $LaBr_3$



PhD thesis work of R. Billnert
Phys. Rev. C 87, 024601 (2013)

$^{252}Cf(SF)$: 2″× 2″ $LaBr_3$



PhD thesis work of R. Billnert

R. Billnert et al., Phys. Rev. C 87, 024601 (2013)

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Comparison

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Results	ν_γ (per fission)	ϵ_γ (MeV)	$E_{\gamma,\mathrm{tot}}$ (MeV)
This work ($LaBr_3$:Ce)	8.30 ± 0.08	0.80 ± 0.01	6.64 ± 0.08
This work ($CeBr_3$)	8.31 ± 0.10	0.80 ± 0.01	6.65 ± 0.12
Verbinski *et al.* [5]	7.80 ± 0.30	0.88 ± 0.04	6.84 ± 0.30
Pleasonton *et al.* [6]	8.32 ± 0.40	0.85 ± 0.06	7.06 ± 0.35
Chyzh *et al.* [27]	8.14 ± 0.4	0.94 ± 0.05	7.65 ± 0.55
ENDF/B-VII.0[a]	7.48	0.76	5.71

In the meantime ENDF/B-VII.1 released still with an underestimation of $E_{\gamma,tot}$ by 9%

PhD thesis work of R. Billnert
R. Billnert et al., Phys. Rev. C 87, 024601 (2013)

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$^{235}U(n_{th},f)$: @ KFKI, Budapest ♥

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

Twin Frisch-grid ionization chamber

$LaBr_3$ 2”× 2”

$CeBr_3$ 1”× 2”

$CeBr_3$ 1”× 2”

$LaBr_3$ 2”× 2”

♥ This work was supported by the ERINDA programme of the European Commission (agreement number 269499)

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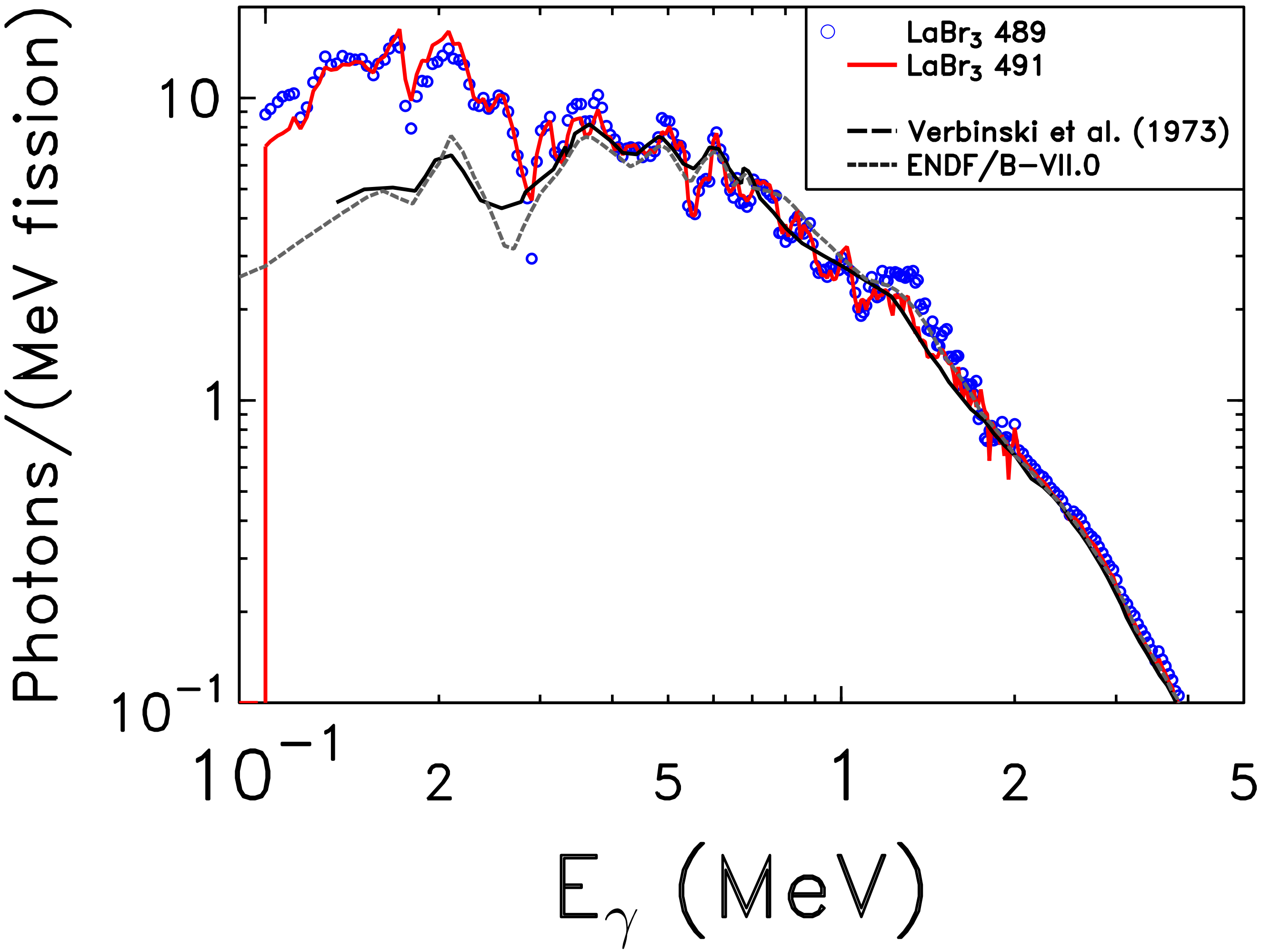
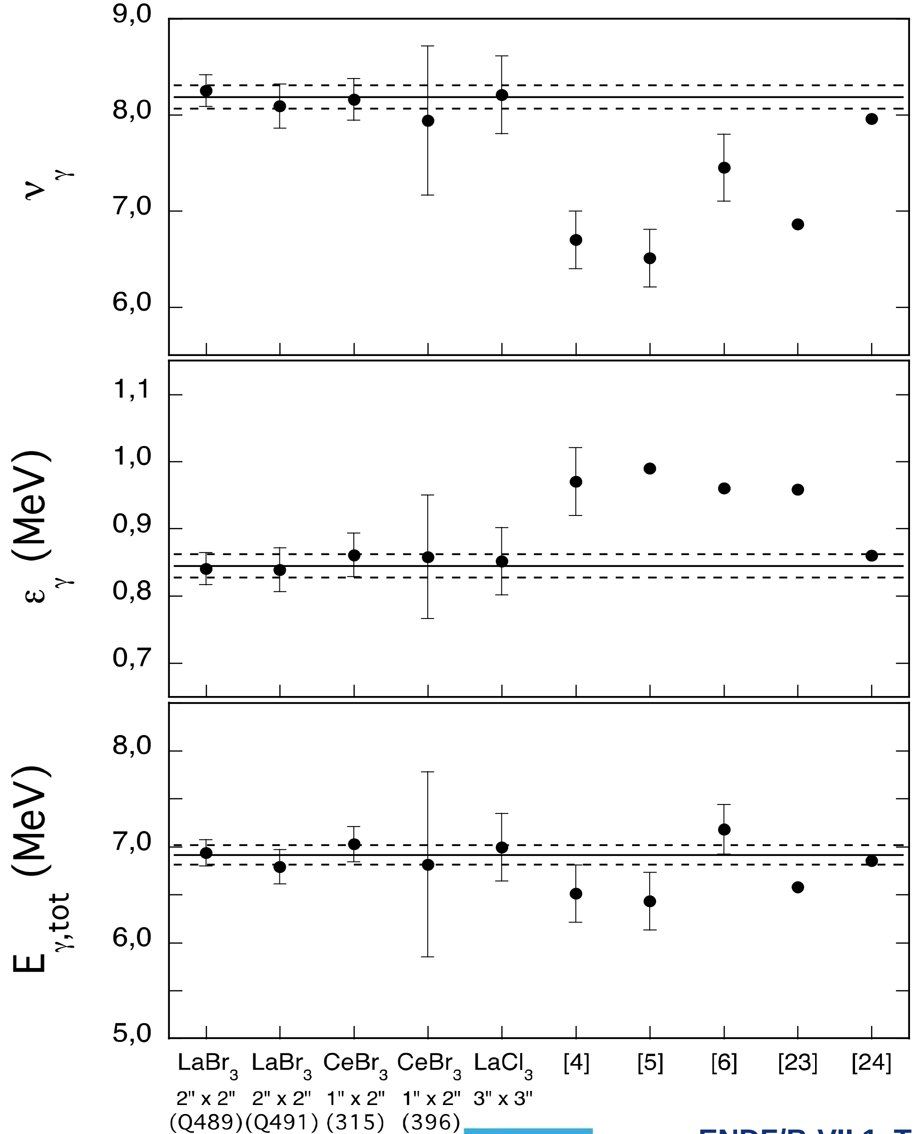
$^{235}U(n_{th},f)$: 2 $LaBr_3$ (2″ x 2″)



- This work was supported by the EFNUDAT programme of the European Commission (agreement number 31027)
- This work was supported by the ERINDA programme of the European Commission (agreement number 269499)

Comparison



ENDF/B-VII.1 Talou et al. (to be published)

New detector developments

VERDI - double (v,E) spectrometer

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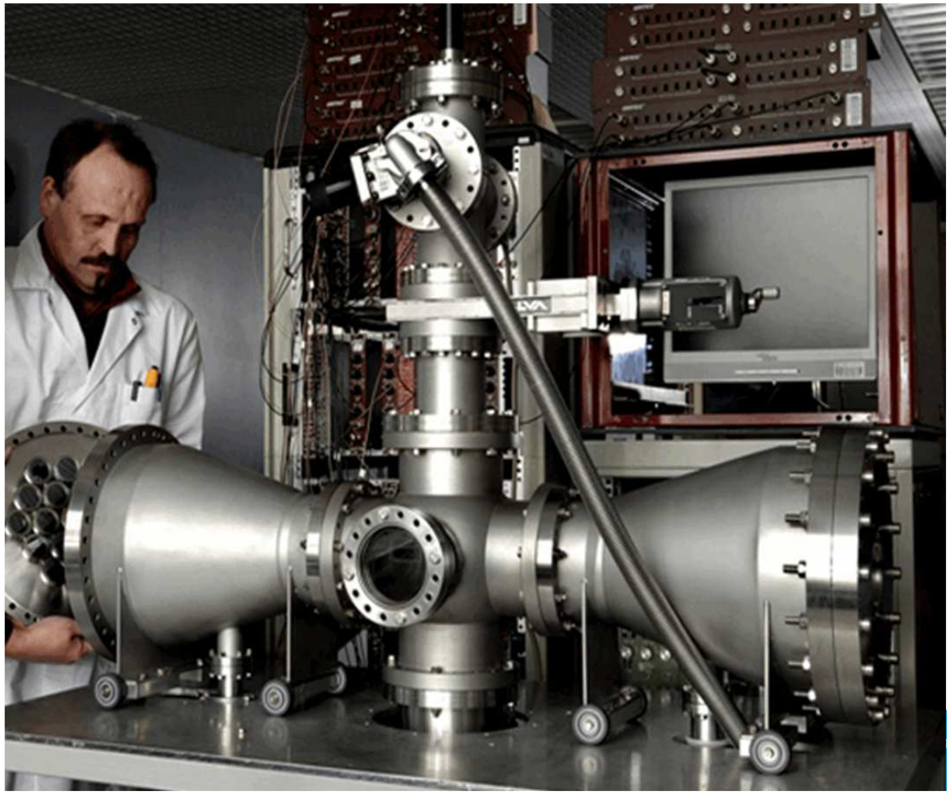
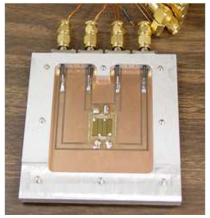
VElocity foR Direct particle Identification

Determination of fission fragment properties {A, E_{kin};Z}

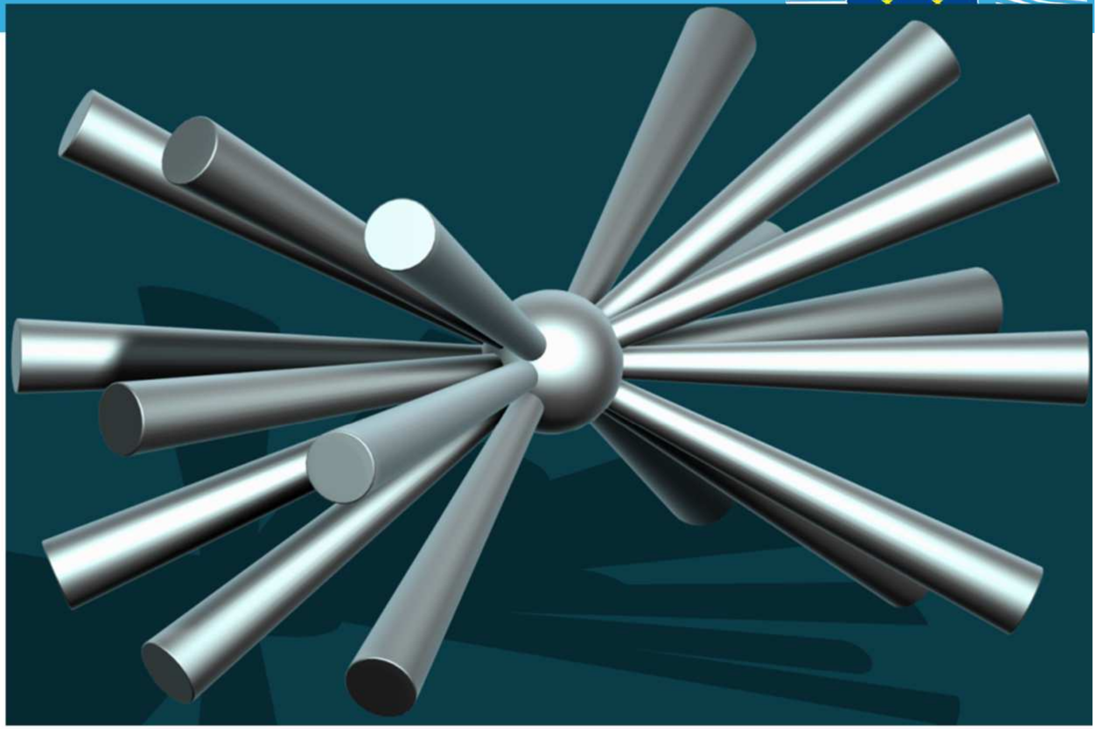
See presentation M.-O. Fregeau





- start signal: ultra-fast (segmented) diamond detectors (< 150 ps)
- stop and energy signal: large-area silicon-detector array
- ❑ coupling of ancillary detector arrays for neutron and γ-ray detection

SPIDER (LANL)

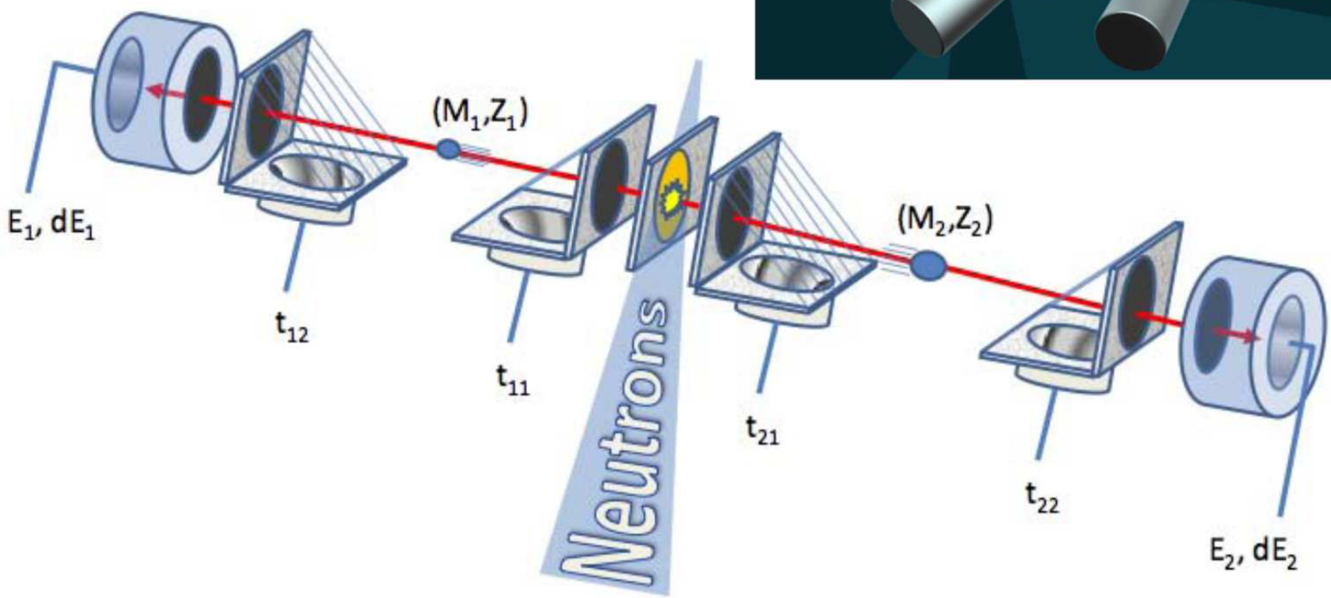


2% Efficiency

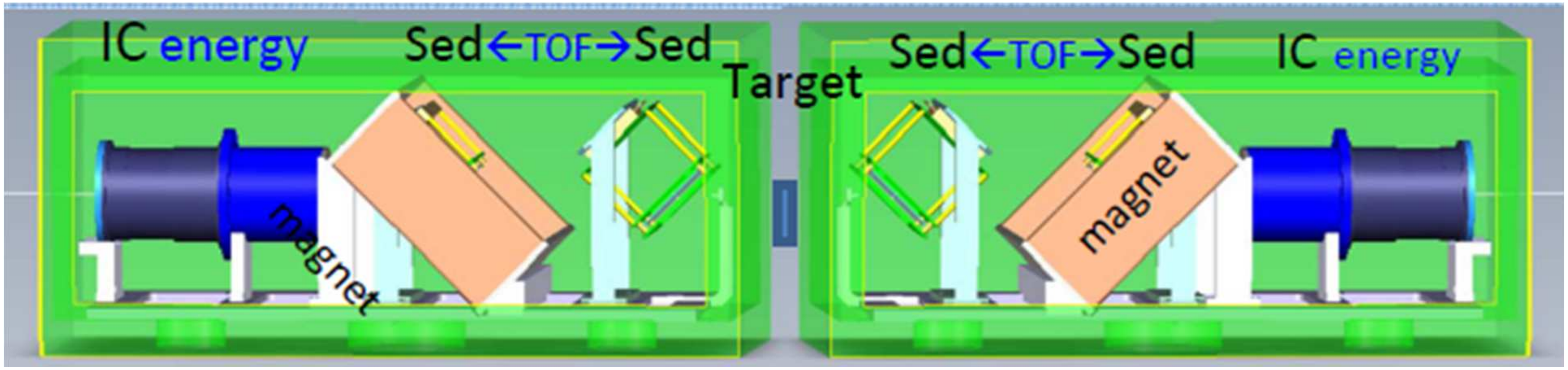
MCP time detectors

Ion chambers for energy

See presentation F. Tovesson



FALSTAFF (CEA)



Secondary Electron Detector (SED) as time detectors

Ion chambers for energy

See presentation D. Dore

and STEFF Manchester University

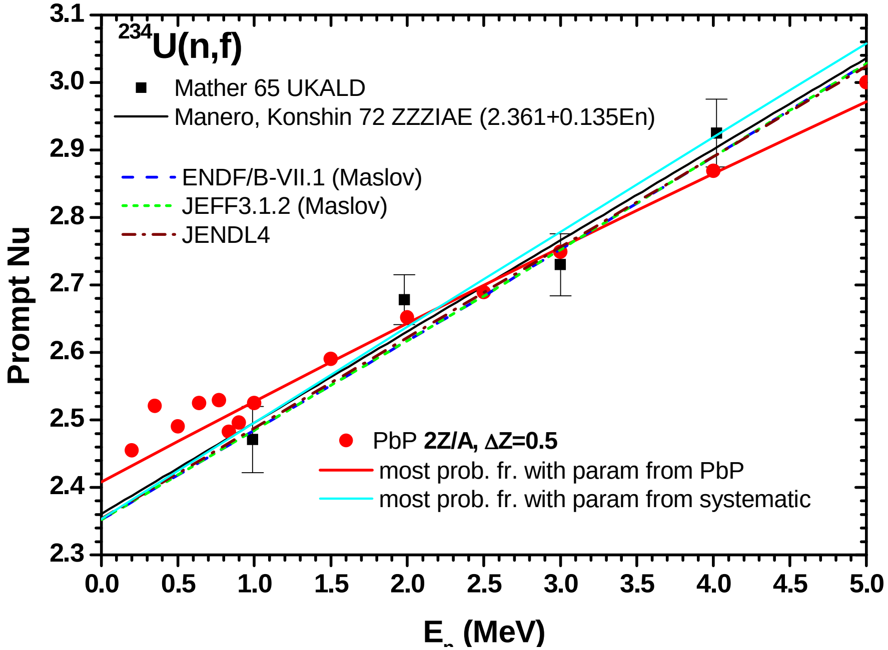
Modelling

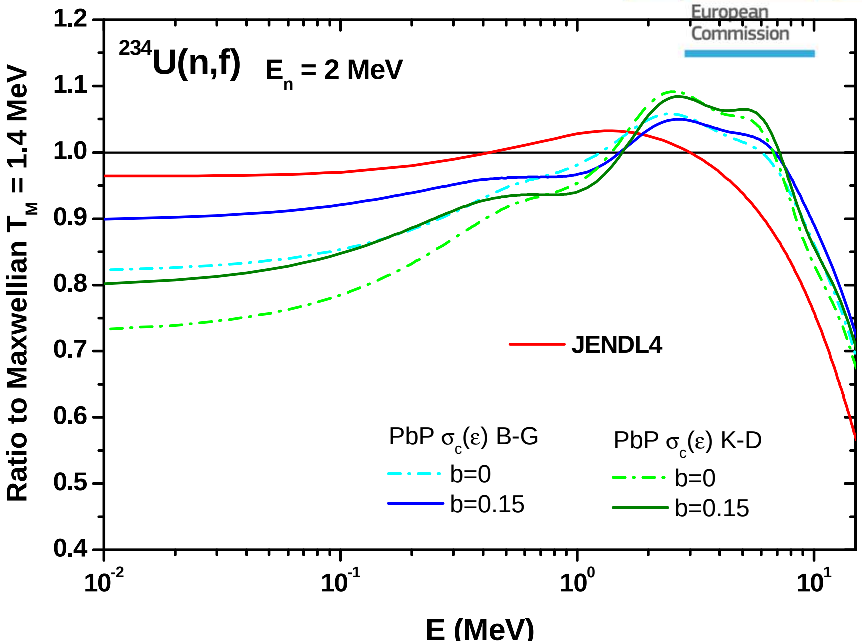
- ✓ Reaction cross sections including fission cross section
- ✓ Neutron multiplicities and spectral data
- ✓ Requirements:

  Experimental mass and kinetic energy distributions of fission fragments

Models: Point by Point (PbP), FIFRELIN, GEF

Prompt neutron emission in $^{234}U(n,f)$

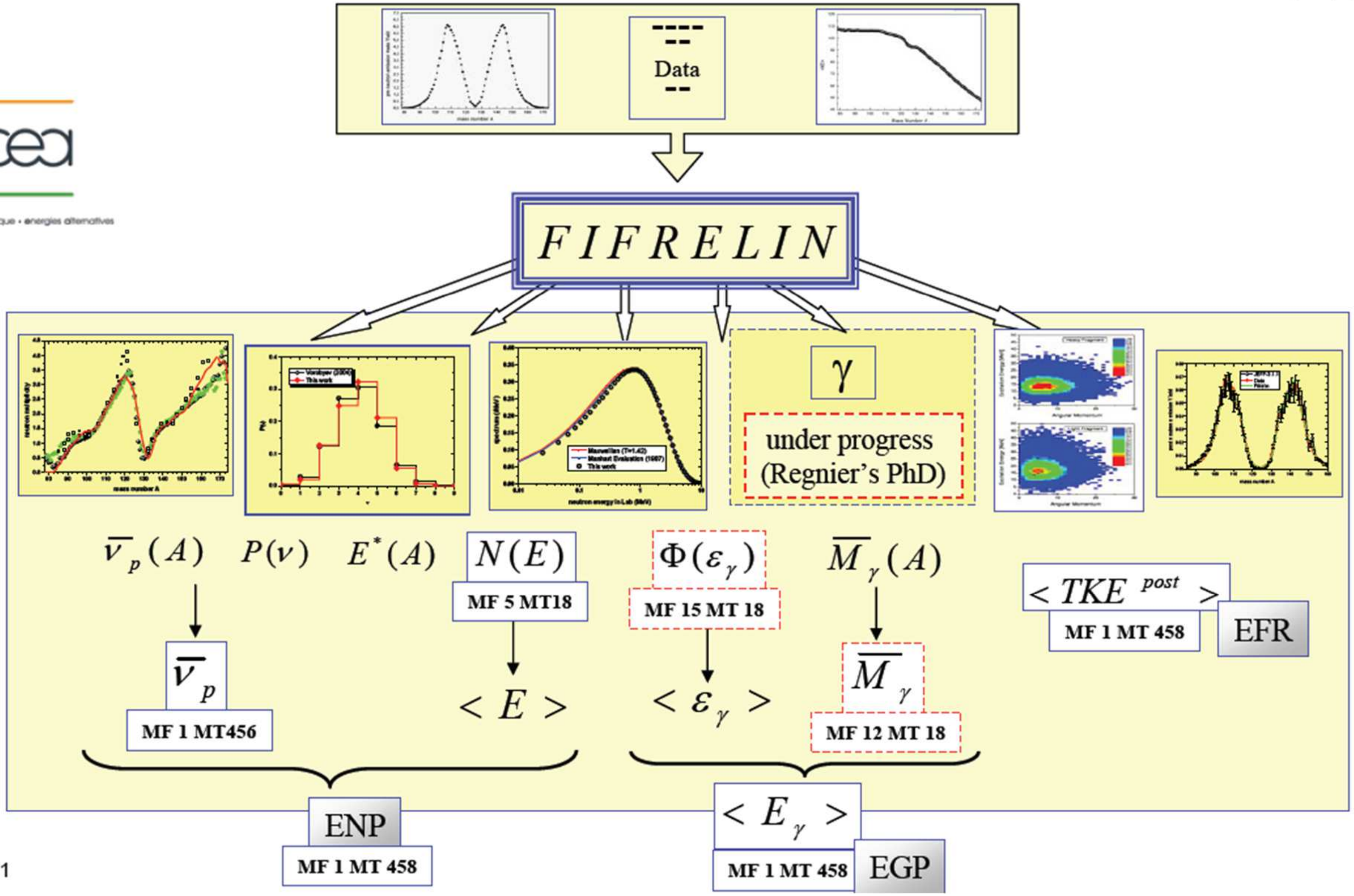




- **Calculations based on first complete experimental data measured at JRC-IRMM (mass and TKE distributions)**
- **Prompt neutron multiplicity and spectrum deduced from experimental mass and TKE distributions**

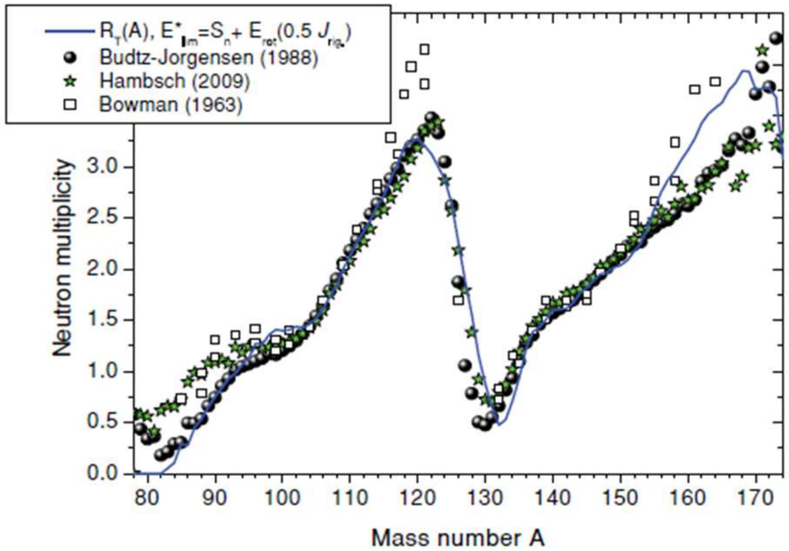
-> Obvious discrepancies between the present calculations and evaluated neutron data libraries

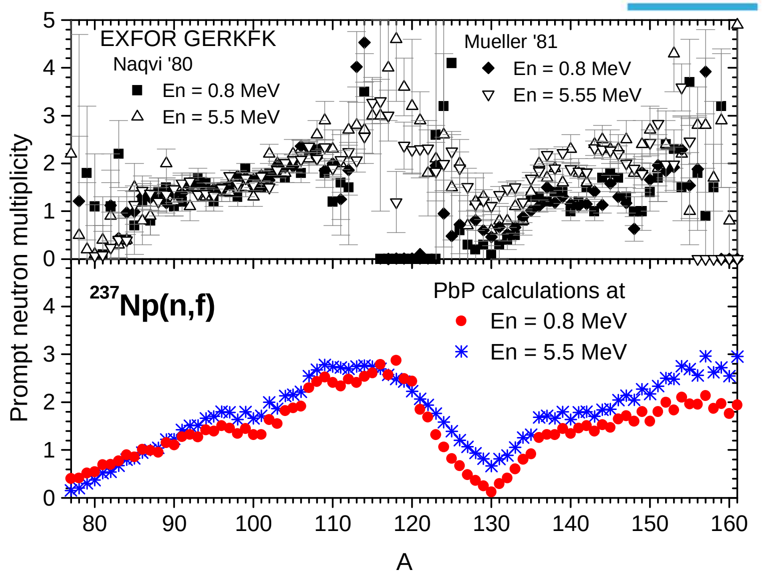
Modelling n-distributions: FIFRELIN

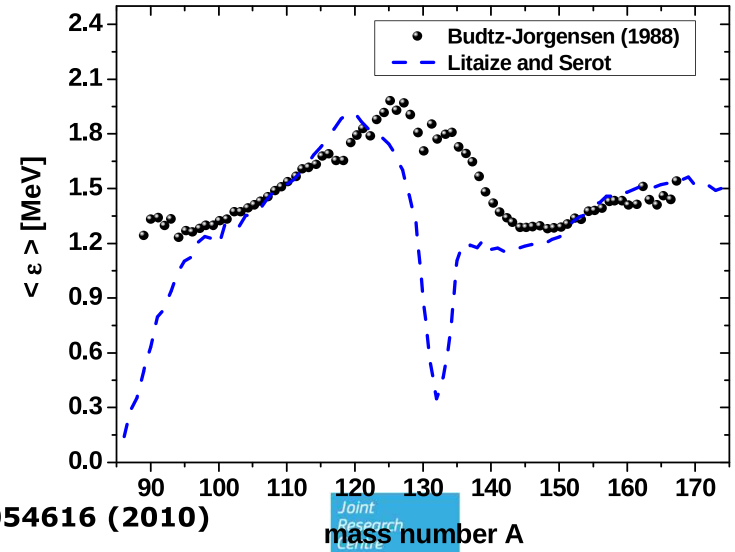


O. Litaize, GEDEPEON-JEFF meeting, 2010, JEFdoc 1350

Modelling prompt n-emission







O. Litaize, O. Serot, PRC 82, 054616 (2010)

Experimental and calculated data (ν(TKE))

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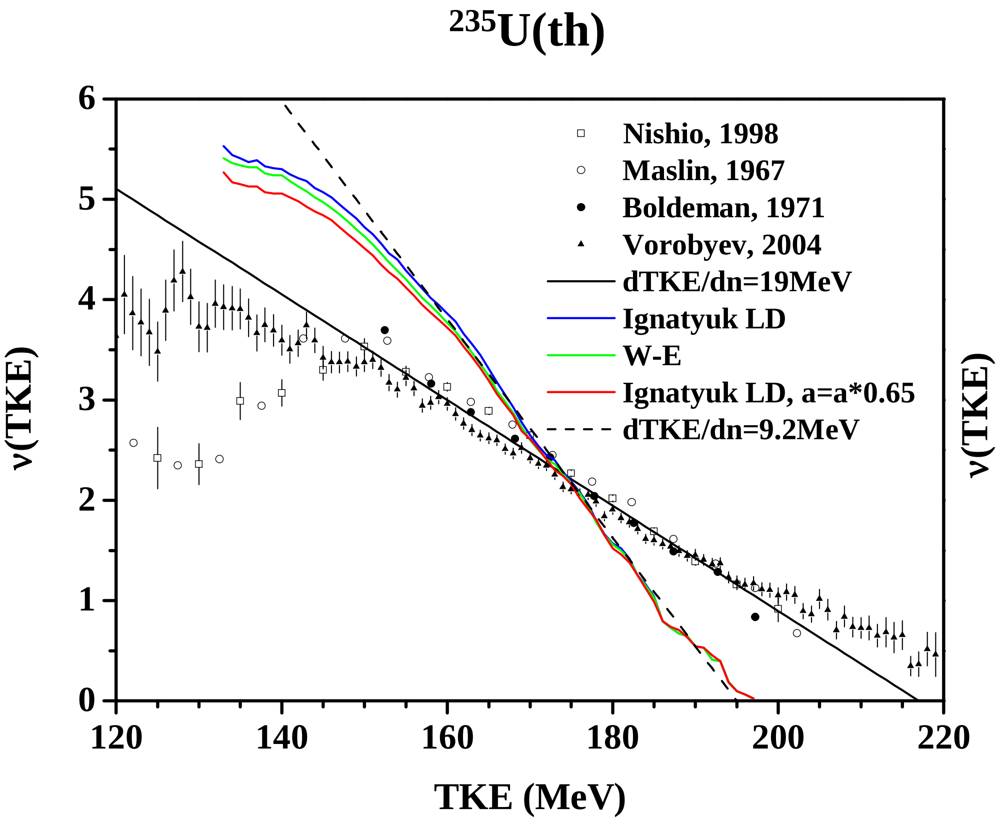

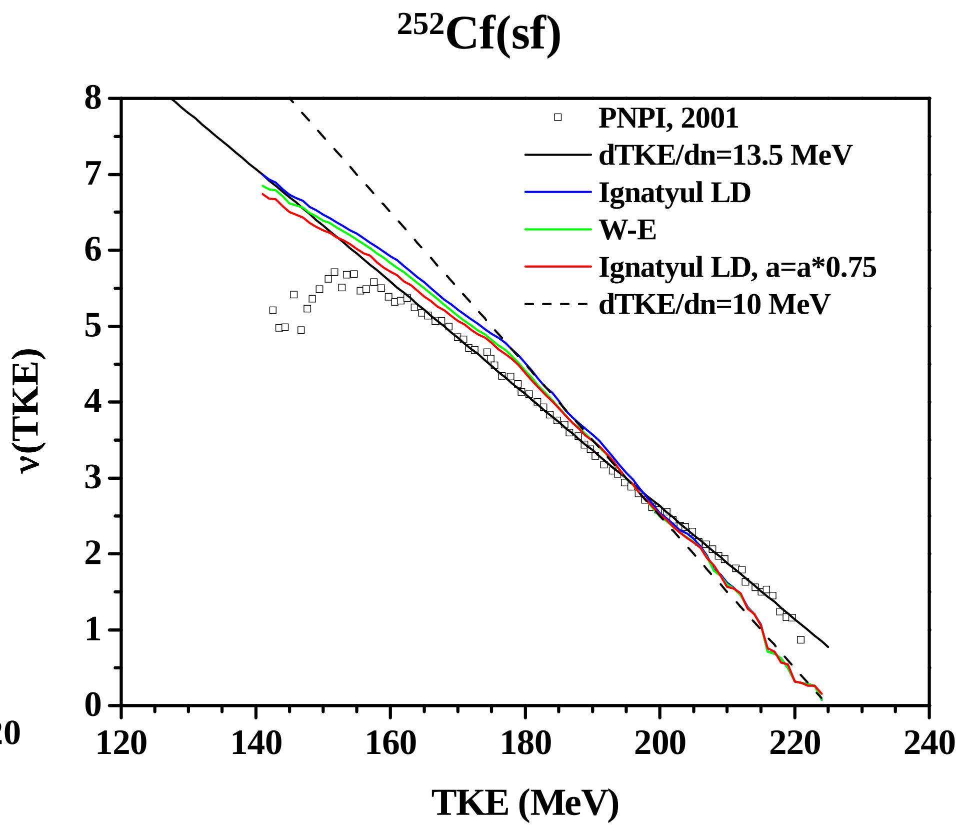

From N. Kornilov presentation at GAMMA-2 workshop, Serbia

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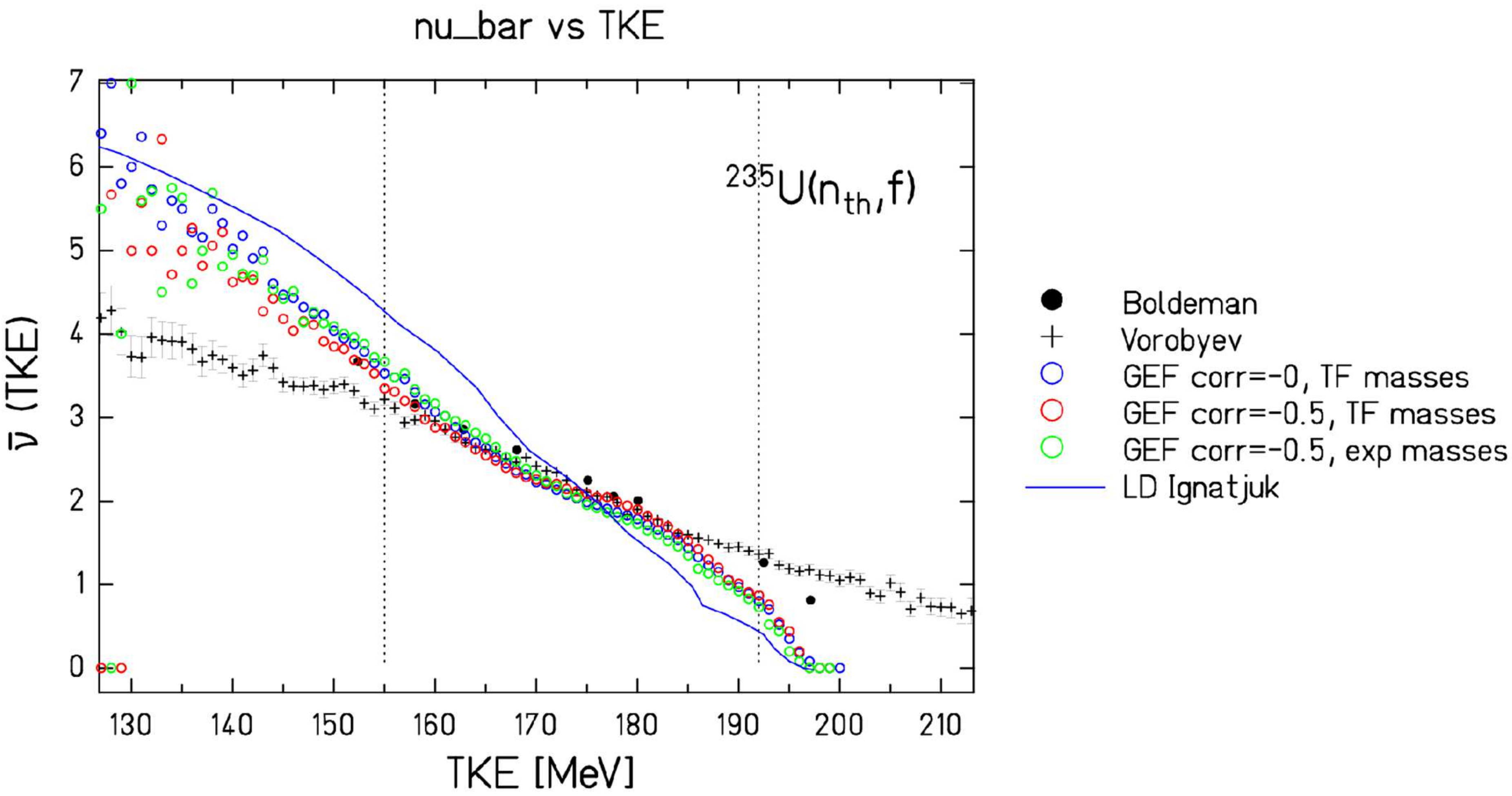
GEF calculations



Modelling mass distributions: GEF

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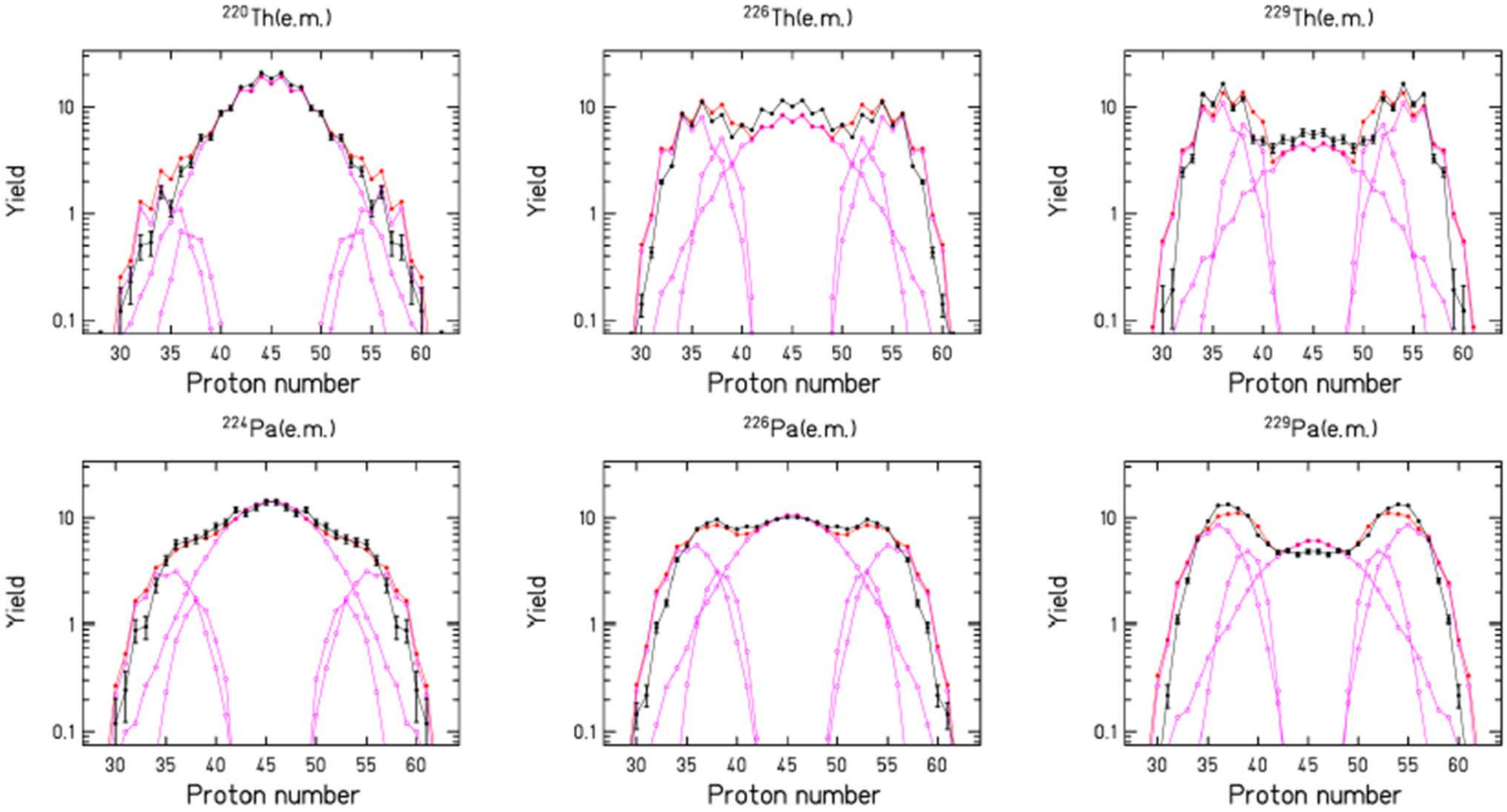
Transition from symmetric to asymmetric fission around A=226



K.-H. Schmidt, JEFdoc 1344

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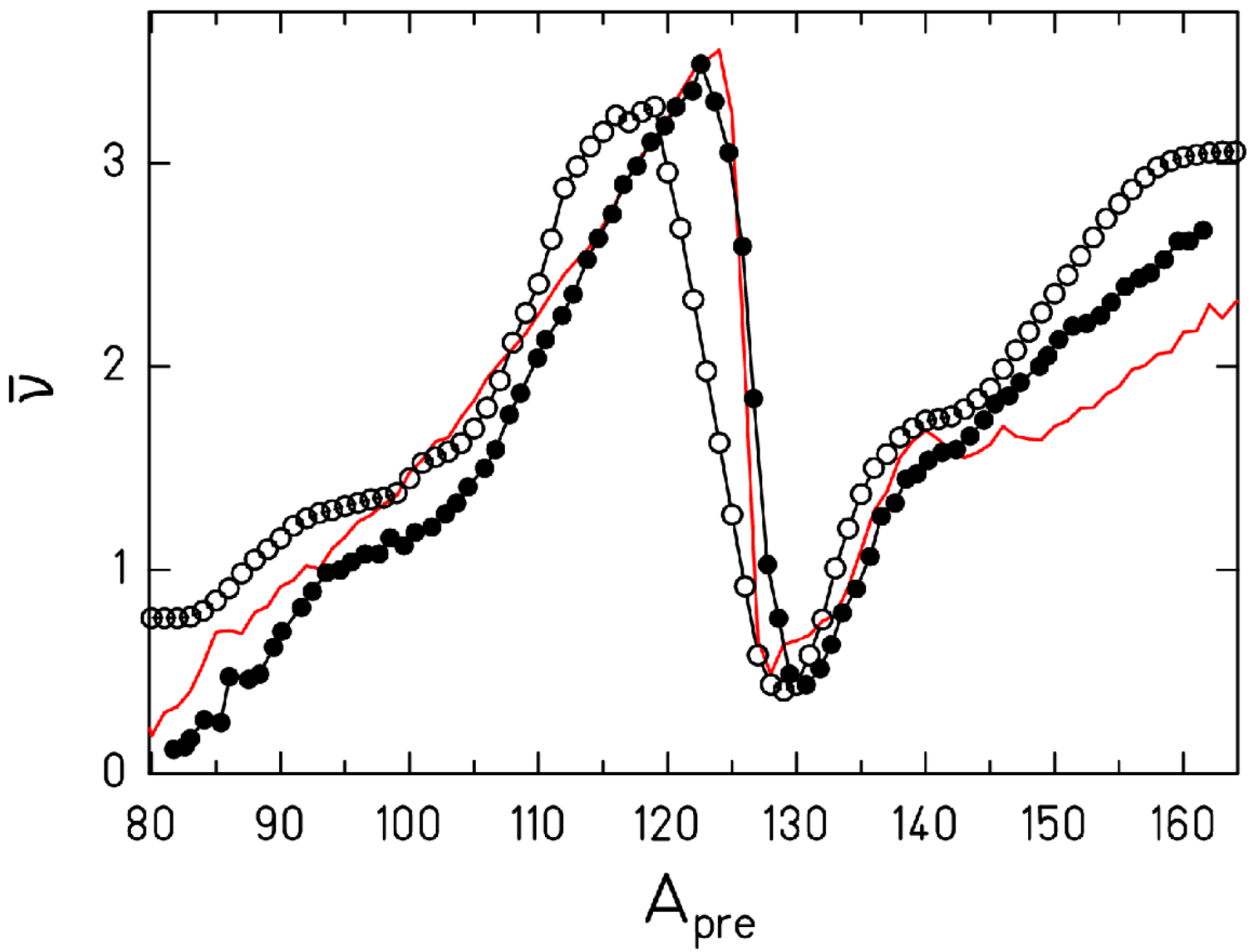
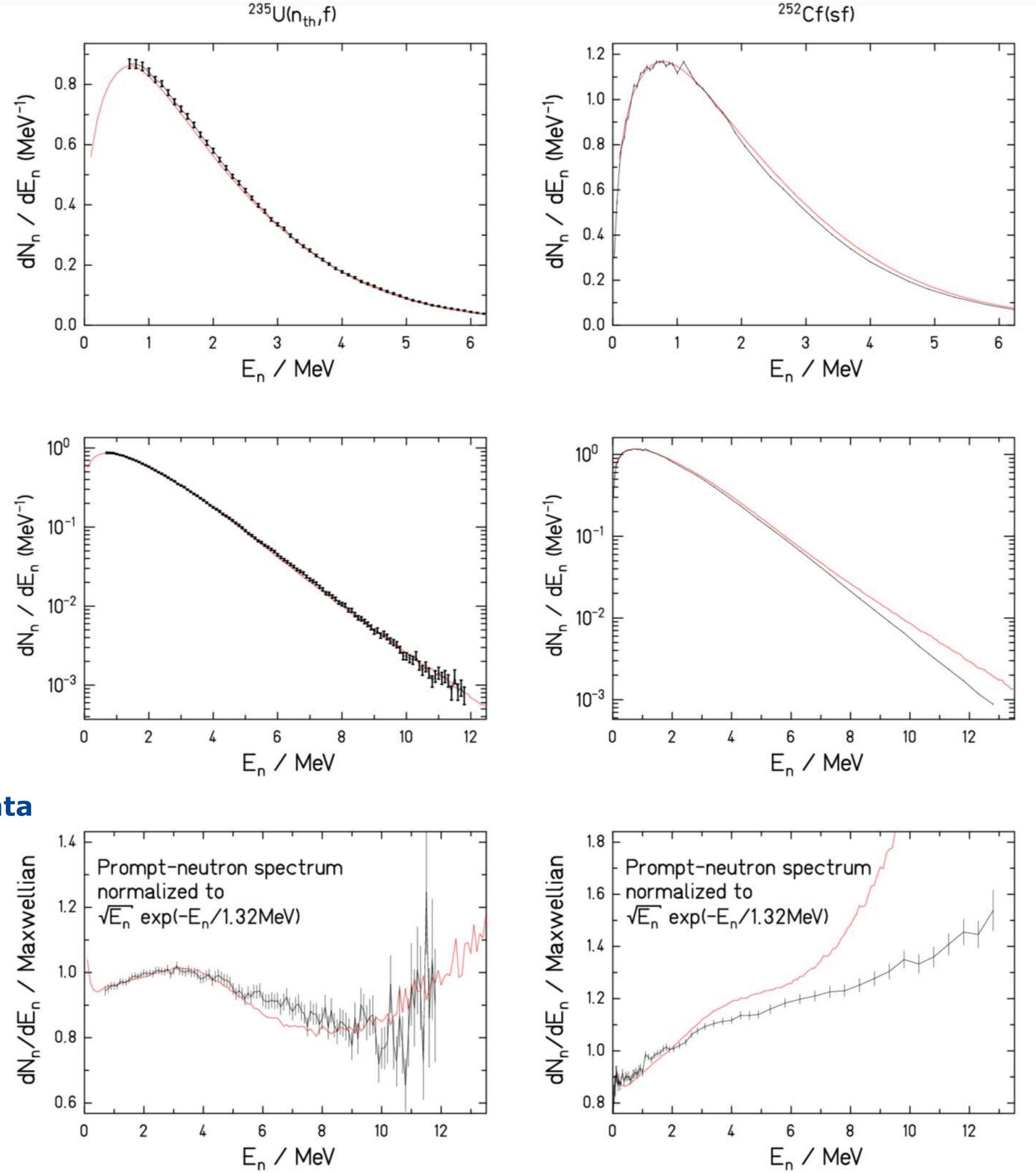
Modelling ν(A): GEF



Red line : GEF calculations, open Symbols: Wahl systematics
Full symbols: Budtz-Jorgensen, Knitter (1988)

PFNS: GEF



Red line : GEF calculations,
Open symbols: experimental data

K.-H. Schmidt, JEFdoc 1423

Conclusions

European Commission

- **Prompt neutron emission data are scarce**

- **Need for better data and especially for neutron-FF correlation data**

- **Need for high resolution double ToF detectors systems**

- **Improved modelling require better and more detailed experimental data especially correlation data of fission fragments with prompt neutron and γ-ray emission**

World at night

Thank you for your attention

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