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^{235}U(n,f) in the resolved resonance region

Fragment Properties, Neutron Emission and Energy Balance

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ND2016

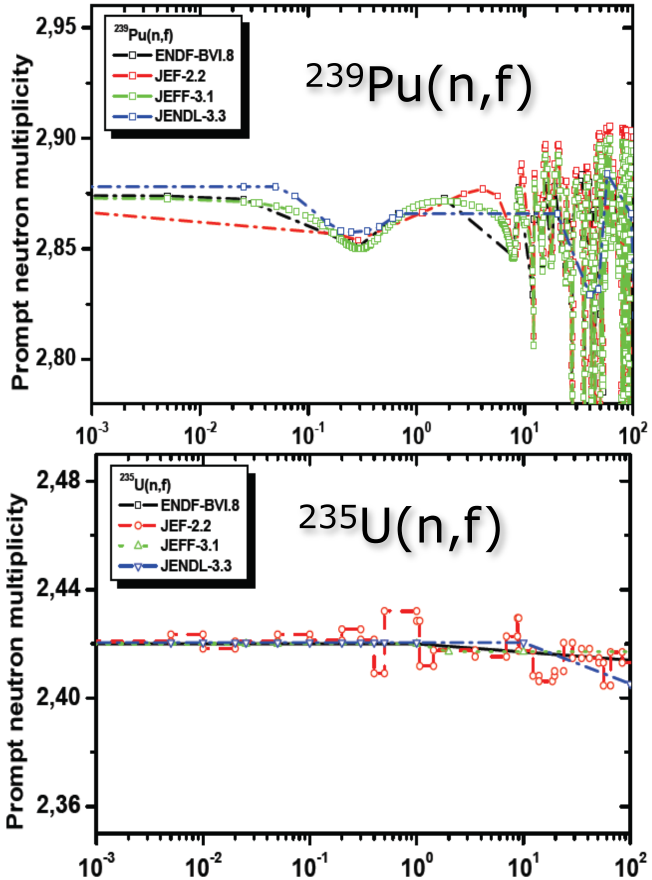
European Commission

Introduction

PFN multiplicity in the resonance region

Data relevant for improved evaluations as requested by the OECD/Working Party on Evaluation Cooperation (WPEC)

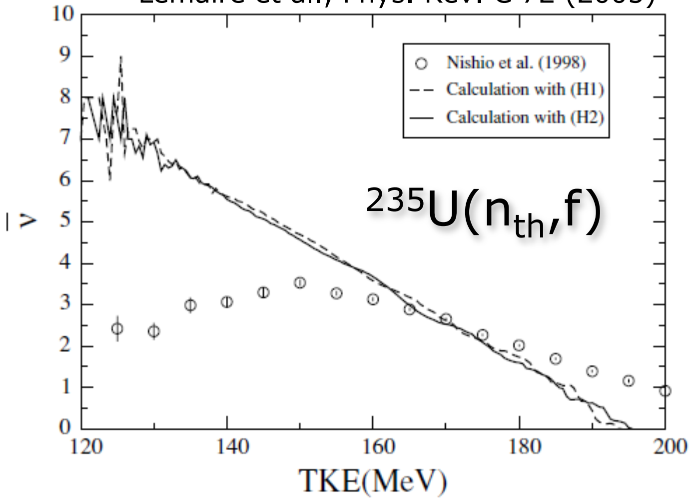
- ^{235}U, ^{239}Pu fluctuations of fission fragment properties (TKE and mass distribution)
- ^{239}Pu fluctuations of neutron multiplicities
- Measure neutron multiplicity as a function of neutron energy
- Study correlations between the fragment properties and the neutron multiplicities



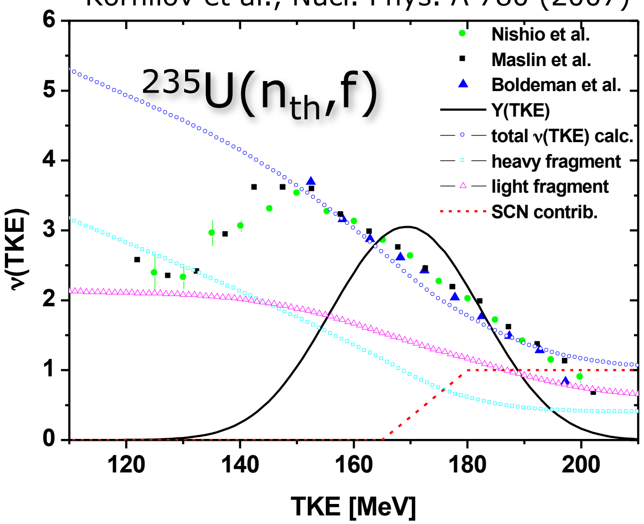
Introduction

PFN multiplicity correlations with fragment observables

Lemaire et al., Phys. Rev. C 72 (2005)



Kornilov et al., Nucl. Phys. A 780 (2007)



Based on energy balance in fission

- Detailed modelling (CGMF, Fifrelin, Freya…)
  - successfully reproducing correlations
  - in the case $^{235}U(n,f)$
    - » difficulties: in particular ?(TKE)

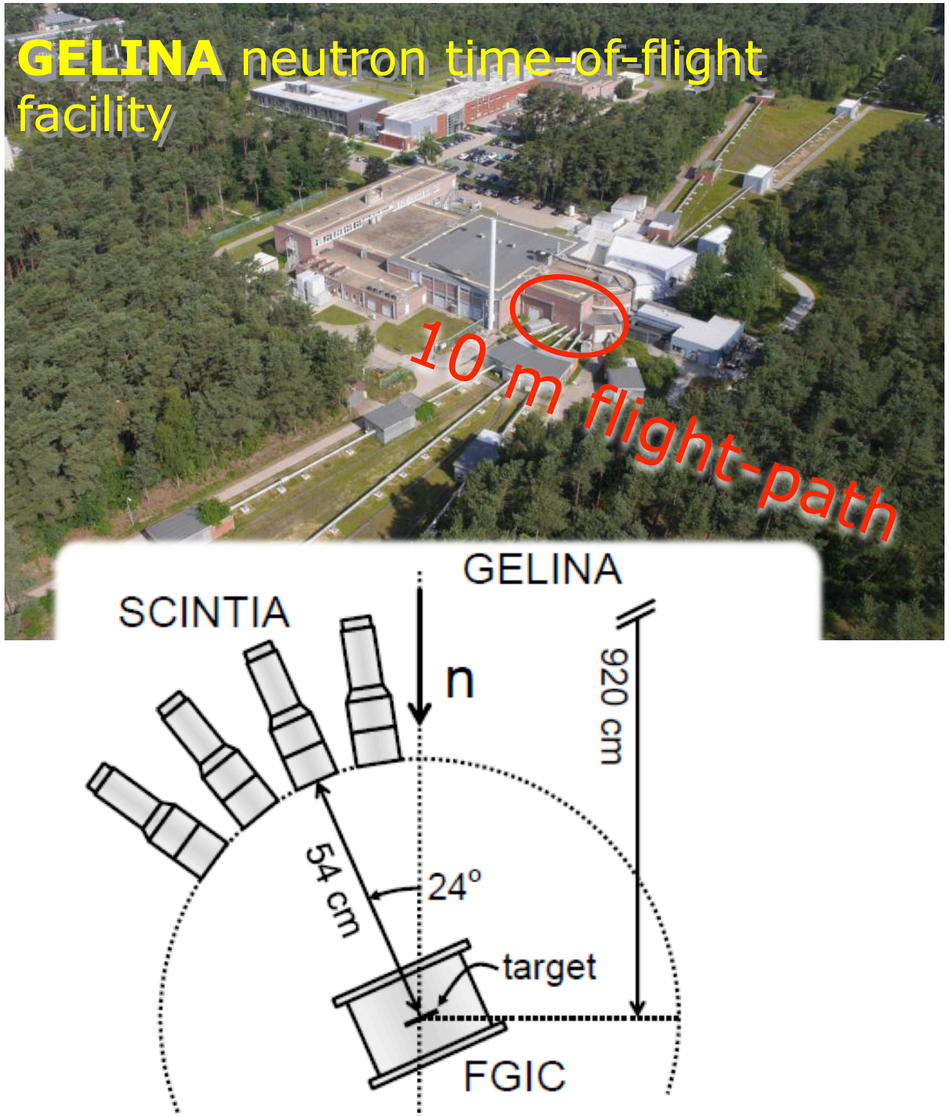
Lemaire et al. (2005)

*"…a **dramatic deviation** between calculation and experiment on ? is observed **at low TKE** that would indicate the presence of **additional opened channels**"*

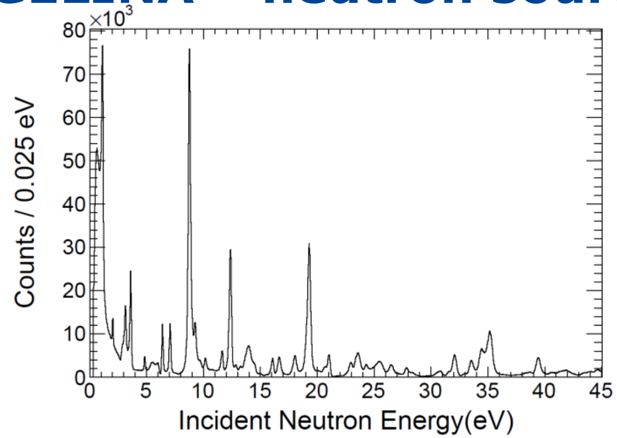
Kornilov et al. (2007)

*"The **incorporation of** the **SCN emission** leads to a much **better agreement** between theoretical and experimental data for ?(TKE) in the high energy range. However, the assumption of **SCN emission at high TKE should be confirmed with direct experimental data**"*

Experimental setup



GELINA – neutron source



Twin Ionization Chamber

- Fission fragments
  - ➢ Energies
  - ➢ Masses - 2E-technique
  - ➢ Fission axis orientation

Neutron Detector Array SCINTIA

- 12 x Scintillators
- Prompt fission neutrons
  - ➢ Energy (time-of-flight)

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Experimental method

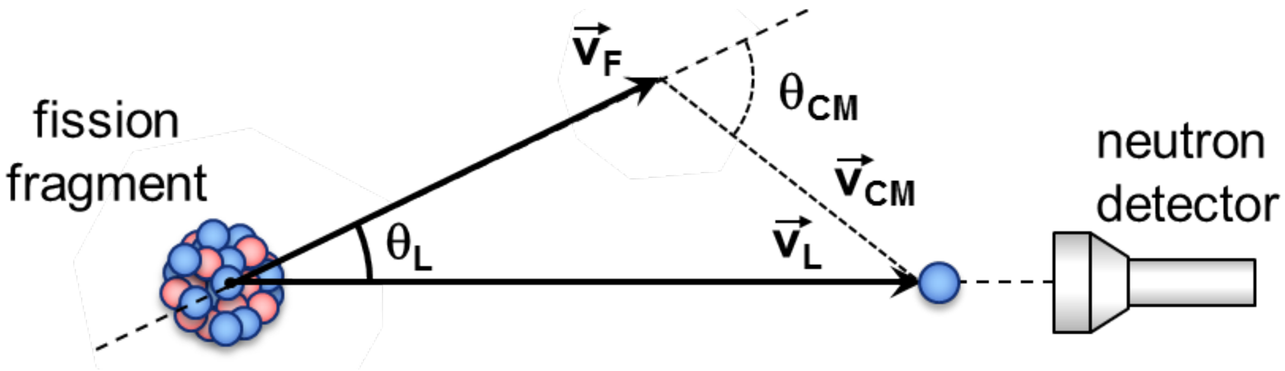
❑ Neutron energy detection threshold (0.5 MeV)

  ? Biasing of multiplicity-data?

❑ Emission of neutrons mainly from fully accelerated fragments

  ❑ Obtain basic kinematic information in laboratory-frame

  ❑ Reconstruct emission process in fission fragment rest-frame



- "Unbiased" selection of events: $\cos ?_{CM} \geq 0$
- Results show consistency with methods that do not suffer from neutron energy detection threshold

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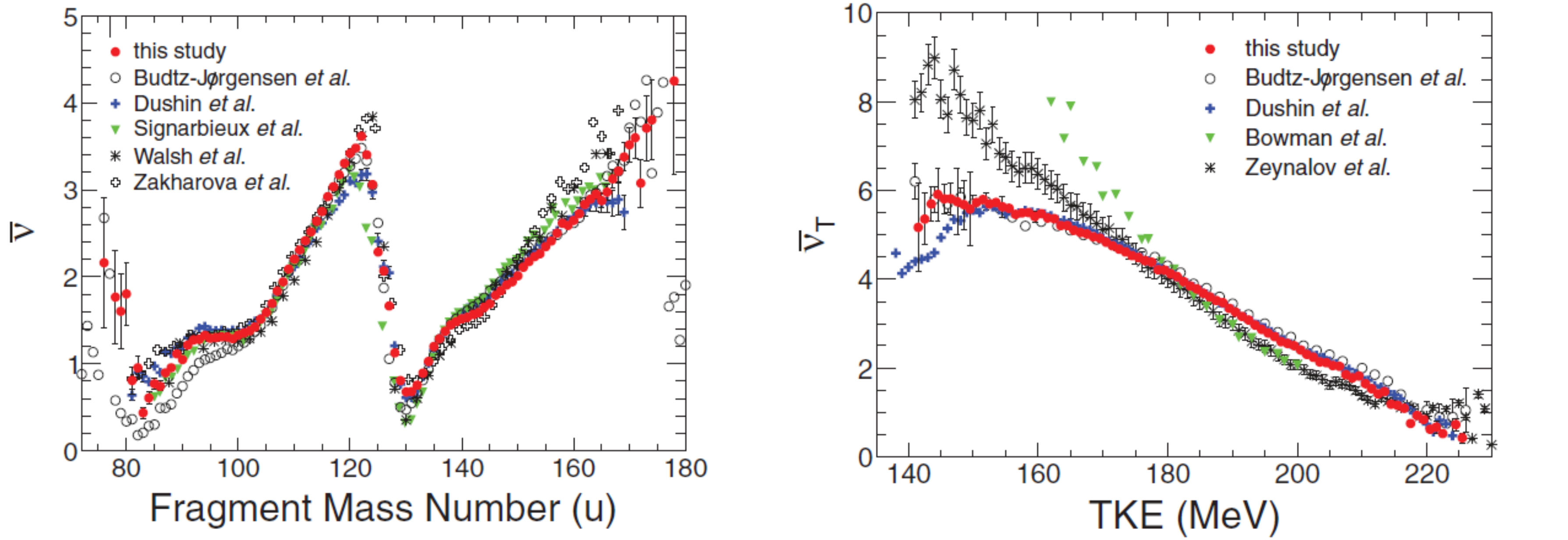
Validation of method $^{252}Cf(sf)$

PHYSICAL REVIEW C **90**, 064611 (2014)



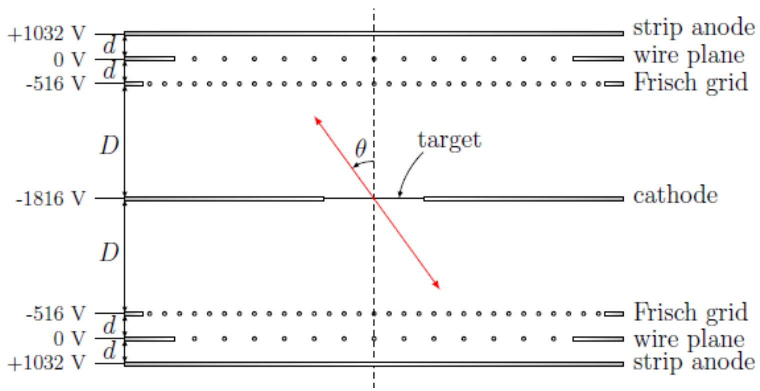
- Results show consistency with literature data
- Specifically with methods that do not suffer from neutron energy detection threshold
  - (Dushin et al.) Gd-loaded 4π scintillator tank

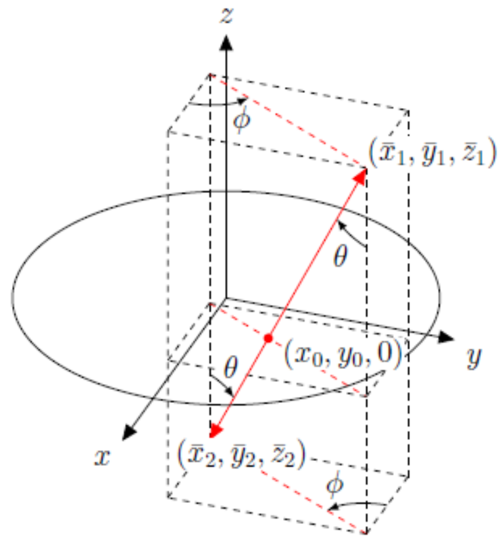
Position sensitive ionization chamber

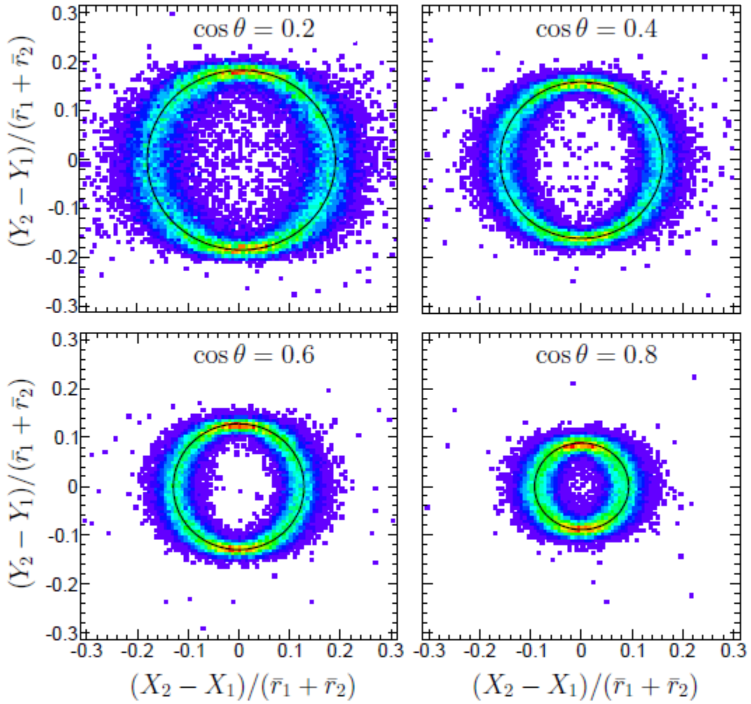
Orientation of the fission axis in 3D-space is a requirement

Twin Ionization Chamber

- *Electron collector replaced by position sensitive electrode*
- *Charge-division readout*

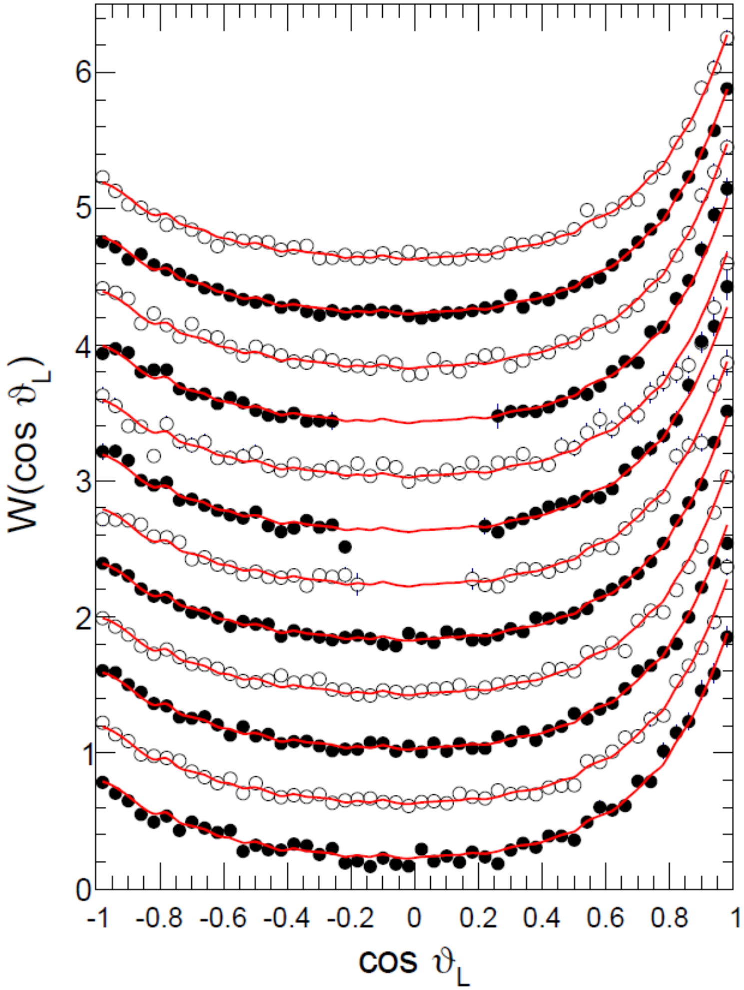




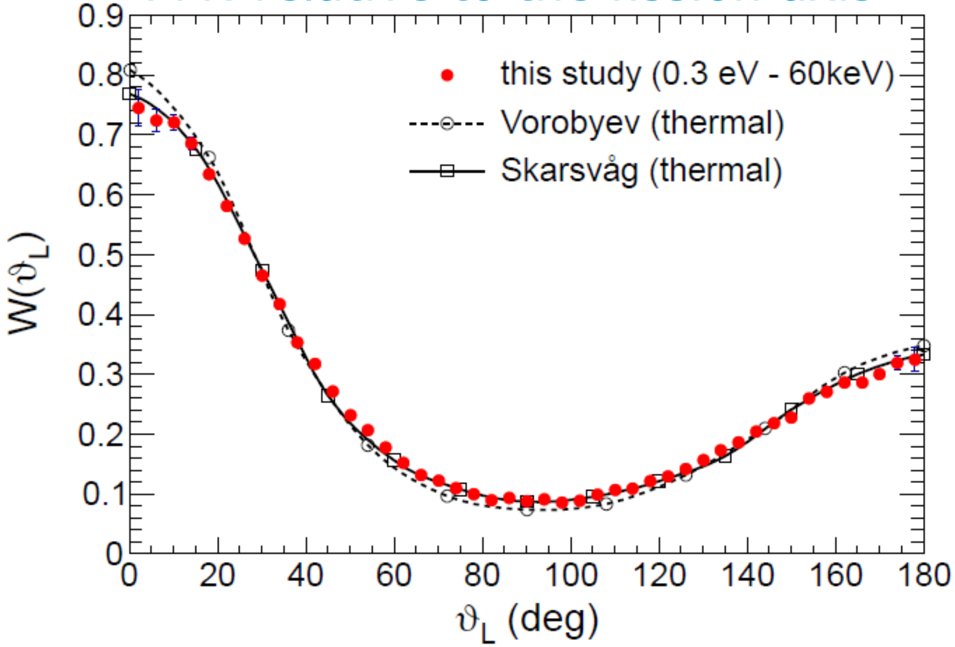


$^{235}U(n,f)$ - PFN angular distributions

Consistent results from the 12 individual detectors



Integral angular distribution of PFN relative to the fission axis



Results agree well with Skarvsåg (1963)

Göök et al., Nucl. Instr. and Meth. A **830** (2016) 366

2E-analysis of FF data

Conservation of linear momentum

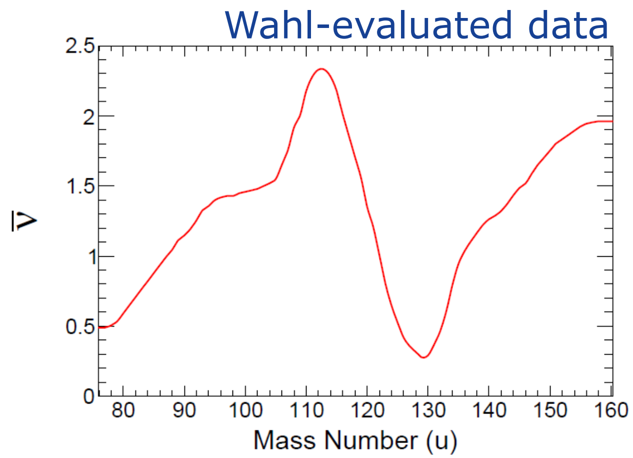
$$m^*_{1,2} = m_{cn} \cdot \frac{E^*_{2,1}}{E^*_1 + E^*_2}$$

Correction for PFN emission

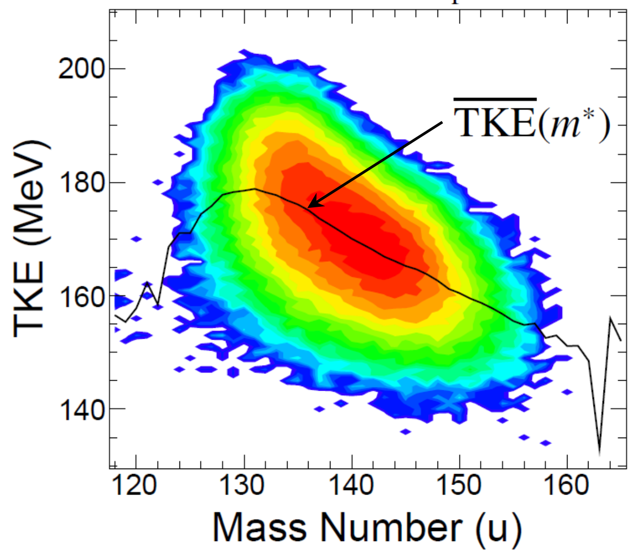
$$E^* = E \cdot \frac{m^*}{m^* - \bar{\nu}(m^*, \mathrm{TKE})}$$

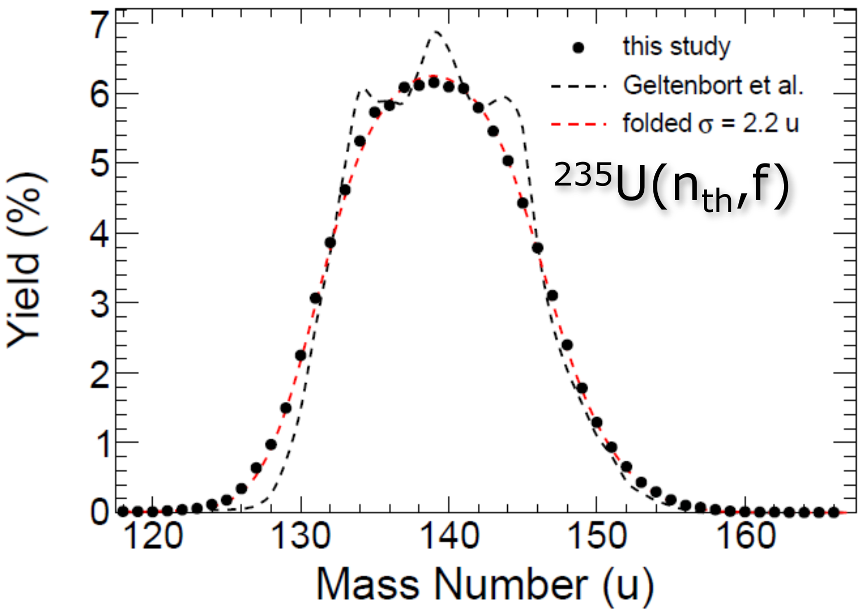
TKE dependence of neutron emission

$$\bar{\nu}(m^*, \mathrm{TKE}) = \bar{\nu}(m^*) + \frac{\bar{\nu}(m^*)}{\bar{\nu}(m^*) + \bar{\nu}(m_{cn} - m^*)} \cdot \Delta_{\mathrm{TKE}}$$



$$\Delta_{\mathrm{TKE}} = \frac{\overline{\mathrm{TKE}}(m^*) - \mathrm{TKE}}{E_{sep}}$$





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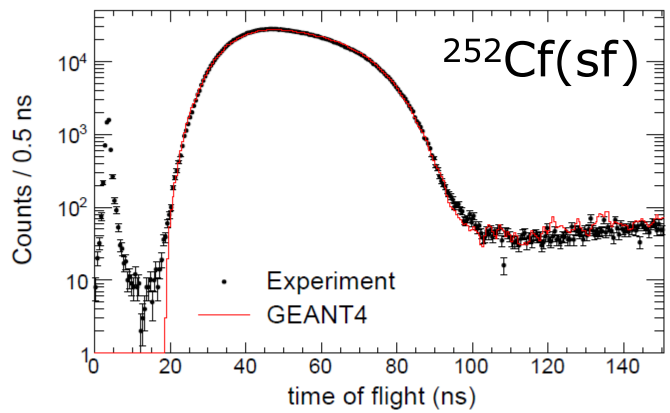
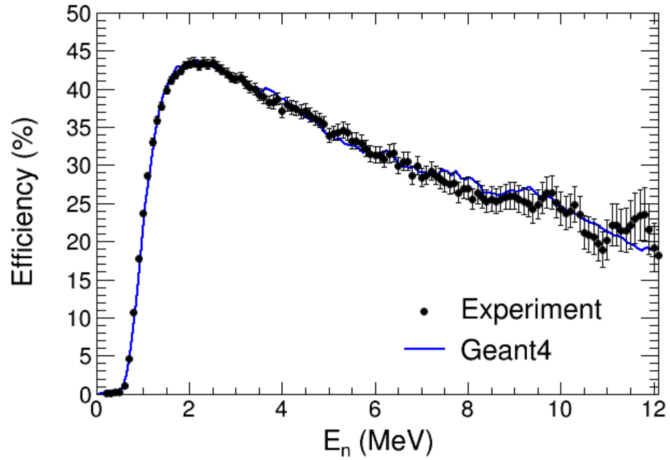
Neutron Detector Responses

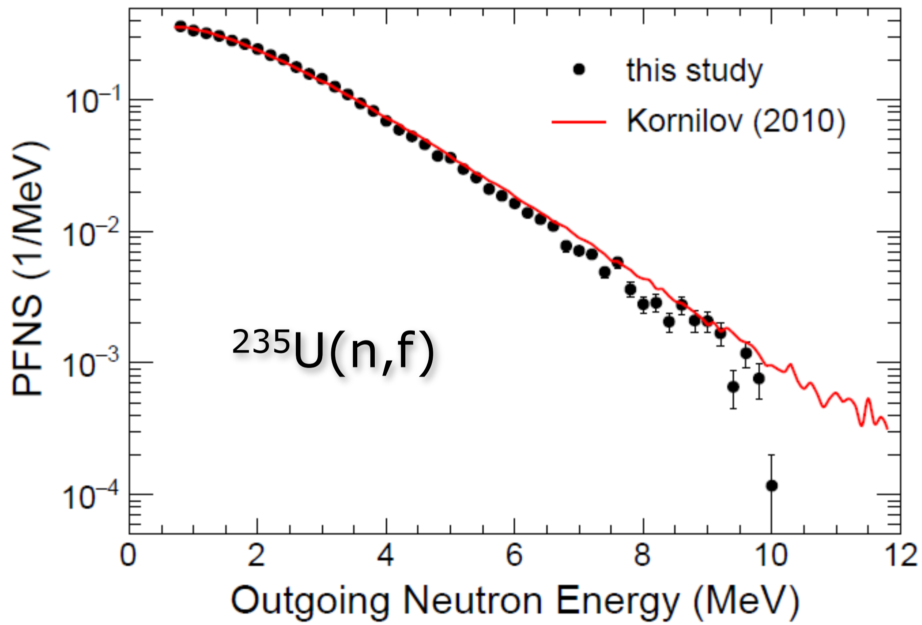
Neutron detector responses are modelled with GEANT-4

The simulations are benchmarked against PFNS of $^{252}Cf(sf)$

Multiple scattering correction calculated with GEANT-4

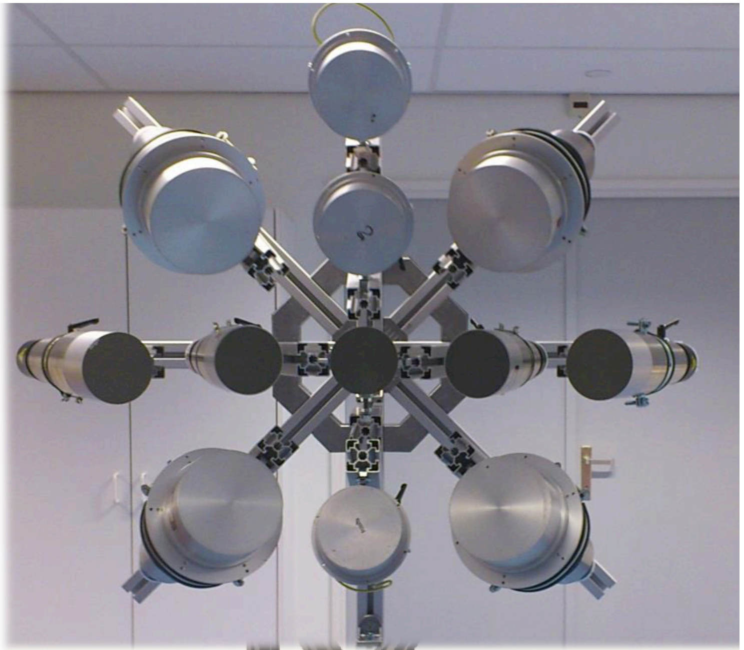


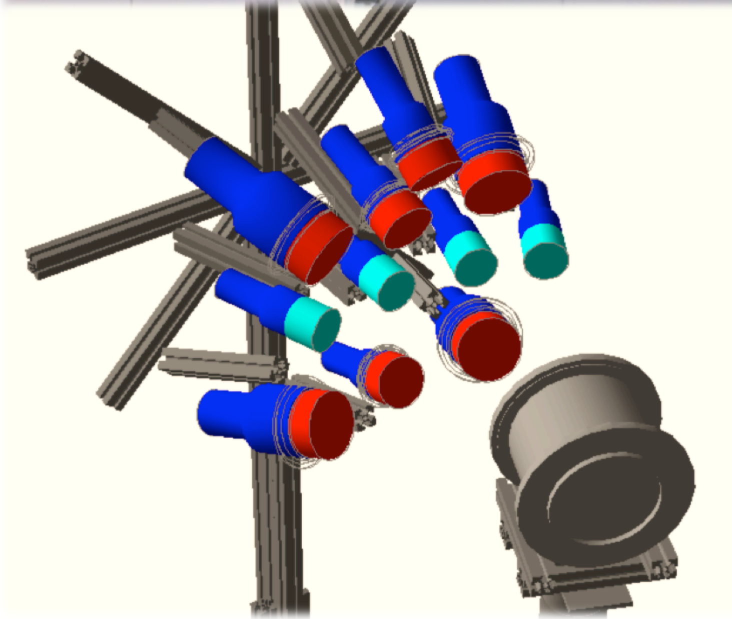




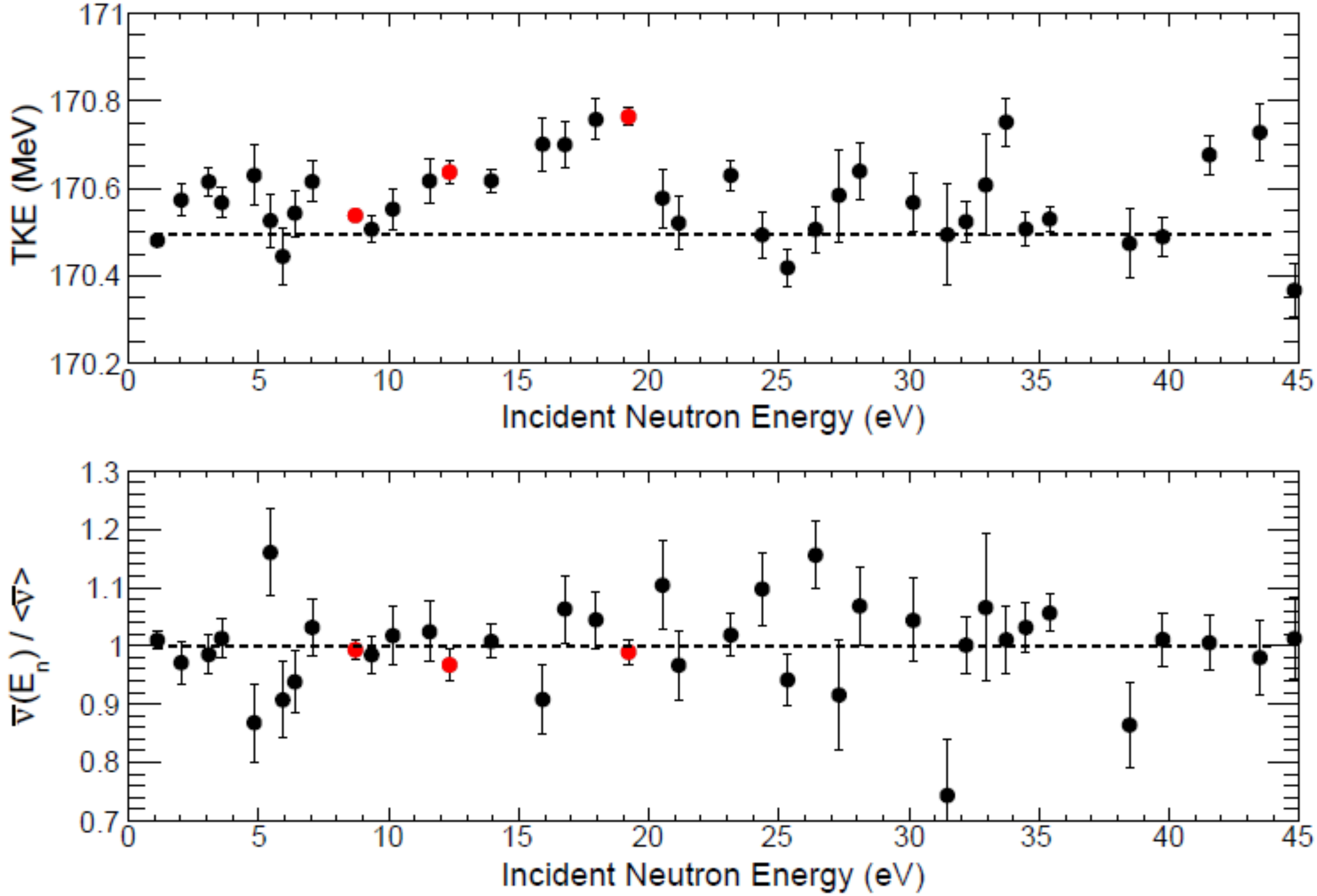
Status of the Experiment

- Divided in 3 campaigns
  - **3rd** **:** after summer break
    - Extended array 20 detectors
  - **2nd** **:** data analysis ongoing
  - **1st** **: results presented here**
- Statistics at present stage
  - **E_n ? [0.3 eV, 60 keV]**
  - **1.2 x 10^7 fission-events**
  - **1.6x 10^5 PFN coincidences**
  - **ca. 20 % of expected total number of counts**
- Results presented here focuses on FF and PFN correlations summed over E_n ? [0.3 eV, 60 keV]





Resonance Energy vs. Fragment TKE



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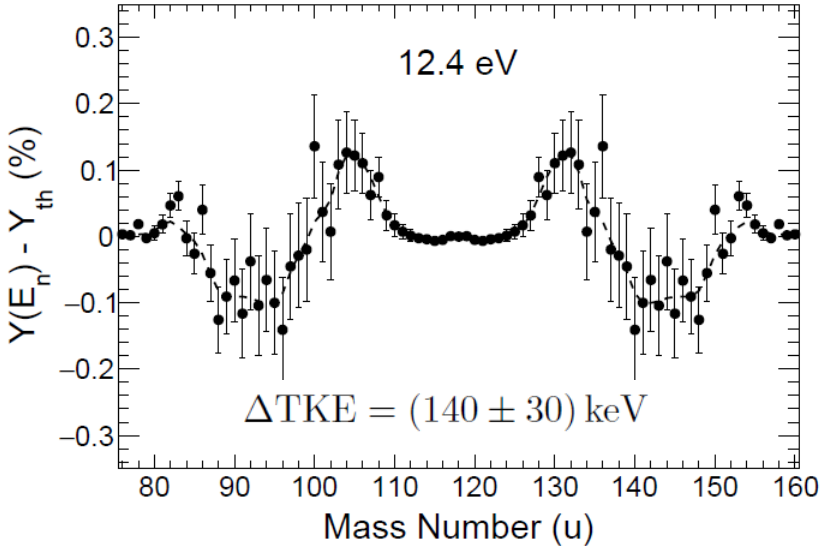
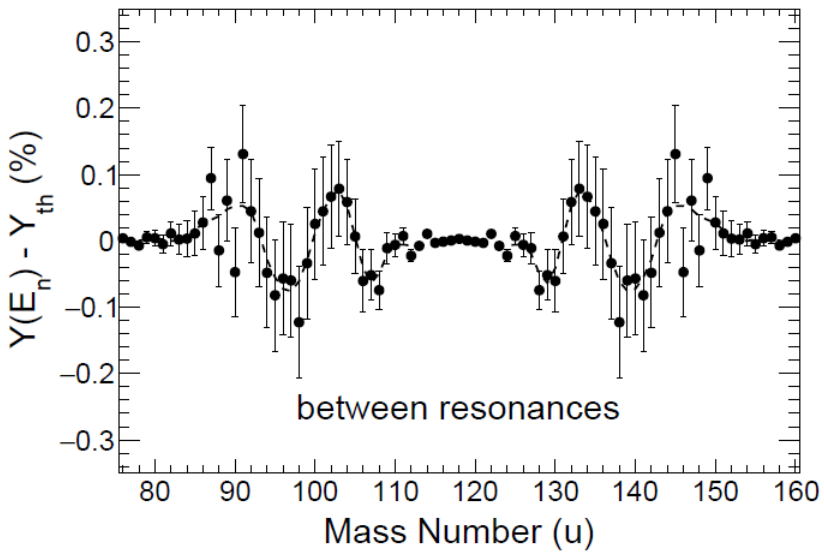
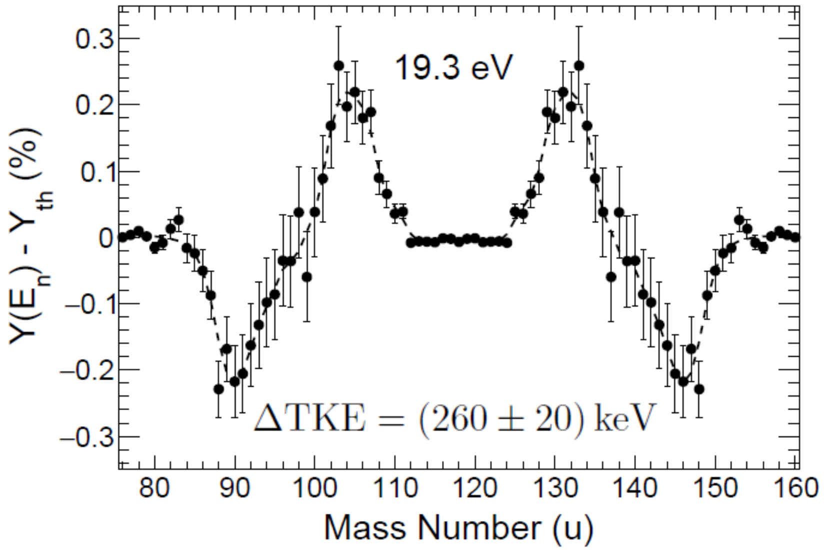
Mass Distributions in the Resonances

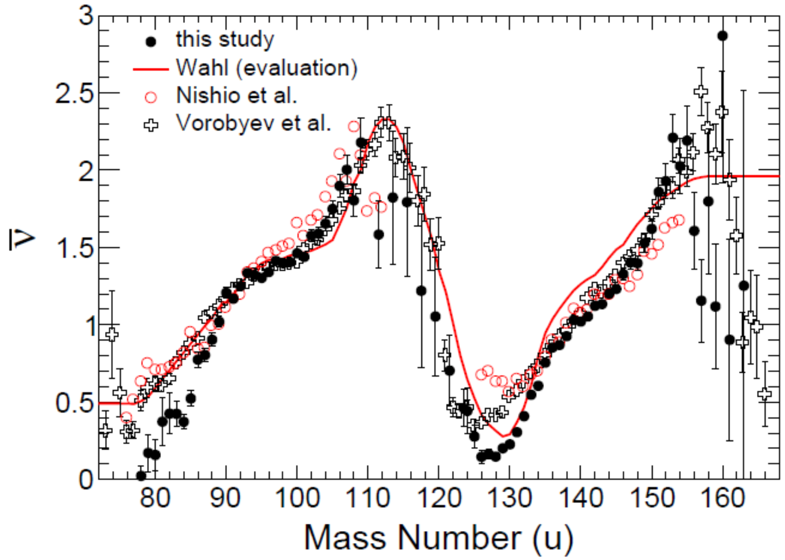
- *Fluctuations of the TKE can be explained by changes in the mass-yield*
- *TKE increase is correlated with increased yield around A_H=132 u*

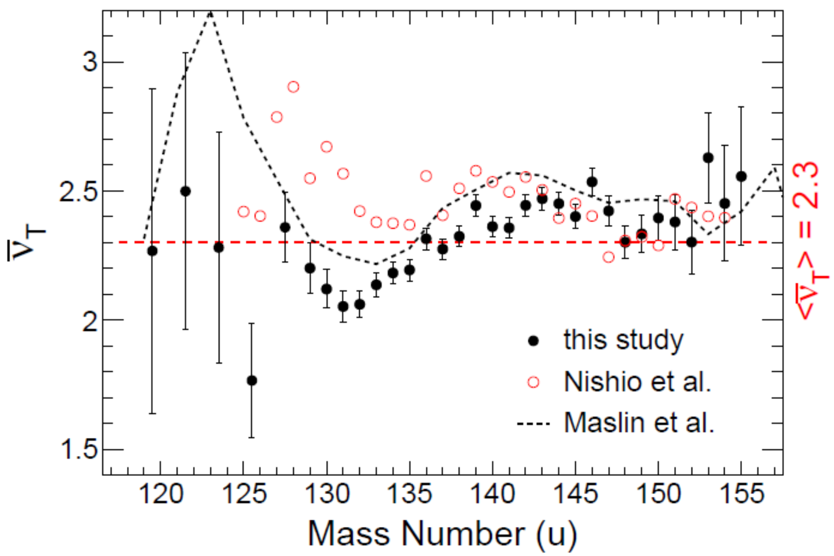






Multiplicity vs. Fragment Mass





Neutrons per fragment

Saw-tooth distribution

Shoulders around A_L=100 and A_H=140

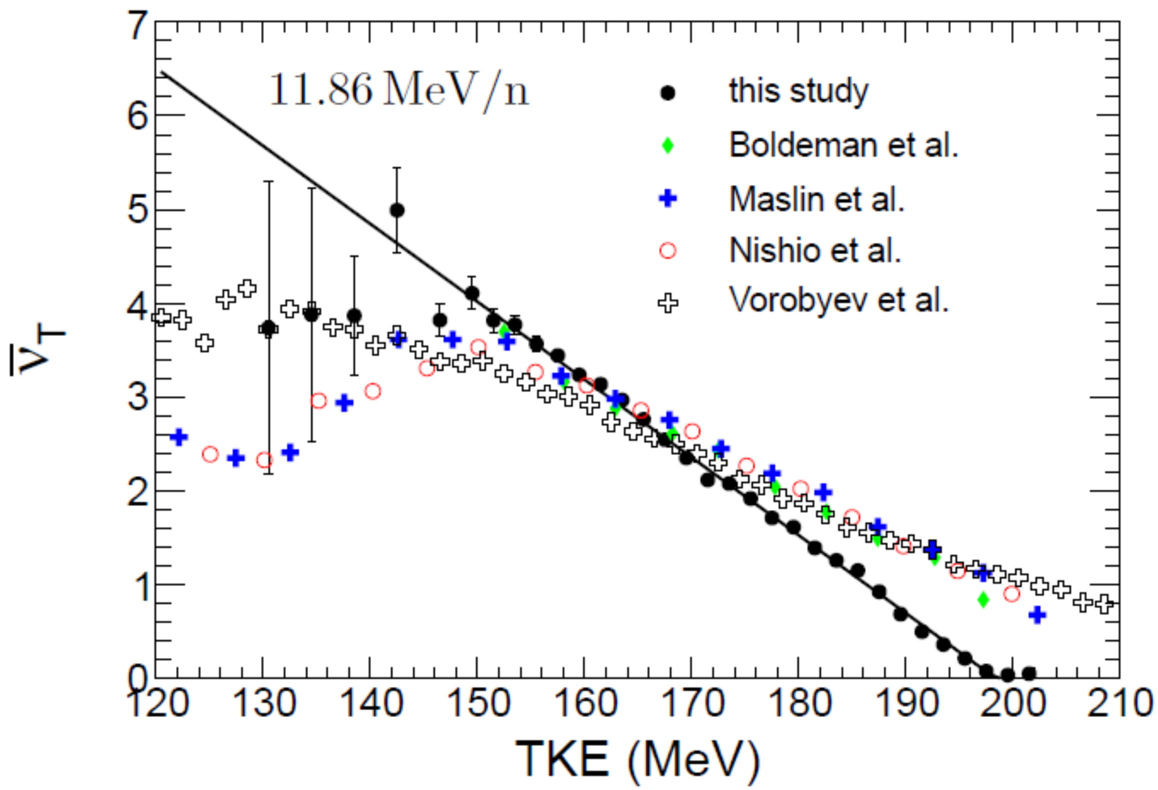
Pronounced minima around A_L=80 and A_H=130

Neutrons per fission

Flat distribution

Pronounced minimum around A_H=132

Multiplicity vs. Fragment TKE



Close to linear dependence

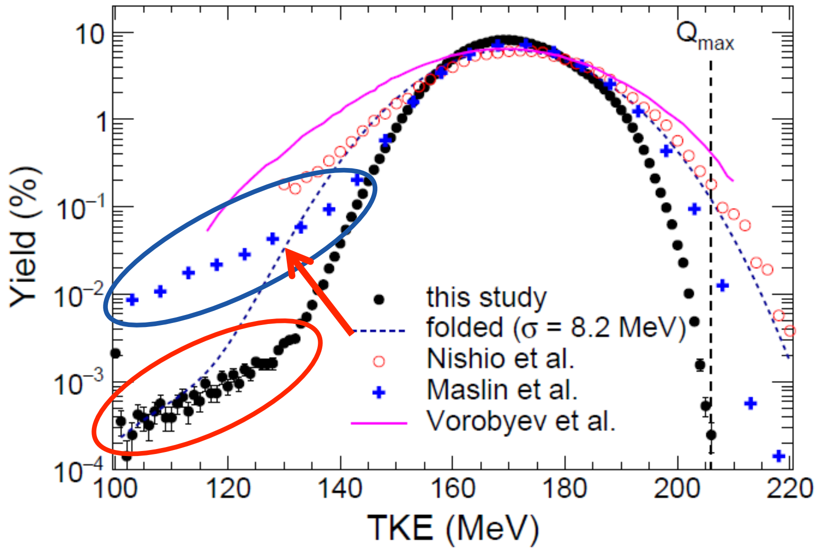
$$-\frac{\mathrm{dTKE}}{\mathrm{d}\,\overline{\nu}_T} = 11.86\,\mathrm{MeV/n}$$

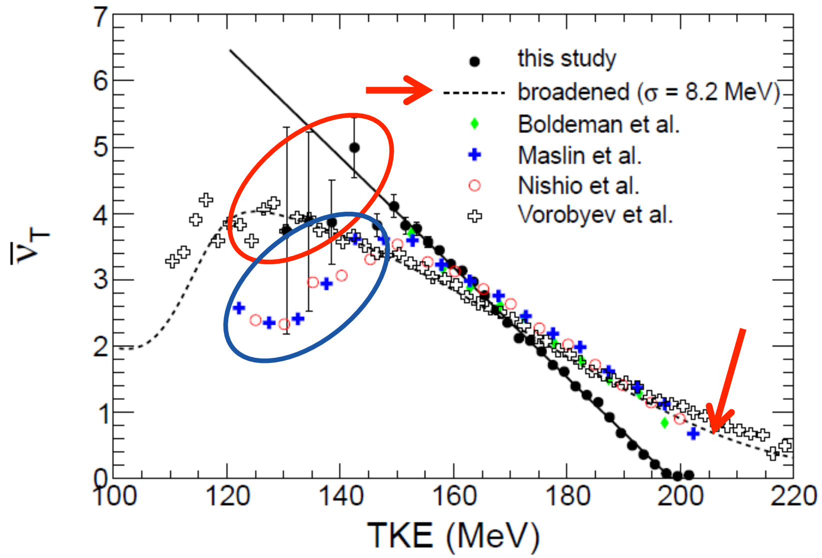
The slope is much steeper than earlier studies

$$-\frac{\mathrm{dTKE}}{\mathrm{d}\,\overline{\nu}_T} = 16.7 - 18.5\,\mathrm{MeV/n}$$

The difference cannot be explained by difference in incident neutron energy

Multiplicity vs. Fragment TKE





- Wide TKE-distributions
- Significant Yield at TKE>Q_{max}

? Resolution broadening

- Decreased slope
- Increased neutron yield at Q_{max}

Tailing of TKE distribution

- Energy degraded scattered fission fragments
- Neutron yield should approach average nubar
  - Drop in nubar at low TKE
  - Present also in our data

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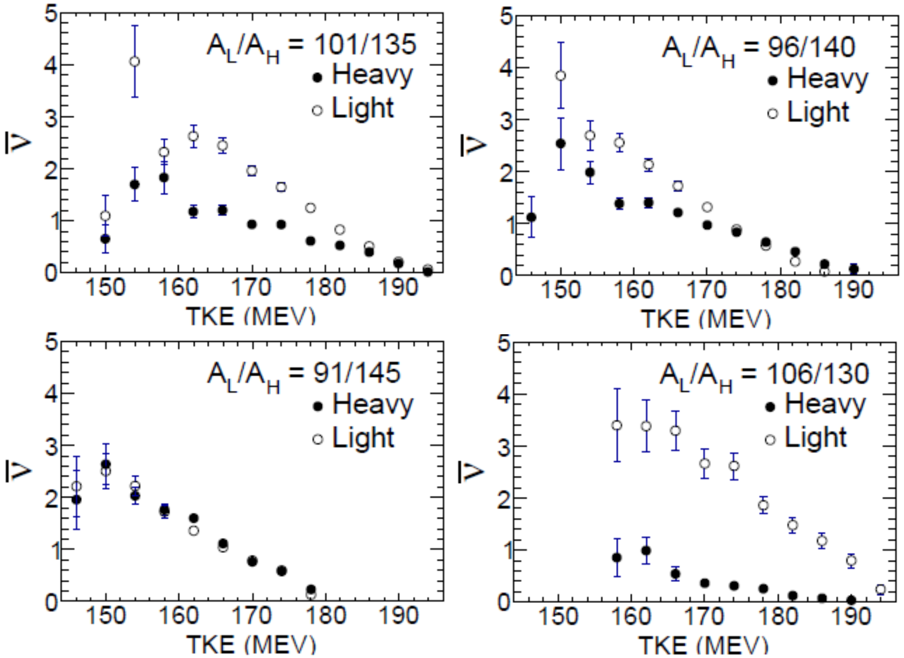
Multiplicity vs. Fragment TKE

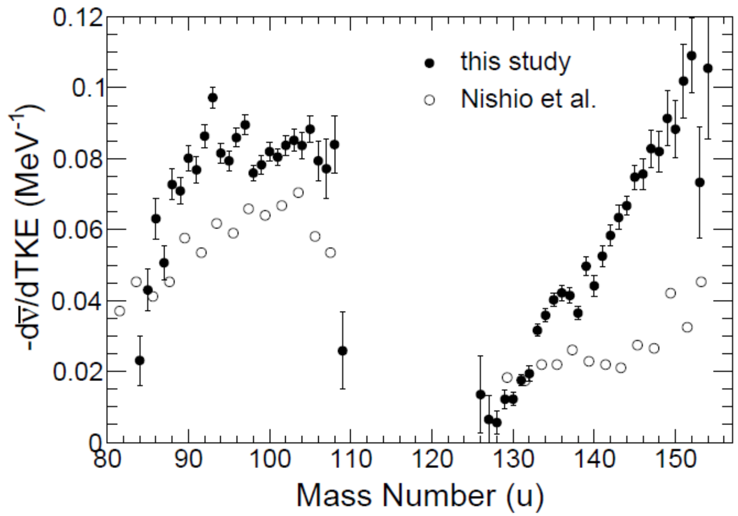
For selected fragments

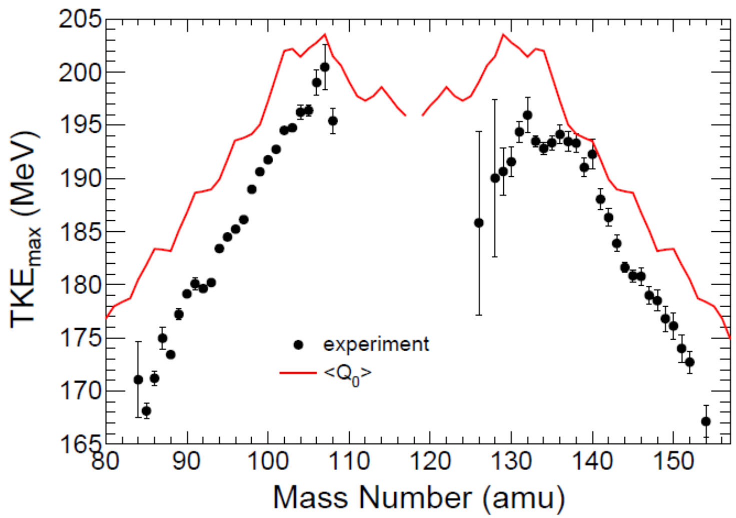
Close to linear dependence

Slope shows pronounced saw-tooth

Neutron emission does not stop at the same TKE for light and heavy fragment

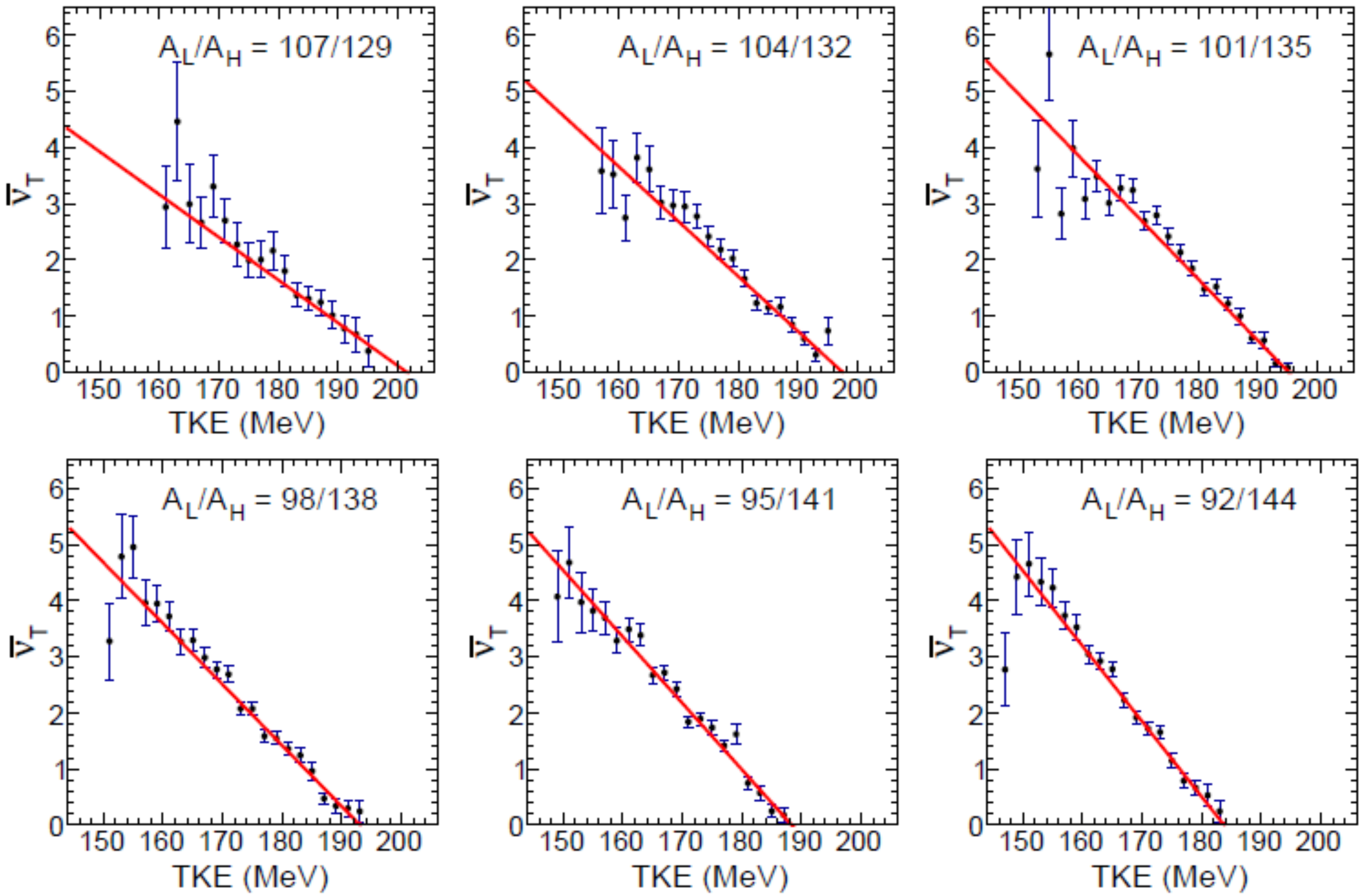






Multiplicity vs. Fragment TKE

For selected fragment pairs

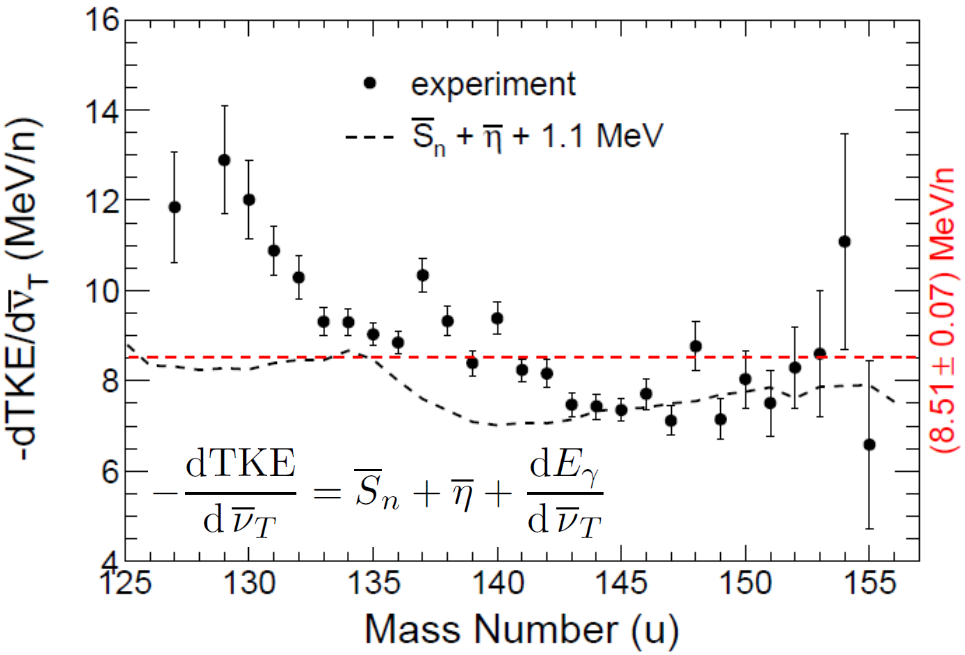


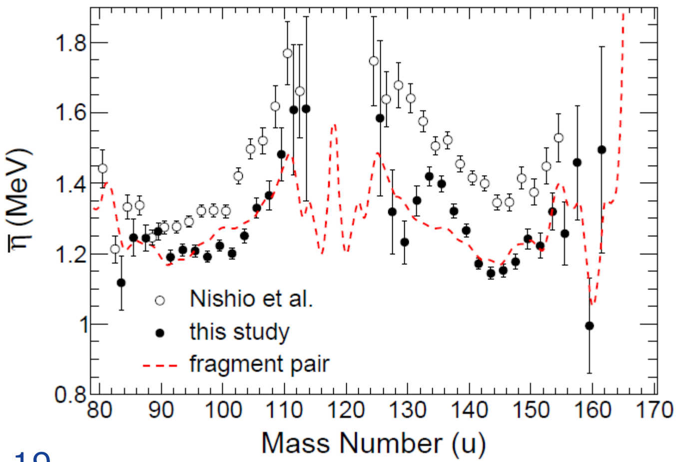
Slope gives directly the change in TXE per emitted neutron

$$\mathrm{TXE} = \mathrm{Q}_0 - \mathrm{TKE}$$

$$\frac{\mathrm{dTXE}}{\mathrm{d}\,\overline{\nu}_T} = -\frac{\mathrm{dTKE}}{\mathrm{d}\,\overline{\nu}_T}$$

Energy cost per neutron





Average energy necessary to emit a neutron

(8.51 ? 0.07) MeV/n

Calculations based on tabulated neutron binding energies (AME2012)[1] underestimates data

Pointing to a more complex dependence of prompt neutron/gamma competition[2]

$$E_\gamma = [1.1\,\overline{\nu} + 1.75] MeV$$

1.) G. Audi et al., Chinese Physics C 36 (2012) 1287

2.) H. Nifenecker et al, 3rd IAEA Symp. Phys. And Chem. of Fission 2 (1973) 117

Conclusions

Fluctuation of fission fragment TKE from resonance to resonance observed in earlier studies is confirmed by the present experiment.

No statistically significant fluctuation of neutron multiplicity is observed at the present stage of the experiment.

The saw-tooth shape of the average number of neutrons emitted per fragment show more pronounced minima at A_H=130 u and A_L=80 u.

The TKE dependence of the number of neutrons emitted per fission shows an inverse slope dTKE/d? ca. 35% weaker than observed in earlier studies. The difference can be explained by improved fission fragment TKE resolution in the present experiment.

The average energy cost per emitted neutron (8.51 ? 0.07) MeV/n has been determined from the dependence of the neutron multiplicity on TKE for individual mass splits.

The present result should have strong impact on the modelling of both prompt neutron and prompt ?-ray emission in fission. Especially considering the strong differences observed in the TKE dependence of the prompt neutron multiplicity.

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Thank you for the attention!

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