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Prompt Neutron Emission in the Reaction $^{235}U(n,f)$

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European Commission
JRC - Geel

ISINN-25
Frank Laboratory of Neutron Physics
Joint Institute for Nuclear Research
Dubna, Russia
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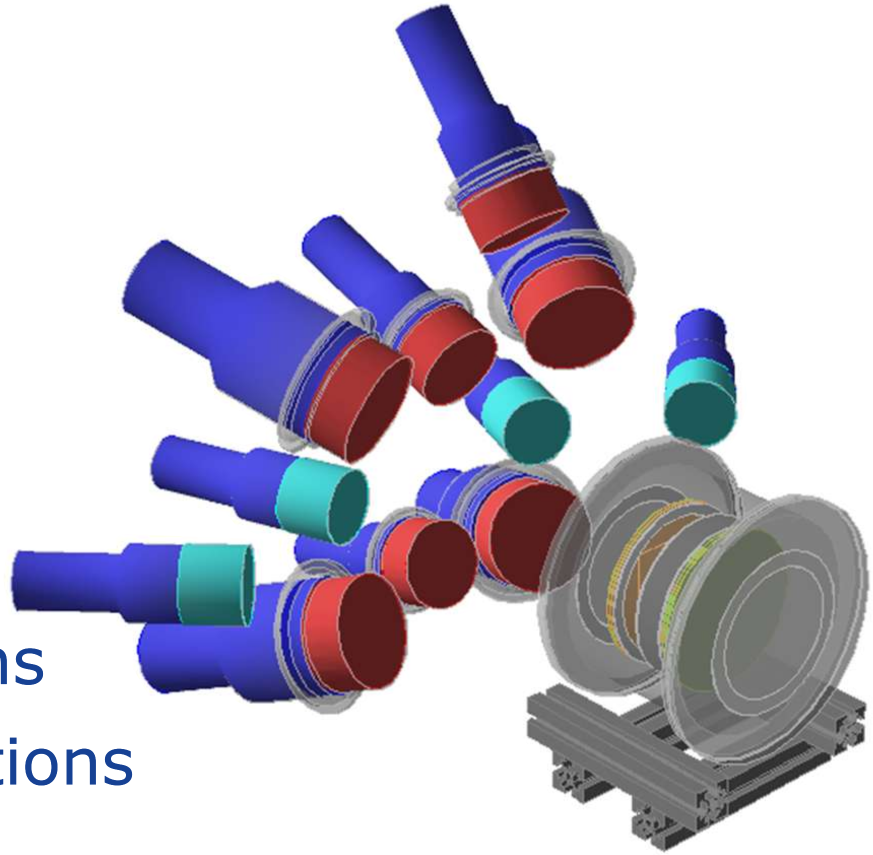
Outline

- Introduction & Motivation
- Experimental Setup
  - SCINTIA array
  - 3D ionization chamber
- Experimental Results
  - PFN angular distributions
  - PFN multiplicity correlations with fission fragments
- Conclusions



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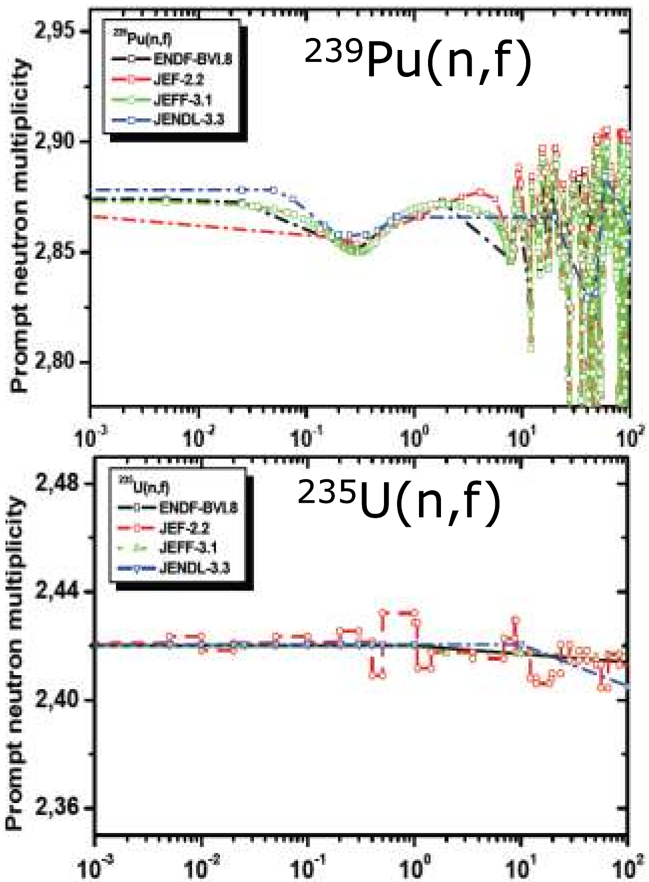
Introduction & Motivation

Prompt Fission Neutron (PFN) multiplicity in resonances

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

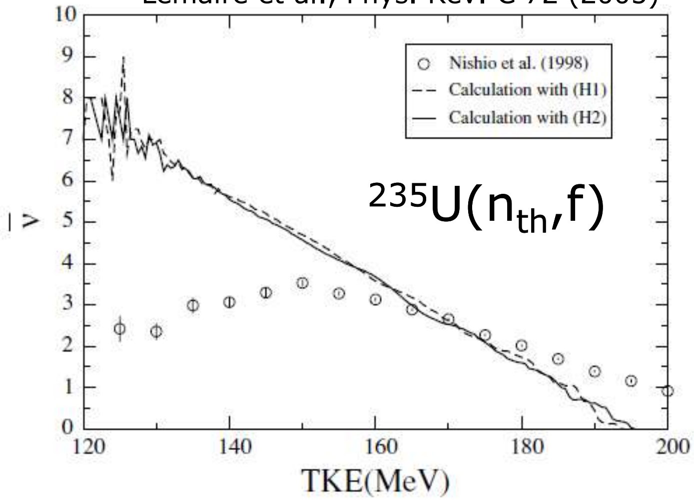
- ^{239}Pu - strong fluctuations of neutron multiplicities
- ^{235}U - minor fluctuations of neutron multiplicities
- Measure neutron multiplicity as a function of neutron energy
- ^{235}U, ^{239}Pu fluctuations of fission fragment properties (TKE and mass distribution)
- Study correlations between the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



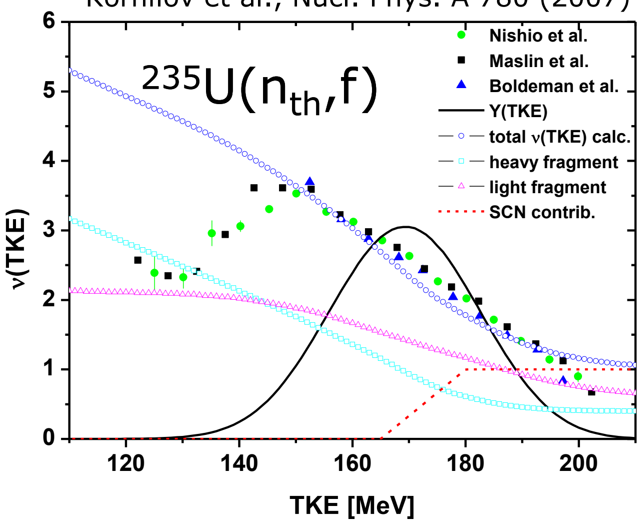
Introduction & Motivation

PFN multiplicity correlations with fragment observables

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



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



Fission fragment de-excitation models

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

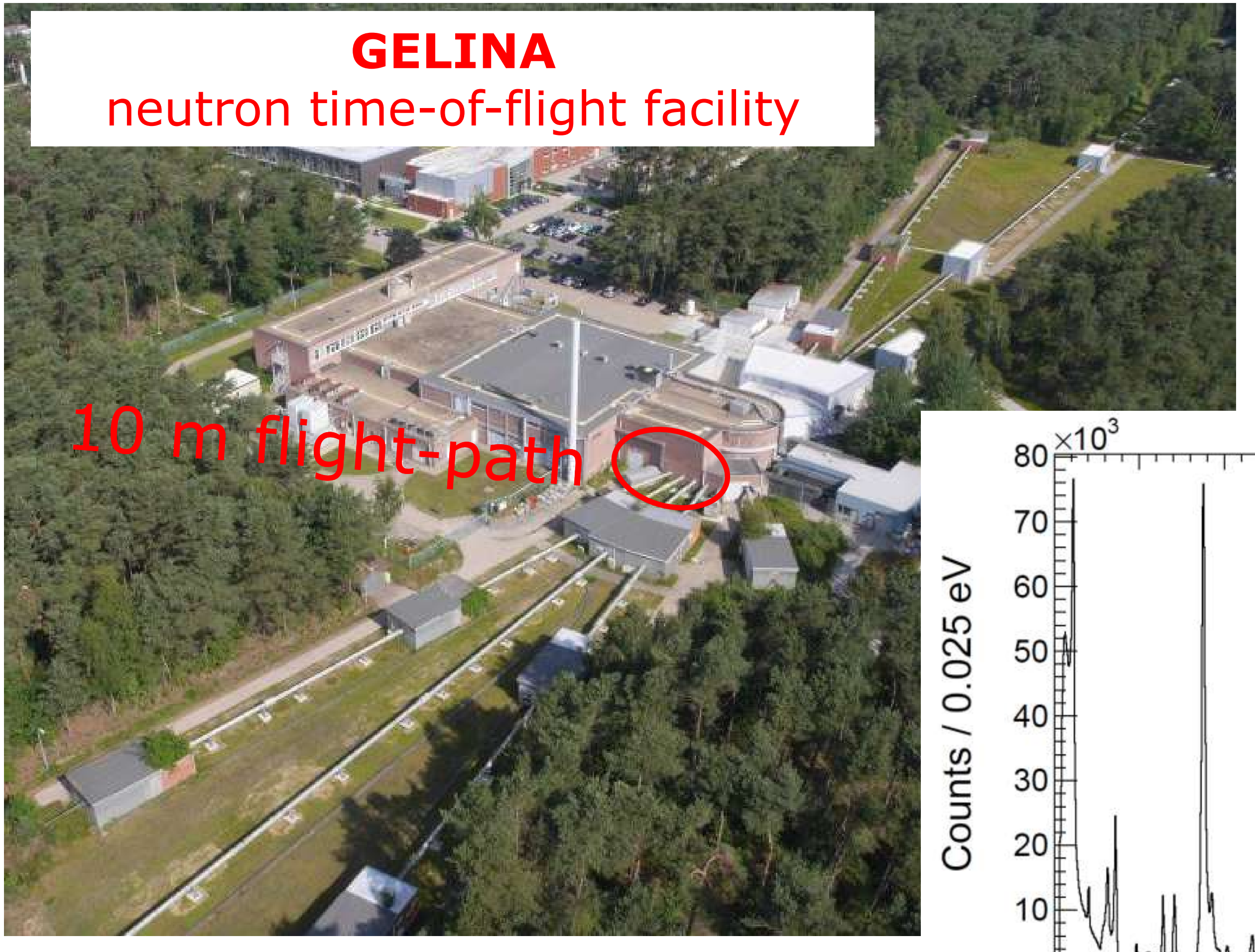
Lemaire et al. (2005)

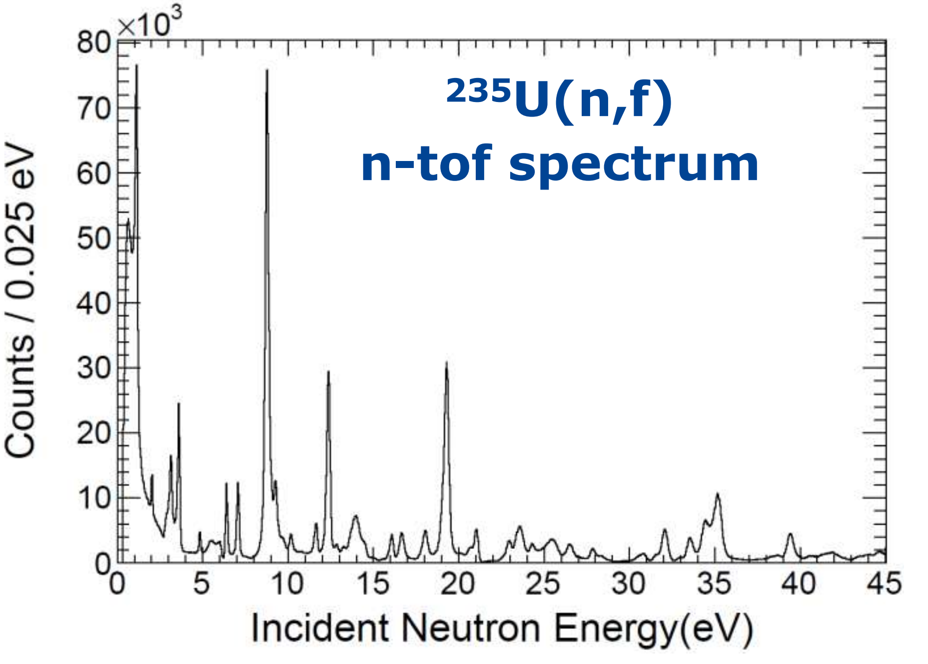
*"…a **dramatic deviation** between calculation and experiment on ν is observed **at low TKE** that would indicate the presence of **additional opened channels**"*

Kornilov et al. (2007)

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

Experimental setup – neutron source





Experimental Setup – SCINTIA array

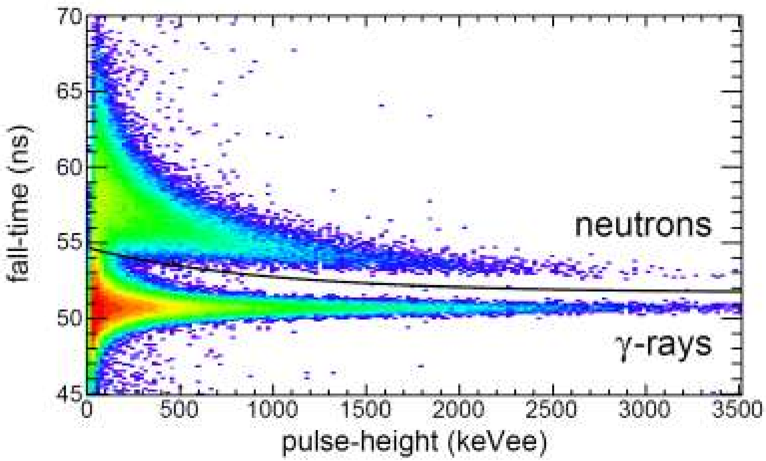
Fission fragments detection

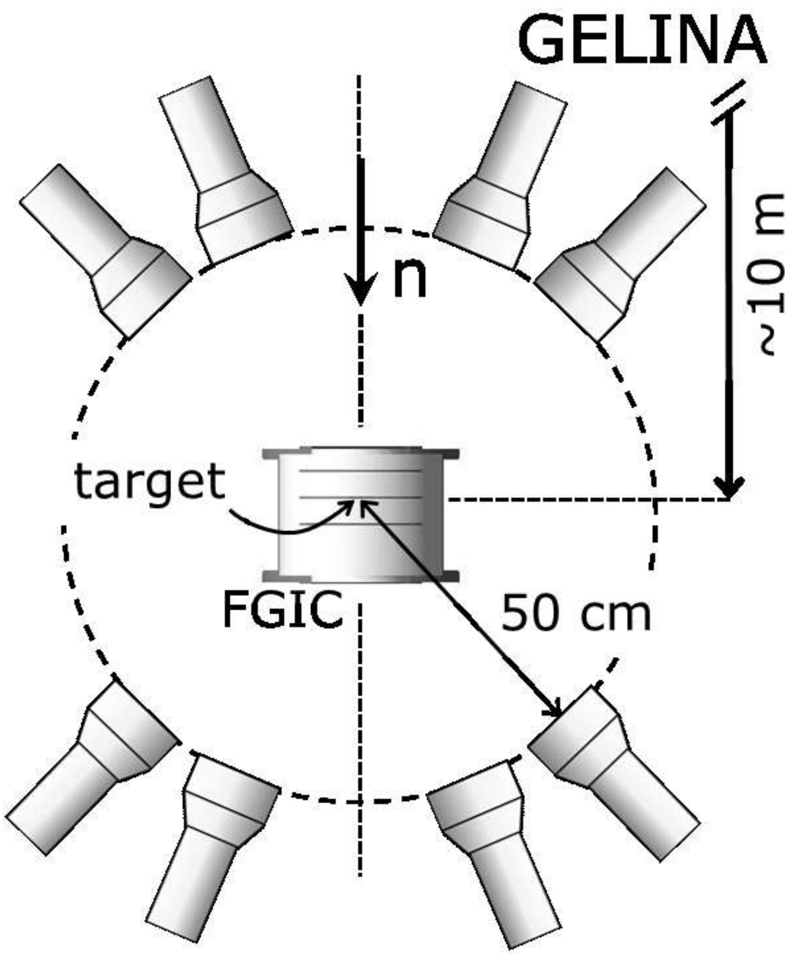
- Twin Ionization chamber

Prompt neutron detection

- Array of 22 scintillators
  - 18 LS-301 (NE-213 eq.)
  - 3 p-therphenyl
  - 1 stilbene
- Detection Threshold:

  0.5 MeV



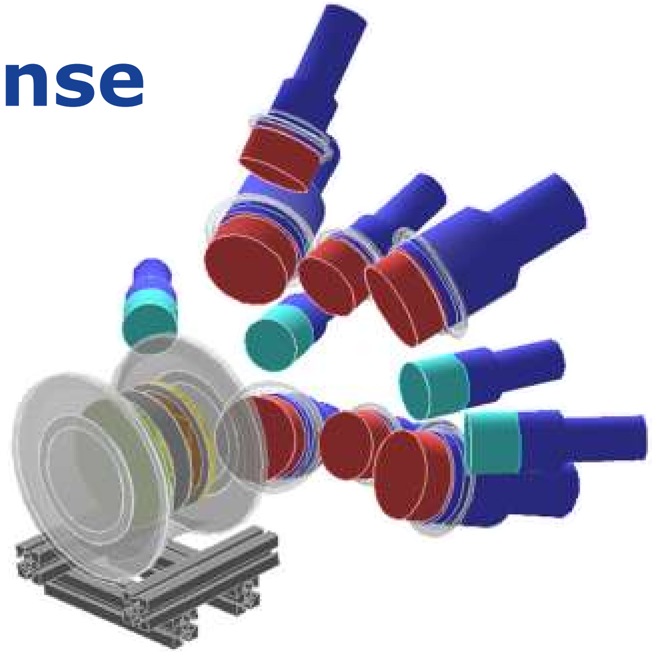


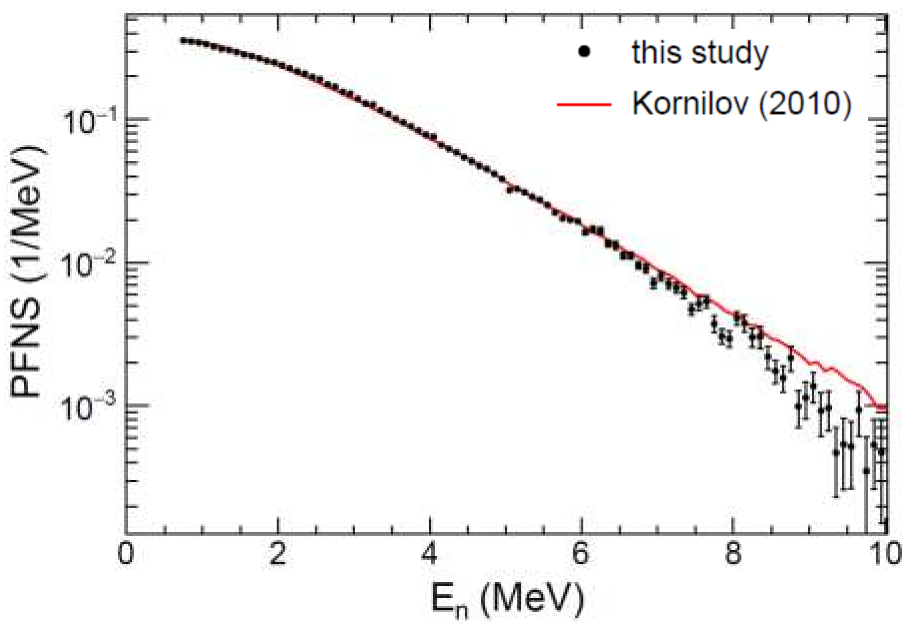
Neutron Detection Response

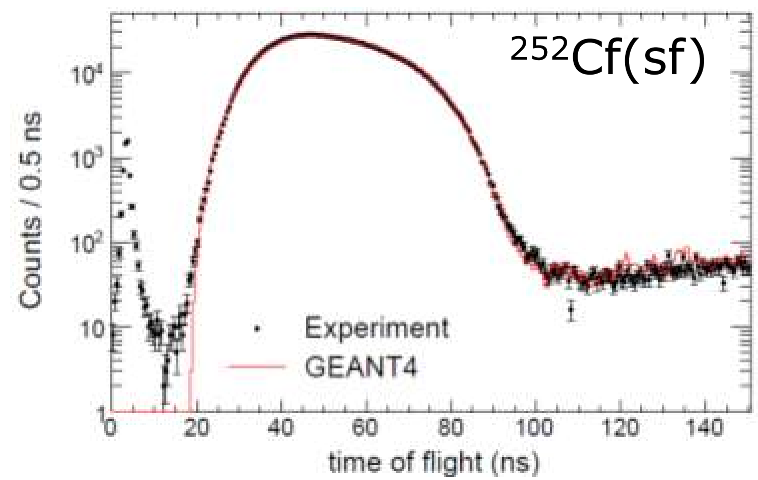
Neutron detection response is modelled with GEANT4

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

Multiple scattering correction calculated with GEANT4







3D - Ionization Chamber

The experimental method is based on kinematic reconstruction of the neutron emission in the rest frame of the fission fragment

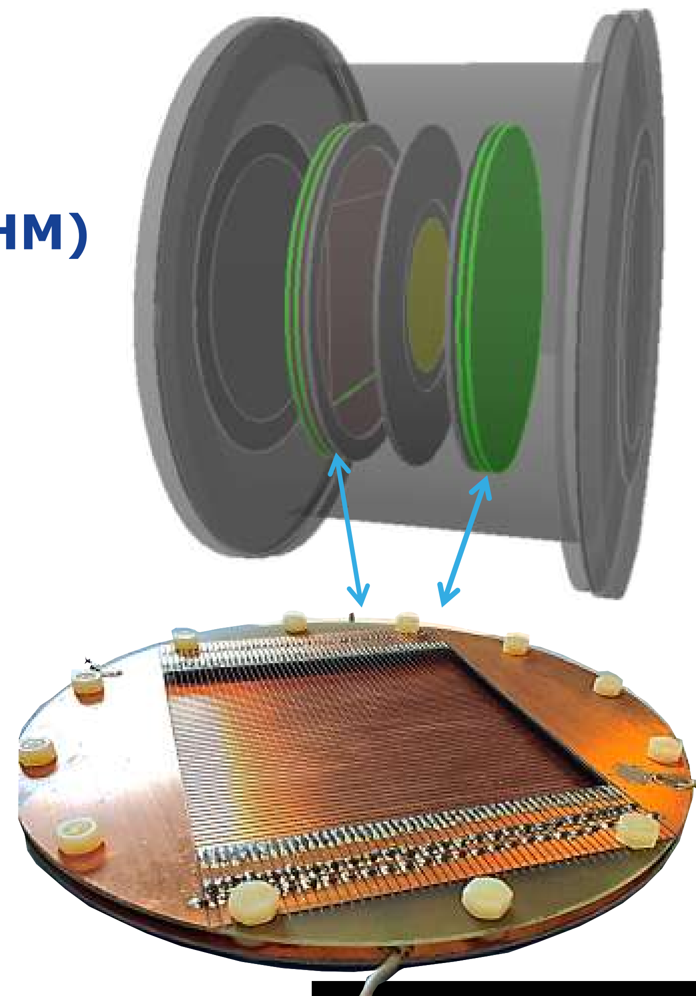
Twin Ionization Chamber

- ✓ **Large Geometrical Efficiency**
- ✓ **Timing Resolution ~1 ns (FWHM)**
- ✓ **Energies and Masses of fission fragments**
- ✓ **Polar angle θ of fission axis orientation**

Position Sensitive Electrode

- ➢ **Replaces anodes**

  Projection of fission-axis on the (x,y) – plane



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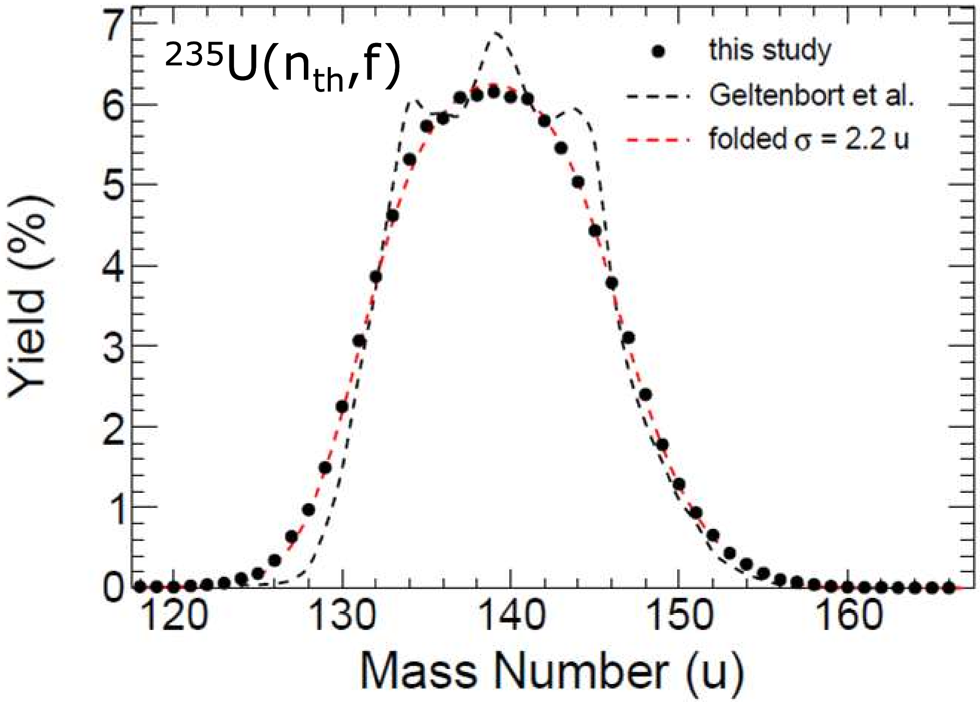
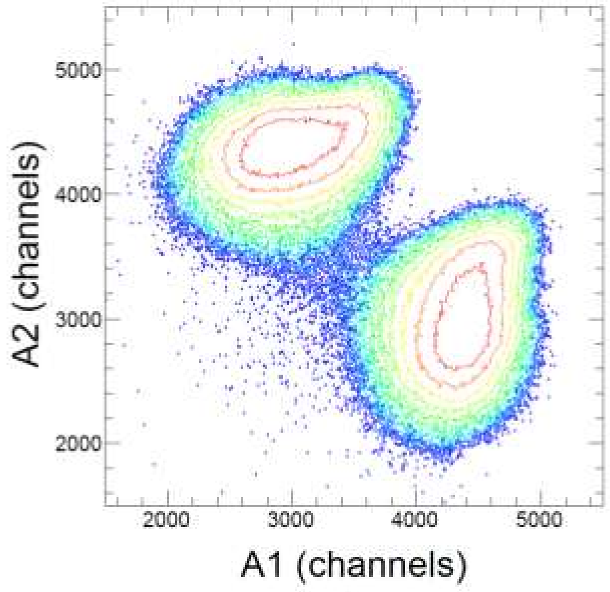
Mass Determination

Fragment masses determined via 2E-technique

- Corrections
  - Energy loss in sample & backing
  - Neutron Evaporation
- Good agreement with high resolution (2v) measurement
- Resolution: ~5 u (FWHM) mainly limited by PFN emission

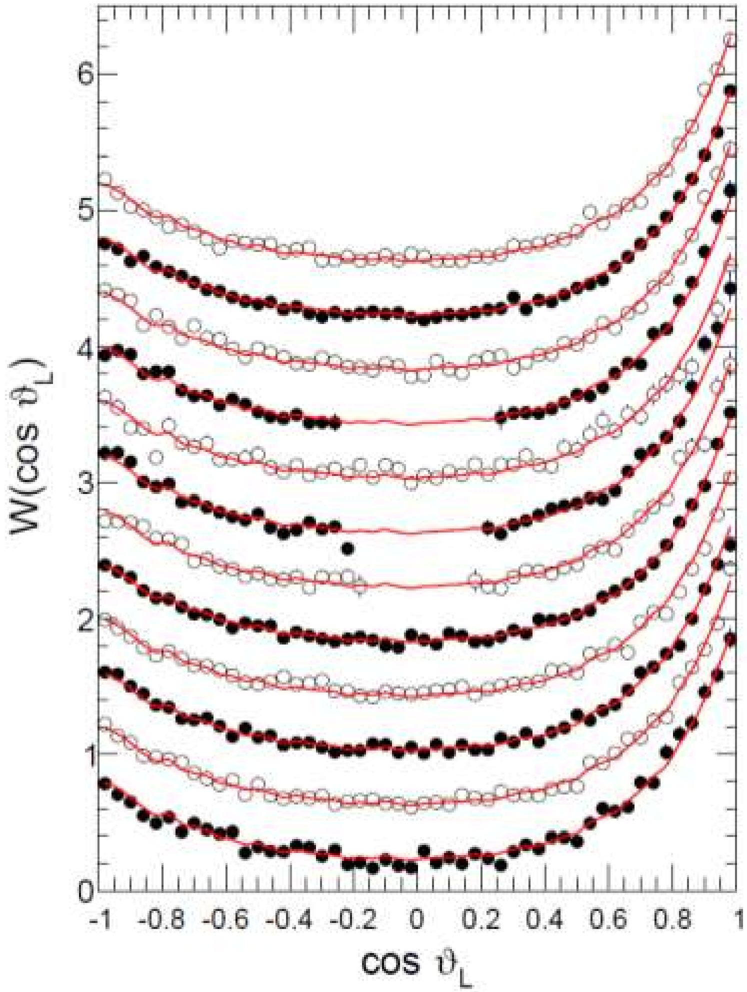




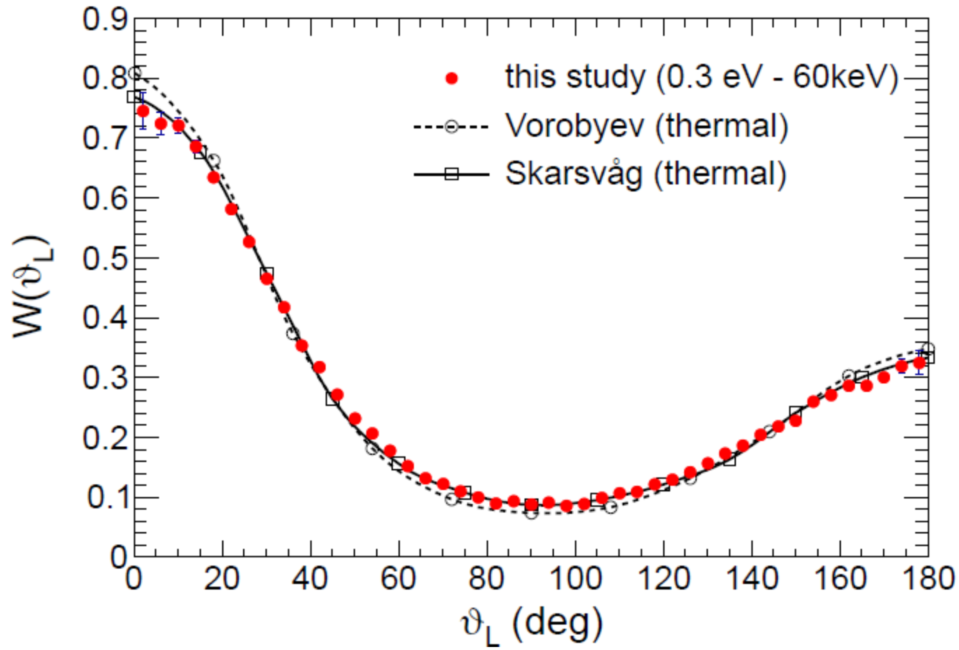
Geltenbort et al. Rad Eff 93 (1986) 393.

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

Consistent results from the individual detectors



Integral angular distribution of PFN relative to the fission axis



Results agree well with Skarsvåg (1963)

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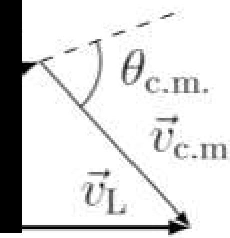
Analysis of PFN angular distributions

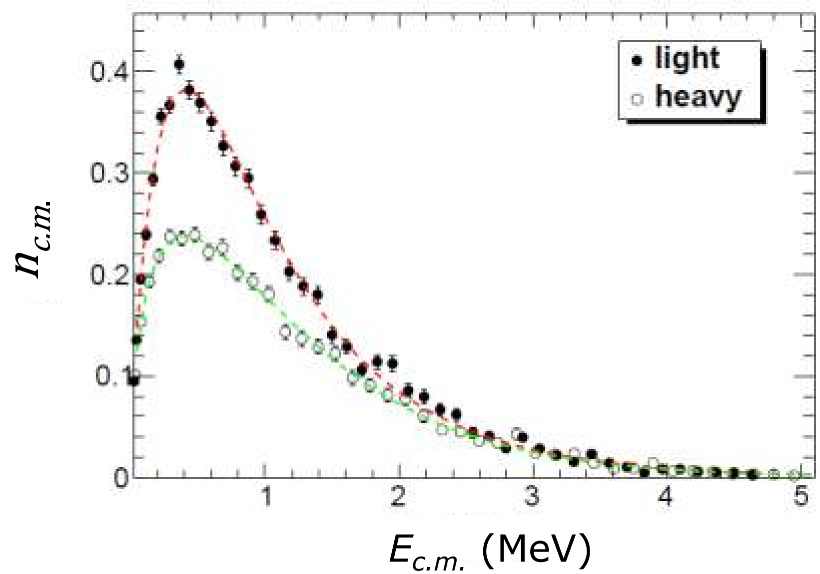
Assuming emission from accelerated fragments

[redacted]



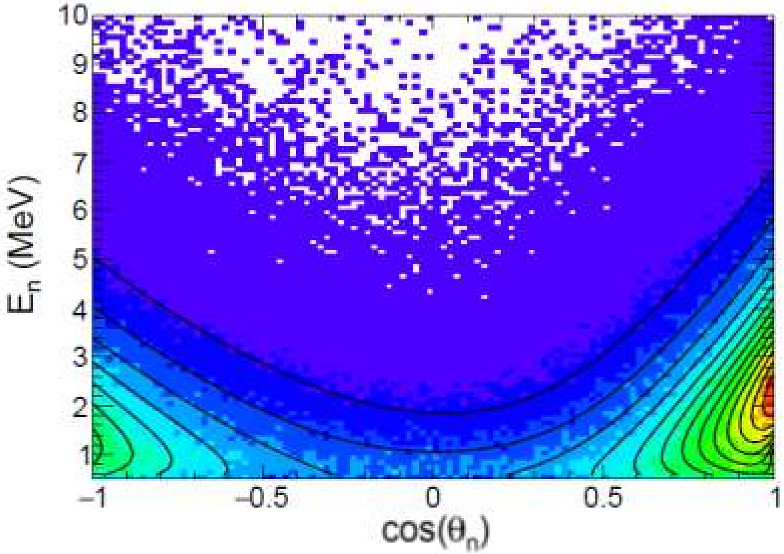
Simplified model

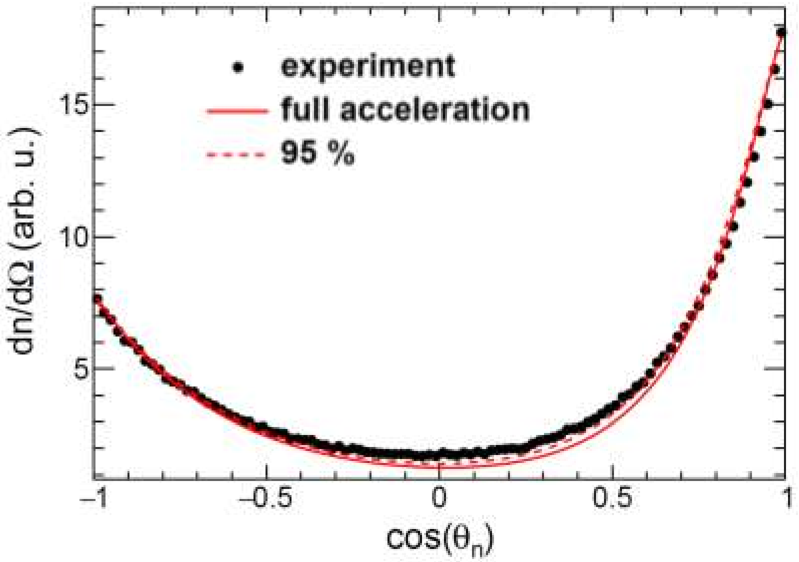
- [redacted]
- [redacted]
- **PFNS in c.m. determined from small angle data**

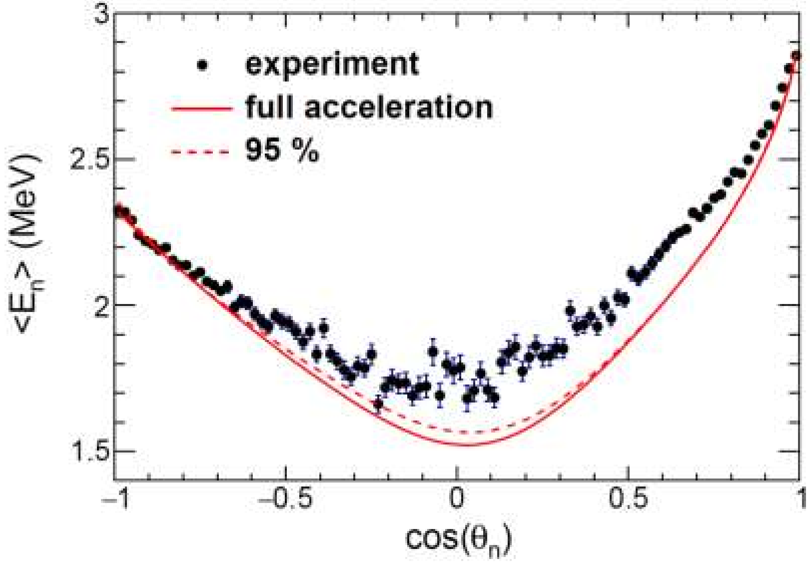


Analysis of PFN angular distributions

- Underestimation of yield at large angles:
  - 6% of the total number of neutrons
- Assuming emission at 95 % of full acceleration
  - Marginally better description



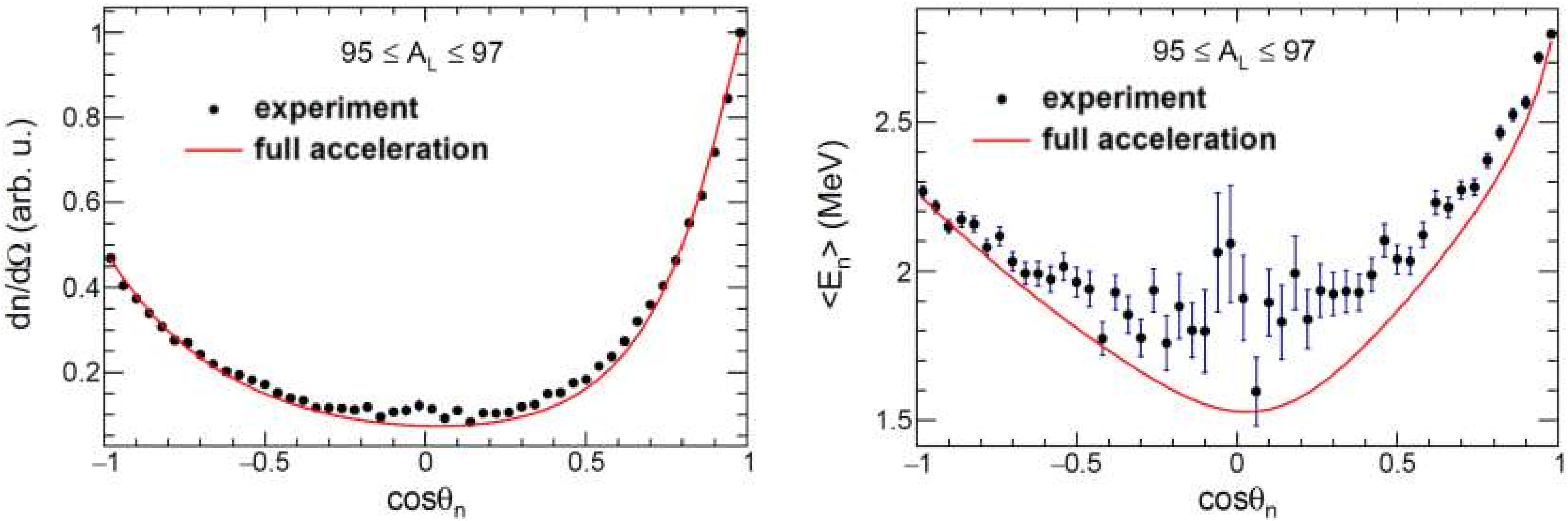




Analysis of PFN angular distributions

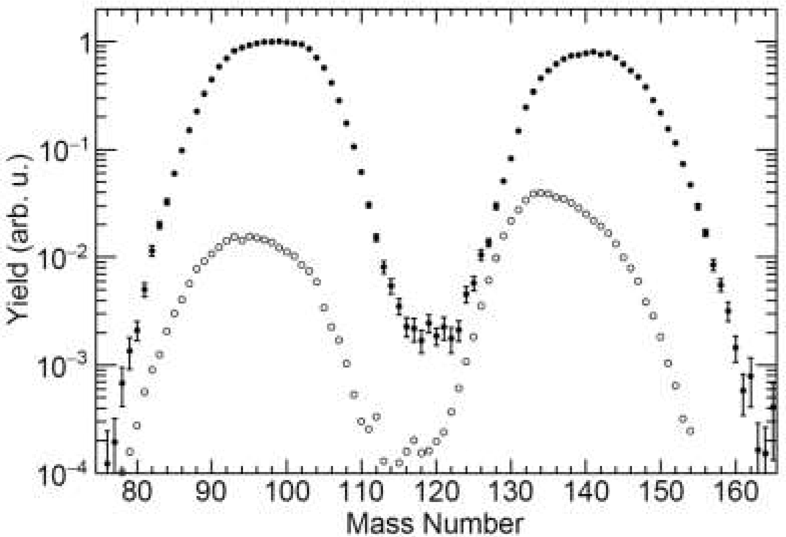
Similar result for selection of mass pairs

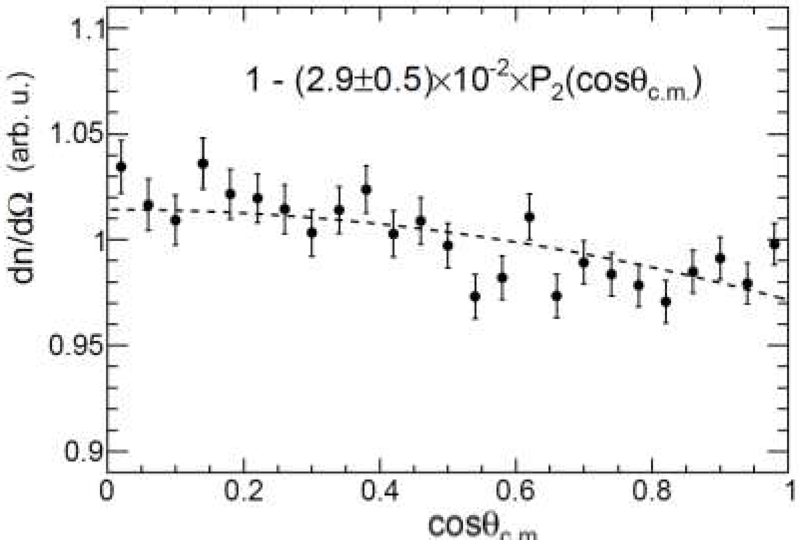
- Underestimation of yield at large angles:
  - 6% of the total number of neutrons
- Underestimation of $<E_n>$ at large angles



Results in c.m. - frame

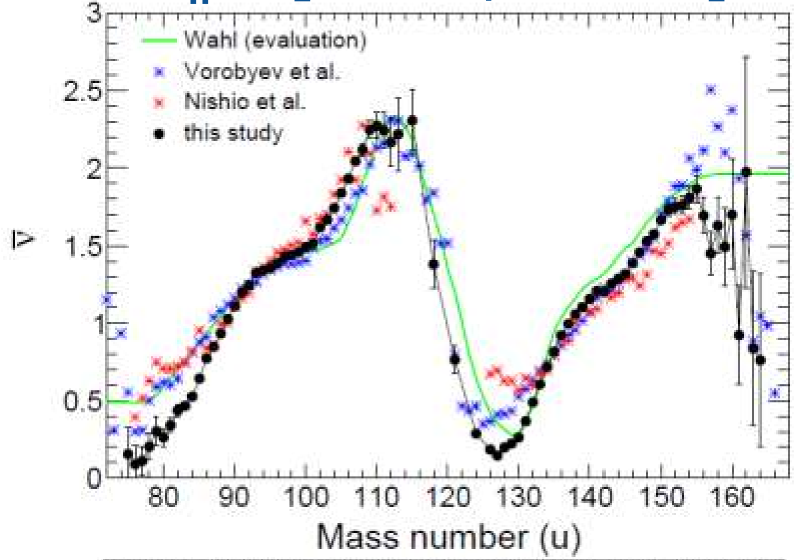
- Event by Event transformation into the c.m. frame
- Selection $\cos\theta_{c.m.} \geq 0$
- Measured distribution consist of neutron from both fragments
  - Main contribution is from fragment directed towards detector
  - Complimentary fragment neutrons are treated as perturbation
  - Probability of detecting neutron from complementary fragment is calculated based on assumption of isotropic emission from fully accelerated fragments
- Resulting angular distribution shows small anisotropy in c.m.

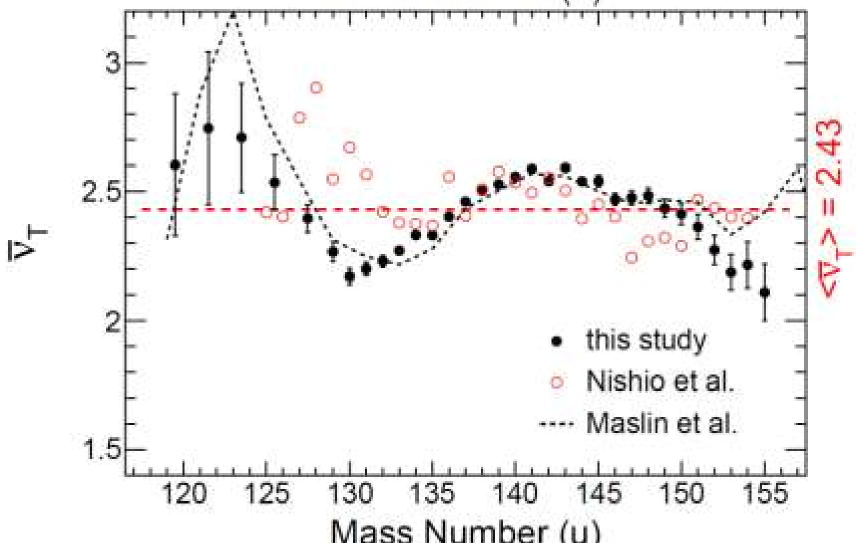




Multiplicity vs. Fragment Mass

$E_n \in [0.3\ \text{eV}, 60\ \text{keV}]$





Neutrons per fragment

Saw-tooth distribution

Pronounced minima around A_L=80 and A_H=130

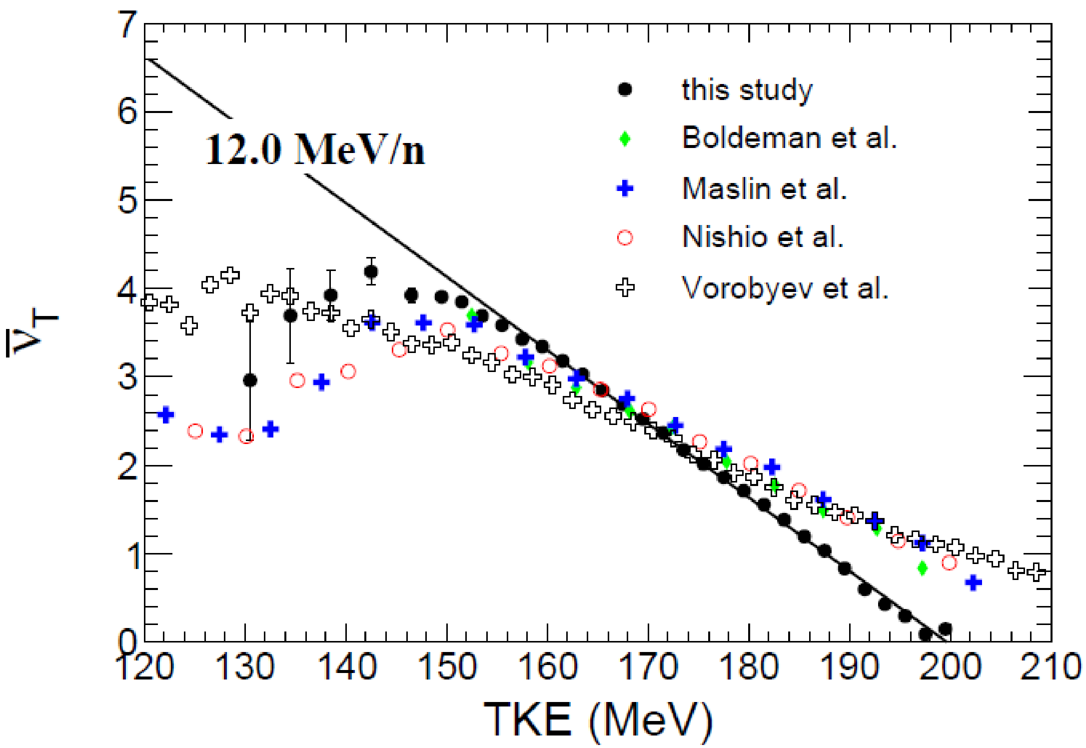
Shoulders around A_L=100 and A_H=140

Neutrons per fission

Flat distribution

Pronounced minimum around A_H=130

Multiplicity vs. Fragment TKE



Close to linear dependence

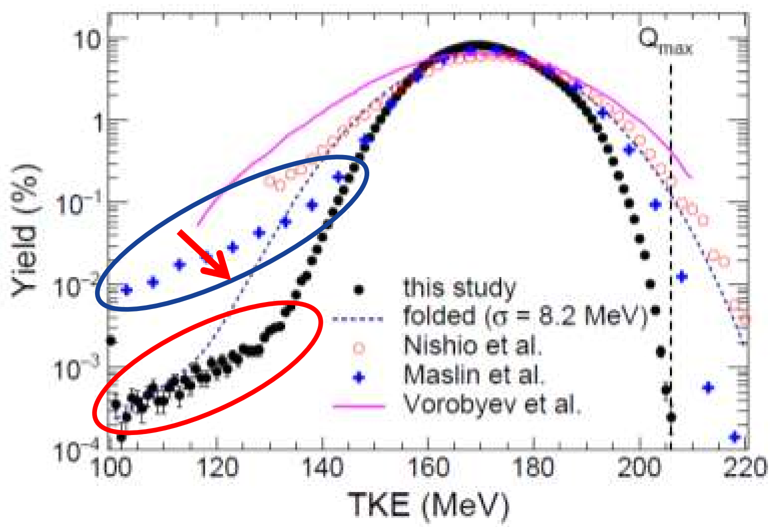
[redacted]

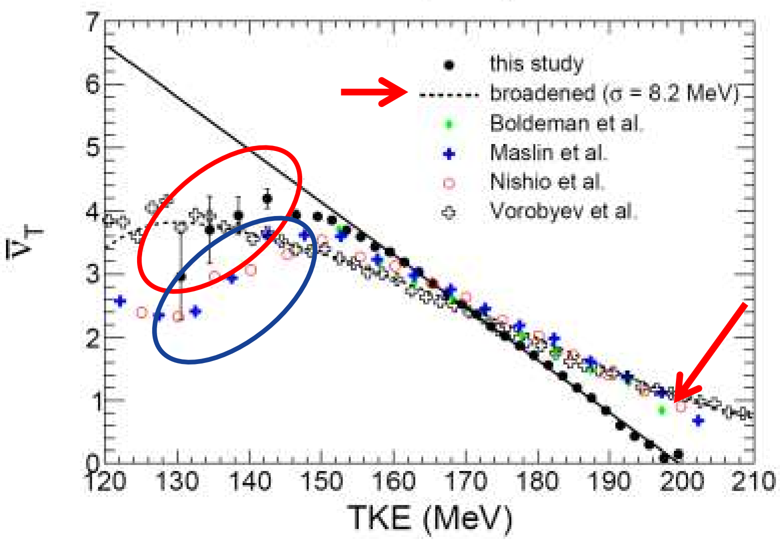
The slope is much steeper than earlier studies

[redacted]

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}

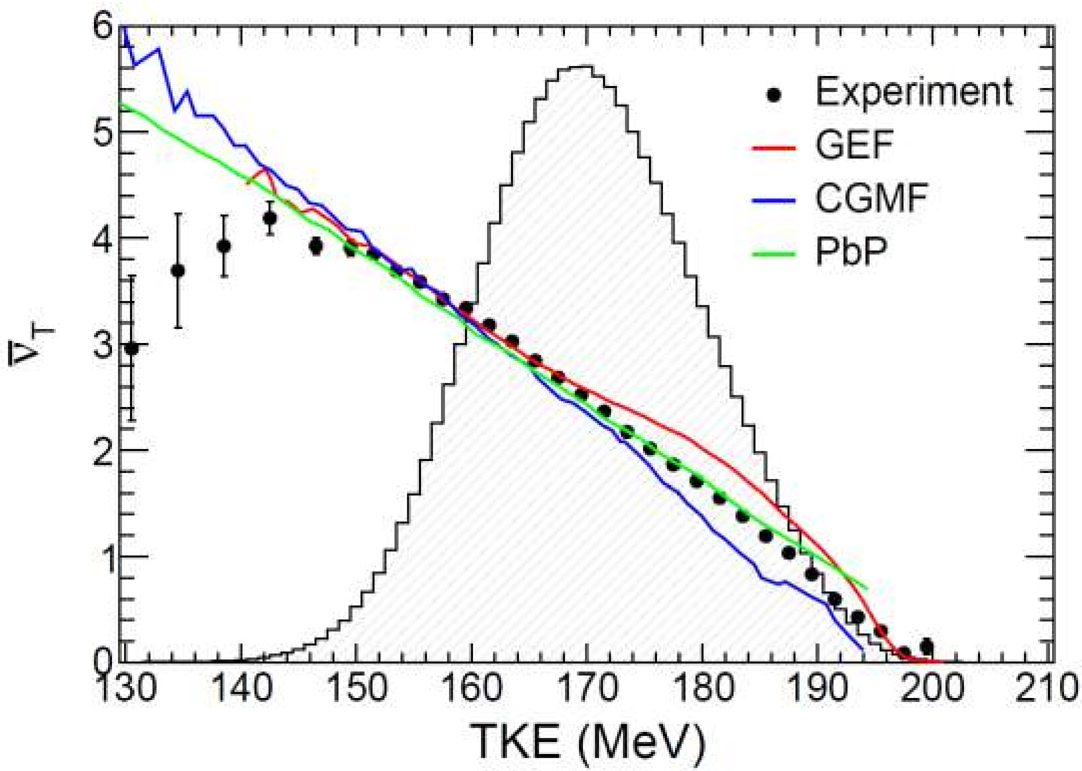
Tailing of TKE distribution

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

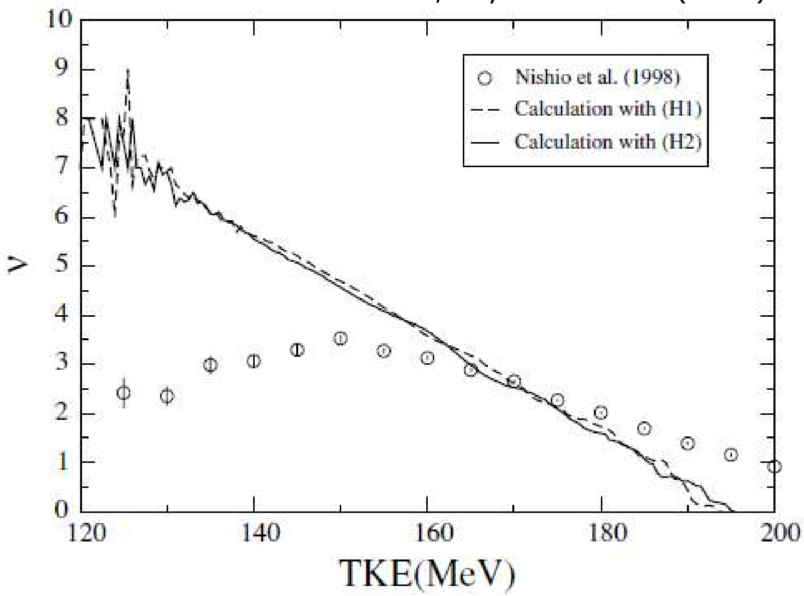
Multiplicity vs. Fragment TKE

Comparison with available de-excitation models

- Major discrepancy between theory and experiment resolved
- No additional sources of neutrons necessary at high TKE

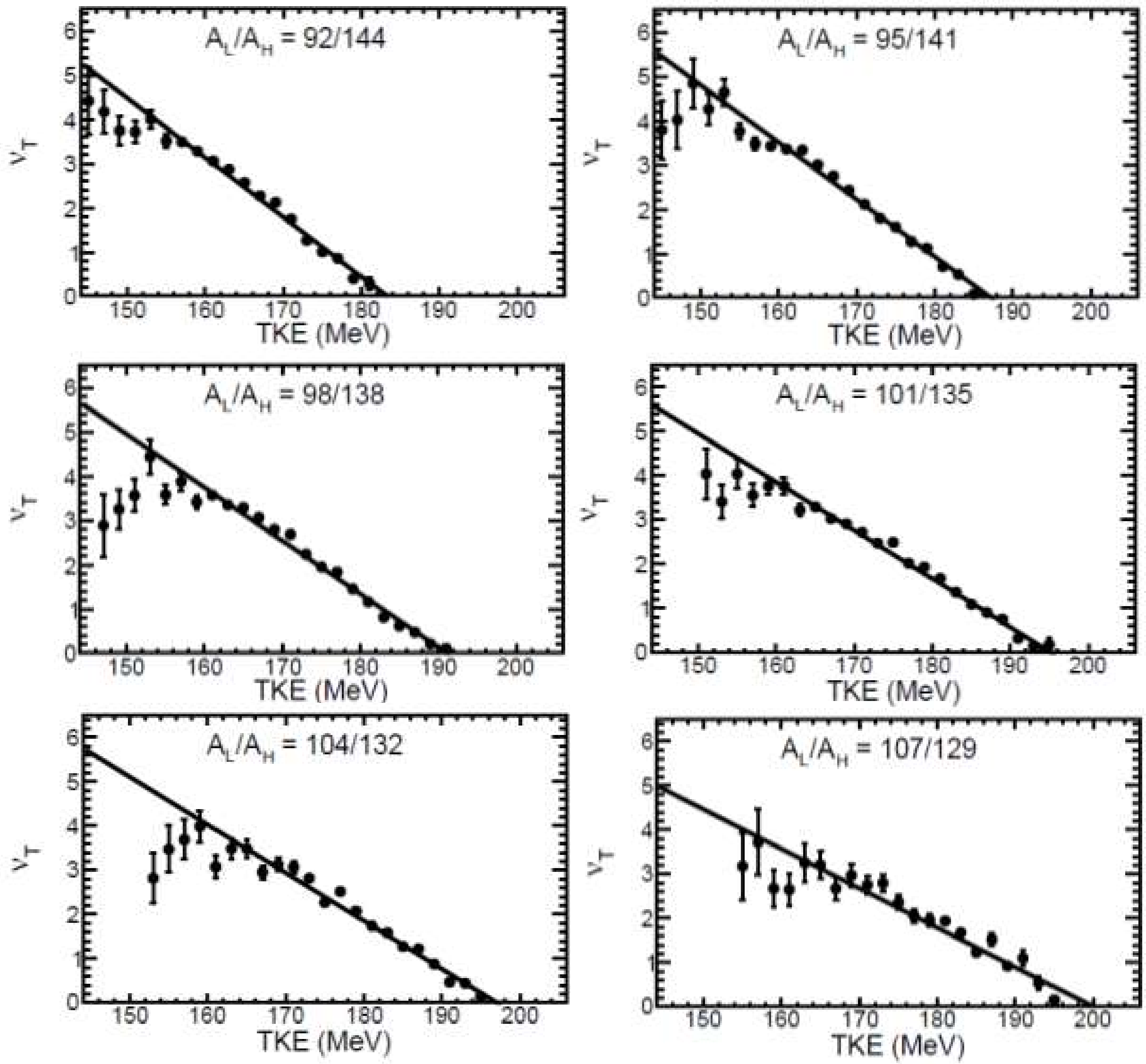


Lemaire et al., Phys. Rev. C 72 (2005)



Multiplicity vs. Fragment TKE

For selected fragment pairs

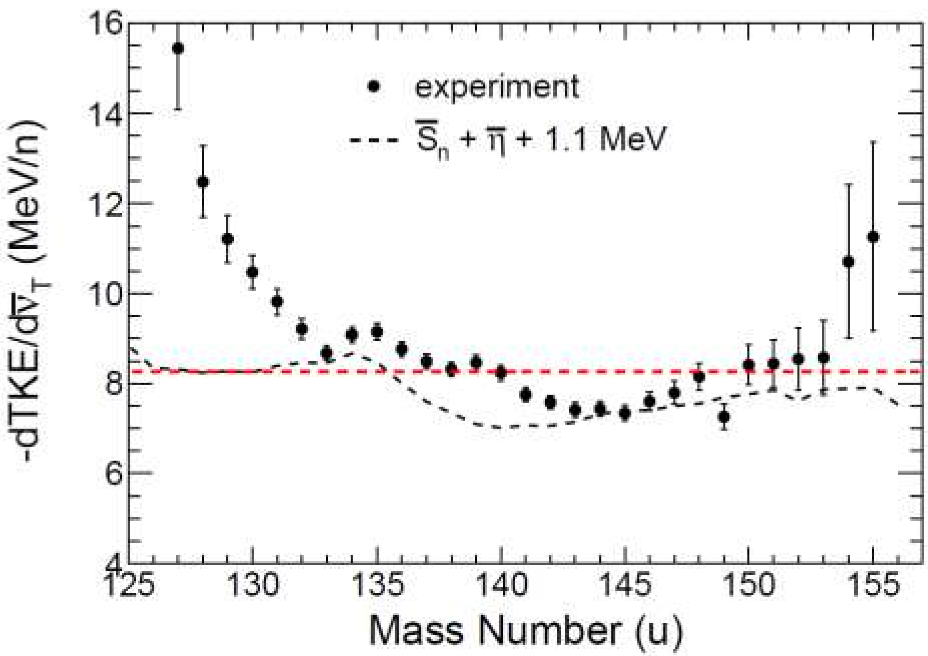


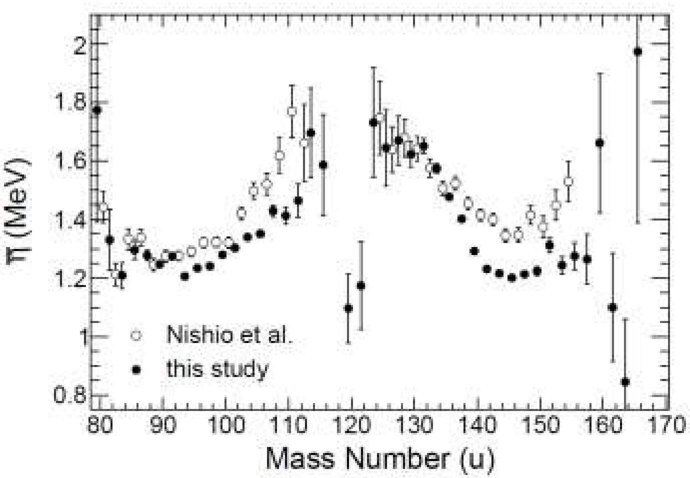
Slope gives directly the change in TXE per emitted neutron

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

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

Energy cost per neutron





Average energy necessary to emit a neutron

(8.3 ± 0.1) MeV

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

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

$$E_\gamma(A, \mathrm{TKE}) = [1.1\,\overline{\nu}(A, \mathrm{TKE}) + 1.75]\,\mathrm{MeV}$$

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

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Conclusions

Broad features of PFN angular distributions can be **described by** the assumption of **isotropic emission from fully accelerated fragments**, but underestimates the data at large angles and high energies. The **underestimation amounts to 6% of the total number of neutrons**.

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** as well as **additional structures around A_H=140 u and A_L=100 u**.

The TKE dependence of the number of neutrons emitted per fission shows an inverse slope **dTKE/dν ca. 35% smaller** than observed in earlier studies. The **difference can be explained by improved fission fragment TKE resolution** in the present experiment. There is **no indication that additional open channels are necessary to describe the dependence**.

The present results should have strong impact on the modelling of both prompt neutron and prompt γ-ray emission in fission due to 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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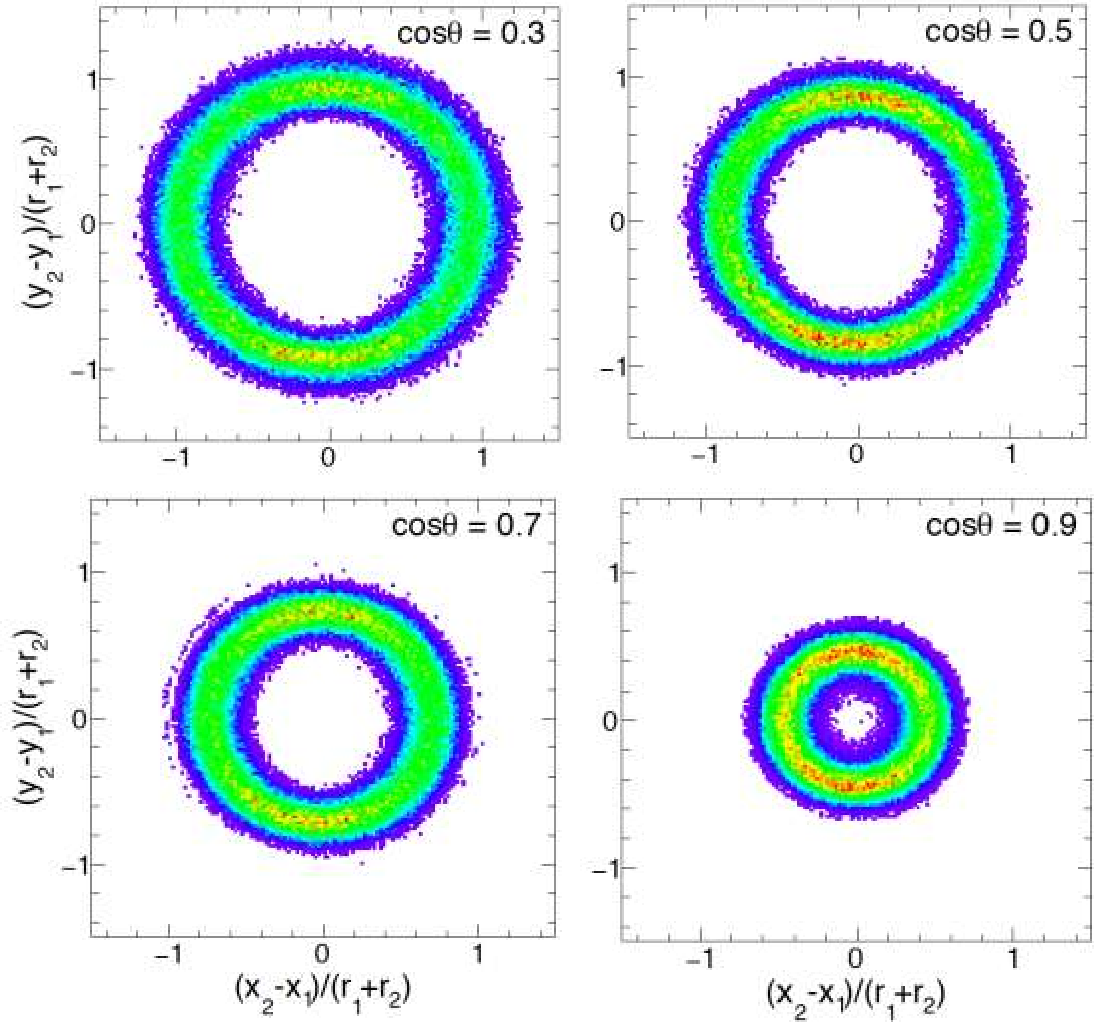
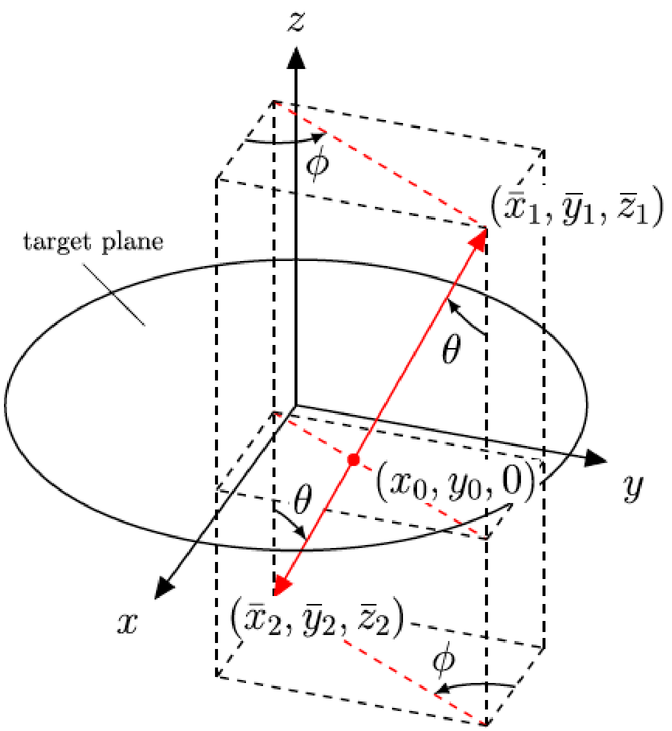
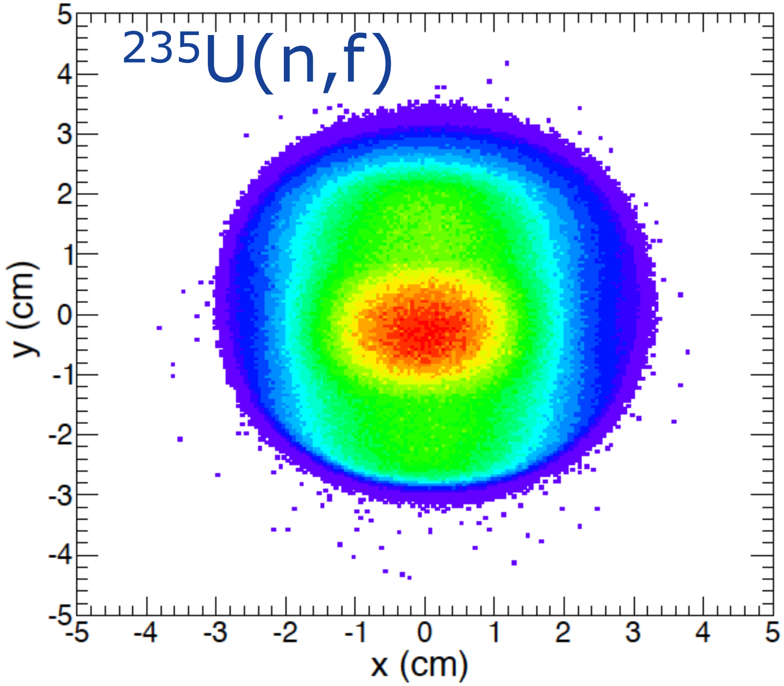
Position sensitive ionization chamber



Demonstration of the position sensitivity. Difference in x-coordinates and y-coordinates for the fission fragments detected on the opposite chamber sides.



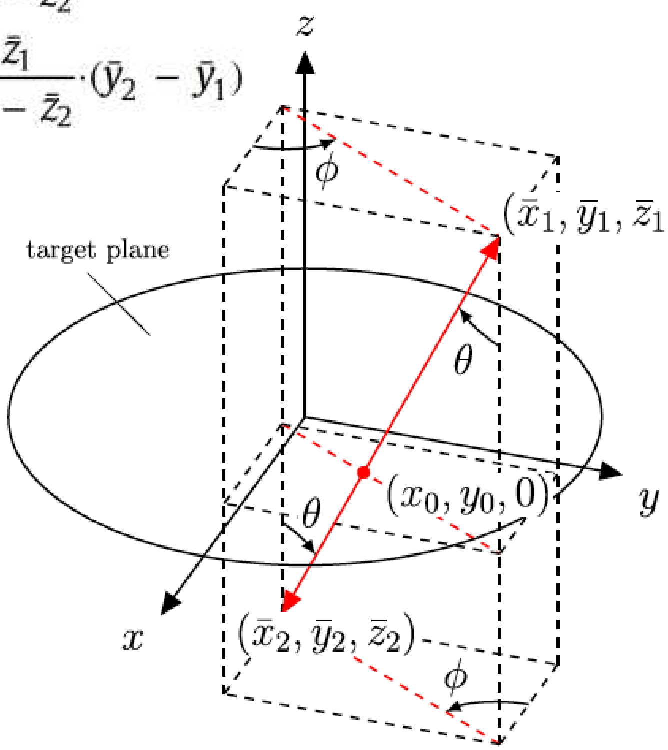
Position sensitive ionization chamber



Distribution of fission events on the target plane. Determined by linear interpolation between the coordinates of fission fragments detected on opposite side of the ionization chamber.

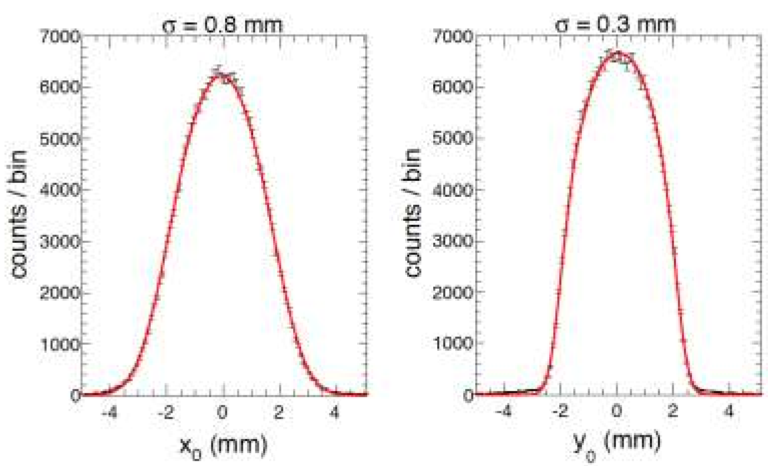
$$x_0 = \bar{x}_1 + \frac{\bar{z}_1}{\bar{z}_1 - \bar{z}_2} \cdot (\bar{x}_2 - \bar{x}_1)$$

$$y_0 = \bar{y}_1 + \frac{\bar{z}_1}{\bar{z}_1 - \bar{z}_2} \cdot (\bar{y}_2 - \bar{y}_1)$$

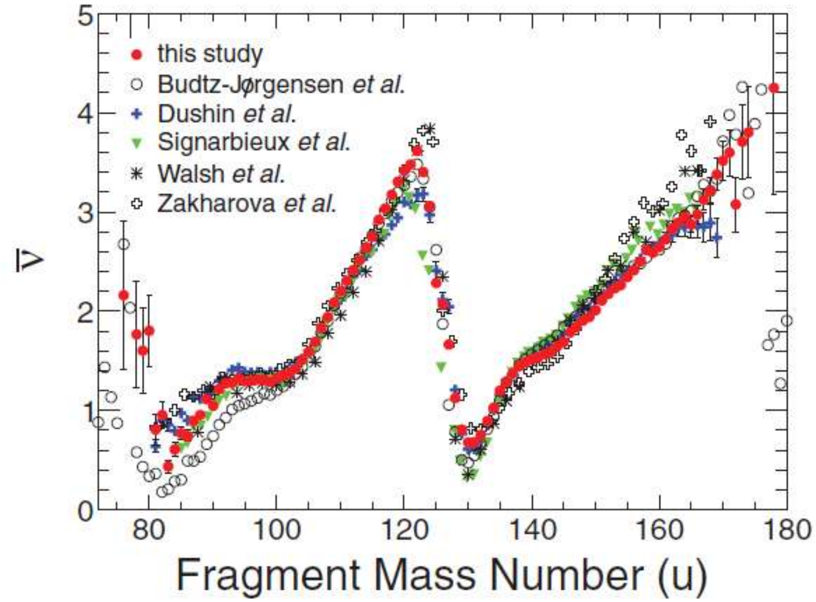


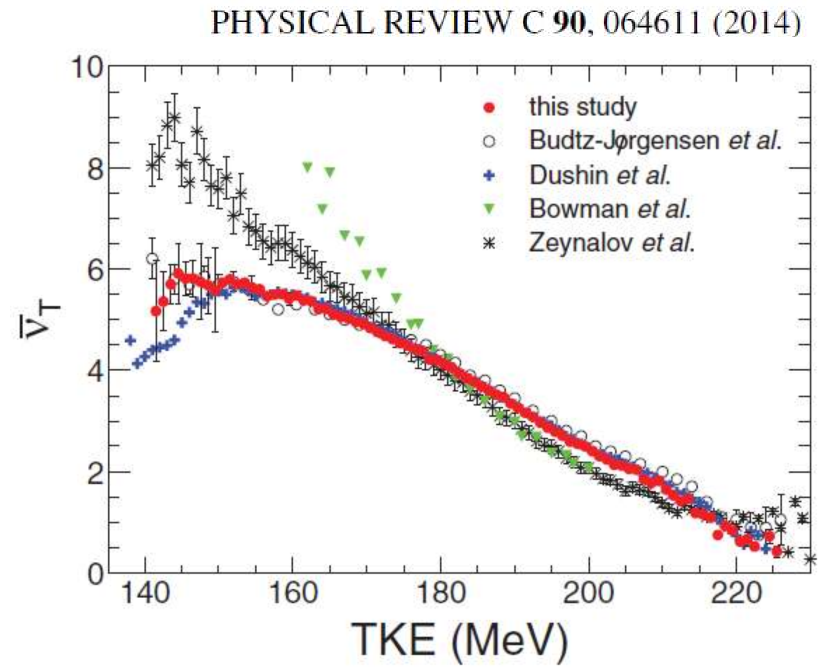
^{252}Cf – source

Circular spot
5 mm diameter



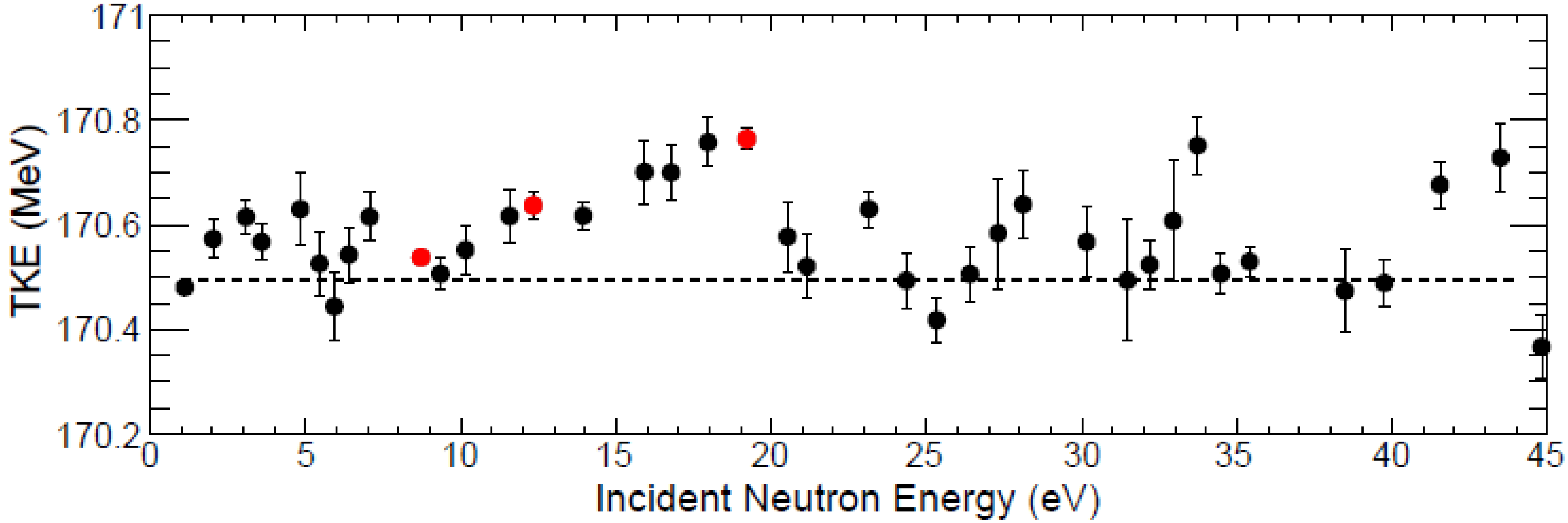
^{252}Cf(sf) : Validation of method

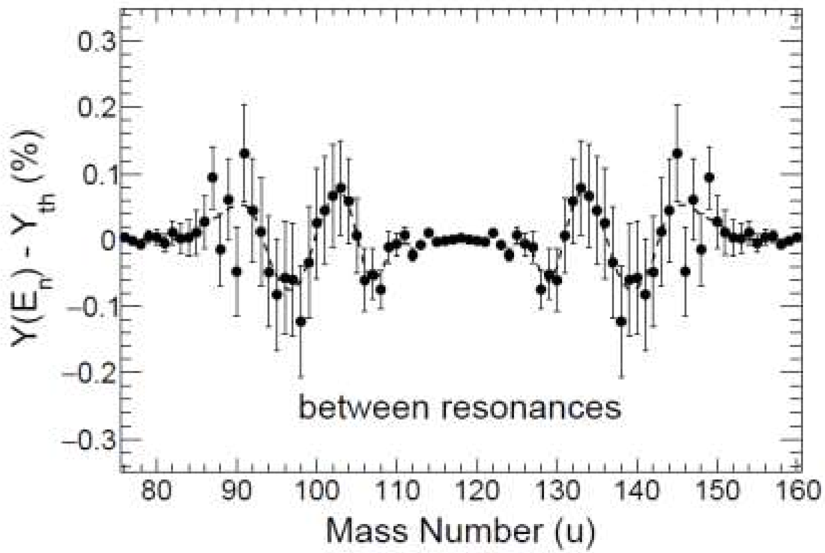


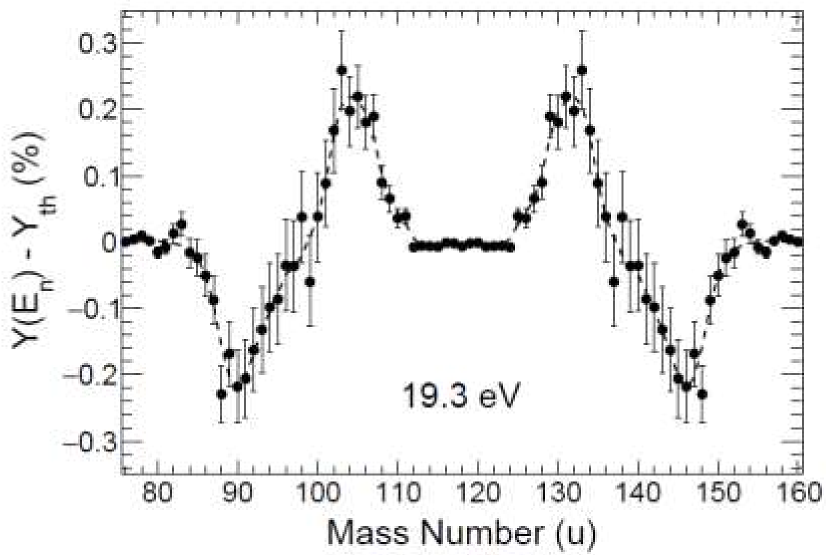


- Results show consistency with literature data
- Specifically with methods that do not suffer from neutron energy detection threshold
  - (Dushin et al.) Gd-loaded 4π scintillator tank

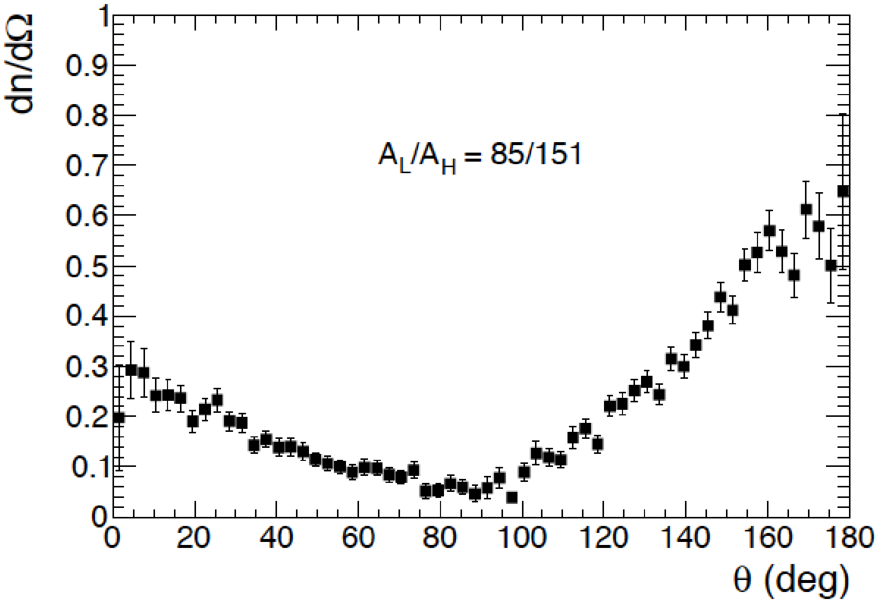
Resonance Energy vs. Fragment TKE

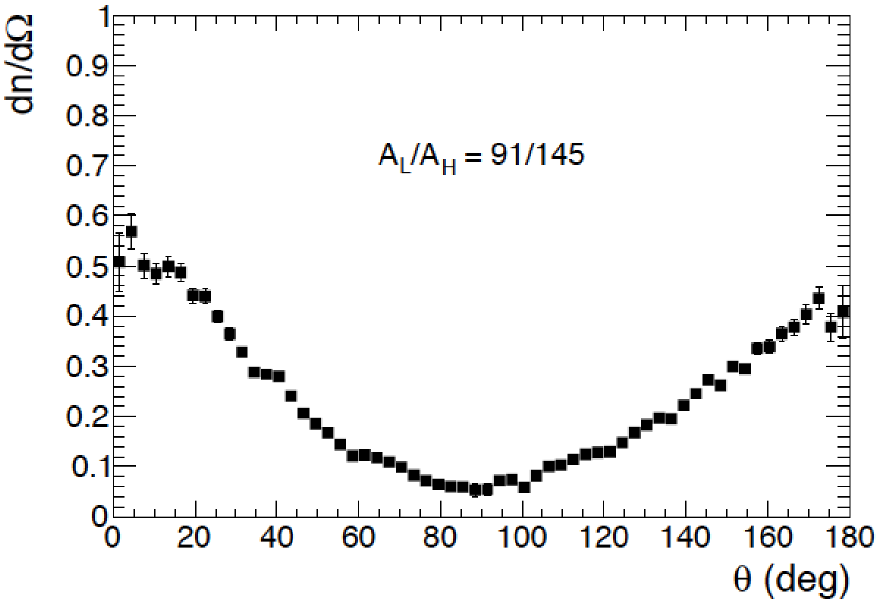


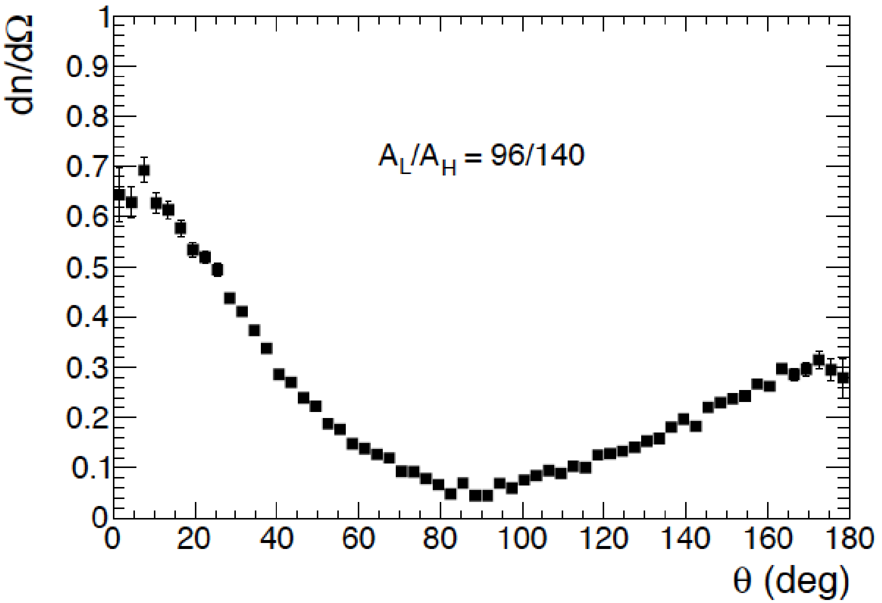


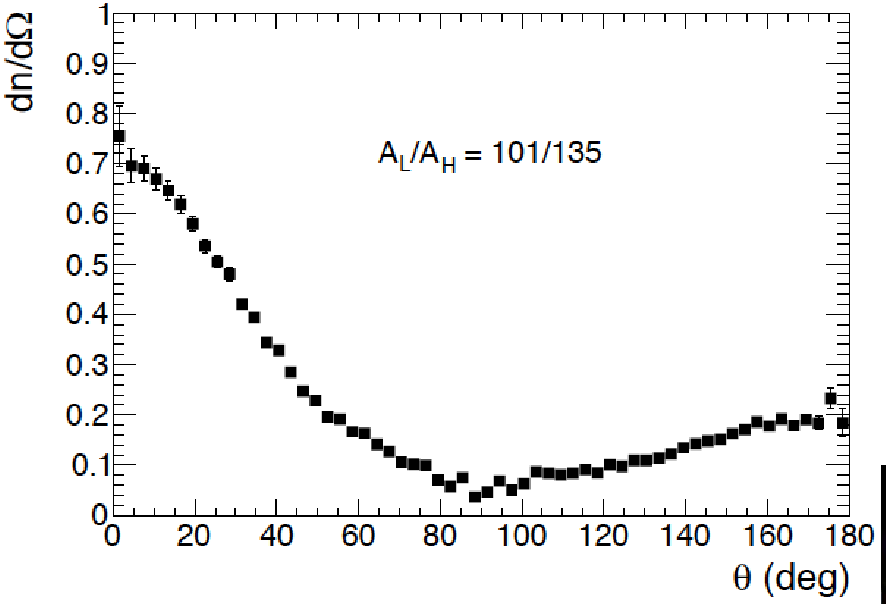


PFN angular distributions



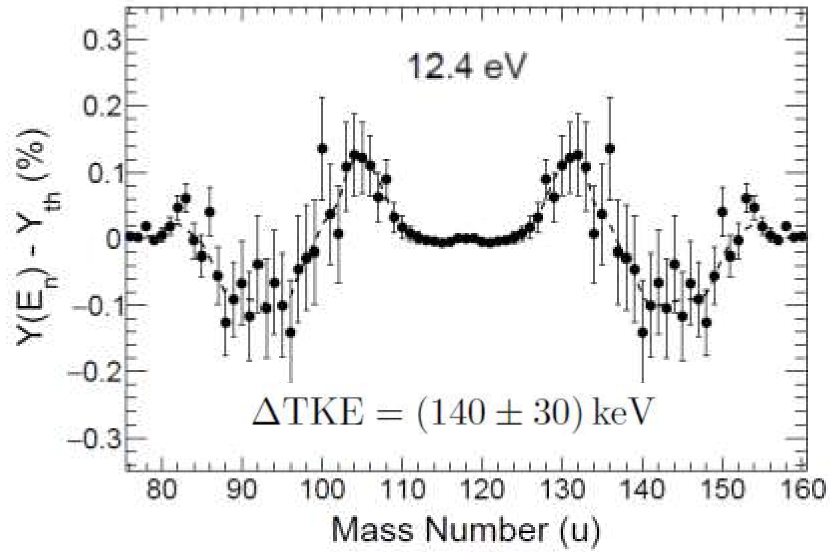


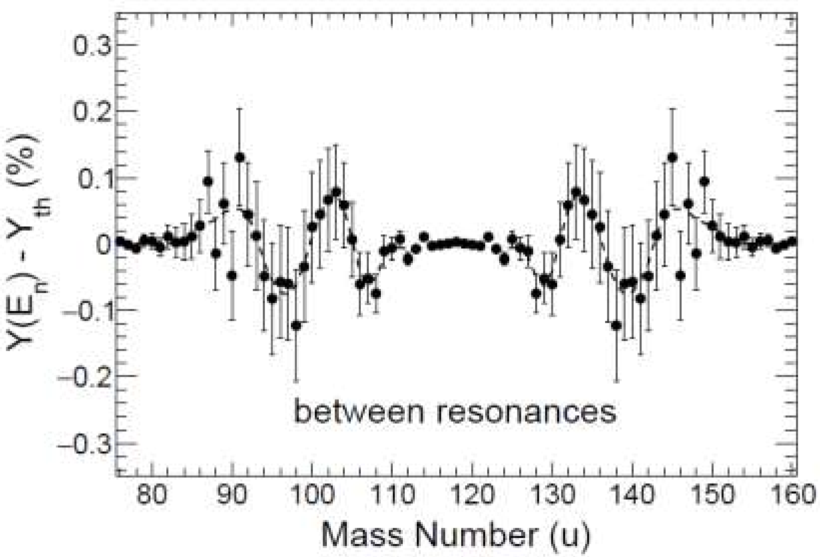


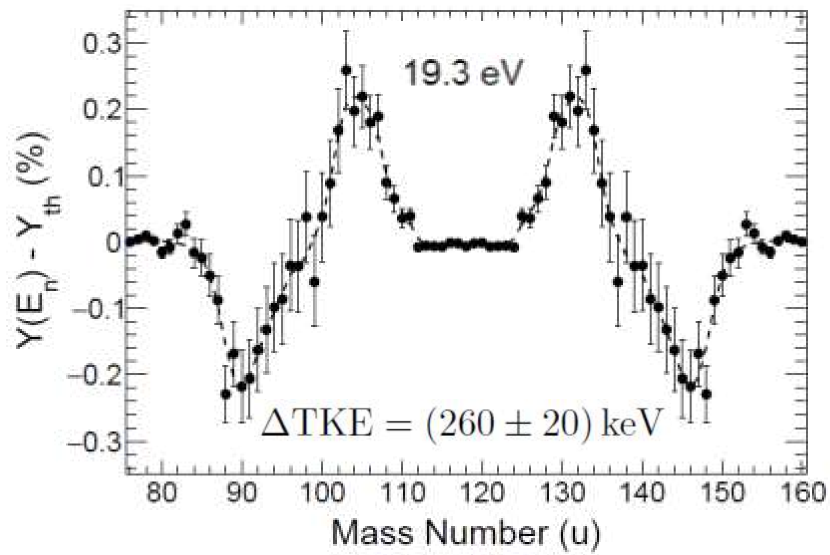


Mass Distributions in the Resonances

- 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
- Verifies earlier results
  Hambsch et al. NPA491 (1989) 56



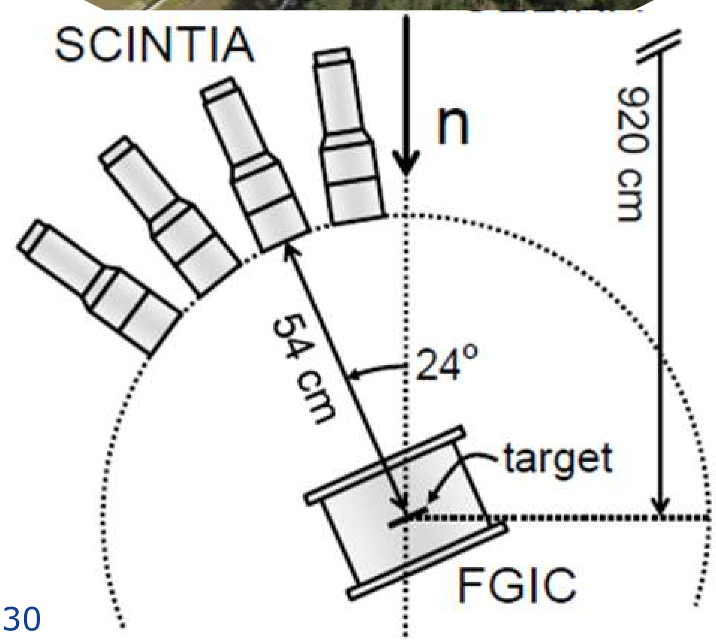




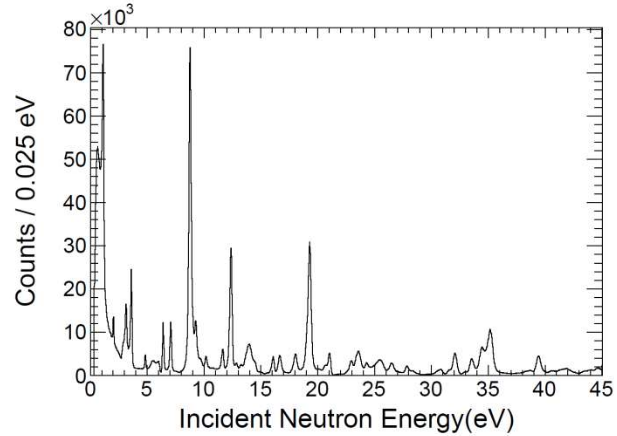
Experimental setup

GELINA

neutron time-of-flight facility



GELINA – neutron source



Twin Ionization Chamber

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

Neutron Detector Array SCINTIA

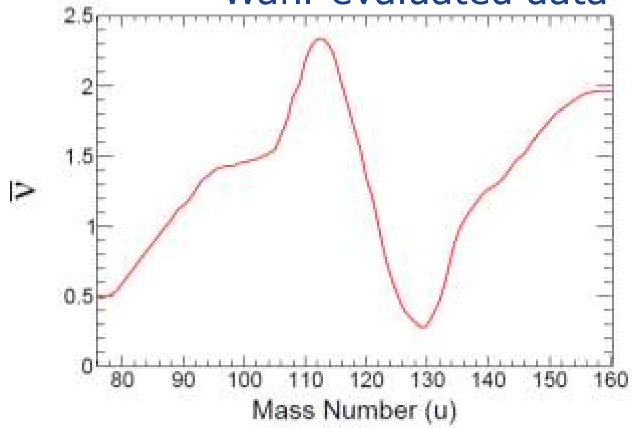
- 12 x Scintillators
- Prompt fission neutrons
  - ➢ Energy (time-of-flight)

2E-analysis of FF data

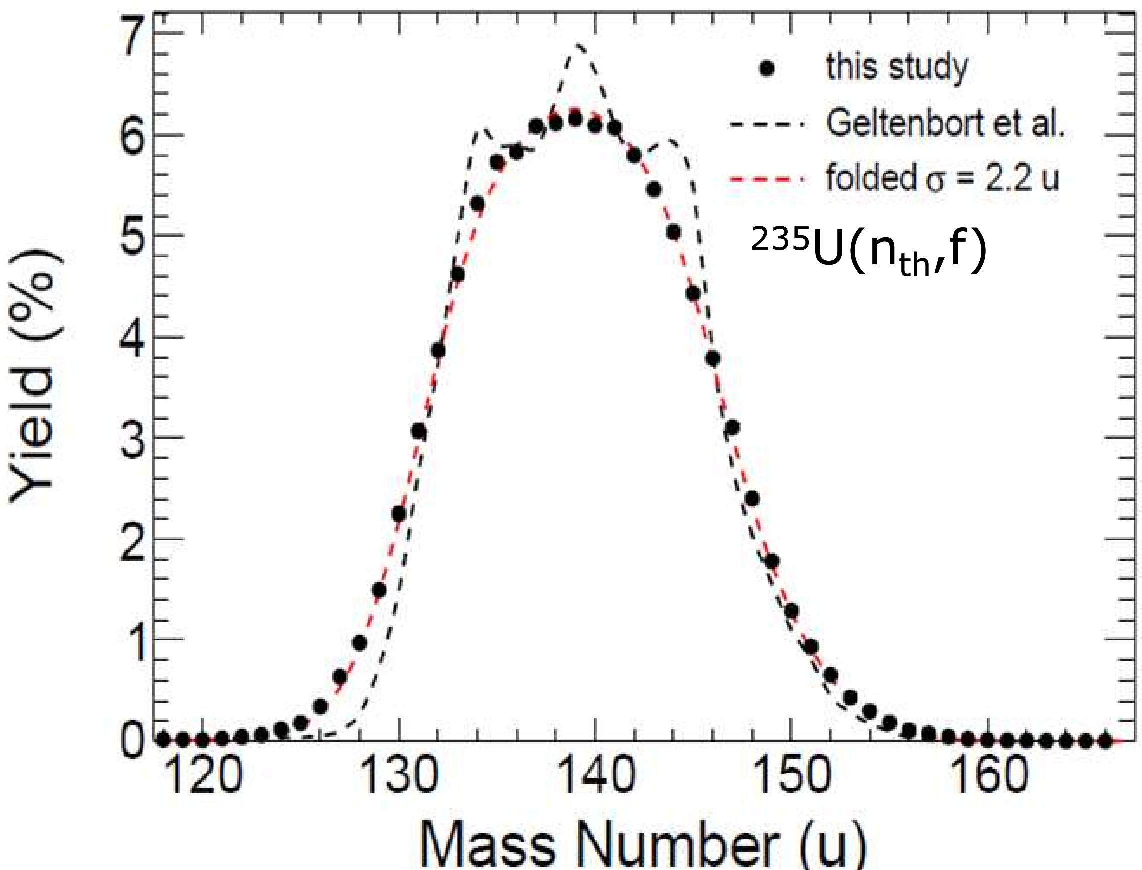
Conservation of linear momentum

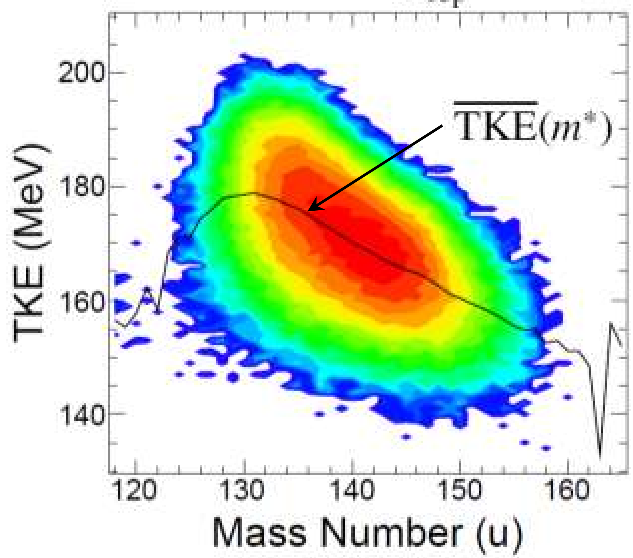
Correction for PFN emission

Wahl-evaluated data



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





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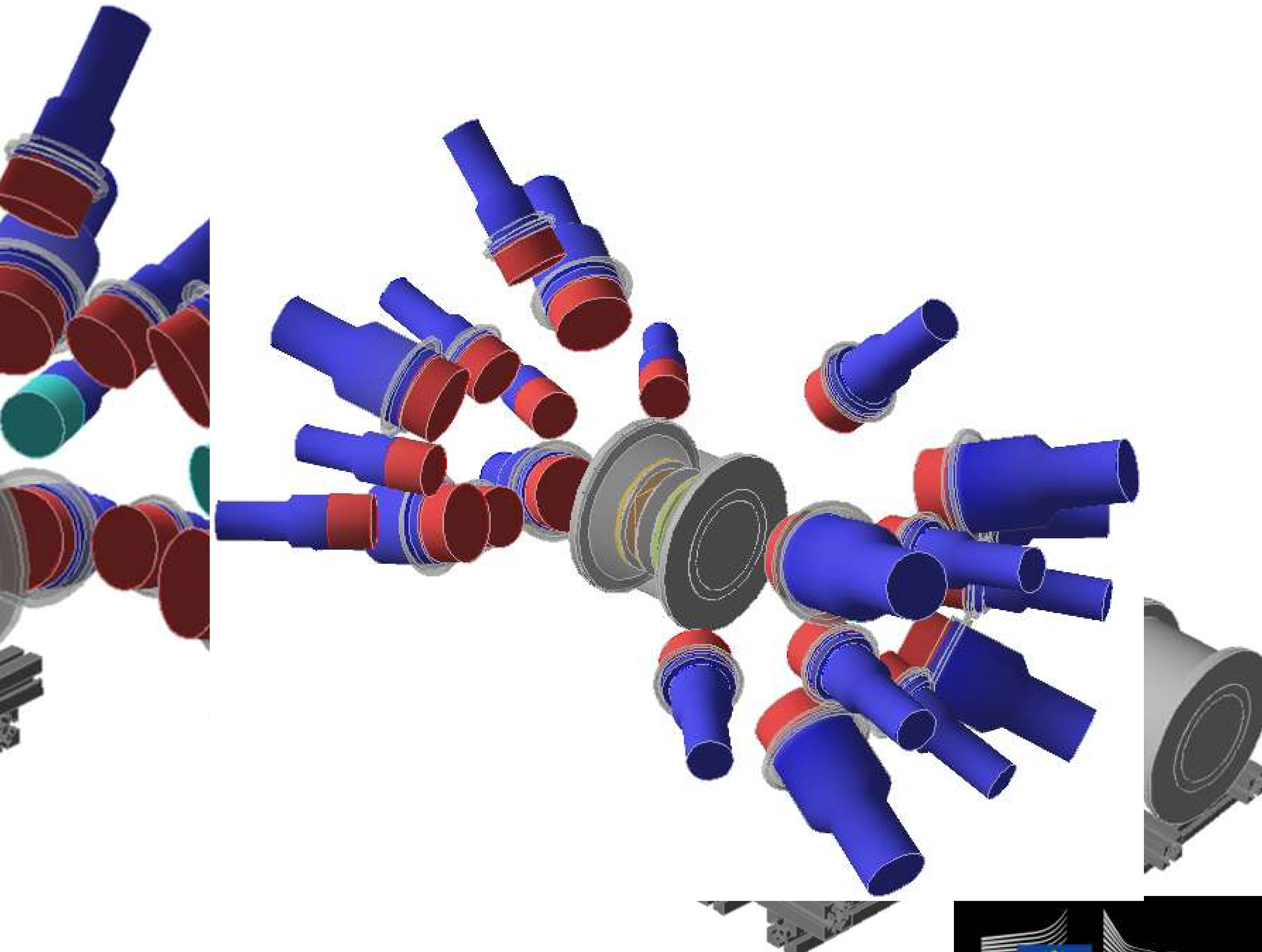

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