Prompt fission neutron multiplicity measurement

Needs, evolution of experimental techniques

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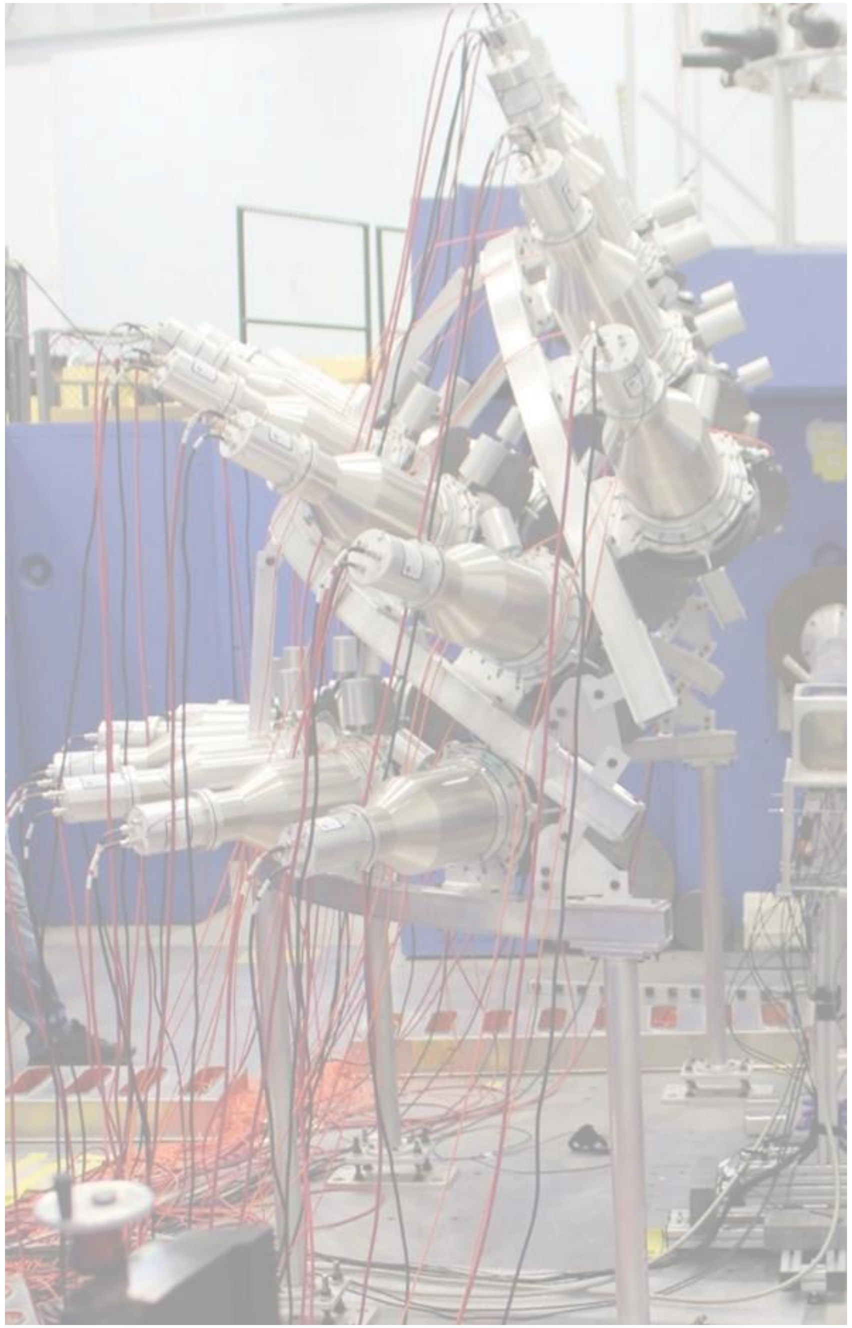
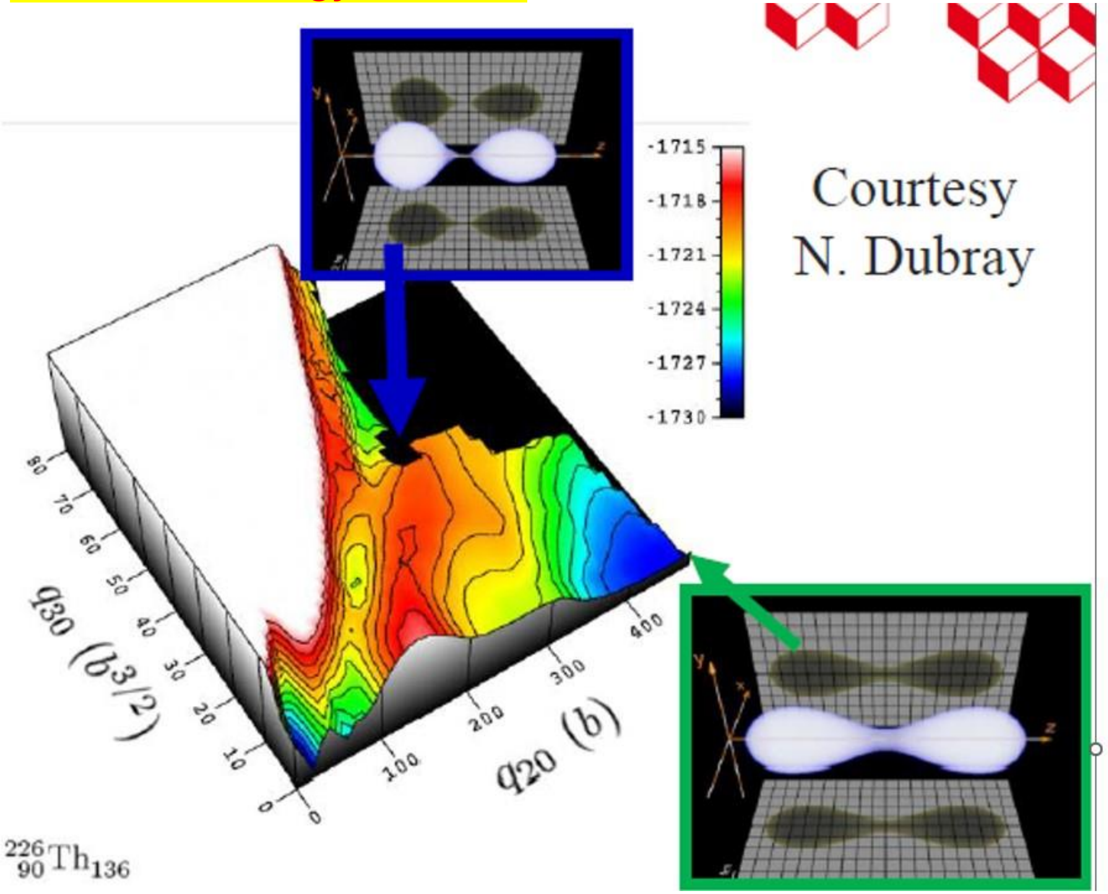
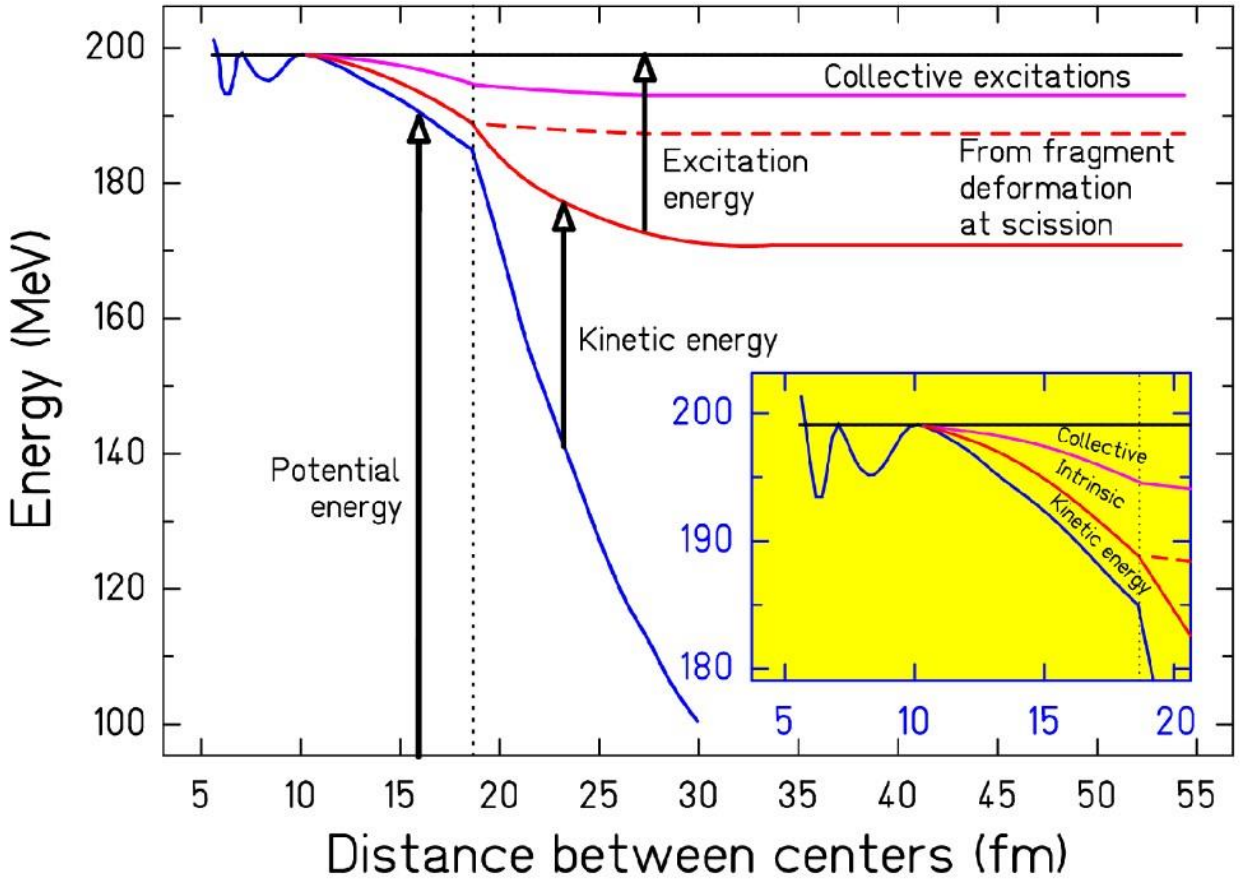


1. Neutron emission in fission

Fission energetics

Potential energy surface





From K.H Schmidt et al

Fission Fragments excitation energy

Two major reservoirs

Deformation energy

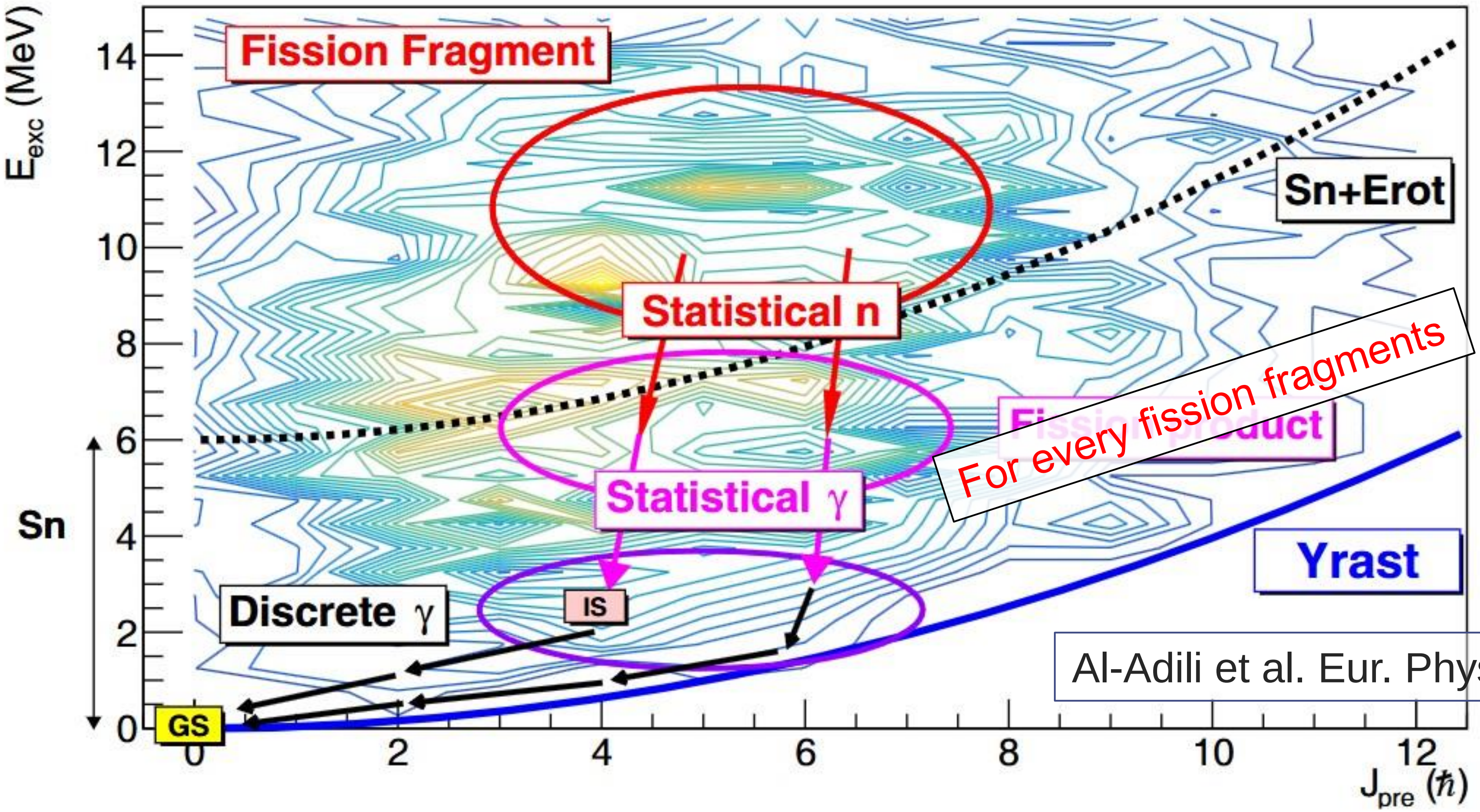
- Depends on the path to scission
- Relates to the shape of Fission fragments at scission
- Relax very quickly into excitation energy

Intrinsic excitations

- Related to dissipation from saddle to scission
- Increase with compound nucleus E*
- Is shared between both fragments

Complex to estimate very accurately

Fission Fragments deexcitation process



oversimplified view

A 3-step process

- Statistical neutron emission
- Statistical gamma (E1)
- Discrete gamma transitions (E2)

Al-Adili et al. Eur. Phys. J. A (2019) 55: 61

Number of emitted neutrons difficult to evaluate accurately

2. Needs for accurate neutron multiplicity estimate

Importance of neutron multiplicities for applications

The mean neutron multiplicity $\bar{\vartheta}$ $(nubar)$

Key parameter → evolution of a chain reaction

Most sensitive ND → Nuclear reactor k_{eff}

Safety concerns → k_{eff} accuracy goal : 0.1%

Fully correlated → $\bar{\vartheta}$ accuracy goal : 0.1%

Reduce uncertai. → 70+ years of experimental efforts

A wealth of high-quality measurements

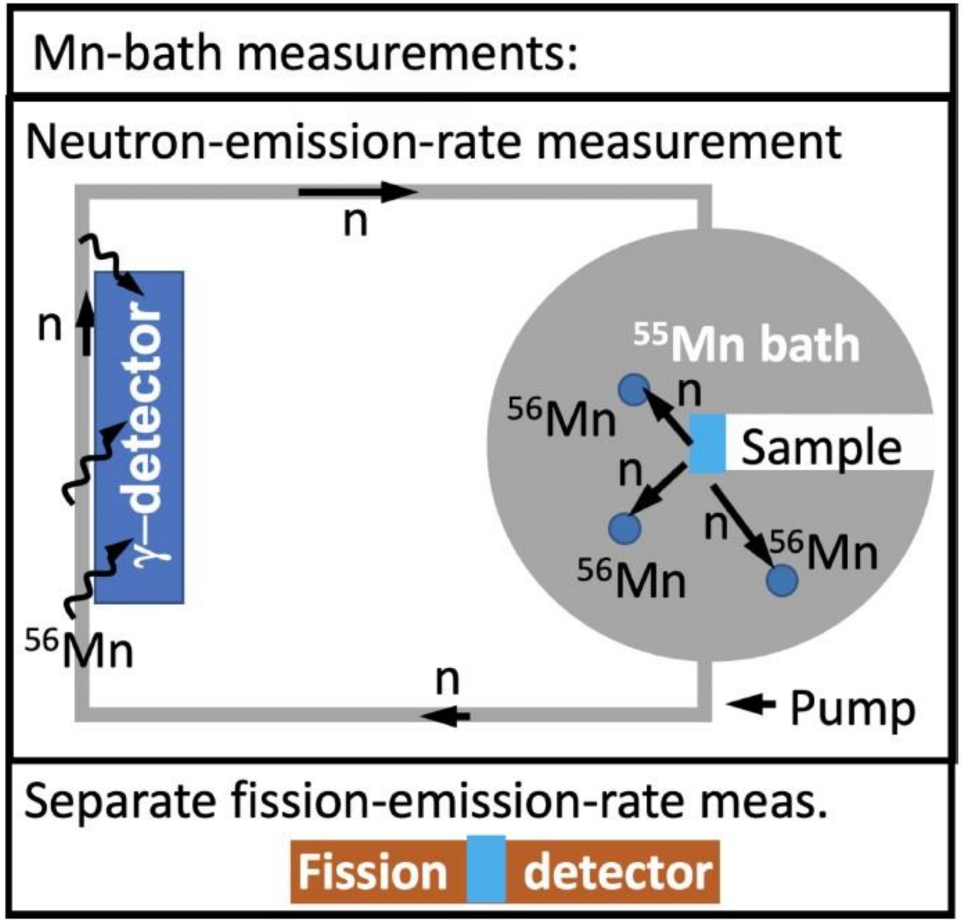
High resolution measurements started in the 50's

- Lots of high-quality data from various experimental techniques (USA, USSR, Europe)
  - See Neudecker et al EPJN 9, 30 (2023) and references within
- Prompt or total neutron multiplicity measurements
- Delayed neutrons measured with different experimental approaches
  - Neutron emission after beta emission .. Different time scale (seconds to minutes)
  - Not discussed here
- Experimental approaches related to the fission ”context”
  - Some techniques are suitable for spontaneous fission measurements only
  - Most are designed for neutron induced fission experiments

Mn-bath approaches

Experimental approach used for spontaneous fission nubar measurements

- Activation measurement
- 2-step method
  - Spontaneous fission rate with a fission detector
  - Activation of ^{55}Mn from fission neutrons
- Sample immersed into a Mn salt bath
- The salt is pumped out toward a gamma detector
  - ^{56}Mn production is counted
  - Proportional to the neutron count in the bath
- Exotic approach independent from classical
  - Uncorrelated data

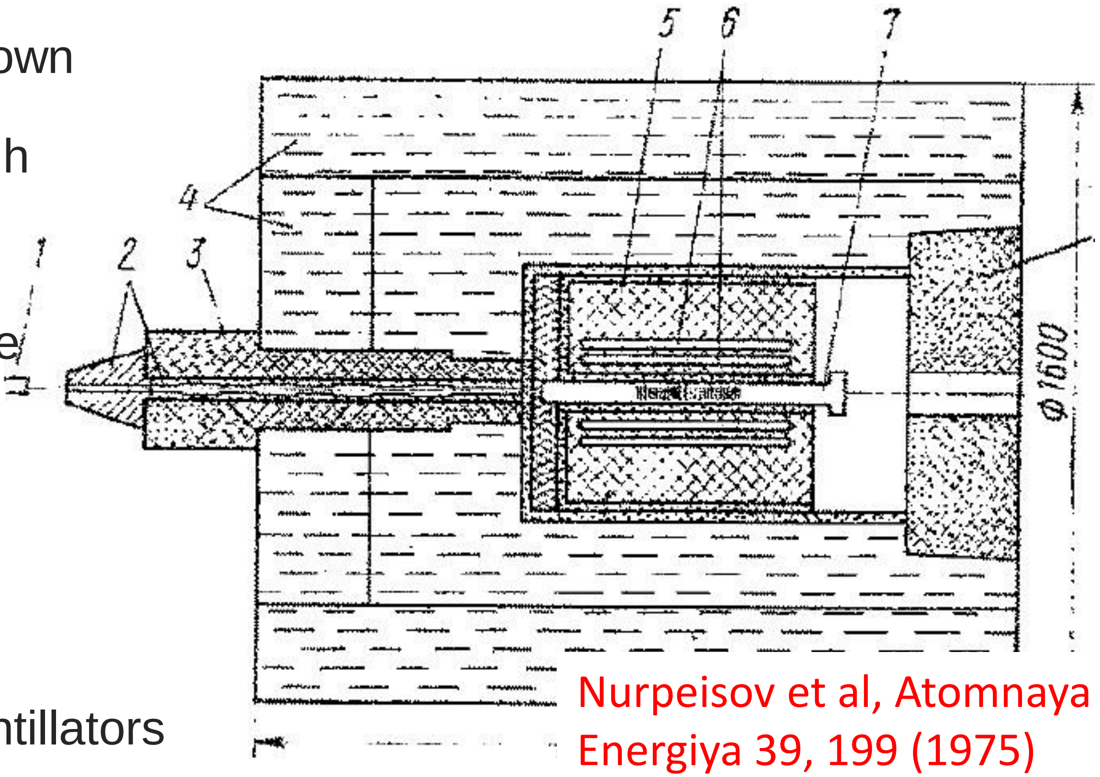


From Neudecker et al EPJN 9, 30 (2023)

Direct neutron detection techniques

Suitable for both spontaneous and neutron-induced fission measurements

- Monoenergetic neutron beam make it though the whole set up
- Fission are induced and tagged, neutron are detected within a coincidence window
- Most efficient way to detect neutrons is to slow them down
  - Neutron energy reduced from MeV to sub-eV through elastic scattering in hydrogen rich material
- After slowing-down, neutron induces a radiative capture in a suitable material
  - Here : slowing down in Polyethylene blocks
  - Capture in ^{3}He counters (exotic)
  - Largely independant from experiment with liquid scintillators

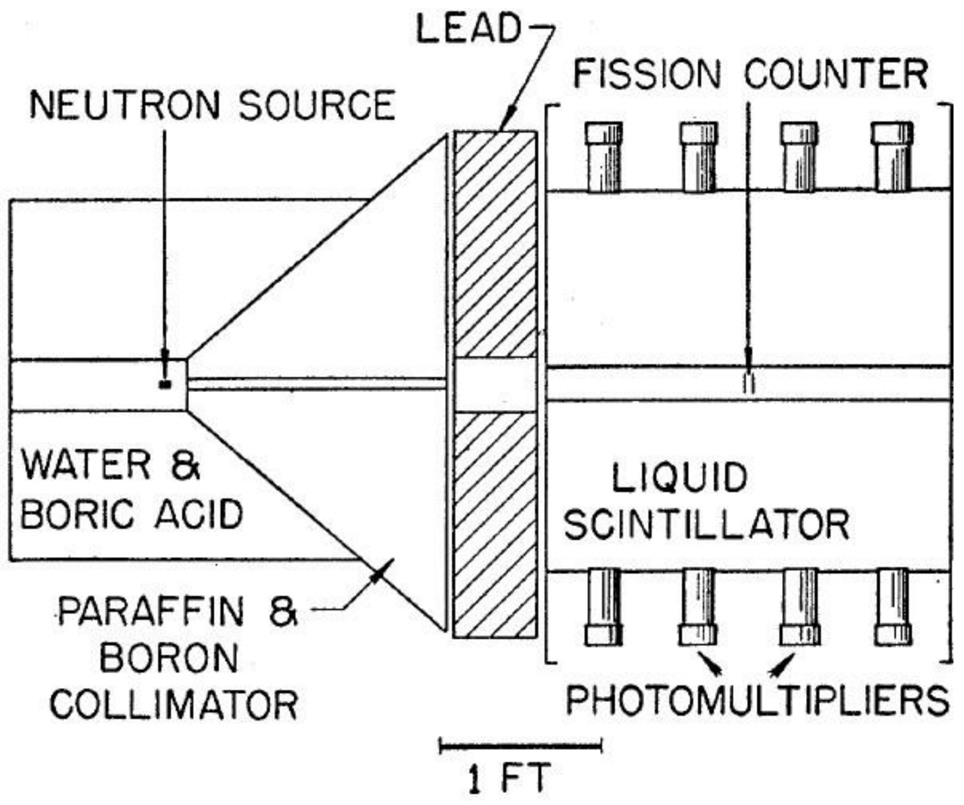


Nurpeisov et al, Atomnaya Energiya 39, 199 (1975)

Direct neutron detection techniques (2)

Most experiments use loaded liquid scintillator tanks

- Monoenergetic neutron beam make it though the whole set up
- Fissions are induced in a FC, neutron are detected within
  - a well chosen coincidence window
- The liquid scintillator acts as a moderator
  - Organic scintillators are hydrogen-rich
- The neutrons are eventually captured in a doping material
  - Dissolved in the scintillator
  - High capture cross-sections
  - Large Q-value => gamma multiplicity and energy
- Efficiency evaluated from a ^{252}Cf(sf) run

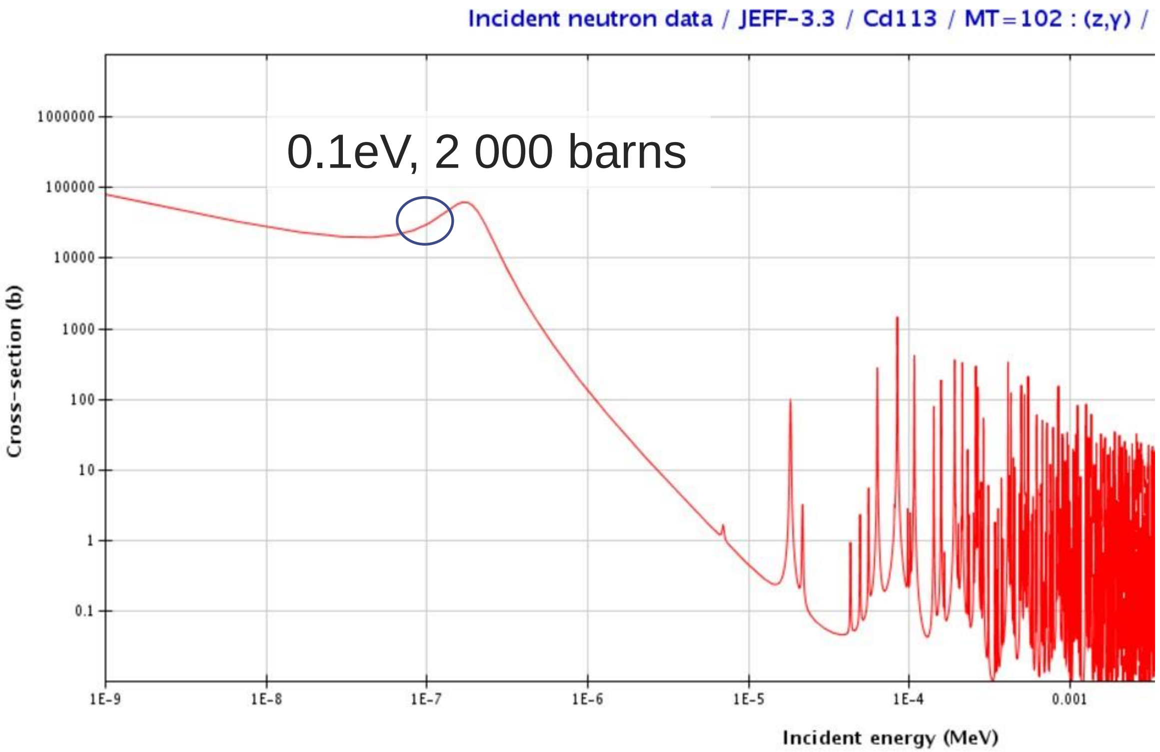


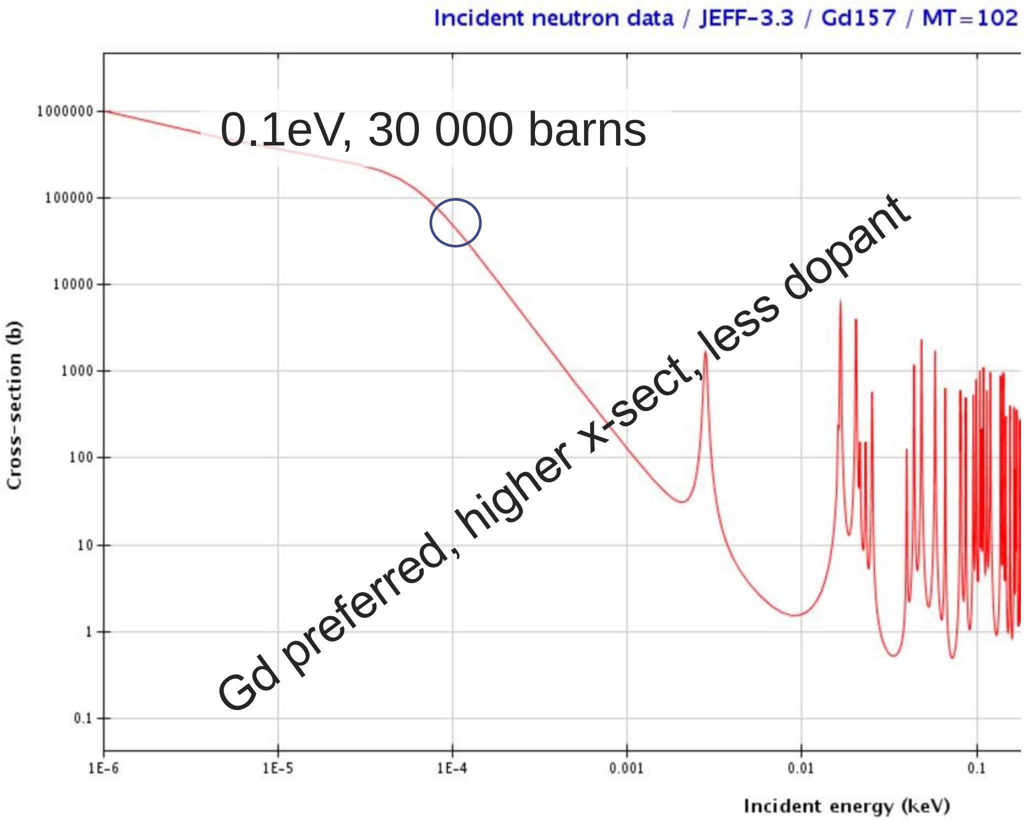
Diven et al Phys Rev 101-3 1012 (1956)

Direct neutron detection techniques (3)

Doping element choice

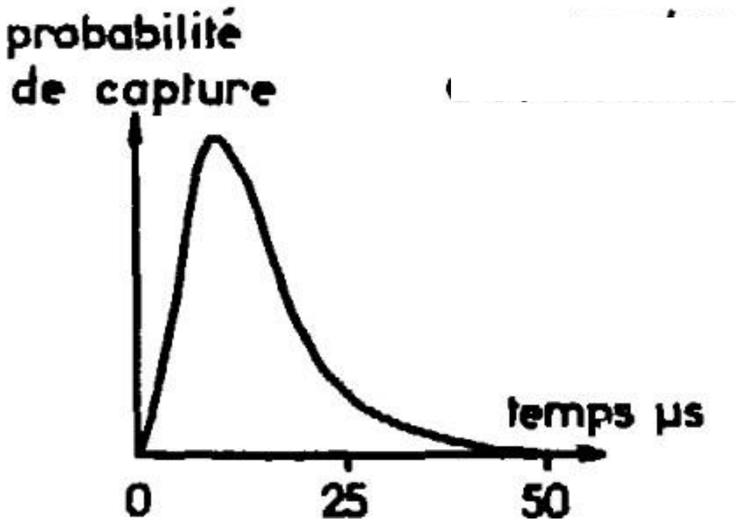
- Cadmium and gadolinium are classical choices
- 8 to 9 MeV gammas emitted by the neutron capture





Doped-Liquid scintillator method

- Incredibly efficicent detector
  - The neutron capture in Gd is clearly seen by photomultipliers
  - Typically 80 to 90% efficiency (fission neutrons)
- Neutron capture kinematics is relatively slow
  - Onset of capture : 3-5 us
  - Total capture time as long as 40 to 100 us
    - Doping type and concentration dependent
- Counting time is of 10s of us
  - Noise sensitive detector
  - All low energy neutron coming into the detector are measured
  - Refined background substraction technique needed



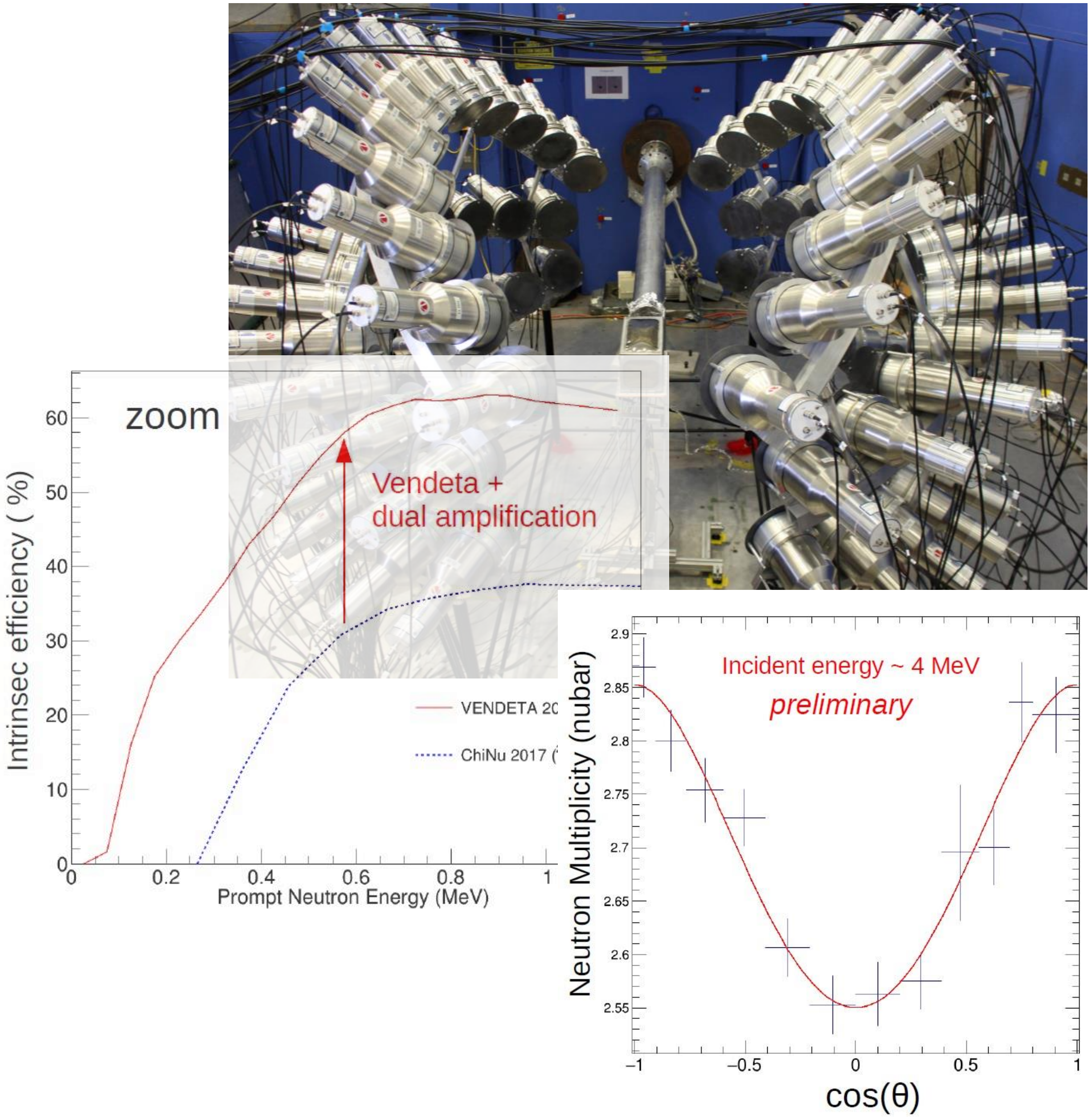
Doped-Liquid scintillator method

- Background minimization techniques
  - Low neutron beam intensity (background prop to the beam intensity)
- Stack of actinide targets to ensure a reasonable fission rate
  - Beam energy possibly degraded along the fission detector
- Caveat : actinide fission neutrons can be different from ^{252}Cf(sf) neutrons
  - PFNS
  - Angular distribution (anisotopy and experimental cuts)
- Detection efficiency corrections
  - Small effects (sub percent)
- New neutron detector derived from that approach: SCONE
  - Solid state scintillator
  - No vessel

PFNS measurement based experimental approach

From our PFNS experiments, we infer the nubar

- Largely different approch
- Partially independent from classical experiments
- No slowing down
- Neutrons detected ”as emitted”
- Double differential distribution evaluated
  - $d^2N/dEd\theta$
  - Explicit integration (vs implicit)
- Require the maximum energy and angular coverage
  - Driving force for the development of the vendeta array
  - Efficient in 100 keV to 14 MeV range
  - 12 polar angle from very forward to very backward
  - Very small energetic and angular extrapolation

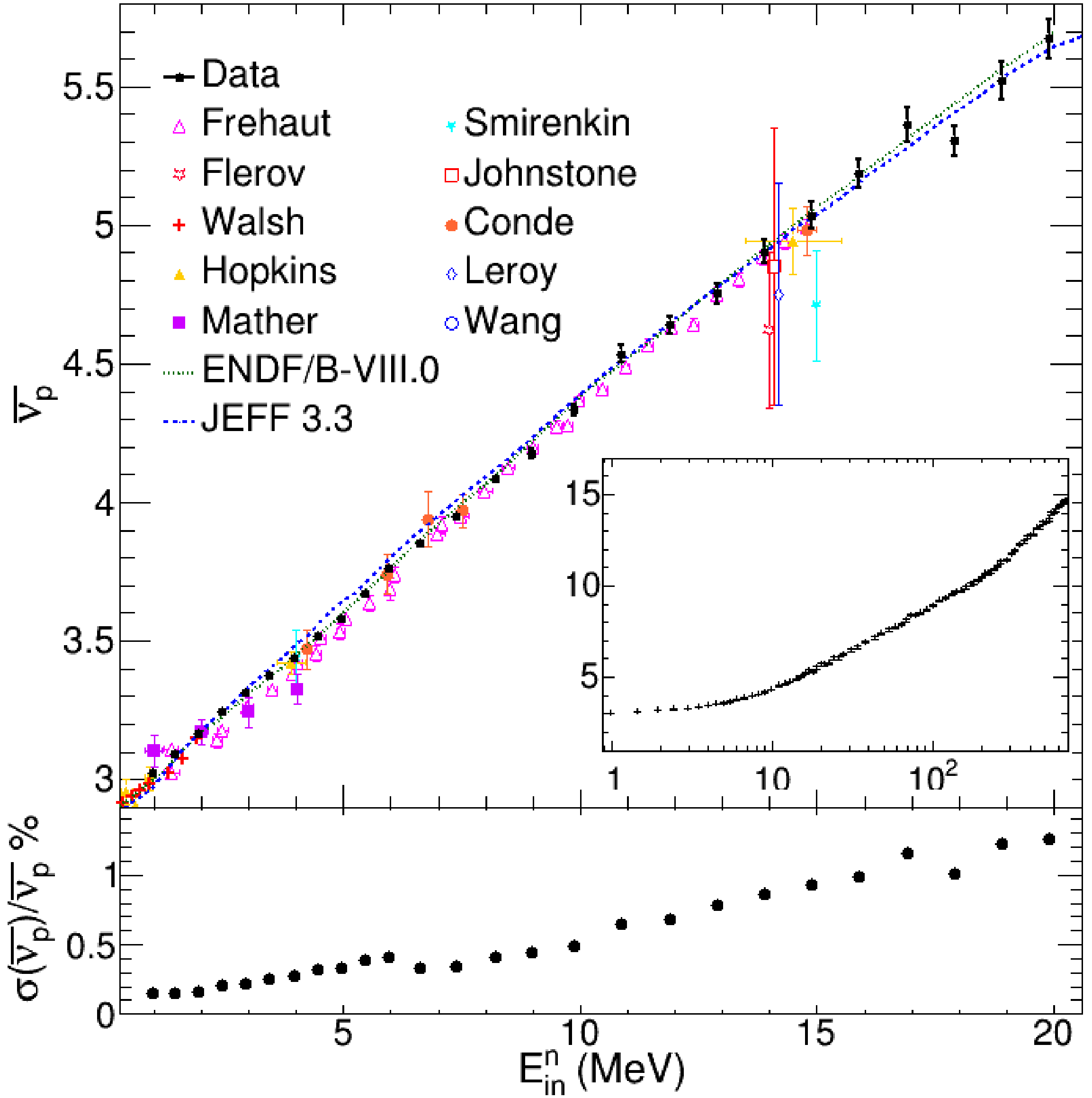


PFNS measurement based experimental approach

- No slowing down
  - Short counting gate duration (200ns)
- No sensitivity to thermal neutrons
  - Very limited background (few percents)
  - Monitored online
- Much lower detection efficiency
- Not suitable for very exotic fissioning nuclide
  - 10s of mg needed
- Strong neutron source needed (WNR)
- Efficiency calibration from a ^{252}Cf chamber
  - Data fully correlated to the ^{252}Cf nubar

Data for $^{239}Pu(n,f)$

- Data from the CEA Chi-Nu detector run in 2017
- Consistent data over [1;20 MeV]
- In agreement with previous measurements
  - Usually lower uncertainty
- Low uncertainty below 15 MeV
  - Statistics is lacking above
- Above 20 MeV, lower limit only
  - Some preequilibrium neutrons not accounted for
- Published excluding the $^{252}Cf(sf)$ nubar uncertainty



Marini et al Phys. Lett B835 13513 (2022)

Impact of the “efficiency” correction

- The ^{252}Cf run provides us with a detector efficiency for all 72 neutron detectors
  - Some neutrons are scattered and bounce back to the detectors
  - We evaluate an ”effective” efficiency
- How does this affect the nubar measurement
- Source of uncertainty : PFNS difference between 252Cf(sf) and studied actinide
- Full monte-Carlo simulation based on GEANT 4
  - Realistic geometry
  - Realistic spectra used (from the PFNS data) for all energy bins
- Impact evaluated for ^{235}U nubar, including the experimental cuts
  - Maximum deviation of 0.2% at 6 MeV, lower than 0.1% below 5.5 MeV

Conclusion

- New experimental approach for measuring nubar based on the PFNS measurement developed
- We profit from the high intensity neutron beam from WNR
- And the recent VENDETA array
- We could provide high accuracy results over the whole energy range
- Data largely independent from previous measurement
  - Excluding the ^{252}Cf nubar normalisation
- ^{239}Pu data (ChiNu detector array) published
- ^{235}U data (ChiNu detector array) final, to be published
- ^{238}U data (1st VENDETA experiment) to be finalized

3. Conclusion