Fission Experiments

Or: How I Learned to Stop Worrying and Learn to Love Fission

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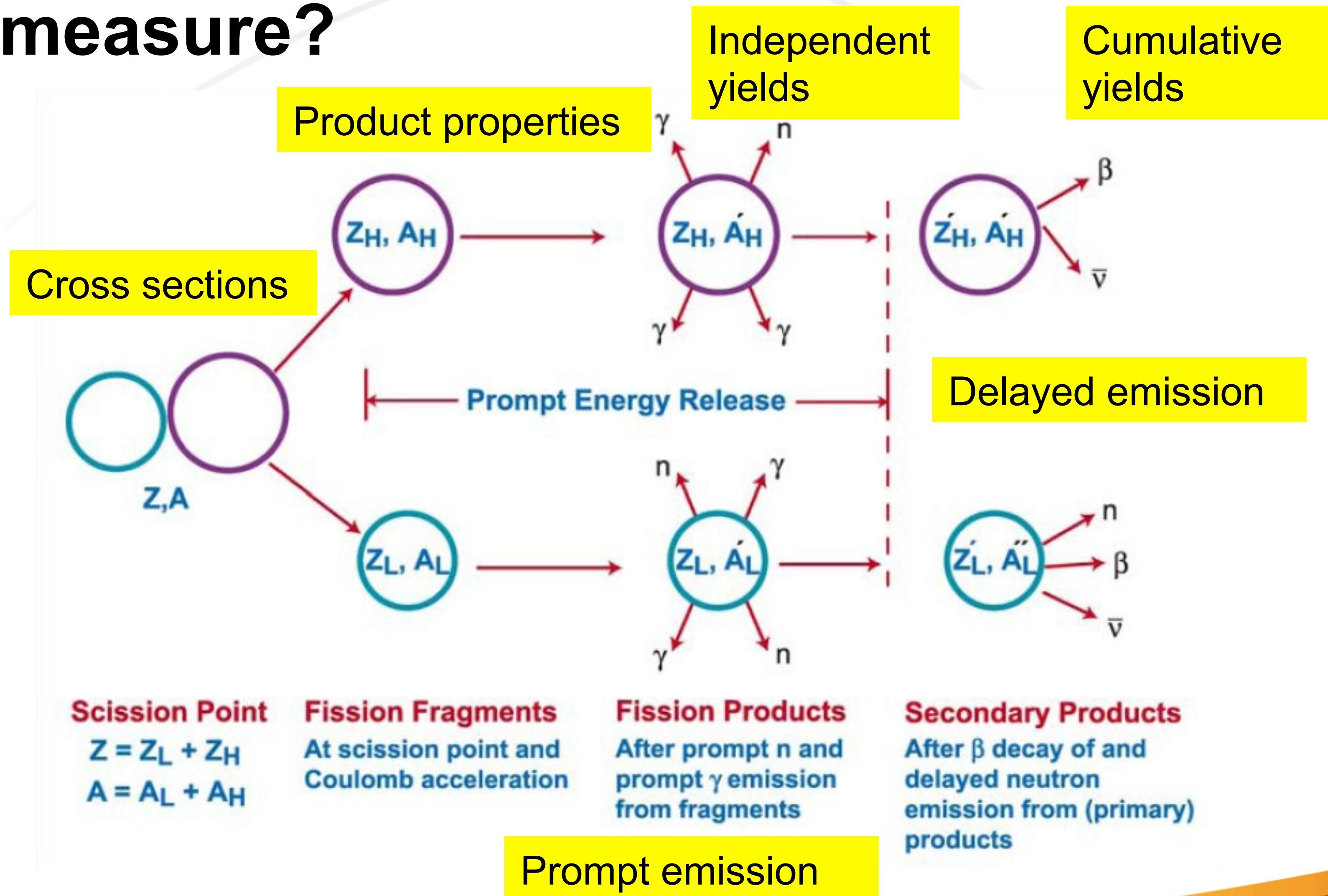
Outline

- Introduction
- Experimentally studied properties of fission
- Experimental facilities
- Detectors
- State of the art and future developments

Discovery of nuclear fission

- Ida Noddack suggested that uranium nuclei might break up under neutron bombardment in 1934.
- Hahn and Strassmann, 1938: Neutron irradiation of uranium produces barium.
- Communicates results to Lise Meitner, who is in Sweden as a war refugee.
- Lise Meitner and her nephew Otto Frisch explains the result as nuclear fission, makes estimate of energy release.
- Frisch uses uranium-lined ionization chamber and radium beryllium source to confirm fission. [Nature **143**, p. 276 (1939)]
- Hahn receives the Nobel price in chemistry in 1944 for the discovery of fission

Fission experiments – what can we measure?



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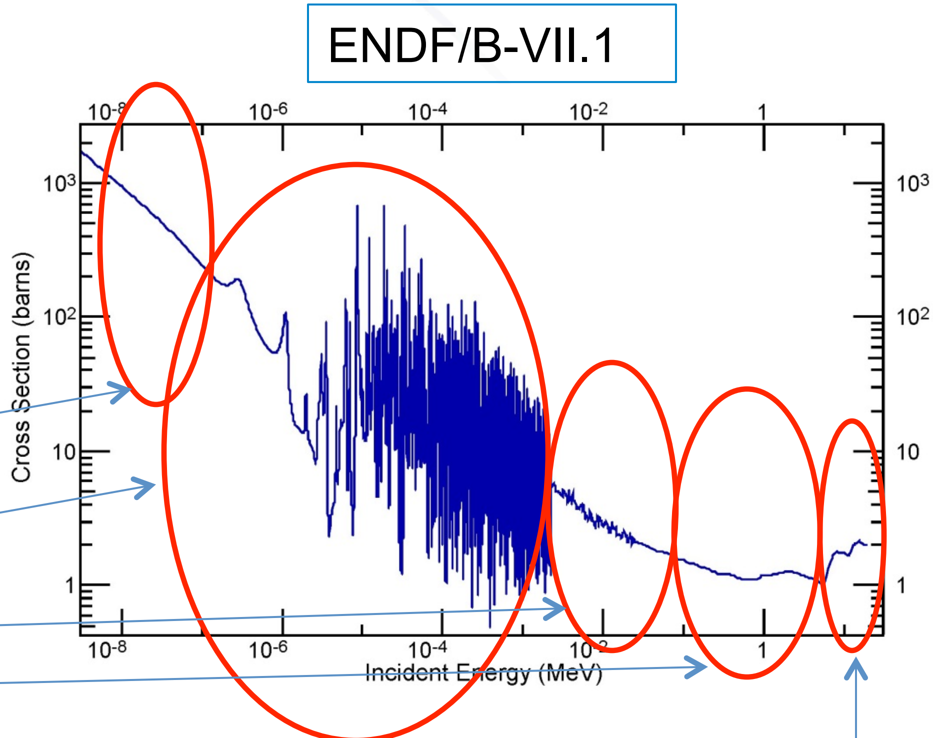
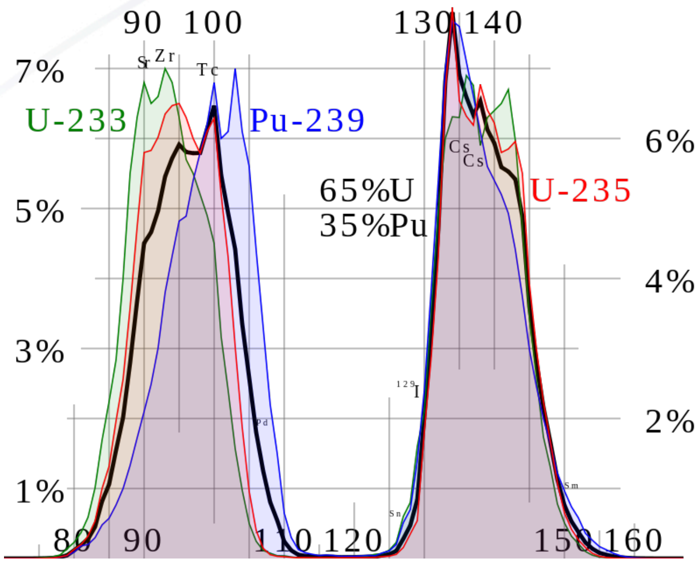
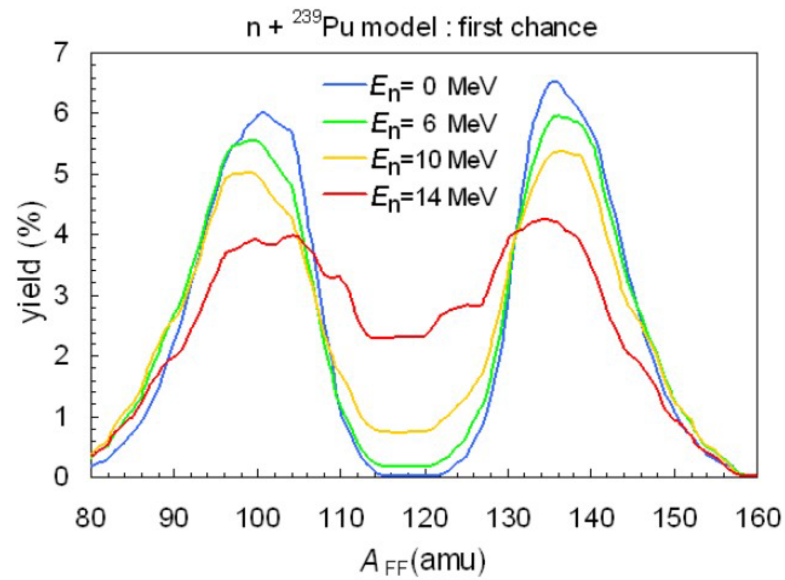
Cross sections

- Fissility of isotopes
  - **Fissile** = no threshold for neutron induced-fission
  - **Fissionable** = has threshold energy for neutron-induced fission
  - All the other isotopes that won't fission no matter what
- Neutron energy regions
  - Thermal
  - Resonance region
  - Unresolved resonance region
  - Fast region
  - Multiple-chance fission = fission following neutron emission



Fission fragment mass





J. Lestone, Nuclear Data Sheets **112**, 3120 (2011)

- Actinides generally exhibit asymmetric mass distributions, with small symmetric component
- Heavy peak about the same for all actinides, light peak shifts to make up for difference in compound system mass
- Relative contribution from symmetric fission increases with increasing excitation energy

Fission fragment charge

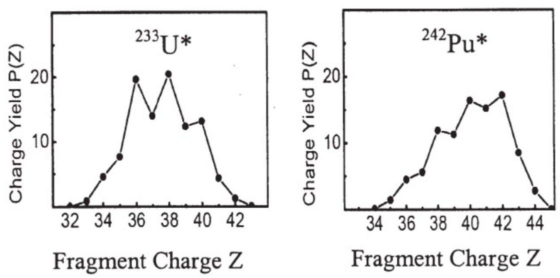


Fig. 1: Charge distribution in (n_{th},f) of ^{232}U and ^{239}Pu

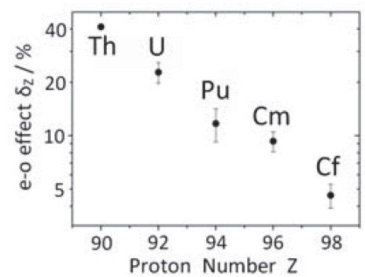


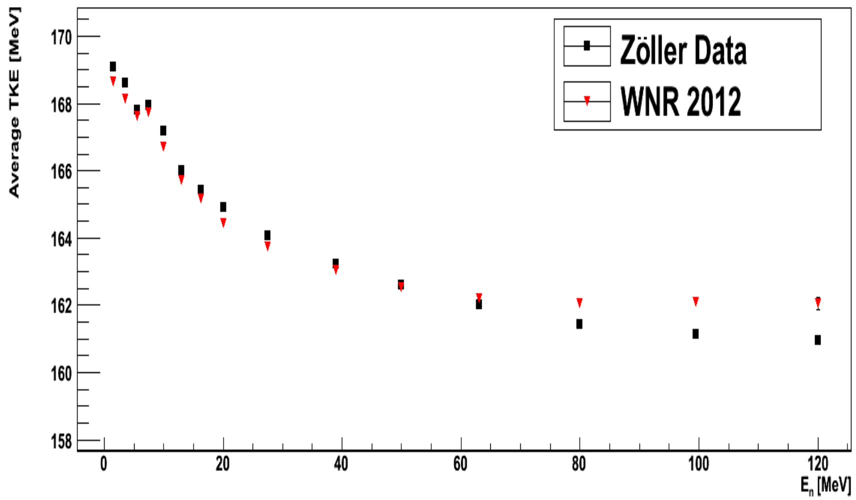
Fig. 2: Even-odd effect δ_Z vs Z of CN nucleus

F. Gönnenwein, Physics Procedia **47**, 107 (2013)

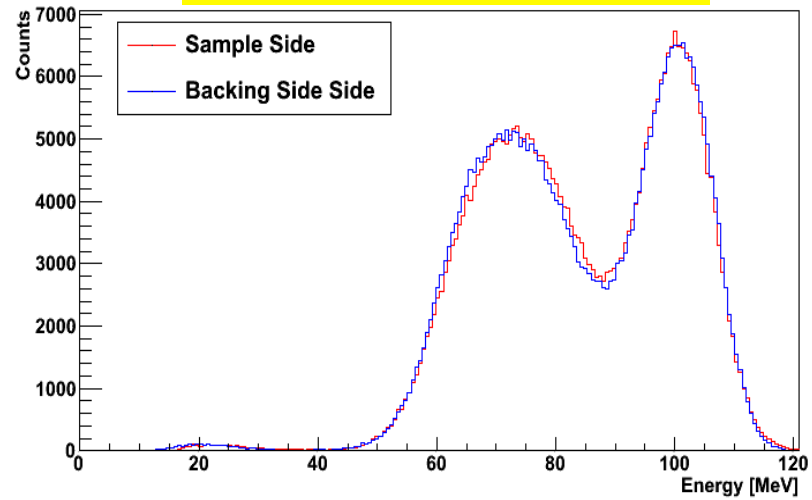
- Fission fragment charge distributions exhibit strong odd-even effects
- Effect decreases with increasing mass of the fissioning system

Fission fragments – kinetic energies

Total kinetic energy



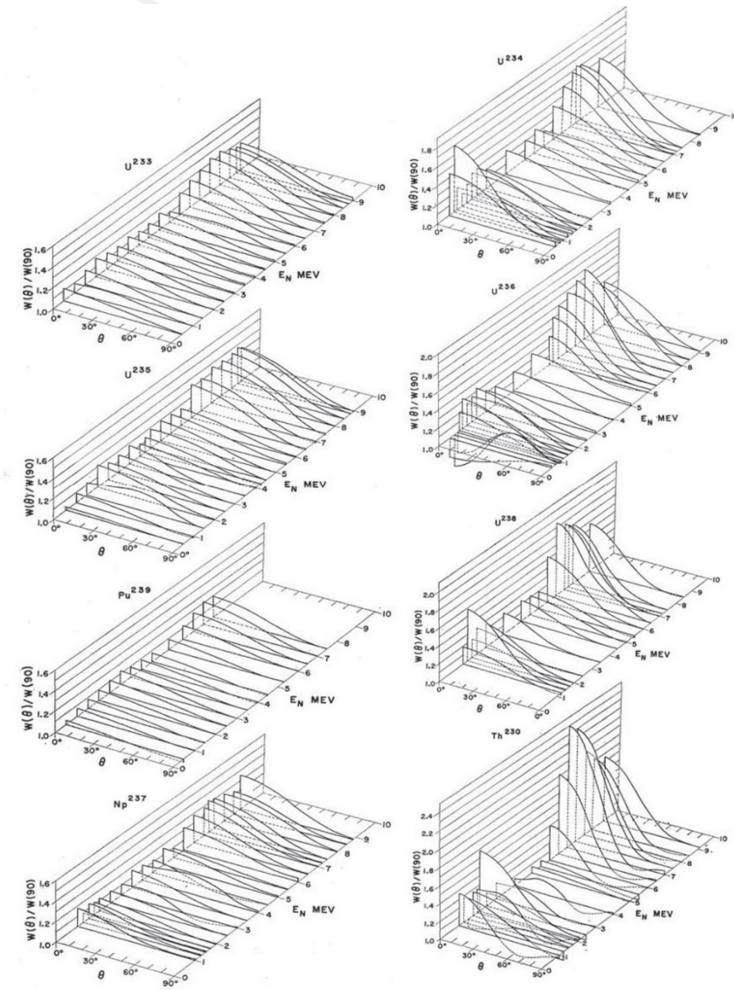
Fragment distributions



- Most energy released in fission is in the form of kinetic energy of the fission fragments
- Total kinetic energy (TKE) release is about 160-180 MeV (on average)
  - Decreases with increasing incident neutron energy – more energy goes to excitation of fragments
  - TKE distribution have a FWHM of about 25 MeV
- Light fragment has more narrow distribution of kinetic energies than heavy fragment

Fission fragment angular distributions

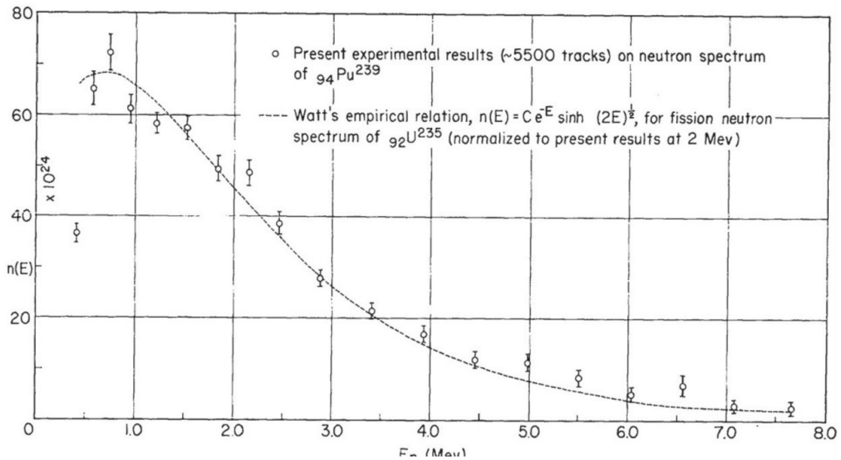
- Fission fragments angular distributions are generally not isotropic in neutron-induced fission
- Experimental data often presented at anisotropy (w(0)/w(90))
- Detailed measurements in 1950s of several isotopes, 0-10 MeV



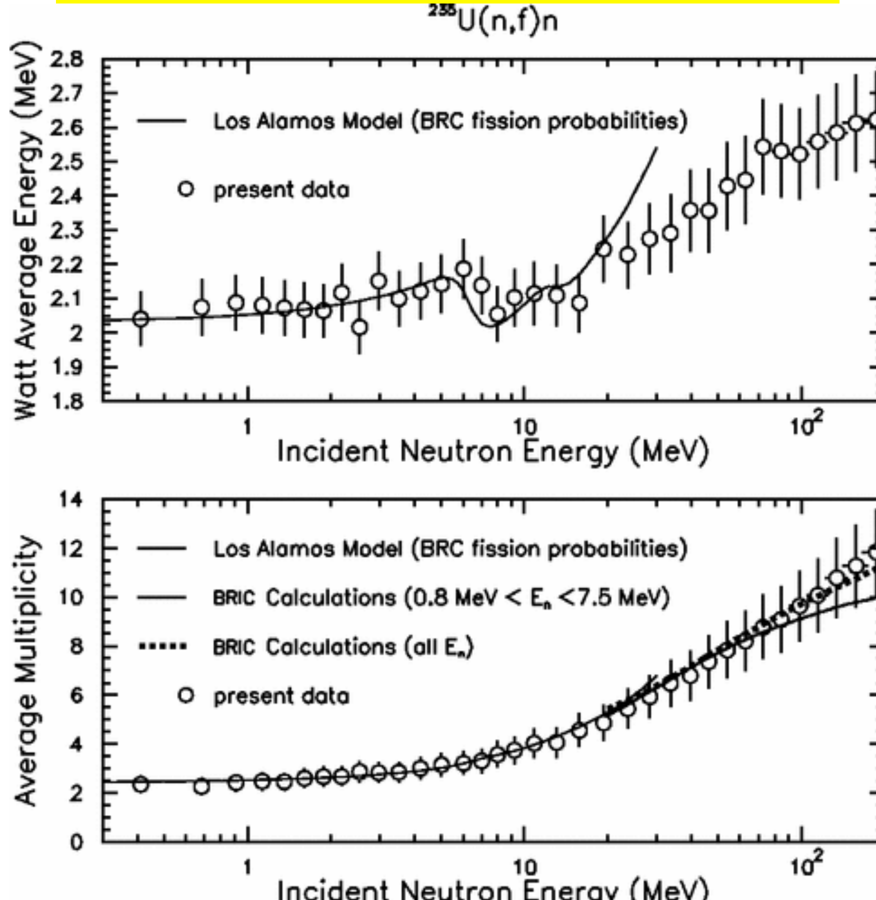
J. E. Simmons et al., Phys. Rev. 120, 198 (1960)

Prompt Neutrons

N. Nereson, Los Alamos Sci. Lab. Report #LA-1078 (1950)



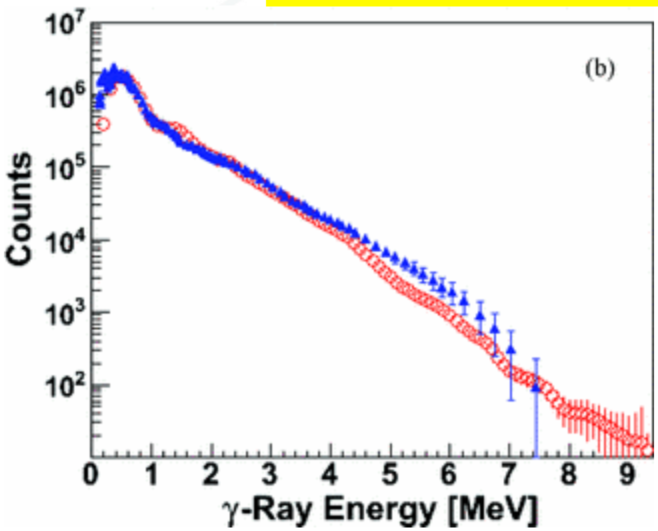
T. Ethvignot et al., Phys. Rev. Lett. **94**, 31 (2005)

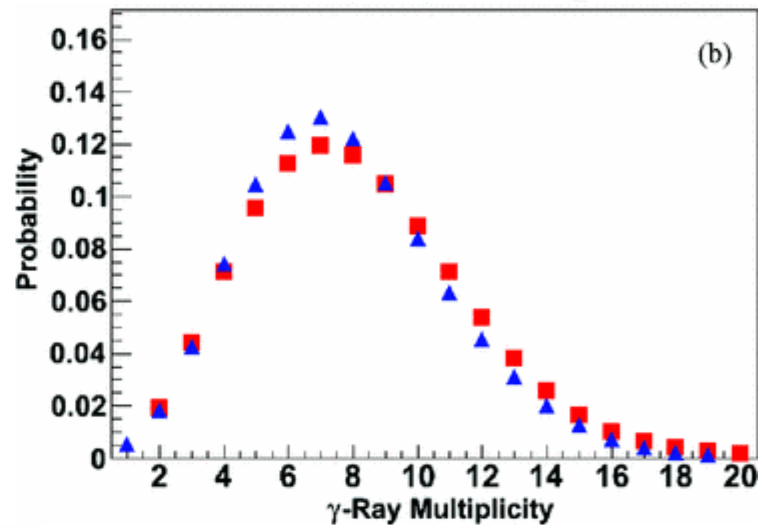


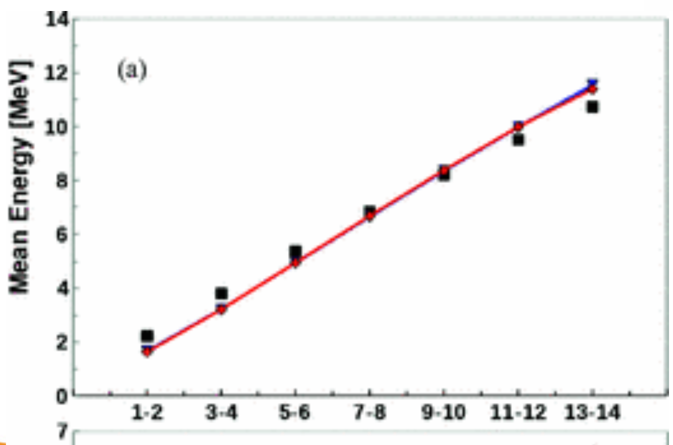
- Average number of prompt neutron emitted = 2.5
- Average energy = 2 MeV
- Energy distribution well described by Watt function

Prompt gamma rays

Chyzh et al., Physical Review C **85**, 021601 (2012)



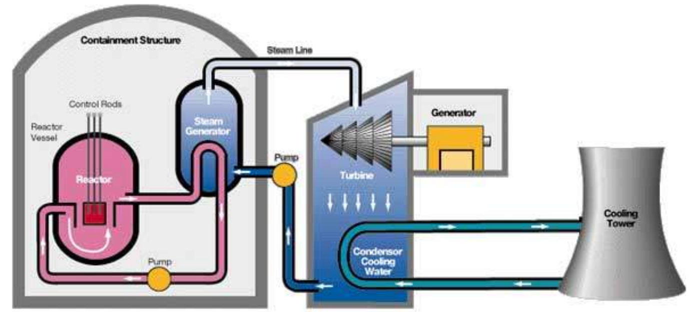


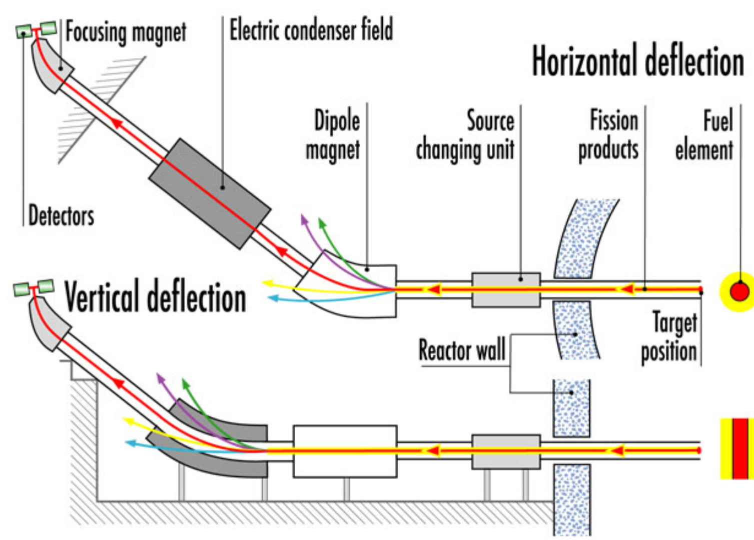


- Gamma ray multiplicity is high in fission, 7-8 on average
- Most individual gamma rays are <1 MeV
- Average energy released per fission is about 6-7 MeV

Neutron facilities – reactors

- Reactors are intense sources of thermal neutrons
  - ILL high-flux reactor produces 10^{15} neutron per cm^2 and second in the moderator region
- Some experiments can only be performed at reactors
  - The Lohengrin fission product spectrometer provides excellent data, but low efficiency require high fission rates
- Disadvantage of reactor experiments is that we often want to study changes in the fission process as a function of excitation energy





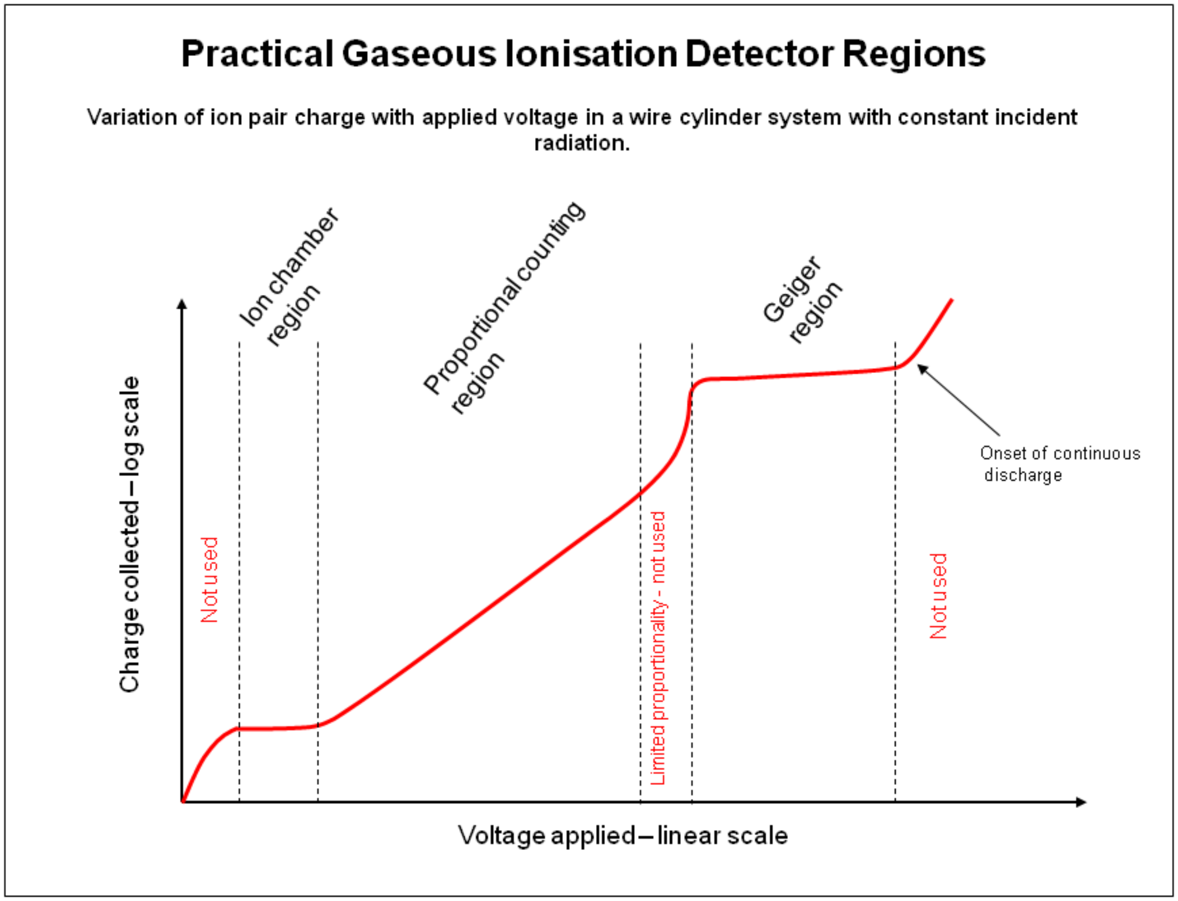
Neutron facilities – mono-energetic

- Mono-energetic neutrons can be made through several reactions
  - Li(p,n)
  - ^{2}H(d,n)^{3}He
  - ^{3}H(p,n)^{3}He
  - ^{3}H(d,n)^{4}He
- Van de Graaff accelerators are often used to produce mono-energetic neutrons
  - Example: 7 MV VdG at IRMM, Geel, Belgium
    - Produces mono-energetic neutron beams from 0.1 to 24 MeV
- Other accelerators, such as cyclotrons, are also used to produce mono-energetic neutrons
  - Example: The Svedberg Laboratory, Uppsala Univ., Sweden
    - High energy mono-energetic neutrons made through Li(p,n)
    - Neutron energies are 0 – 200 MeV

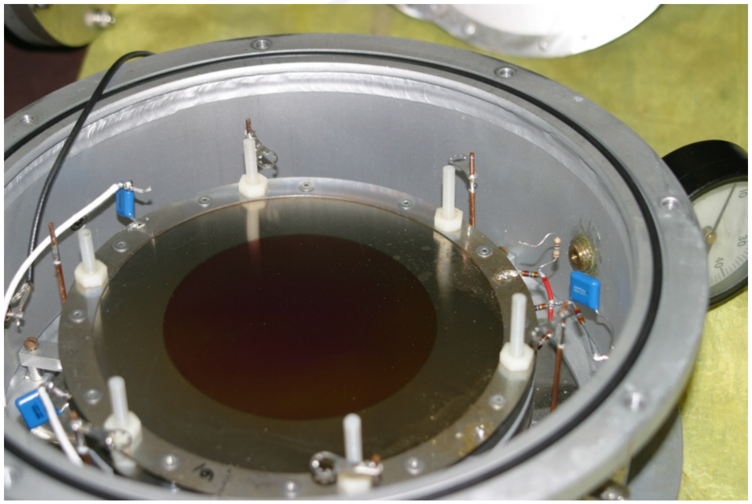
Neutron facilities – time-of-flight

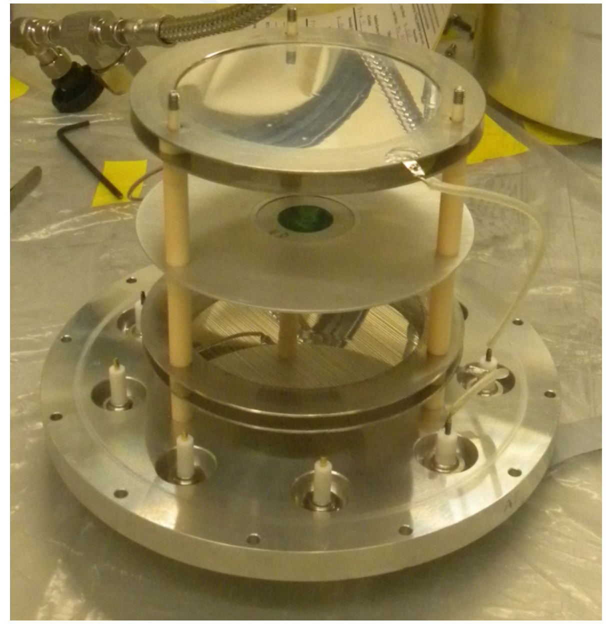
- White spectrum of neutrons is produce by pulsed beam
- Energy of neutrons are determined by measuring the time-of-flight (TOF) over some flight path
- Electron beam facilities
  - GELINA
    - Linear electron accelerator, 100 MeV, 800 Hz repetition rate, 10 ns wide pulses
    - Uranium target: electron beam produces bremsstrahlung, photonuclear reactions make neutrons
    - Flight path lengths are 10, 30, 50, 60, 100, 200, 300 and 400 meters
- Spallation facilities
  - Neutrons produced when high energy ion beam hits high-Z material
  - Makes neutrons ranging from 0 to hundreds of MeV
  - LANSCE-WNR
    - 800 MeV proton beam on tungsten (wolfram) target
    - Flight pats 6 – 25 meters
    - 1.8 us repetition rate -> lower neutron energy limit is about 100 keV
  - N_TOF
    - 20 GeV proton beam hit lead target
    - 20 and 200 meter flight paths
    - 0.5 Hz repetition rate -> usable neutron spectrum for thermal to hundreds of MeV

Fragment detectors – gas



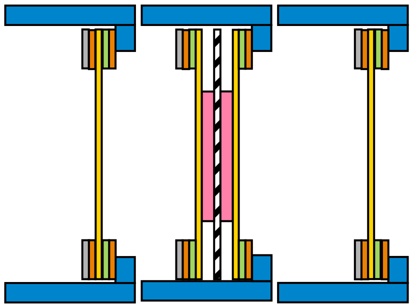
Fragment detectors – ion chambers

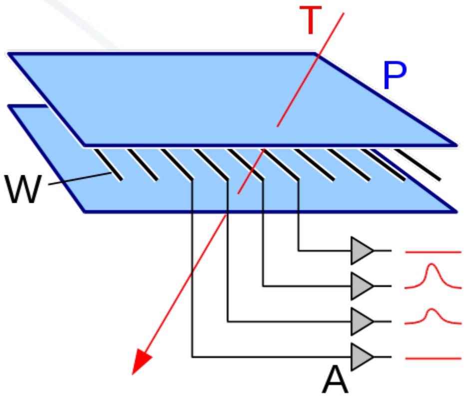




- Parallel plate ionization chambers
  - Signal proportional to energy and angle
  - Fragments don't range out
  - Good alpha particle to fission separation
- Bragg chamber (Frisch-gridded)
  - Anode shielded by grid
  - Signal directly proportional to energy, independent of angle
  - The grid signal can be used to measure particle emission angle

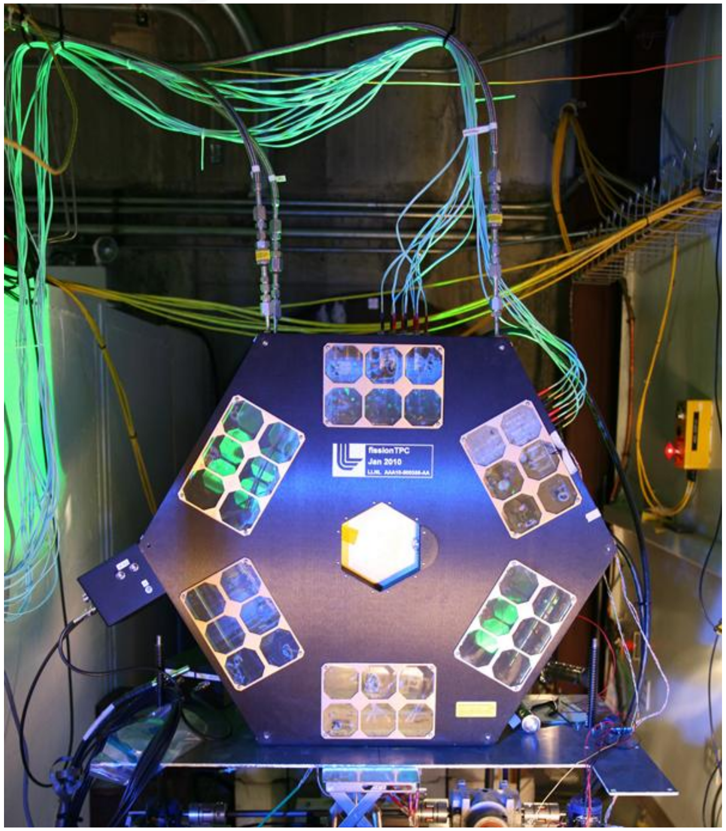
Fragment detectors – proportional counters

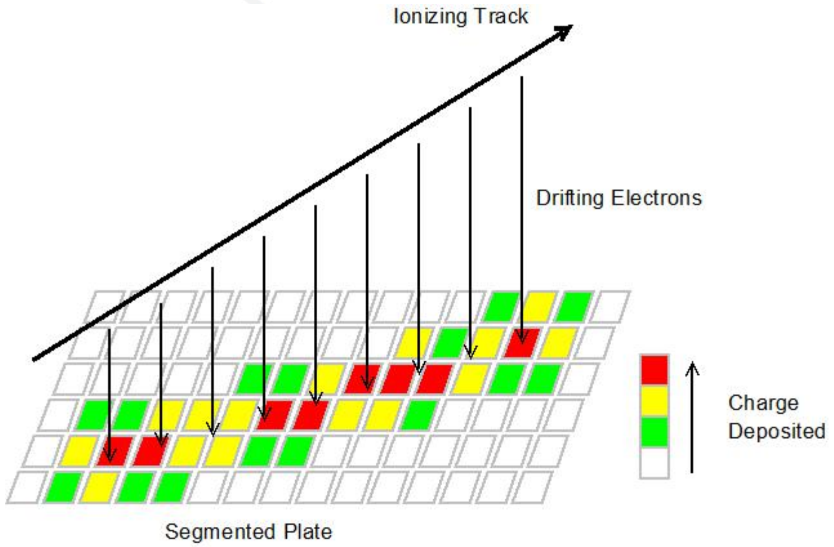




- Parallel Plate Avalanche Counter (PPAC)
  - 30% energy resolution for fission
  - Very fast timing response (<1ns)
- Muli-wire proportional chamber (MWPC)

Fragment detectors – TPC

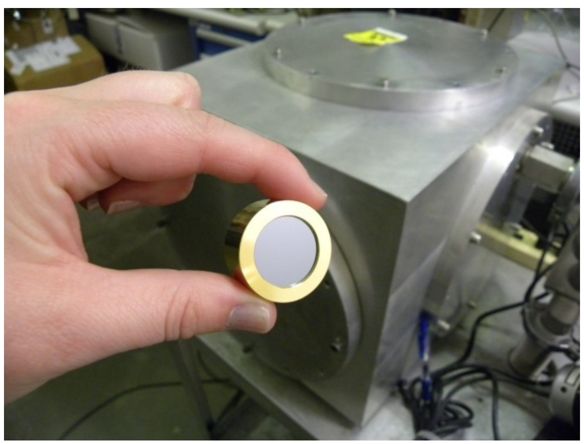




- Provides 3D particle tracking
- Energy resolution of few percent

Fragment detectors – Surface barrier

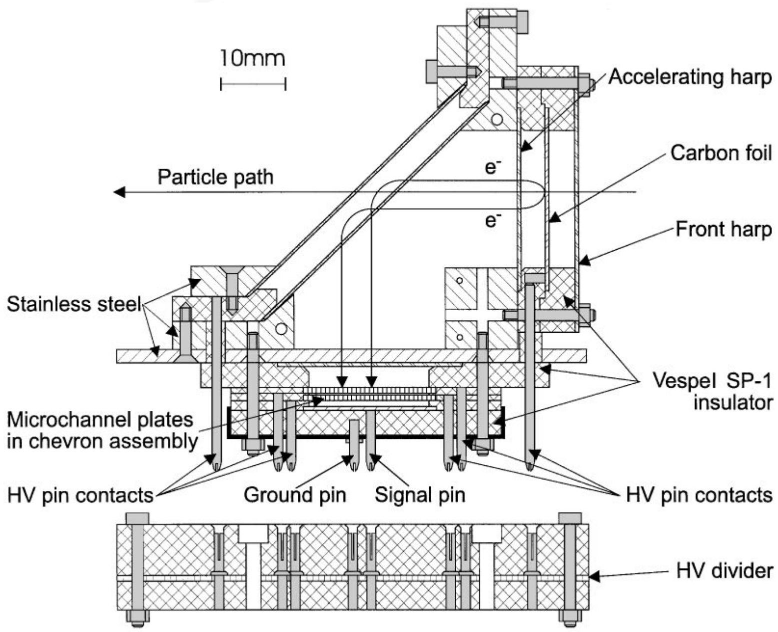
- Relative good energy resolution for fission fragments: 2%
- Higher pulse height defect compared to gas detectors
- Sometime segmented to provide position information
- Solar cells have been used to detect fission fragments – low cost fission trigger

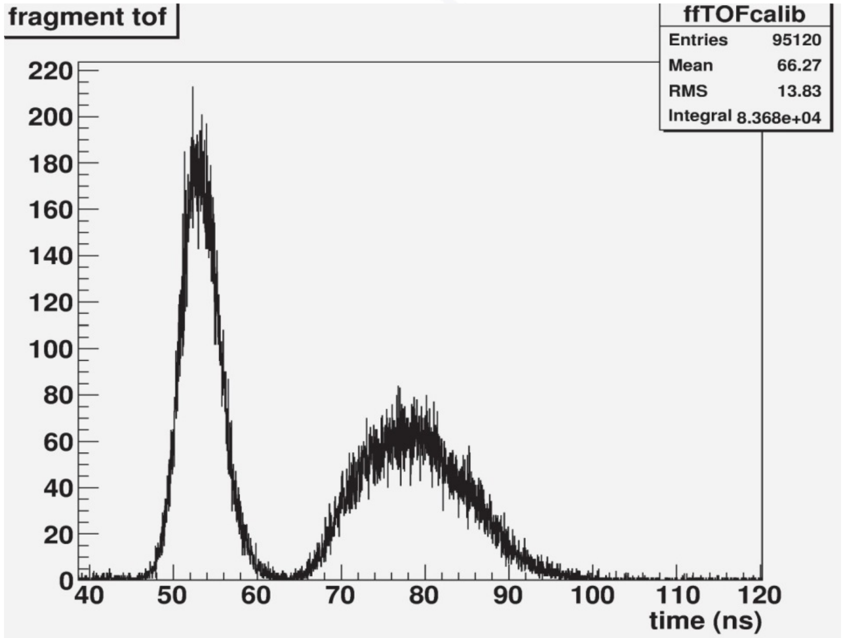


Passivated Implanted Planar Silicon (PIPS) Detector from Canberra

Fission fragment – Time-of-flight

A.V. Kuznetsov, Nucl. Inst. Meth. A 452, 525 (2000)

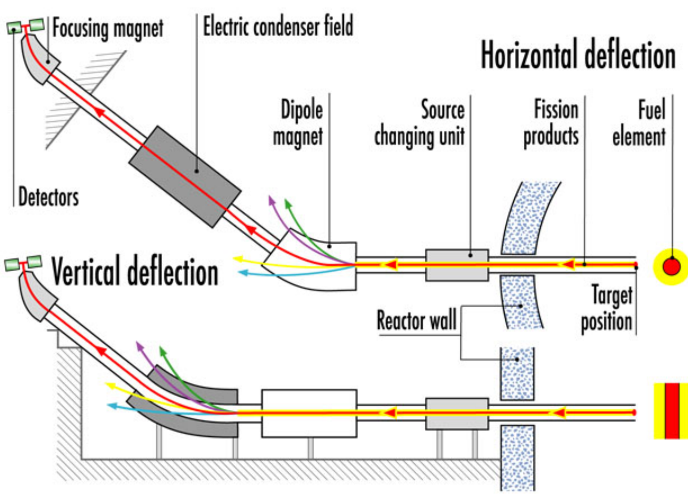


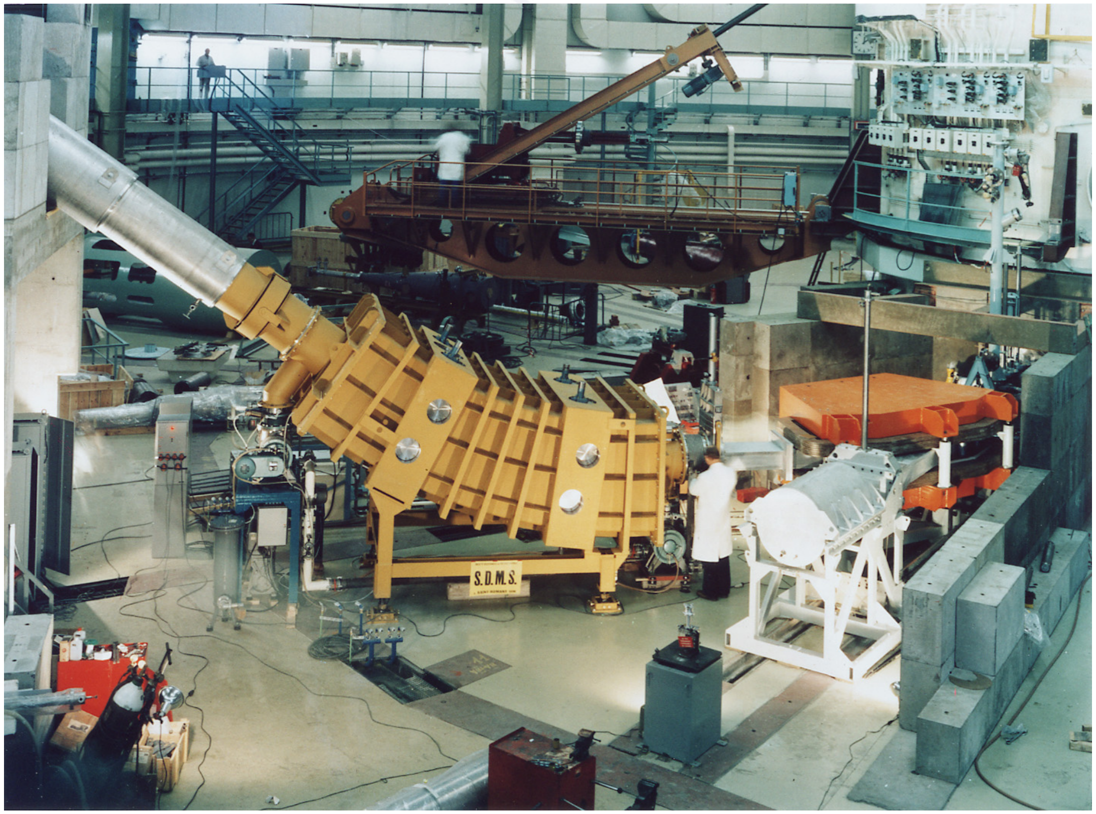


- Time signal can be obtained by detecting the secondary electrons produced when fission fragments pass through thin film
- Micro-channel plates (MCP) commonly used to detect secondary electrons due to fast timing response (0.2-2 ns rise time)

Mass separators

- Masses are selected using electromagnetic fields

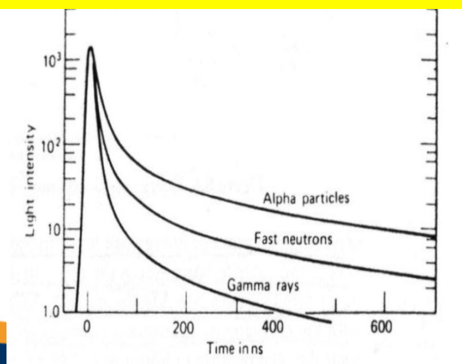




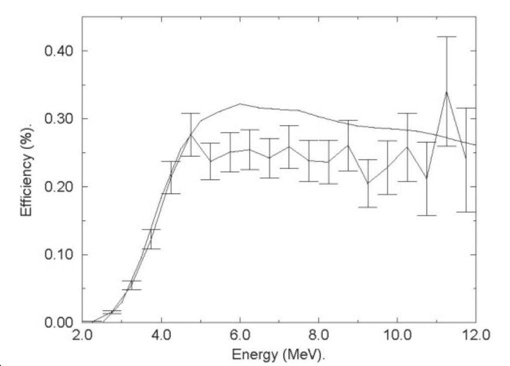
Neutron detectors – High Energy

- Plastic or liquid scintillators are used to detect fast neutrons
- Neutrons interacts with protons in the scintillating material
- Photons undergo Compton scattering on electrons
- The charged particles excite molecules in the scintillator, and they subsequently de-excite by emitting visible light
- The photons cases a cascade of electrons in the photomultiplier tube through the photo-electric effect
- Some scintillators, such as NE213, exhibit different signal decay times for neutrons and photons, which can be used to separated the two types pf radiation

NE213 response for different radiation types

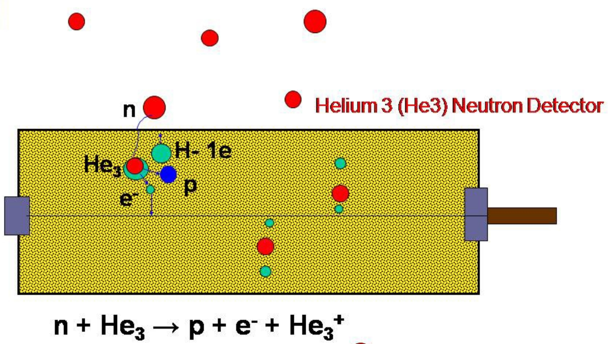


NE213 neutron detection efficiency



Neutron detectors – Low energy

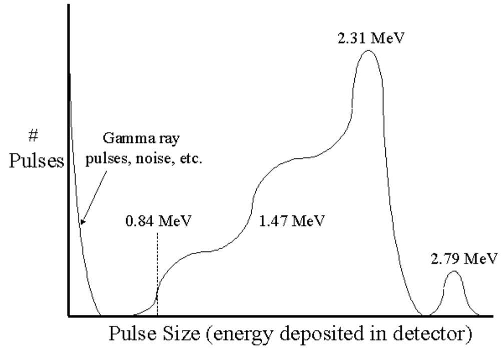
He-3 tubes



- Insensitive to gamma rays
- Highly efficient for thermal neutrons
- Shortage of ^3He is effecting availability

BF_3 chambers

- $^{10}B + n \rightarrow {}^7Li + \alpha$
- Q-values:
  - 2.79 MeV (Li in excited state)
  - 2.31 MeV (Li in ground state)



Li-glass

- $^6Li + n \rightarrow {}^3He + \alpha$
- Q-value: 4.78 MeV
- Have found new use in fibers

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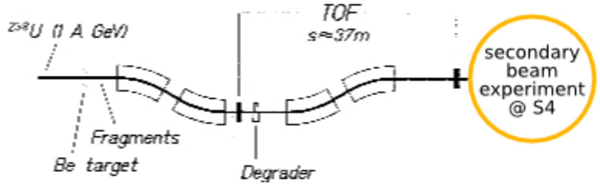
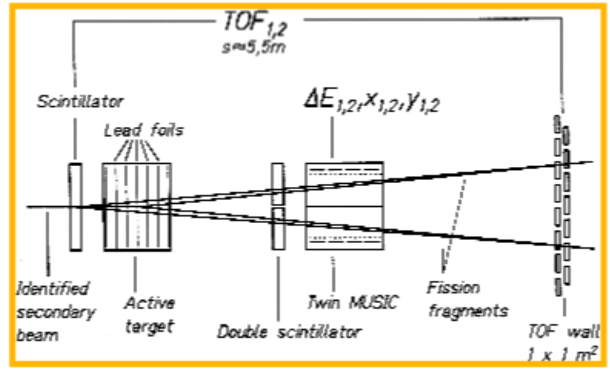
State of the art and future development

- Inverse kinematics
  - Excellent mass and charge resolution
  - GSI measurements
  - New spectrometer
  - FRIB
- 2E-2v instruments
  - Some masses and charges resolved
  - Cosi-fan-tuti (1980’s)
  - SPIDER, STEFF, VERDI, …
- Time projection chambers (TPC)
  - Tracking opens up new possibilities
  - New technology brings cost down
- New neutron facilities
  - N_Tof
  - LANSCE with pulse stacking

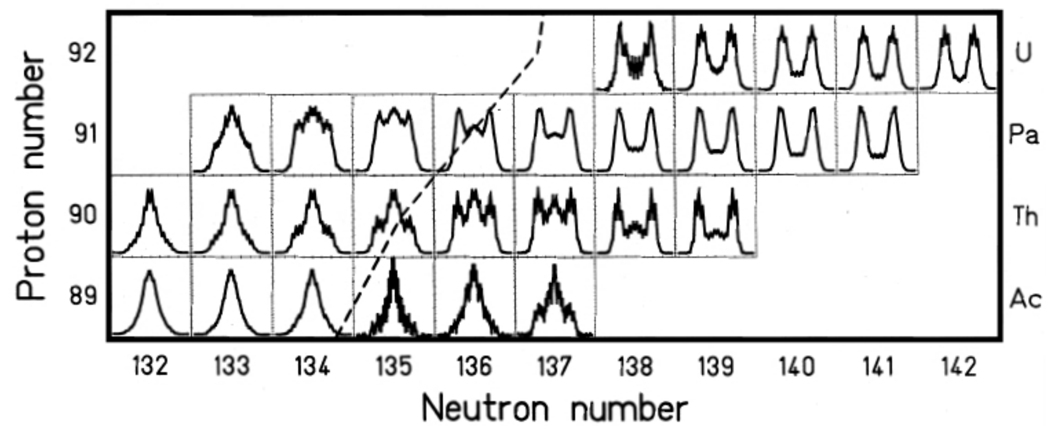
Inverse kinematics - GSI



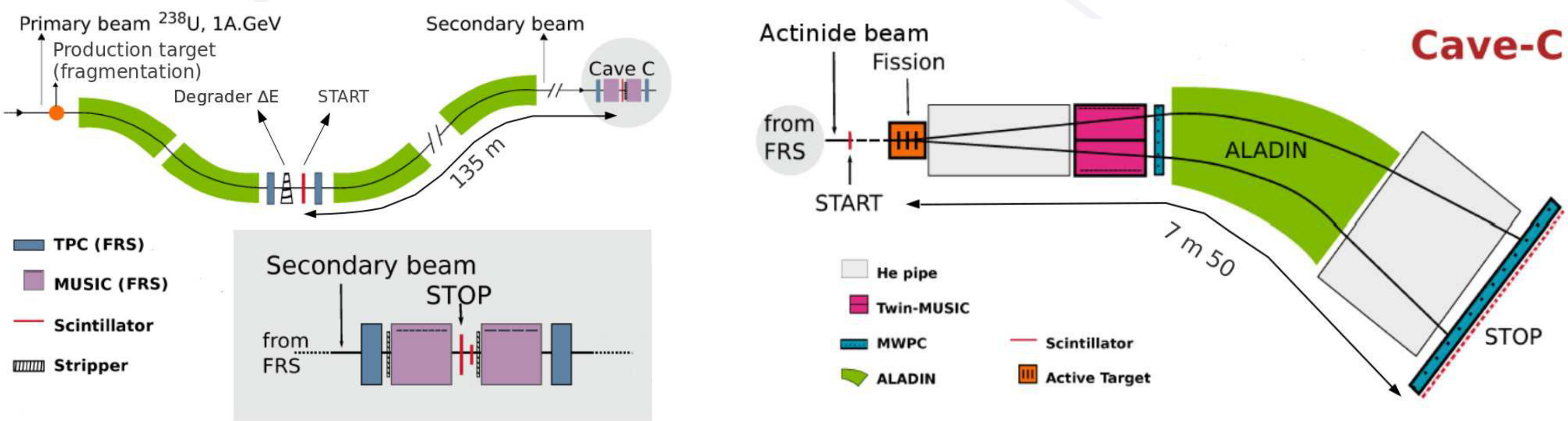


- 1 GeV U-238 beam fragmented on lead target
- Secondary fragment species identified in terms of A and Z
- Fragment beam hit second lead target, undergoing coulomb fission with 11 MeV excitation energy on average
- The fragments were identified in terms of Z using dE/E
- Gives access to large number of fissioning systems in one experiment
- Demonstrates the regions on the nuclear map where transition from asymmetric to symmetric fission occur

K.H. Schmidt et al., NPA **665**, 221 (2000)

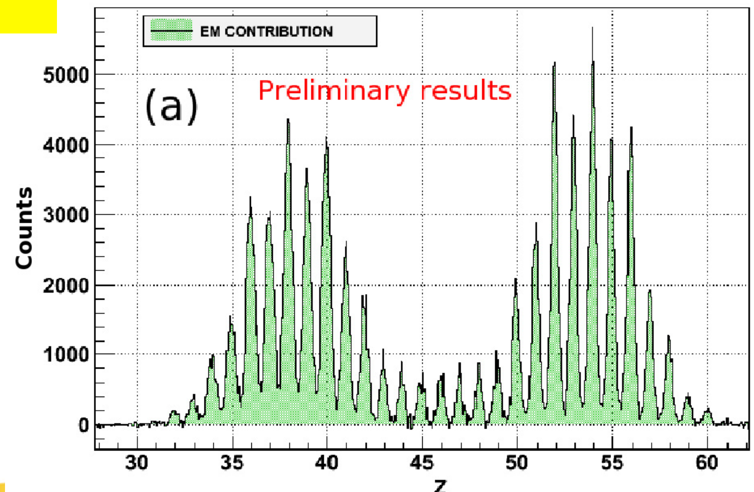


Inverse kinematics – SOFIA

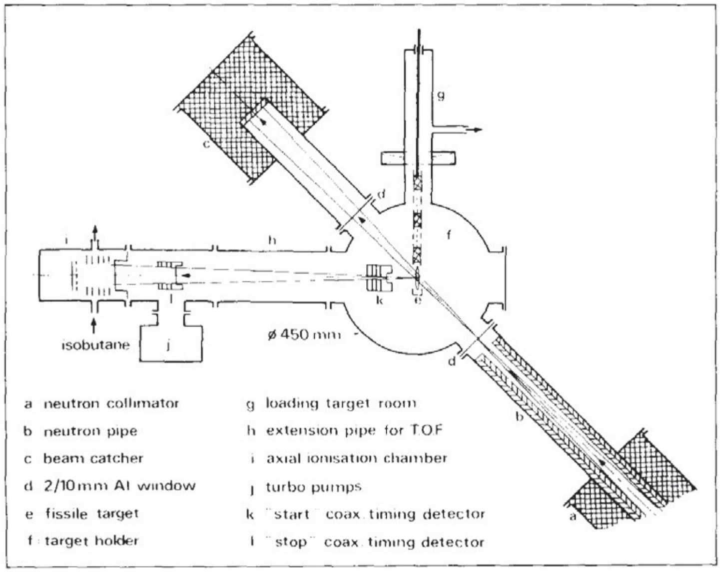


G. Boutoux et al., Physics Procedia **47**, 166 (2013)

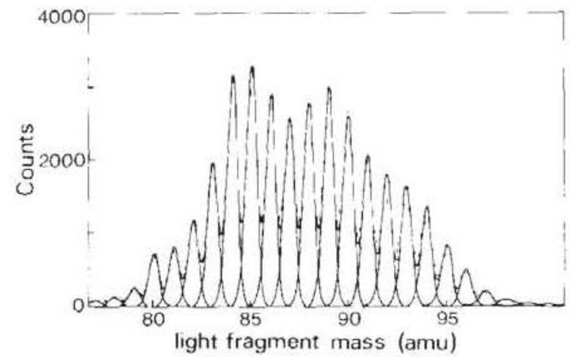
- Inverse kinematic with mass and charge identification of fission fragments



2E-2v – Cosi-fan-tutte



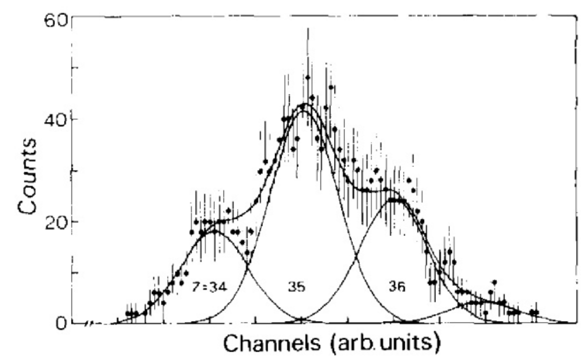
FPY measured with COSI-FAN-TUTTE



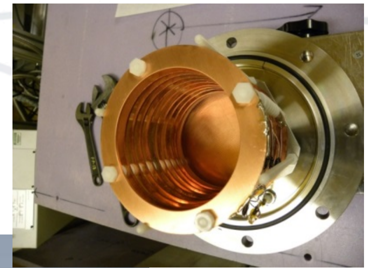
N. Boucheneb et al., NPA 502, 261 (1989)

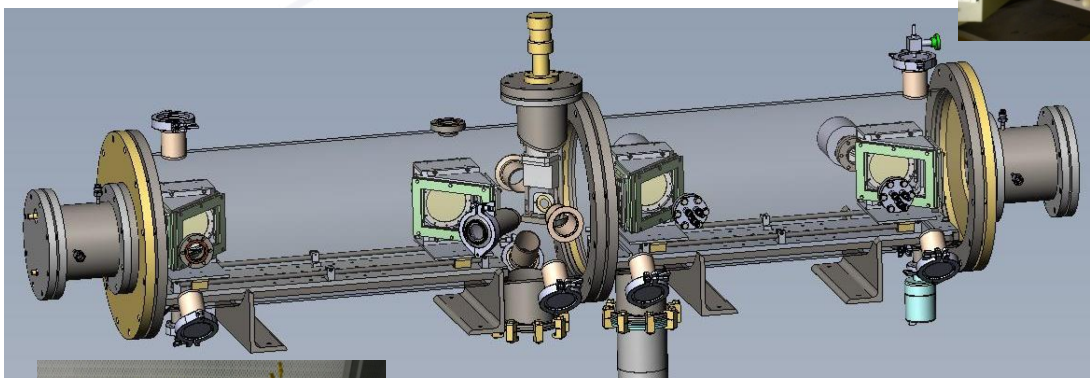
- Neutron induced fission
- Energy and velocity of fragments measured
- Light fragments resolved

Nuclear charge distribution for A=87

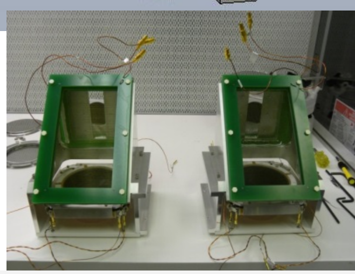


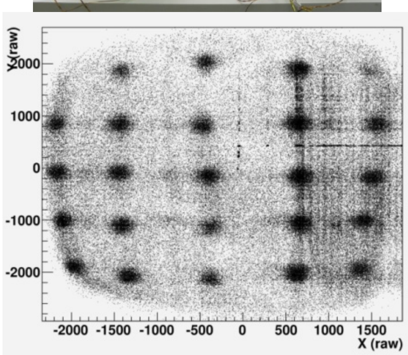
2E-2v - SPIDER

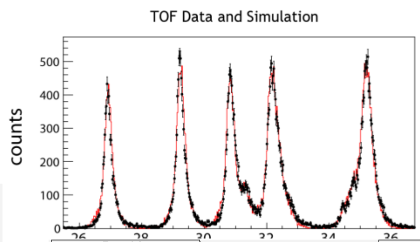


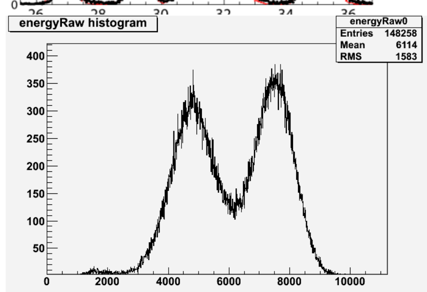


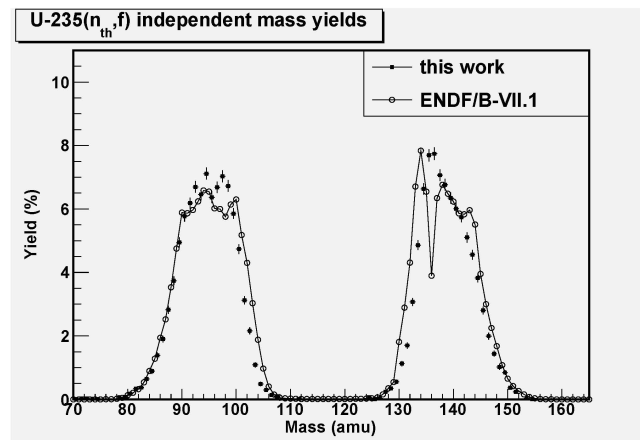
- Relative high efficiency (0.2%)
- Development ongoing to reduce energy straggling in windows











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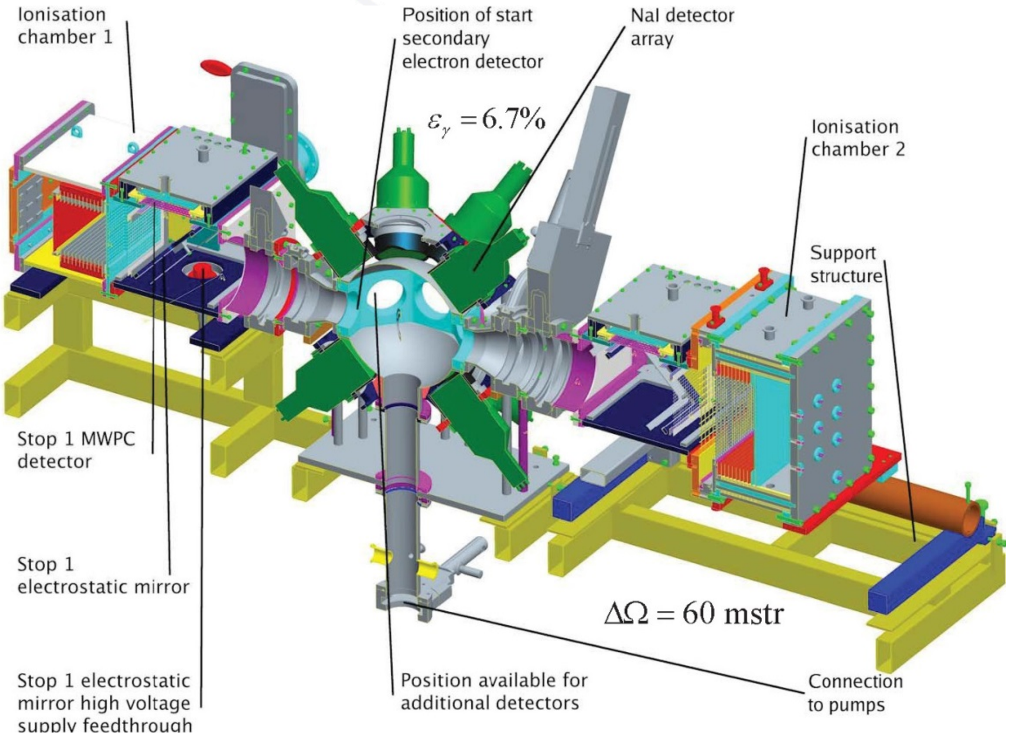
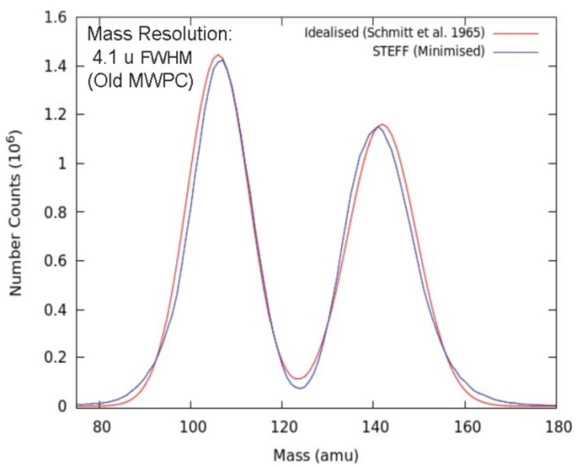
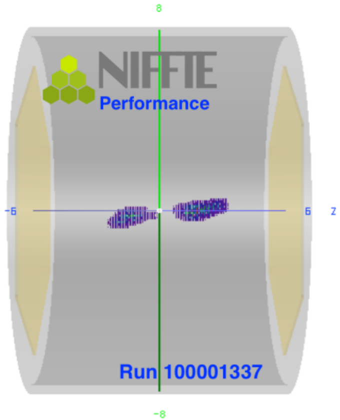
2E-2v - STEFF

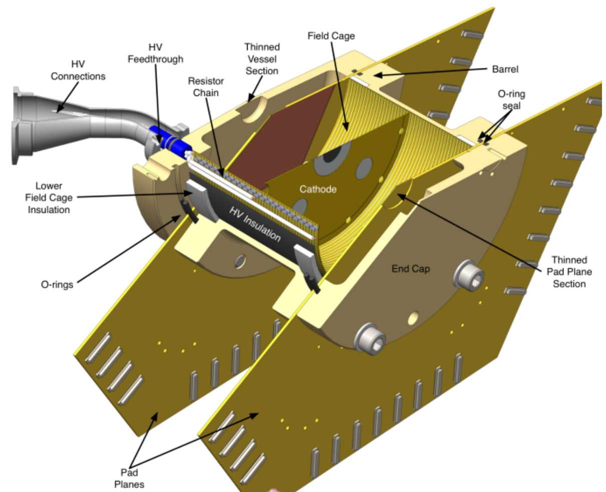
- 2E-2v spectrometer combined with gamma-ray detectors
- Currently at ILL
- Plan to run at n_TOF
- Mass resolution 3%

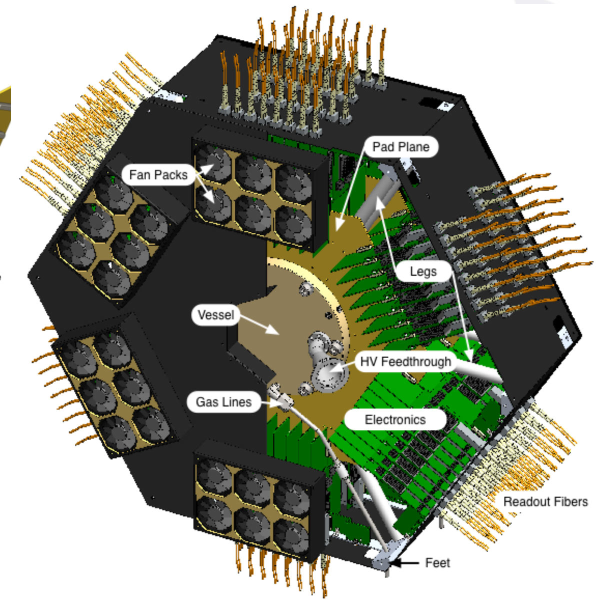




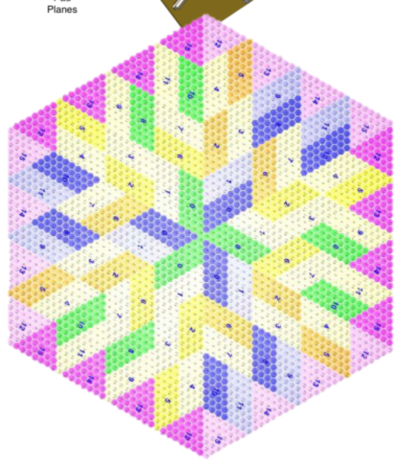
The fission TPC

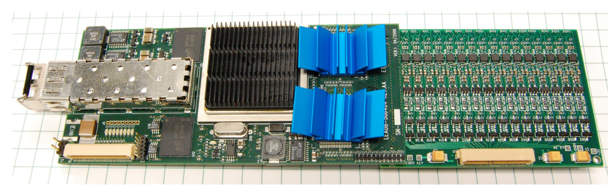






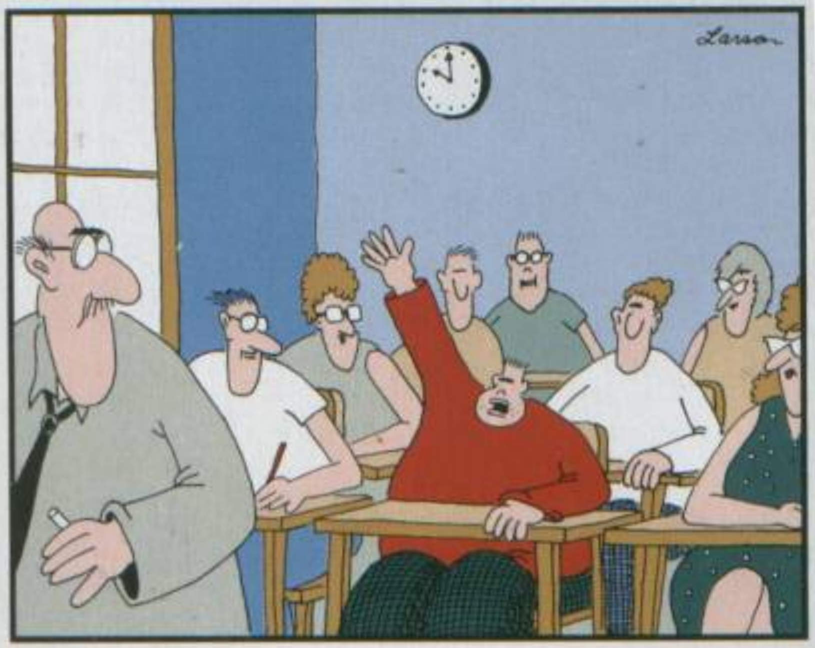
- Developed for high precision cross sections
- Other potential uses
  - Ternary fission
  - Angular distributions





M. Heffner, D.M. Asner, R.G. Baker, *el al.*, *A Time Projection Chamber for High Accuracy and Precision Fission Cross Section Measurements*, **submitted to Nucl. Instr. and Meth.**

Questions?



"Mr. Osborne, may I be excused?
My brain is full."