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Detection of Neutrons: Part II

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Recoil Detectors:
Proton Telescopes

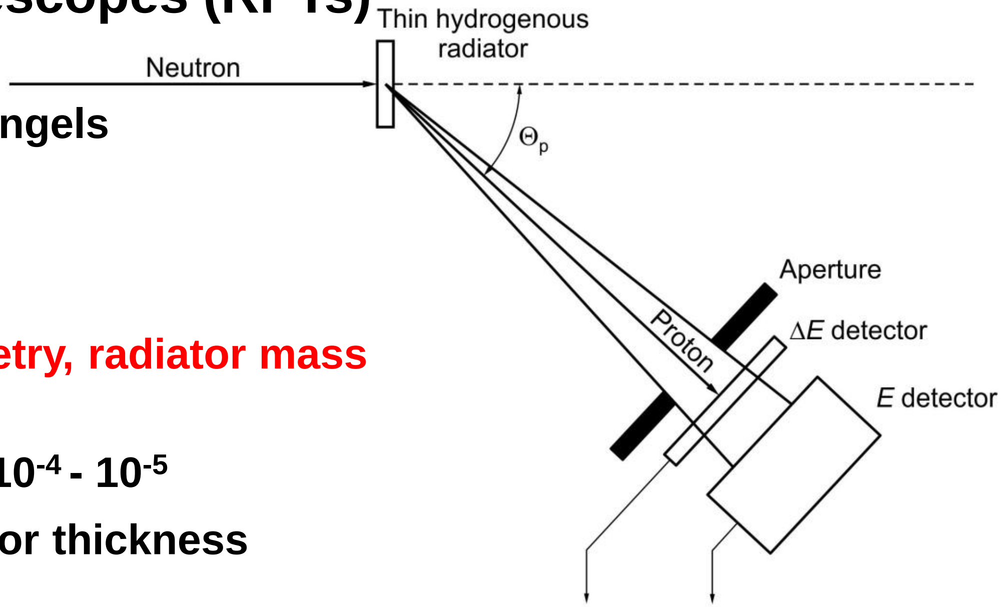
Recoil Telescopes as Reference Instruments

- **Scintillation detector used as primary reference instrument?**
  - Properties of the scintillators show variations: **Light output, H/C ratio**
  - Full angular distribution for n-p scattering required
  - Interference from $^{12}C(n,x)$ interactions
  - Detection efficiency difficult to calculate 'accurately' (1-2% uncertainty)
  - $\Rightarrow$ **Calibration required!**

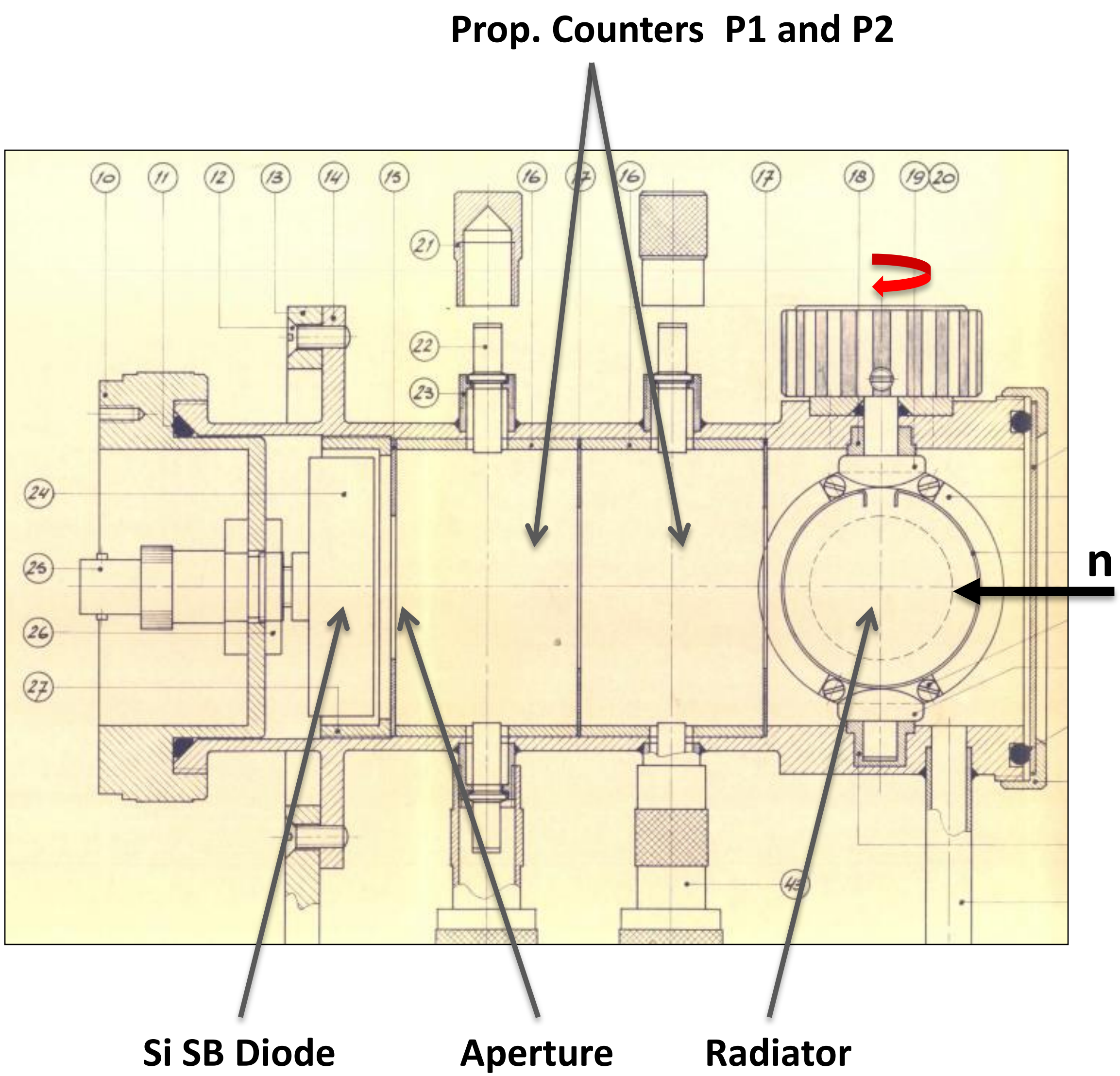
- **Way-out: Recoil Proton Telescopes (RPTs)**
  - **Only n-p scattering contributes**
  - Restricted range of scattering angels

$$E_p = E_n \cos^2 \Theta_p$$

  - 'Localized' response function
  - **Efficiency determined by geometry, radiator mass and diff. cross section**
  - Detection efficiency small: $\varepsilon = 10^{-4} - 10^{-5}$
  - Energy range depends of radiator thickness



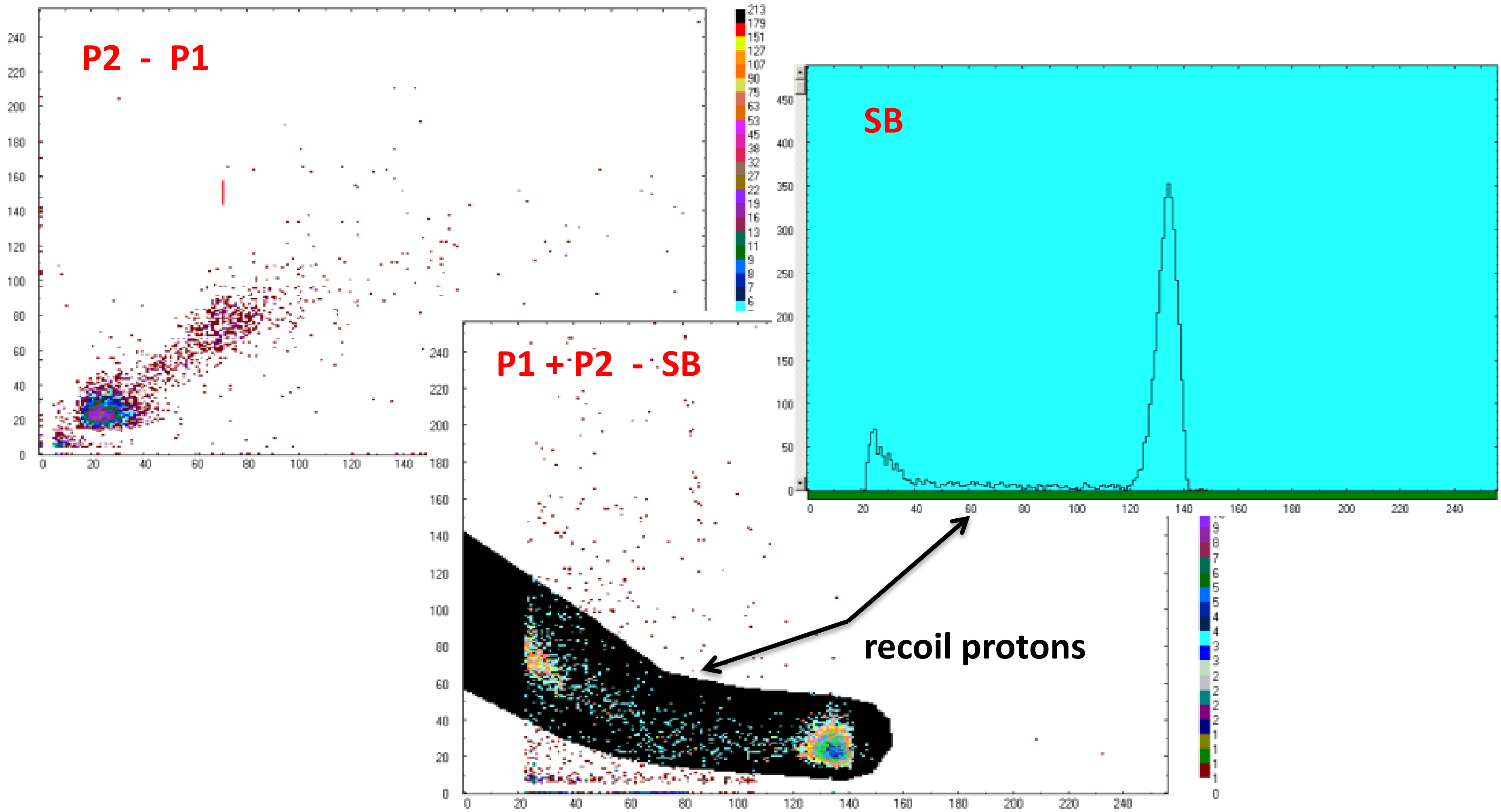
The Classical Low-Energy Telescope: T1 of PTB



Los Alamos in-beam design:

- Two CO_2 prop. counters: ΔE
- Surface barrier detector: E
- Radiator – source distance: 20-35 cm
- 1 mm Ta aperture: $^{\varnothing}$(20.98±0.01) mm
- Energy range :
  - 1.2 MeV – 15 MeV using three radiators
  - up to 20 MeV with degrader foils
- Single rates: < 10^4 s^{-1}
- Coincidence rate: 0.5 – 2 s^{-1} P1 × P2 × SB
- Coincidence resolution: 2 µs
- Multi-parameter DAQ

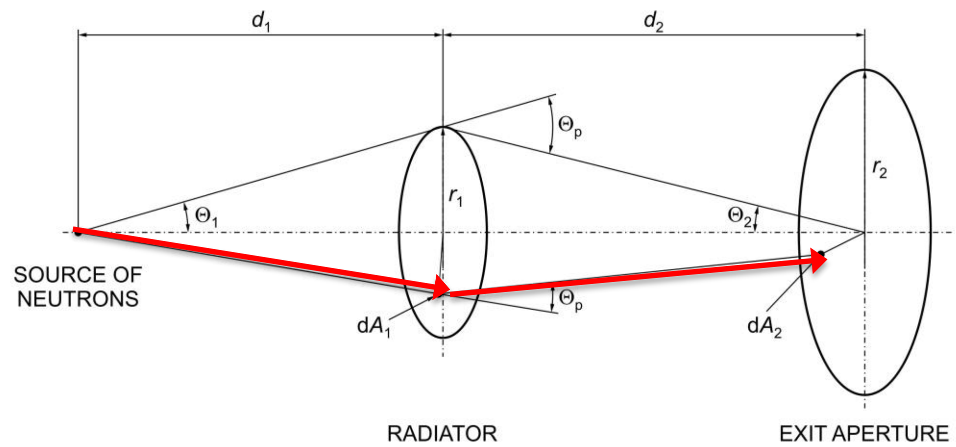
T1: Recoil Proton Spectra



- $D(d,n)^3He$, D_2 gas target, $E_{d,0}$ = 7.11 MeV, <E_n> = 10.02 MeV

T1: Analysis

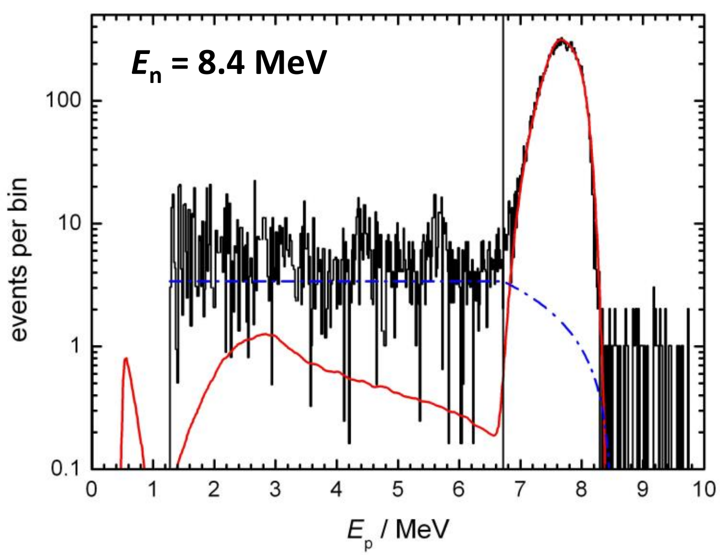
- **Calculation of the efficiency:**
  - (Semi)analytical integration
  - Monte Carlo simulation
  - Relativistic kinematics for CM → LAB
  - Anisotropic source: D(d,n)



$$\left(\frac{d\sigma_{np}}{d\Omega_p}\right) = A(\Theta_p, E_n)\cdot\frac{\sigma_{np}(E_n)}{\pi}$$

$$\varepsilon_{geo} = \int_{A_1}\int_{A_2}\frac{A}{\pi}\left(\frac{\cos\Theta_1}{d_1^2}\right)\left(\frac{\cos\Theta_2}{d_2^2}\right)dA_1 dA_2$$

$$\Rightarrow N_p = \varepsilon_{geo} n_H \sigma_{np} Y$$

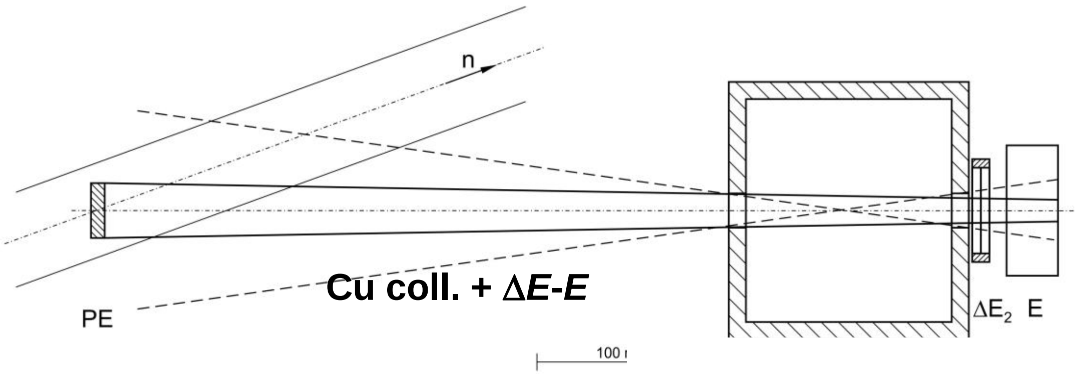


- **Main contributions to uncertainty**
  - Counting statistics: u_N/N = 1% - 2%
  - Efficiency: $u_\varepsilon/\varepsilon$ = 1%
  - Diff. n-p cross section: u_A/A = 0.2% - 1%

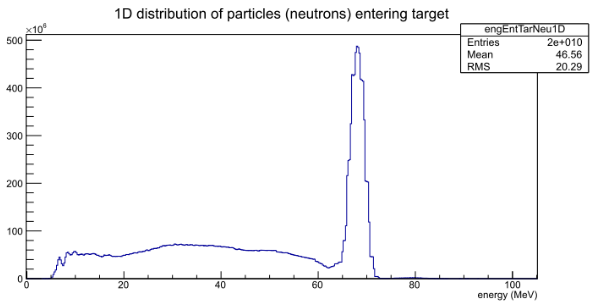
RPT Design Exercise: 75 MeV

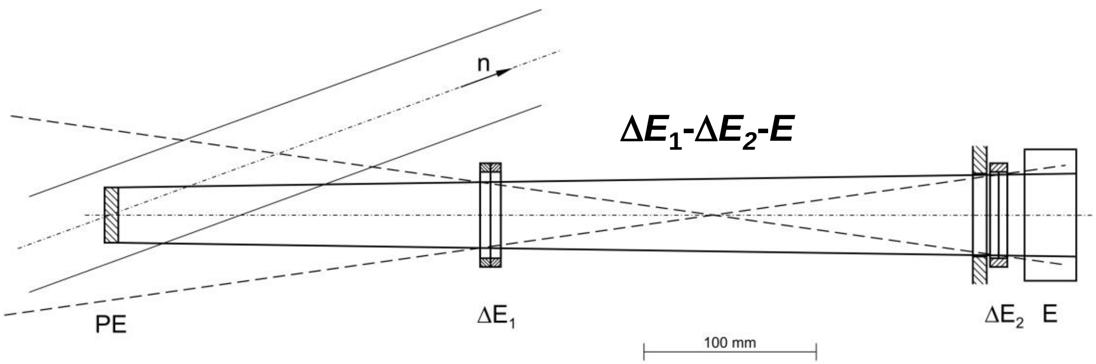
Test of a proton recoil telescopes for TLABS neutron beam facility:

- **Neutron Source: ^{nat}Li (8 mm) + p (75 MeV):** **quasi-monoenergetic spectrum,** **$\langle E_{n,0+1} \rangle$ = 71.6 MeV (FWHM ≈ 3.2 MeV)**
- **Collimated beam (50 × 50 mm)^2**



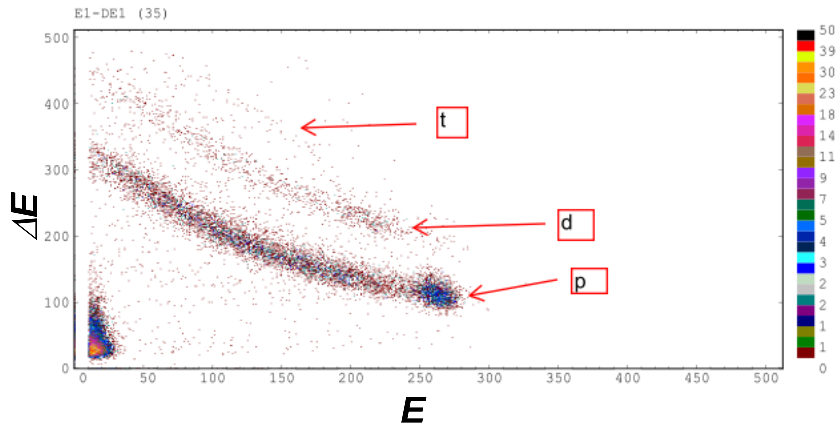
… which one made the race?

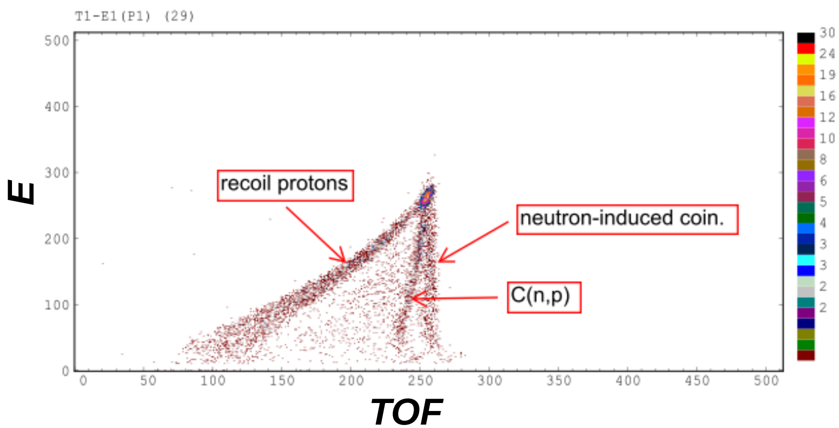




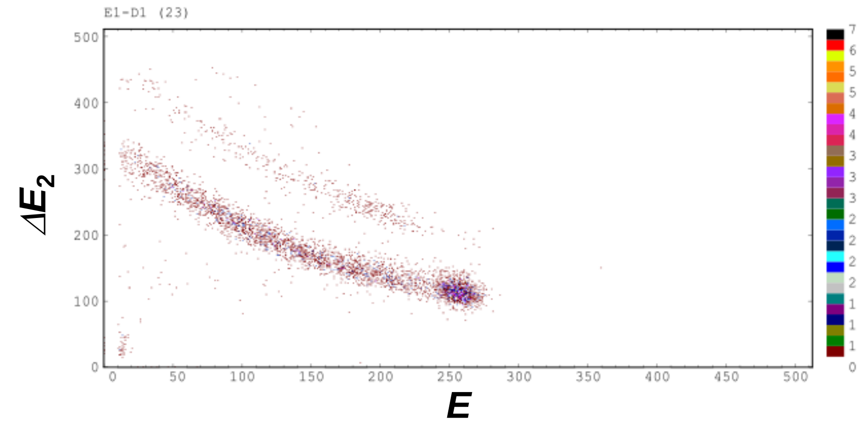
RPT Design Exercise: Results

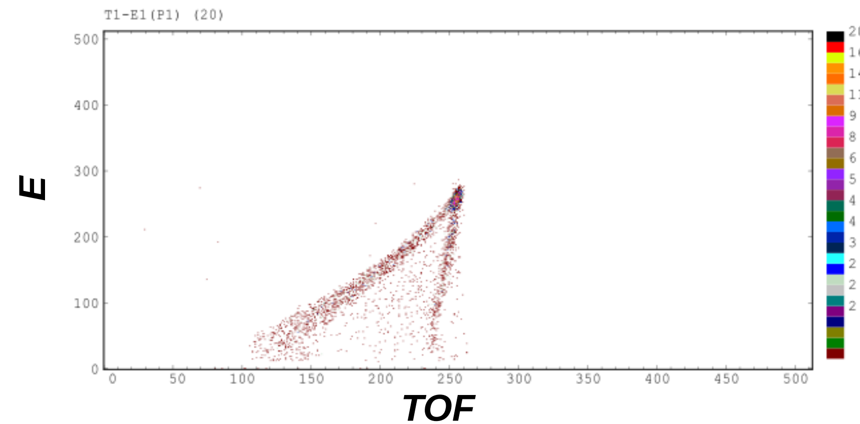
Double stage RPT: Cu-coll. + Δ*E*-*E*





Triple stage RPT: ΔE_1-ΔE_2-*E*

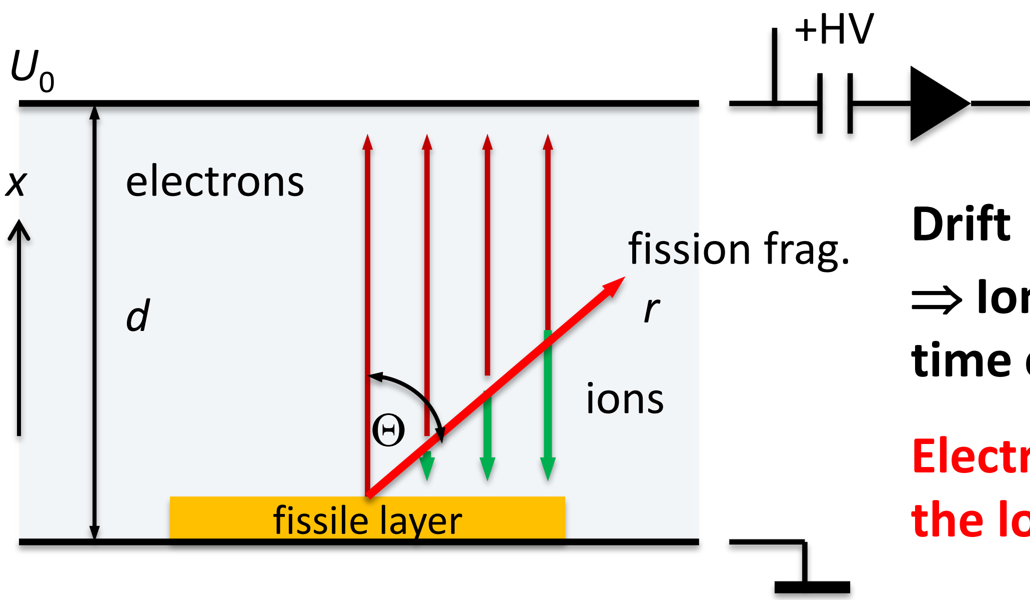




- **Good particle discrimination with 500 µm Si-PIPS as Δ*E* detectors**
- **Less neutron induced coupling with ΔE_1-ΔE_2-*E* scheme**

Fast Neutrons: Ionization Chambers

Fission Ionization Chambers



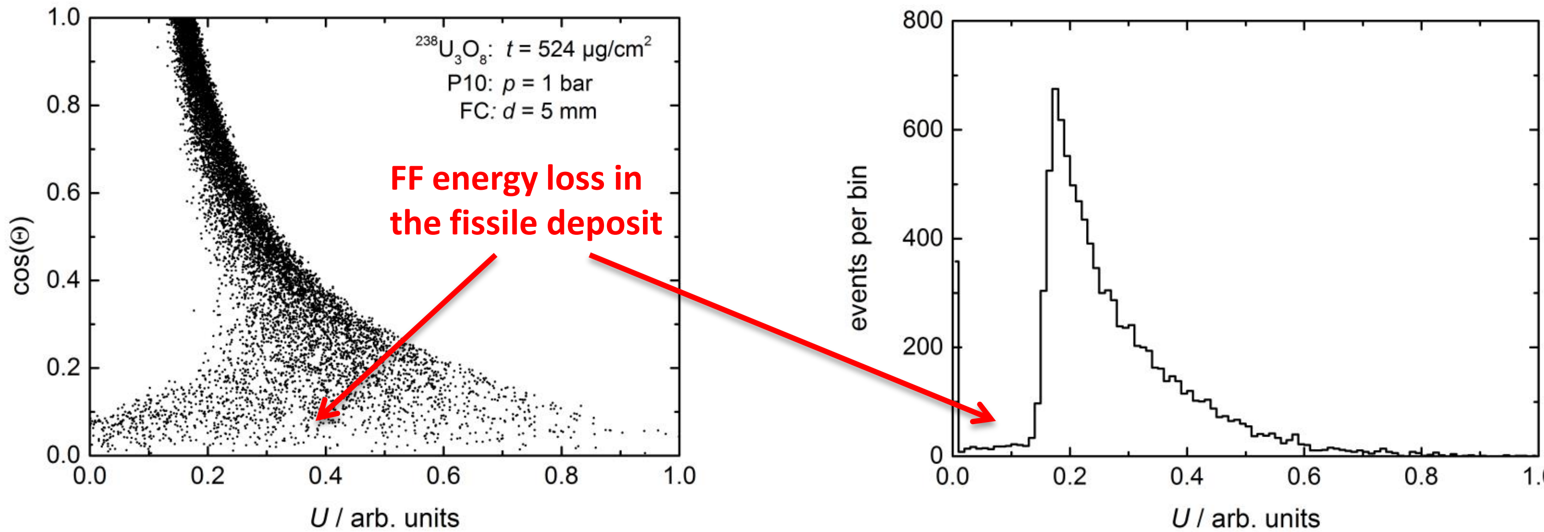
Drift velocities: $v = \mu \cdot E/p$, v_{el} >> v_{ion}

⇒ Ion-induced signal suppressed by time constant of the pre-amp.

Electron-induced signal depends on the location of the ionizing event

- **Electrical field:** $$E = U_0 / d$$
- **Charge per unit track segment:** $$q = \frac{e_0}{W}\left(\frac{dE_{ff}}{dr}\right)$$
- **Voltage change induced by drift along dx:** $$C U_0 \, dU = q \, E \, dx$$
- **Integration along frag. track:** $$U = \frac{e_0}{C}\int_0^R \left(\frac{1}{W}\frac{dE}{dr}\right) \cdot \left(1 - \frac{r}{d}\cos\Theta\right) dr$$

Simulated Pulse-Height Spectra



Monte Carlo calculations:

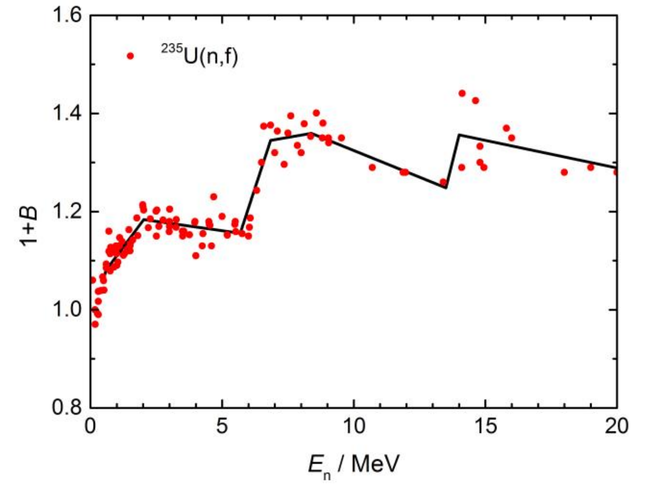
- **(A, Z) of the fissioning system: multiple-chance fission!**
- **Range data for U_3O_8 and Ar/CH_4**
- **Model for the surface roughness: $\langle r_a \rangle$**
- **FF distributions: $Y(E_n, A_{ff}, Z_{ff})$**
- **FF anisotropy: $W(\Theta^{CM}) = (1+B\cdot\cos\Theta^{cm})/2\pi$**
- **Incomplete momentum transfer**

Analytical Calculation of the Detection Efficiency

Absorption of fragments in the fissile layer:

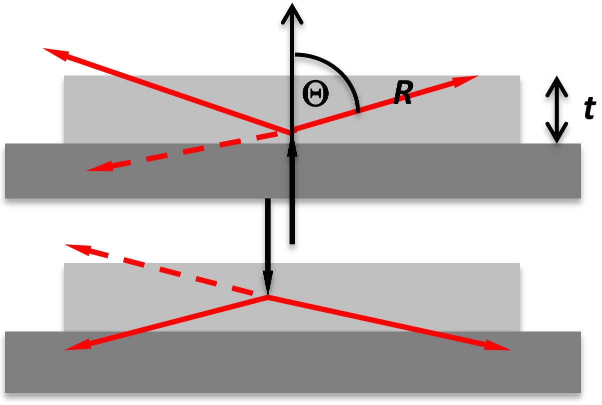
$$\varepsilon_{\mathrm{f}} = 1 - \frac{t}{2R_{\mathrm{ff}}} + \ldots \approx 0.94 - 0.99$$

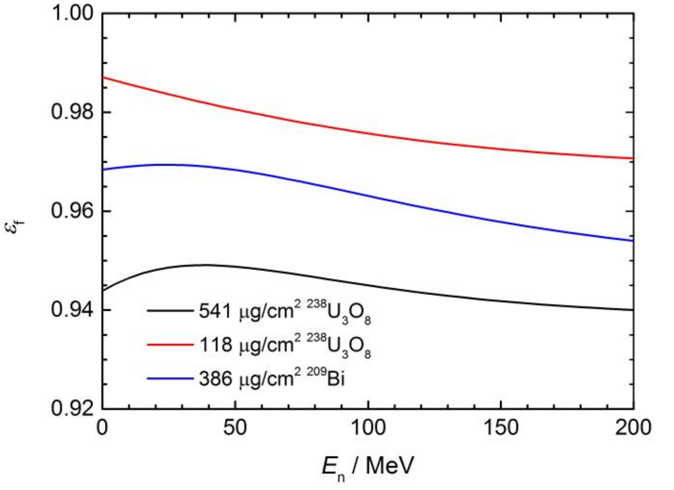
$W(\Theta) = (1+B\cos(\Theta))/2\pi$



Higher order contributions:

- Anisotropic fragment emission
- Momentum transfer



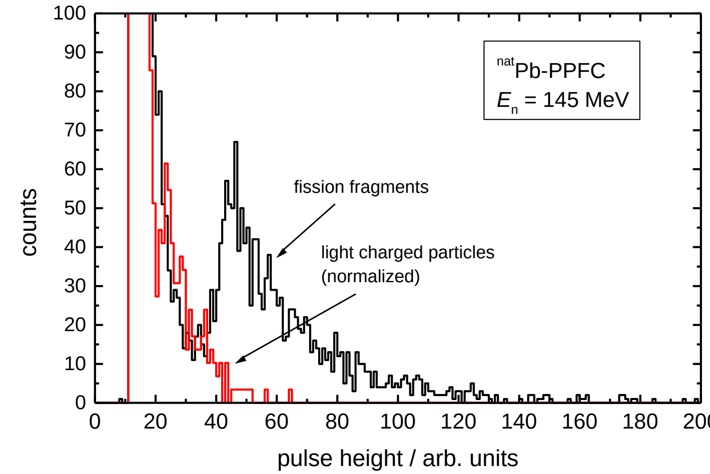


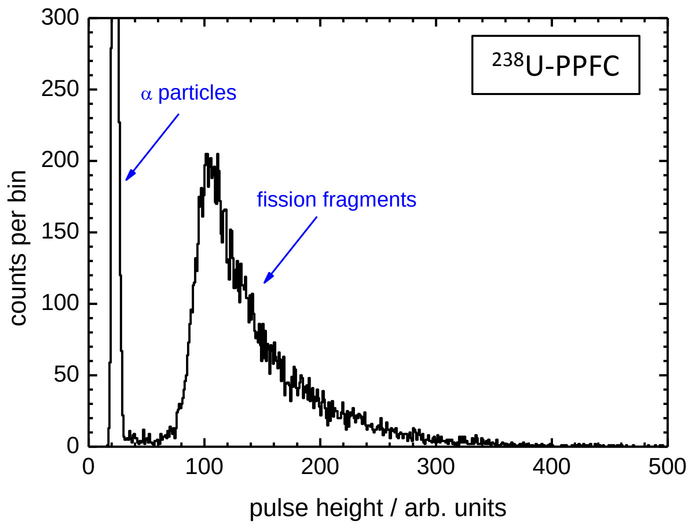
- Uncertainty: $u_\varepsilon/\varepsilon_\mathrm{f}$ ≈ 1% - 2% depends very much on sample quality

Ref.: G.W. Carlson, NIM 119 (1974) 97-100

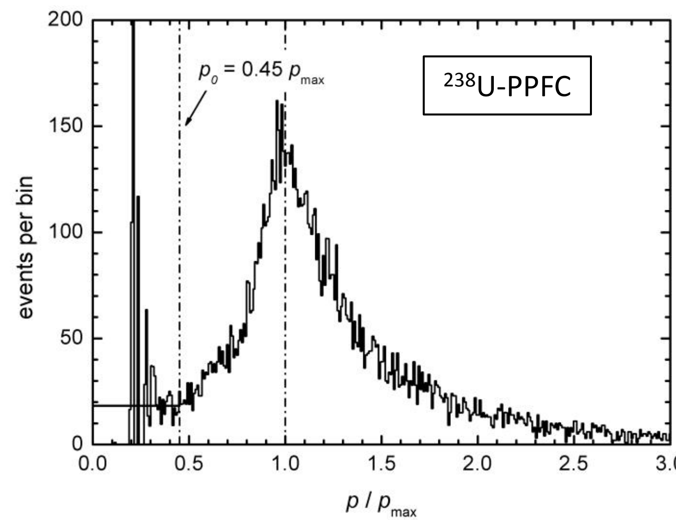
Fission Fragment Detection Efficiency

- **Background at small pulse heights**
  - **α decay of fissile nuclei**
  - **recoil nuclei from backing materials**
- **Extrapolation of fission events into this region**
  - **thickness and 'roughness' of deposits**
  - **biasing scheme**





Painted $^{238}U_3O_8$ layers

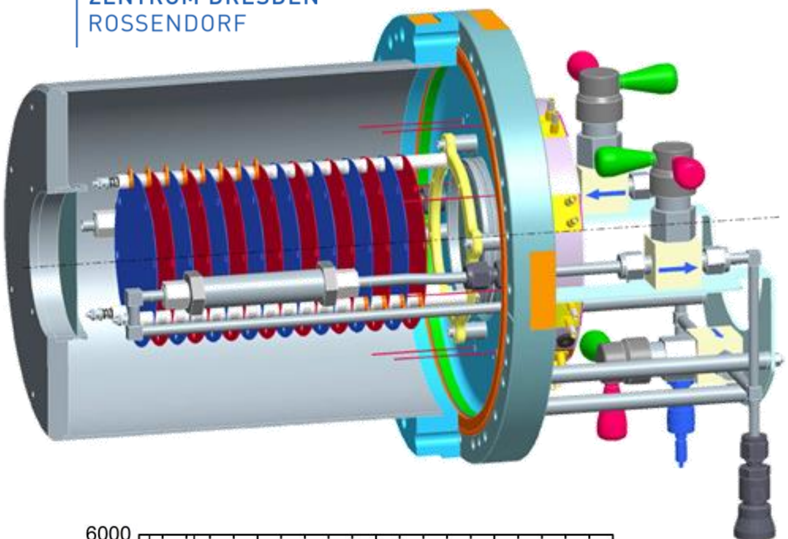


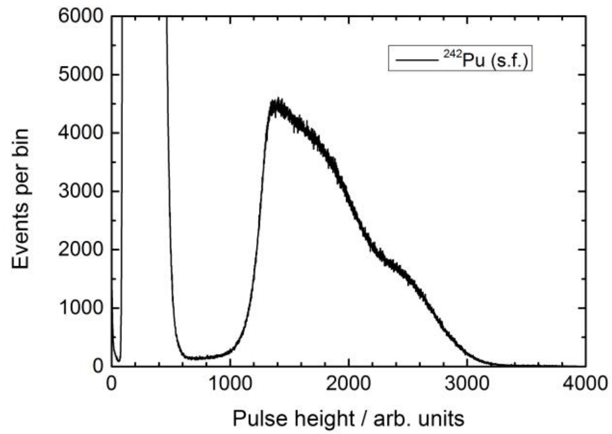
Electro-sprayed $^{238}U_3O_8$ layers

^{242}Pu Fission Chambers for Cross Section Measurements

HZDR

HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

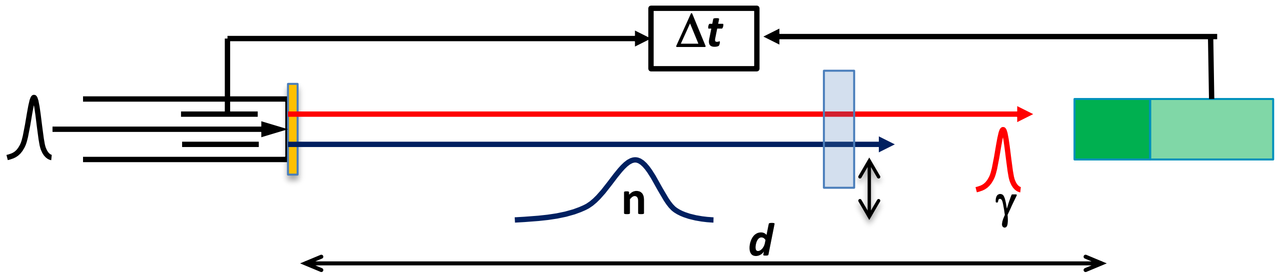




- ^{242}Pu layers produced by molecular plating (U. Mainz)
  - m_{Pu} = 42 mg, ^{242}Pu: 99.9668 %
  - eight layers: 116 μg/cm^2
  - A_α= 6.17 MBq
  - R_{sf} = 34 s^{-1}
- Number of fissile atoms N_{Pu}:
  - Spontaneous fission rate $t_{1/2}$ = (6.77 ± 0.07)×10^{10} a
  - Narrow-geometry alpha counting
- Fast pre-amp.'s: α pile-up!
- Continuous P10 flow (nanofilters)

The Measurement of Neutron Energy Distributions: TOF Methods

TOF Spectrometry: Principles



- **Neutron energy determined from a velocity measurement:**

$$v = \frac{d}{t} \quad \Rightarrow E = (\gamma - 1) \cdot mc^2, \quad \gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

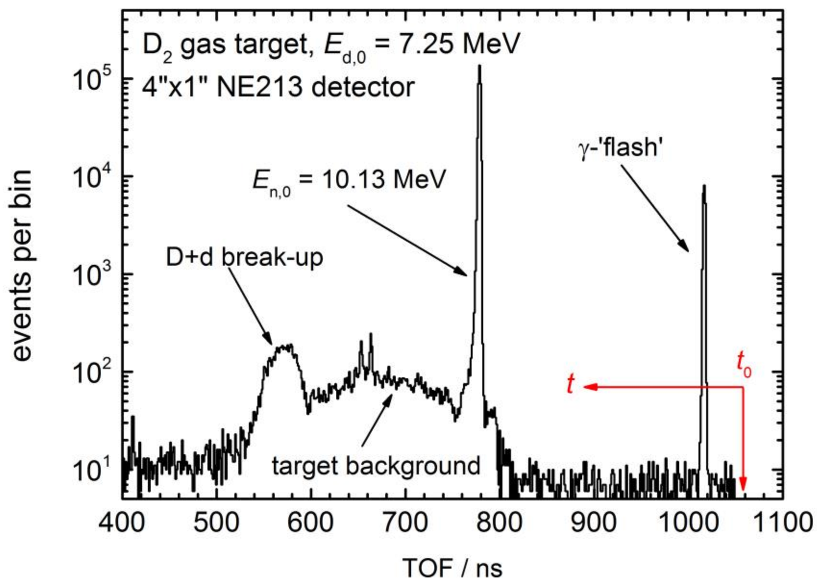
- **Energy resolution:**

$$\frac{\delta E}{E} = (\gamma + 1)\gamma \frac{\delta v}{v}, \quad \frac{\delta v}{v} = \sqrt{\left(\frac{\delta t}{t}\right)^2 + \left(\frac{\delta d}{d}\right)^2}$$

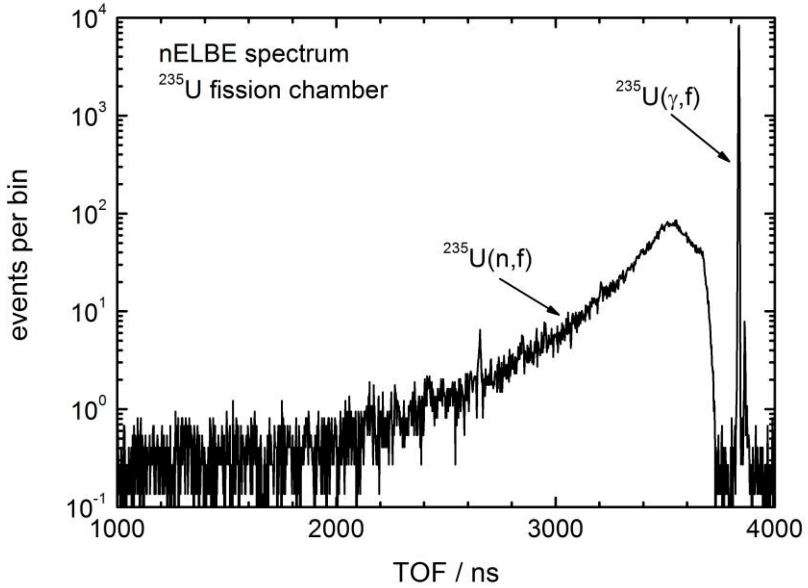
Time and distance resolution contribute in same way:
$\Rightarrow$ express flight time δt by an equivalent distance δd_{eq}

Measurement of TOF Distributions

Quasi-monoenergetic source



'White' source



- **Start signal: neutron detector**
- **Stop signal: beam pick-up**
- **Inverted time scale: TOF = $t_{stop} - t_{start}$**
- **<u>Measured</u> neutron flight time: $t_m = TOF_\gamma + d/c - TOF_n$**

NB: Measured flight time t_m includes time spent in target and detector!

Width of TOF Peaks

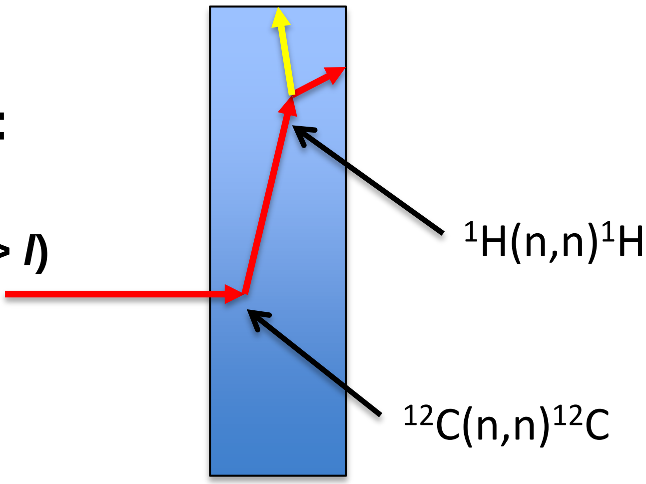
- **Contributions to the width of TOF peaks :**
  - **Beam: time spread of the beam pulse** δt_{beam}
  - **Source: beam transit time** $\delta t_{\mathrm{src}} = d_{\mathrm{src}}/v$
    energy-loss broadening $\delta E_{\mathrm{src}} = f_{\mathrm{kin}}(E_{\mathrm{beam}}, E_{\mathrm{n}})\cdot(\mathrm{d}E/\mathrm{d}x)\cdot d_{\mathrm{src}}$
    kinematical broadening $f_{\mathrm{kin}}(E_{\mathrm{n}}, \Theta)\cdot\delta\Theta$
    slowing-down time $\delta t_{\mathrm{slow}} \approx A/\Sigma_{\mathrm{s}} v$
  - **Sample: kinematical spread** $\delta E_{\mathrm{spl}} = f_{\mathrm{kin}}(E_{\mathrm{n}}, \Theta)\cdot\delta\Theta$
  - **Detector: transit time** $\delta t_{\mathrm{det}} = d_{\mathrm{det}}/v$
    multiple scattering spread δt_{ms}
- **Total TOF spread:**

$$\delta t^2 = \sum_i \delta t_i^2 + \sum_j \left(\frac{t_j(E_{\mathrm{n},j}, l_j)}{2E_{\mathrm{n},j}} \right)^2 \delta E_{\mathrm{n},j}^2$$

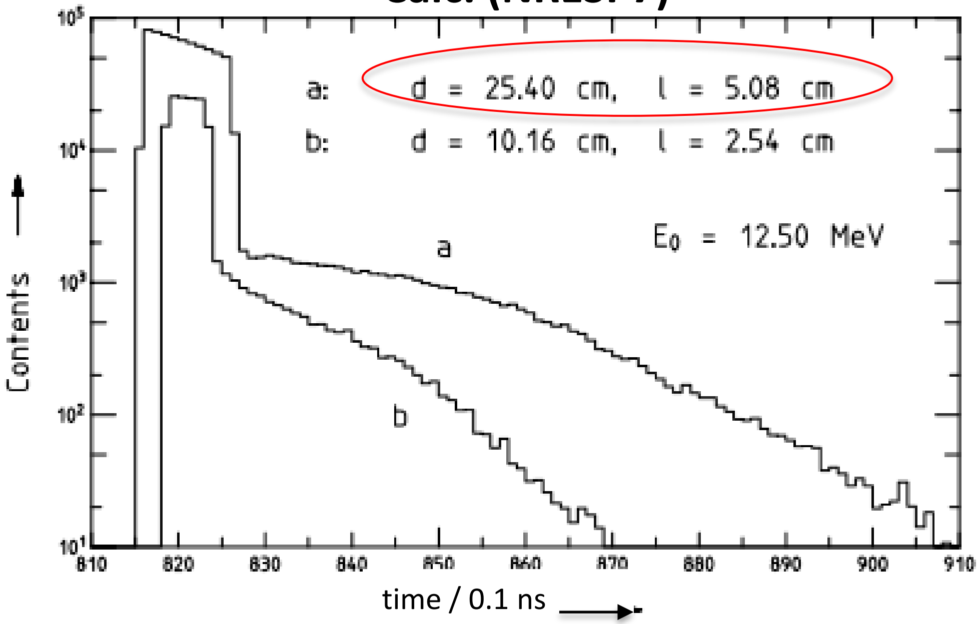
- **Relative importance of time and energy broadening depends on the details of the setup:**
  - **Masses of projectiles and target nuclei: source and sample**
  - **Flight paths: source and sample**

Time Response of Organic Scintillation Detectors

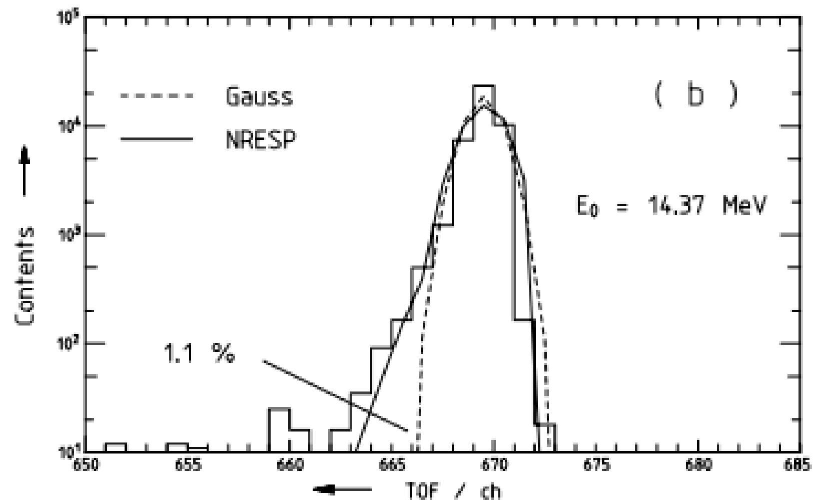
- **Multiple scattering affects time response:**
  - **Width of the main peak: flight time through det.**
  - **Exponential tails for pancake-like detectors (*d* >> *l*)**
  - **Non-Gaussian time response: *R*(*E*,*t*)**
  - **Modeled with Monte Carlo codes**



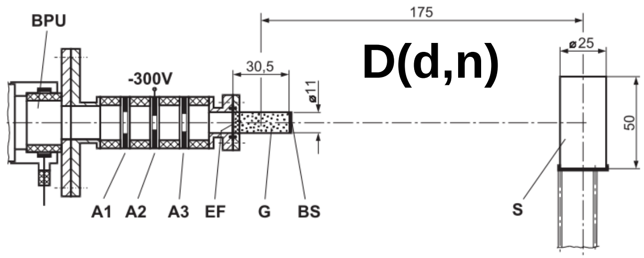
Calc. (NRESP7)



Exp.

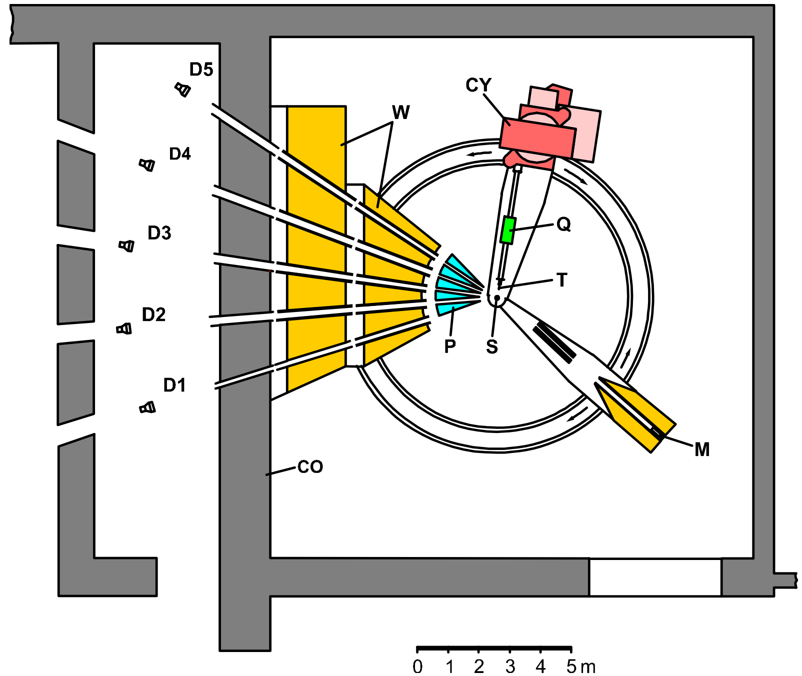


Example: PTB TOF Spectrometer



Parameters of the PTBs TOF spectrometer

Projectile	
Deuteron energy	≈5–11 MeV
Averaged current	0.7–2.2 μA
Pulse width (FWHM)	1–3 ns
Repetition frequency	<1 MHz
Deuterium gas target	
Length	30 mm
Diameter	10 mm
Gold backing	0.5 mm
Molybdenum entrance foil	5 μm
Gas pressure	0.2 Mpa
Neutron energy	≈8–14 MeV
Sample	
Shape	Full cylinder
Height	50 mm
Diameter	25 mm
Distance from target	175 mm
Neutron TOF spectrometer	
5 detectors	NE-213
Scintillator diameter	10.16 cm (det. 1)
	25.40 cm (dets. 2–5)
Scintillator length	2.54 cm (det. 1)
	5.08 cm (dets. 2–5)
Mean flight path	12.000 m



$E_{n,0}$ = 10 MeV

– δt_{beam} = 1.6 ns

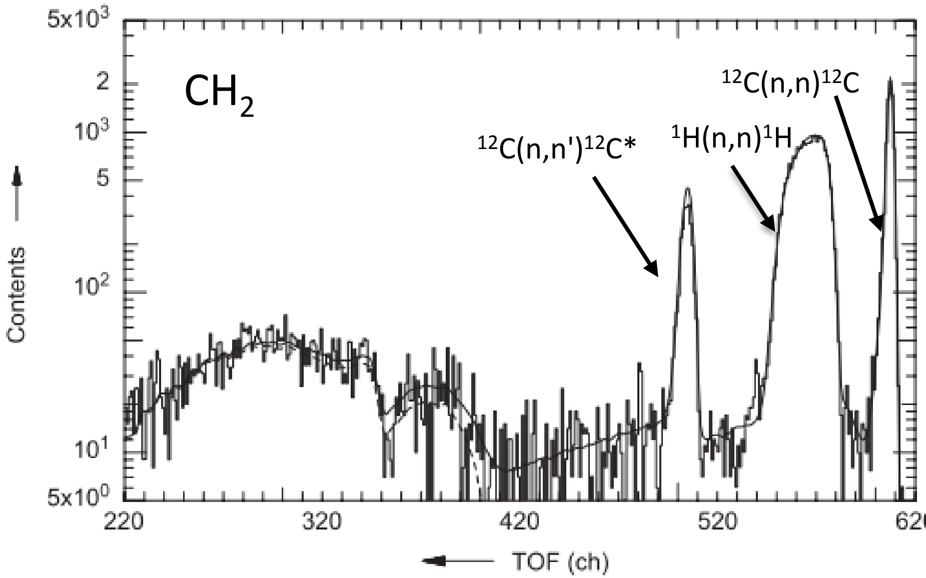
– $\delta E_{n,src}$ = 106 keV

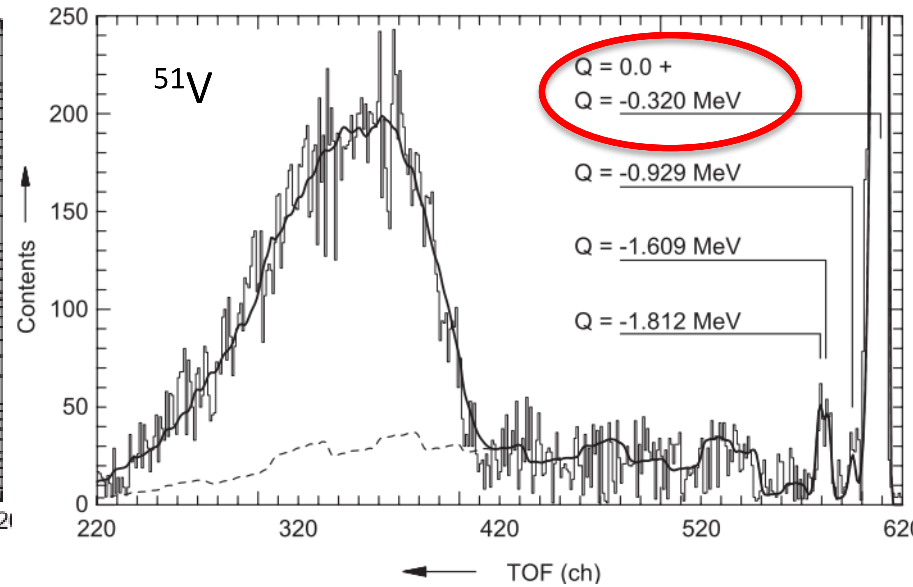
– d_{src} = 17 cm, d_{det} = 12 m

⇒ $\delta E_n/E_n$ = 1.4 % for $E_{n,det}$ = 2 MeV

1.8 % for $E_{n,det}$ = 10 MeV

Example: PTB TOF Spectrometer





Kinematical broadening

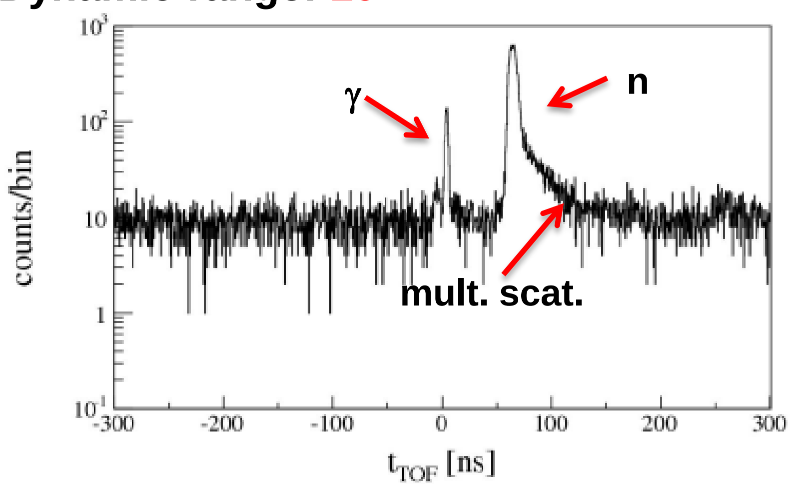
- Polyethylene (PE) sample
- Incident energy: $E_{n,0}$ = 10.21 MeV
- Scattering angle: Θ = 29.3°

Separation of TOF peaks

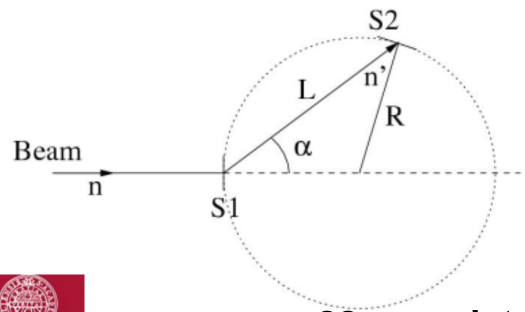
- Vanadium sample
- $E_{n,0}$ = 10.21 MeV
- Θ = 36.8°

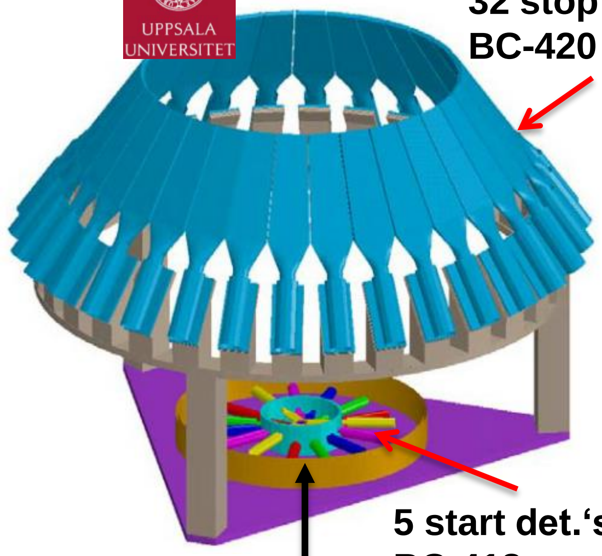
Self-TOF Spectrometers

- **Source of the TOF Start/Stop signal:**
  - **Pulsed beam (pick-up, RF)**
  - **Time-correlated associated particle (TCAP)**
  - **Recoil particle double-scattering experiment**
    ⇒ self-TOF spectrometry
- **Example: TOFOR spectrometer at JET**
  - **Designed for DD plasmas: $\langle E_n \rangle = 2.5$ MeV**
  - **Energy resolution: $\Delta E/E \approx 7\%$**
  - **Dynamic range: 10^5**



Ref. : M. Gatu-Johanson *et al.*, NIMA 591 (2008) 417-430





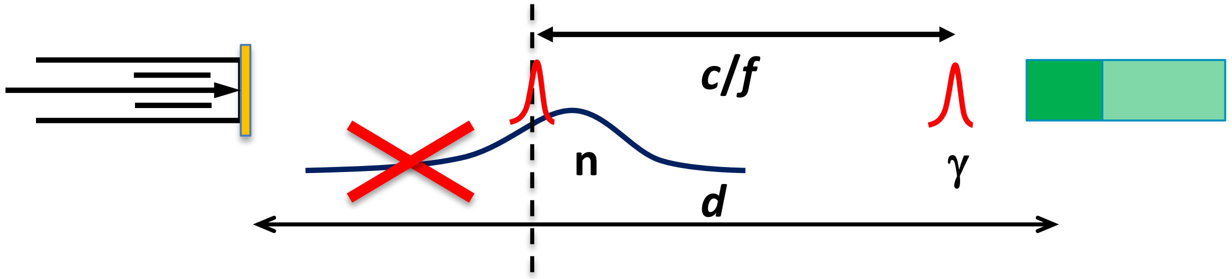
$$E_{n'} = E_n \cos^2(\alpha) \Rightarrow E_n = 2m\left(\frac{R}{t}\right)^2$$

TOF Spectrometry of Incompletely Pulsed Beams

Pulsed beams with rep. frequency *f* and flight path *d*

$\Rightarrow$ **Frame-overlap threshold: ‘only one pulse at a time’**

$$v_c = d \cdot f \Rightarrow E_c = (\gamma_c - 1) \cdot mc^2 \approx \frac{1}{2} m v_c^2$$



Possible workarounds:

- **Spectrometry using recoil detectors**
- **Bonner Sphere spectrometry**

$\Leftarrow$ **Spectral fluence Φ_E for $E > E_c$ from TOF measurement**

- **Combination of measurements at different flight paths *d* and Monte Carlo calculations for very low energies**

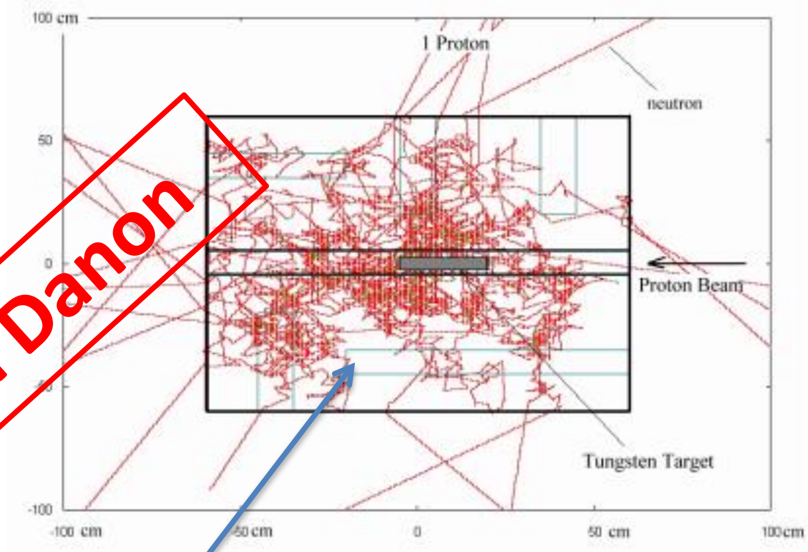
Lead Slowing-Down Spectrometer (LSDS)

- **Semi-empirical relation between energy $\bar{E}$ and slowing-down time t:**

$$\bar{E}(t) = \frac{K}{(t - t_0)^2}$$

- **K and t_0 :**
  - **MC simulations**
  - **resonance analysis**
- **Very high neutron flux**
- **Energy range 0.1 – 100 eV**
- **Application:**
  - **Reactions with rare isotopes**
  - **Fission of very radioactive isotopes**
  - **Fission of isomers**

See lecture by Yaron Danon



Detectors inserted in the moderator:
- **Compensated fission chambers**
- **Solar cells with fissile layers**
- **…**

Neutron Detectors for TOF Measurements

- **^{6}LiGlas Detectors:**
  - Suitable for neutron range $E_n < 1$ MeV
  - Strong photon sensitivity, stong energy dependence around 250 keV res.
  - Complicated time response due to 250 keV resonance: $\delta t \approx 3 - 4$ ns
  - Sensitive to (epi)thermal background neutrons: $\sigma \propto 1/v$
- **Fission Chambers**
  - Secondary standard cross sections: $^{235,238}U(n,f)$
  - Low but calculable detection efficiency: reference instrument
  - Slow time response requires long flight paths: $\delta t \approx 3 - 6$ ns
- **Organic scintillation detectors: working horses for TOF meas.**
  - Fast response: $\delta t \approx 1 - 2$ ns, often limited by PMT's
  - High detection efficiency: $\varepsilon \approx 10 – 20\%$
  - Many sizes and shapes possible: 1 cm - 1 m
  - Diff. n-p cross section is primary standard
  - Discrimination of photon background by PSD
  - Quenching requires low pulse-height thresholds for $E_n < 1\text{-}2$ MeV

The Measurement of Neutron Energy Distributions: Unfolding Methods

Need for 'Non-TOF' Spectrometry

- **There are situations where TOF cannot be used:**
  - **Accelerators based sources with high rep. rates: *f* > 0.1 - 1 MHz**
  - **Neutron diagnostics at nuclear fusion experiments**
  - **Sources without well-defined flight paths: Transmission through shields, fusion benchmarks**
  - **Neutrons in the environment**
  - **…**
- **But there is a way-out:**

The spectral neutron distribution (dΦ/dE) is related to the distribution of 'events' (dN/dL) in the detector:

$$N_L = \int R(L,E) \cdot \Phi_E \, \mathrm{d}E \rightarrow N_i \approx \sum_j R_{i,j} \Phi_j$$

(Fredholm integral equation of the first kind)

The attempt to solve this equation is called 'spectrometry'

Spectrometric Methods

- **High-resolution spectrometry**
  - Spectrometry of recoil nuclei:
    - organic scintillation detectors
    - recoil telescopes
  - Spectrometry using reaction products:
    - ^{3}He counters and ionization chambers
    - sandwich spectrometers
    - diamond detectors
  - Capture-Gated spectrometry

$\Leftarrow$ **Make response matrix *R* as diagonal as possible!**

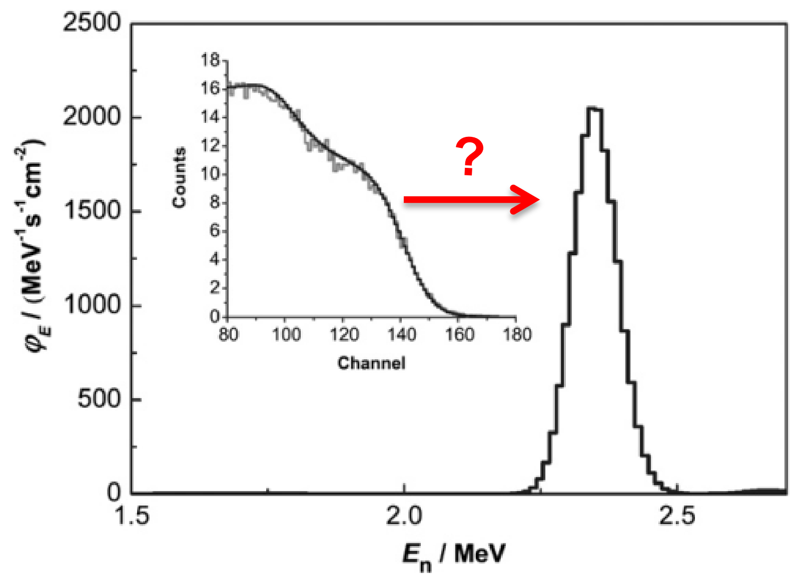
- **Low-resolution spectrometry**
  - Multi-sphere spectrometry
  - Spectrometry using threshold activation foils

Unfolding Problem

- **Unfolding problem:**
  How to get from N_j (data space) to Φ_j (space of possible solutions)

- **Problem of unfolding:**
  - **There is a multitude of solutions Φ_j which produce the same N_j**
  - **The response $R_{j,i}$ is not exactly known**
  - **The N_j have uncertainties u_i**

$$\Rightarrow \boxed{N_i + u_i = \sum_j R_{i,j}\Phi_j}$$



Nota bene:

- **There is no exact solution!**
- **What is needed is a consistent <u>approximate</u> solution**
- **Usually prior information is available and <u>must</u> be included**

Technical Approaches to Unfolding

- **Direct matrix inversion:** $N \approx R \cdot \Phi \Rightarrow \Phi \approx (R^{\mathrm{T}} \cdot R)^{-1} \cdot R^{\mathrm{T}} \cdot N$

  but: $(R^{\mathrm{T}} \cdot R)^{-1}$ **is usually ill-conditioned if it exists at all:**

  $$(R^{\mathrm{T}} \cdot R)^{-1} = V \cdot \Sigma^{-1} \cdot U^{T} \quad \text{with}\, U, V \text{ orth}, \Sigma = \mathrm{diag}(\gamma_i), \gamma_1 \geq \gamma_2 \geq \ldots \geq 0$$

  $\Rightarrow$ **'noise' is amplified, $\Phi_j < 0$ possible!**

$\Rightarrow$ **More suitable methods are required:**

- **Iterative procedures:** usually black-magic recipes!
- **Stochastic methods:** Monte Carlo, genetic algorithms, …
- **Regularisation:** add constraints to enforce smoothness
- **Least-squares adjustment:** usually linearization required
- **Bayesian parameter estimation:** requires an analytical model
- **Maximum entropy principle:** justifiable from information theory consistent treatment of prior information and uncertainties

Ref: M. Reginatto: Radiat. Meas. 45 (2010) 1323-1329

The PTB scintillation spectrometer : Response Matrix

2" x 2" BC501A cell

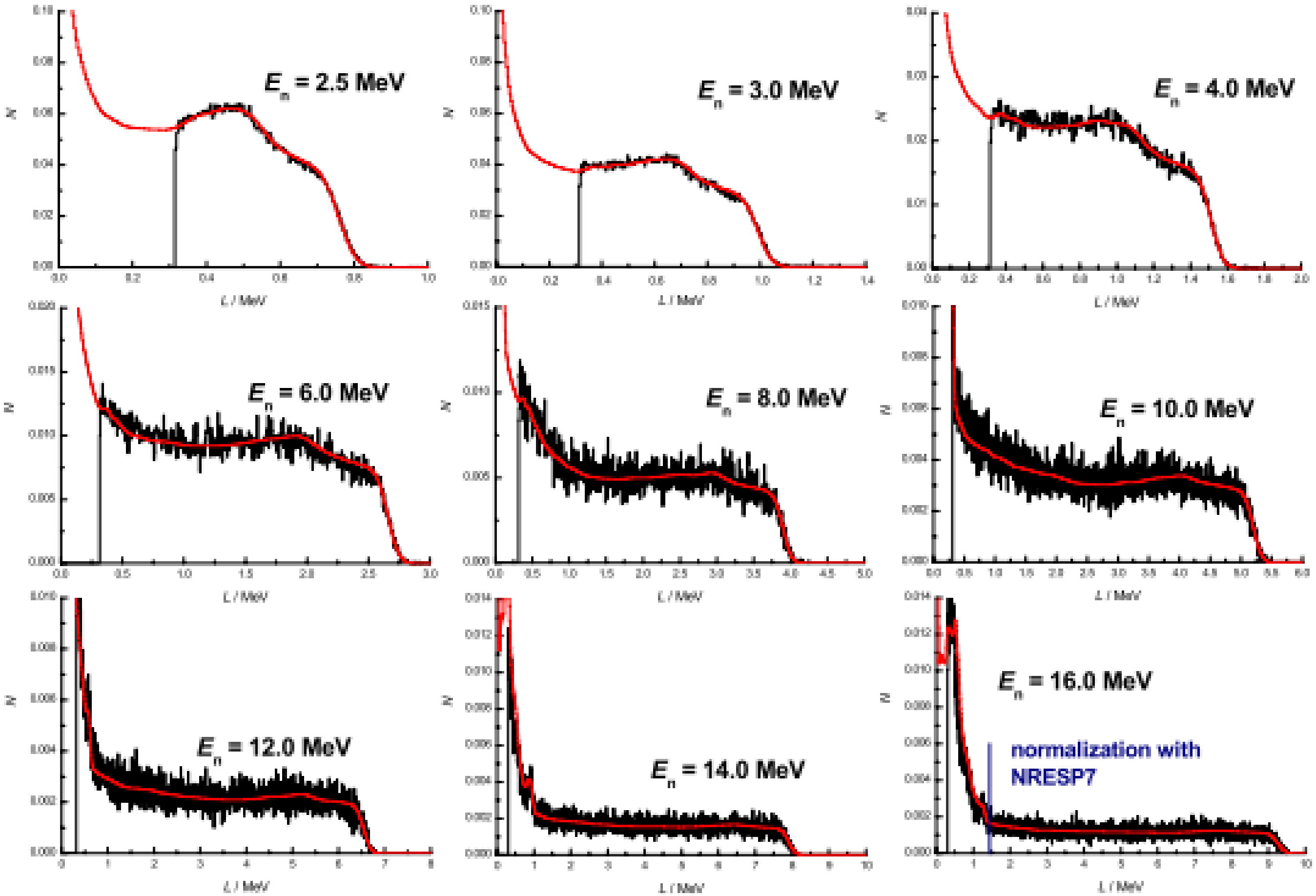
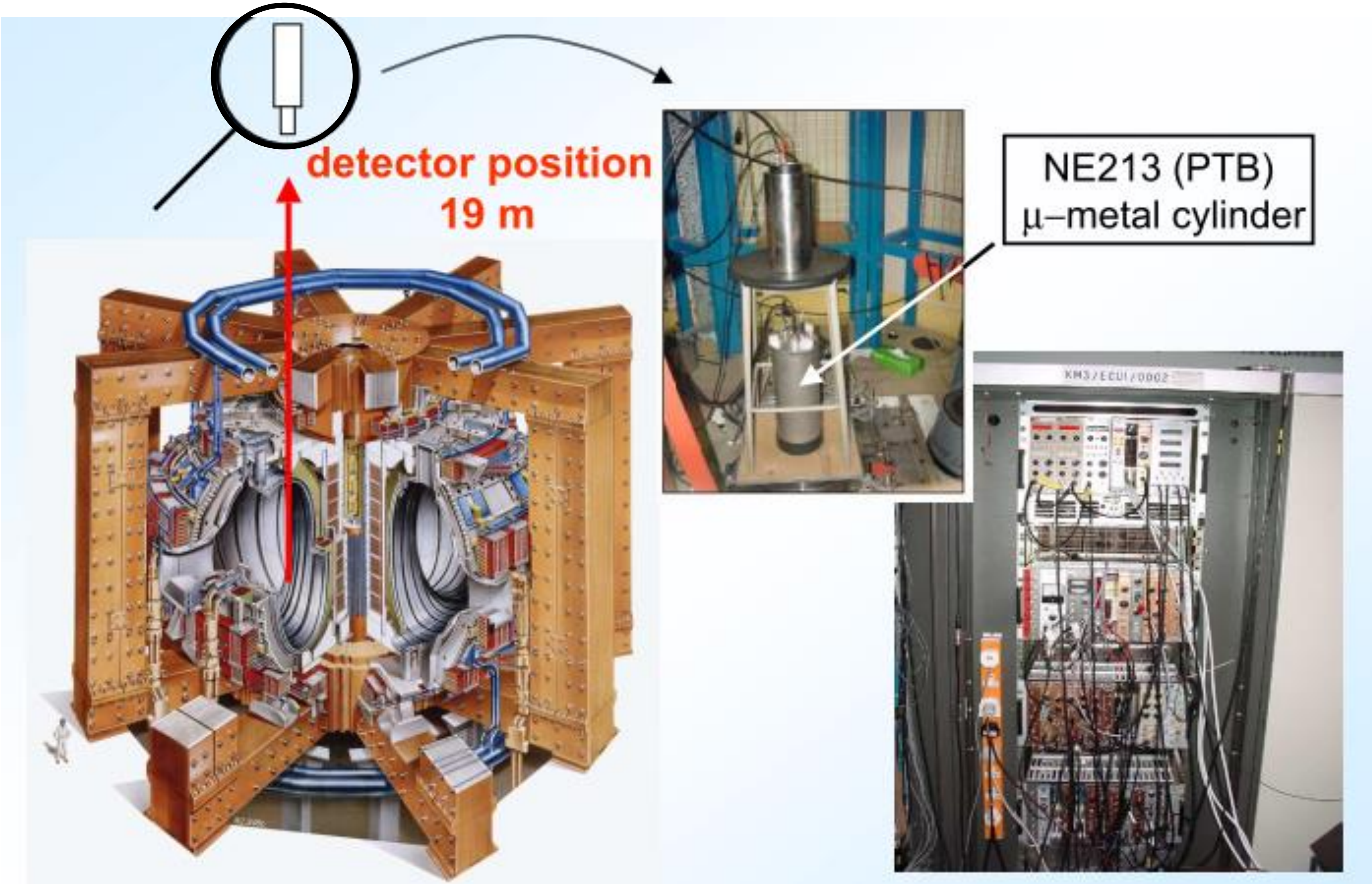


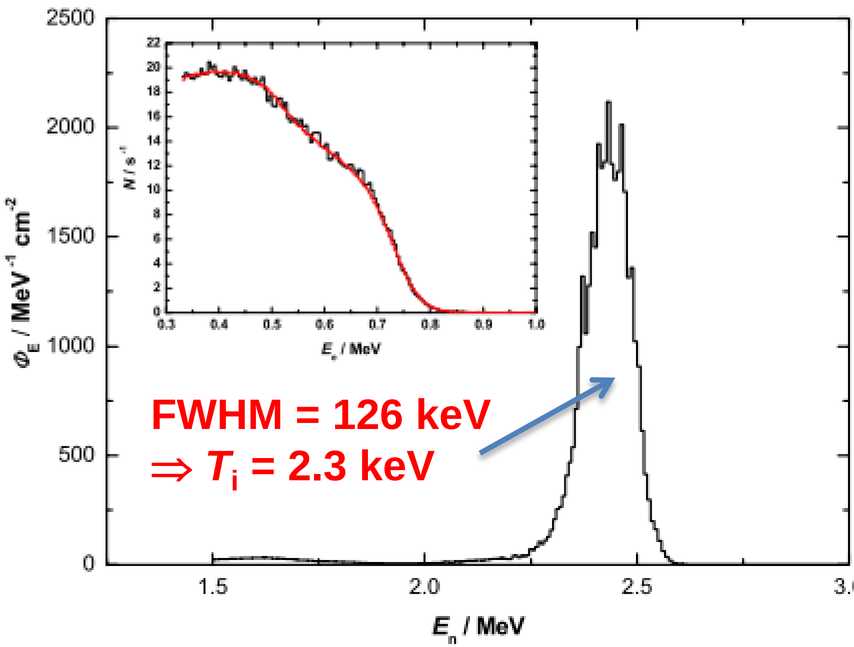
Figure 3: Response functions of the NE213 scintillation detector for 9 neutron energies selected between 2.5 MeV and 16 MeV by time-of-flight slices. The experimental spectra (black histogram) are compared with and normalized to responses calculated with the NRESP7 code (red lines).

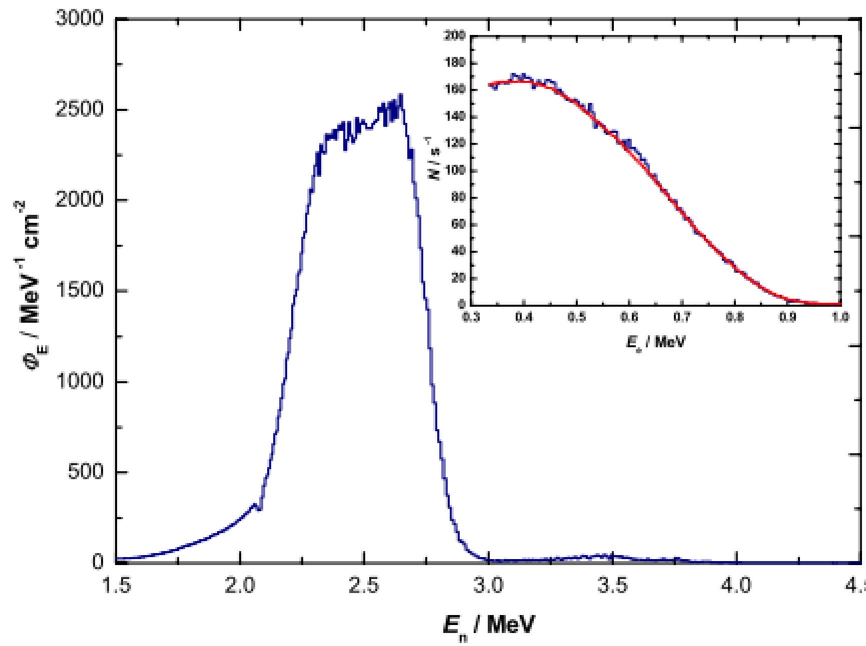
Ref.: A. Zimbal *et al.,* PoS(FNDA2006) 035 www.pos.sissa.it

Measurements at JET



Ohmic and NBI Heated JET Discharges (DD)



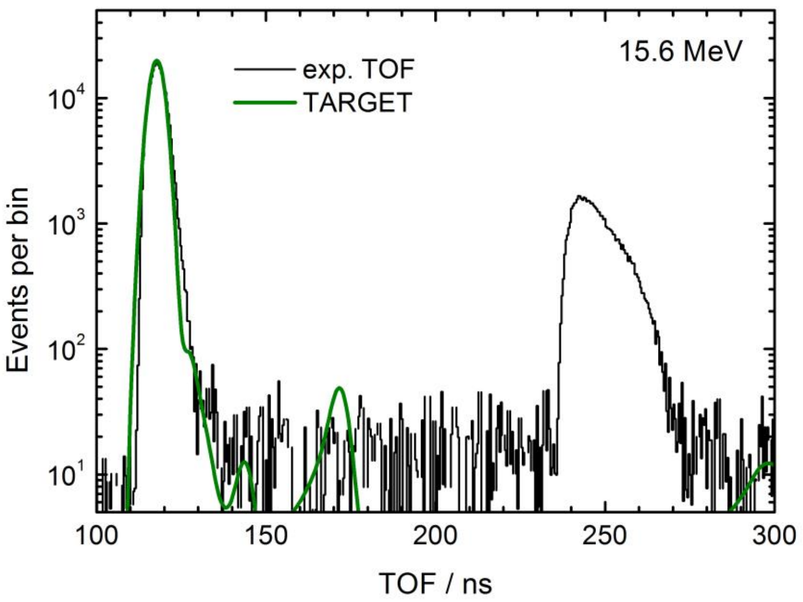


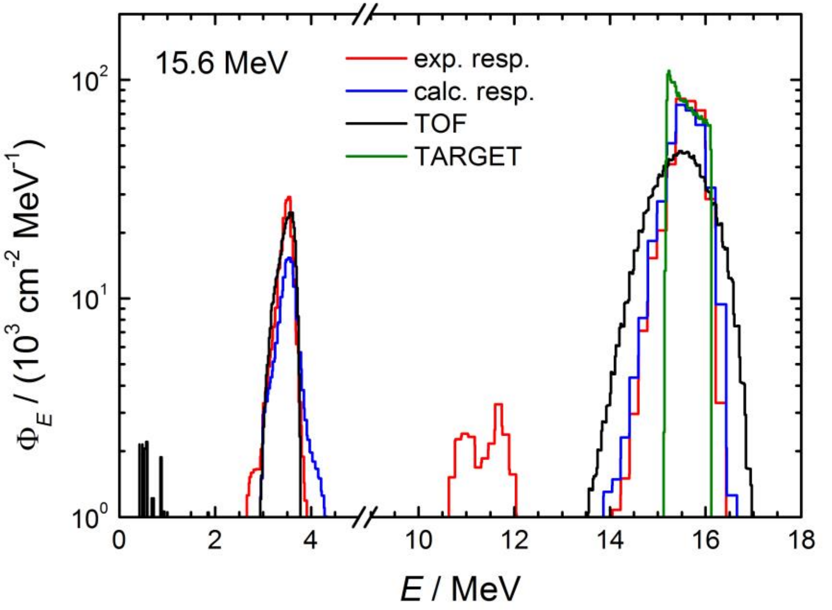
- **Passsive (offline) gain stabilization: $f_{LED} \approx 1$ kHz**
- **Unfolding with MAXED using a flat (uninformative) prior**

Ref.: A. Zimbal *et al.,* PoS(FNDA2006) 035 www.pos.sissa.it

The Dark Side of Unfolding: Artefacts

T(d,n), E_d = 643 keV, Θ = 0°: 2"×2" BC501A detector with *A* = 7.2%, *B* = 10.5%

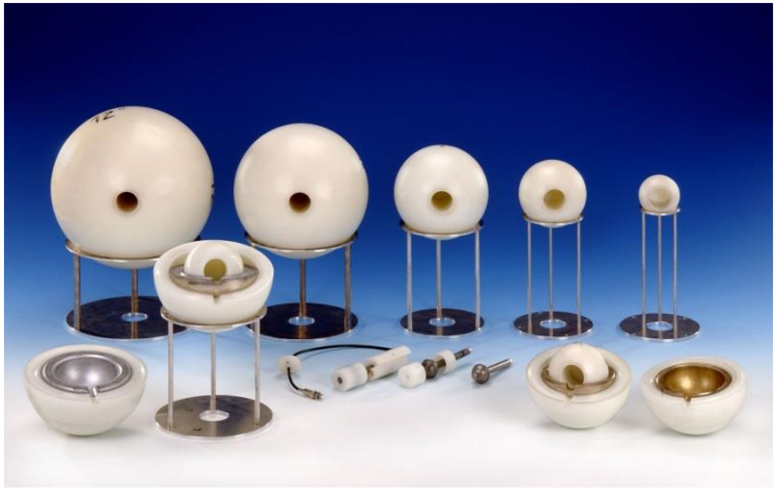




Artefacts result from imperfect response function:

- **Calc. response matrix:** **cross sections, e.g. ^{12}C(n,n'3α), light yield $L(E_n)$, resolution $\Delta L/L$**
- **Exp. response matrix:** **imperfect CFD timing (walk effect), imperfect satellite subtraction**

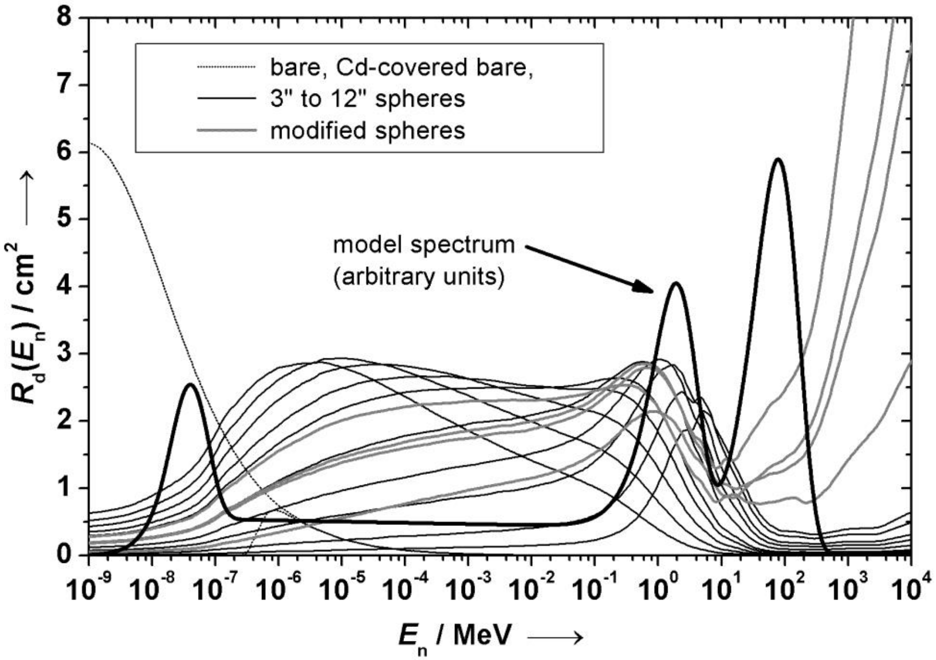
Few-Channel Unfolding: Multi-Sphere Spectrometry



- Response matrix: MCNPX
- Precise dimensions
- Measured PE densities
- Calibrated ^{3}He pressures
- Regular stability checks
- Background studied in UDO underground laboratory

BS spectrometer NEMUS

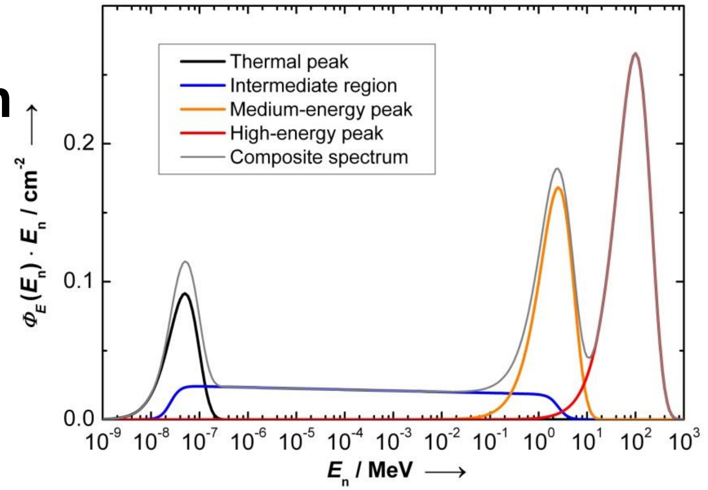
- ^{3}He detector inside moderators
- bare counter: (epi)thermal
- 12 PE spheres (3"-18"): E_n < 20 MeV
- 4 PE/(Pb,Cu) spheres: E_n < 1 GeV

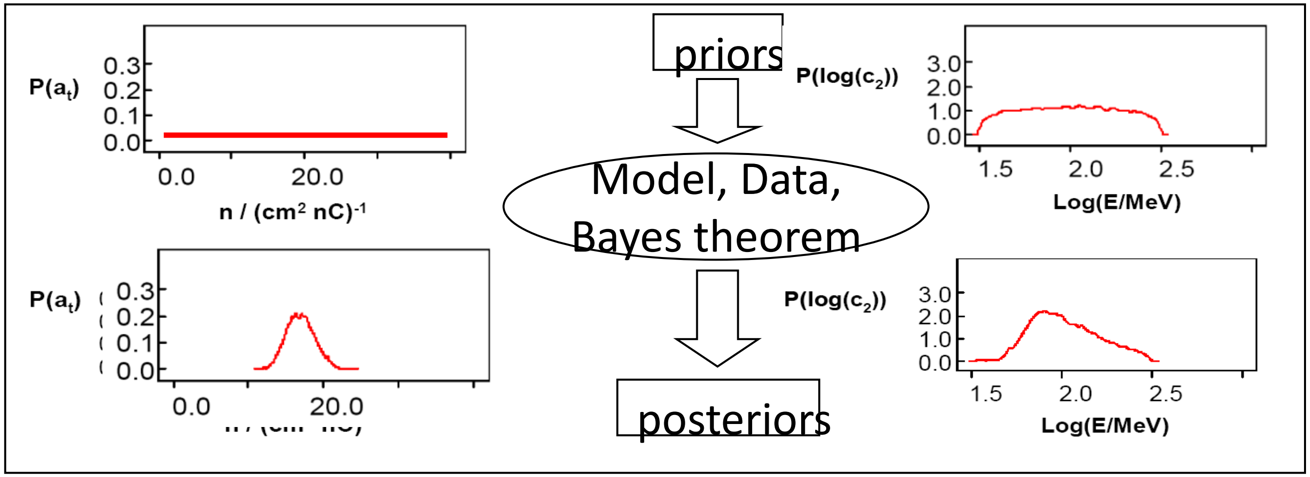


Analysis: Bayesian Parameter Estimation

- **Response functions are very similar**
- **Components of neutron spectra known**
  - **Thermal peak : ≈ 25 meV**
  - **Slowing-down cont.: ≈ flat**
  - **Evaporation peak: ≈ 2-3 MeV**
  - **'Spallation' peak: ≈ 100 MeV**

⇒ Analytical model and Bayesian parameter estimation

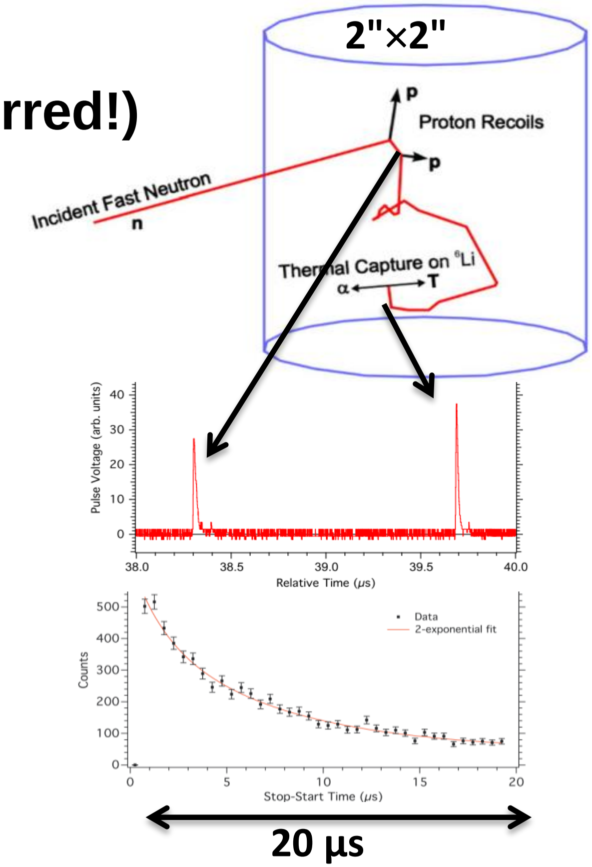




⇒ The 'spallation' peak (≈100 MeV) cannot determined only from the data!

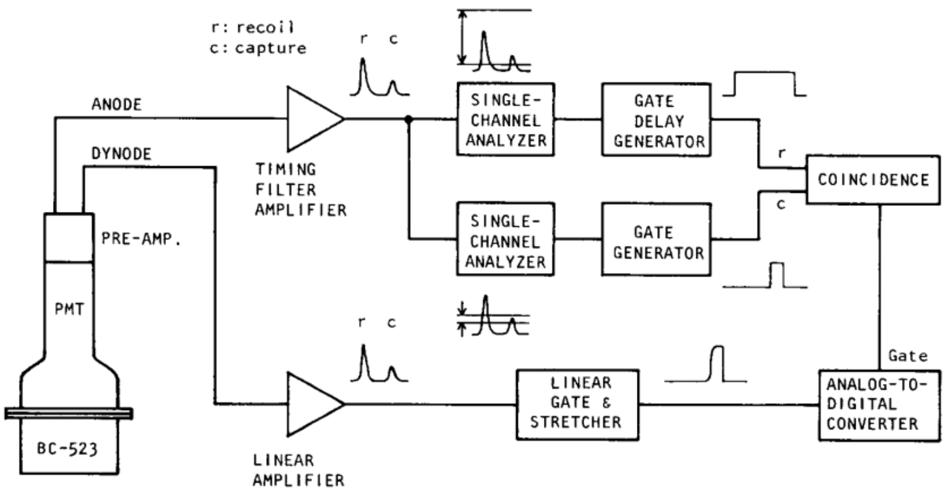
Capture-Gated Spectrometry

- **Full-energy events in doped organic scintillators ‘tagged’ by capture signal $\Rightarrow$ response ‘more diagonal’**
- **Triggers: ^{10}B(n,α)^{7}Li Q = 2.79 MeV**
  ^{6}Li(n,t)^{4}He Q = 4.78 MeV (preferred!)



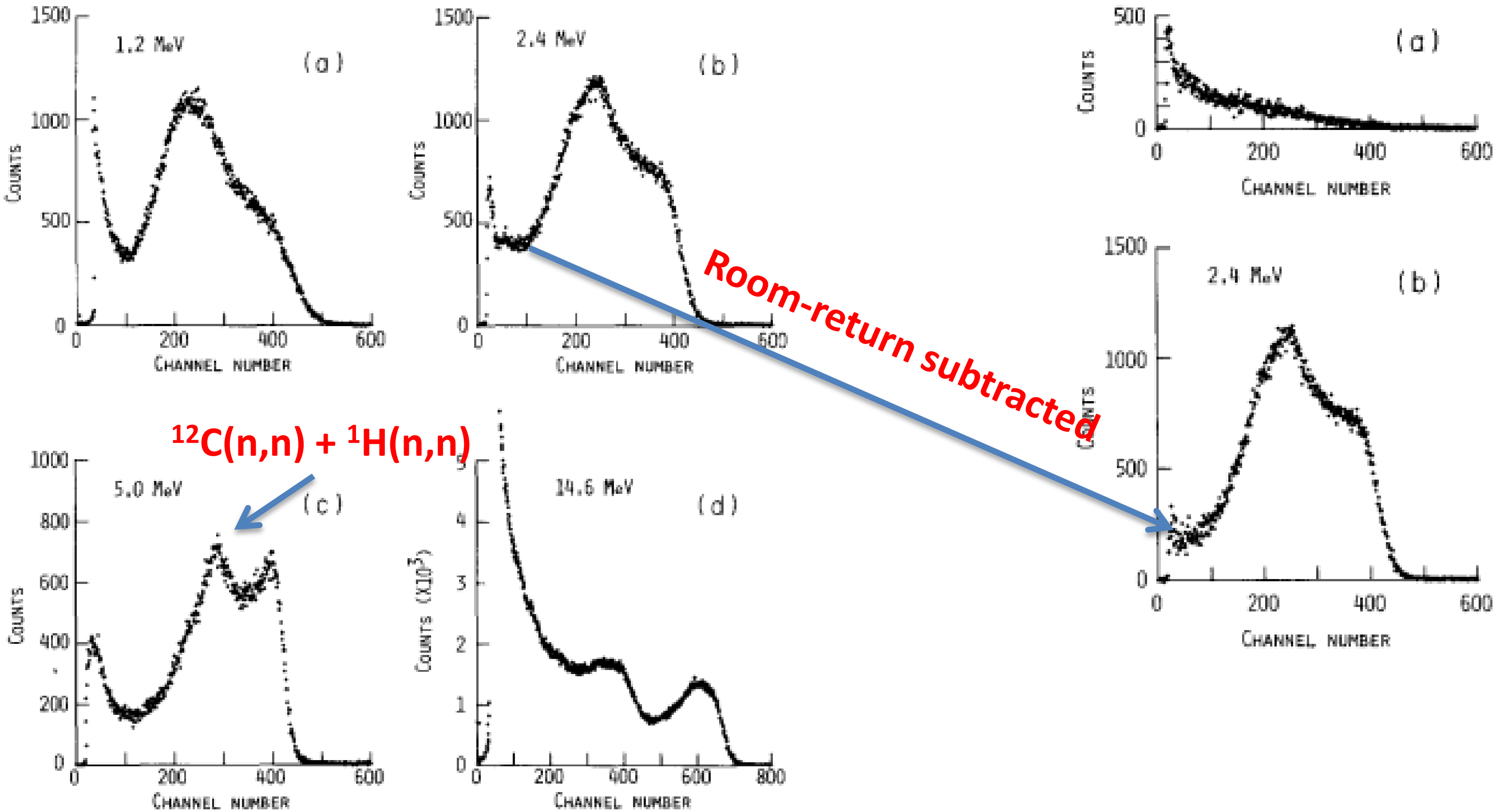
- **PH signal only from fast recoils: $t_{int} << t_{life}$**

$\Rightarrow$ Total pulse height $L(E_n)$ not prop. to E_n!



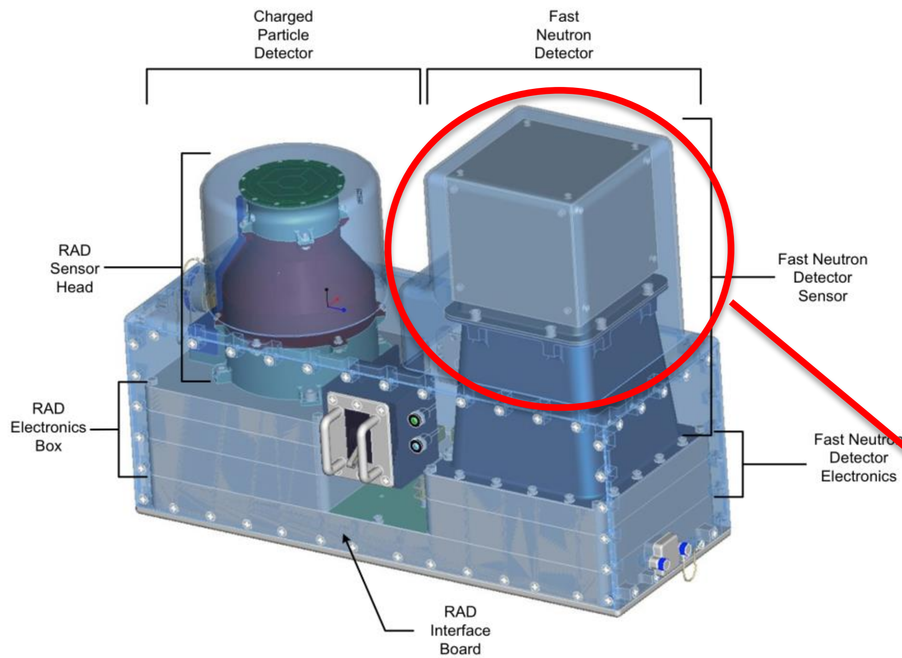
Ref.: B.M. Fisher, NIMA 646 (2011) 126 – 134
T. Aoyama, NIMA 333 (1993) 492- 501

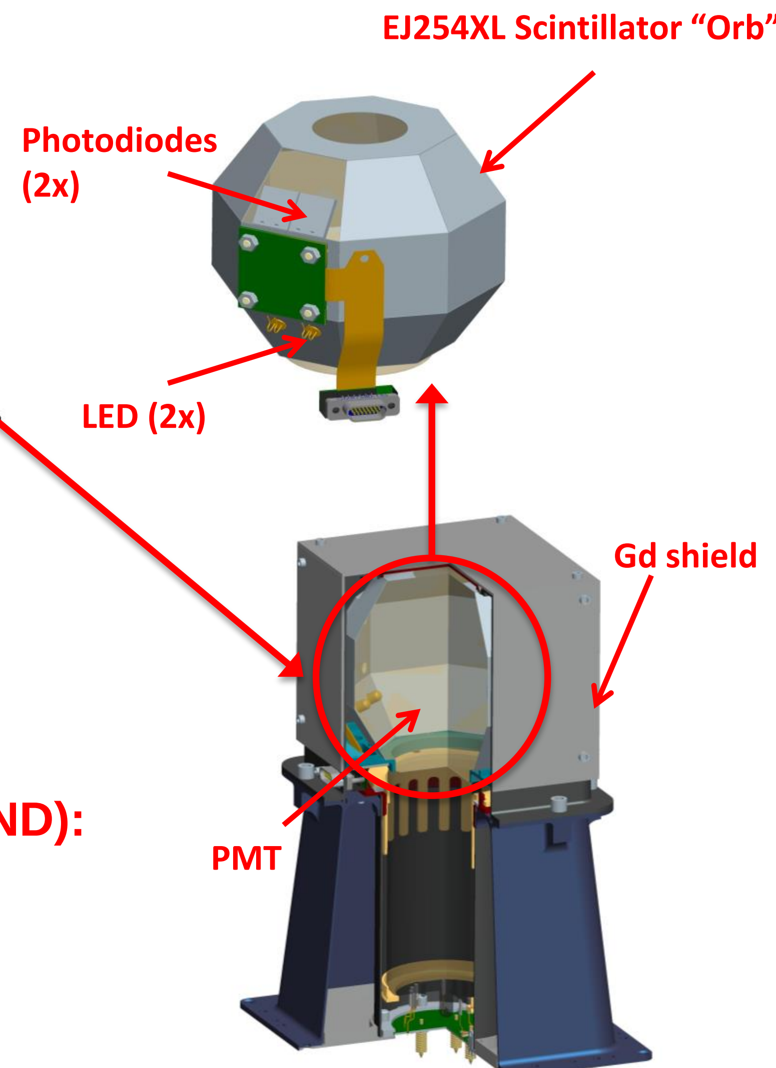
Example: 5"×"3 boron-loaded detector (BC454)



Ref.: T. Aoyama, NIMA 333 (1993) 492- 501

NASA Mars Mission





Radiation detectors on NASA Mars Rover:

- **Charged Particle Detector (CPD)**
- **Capture-Gated Fast Neutron Detector (FND):**
  - **EJ254XL ^{10}B-loaded scintillator**
  - **Calibration: LED + Diode**
  - **PMT readout**
  - **E_n = 0.5 – 8 MeV**

Courtesy: C. Zeitlin, Southwest Research Institute, Boulder (Colorado)

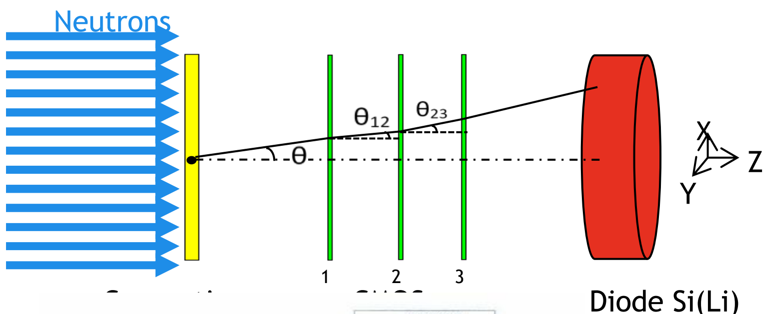
Modern Spectrometry with RTPs: Proton Tracking

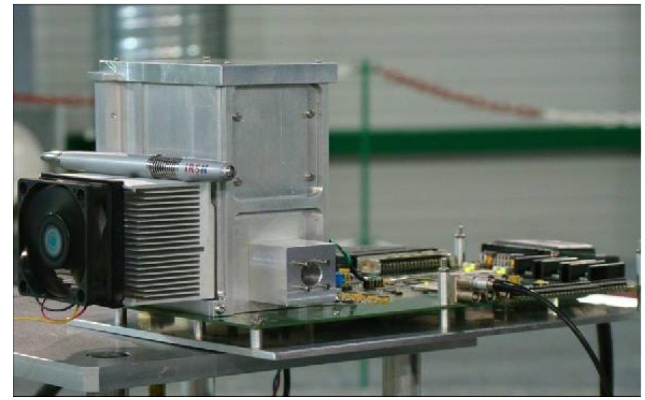
Recoil telescope with track reconstruction:

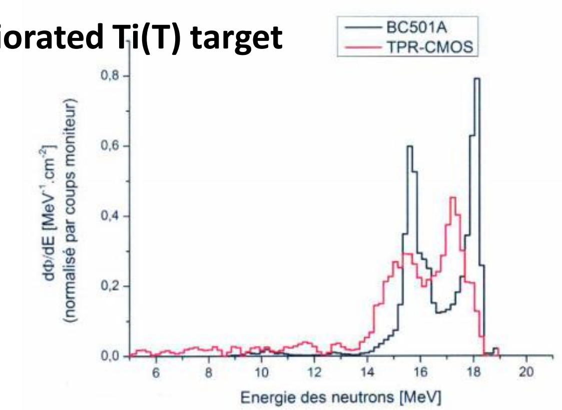
- E detectors: E_p
- ΔE detector: track reconstruction, Θ_p

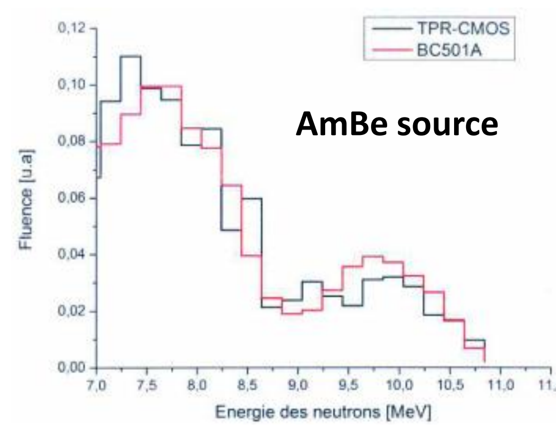
$\Rightarrow$ $E_n = E_p \,/\, \cos^2\Theta_p$

- Example: TPR-CMOS (IRSN Cadarache)









Ref.: J. Taforeau: Un spectromètre à pixels actifs pour la métrologie des champs neutroniques, Thèse, Université de Strasbourg 2013

Spectrometry using Exothermic Reactions

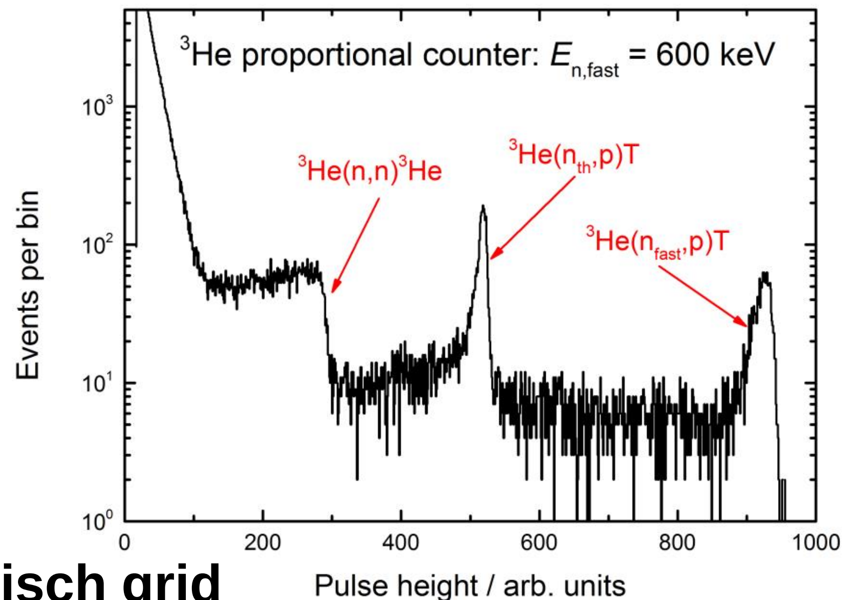
- $^{6}Li(n,t)^{4}He$, Q = 4.78 MeV,
  $^{3}He(n,p)T$, Q = 0.76 MeV
- High thermal cross section: $\sigma = \sigma_0 \cdot (v_0/v)$ for $E_n < 100$ keV

⇒ Spectrometry by detection of both reaction products:

- (epi)thermal peak: c_{th}
- fast peak: c_f
- zero bias: c_0

$$E_n = \frac{c_f - c_{th}}{c_{th} - c_0} Q$$

NB: constant *W*-value assumed !

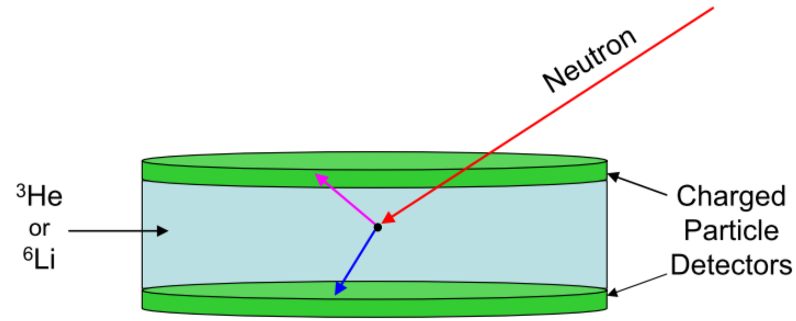


- Proportional counters
- Ionization chambers with Frisch grid

^{3}He and ^{6}Li Sandwich Spectrometers

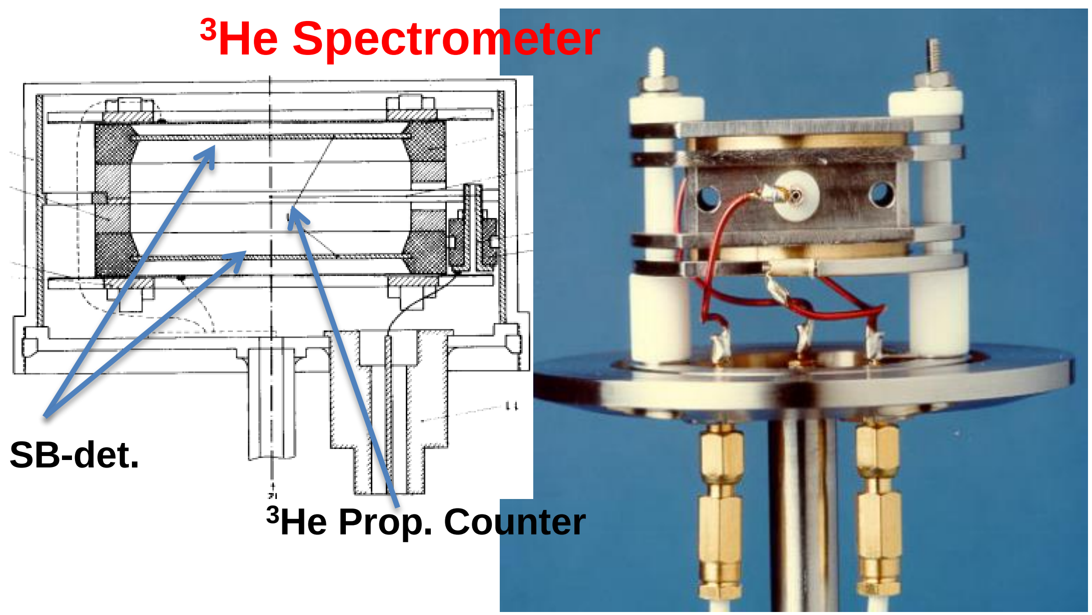
^{3}He spectrometer

- Small recoil energies
- n/γ interference
- High efficiency
- Small energy loss



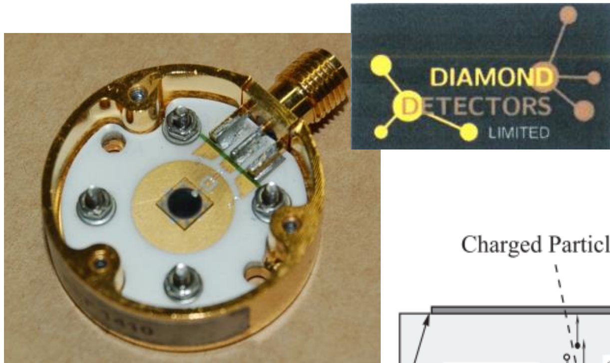
^{6}Li spectrometer:

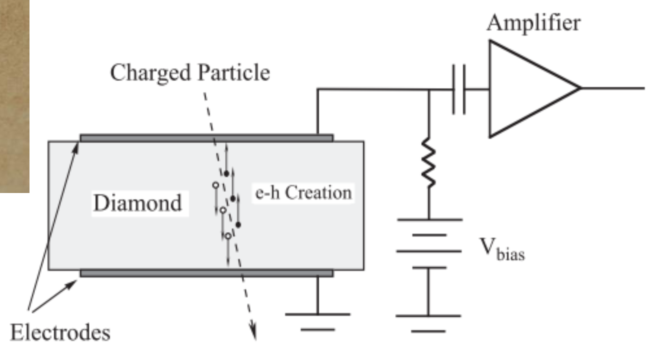
- High recoil energies
- Good γ suppression
- Resolution depends on radiator thickness
- $E_{n,min}$ = 100 - 500 keV



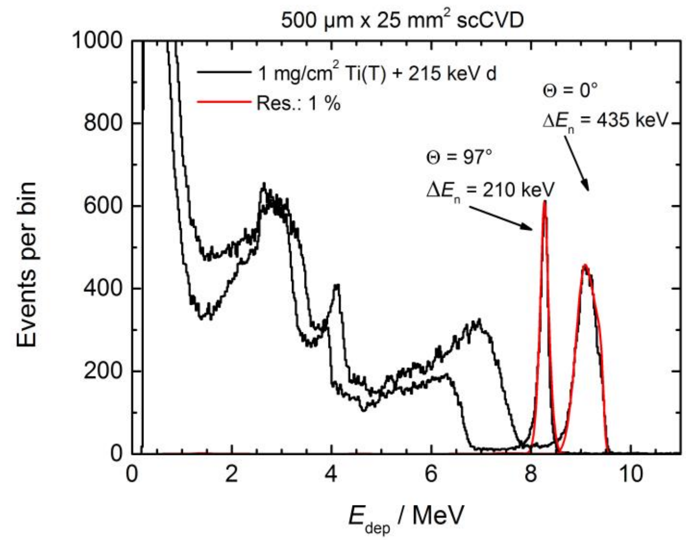
Ref.: H. Bluhm *et al.,* NIM115 (1974) 325-337

Spectrometry using scCVD Diamond Detectors





Ref.: H. Kagan, NIMA 546 (2005) 222-227



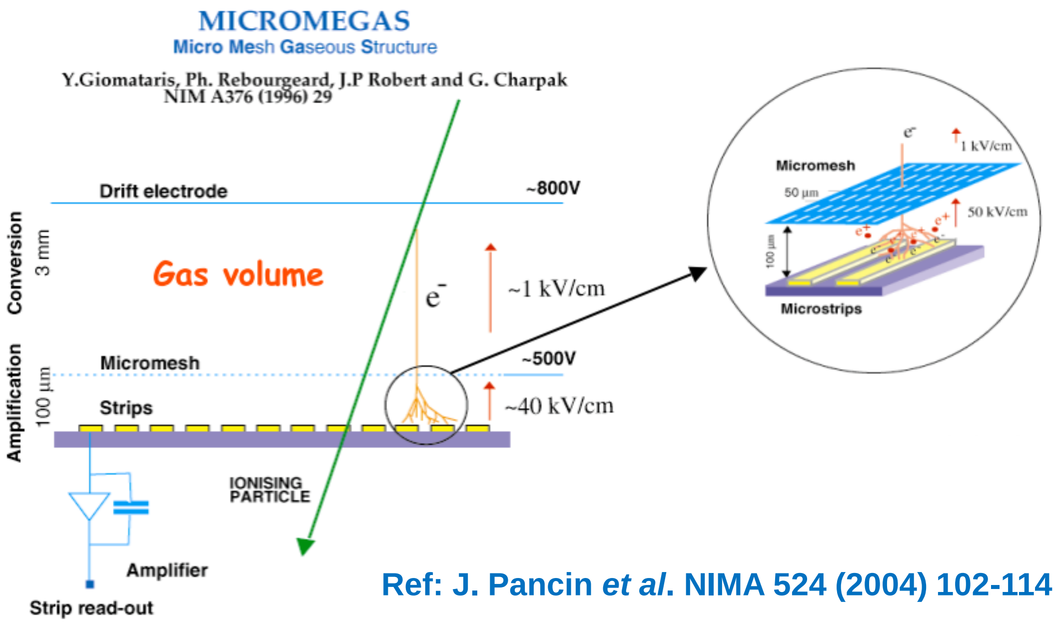
Single-crystal chemical vapor deposition diamond detectors (scCVD):

- Neutron detection via $^{12}C(n,\alpha)^{9}Be$: full-energy peak
- Large displacement energy (42 eV/atom) $\Rightarrow$ high radiation hardness
- High thermal conductivity $\Rightarrow$ operation at elevated temperature
- But: large band gap (5.5 eV) $\Rightarrow$ resolution not as good as silicon (1.11 eV)

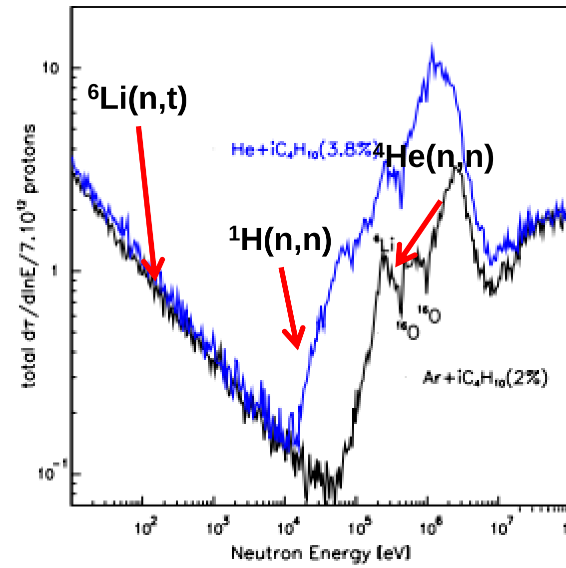
$\Rightarrow$ Very attractive material for neutron spectrometers

The Measurement of Spatial Neutron Distributions

The Micromegas Beam Imager for n_TOF

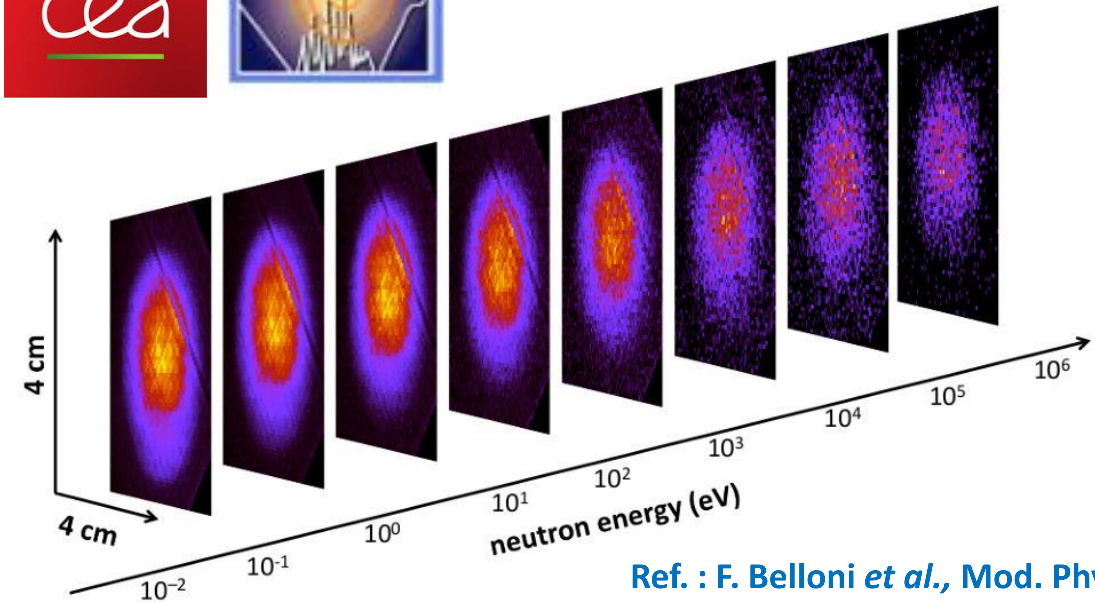


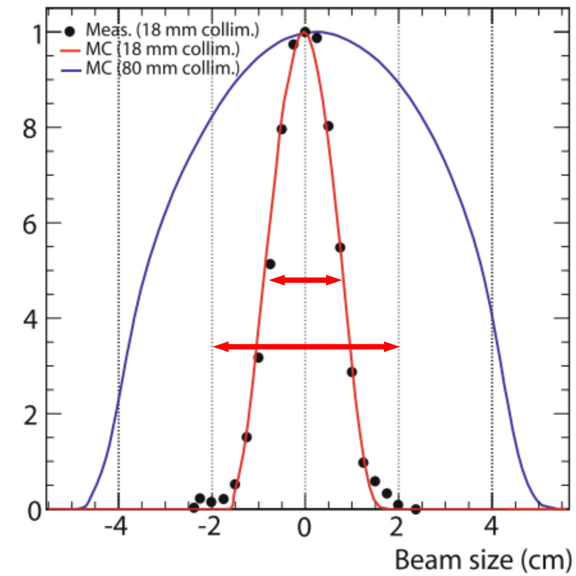
Ref: J. Pancin *et al*. NIMA 524 (2004) 102-114



- **Neutron detection:**
  - **^{6}Li, ^{10}B converter**
  - **Counting gas: p, He recoil**
- **Energy-resolved images: 10 eV – 20 MeV**
- **Several 1-dim. and 2-dim. (strips or pixels) read-out schemes**
- **Spatial resolution: ≈ 0.5 mm**

Micromegas Results





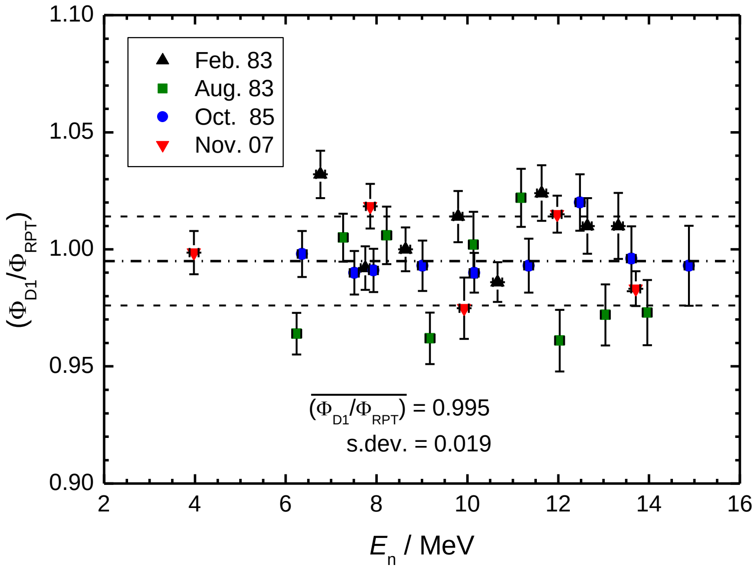
Ref. : F. Belloni *et al.,* Mod. Phys. Letters A 28 (2013) 1340023

- **Profile of the n_TOF neutron beam:**
  - **Converter: LiF, $^{10}B_4C$**
  - **Readout anode: 6 cm × 6 cm with 106 x and y strips, Gassiplex readout chip**
- **Determination of beam coverage factors for large sample**

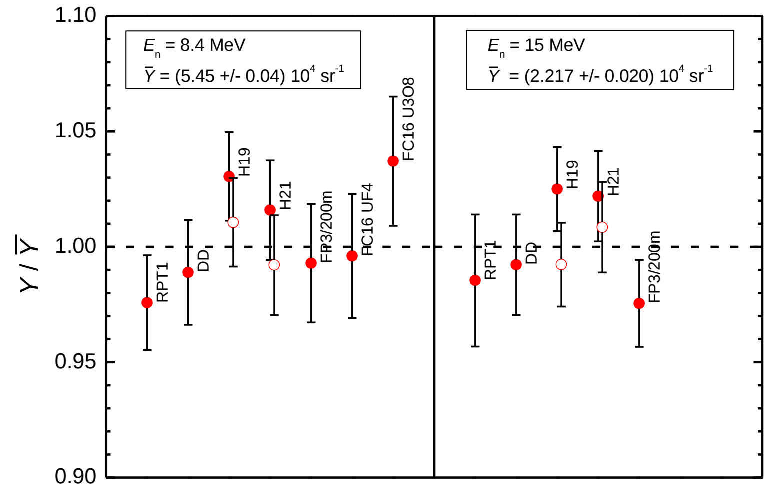
Absolute Methods, Key Comparisons

Stability and Consistency of Neutron Measurements

Stability



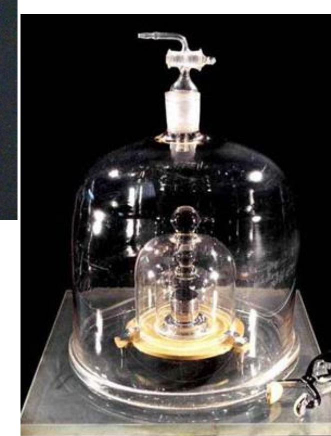
Consistency



- **Ref. detectors depend on ref. materials**
  - **Purity of gases (H_2, CH_4, C_3H_8): RPPC**
  - **Tristearin ($C_{57}H_{110}O_6$) radiators: RPT**
  - **^{235,238}U deposits: FC**

⇒ Test of stability and consistency

⇒ Comparison with ‘absolute methods’



Standards: Absolute Methods

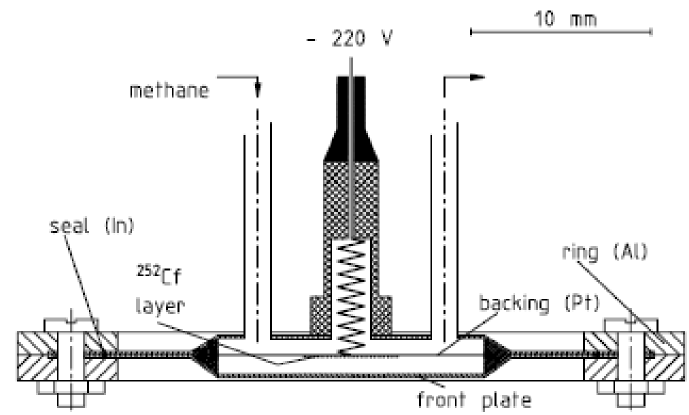
Traceability of detector calibrations to the SI requires

‘Absolute’ methods for neutron production:

- Manganese bath: ^{56}Mn(n,γ) in a saturated $MnSO_4$ solution
  - only for radionuclide sources
  - 50% correction for capture and leakage
  - 0.5 % uncertainty of the emission rate
- Time-correlated associated particles (‘tagged neutrons’):
  - ^{252}Cf(s.f.): standard technique, relies on <ν> ✓
  - D(d,n)^{3}He: standard technique, difficult ✓
  - T(d,n)^{4}He: standard technique ✓
  - H(n,n)p: low count rates ✓
  - D(γ,n)p: requires a tagged bremsstrahlung beam
  - D(p,n)2p: very difficult
- Uncertainty of (TC)AP method: 1% - 1.6%
  for T(d,n)^{4}He, $E_n \approx 14.2$ MeV

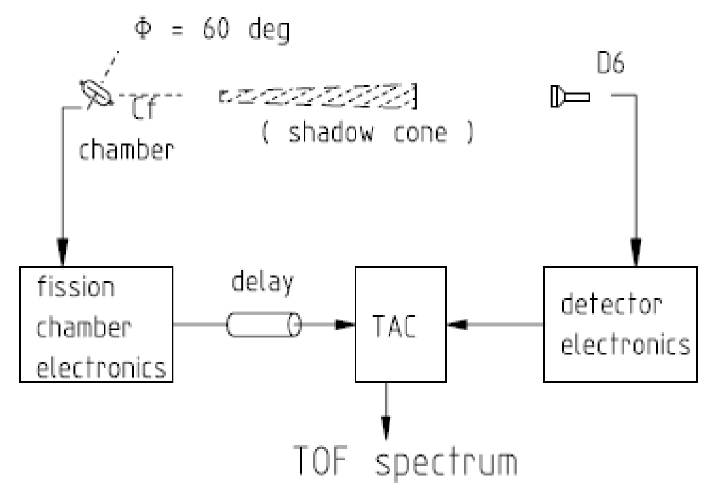
^{252}Cf(s.f.) Ionization Chamber

- **Low-mass parallel-plate IC with ^{252}Cf source:**
  A_a = 4.5 MBq ⇒ R_{sf} = 1.4·10^5 s^{-1}
  time resolution: ≈ 1 ns



- **Neutron 'tagged' by fission fragments**

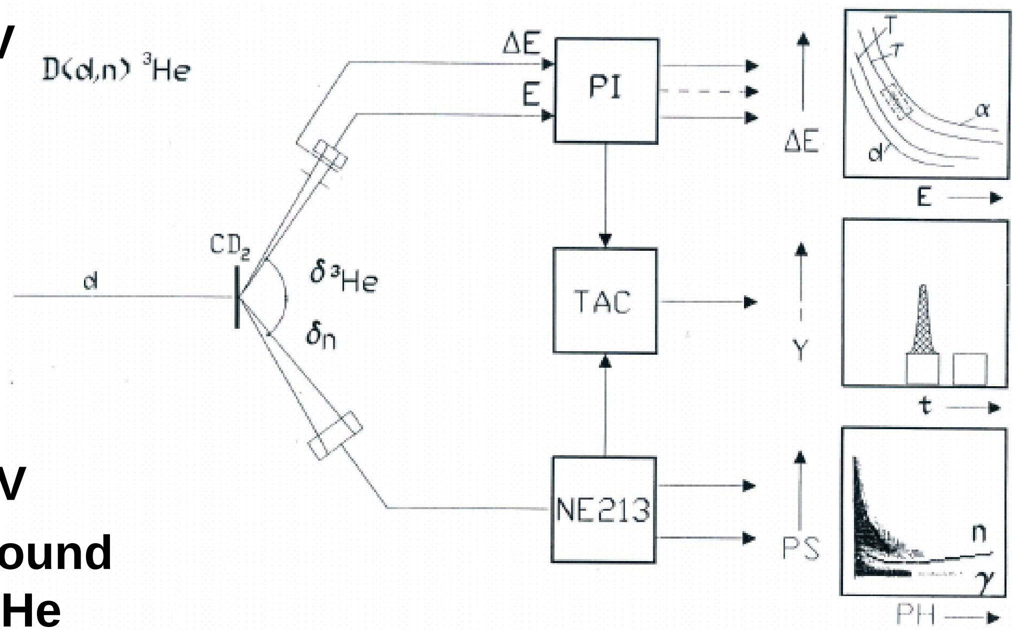
- **Prerequisites:**
  - **Evaluated ^{252}Cf neutron spectrum and $\bar{\nu}$**
  - **Corrections:**
    - deadtime and uncorrelated stops
    - fragment detection efficiency
    - neutron emission anisotropy
    - neutron transport, air scattering



TCAP: $T(d,n)^4He$, $D(d,n)^3He$

'Tagging' of neutrons by the associated charged particle

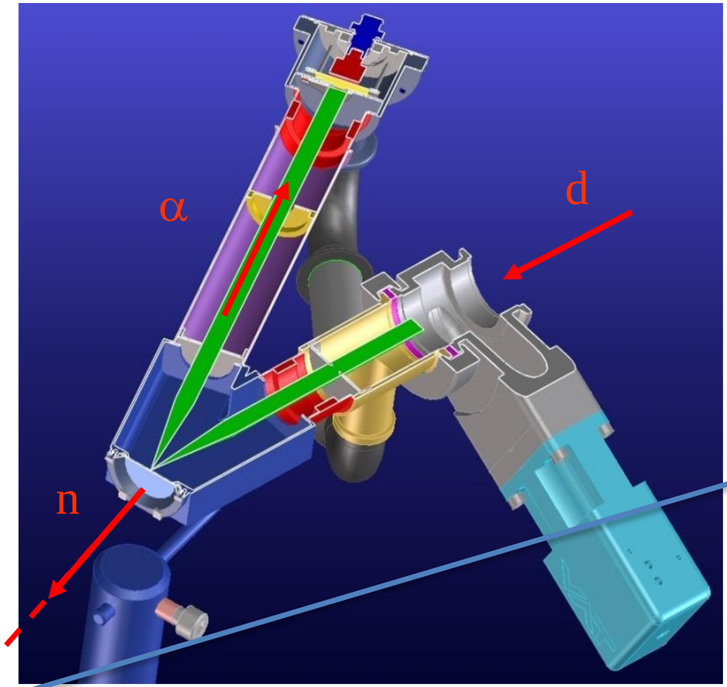
- **$T(d,n)^4He$, E_d = 150 keV**
  - $\Theta_n = 26.5°$, $\Theta_\alpha = -150°$
  - E_n = 14.48 MeV, E_α = 2.46 MeV
  - no (d,d) background
  - $^3He(d,p)^4He$ can be a problem
  - 'routine' 14 MeV standard

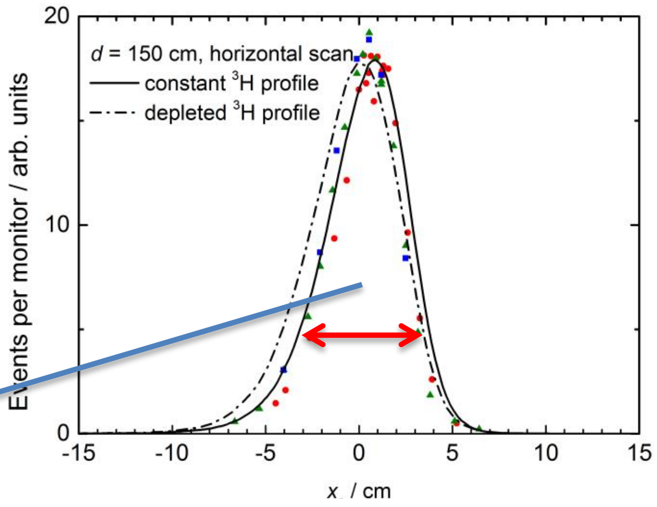


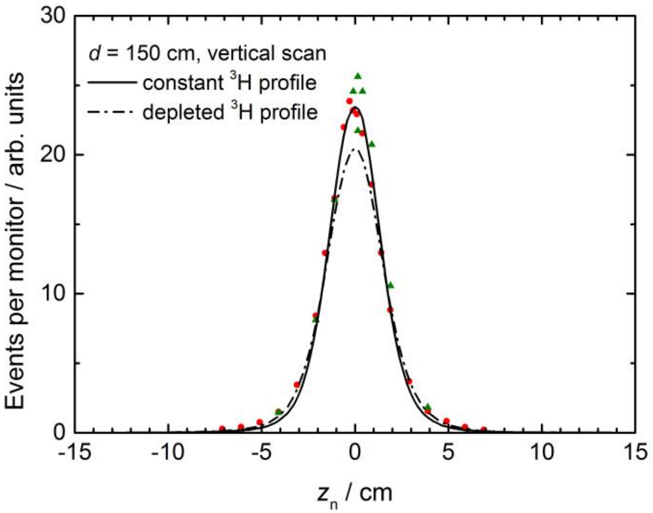
- **$D(d,n)^3He$, E_d = 4 MeV**
  - $\Theta_n = 40°$, $\Theta_{3He} = -59.8°$,
  - E_n = 6.13 MeV, E_{3He} = 1.14 MeV
  - strong (d,d) and (d,p) background requires ΔE-E separation of ^3He

- **Problem of all TCAP experiments:**
  Loss of correlation due to angular straggling!

TCAP with T(d,n) at $E_{d,0}$ = 150 keV





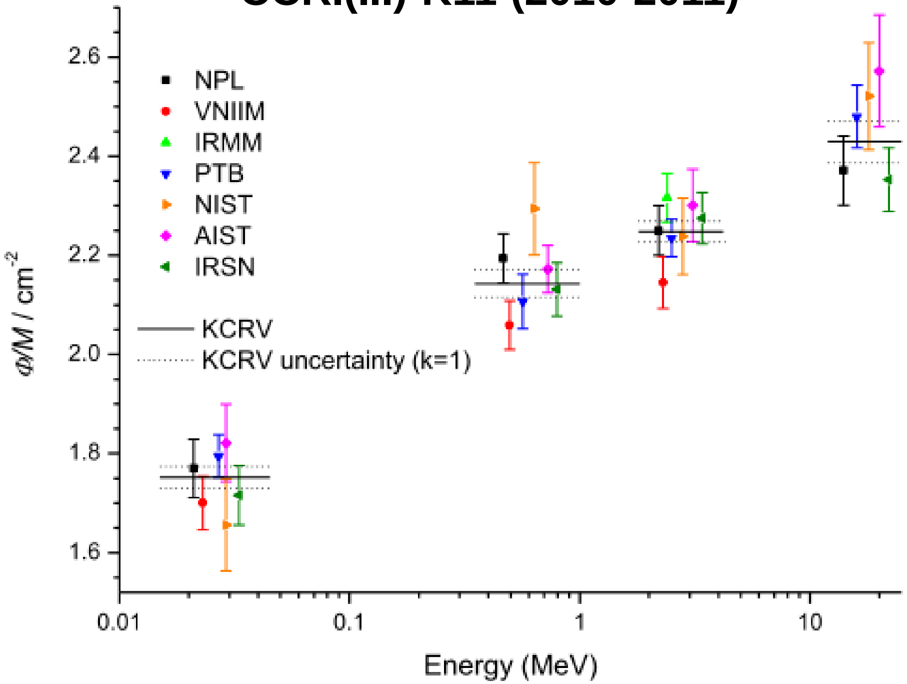


- **Shape of the associated neutron cone:**
  - **Tritium depth profile in Ti(T) target**
  - **Position of the beam spot**
- **Modeling of the transport of 150 keV d in Ti(T) is a challenge!**

Metrological Cooperation: Key Comparisons

- Organized within the CCRI(III) of the BIPM
- Regular Key Comparisons (every 10 years)
- Results go into the KCDB: www.bipm.org
- the ‘usual suspects’:
  - CIAE (PR China)
  - LNE / IRSN (France)
  - IRMM (EU)
  - NPL (UK)
  - NMIJ (Japan)
  - NIST (USA)
  - PTB (Germany)
  - VNIIM (Russia)
- Typical uncertainties:
  - KCRV: 1 – 1.5 %
  - Standard deviation: 2 – 4 %

CCRI(III)-K11 (2010-2011)



Summary:

Neutron detection means conversion to charged particles:

- **Products of two-particle reactions with high *Q* value**
- **Recoil particles**
- **Fission fragments**

Measurements techniques:

- **Time-of-flight spectrometry**
- **Unfolding of signal distributions**

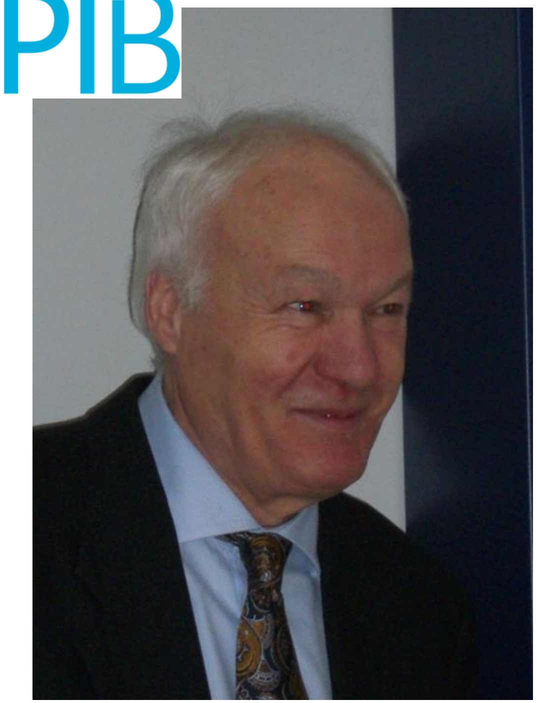
Normalization:

- **relative to cross sections standards**
- **‘absolute’ neutron counting**

Tributes

Frank Brooks

1931-2012



Horst Klein

Thank you for your attention!

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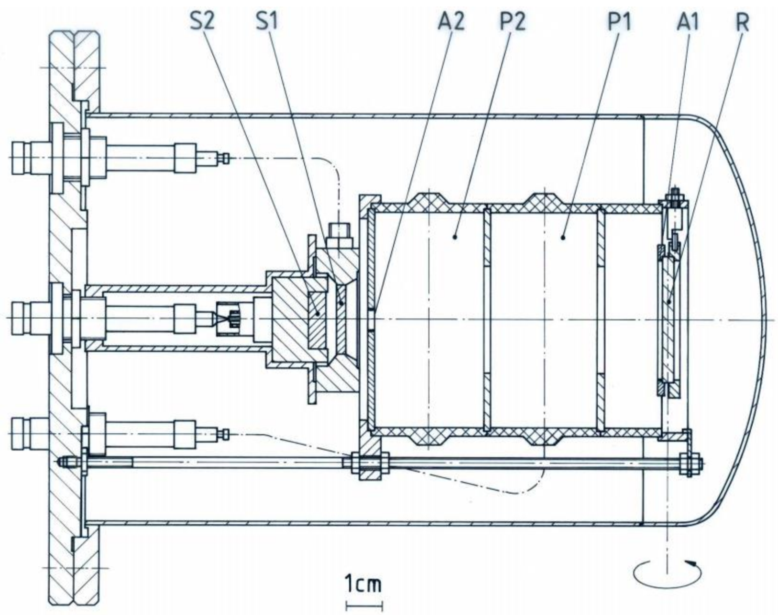
www.ptb.de

Additional Material

High-Energy Telescopes

Neutron energies above 20 MeV pose special challenges:

- **Large proton ranges: degraders, thick stopping detectors**
- **Charged particles from n+^{12}C: high-resolution ΔE-E particle discrimination**
- **Neutron induced coincidences: more coincidence conditions**
- **'Grey' apertures: active collimation by veto detectors (E_n > 100 MeV)**



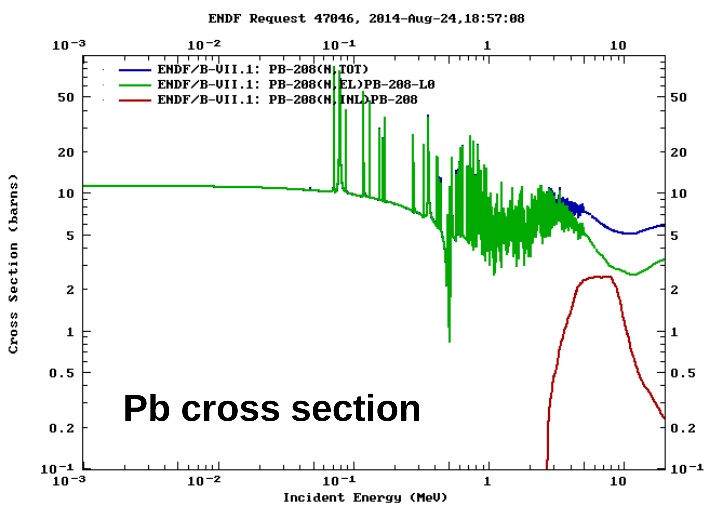
Proton recoil telescope T2: E_n = 20 – 60 MeV

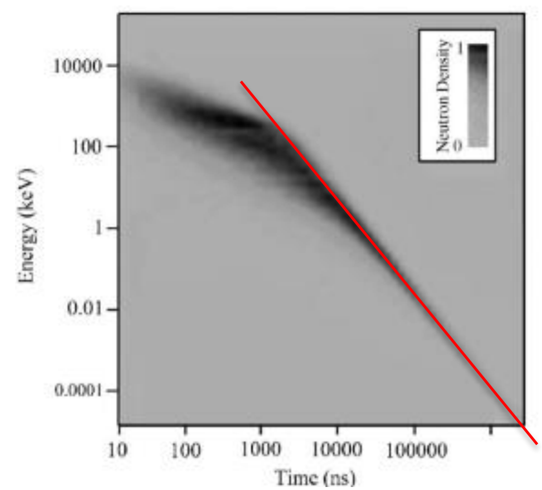
TOF Variants : Slowing-Down Spectrometry

Heavy (A = 208) non-absorbing moderator with constant isotropic scattering cross section:

- **Small mean log. energy loss per collision:** $\xi = \dfrac{2}{A + 2/3} = 9.5 \times 10^{-3}$
- **Rel. std. deviation of slowing-down time:** $\sqrt{\dfrac{\sigma_{t_E}^2}{\bar{t}_E^2}} \approx \sqrt{\dfrac{2}{3A}} = 5.7 \times 10^{-2}$, **mean energy:** $\sqrt{\dfrac{\sigma_{\bar{E}}^2}{\bar{E}^2}} \approx \sqrt{\dfrac{8}{3A}} = 0.11$

$\Rightarrow$ Time dependence of the velocity v: $\boxed{v(t) = \dfrac{2}{\xi \Sigma_s t} \quad (v << v_0)}$



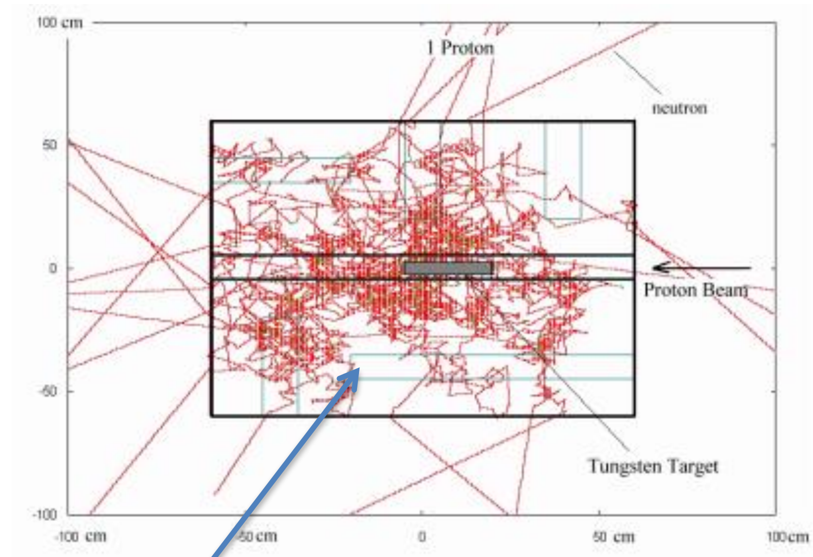


Lead Slowing-Down Spectrometer (LSDS)

- **Semi-empirical relation between energy $\bar{E}$ and slowing-down time *t*:**

$$\bar{E}(t) = \frac{K}{(t - t_0)^2}$$

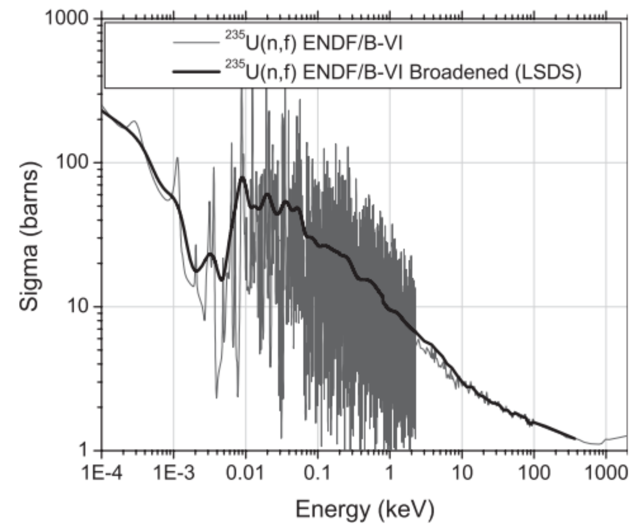
- **K and t_0 :**
  - **MC simulations**
  - **resonance analysis**
- **Very high neutron flux**
- **Energy range 0.1 – 100 eV**
- **Application:**
  - **Reactions with rare isotopes**
  - **Fission of very radioactive isotopes**
  - **Fission of isomers**



Detectors inserted in the moderator:
- **Compensated fission chambers**
- **Solar cells with fissile layers**
- **…**

The LANSCE Slowing-Down Spectrometer

Resolution broadening



Ref.: D. Rochman *et al.*, NIMA 550 (2005) 397-413

- **High-purity lead cube: V = (1.2 m)^3**
- **WNR beam (800 MeV p), tungsten target**
- **Resolution: $\Delta E/E \approx 0.29$**