Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
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Detection of Neutrons: Part I

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Table of Contents

Where to Find More Reference Material?

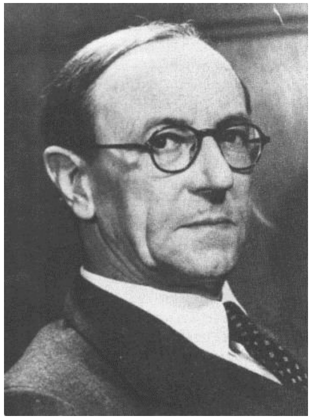
- **W.D. Allen:** **Neutron Detection (1960)**
- **J.B. Marion, J.L. Fowler:** **Fast Neutron Physics (1960)**
- **K.H. Beckurtz, K. Wirtz:** **Neutron Physics (1964)**
- **W.R. Leo:** **Techniques for Nuclear and Particle Physics Experiments (2nd ed. 1994)**
- **G. Knoll:** **Radiation Detection and Measurement (4th ed. 2010)**

Conference proceedings:

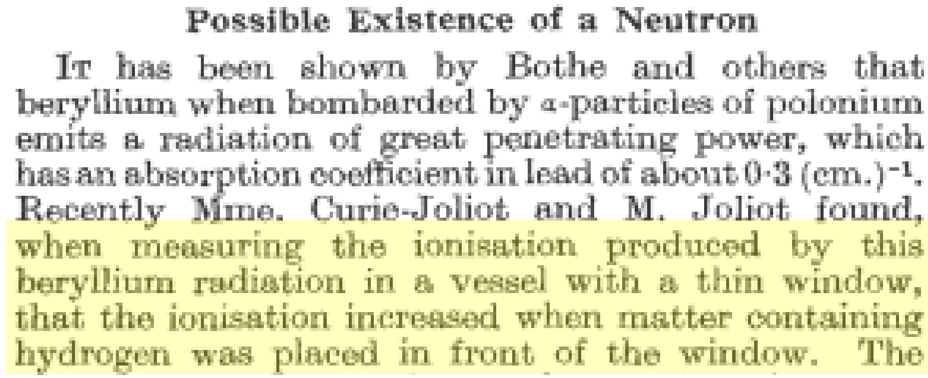
- **H. Klein *et al.* :** **Proc. NEUSPEC 2000 NIMA 475 (2002)**
- **SORMA, Crete, ND, …**

Historical Prelude: Chadwick's Discovery of the Neutron

- Sir James Chadwick (1932)



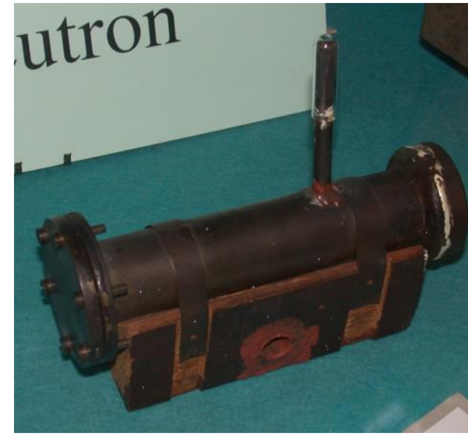
…the man who never laughed



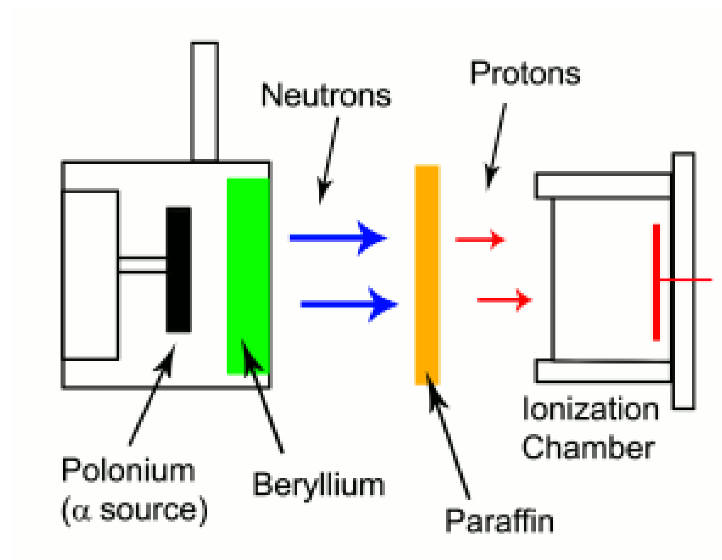
Possible Existence of a Neutron

It has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The

Ref.: J. Chadwick, Nature 132 (1932) 3252



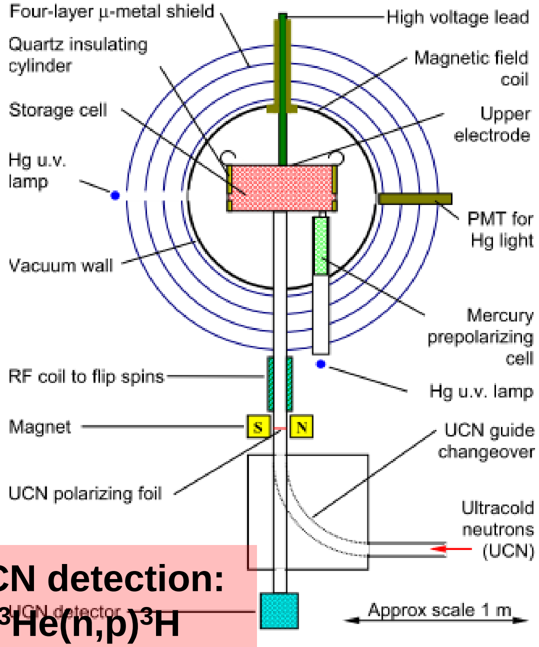
- Correct explanation of the experiments by I. Curie and F. Joliot
- All elements of a modern neutron detector were present:
  - Neutron converter
  - Detector for charged particles



Neutrons in Science …

- **Laboratory for fundamental physics: EDM, …**

$$\hbar\omega_L \sim \mu \cdot B + d \cdot E$$

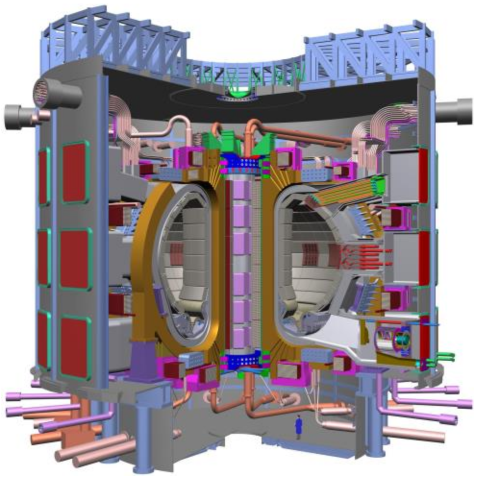


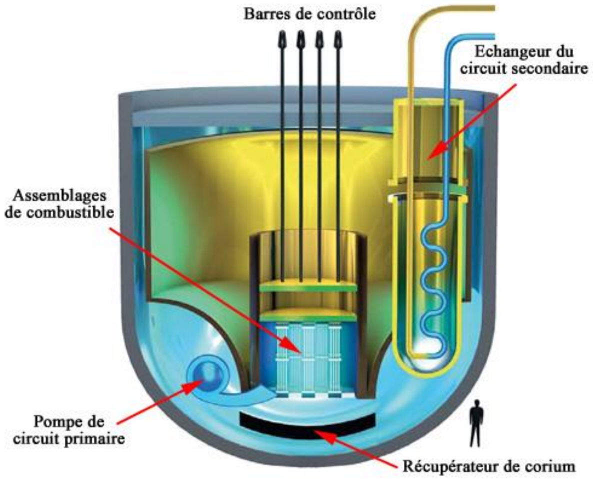
UCN detection: $^3He(n,p)^3H$

- **Ideal tool for probing matter:**
  - **No Coulomb force: deep penetration**
  - **Strong Interaction: isotope-specific detection**
  - **Magnetic moment: magnetic structures**
  - **Low energies: crystal structures**

… Technology

- Neutrons can be used to produce energy
  - Fusion
  - Fission





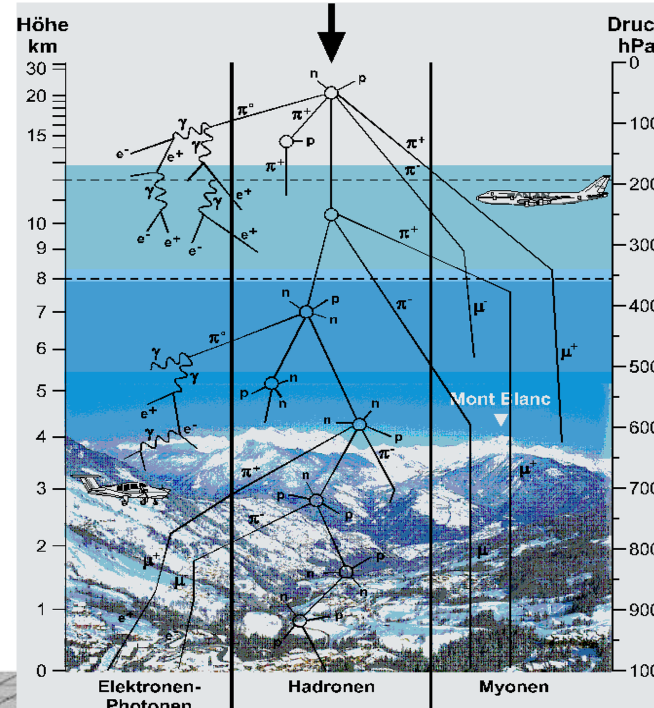
- Biggest disadvantage: the (free) neutron is unstable:

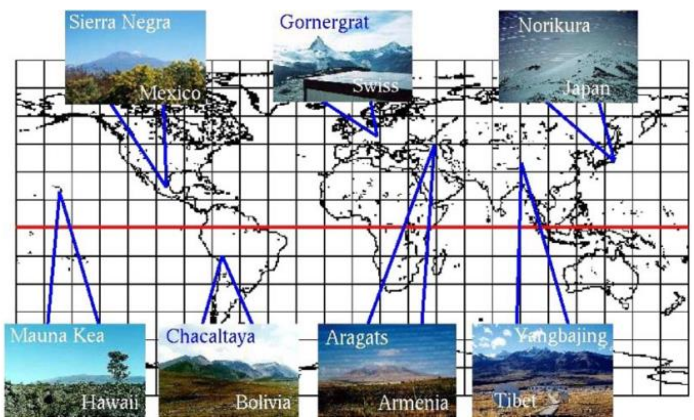
$$\tau \approx 880 \text{ s}$$

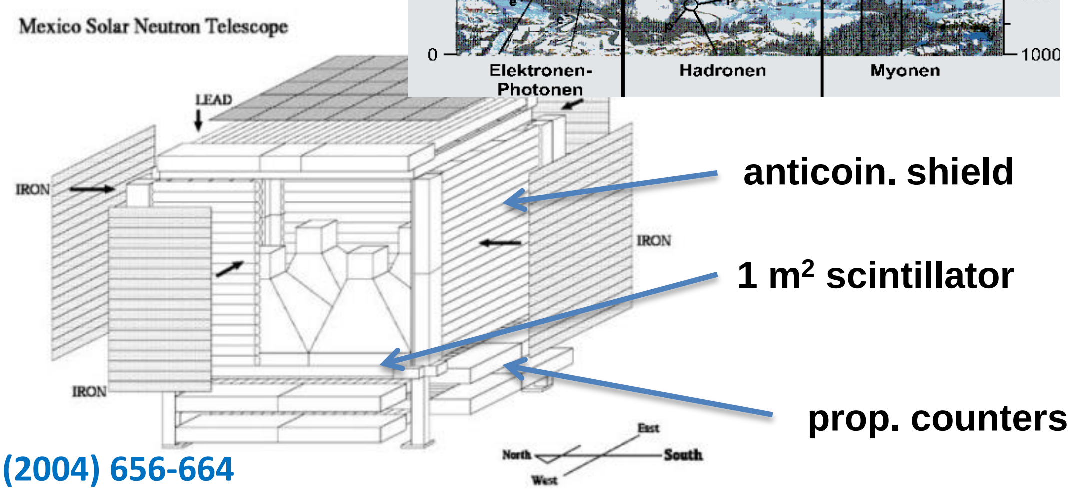
- Intense neutron sources require considerable efforts:
  - Reactors
  - High-power low-energy accelerators
  - Spallation sources

… and the World Around

- **Cosmic Neutron:**
  - **Production in the atmosphere by galactic radiation**
  - **Production on the sun**
- **Neutron monitors:**
  Diagnostic for solar processes
- **Radiation protection at flight levels:**
  d*H** $_{n}$ **/dt ≈ 1 - 4 µSv/h at 12 km**



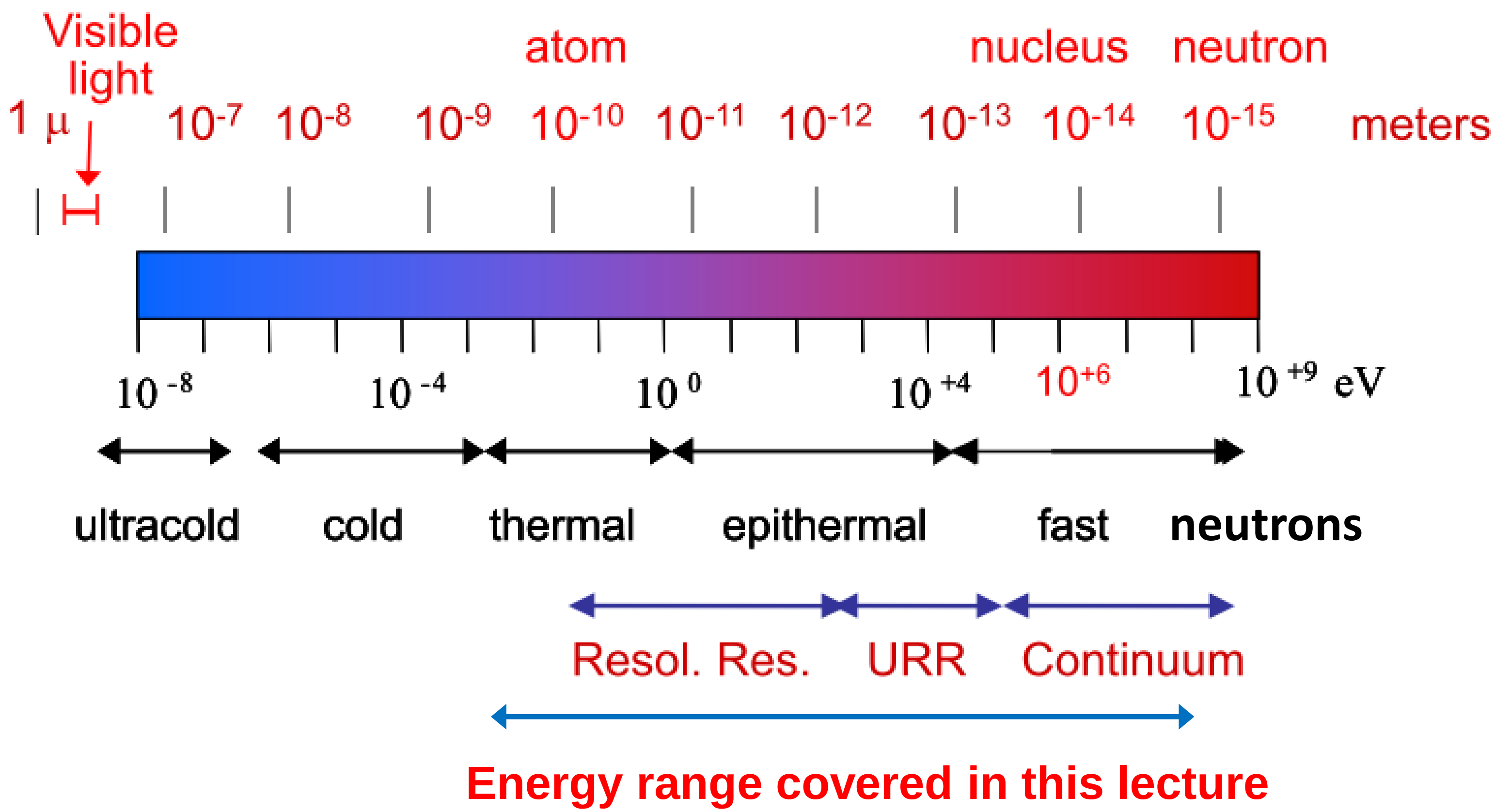




Ref.: J.F. Valdéz-Galicia *et al*., NIMA 535 (2004) 656-664

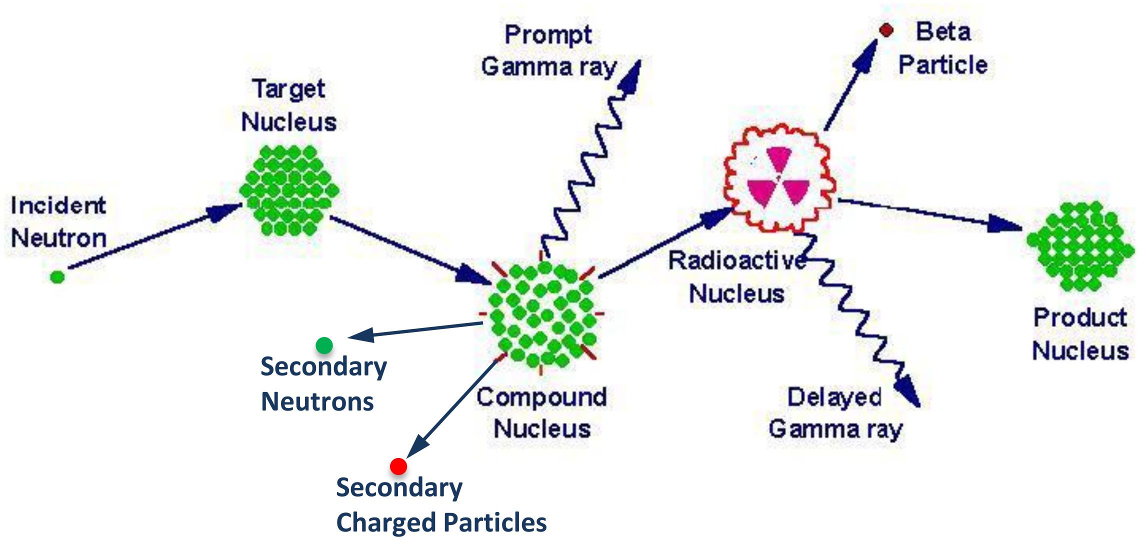
Classification of Neutrons

de Broglie wavelength: $\lambda = h / p$



General Detection Principles

- **Neutron detectors do not detect neutrons but products of neutron interactions!**



- **Almost all detector types can be made neutron sensitive:**
  - **external converter (radiator)**
  - **converter = detector**

The Neutron Detection Process

- **Detection of a neutron is a sequential process:**
  1. **Interaction of the incident neutron: Neutron transport**
  2. **Transport of secondary particles to or within sensing elements: Hadron, ion, photon transport**
  3. **Primary ionization by secondary particles**
  4. **Conversion to optical photons, gas amplification: Transport of electrons and optical photons**
  5. **Conversion to electrical signal *S***
- **These steps are described by transfer functions $T_i\,(s_{i\text{-}1}, s_i)$**
- **Convolution of the T_i's: Response function $R(S,E)$**

$$N_S(S) = \int R(S,E)\,\Phi_E(E)\,\mathrm{d}E$$

… How to solve this integral equation?

General Detection Principles

Basic requirements for neutron detection:

- Slow neutrons: high Q-values, no resonances!
- Fast and high-energy neutrons: large smooth cross sections!

Basic types of neutron detectors:

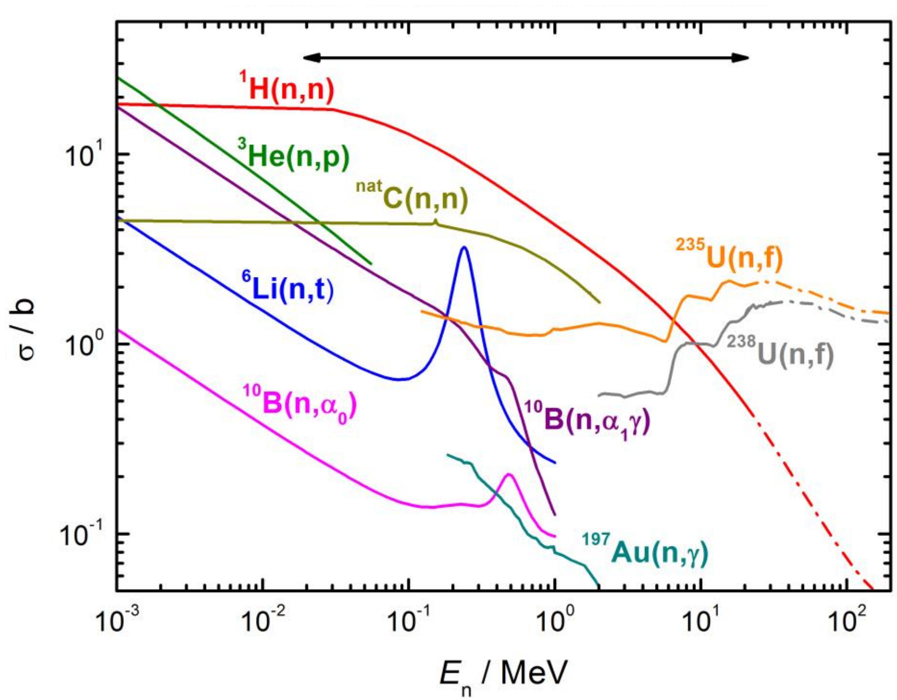
- Neutron counters
  - Signal does not depend on neutron energy
  - Typical for detection of thermal neutrons
- Neutron spectrometers
  - Signal <u>somehow</u> related to neutron energy
  - Inversion procedures are used to infer the neutron energy distribution

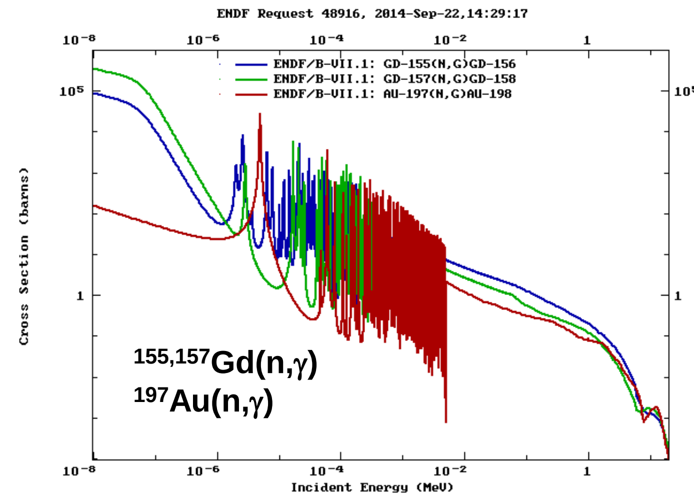
Interaction of Neutrons with Matter

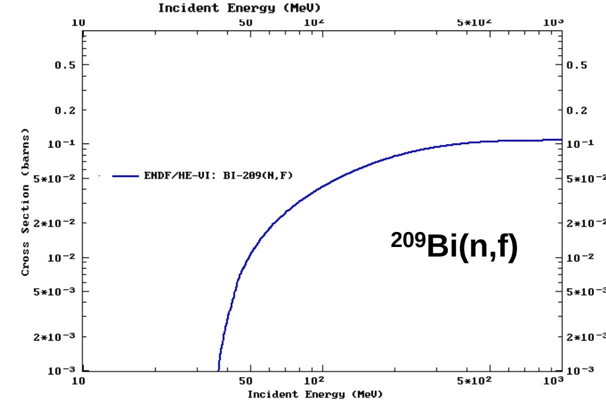
Neutrons can only be detected after conversion to charged particles or photons:

- **Elastic scattering:** $^{A}X(n,n)^{A}X \rightarrow$ recoil nucl. $^{A}X^{z+}$
- **Inelastic scattering:** $^{A}X(n,n'\gamma)^{A}X \rightarrow$ recoil nucl. $^{A}X^{z+}$, e^{-}
- **Radiative capture:** $^{A}X(n,\gamma)^{A+1}Y \rightarrow e^{-}$
- **Neutron emission:** $^{A}X(n,2n)^{A-1}Y \rightarrow$ radioact. daughter
- **Charged-particle emission (lcp = p, d, t ,h, α):**
  $^{A}X(n,lcp)^{A'}Y \rightarrow$ lcp, recoil nucl. $^{A'}Y^{z+}$
- **Fission:** $n+^{A}X \rightarrow ^{A1}X_1 + ^{A2}X_2 + \nu n \rightarrow$ fission fragments

Cross Sections Relevant for Neutron Detection







- **List of reactions relevant for neutron detection:**
  Cross section standards + dosimetry standards!
- **some additional reactions: ^{187}Au(n_{th},γ), ^{155,157}Gd(n_{th},γ), ^{209}Bi(n,f),**

Kinematics of Nuclear Reactions: A(a,b)B

Kinematical properties of two-particle reactions relevant for neutron detectors:

- **Strict correlation between ejectiles**
  this is important for tagging neutrons

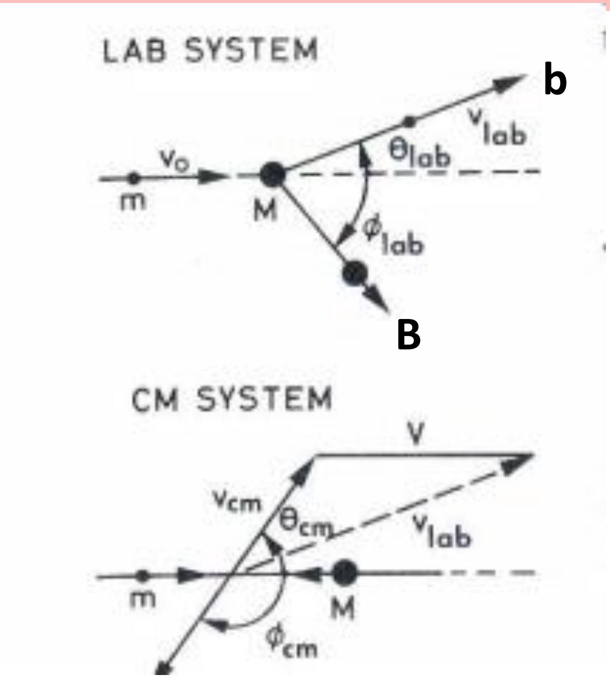
$$\vec{p}_b^{\,cm} = -\vec{p}_B^{\,cm}$$

- **Energy E_B of recoil nucleus**

$$E_B = E_0 \frac{4A}{(A+a)^2} \cdot \cos^2 \phi_B^{lab}$$

- **Center-of-mass ↔ laboratory system**

$$\cos \phi_B^{lab} = \cos(\phi_B^{cm} / 2)$$



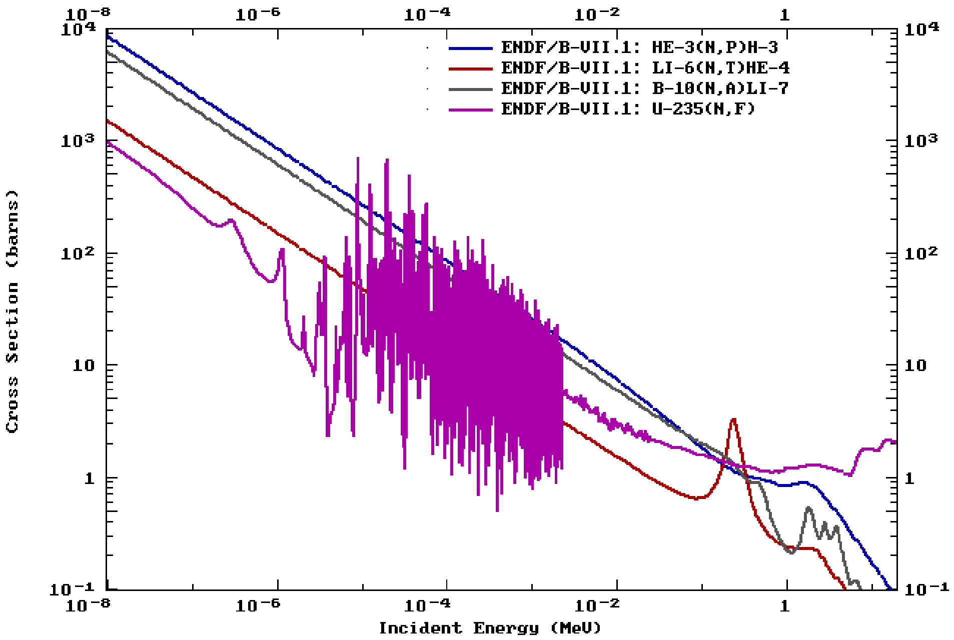
⇒ **Energy distribution of recoils**

$$\frac{dN}{dE_B} \propto \frac{1}{E_a} \frac{(A+a)^2}{4A} \left(\frac{d\sigma}{d\Omega^{cm}} \right) (E_a)$$

this is 'employed' in recoil detectors

Thermal and Slow Neutrons

Two-Particle Reactions with high Q-Value



- $^{10}B(n,\alpha_0)^7Li$: $Q_0 = 2.792$ MeV
  $^{10}B(n,\alpha_1\gamma)^7Li$: $Q_1 = 2.310$ MeV
- $^6Li(n,t)^4He$: $Q = 4.78$ MeV
- $^3He(n,p)^3H$: $Q = 0.764$ MeV
- $^{235}U(n,fiss)$: $Q \approx 200$ MeV

Slow neutrons: $E_n \ll Q$

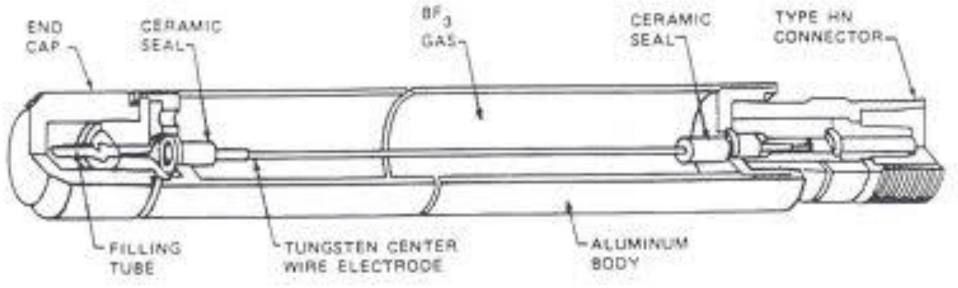
$$p_1 \approx -p_2, \quad E_1 + E_2 \approx Q$$

- **Cross section:** $\sigma(E) = \sigma_0 \cdot (v_0/v)$, $v_0 = 2200$ m/s
  σ_0: Westcott cross section
- **Reaction rate indep. of neutron spectrum n_E:**

$$R = \int \frac{\sigma_0 v_0}{v} \cdot n_E v \, \mathrm{d}E = \sigma_0 v_0 n$$

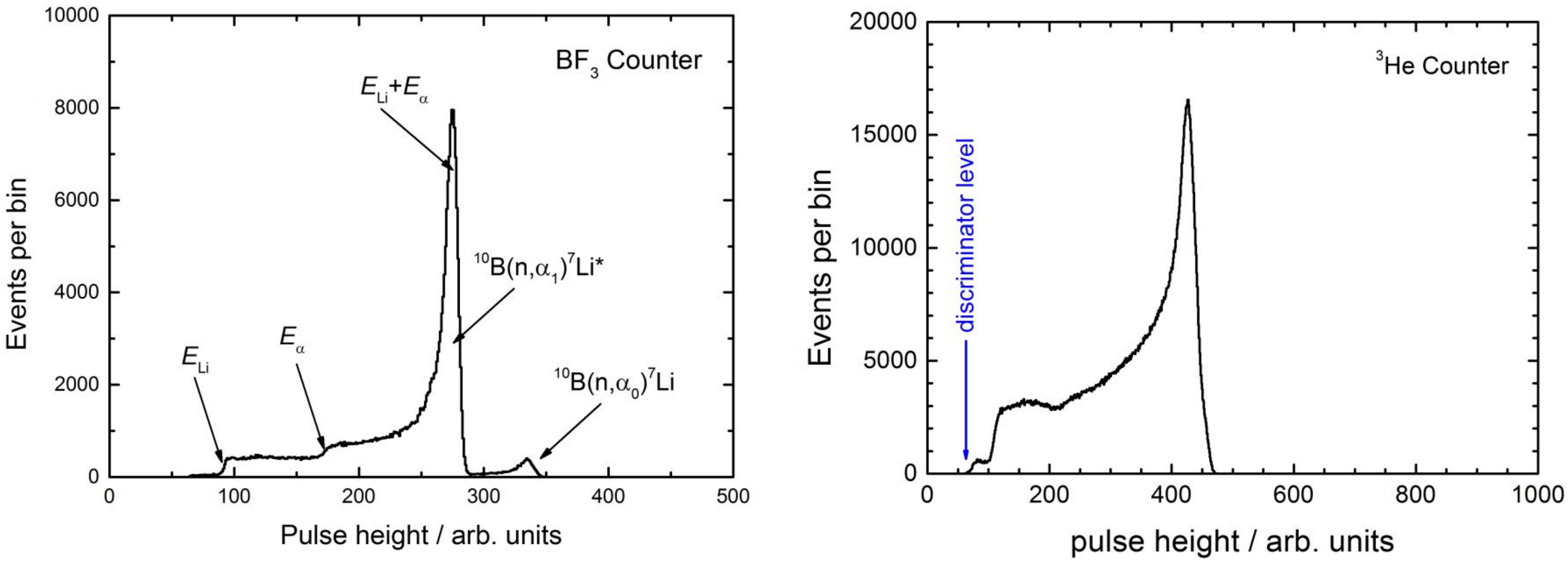
BF_3 and ^{3}He Proportional Counters

- **Cylindrical and spherical shapes**
  Large variety of sizes: *l* < 1 m
  and pressures: *p* < 1 bar (BF_3), 10 bar (^{3}He)
- **Counters must be calibrated:**
  - ^{3}He and BF_3 pressure ?
  - ^{10}B enrichment ?
  - Electrical field ?
  - Wall effects ?



- **n/γ discrimination using a pulse-height threshold**
- **BF_3: aging at high dose rates**
  air transport prohibited: HF formation!
- **^{3}He: more efficient than BF_3 because of larger $\sigma \cdot p$**
  low *Q*-value makes n/γ sep. difficult
- **^{3}He is scarce nowadays ⇒ replacements urgently needed!**

^{3}He and BF_3 Pulse-Height Spectra



- **Wall effect: incomplete energy deposition by one ejectile:**
  $E_1 < E_{dep} < E_1 + E_2$
- **Significant dead times: t_{DT} = 1-10 µs**
- **Photon background suppressed by pulse-height threshold**

Fast Neutrons:
Moderating Detectors

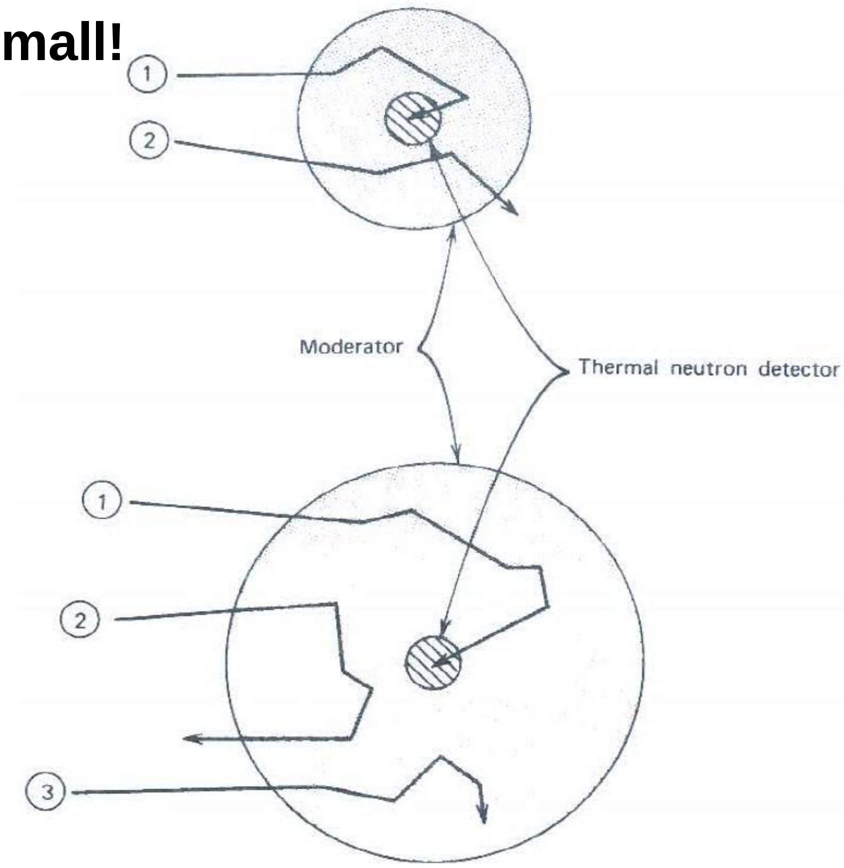
Flat Response Detectors: General Principles

- Fast neutron cross sections are small!

⇒ Cover a thermal detector with a hydrogenous moderator

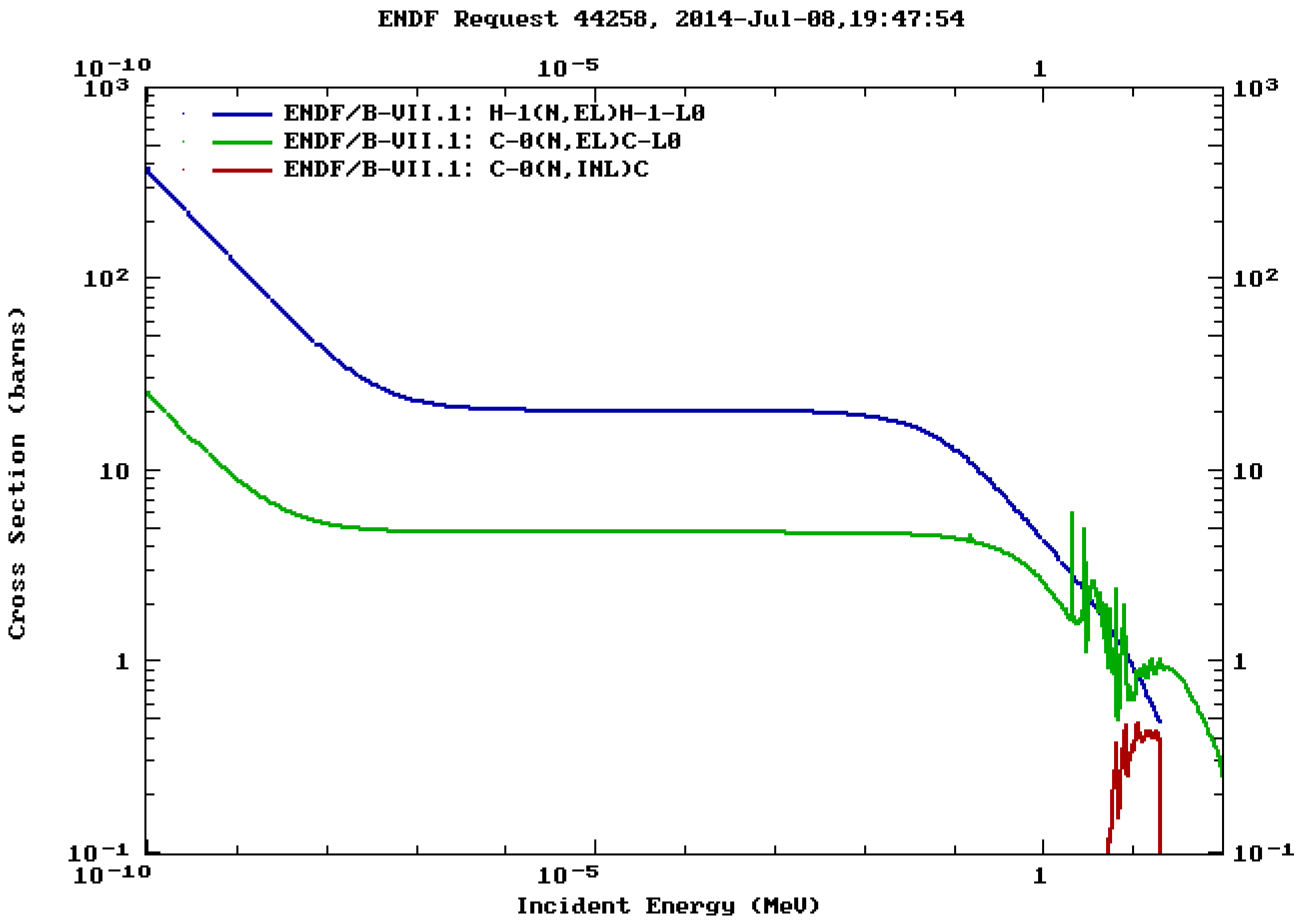
- Response depends on:
  - scattering cross section
  - moderator size
  - neutron energy

⇒ Reliable calculation with transport codes possible



Ref.: G. Knoll, Radiation detection and measurement, 3rd ed., p. 539

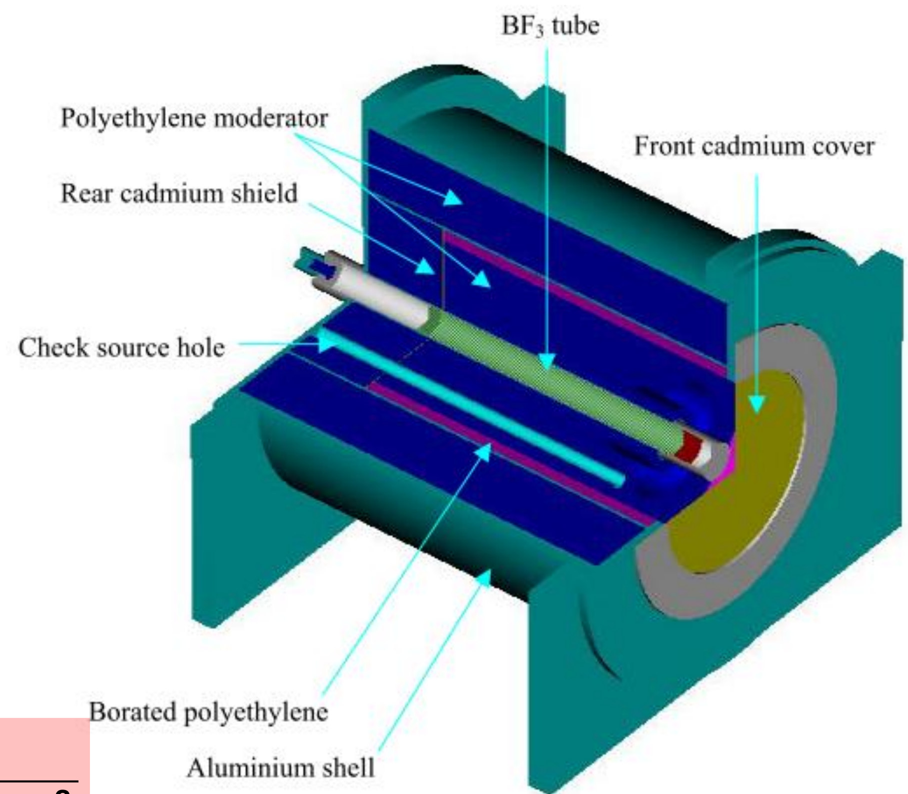
Scattering Cross Section for Hydrocarbons



NB: np scattering dominates for E_n < 20 MeV

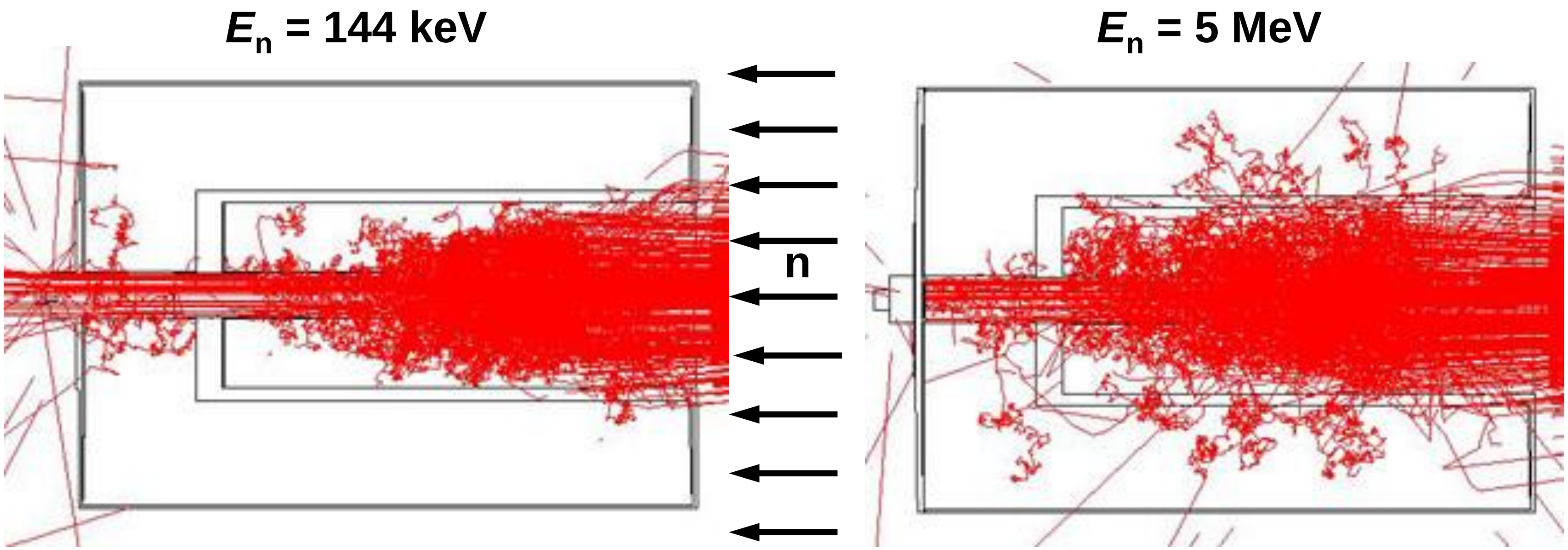
The Long Counter

- **Design from the 1950-60s: *Hanson, De Pangher, McTaggart***
- **Design principles**
  - **Thermal shield for directional response**
  - **Grooves for deeper penetration of low-energy neutrons**
  - **High sensitivty**



- **Large device: l = 44 cm, $^{\varnothing}$38 cm**
- **Flat response:**
  E_n = 0.01 - 10 MeV
  $\delta R_\Phi / R_\Phi \approx \pm 10\%$
- **Effective centre $x_0(E)$:** $$\dot{N} \propto \frac{1}{(x + x_0)^2}$$
- **Sensitive to room-return but very stable ⇒ ideal monitor**

Monte Carlo Modelling of Long Counters

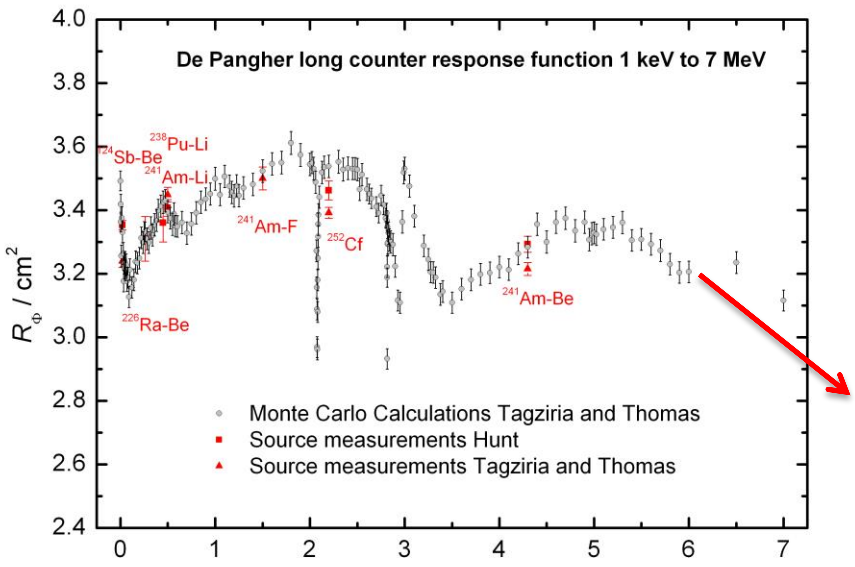


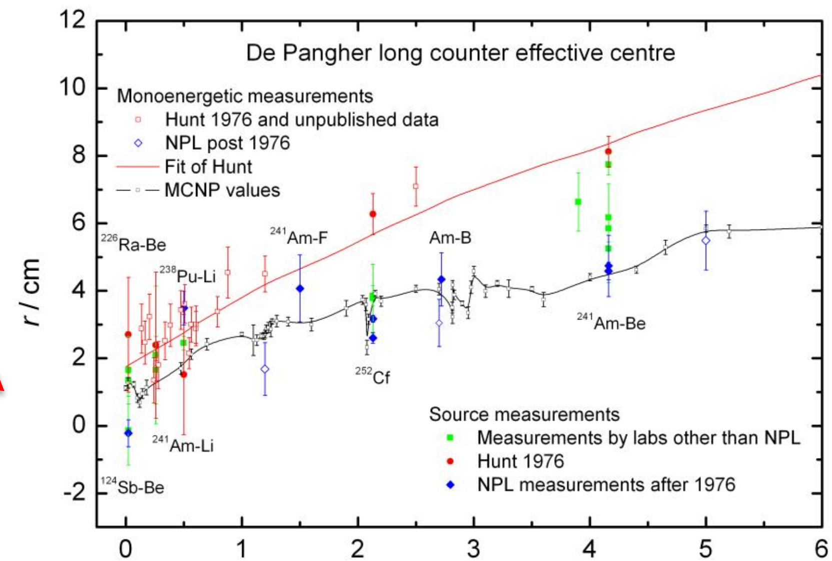
Flat-field irradiation form the right hand side
Only neutron 'tracks' contributing to the response of the thermal detector are shown!

Ref.: N. Roberts *et al.*, NPL Report DQL RN004

- **Annular moderator and borated shield protect the inner moderator from neutrons entering from the sides**
- **Higher energy neutrons penetrate deeper into the moderator**

Long Counter: Response and Effective Center



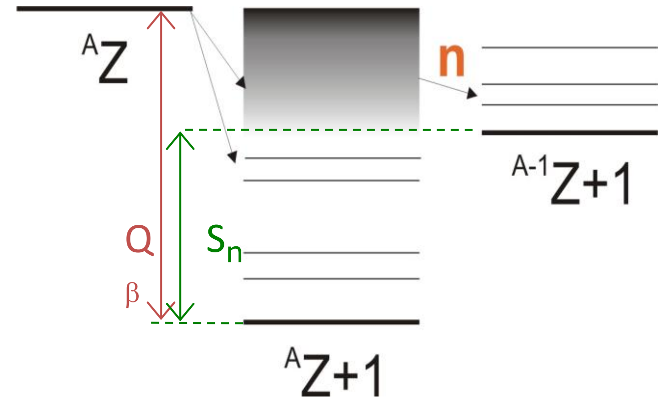


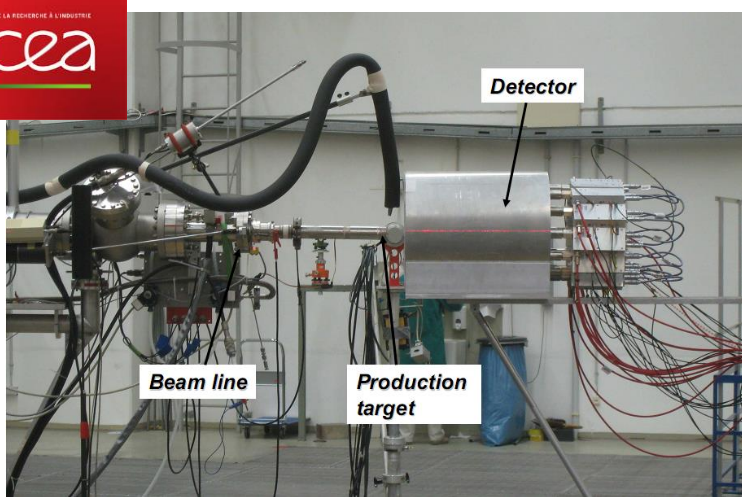
Ref.: N. Roberts *et al.*, NPL Report DQL RN004

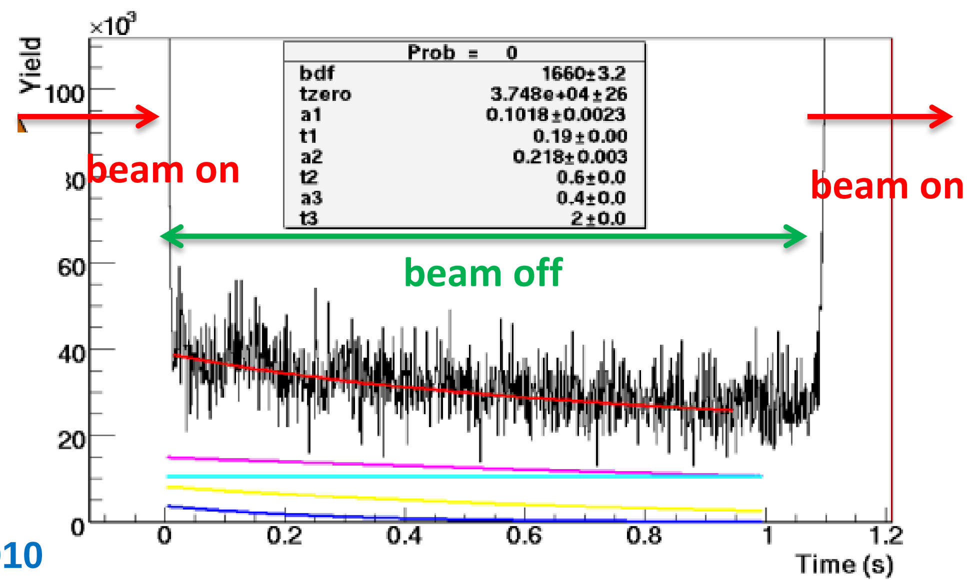
- **Calibration with radionuclide sources: link to activity standard!**
- **Overall uncertainty (NPL): $u_R/R_\Phi = 0.014$, $u_{x0} = 0.63$ cm**
- **Useful energy range: 1 keV – 15 MeV (de Pangher LC) (w/o carbon resonances)**
- **Designs with ext. energy range and/or higher sensitivity available**

Long Counters for Beta-Delayed Fission Neutrons

- **ß-del. fission neutrons: $t_{1/2} \approx 0.1 – 100$ s**
- **PE moderator with ^{3}He counters**
  - **Fissionable sample in central channel**
  - **Neutron detection eff. ε > 10%**
  - **Irradiation sequence:**
    beam on – beam off and counting
  - **Precursors kept in equilibrium**







Ref.: X. Ledoux *et al.*, ERINDA workshop 2010

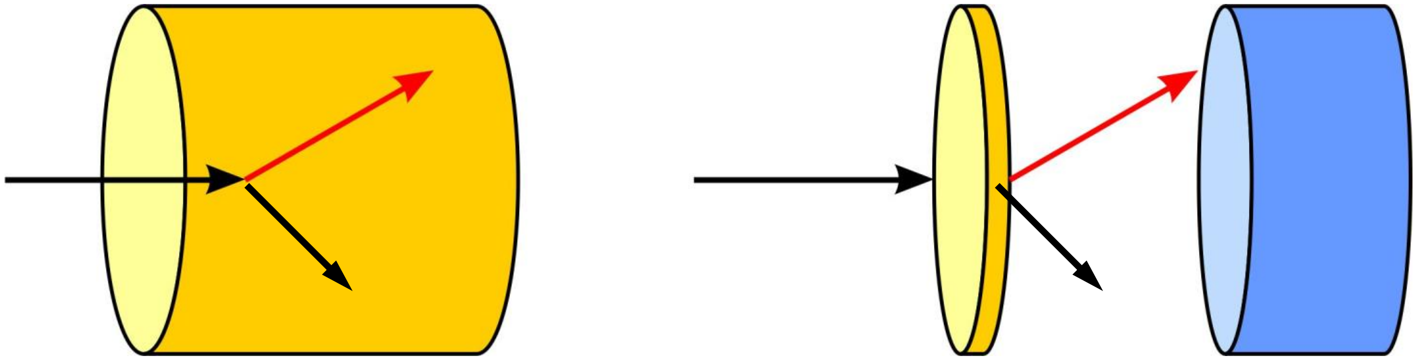
Fast Neutrons:
Recoil Detectors

Recoil Detectors: General Principles

Recoil detectors are the working horses of neutron metrology

- **Based on elastic scattering: Q = 0 MeV**
- **Most important reaction: $^{1}H(n,n)^{1}H$**
- **Differential response determined by $(d\sigma/d\Omega^{cm})$**
- **Interference from other constituents and detector properties**

- **Two approaches for detection of elastic recoils**
  - **Detector = target: full angular distribution**
  - **Separate radiator: only backward angles**

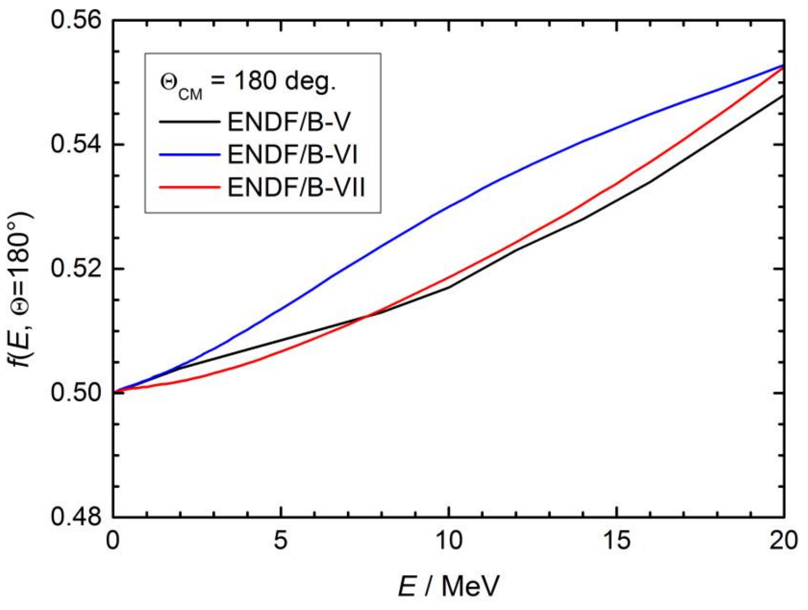


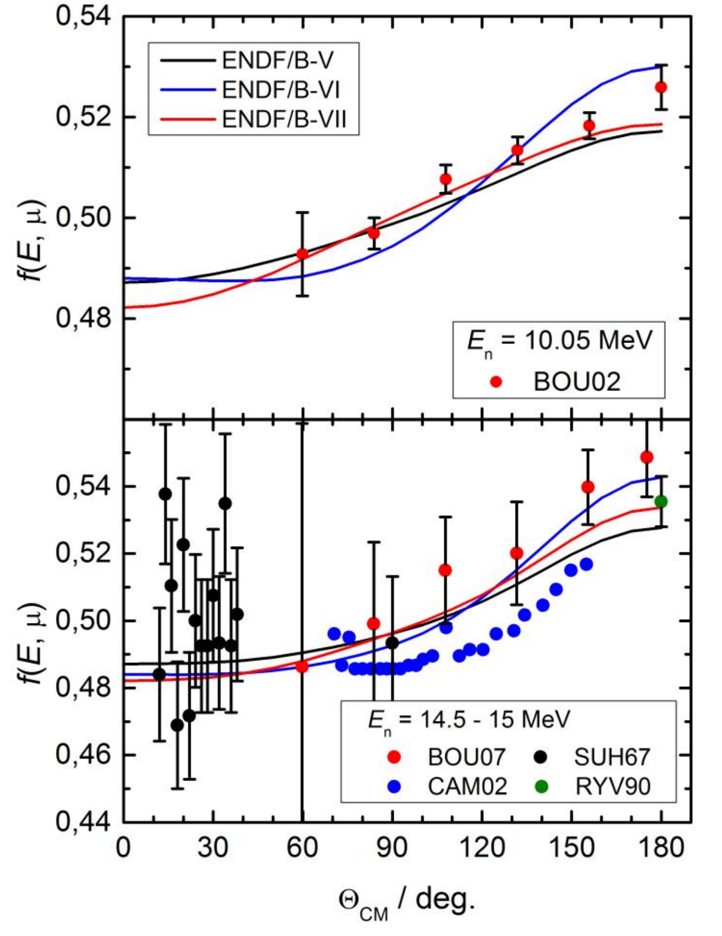
np Scattering: Overview

- **Total np cross section:** $\sigma_{tot} \approx \sigma_{np}$
- **Relative measurements at LANSCE: 5 - 500 MeV**
  Abfalterer et al. (2001), uncertainty < 1%
- **Differential np cross section:** $(d\sigma/d\Omega)$
  relative angular distributions, normalization to σ_{tot}
  - **Analytical fit to exp. data:** **Gammel formula (1960)**
  - **Phase-shift analysis:** **Hopkins-Breit (1970)** $\rightarrow$ **ENDF/B-V**
  - ***R*-matrix analysis:** **Dodder-Hale (1991)** $\rightarrow$ **ENDF/B-VI**
    Dodder-Hale (2006) $\rightarrow$ **ENDF/B-VII**
- **Important for metrology:**
  Backward scattering $(d\sigma/d\Omega)_{CM}(180°)$

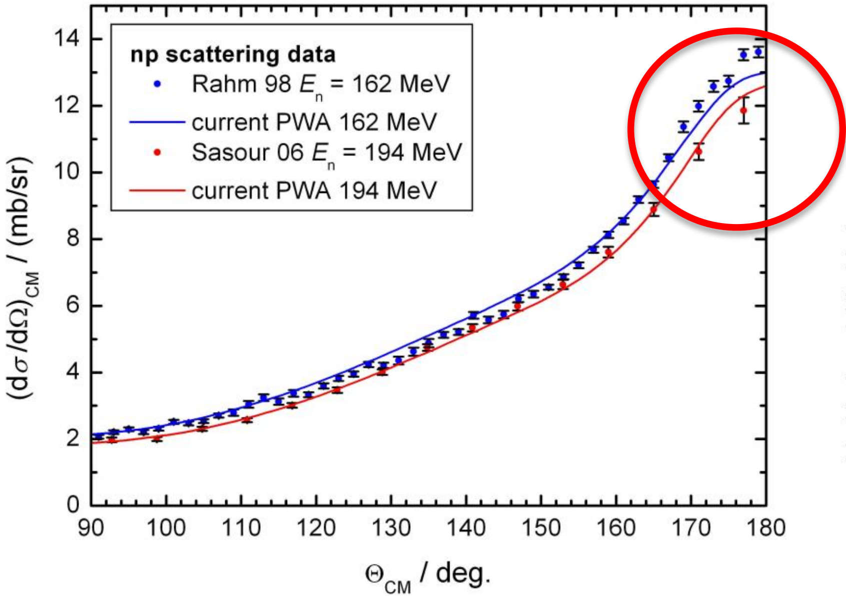
Differential Neutron-Proton Scattering Cross Section

- **only minor changes to σ_{el} uncertainty 0.3% - 0.5% (E < 20 MeV)**
- **($d\sigma_{el}$ / $d\Omega_{cm}$) isotropic up to about 3 MeV**
- **2 % changes for ($d\sigma/d\Omega$) from ENDF/B-V to B-VI**

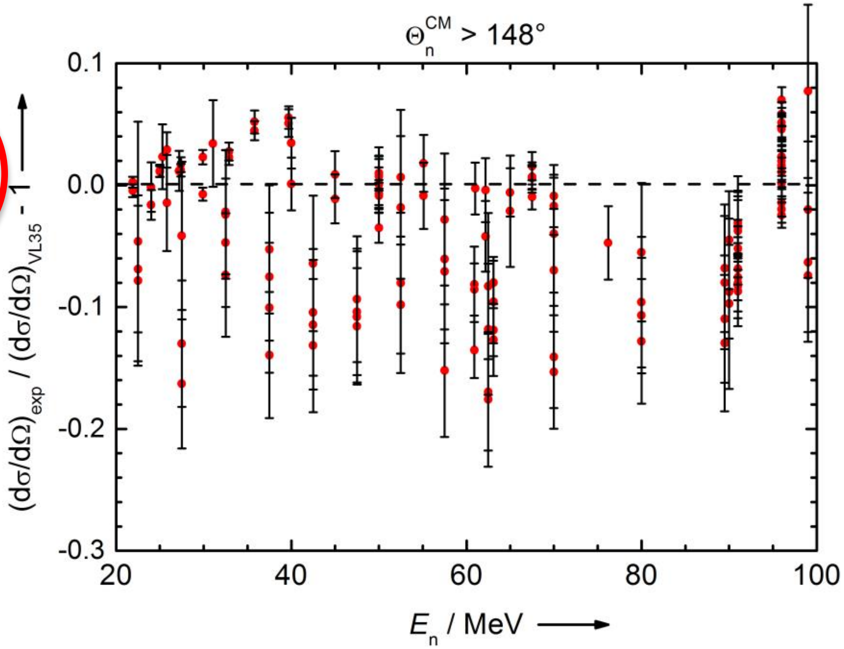




np Scattering above 20 MeV



n-p backward scattering



- **recommend phase shift analysis: VL40**
- **not many new np data: TSL, IUCF, PSI**
- **no uncertainties given: 'about 5%'**

Recoil Detectors: Proportional Counters

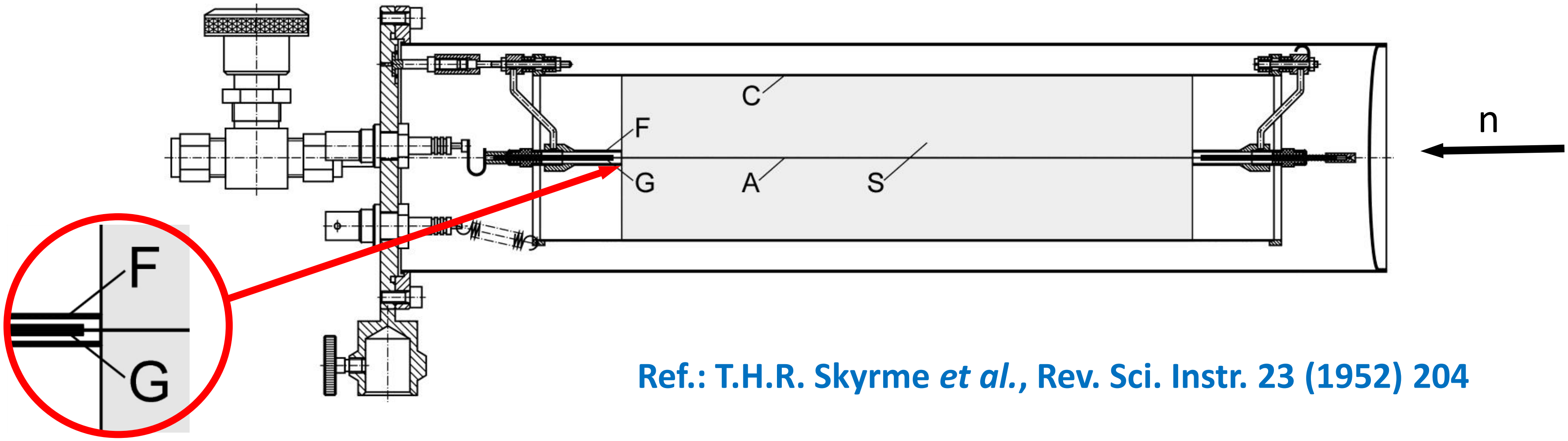
Recoil Proportional Counters

- **Strong quenching for low-energy recoil in organic scintillators:**
  L/E = 0.08 for 100 keV p in BC501A
- **Ranges of recoil particles in solids become very small:**
  R = 1.4 µm for 100 keV p in PE

⇒ **Gaseous detectors for detection of low-energy recoils**

- **Complications:**
  - **design more complicated (el. field, surface treatment, cleanliness)**
  - **need for high-vacuum and gas filling systems**
  - **wall effects important**
  - **large non-constant rise-time ⇒ not well-suited for TOF**
  - **Interference from photons and ^{12}C recoils**
- **Pioneering work of E.F. Bennet *et al*. from the 1950's - 1070's**

The PTB Proportional Counter P2



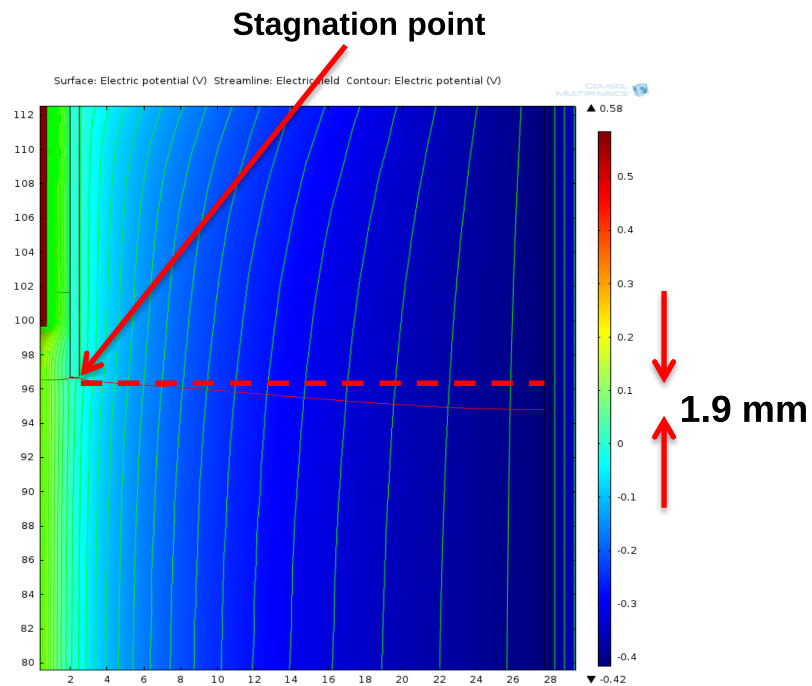
Ref.: T.H.R. Skyrme *et al.*, Rev. Sci. Instr. 23 (1952) 204

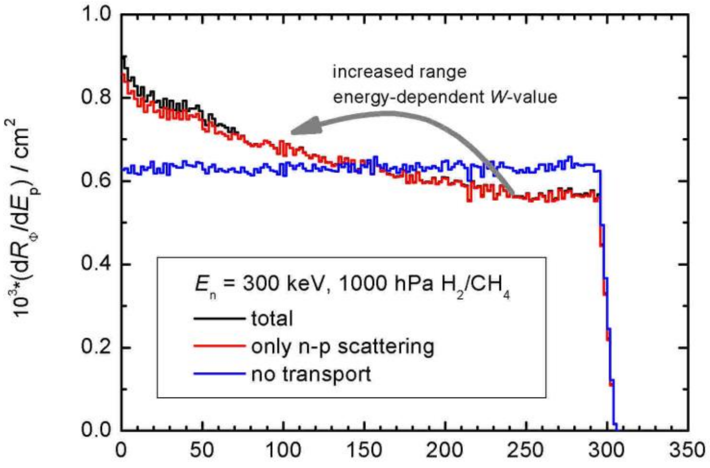
- **total volume: ≈ 1.6 dm³**
- **active volume: ∅55.5 mm, *l* = 193.3 mm**
- **el. field: defined by ∅4 mm field tubes at ground potential**
- **anode: ∅ 100 µm gold-plated tungsten wire (selected)**
- **counting gas: H_2/CH_4 (3.5 vol.%), C_3H_8**
- **energy range: 20 keV – 2 MeV**

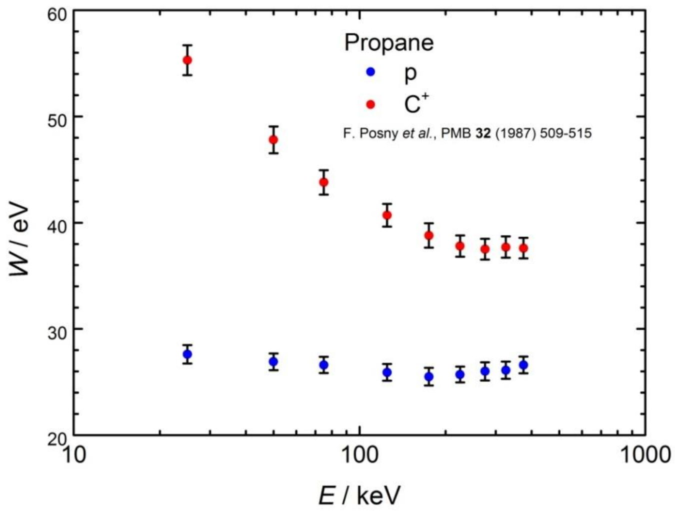
Modelling of the RPPC Response to Neutrons

MC modeling required to describe finite-size and gas-related effects

- **incomplete energy deposition**
- **energy-dependent *W*-value**
- **carbon recoils included**
- **shape of the sensitive volume**

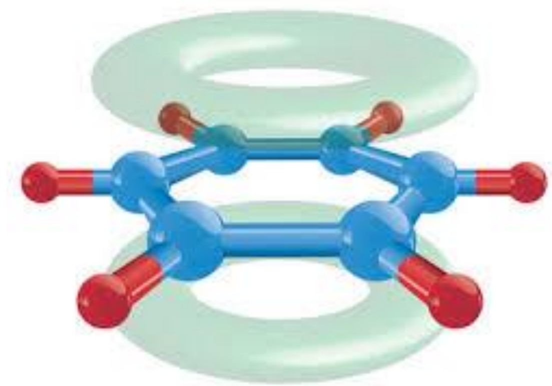






Recoil Detectors:
Scintillation Detectors

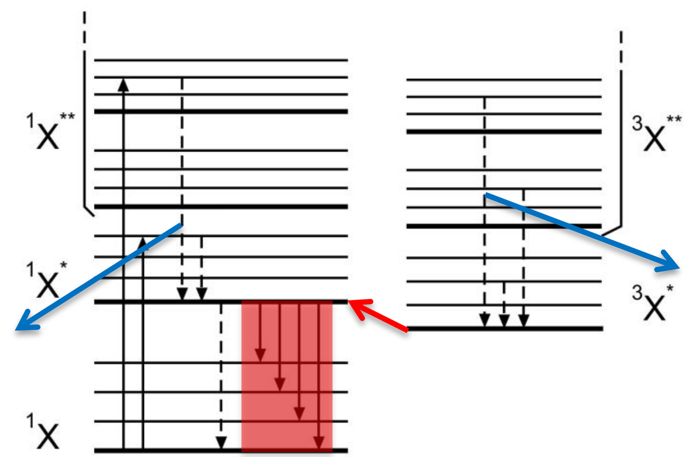
The Physics of Organic Scintillators



Unitary scintillators:

- **Benzene ring: delocalized π orbitals**
- **Singlett (^1X, $^1X^*$, $^1X^{**}$) and triplet ($^3X^*$, $^3X^{**}$) states**

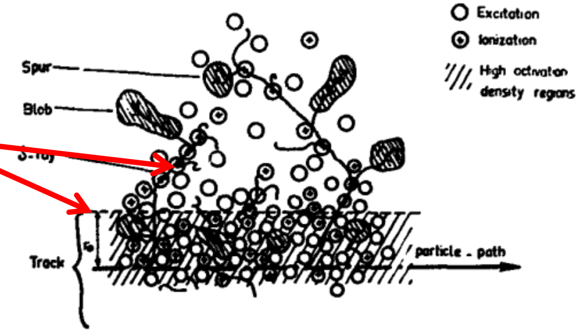
Principal physical processes:



- **Excitation by electron impact, ion-ion recombination, …**
- **Non-rad. efficient internal degradation**
  $^{1,3}X^{**} \rightarrow {}^{1,3}X^*$+ phonon
  drain via competing channels:
  quenching states
- **Rad. decay $^1X^* \rightarrow {}^1X$:**
  prompt fluorescence: τ = 1 – 80 ns, $\lambda_{fluor} > \lambda_{abs}$
- **Rad. transition $^3X^{**} \rightarrow {}^1X^*$ forbidden**
- **Coll. deexc. $^3X^* + {}^3X^* \rightarrow {}^1X^* + {}^1X$ + phonon:**
  delayed non-exp. fluorescence: τ > 300 ns

Ionization Quenching and Pulse-Shape Discrimination

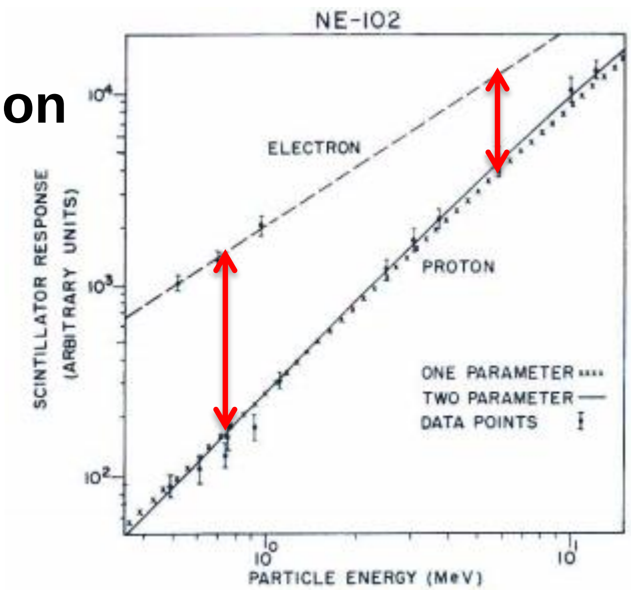
- **Increased ionization density:**
  - **More ion-ion recombination**
  - **Ratio of $^1X^{**}$ and $^3X^{**}$ excitations increases**
  - **Temporal concentration of transient quenching states ($\tau \leq 100$ ps) decreases**



$\Rightarrow$ **Delayed fluorescence <u>less</u> dependent on d*E*/d*x* than prompt fluorescence**

- **Light yield d*L*(*E*)/d*x* is a non-linear function Semi-empirical formulas (Birks *et al.*):**

$$\frac{dL}{dx} = \frac{S\, dE/dx}{(1 + kB\, dE/dx + \ldots)}$$

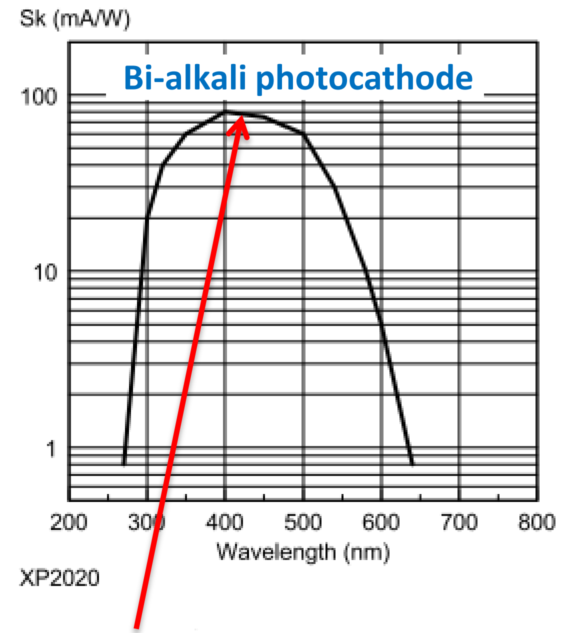


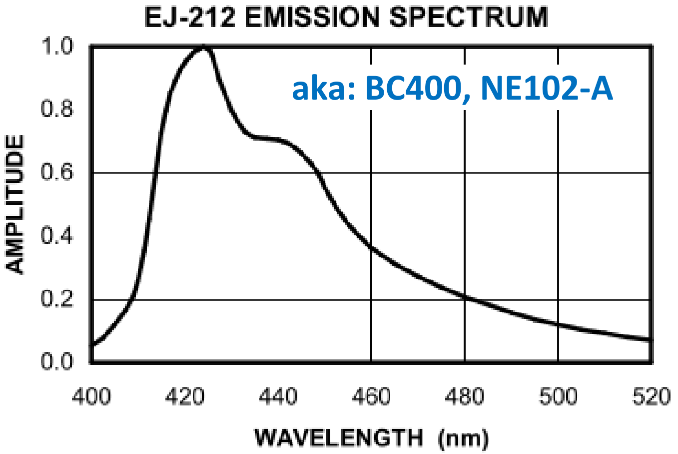
- **Scint. decay depends on d*E*/d*x*:**

$\Rightarrow$ **pulse-shape discrimination of particle species (*Z*, *A*)**

Liquid and Plastic Scintillators

- **Typical unitary scintillators:**
  - Stilbene (1,2-Diphenylethene $C_{14}H_{12}$)
  - Anthracene ($C_{14}H_{10}$): 'gold' standard for scint. efficiency
- **Binary or ternary scintillators**
  - Solvent X: Benzene (C_6H_6), *n*-Methylbenzene ($C_6H_{6-n}(CH_3)_n$), Styrene $[C_6H_5 \cdot C_2H_3]_n$, ...
  - Solutes Y_i: PPO, POPOP, bis-MSB, ...
  - Lower excitation energy: $E_{Y*} < E_{X*}$
- **Prim. processes as in unitary scintillators → $^1X^*$, $^3X^*$**
- **Energy transfer to solutes**
  $^1X^* + {}^1Y \rightarrow {}^1X + {}^1Y^*$ (rad., non-rad.)
  $^3X^* + {}^1Y \rightarrow {}^1X + {}^3Y^*$ (non-rad.)
  → **rise, decay times**
- **Secondary solute: wavelength shifter**





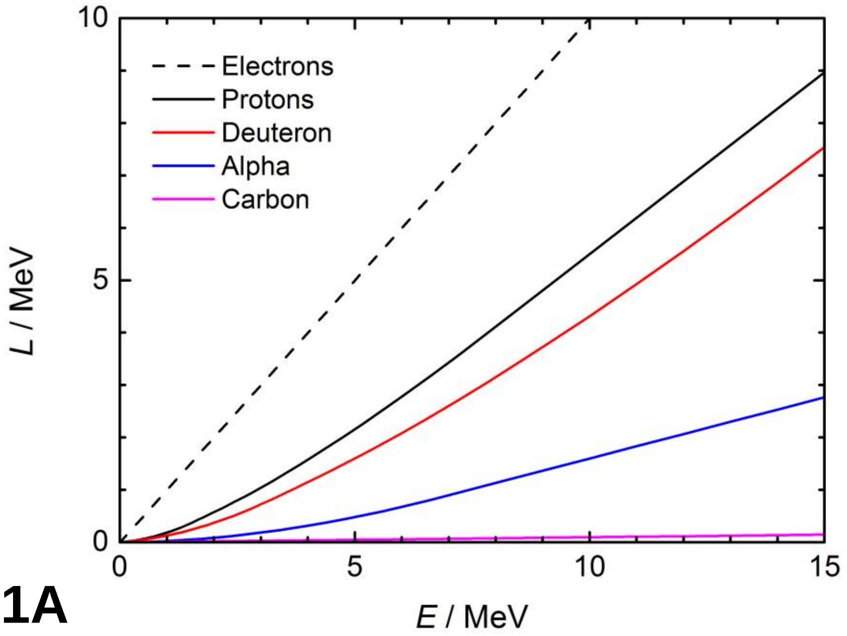
Light Output of Organic Scintillators

- **Light Output calculated from Birks' parameterization:**

$$L(E)=\int_0^E \frac{S\cdot(\mathrm{d}E/\mathrm{d}x)}{1+kB\cdot(\mathrm{d}E/\mathrm{d}x)}\left(\frac{dE}{dx}\right)^{-1}\mathrm{d}E$$

  - **Weak ionization:** $L(E)=S\cdot E$
  - **Dense ionization:** $L(E)=\frac{S}{kB}R(E)$

- **Electrons:** $L_e(E) = S_e\cdot(E - E_0)$
  S_e := 1 MeV^{-1}, E_0 ≈ 5 keV for BC501A

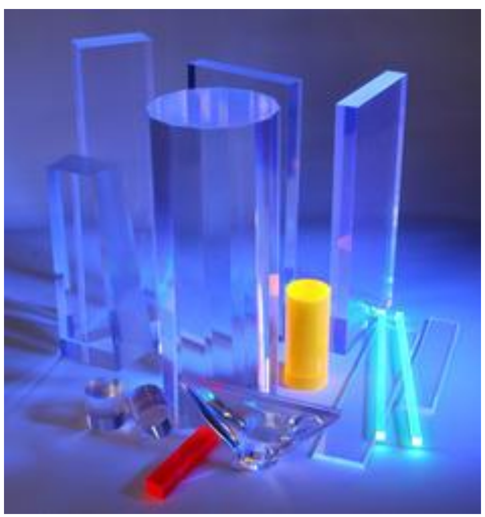


- **Also higher-order formulas are approximations!**

- **Note:**
  - **Experimental data include instrumental effects!**
  - **Electrons produce Cherenkov radiation for $\beta > n^{-1}$: E_e > 170 keV in BC501A**

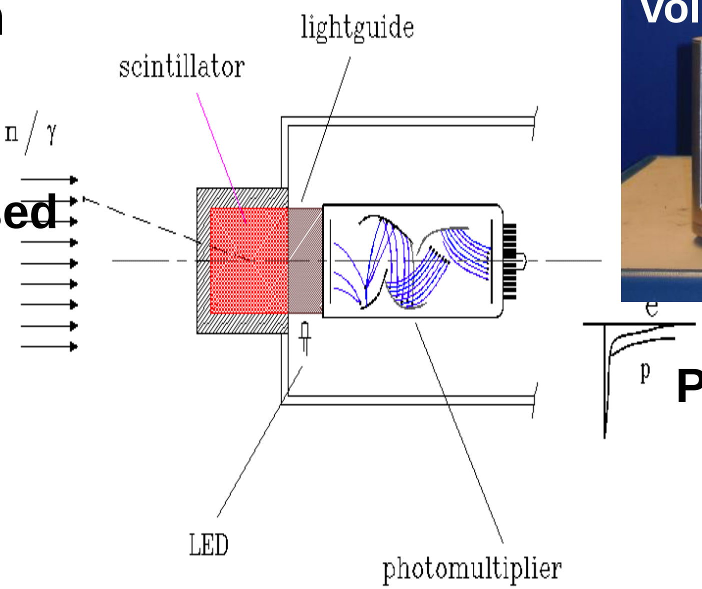
Properties of Organic Scintillators

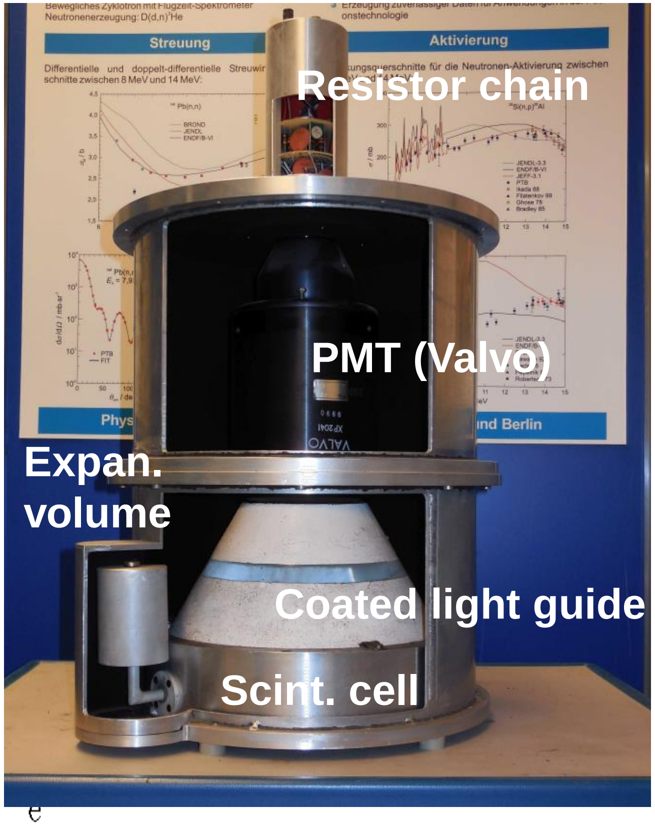
		plastic scint.	liquid scint.
1.	Hydrogen / carbon ratio	≈ 1.1	≈ 0, 1.2 – 2.0
2.	Scintillation efficiency	55 – 65 %	40 – 80 % anthracene
3.	Scintillation spectrum λ_{max}	370 – 490 nm	≈ 425 nm
4.	Transparency	1 - 4 m	
5.	Decay times	1.4 – 3 ns, 230 ns	2 – 4 ns
6.	Pulse-shape discrimination	(yes)	yes
7.	Doping for thermal sensitivity	yes	yes



Components of a Liquid Scintillation Detector

- Scintillator cell + expansion volume
- Light guide (reflective coating)
- PMT with μ-metal shield
- High voltage supply
  - resistor chain + decoupling capacitors
  - transistorized low-power dynode supplies
- Gain stabilization
  - Count rate drifts
  - Temperature drifts
  - ⇒ LED or laser-based systems





Prototype FD detector: 12"×2" NE213

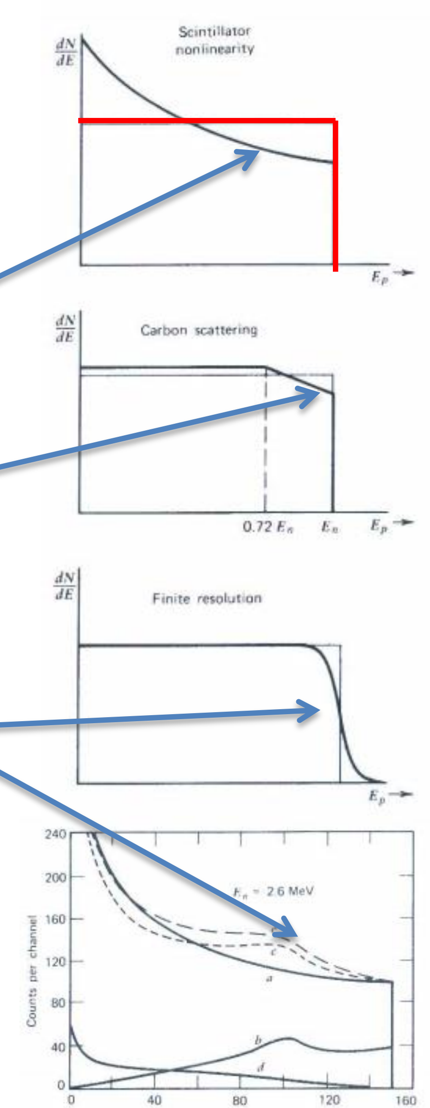
Response of Organic Scintillation Detectors

- **Elastic n-p scattering cross section dominates: dN/dL = const for $L < E_n$**

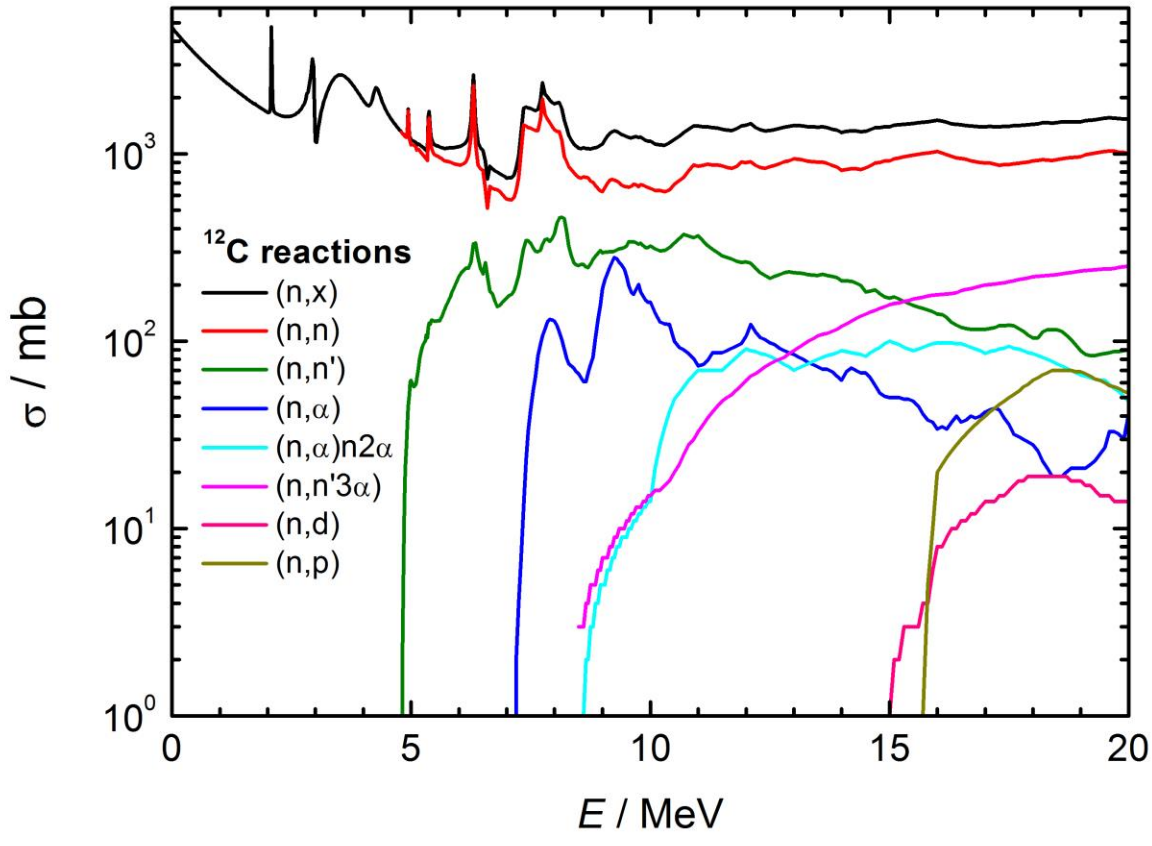
Modification of the rectangular shape:

- **Non-linear light output: $L \propto E^{3/2}$**
  $\Rightarrow dN/dL = (dN/dE)\cdot(dL/dE)^{-1} \propto L^{-1/3}$
- **n-^{12}C scattering: $\Delta E_n < 0.28\cdot E_n$**
- **Multiple n-p scattering: $\Sigma L(E_{p,i}) < E_n$**
- **Finite pulse-height resolution**
- **^{12}C(n,x) reaction:**
  Q value for ^{12}C(n,n',γ): 4.4 MeV

$\Rightarrow$ Simulated using Monte Carlo techniques!



^{12}C(n,x) Reactions for E_n < 20 MeV

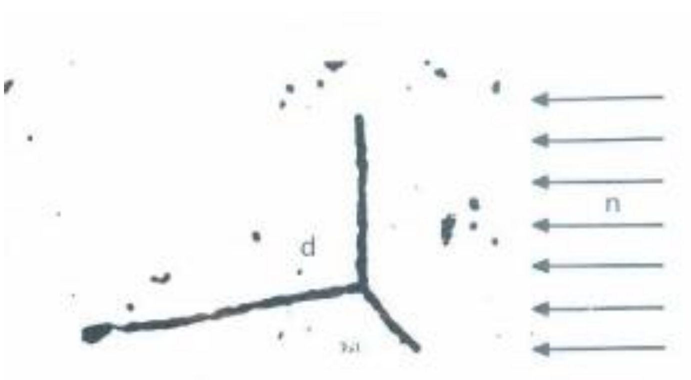


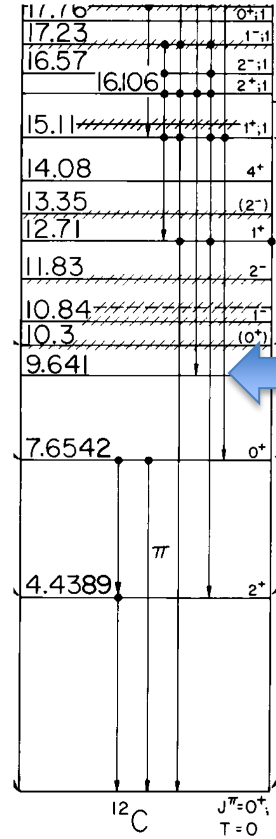
E_n < 15 MeV: only scattering and alpha emission!

Break-Up Reactions

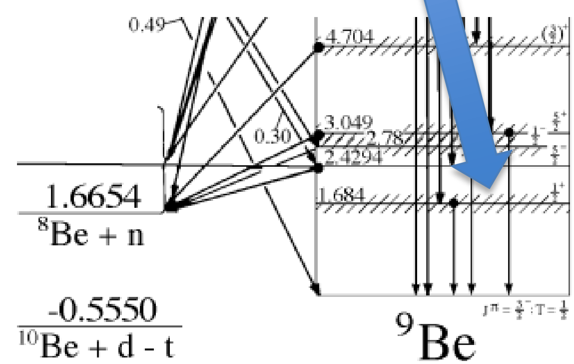
E_n < 20 MeV: $^{12}C(n,n'3\alpha)$

- **Four-body break-up with several channels**
- **Investigated using nuclear emulsions and liquid scintillation detectors**
- **Still insufficient data for MC codes**
  - **NRESP7**
  - **Geant4 (data base from CIEMAT)**

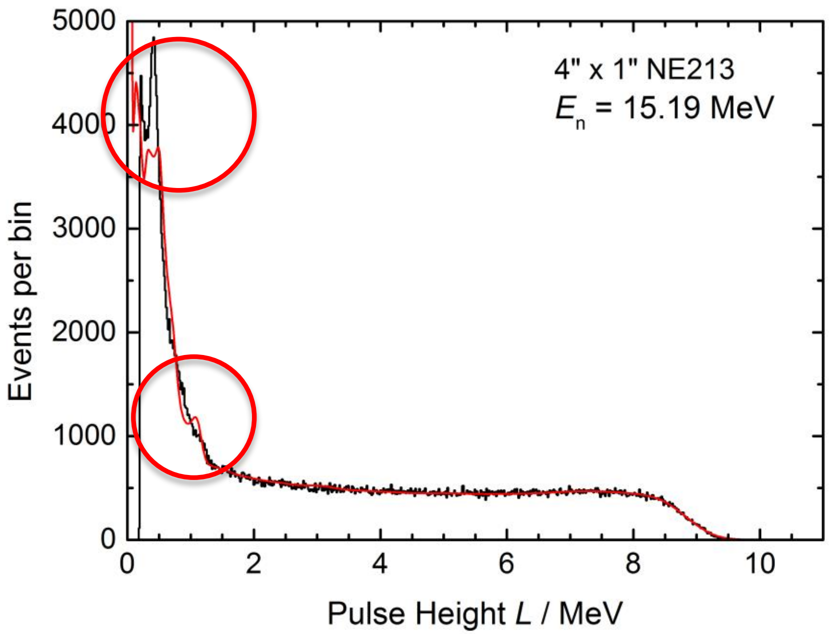


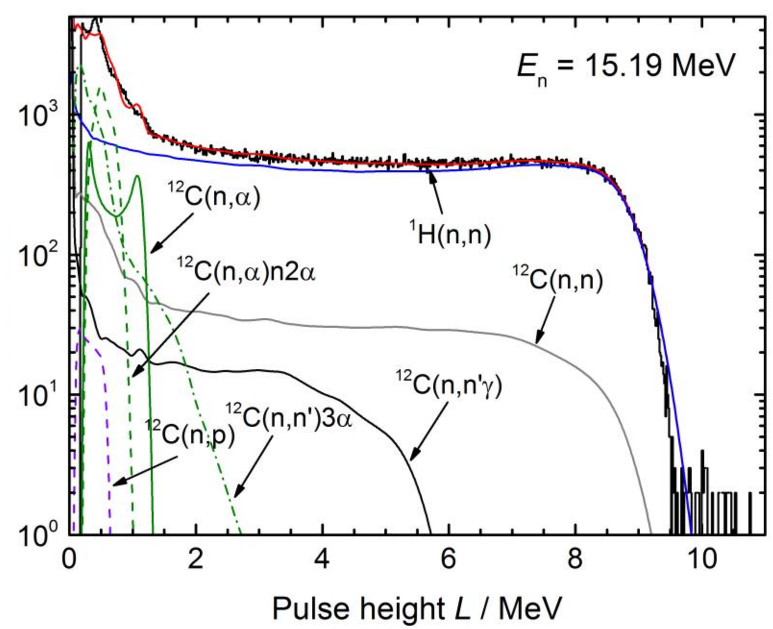


reaction	Q-value MeV
$^{12}C(n,n)^{12}C$	-
$^{12}C(n,n')^{12}C^*$	-4.439
$^{12}C(n,\alpha)^{9}Be$	-5.71
$^{12}C(n,\alpha')^{9}Be^* \rightarrow$ $n + {}^{8}Be \rightarrow 2\alpha$	-8.13
$^{12}C(n,n')^{12}C^* \rightarrow$ $\alpha + {}^{8}Be \rightarrow 2\alpha$	-7.65
	-9.63
	-10.80
	[illegible]11.80
	[illegible]12.70
$^{12}C(n,p)^{12}B$	[illegible]2.61
$^{12}C(n,d)^{11}B$	-[illegible].73
$^{12}C(n,2n)^{11}C$	-[illegible].72
$^{12}C(n,pn)^{11}B$	-1[illegible]96



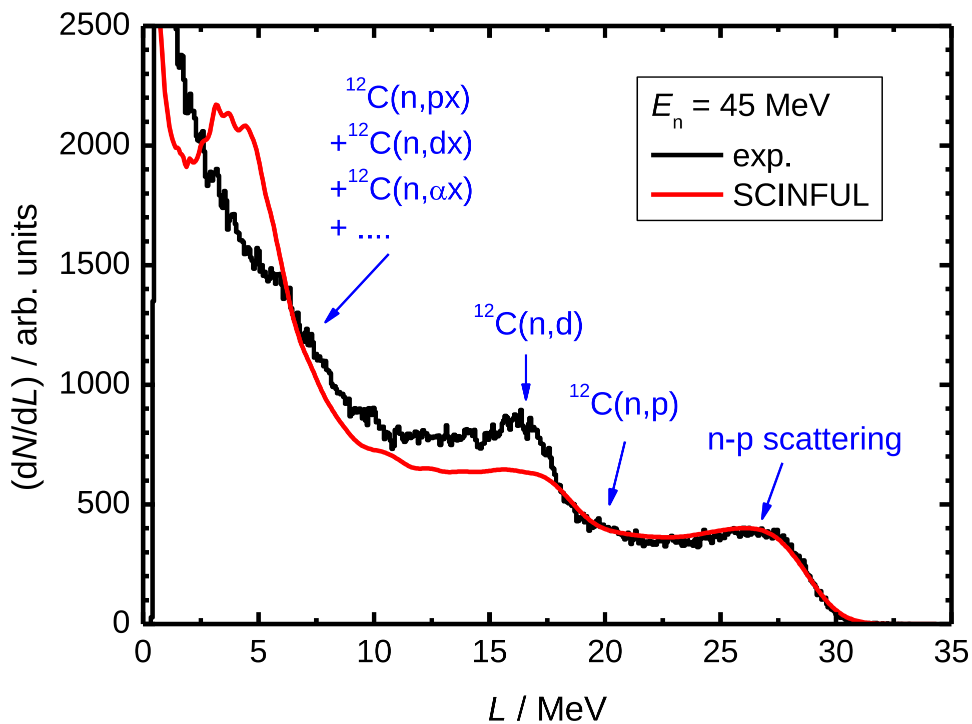
Example: 2"x2" BC501A Detector at E_n = 15 MeV





- **Simulation using NRESP7, similar results with SCINFUL**
- **Generally good agreement for E_n < 16 MeV, but description of α emission channels still problematic!**
- **Partial spectra can be sorted by first interactions**
- **Pulse-height spectra used to determine $^{12}C(n,\alpha)^9Be$ cross section!**
  Ref.: H.J. Brede *et al*., NSE 107 (1991) 22

Response for E_n > 20 MeV

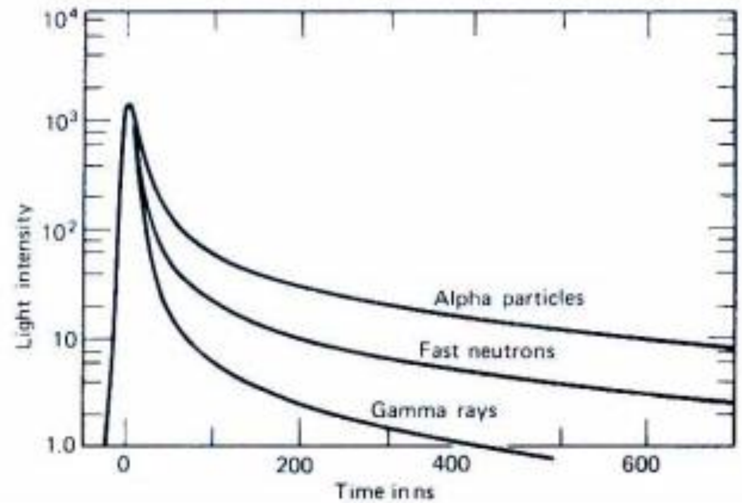


Response dominated by n-^{12}C interaction:

- **Strong contributions from break-up reactions:**
  ⇒ correlation of charged particles from individual interactions!
- **Data libraries (ENDF, JEFF) have only emission tables:**
  ⇒ general-purpose MC codes are not adequate: MCNPX, Geant4

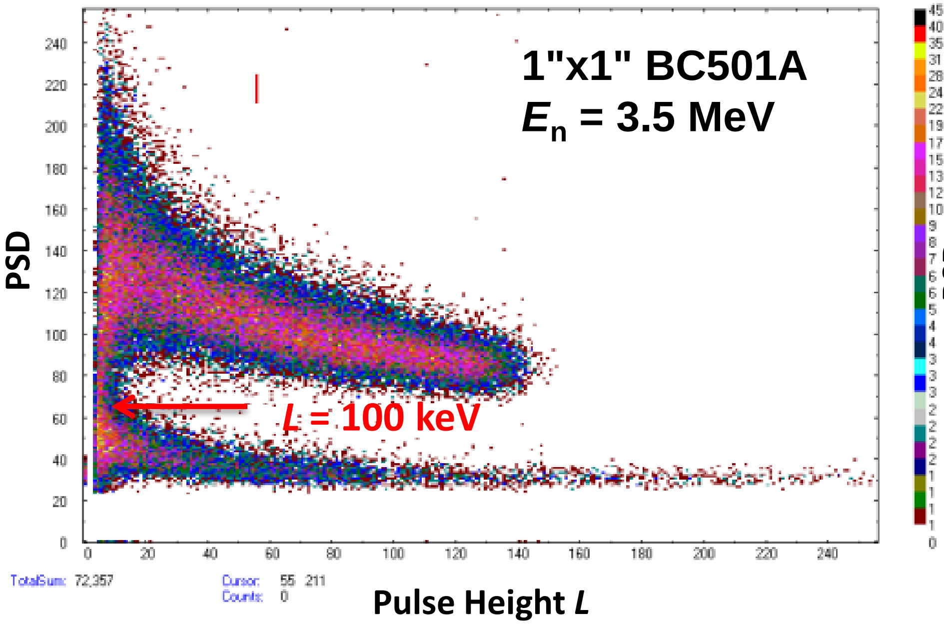
Pulse-Shape Discrimination (PSD)

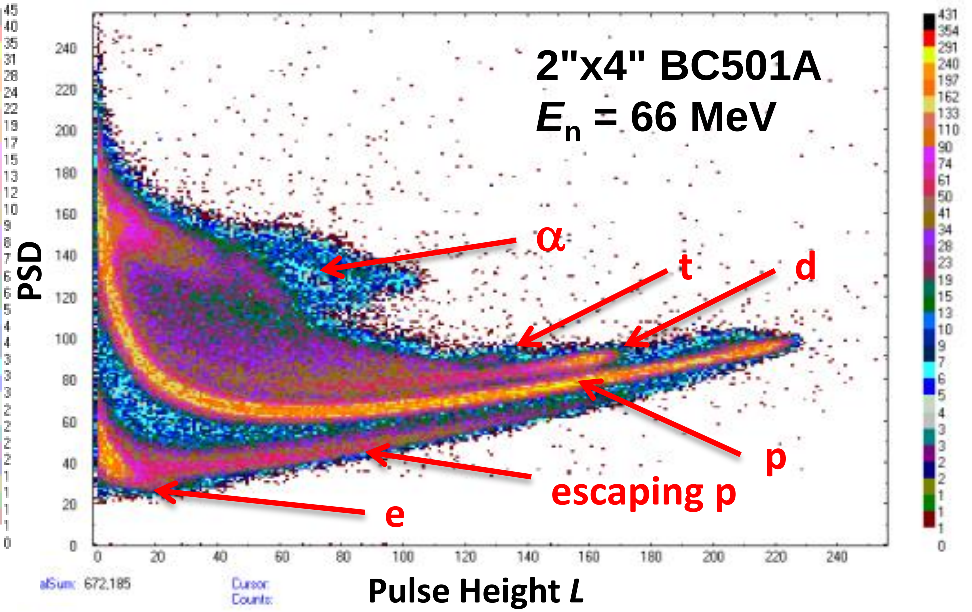
- **PSD properties depend on:**
  - **Neutron energy**
  - **Detector size**
  - **Multiple scattering**
  - **Scintillator composition (oxygen, impurities)**
- **Discrimination of neutron and photon-induced events**
  - **Ambient photons: background reduction!**
  - **Delayed gammas**
  - **Suppression of response induced by $^{12}C(n,n'\gamma)$**



- **PSD yields *Z*/*A* information: particle identification**
- **Techniques:**
  - **Analogue $RC(CR)^2$ shaping → zero crossing**
  - **Analogue or digital integration: Q_{short} vs. Q_{long}**
  - **Fit of the waveform**
- **PSD has limited dynamic range: difficult for *L* < 500 keV**

PSD Examples





PSD: analogue $RC(CR)^2$ technique

- Many older MC codes do not include the $^{12}C(n,n'\gamma)$ channel.

⇒ Photon-induced events must be excluded

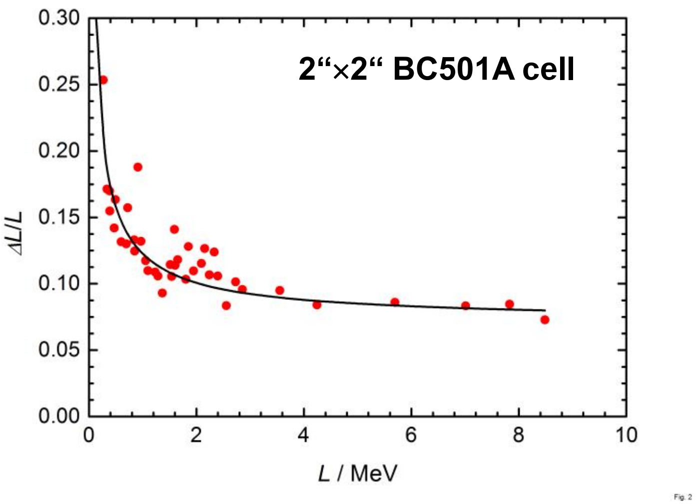
- Problem: Separation of photon-induced and proton escape events

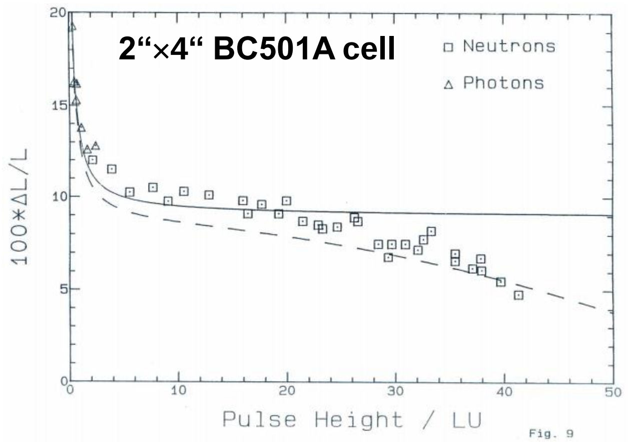
Pulse-Height Resolution

- Pulse-height resolution depends on
  - Light collection: *A*
  - Photoelectron statistics: *B*
  - Electronic noise: *C*

$$\frac{\Delta L}{L} = \sqrt{A^2 + B^2/L + (C/L)^2}$$

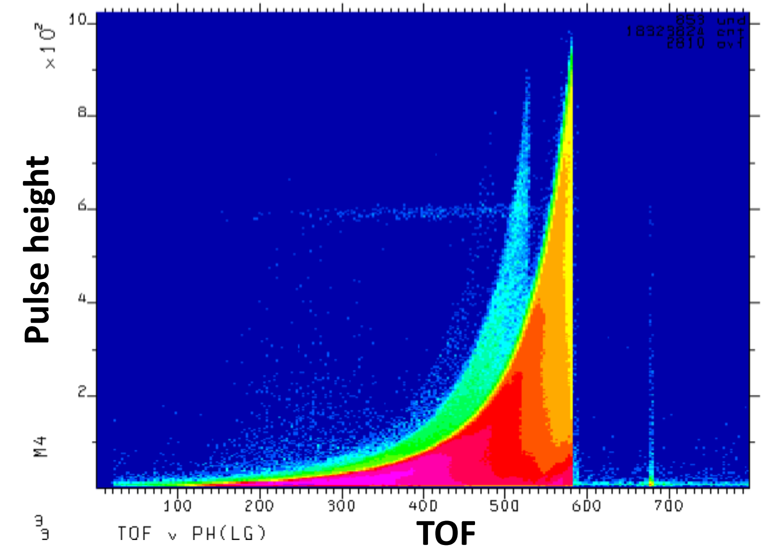
- Elongated cells for high-energy neutrons:
  - Long tracks
  - *A* depends on neutron energy E_n
- Optimisation important for spectrometry
  - Small cells (diameter ≈ depth)
  - Partially coated light guides
- Unfolding: $\Delta E_n/E_n \approx 0.2 \cdot \Delta L/L$

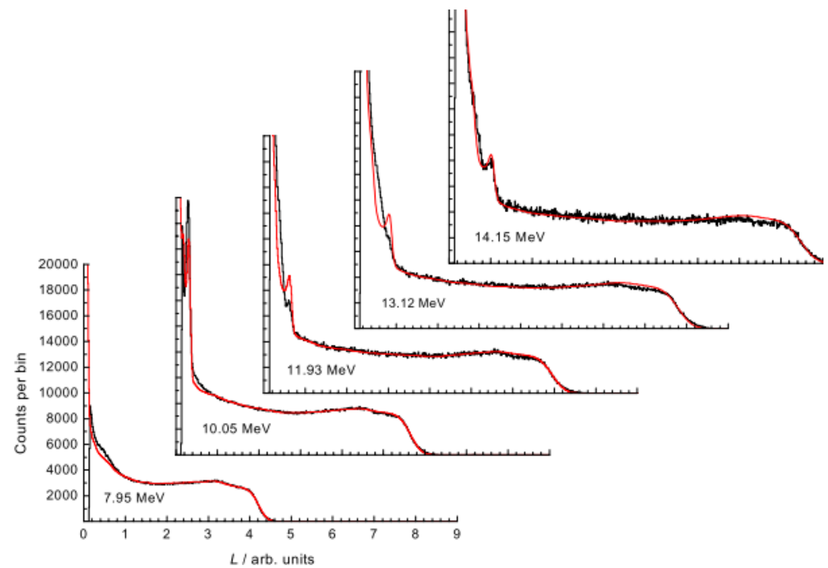




Experimental Characterization of Detectors

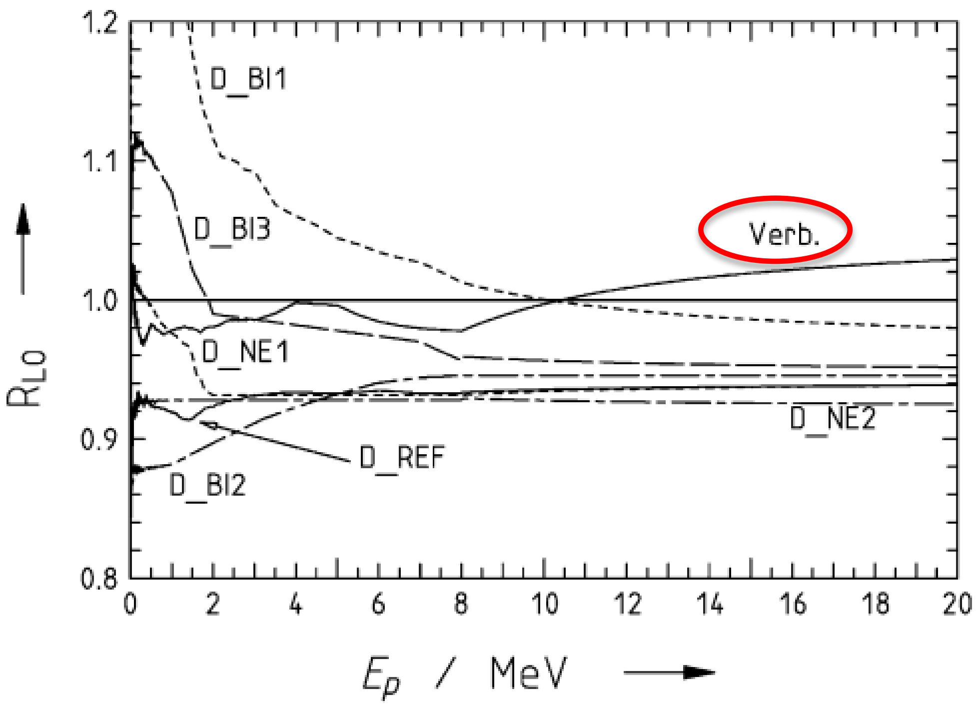
- **Experimental data to be measured for each detector:**
  - Pulse-height resolution
  - Light output function
  - Response matrix (normalized to n-p scattering)
- **Suitable neutron beams:**
  - Monoenergetic: time consuming!
  - 'White' (Be+p, C+p, D+d): E_n selection via TOF
  - TCAP: 'absolute' measurements
- **Normalization in the n-p part: response matrix: $(dR_\Phi/dL)(E_n)$**
- **This works up to 60-70 MeV**





Investigation of a set of NE213/BC501A detectors

- LO: up to 10% deviation from ref. data
- R_Φ: up to 4% rescaling of calculated response functions



Re-normalization factors for NRESP7 response functions for monoenergetic neutrons

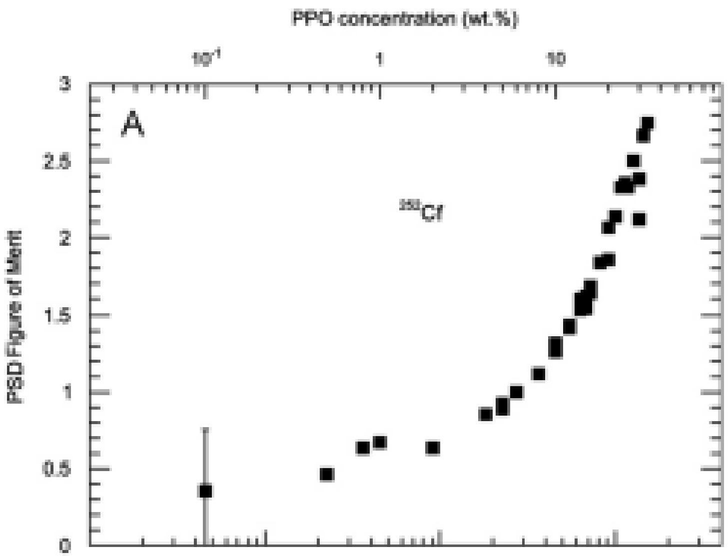
Detector	Diff. to unity (%)
D_NE1	$+0.3 \pm 1.3$
D_NE2	$+0.0 \pm 0.9$
D_BI1	$+1.2 \pm 0.6$
D_BI2	$+4.7 \pm 1.6$
D_BI3	$+1.3 \pm 0.8$

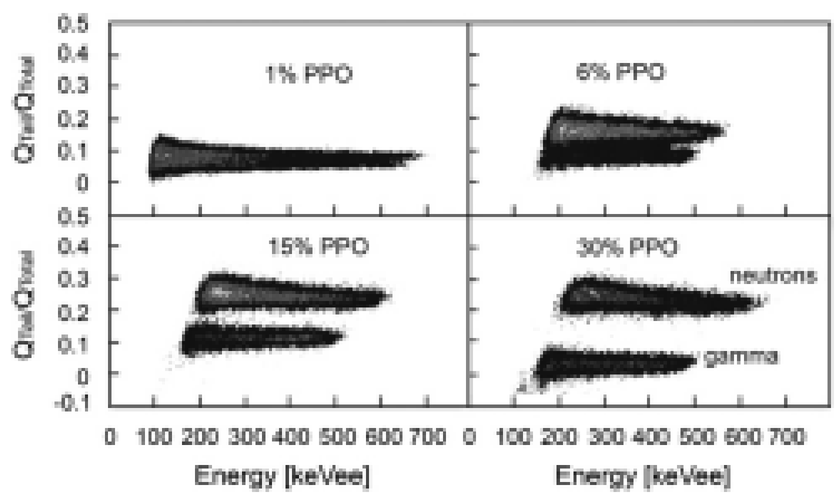
Ref.: D. Schmidt *et al.*, NIMA476 (2002) 186-189

Recent Developments: PSD with Plastic Scintillators

- Liquid and plastic scintillators: binary or ternary systems
- Properties determined by primary solute system:
  PSD: $^3Y^* + {}^3Y^* \rightarrow {}^1Y^* + {}^1Y$
  - Liquid scintillator: strong molecular diffusion of $^3Y^*$
  - Plastic scintillator: long-range dipole – dipole interactions required
    this process is only effective at higher Y concentrations

⇒ Increased concentration of primary solvent could improve PSD

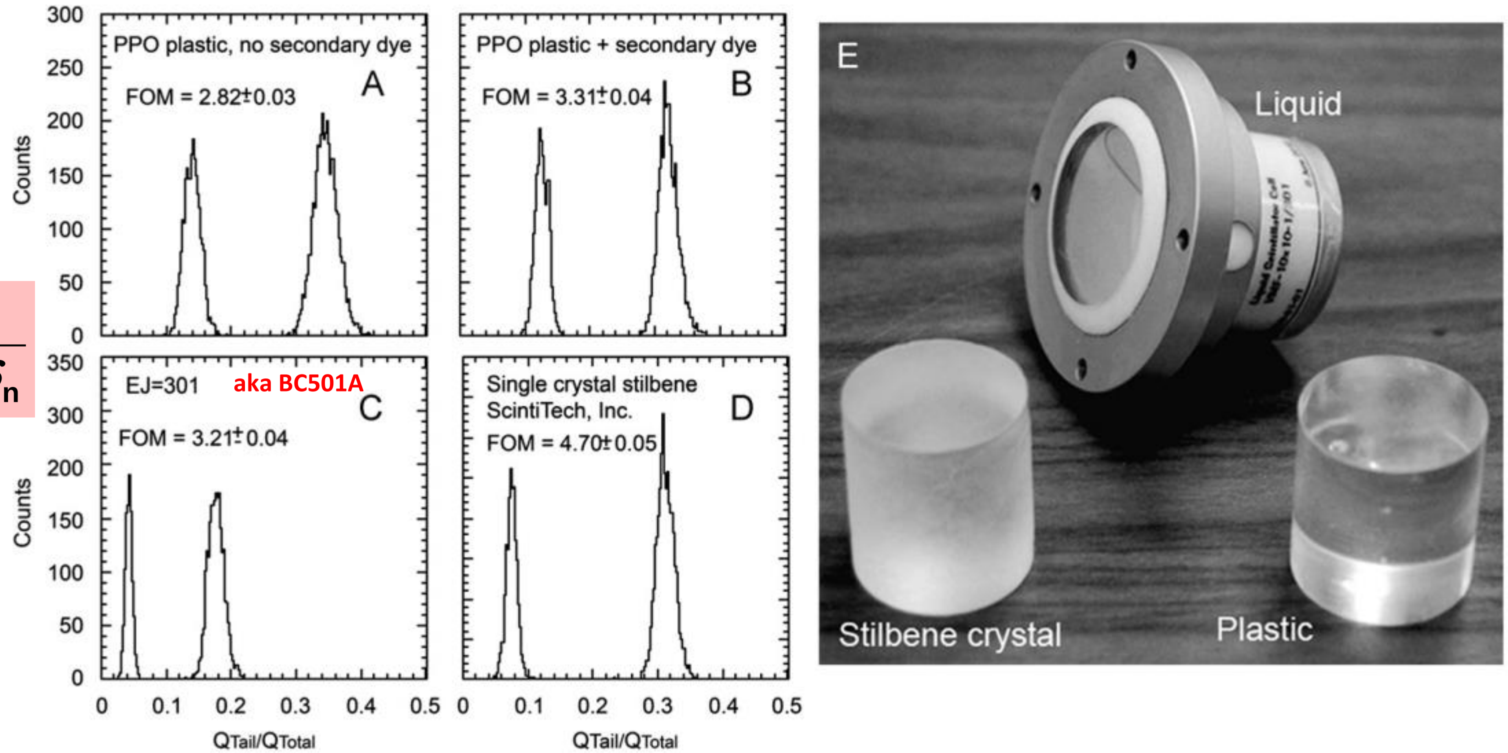




Ref.: N. Zaitseva *et al.*, NIMA668 (2012) 88.93

Commercial Plastic Scintillator with PSD: EJ299-33

$$\mathrm{FOM} = \frac{S_{\gamma,\mathrm{n}}}{\delta_\gamma + \delta_\mathrm{n}}$$



Ref.: N. Zaitseva *et al.*, NIMA668 (2012) 88.93

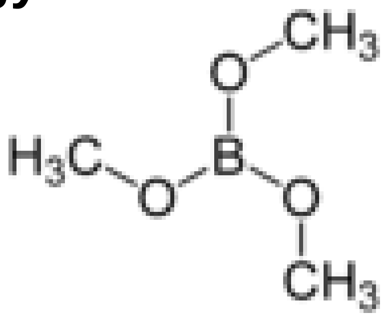
- **PSD properties as good as for liquid or crystal scintillator**
- **Secondary solute improves QE**
- **Practical advantages: non-toxic, non-flammable, no container, all shapes, sizes ≤ 15 cm**

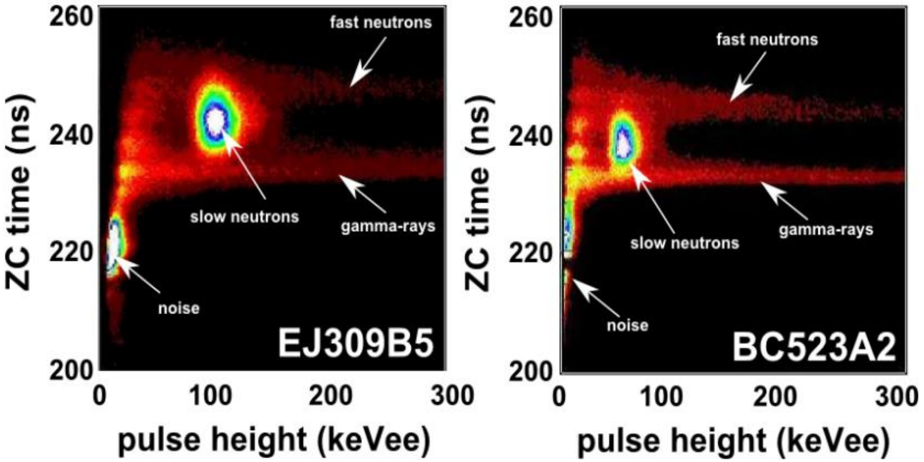
Boron-Loaded Liquid Scintillators

- Main disadvantage of organic scintillators: strong quenching

⇒ Boron doping increases sensitivity to low energy neutrons: $^{10}B(n,\alpha_0)^7Li + ^{10}B(n,\alpha_1)^7Li^*$

  – Up to 4.5 % (wt.) B loaded as $B(OCH_3)_3$
  – Commercially available, e.g.: EJ309B, BC523A
  – Dopant influences light output and PSD!





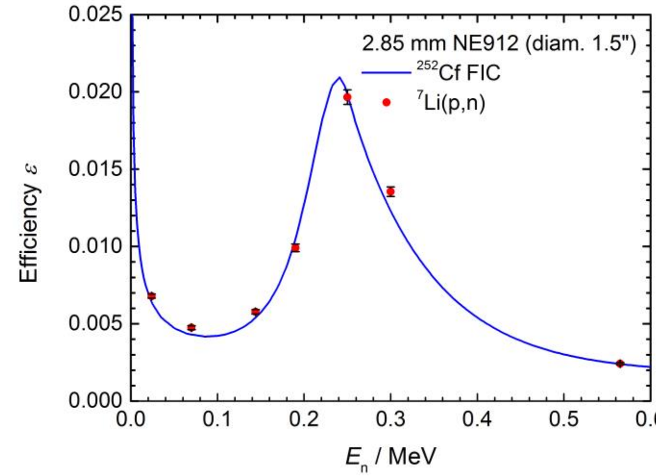
Ref.: J. Iwanowska *et al.*, JINST 7 (2012) C4004 (FNDA2011)

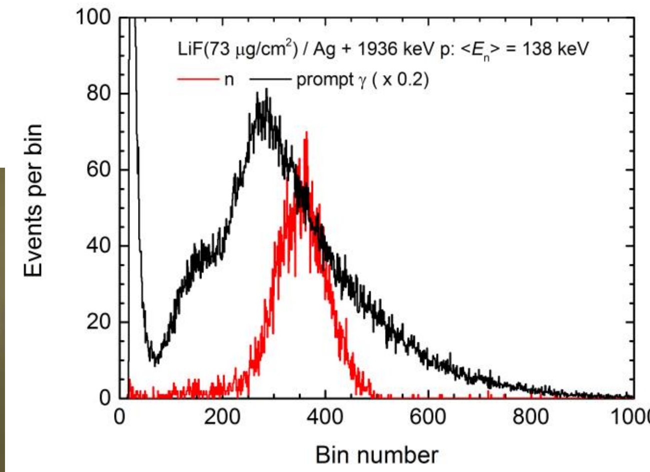
- Same technique applicable for ^6Li and ^{157}Gd
- ^{10}B-loaded plastic scintillators available as well: BC454

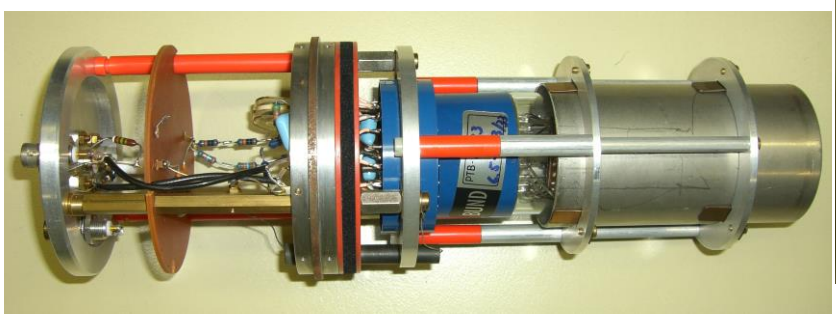
Inorganic Scintillators: ^{6}LiGlass

Ce^{3+} activated lithium silicate glass

- SiO_2: 55-75%, MgO: 4-25%, Al_2O_3: 9-20%, Ce_2O_3: 4-5%, Li_2O: 6-21%
- Depleted (≤ 0.01%) and enriched (≤ 99.9%) in ^{6}Li
  Low-background material: NE912 / NE913
- Low light yield: 5% of NaI for p, He
  15-25% of NaI for electrons
- Poor PSD properties
- Limited n/γ discrimination by PH threshold
- Non-linear light output: $L_{\alpha}(v) \neq L_{p}(v)$
- Main application: TOF spectrometry



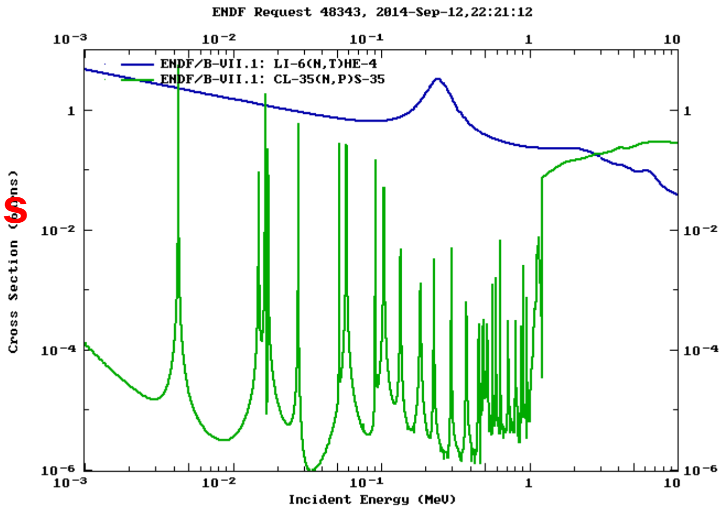


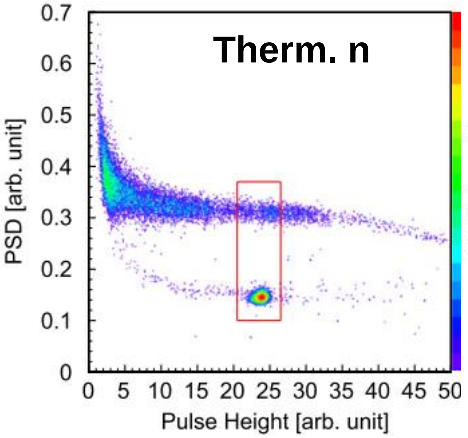


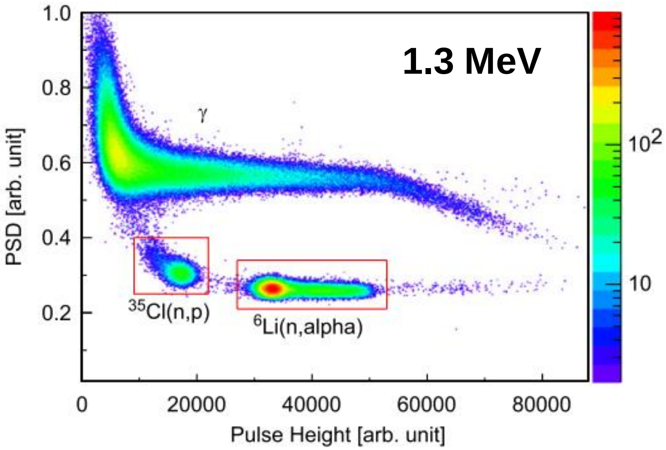
Novel Inorganic Materials: CLYC

CLYC: Cs_2LiYCl_6:Ce

- **High light yield: 40 - 60 % NaI for p, He**
  60 – 90 % NaI for electrons
- **Good PH resolution ⇒ γ and n detector**
- **Neutron detection: ^{6}Li(n,α), ^{35}Cl(n,p)**
- **Excellent PSD properties**
- **Excellent time resolution: Δ*t* < 800 ps**
- **Cracky crystals**
- **Small sizes: ∅ < 2"**
- **Expensive material**



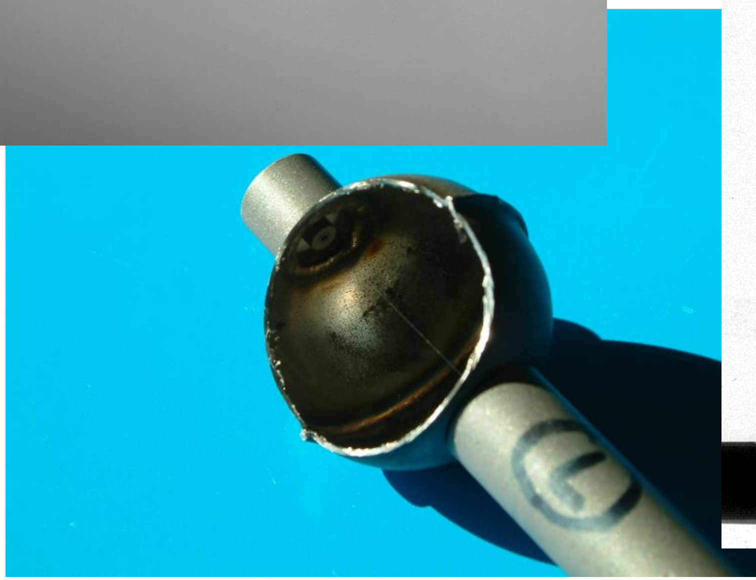


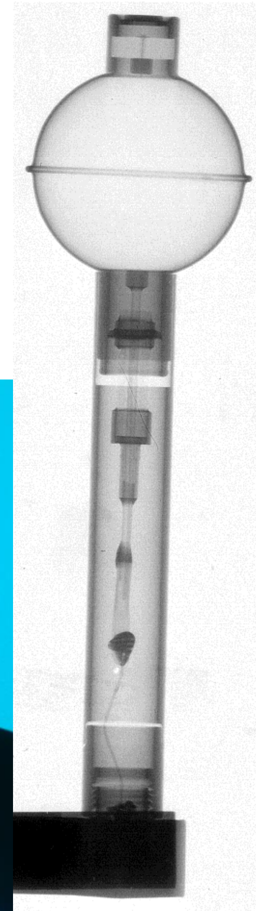


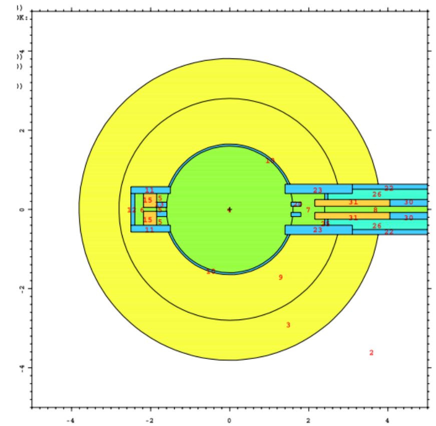
Ref.: N. D'Olympia *et al*., NIMA 714(2013) 121-127

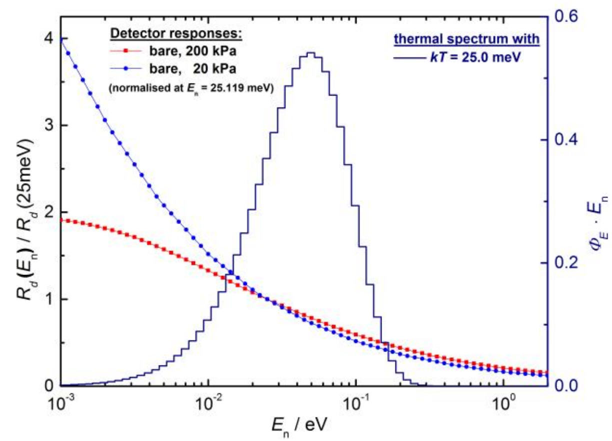
Additional Material

Spherical ^{3}He Counters









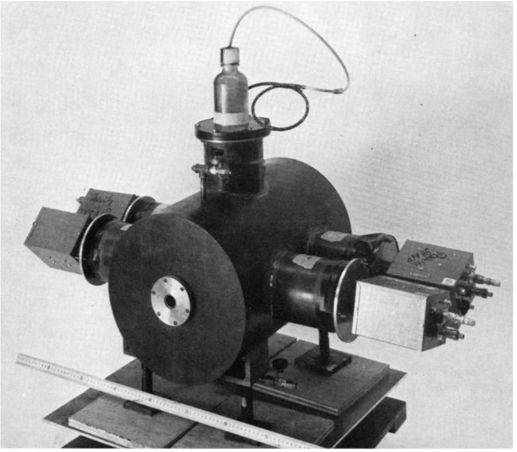
Centronics SP9 Counter: - **almost isotropic response**
- **^{3}He pressure range: 0.2 bar – 2 bar**
- **working horse for thermal neutron measurements**

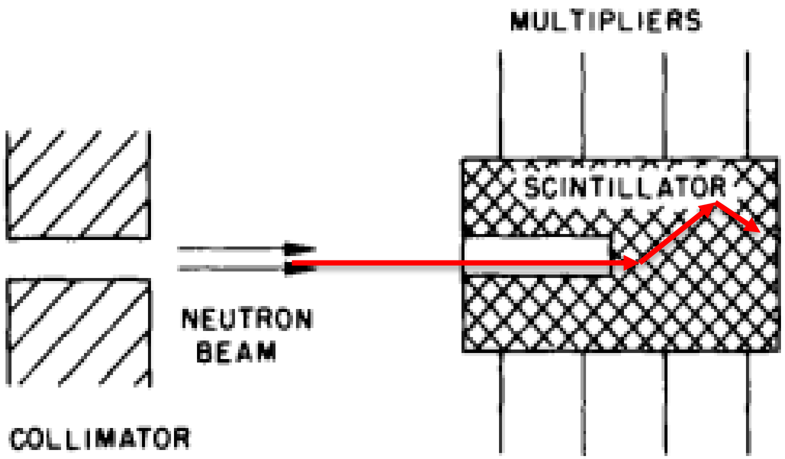
TOF Long Counters: Black Detector

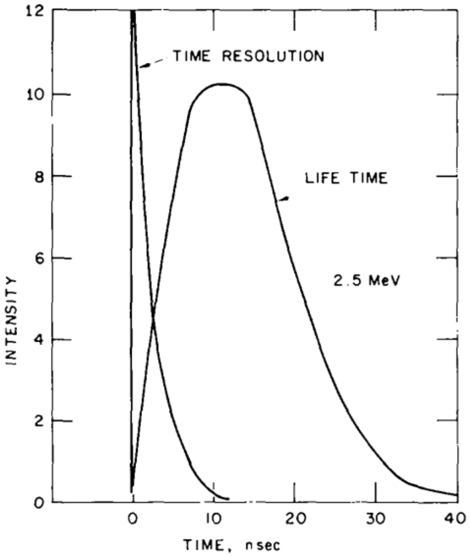
- Moderation time in a long counter: several 10 µs

⇒ not suited for time-of-flight (TOF)

- Black detector:
  - Moderator: liquid scintillator
  - Efficiency ≈ 0.95 ± 0.05 for E_n = 0.5 – 10 MeV
  - Time response determined by $L_p(E)$
  - TOF resolution ≈ 4 ns (tail!)







Ref.: W.P. Pönitz, NIM 109 (1973) 413-420

Long Counters for Beta-Delayed Neutrons

- **ß-del. neutrons in r-process nucleosynthesis:**
  - path back to stability: $A \rightarrow A$-1
  - add. neutron source: P_n
- **BELEN-30 detector:**
  - 1 m³ PE moderator
  - 30 ^{3}He counters in two 'crowns'
  - Precursors implanted in Si-strip detectors
  - Recording of β- and n-events
  - Exp. verification of the MCNPX model: ^{252}Cf(s.f), ^{13}C(p,n), ^{13}C(α,n), ^{51}V(p,n) at PIAF

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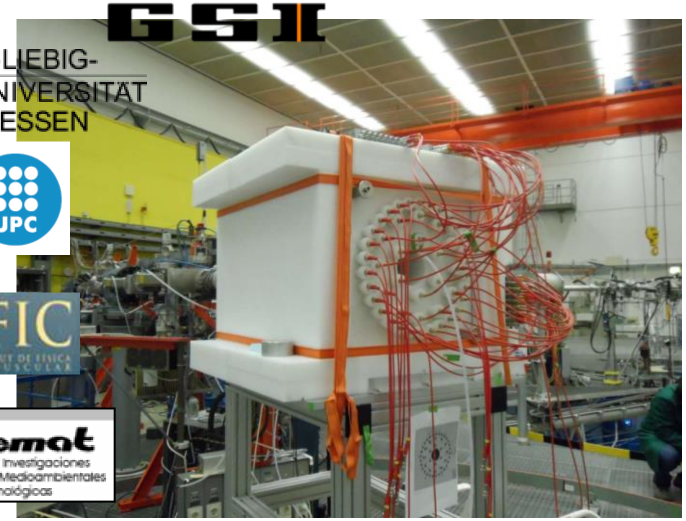
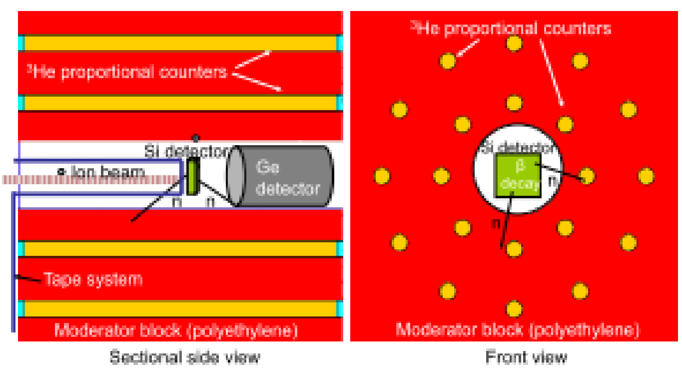
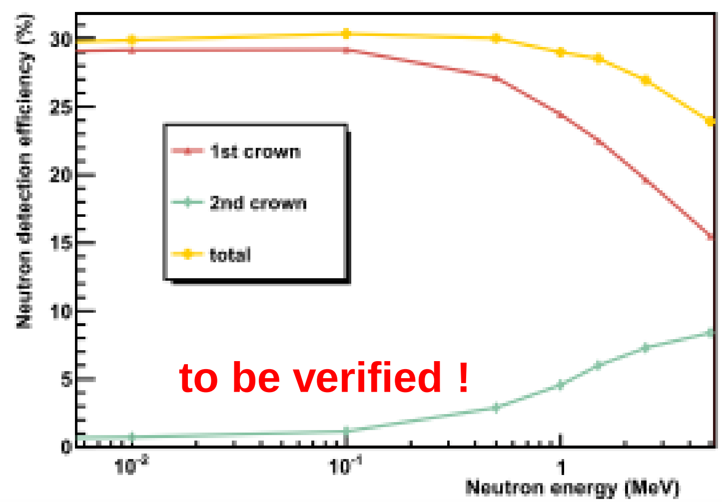
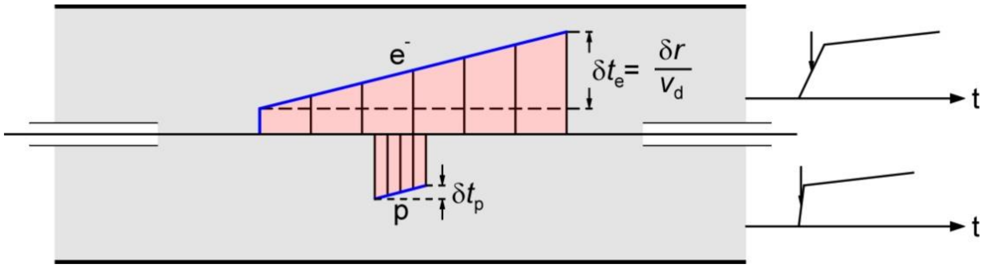






Ref. :M.B. Gómez-Hornillos *et al.*, JPConf 312 (2012) 052008

Photon/Neutron Discrimination



Rise-time measurement:

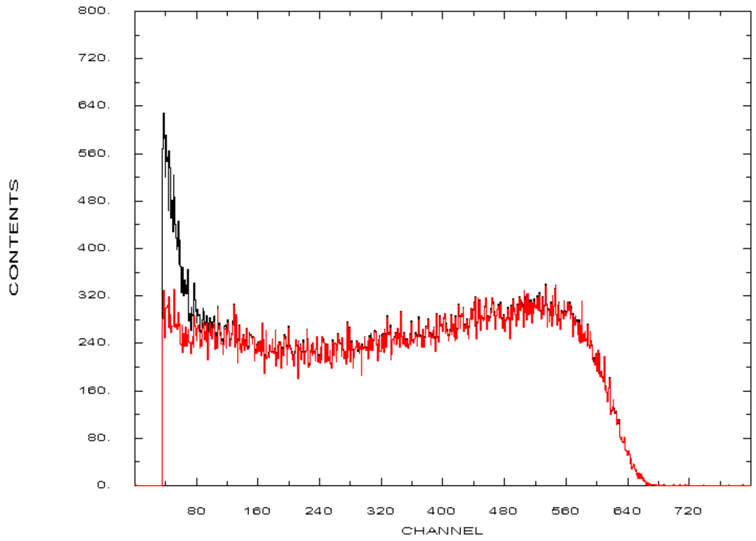
fast filter amp. : t_{diff} = 50 ns, t_{int} = 500 ns

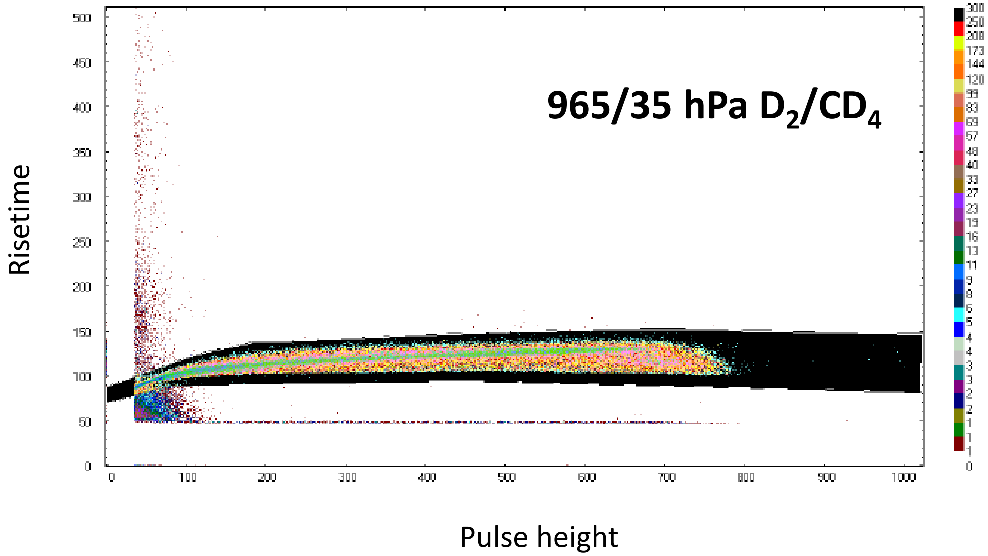
- **start: LE-disc. close to noise**
- **stop: CF-disc. (f = 0.4)**

shaping amp.: t_s = 2 µs

Recoil tracks more localized than electron tracks

⇒ different drift times for sec. electrons

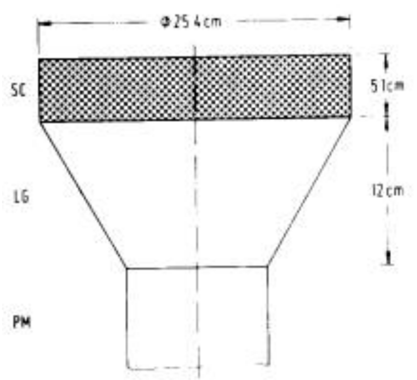


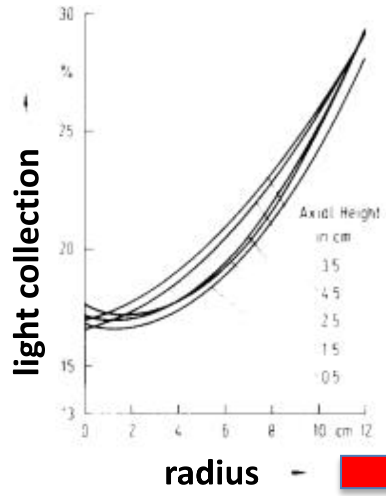


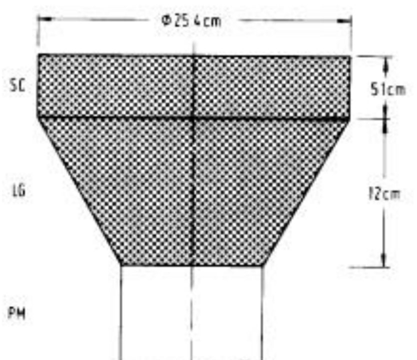
NB: Analogue technique to be replaced by waveform digitizers!

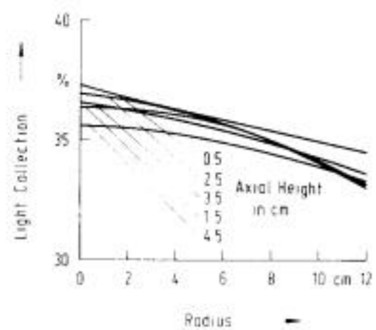
Optimization of the Pulse-Height Resolution

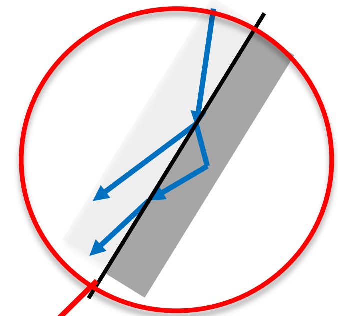
Light transport:
- refraction and reflection
- total reflection
- diffuse reflection on TiO_2 coating

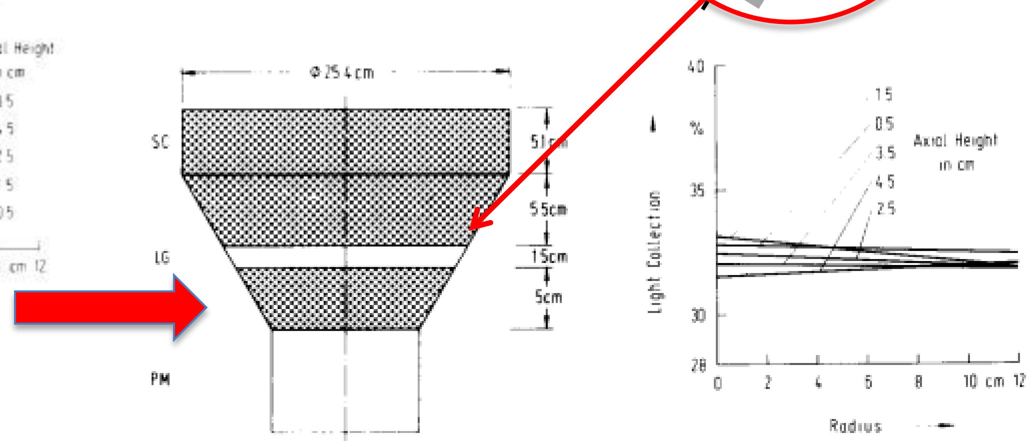










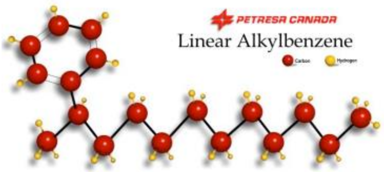


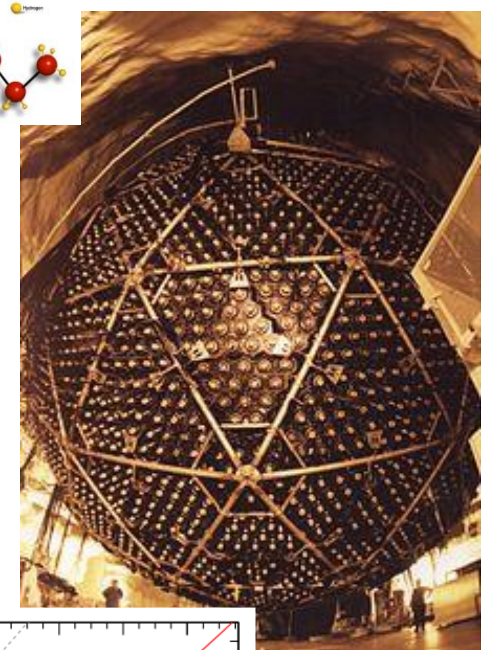
Many Monte Carlo codes available
- Optical properties treated as free parameters
- No quantiative predictive power

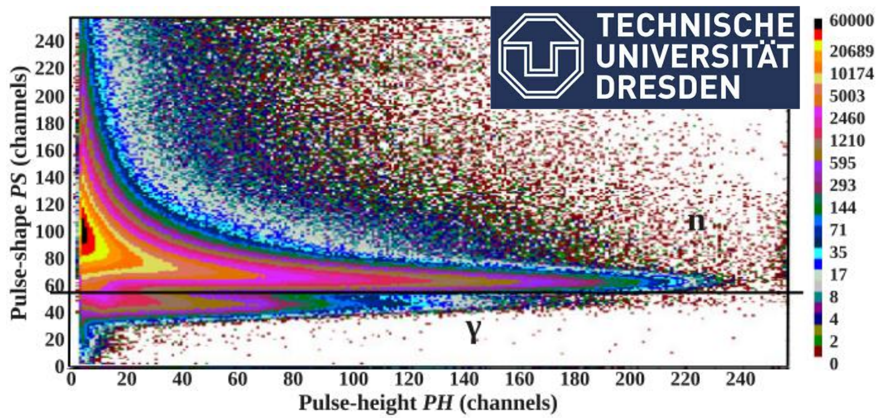
Ref. H. Schölermann et al. NIM 169 (1980) 25-31

‘Unconventional’ Liquid Scintillators: LAB for SNO+

- **SNO+: 0ν2β decay of ^{130}Te, …**
- **Scintillator: 780 t (LAB + 2 g/l PPO)**
- **Quenching data required for background model**







Ref.: B. v. Krosigk *et al.*, EPJC (2013) 73:2390

15 mg/l bis-MSB (wavelength shifter)
Poor PSD properties
proton quenching: *kB* = 0.0093
Design value *kB* = 0.0073

⇒ Important for the background model