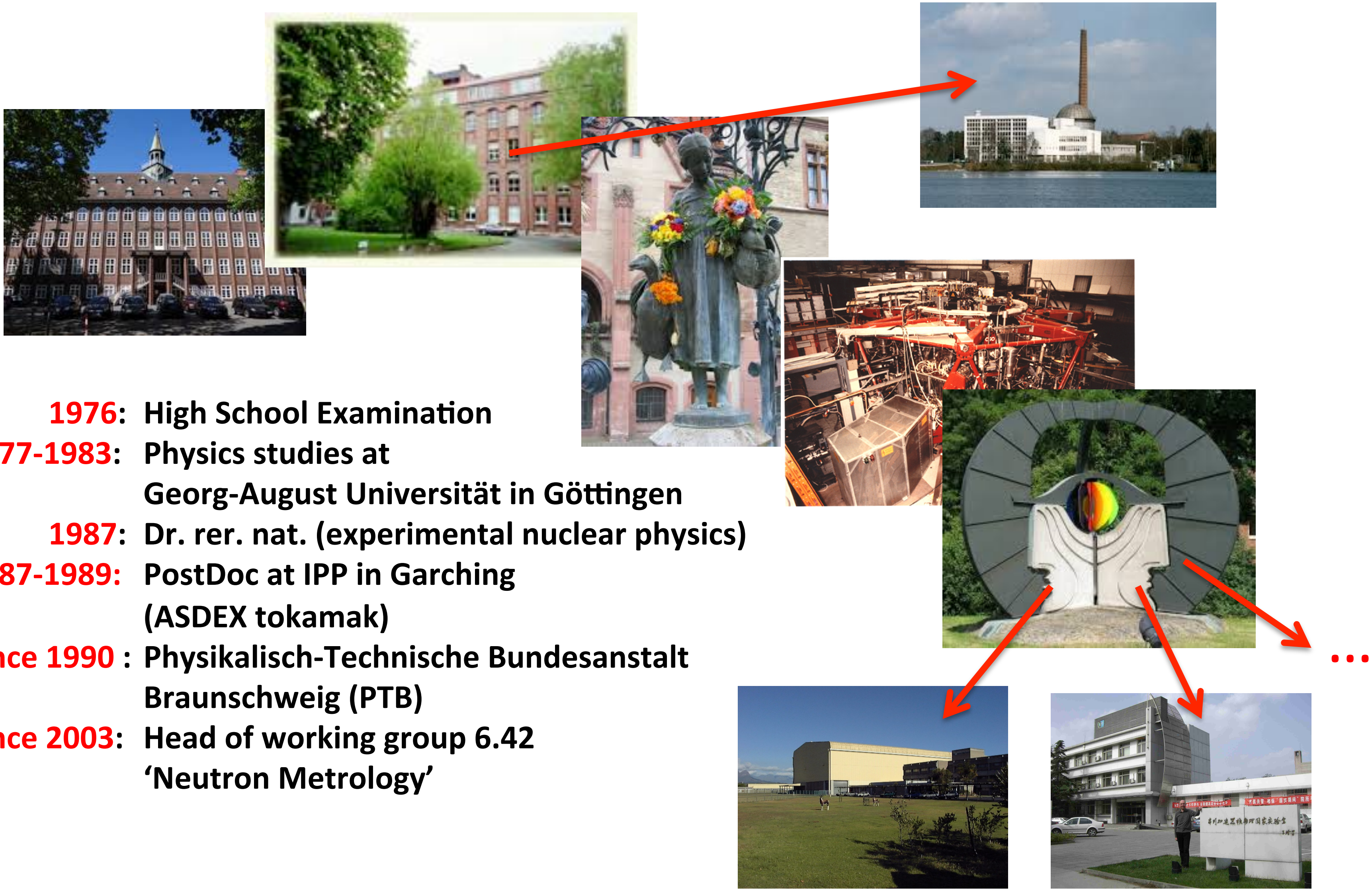
Detection of Neutrons: Part I

Ralf Nolte

Professional CV



1976: High School Examination
1977-1983: Physics studies at Georg-August Universität in Göttingen
1987: Dr. rer. nat. (experimental nuclear physics)
1987-1989: PostDoc at IPP in Garching (ASDEX tokamak)
Since 1990 : Physikalisch-Technische Bundesanstalt Braunschweig (PTB)
Since 2003: Head of working group 6.42 'Neutron Metrology'

The PTB Ion Accelerator Facility (PIAF)

PTB is the National Metrology Institute (NMI) of Germany

PTB department 6.4 operates PIAF:

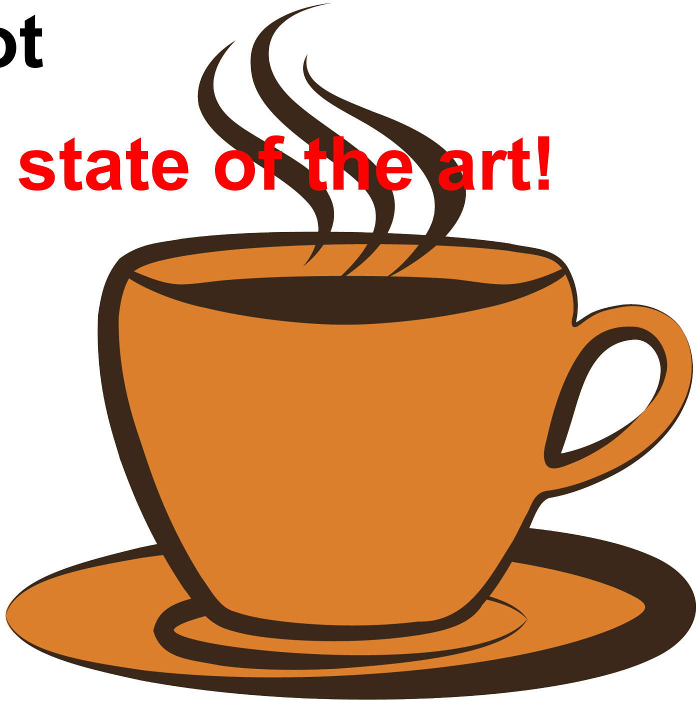
- **3.75 MV van-de-Graaff:** p, d, α beams
  ns pulsing system (1.5 – 3 ns)
  will be replaced by a 2 MV Tandetron in 2016!
- **CV28 isochronous cyclotron:** p, d, α beams
  $E_p < 19$ MeV, $E_d < 13.5$ MeV, $E_a < 28$ MeV
  internal pulse selector ($1/f_{cyc} \approx 1$ µs)

Goal of this lecture:

to present the basic aspects of neutron detection for students

and not

to review the current state of the art!



… so the experts can go and have a coffee!

Table of Contents

Where to Find More Reference Material?


International Workshop on
Fast Neutron Detectors and Applications
University of Cape Town - April, 3-6,

Papers - Talks - Posters - Pictures

2nd International Workshop on
Fast Neutron Detectors and Applications
Ein Gedi / Israel
November 6-11, 2011

CRETE 15
June 14-20, 2015
Crete, Greece

2014 Symposium on
Radiation Measurements and Applications (SORMA XV)
June 9-12, 2014
The University of Michigan
Ann Arbor, Michigan, USA
Abstract Book

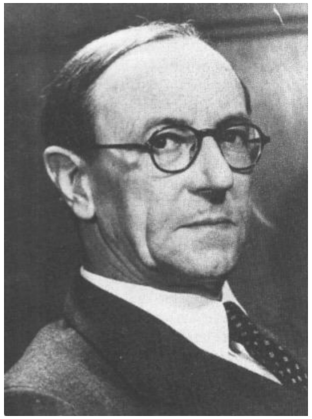
- **W.D. Allen:**
  Neutron Detection (1960)
- **J.B. Marion, J.L. Fowler:**
  Fast Neutron Physics (1960)
- **K.H. Beckurtz, K. Wirtz:**
  Neutron Physics (1964)
- **W.R. Leo:**
  Techniques for Nuclear and Particle Physics Experiments (2nd ed. 1994)
- **G. Knoll:**
  Radiation Detection and Measurement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

Conference proceedings:

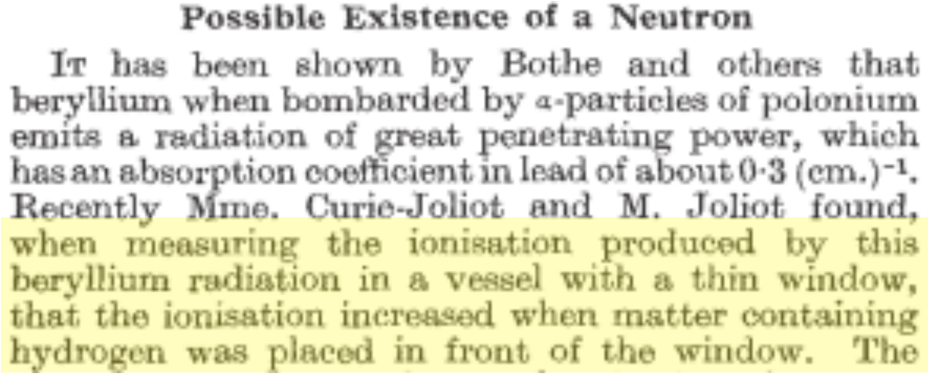
- **H. Klein *et al.* :**
  Proc. NEUSPEC 2000
  NIMA 475 (2002)
- **SORMA, Crete, ND, …**

Historical Prelude: Chadwick‘s Discovery of the Neutron

- **Sir James Chadwick (1932)**



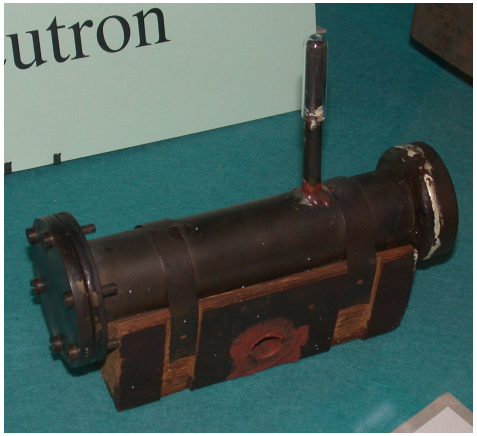
…the man who never laughed



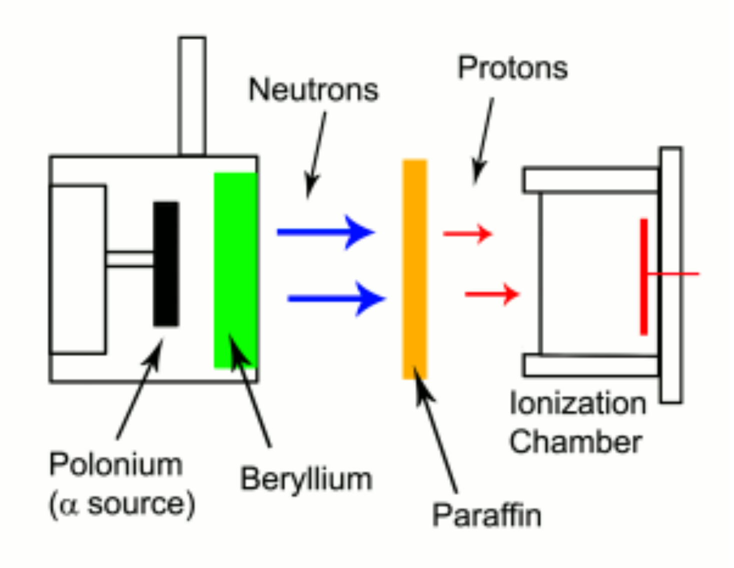
Possible Existence of a Neutron

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 $0{\cdot}3$ (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

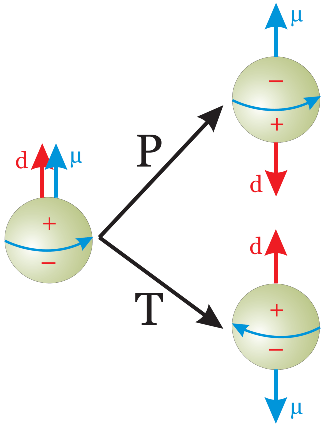


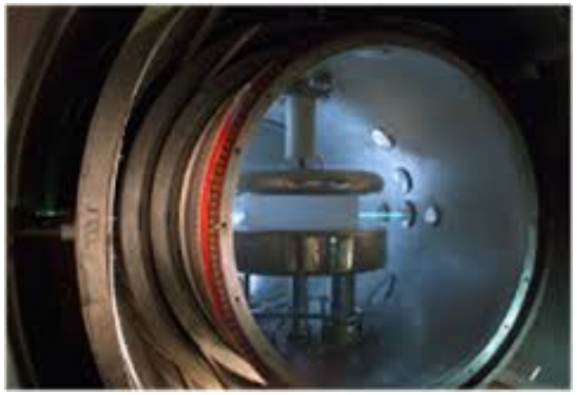
- **Correct explanation of the experiments by I. Curie and F. Joliot**
- **All elements of a modern neutron detector were present:**
  - **Neutron converter**
  - **Detector for charged particles**



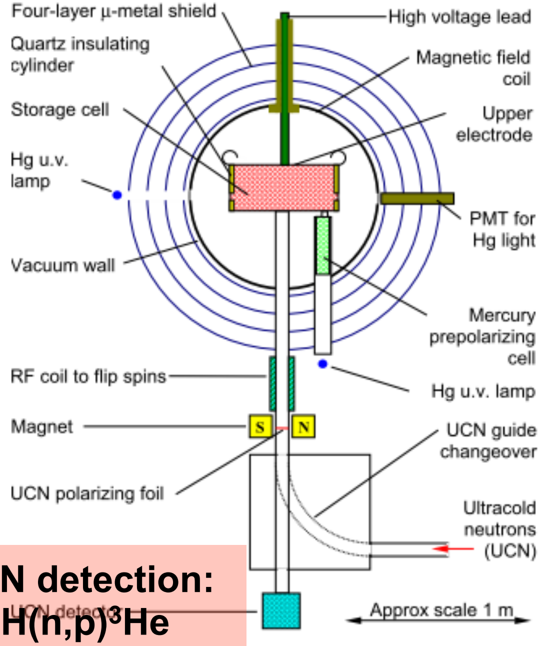
Neutrons in Science …

- Laboratory for fundamental physics: EDM, …





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

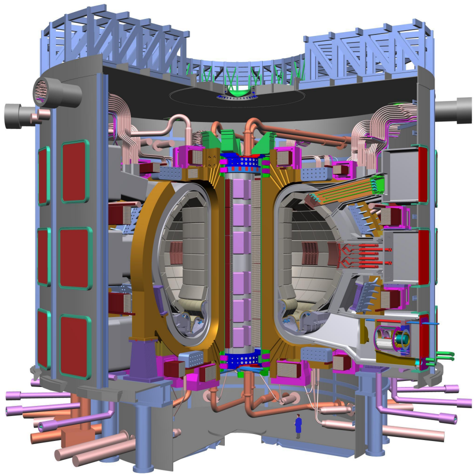


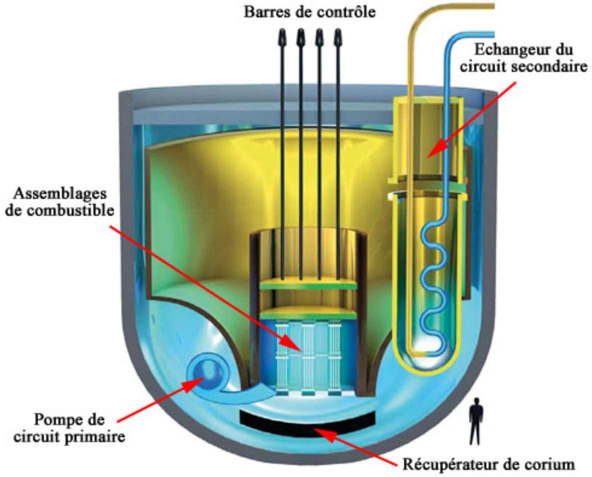
UCN detection:
$^3H(n,p)^3He$

- 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





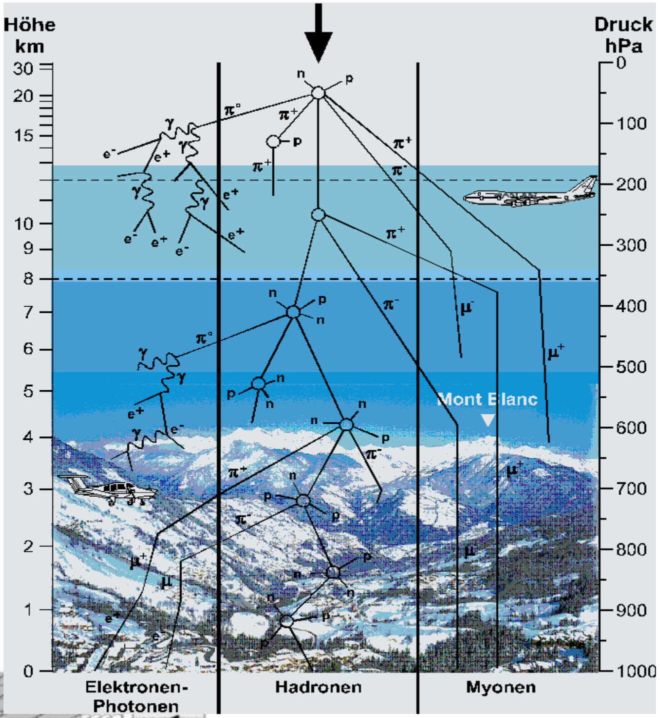
- Biggest disadvantage: the (free) neutron is unstable:

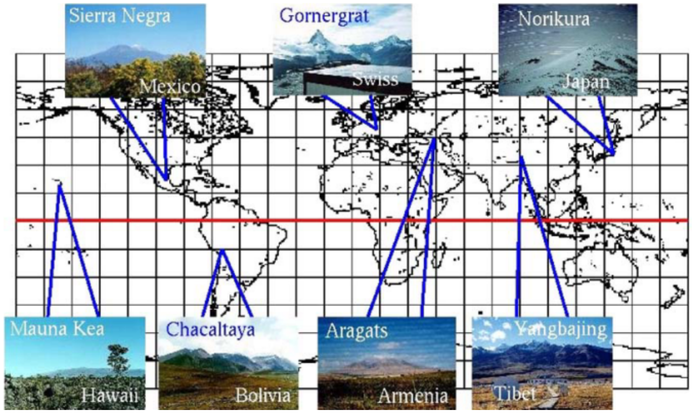
$$\tau \approx 880 \text{ s}$$

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

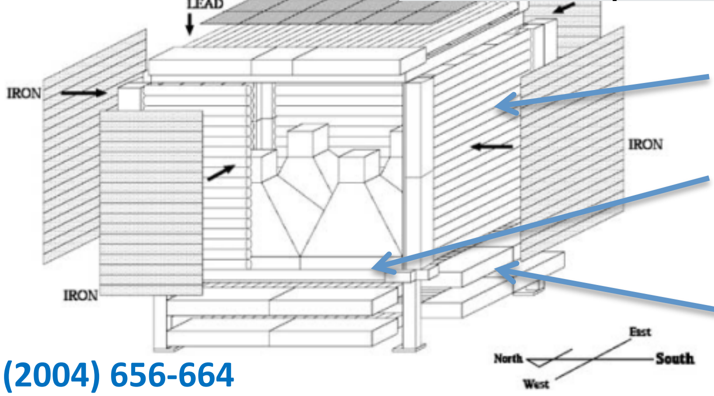
… and the World Around

- **Cosmic Neutron:**
  - Production in the atmosphere by galactic radiation
  - Production on the sun
- **Neutron monitors:**
  Diagnostic for solar processes
- **Radiation protection at flight levels:**
  $dH^*_n/dt \approx 1 - 4\ \mu\mathrm{Sv/h}$ at 12 km





Mexico Solar Neutron Telescope



anticoin. shield

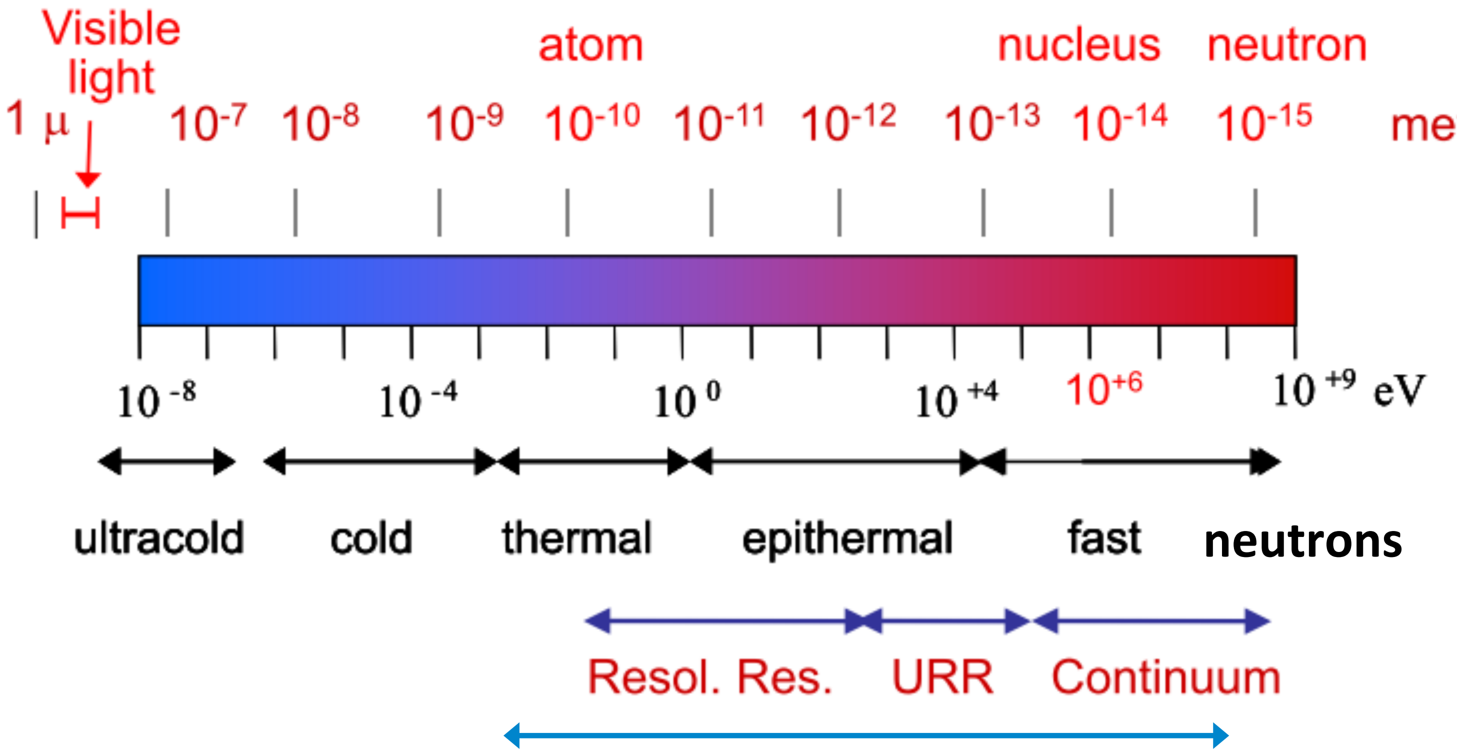
1 m² scintillator

prop. counters

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

Classification of Neutrons

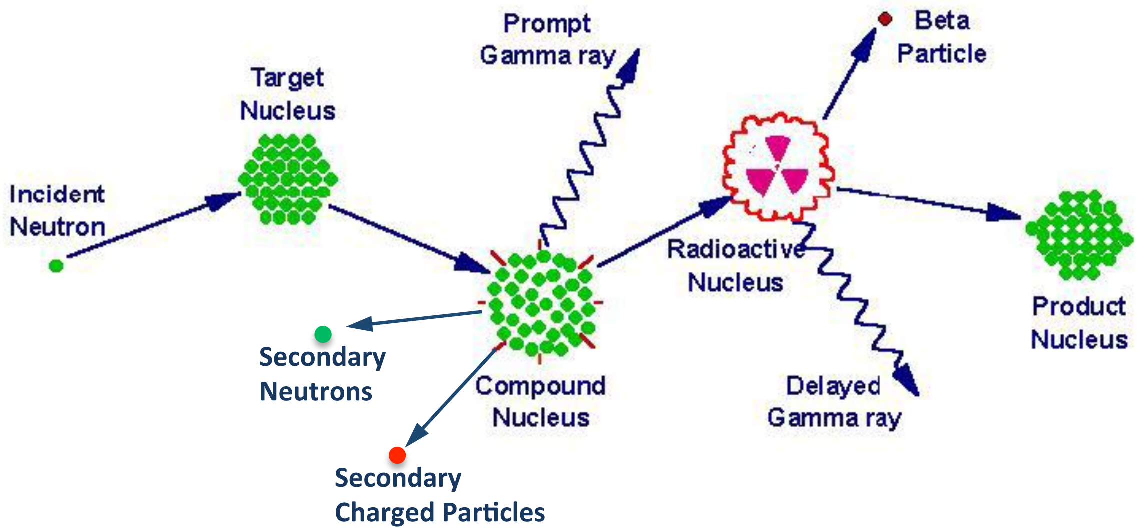
de Broglie wavelength: $\lambda = h / p$



Energy range covered in this lecture

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 $T_i\,(s_{i-1},s_i)$**
- **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:

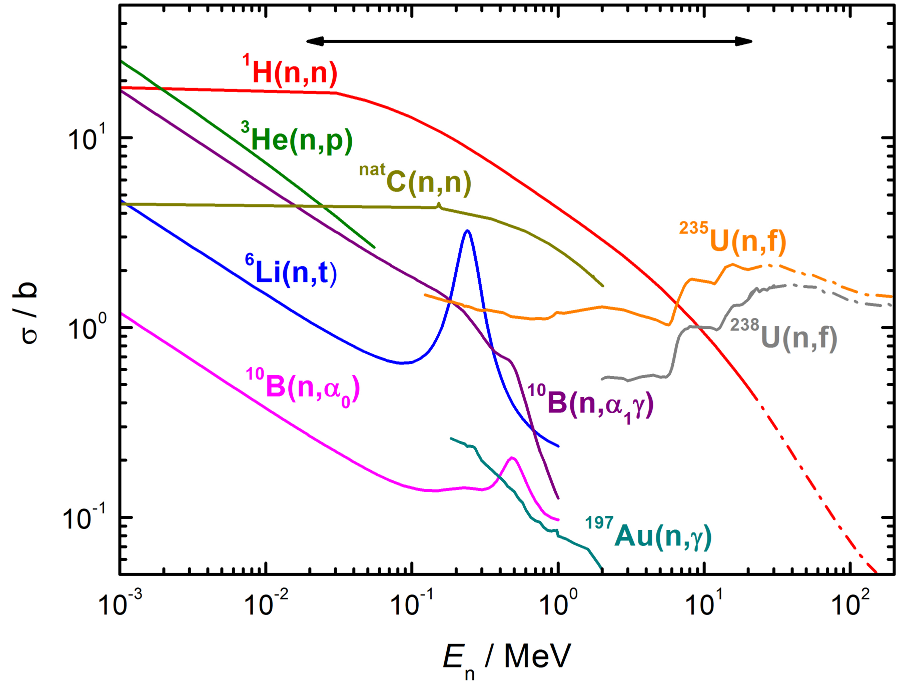
- Neutron counters
  - Signal does not depend on neutron energy
  - Typical for detection of thermal neutrons
- Neutron spectrometers
  - Signal somehow related to neutron energy
  - Inversion procedures are used to infer the neutron energy distribution

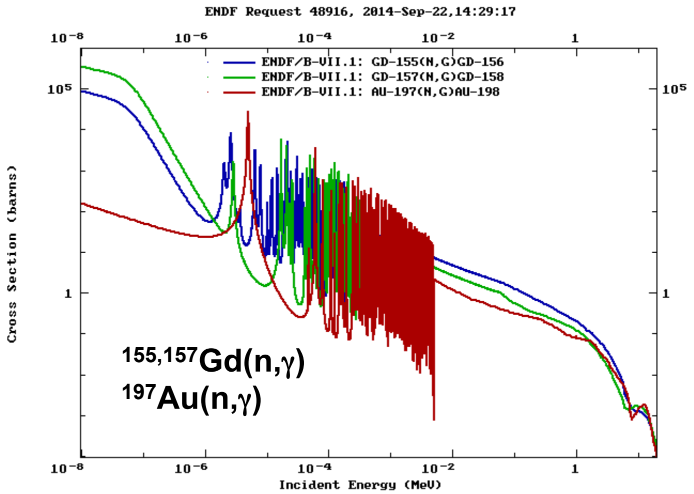
Interaction of Neutrons with Matter

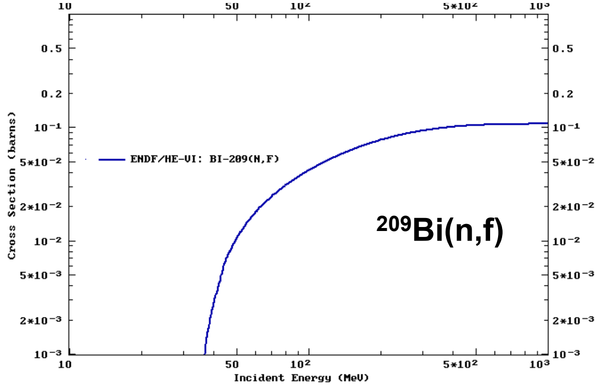
Neutrons can only be detected after conversion to charged particles or photons:

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

Cross Sections Relevant for Neutron Detection







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

...

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

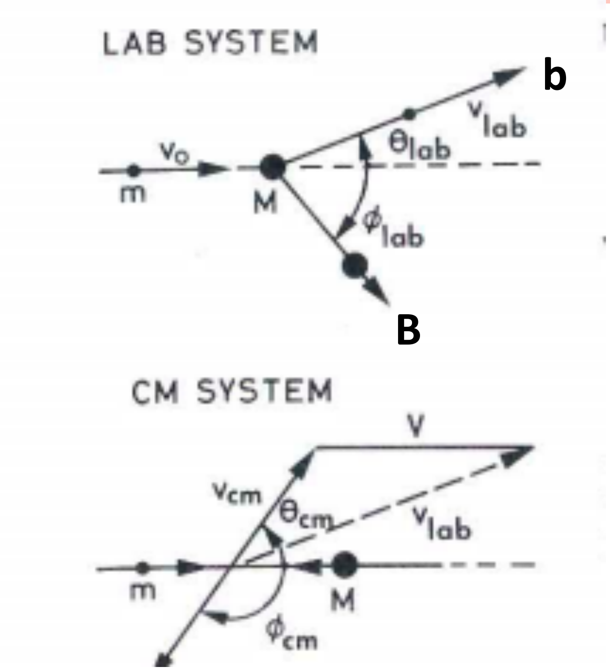
$$\vec{p}_b^{\,cm} = -\vec{p}_B^{\,cm}$$

- **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**

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



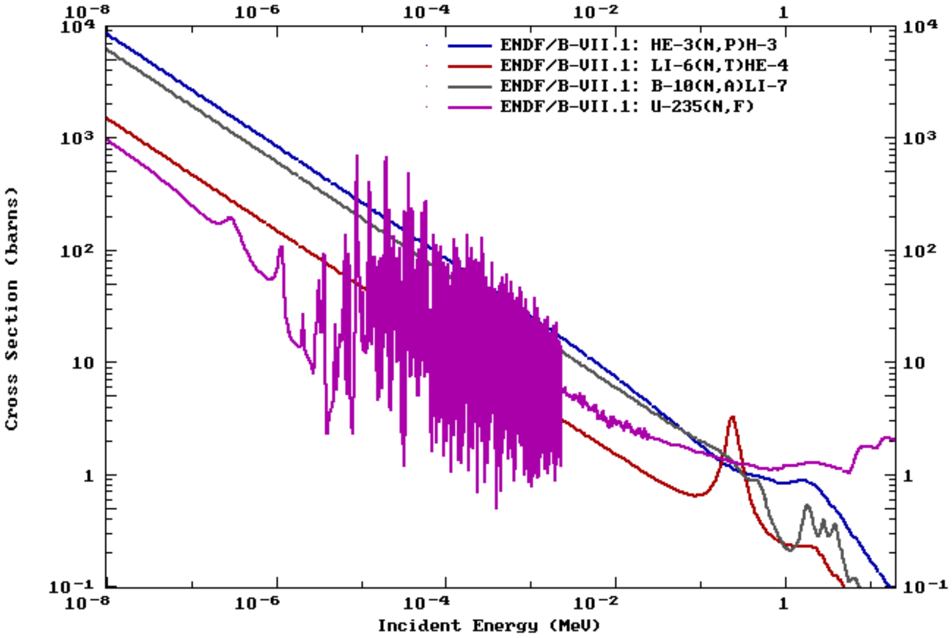
⇒**Energy distribution of recoils**

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

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: $E_n \ll Q$

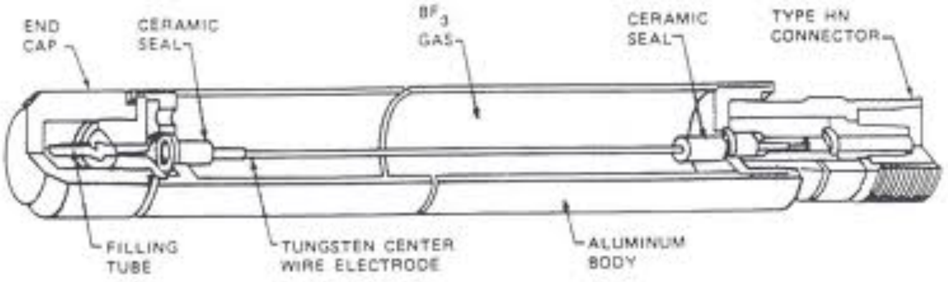
$$p_1 \approx -p_2, \quad E_1 + E_2 \approx Q$$

- **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:**

$$R = \int \frac{\sigma_0 v_0}{v} \cdot n_E v \, dE = \sigma_0 v_0 n$$

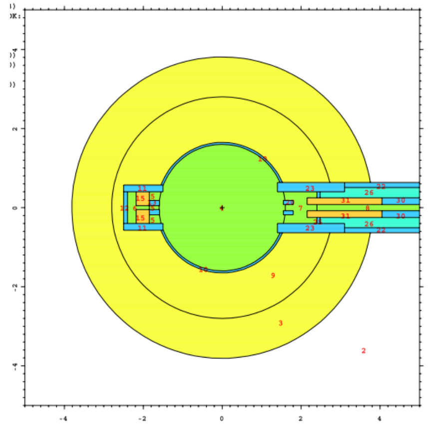
BF_3 and ^{3}He Proportional Counters

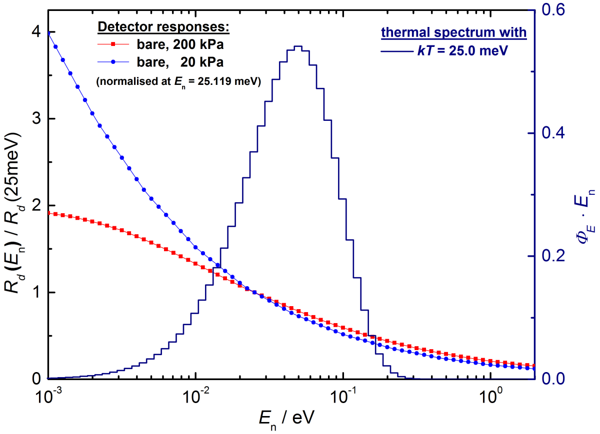
- **Cylindrical and spherical shapes**
  Large variety of sizes: $l < 1$ m
  and pressures: $p < 1$ bar (BF_3), 10 bar (^{3}He)
- **Counters must be calibrated:**
  - ^{3}He and BF_3 pressure ?
  - ^{10}B enrichment ?
  - Electrical field ?
  - Wall effects ?



- **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_3because of larger $\sigma \cdot p$**
  low *Q*-value makes n/γ sep. difficult
- **^{3}He is scarce nowadays ⇒ replacements urgently needed!**

Spherical ^{3}He Counters

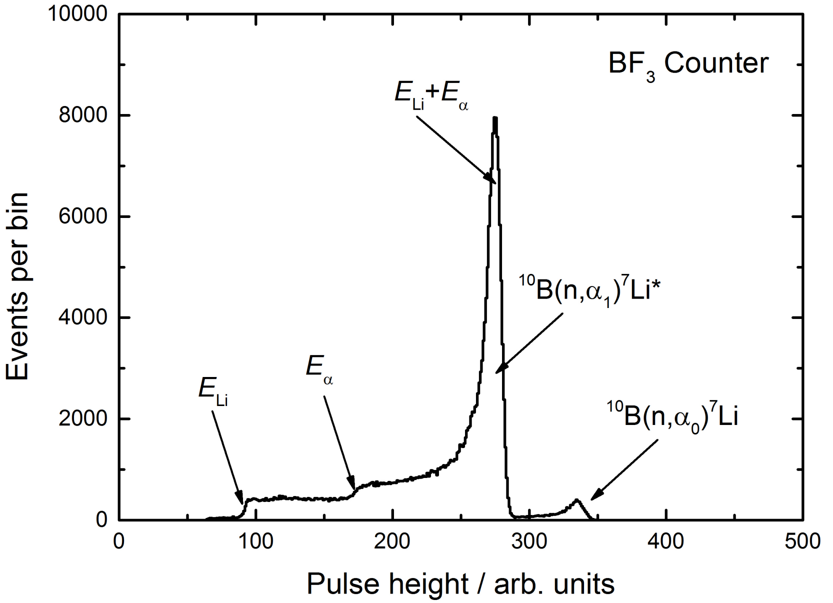


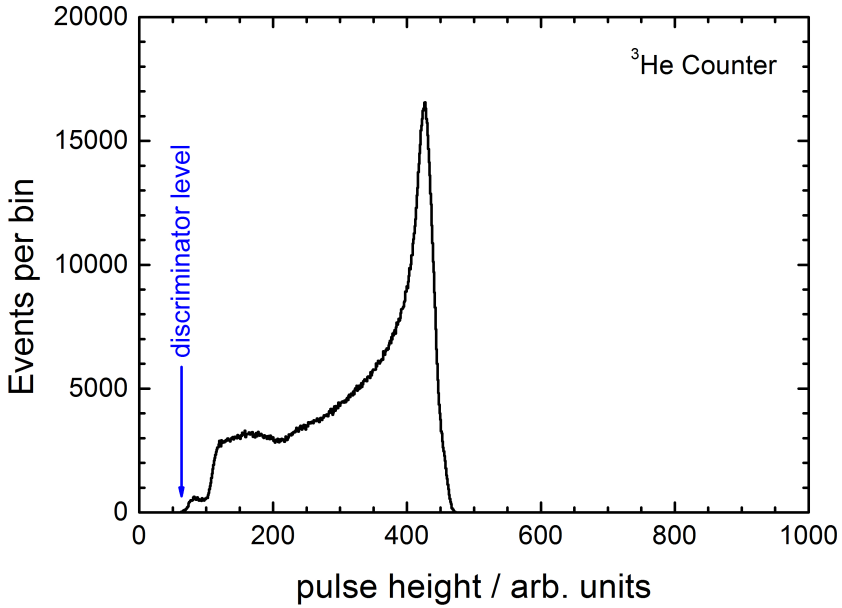


Centronics SP9 Counter: - almost isotropic response

- ^{3}He pressure range: 0.2 bar – 2 bar
- working horse for thermal neutron measurements

^{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

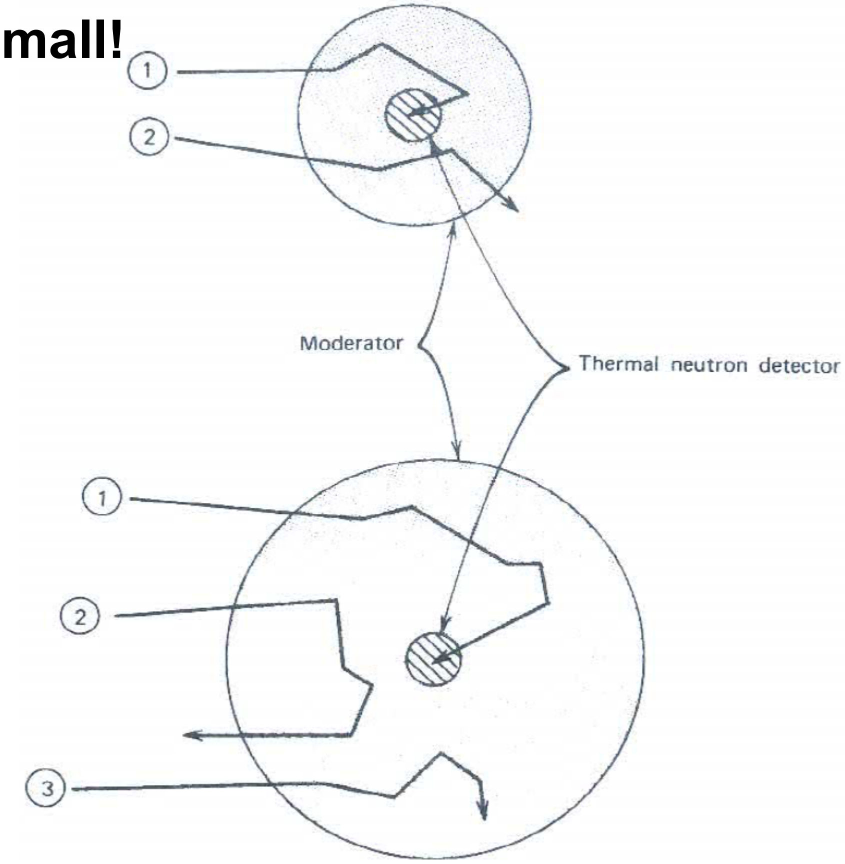
Flat Response Detectors: General Principles

- Fast neutron cross sections are small!

⇒ Cover a thermal detector with a hydrogenous moderator

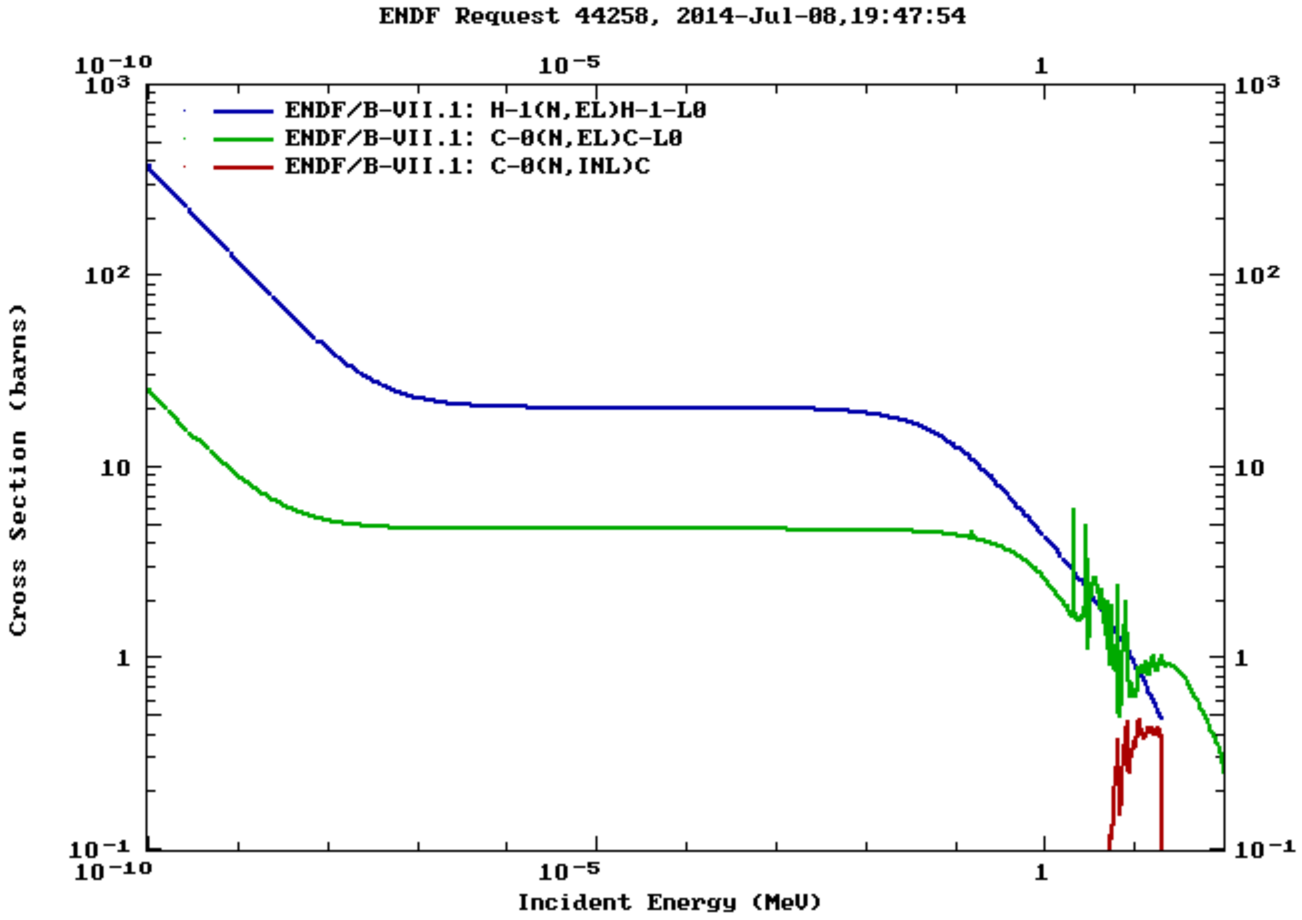
- Response depends on:
  - scattering cross section
  - moderator size
  - neutron energy

⇒ Reliable calculation with transport codes possible



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

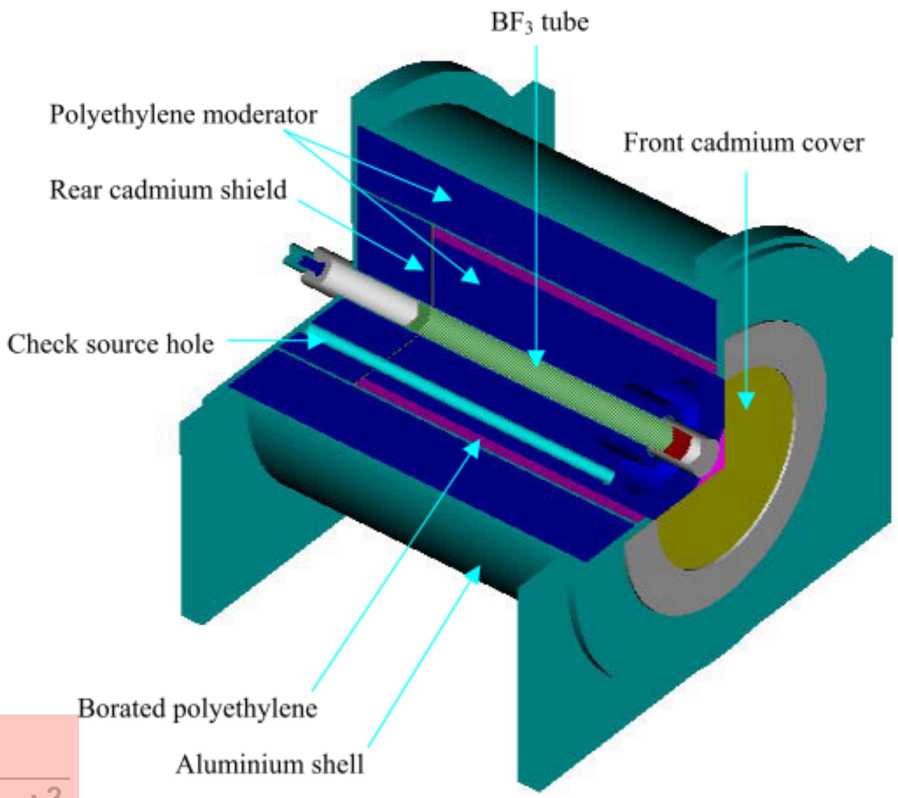
Scattering Cross Section for Hydrocarbons



NB: np scattering dominates for $E_n < 20$ MeV

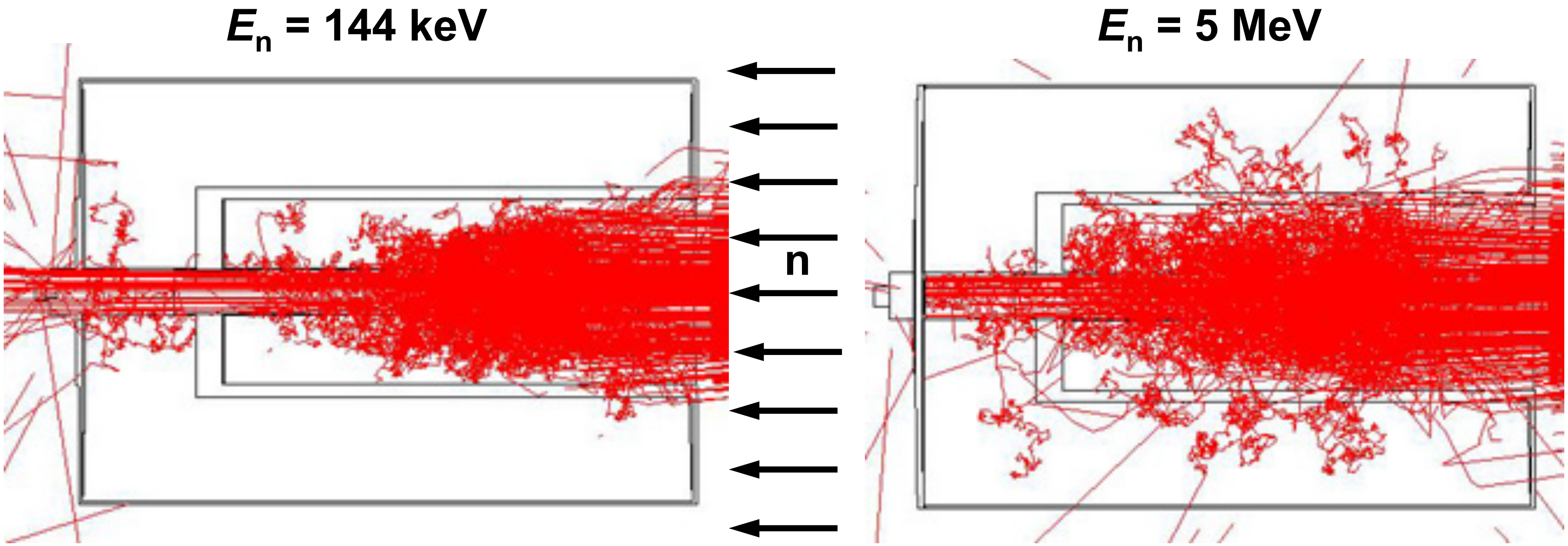
The Long Counter

- **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



E_n = 144 keV

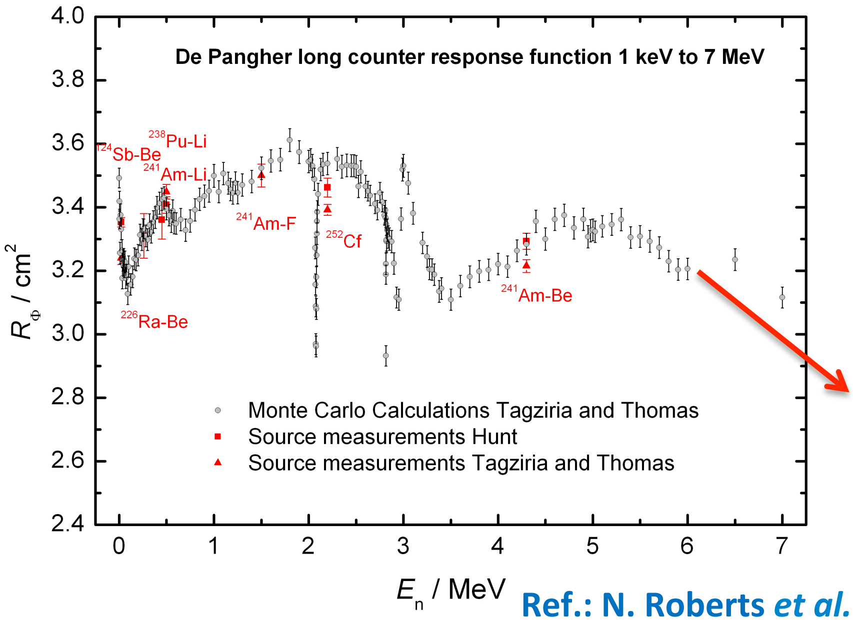
E_n = 5 MeV

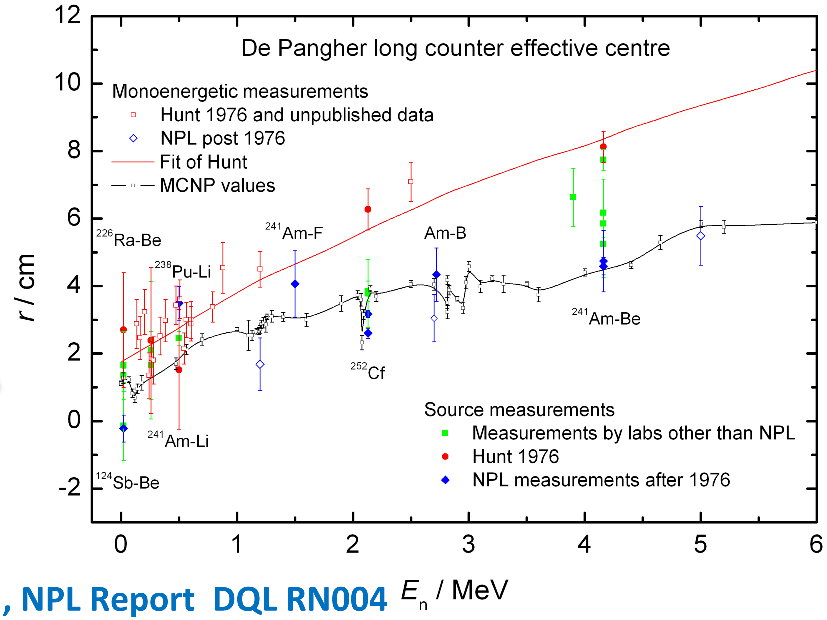
Flat-field irradiation form the right hand side
Only neutron 'tracks' contributing to the response of the thermal detector are shown!

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

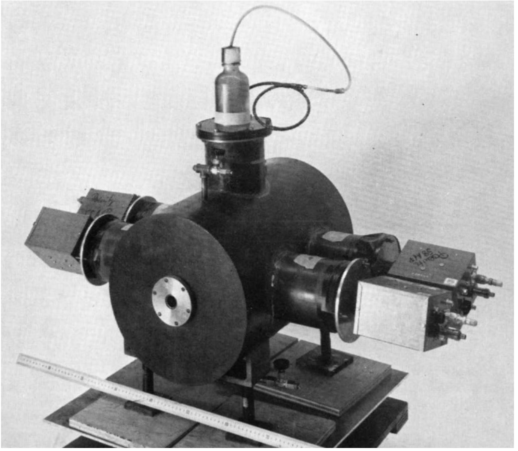
- **Calibration with radionuclide sources: link to activity standard!**
- **Overall uncertainty (NPL): $u_R/R_\Phi = 0.014$, $u_{x0} = 0.63$ cm**
- **Useful energy range: 1 keV – 15 MeV (de Pangher LC) (w/o carbon resonances)**
- **Designs with ext. energy range and/or higher sensitivity available**

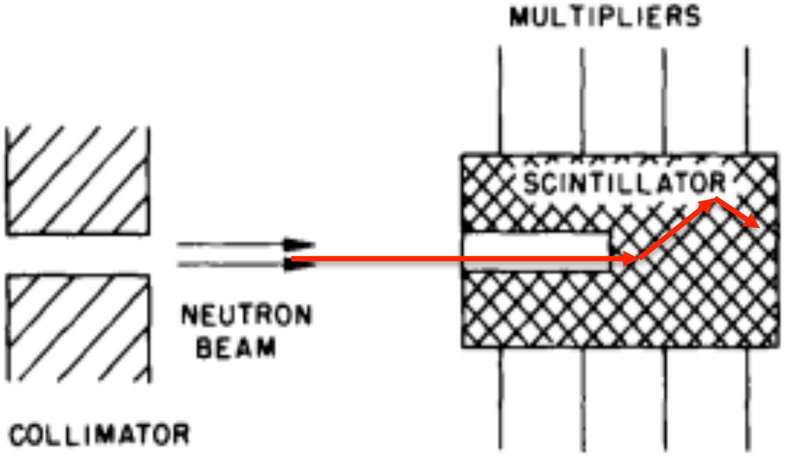
TOF Long Counters: Black Detector

- Moderation time in a long counter: several 10 µs

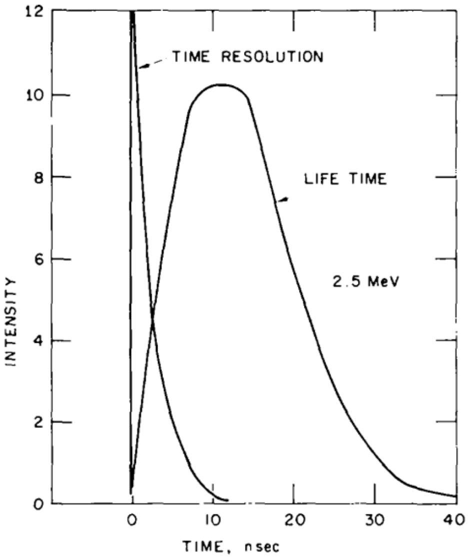
⇒ not suited for time-of-flight (TOF)

- 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!)



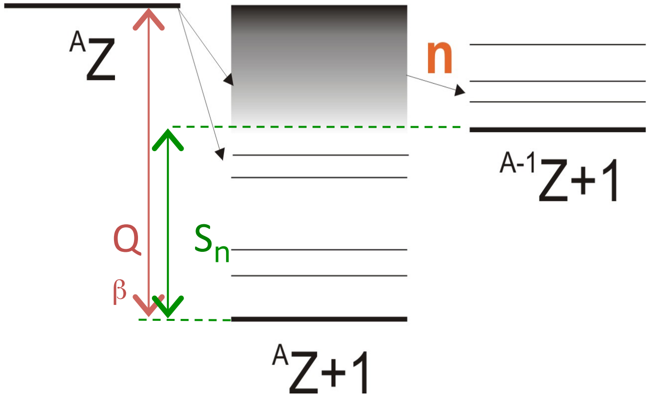


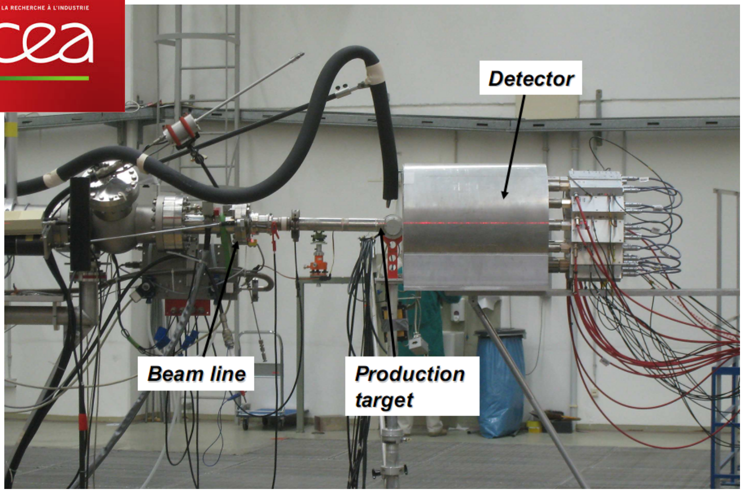
Ref.: W.P. Pönitz, NIM 109 (1973) 413-420

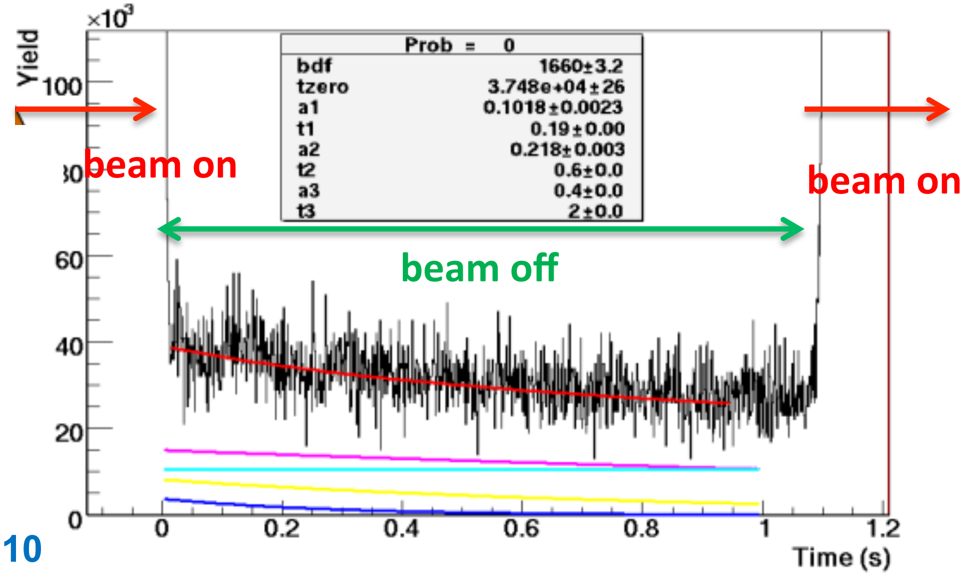


Long Counters for Beta-Delayed Fission Neutrons

- **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

Long Counters for Beta-Delayed Neutrons

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

GSI

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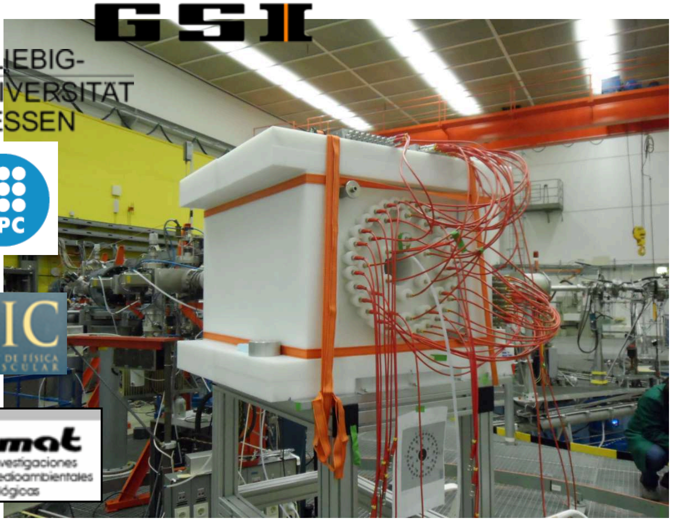
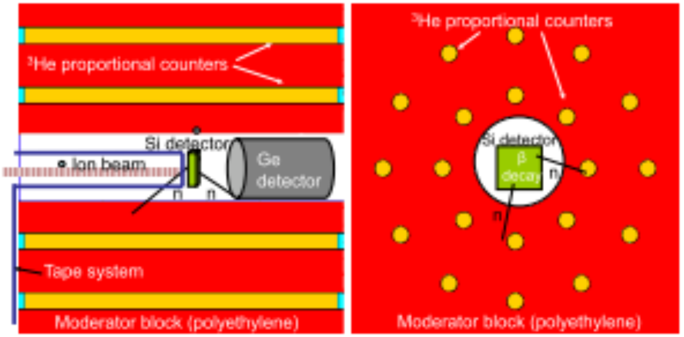
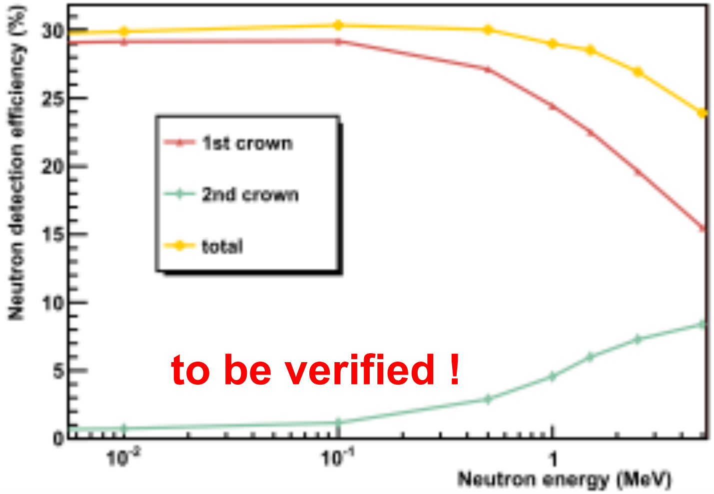
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas





Sectional side view

Front view



to be verified !

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

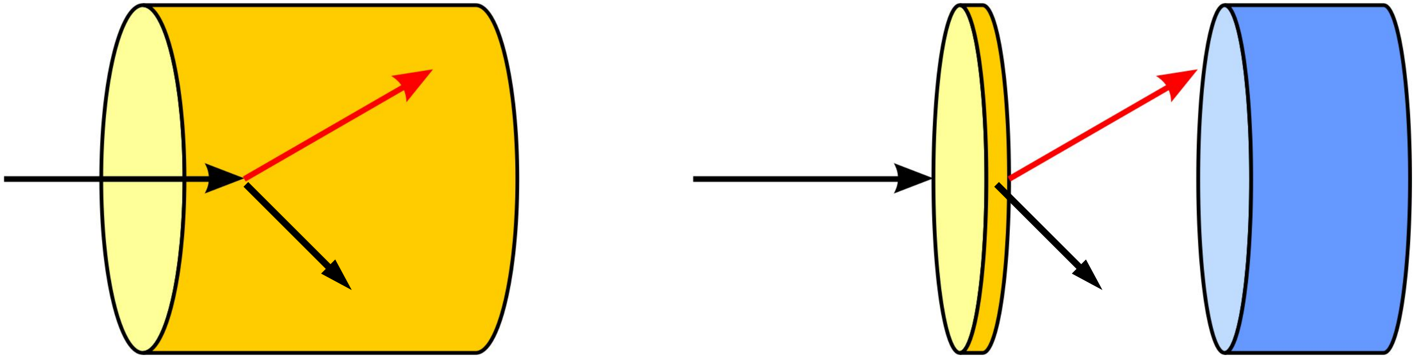
Fast Neutrons:
Recoil Detectors

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**

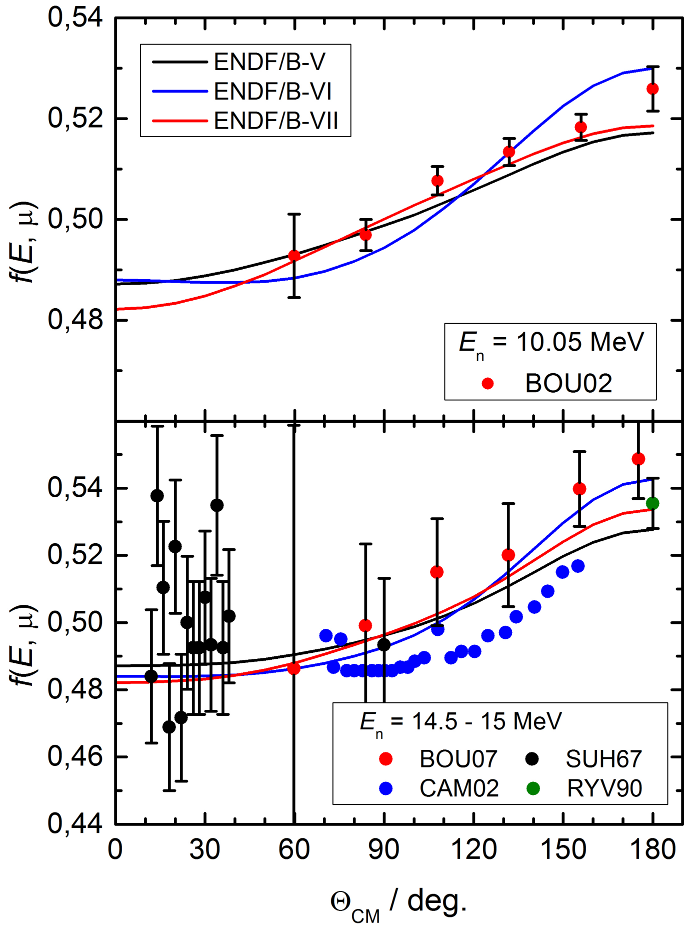


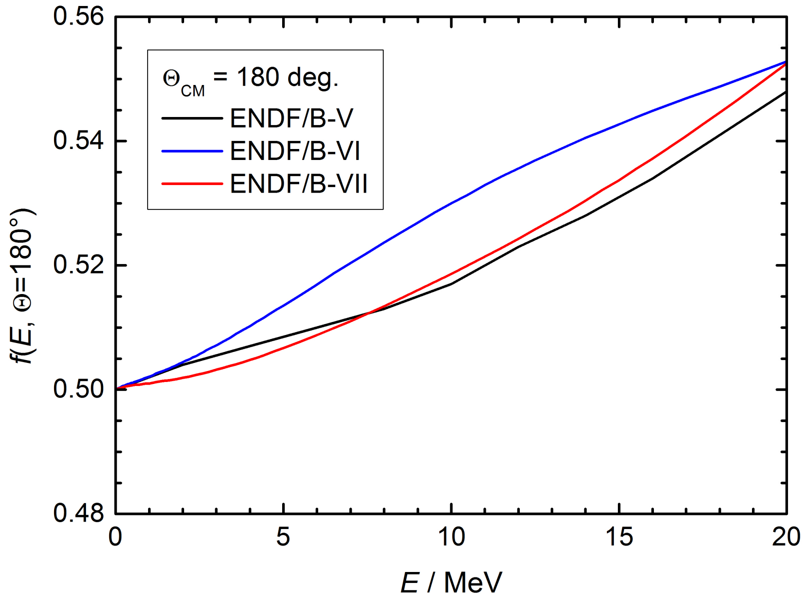
np Scattering: Overview

- **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)** → **ENDF/B-V**
  - ***R*-matrix analysis:** **Dodder-Hale (1991)** → **ENDF/B-VI**
    Dodder-Hale (2006) → **ENDF/B-VII**
- **Important for metrology:**
  Backward scattering $(d\sigma/d\Omega)_{CM}(180°)$

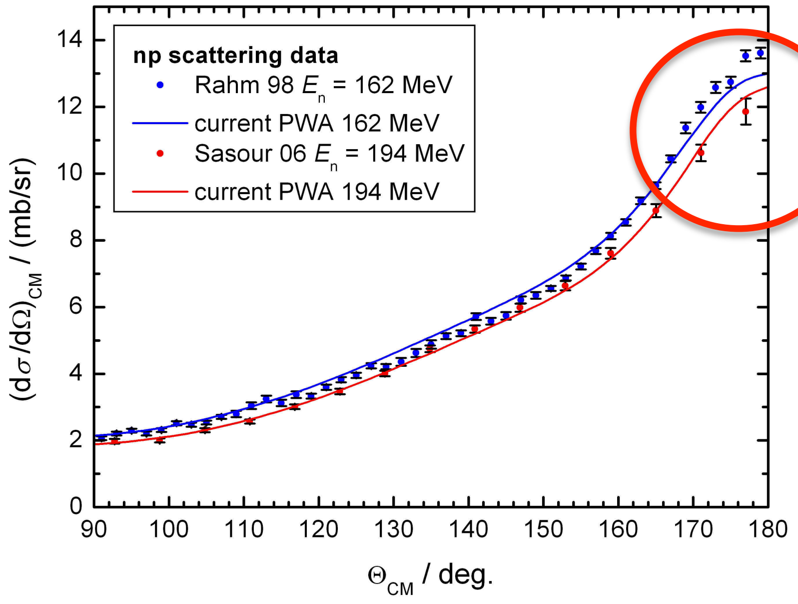
Differential Neutron-Proton Scattering Cross Section

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

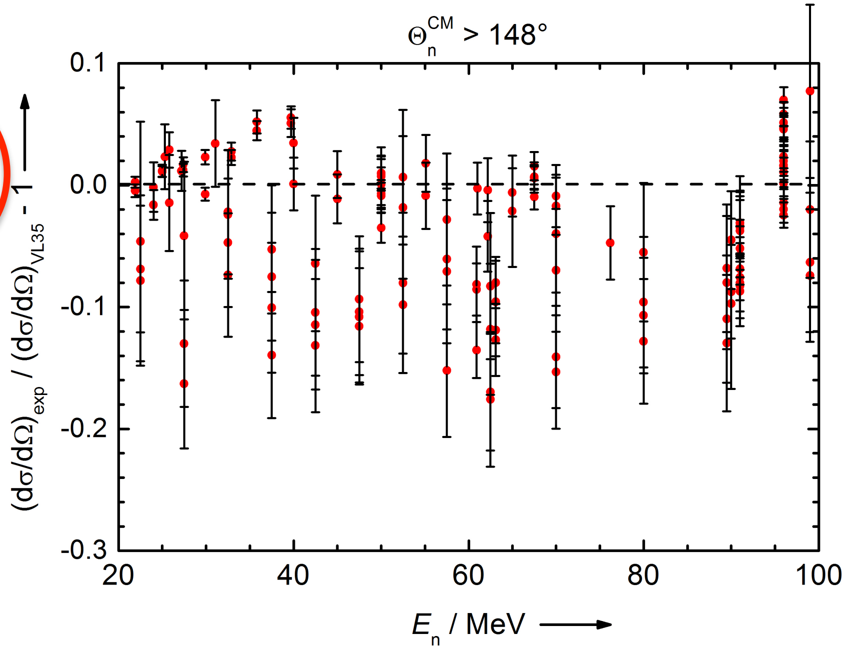




The Energy Range above 20 MeV



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:**

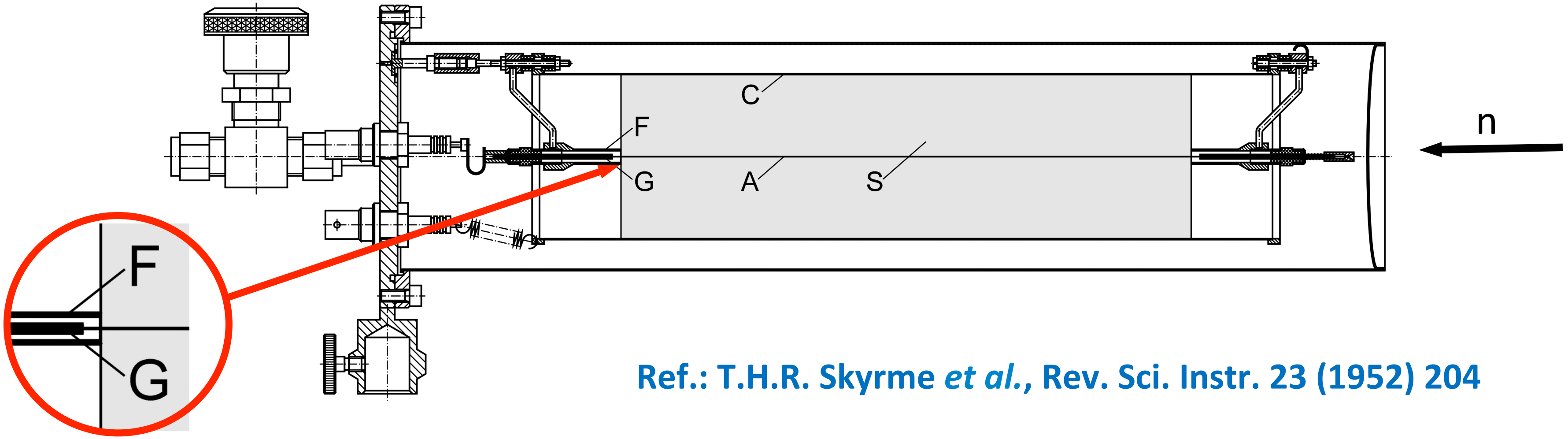
  R = 1.4 µm for 100 keV p in PE

⇒ **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 C recoils**

- **Pioneering work of E.F. Bennet *et al*. from the 1950's - 1070's**

The PTB Proportional Counter P2



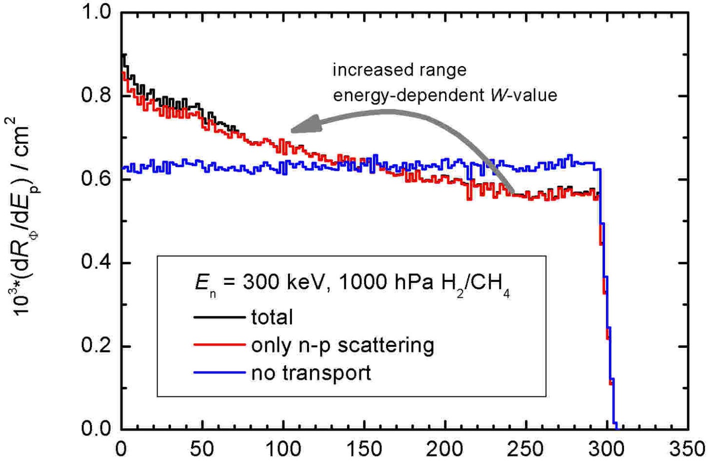
Ref.: T.H.R. Skyrme *et al.*, Rev. Sci. Instr. 23 (1952) 204

- **total volume: ≈ 1.6 dm^3**
- **active volume: $^{\varnothing}$55.5 mm, *l* = 193.3 mm**
- **el. field: defined by $^{\varnothing}$4 mm field tubes at ground potential**
- **anode: $^{\varnothing}$ 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**

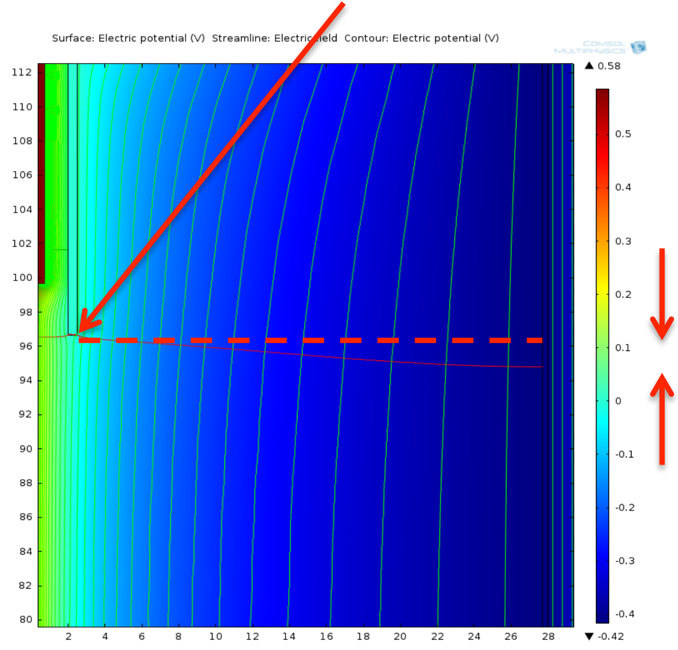
Modelling of the RPPC Response to Neutrons

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

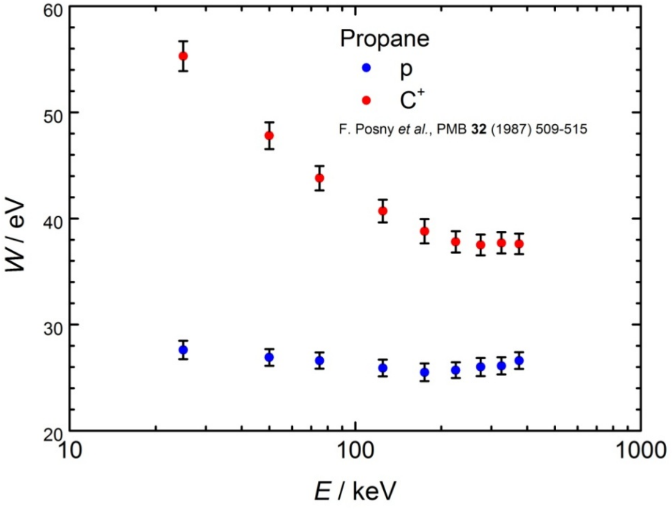
- **incomplete energy deposition**
- **shape of the sensitive volume**
- **energy-dependent *W*-value**
- **carbon recoils included**



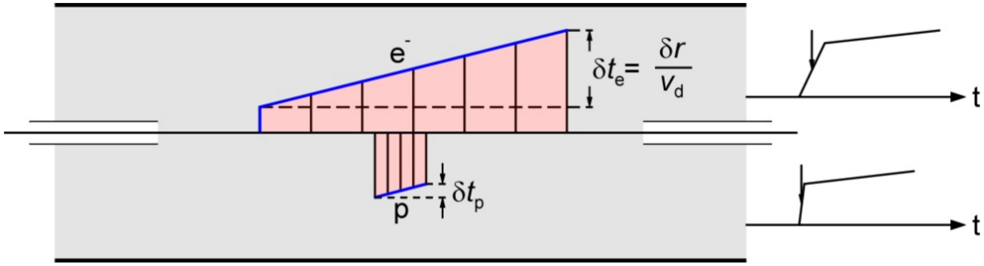
Stagnation point



1.9 mm



Photon/Neutron Discrimination



Rise-time measurement:

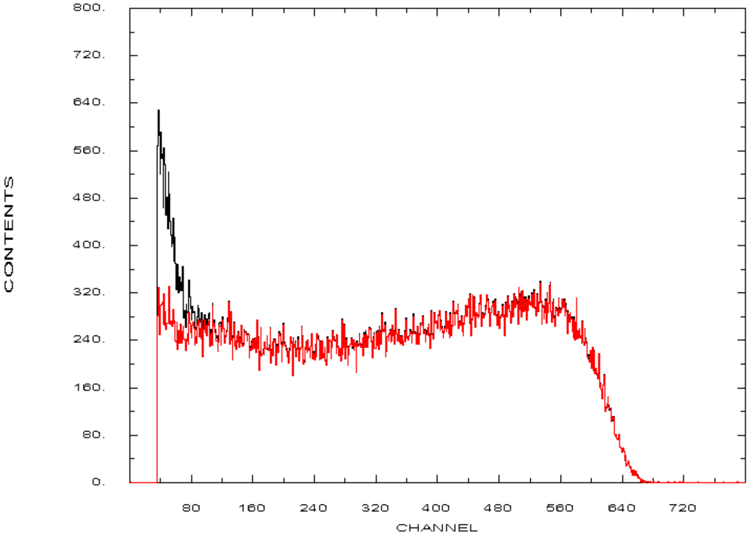
fast filter amp. : t_{diff} = 50 ns, t_{int} = 500 ns

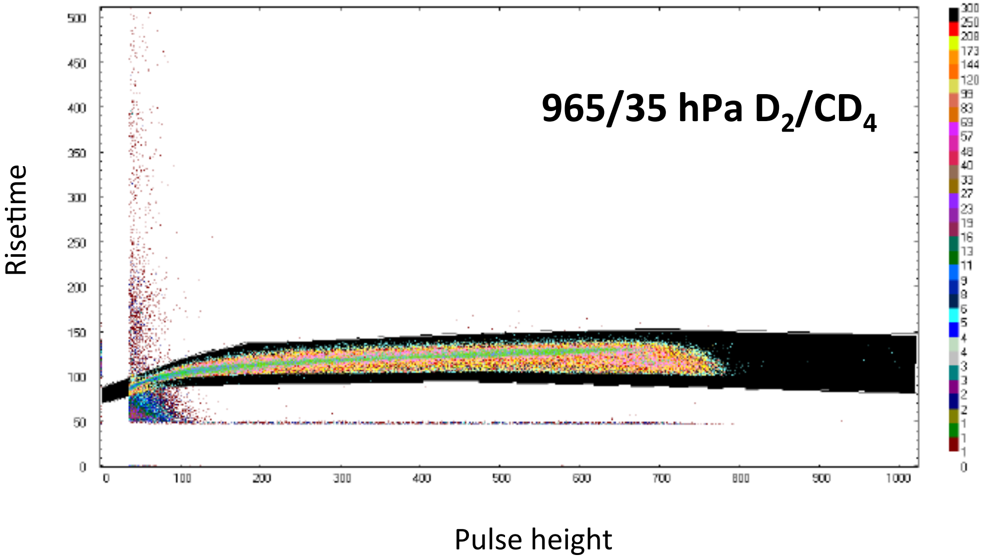
- start: LE-disc. close to noise
- stop: CF-disc. (f = 0.4)

shaping amp.: t_s = 2 µs

Recoil tracks more localized than electron tracks

⇒ different drift times for sec. electrons





965/35 hPa D_2/CD_4

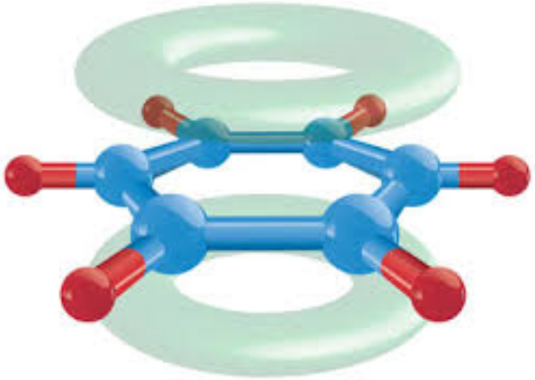
NB: Analogue technique to be replaced by waveform digitizers!

Recoil Detectors:
Scintillation Detectors

The Physics of Organic Scintillators

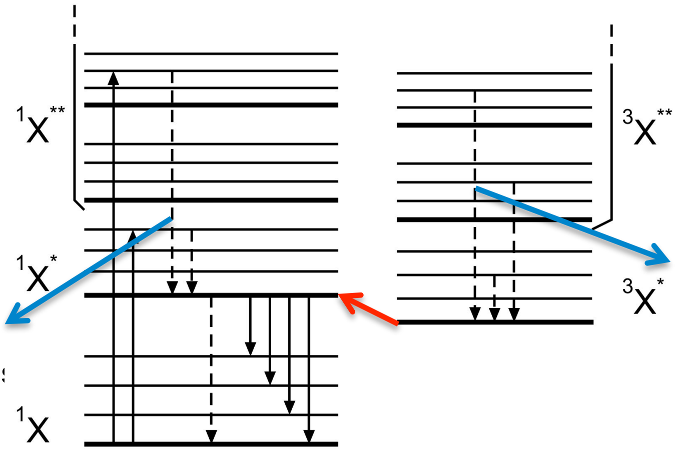
Unitary scintillators:

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



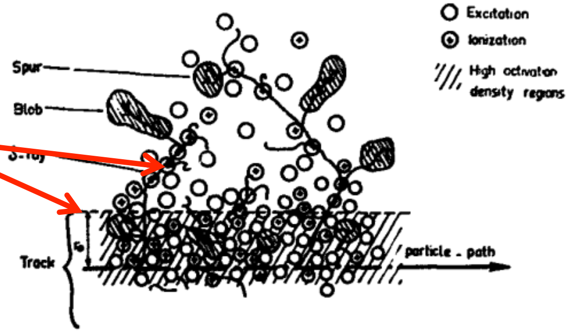
Principal physical processes:

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



Ionization Quenching and Pulse-Shape Discrimination

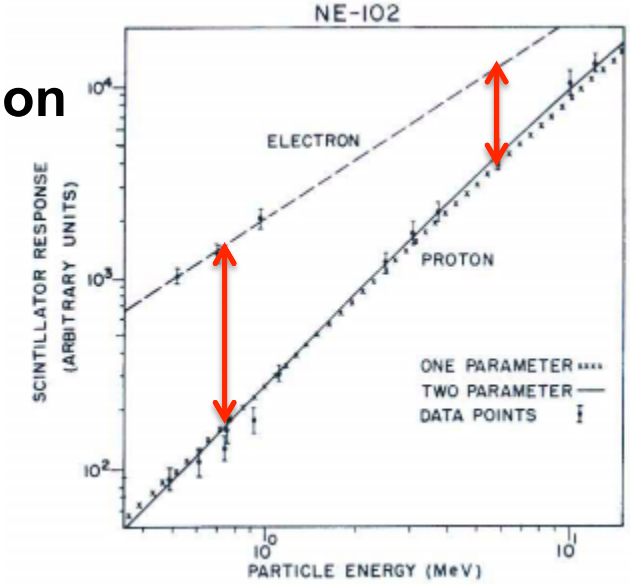
- **Increased ionization density:**
  - **More ion-ion recombination**
  - **Ratio of $^1X^{**}$ and $^3X^{**}$ excitations increases**
  - **Temporal concentration of transient quenching states ($\tau \leq 100$ ps) decreases**



⇒ Delayed fluorescence less 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*:**

⇒ pulse-shape discrimination of particle species (*Z*, *A*)

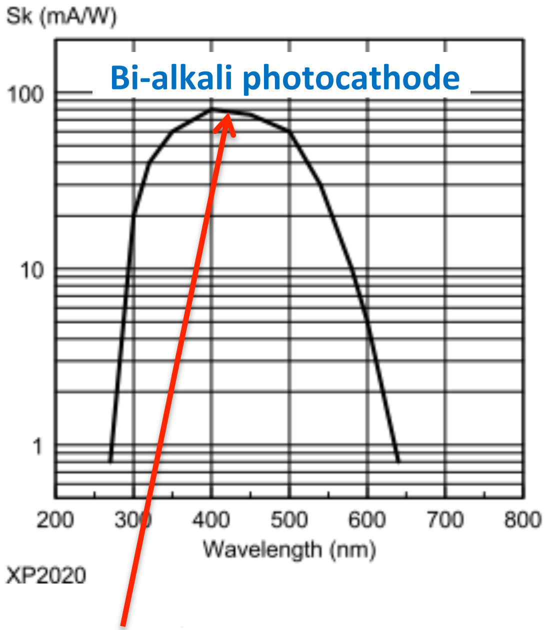
Liquid and Plastic Scintillators

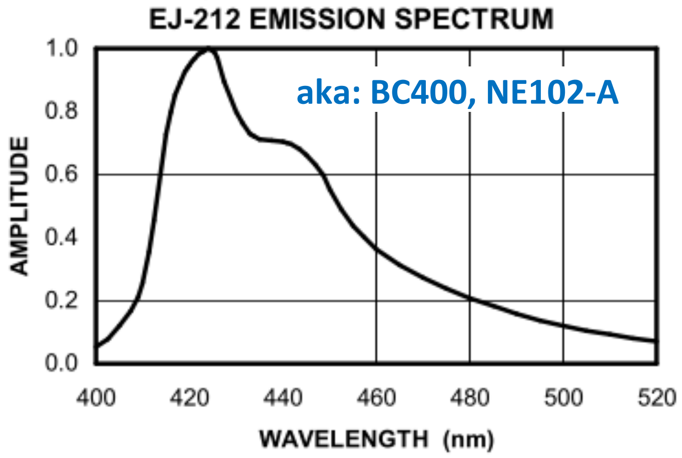
- **Typical unitary scintillators:**
  - Stilbene (1,2-Diphenylethene $C_{14}H_{12}$)
  - Anthracene ($C_{14}H_{10}$): ‘gold’ standard for scint. efficiency
- **Binary or ternary scintillators**
  - Solvent X: Benzene (C_6H_6),
    n-Methylbenzene ($C_6H_{6-n}(CH_3)_n$),
    Styrene $[C_6H_5{\cdot}C_2H_3]_n$, ….
  - 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**



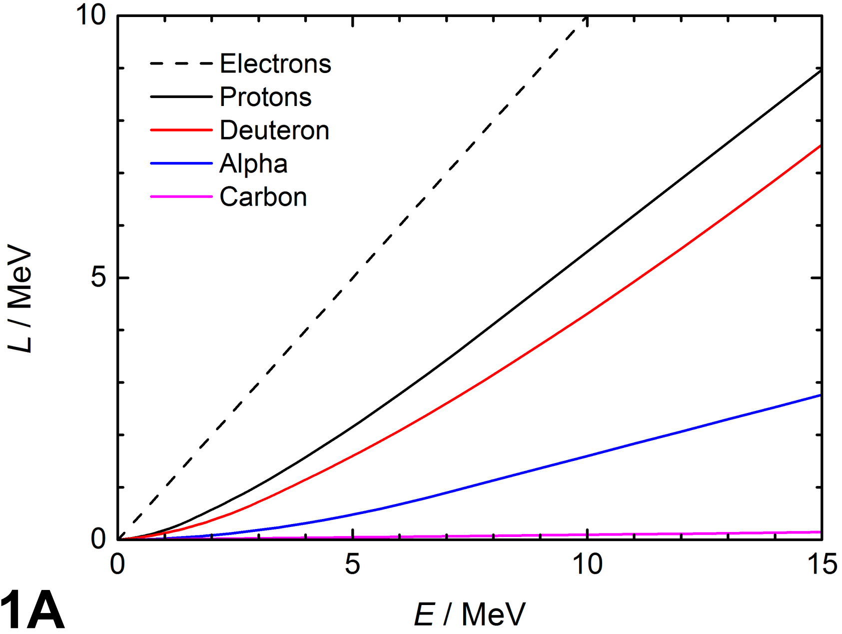


Light Output of Organic Scintillators

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



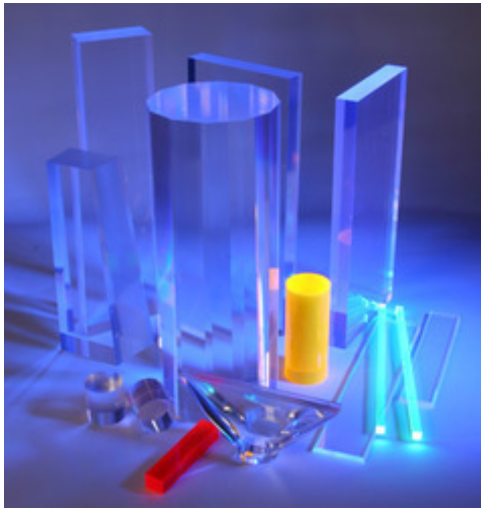
- **Electrons:** $L_e(E) = E - E_0$
  S_e := 1 MeV^{-1} $E_0 \approx$ 5 keV for BC501A

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

- **NB: Experimental data include instrumental effects!**

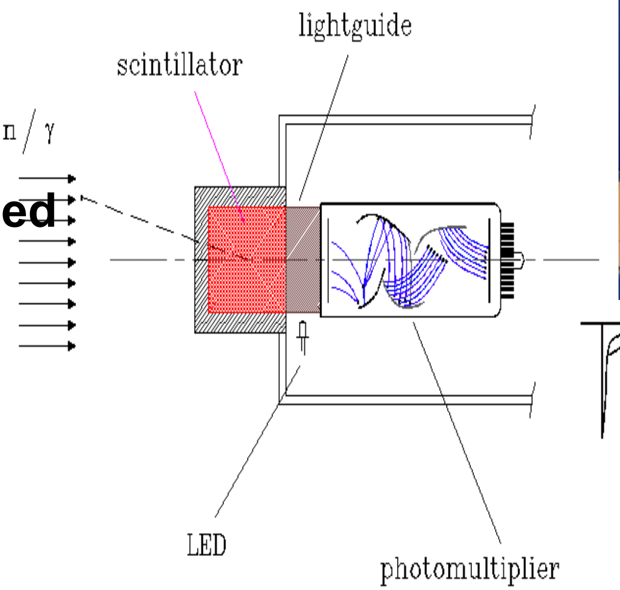
Properties of Organic Scintillators

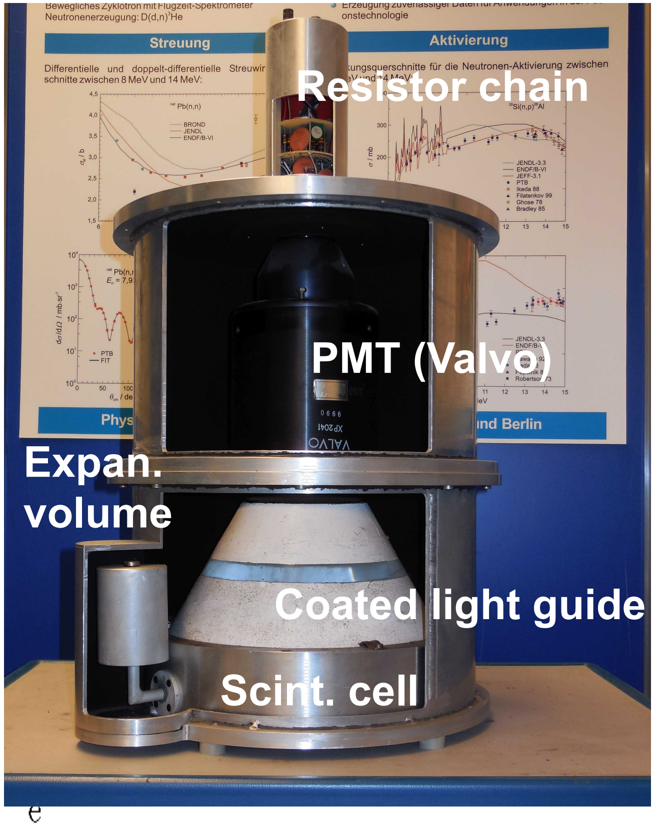
	plastic scint.	liquid scint.
1. Hydrogen / carbon ratio	≈ 1.1	≈ 0, 1.2 – 2.0
2. Scintillation efficiency	55 – 65 %	40 – 80 % anthracene
3. Scintillation spectrum λ_{max}	370 – 490 nm	≈ 425 nm
4. Transparency	1 - 4 m	
5. Decay times	1.4 – 3 ns, 230 ns	2 – 4 ns
6. Pulse-shape discrimination	(yes)	yes
7.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

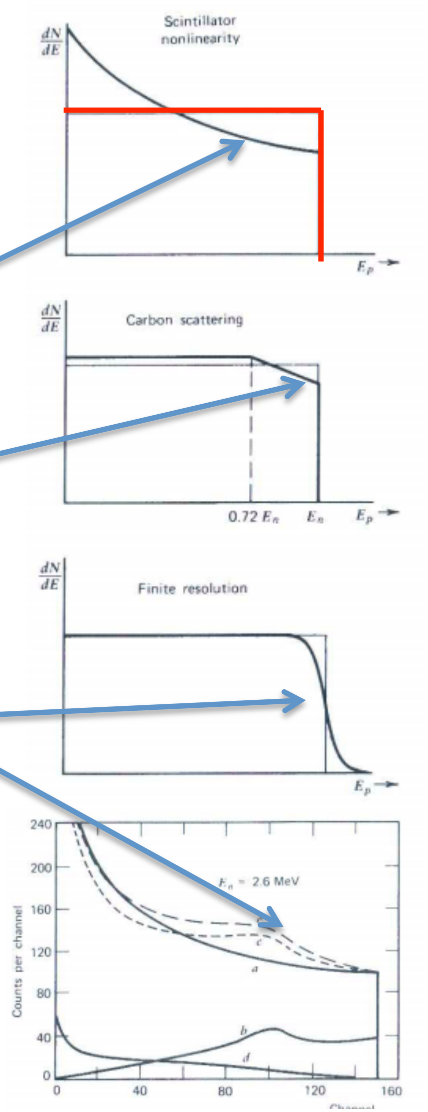
Response of Organic Scintillation Detectors

- Elastic n-p scattering cross section dominates: $dN/dL = \text{const for } L < E_n$

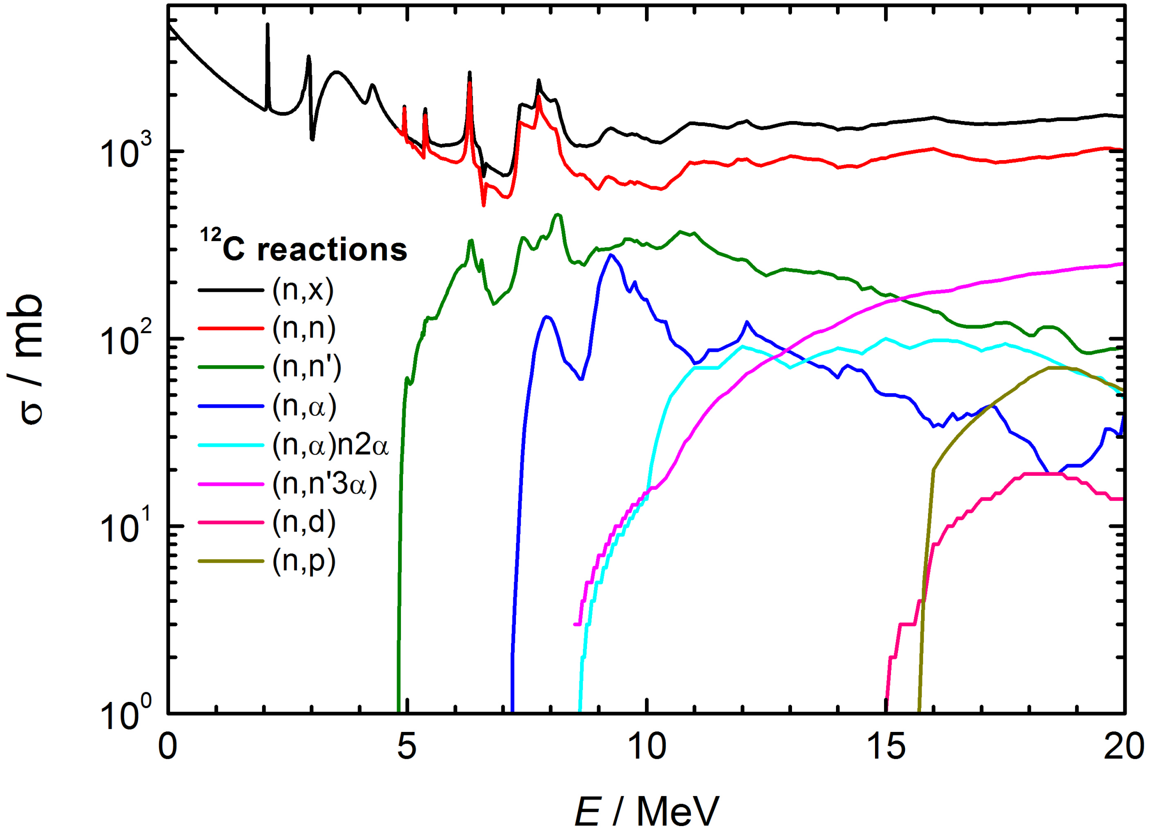
Modification of the rectangular shape:

- Non-linear light output: $dL/dE \propto E^{3/2}$
  $\Rightarrow dN/dL = (dN/dE)\cdot(dL/dE)^{-1} \propto L^{-1/3}$
- 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

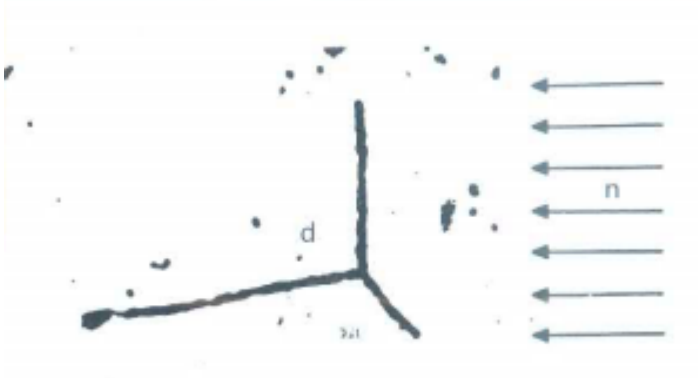


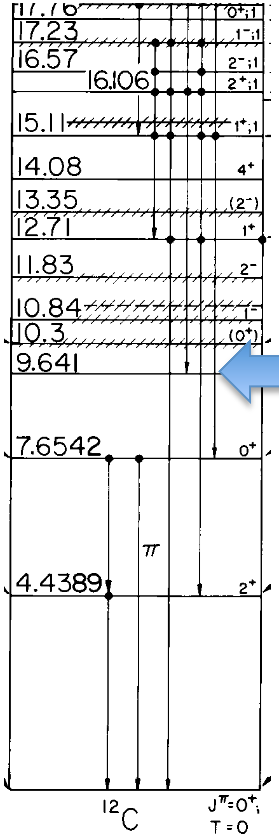
E_n < 15 MeV: only scattering and alpha emission!

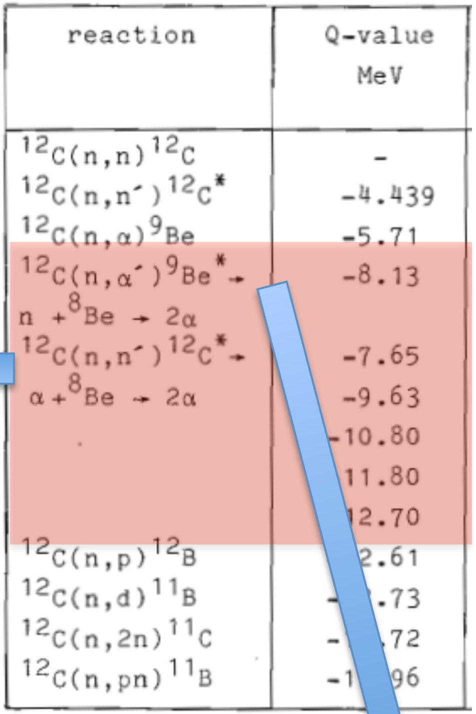
Break-Up Reactions

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

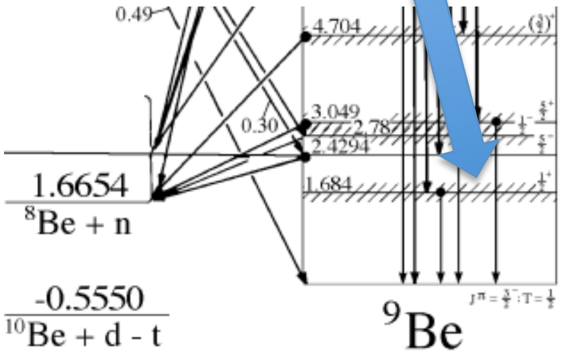
- Four-body break-up with several channels
- Investigated using nuclear emulsions and liquid scintillation detectors
- Still insufficient data for MC codes
  - NRESP7
  - Geant4 (data base from CIEMAT)



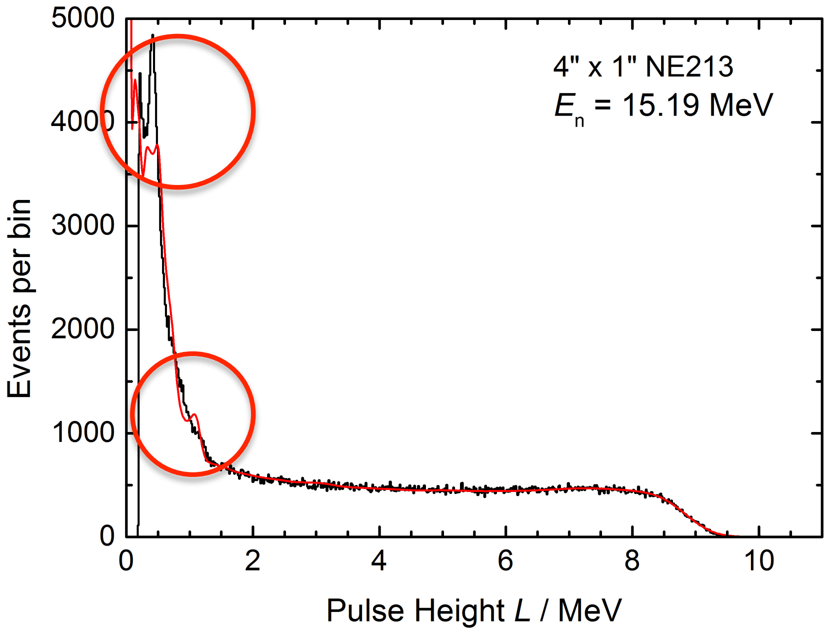


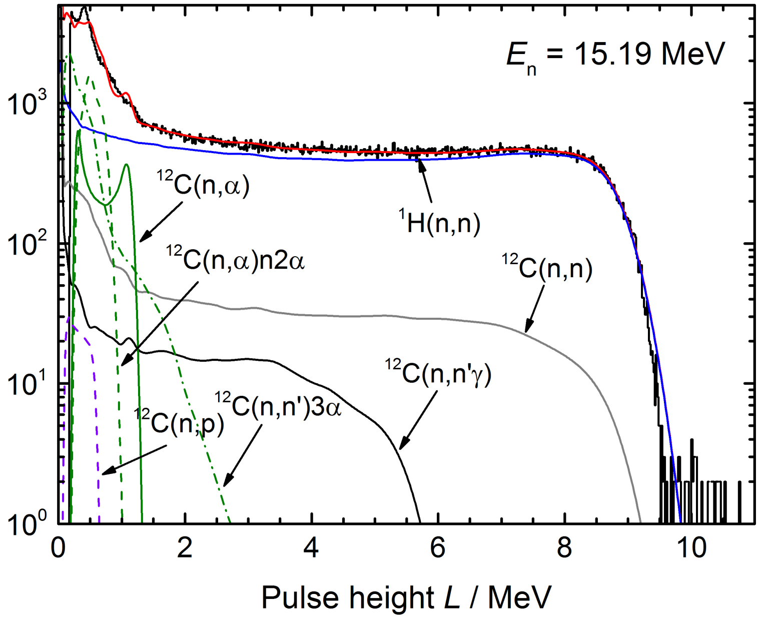


reaction	Q-value MeV
$^{12}C(n,n)^{12}C$	-
$^{12}C(n,n')^{12}C^*$	-4.439
$^{12}C(n,\alpha)^{9}Be$	-5.71
$^{12}C(n,\alpha')^{9}Be^* \rightarrow$ $n + {}^{8}Be \rightarrow 2\alpha$	-8.13
$^{12}C(n,n')^{12}C^* \rightarrow$ $\alpha + {}^{8}Be \rightarrow 2\alpha$	-7.65 -9.63 -10.80 11.80 12.70
$^{12}C(n,p)^{12}B$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



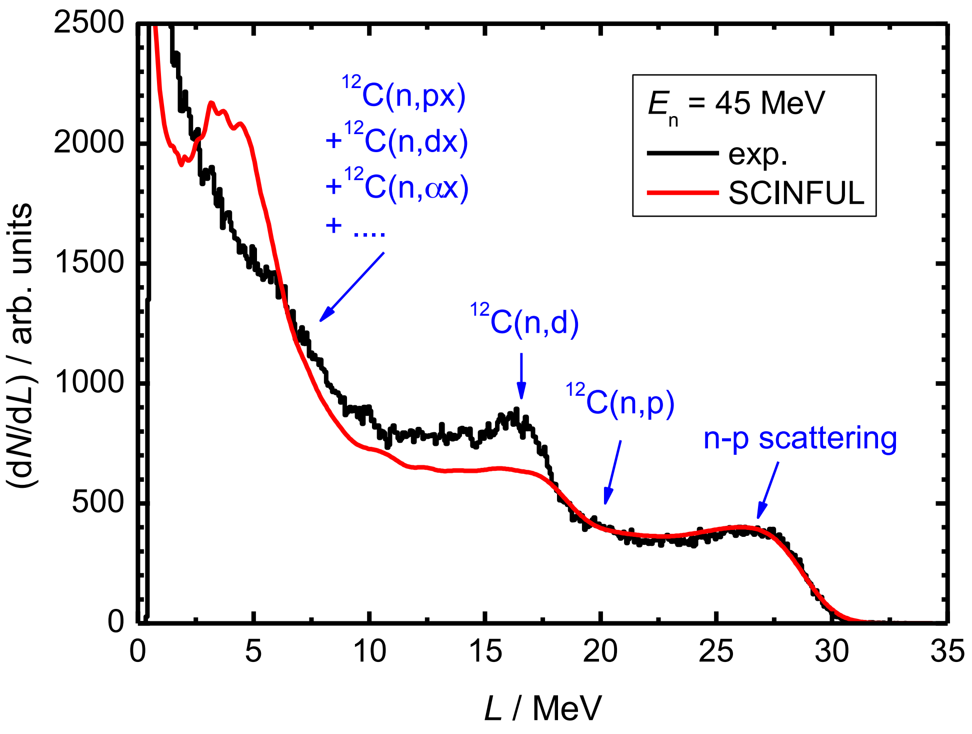
Example: 2"x2" BC501A Detector at E_n = 15 MeV





- **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,α)^{9}Be cross section!**
  Ref.: H.J. Brede *et al.*, NSE 107 (1991) 22

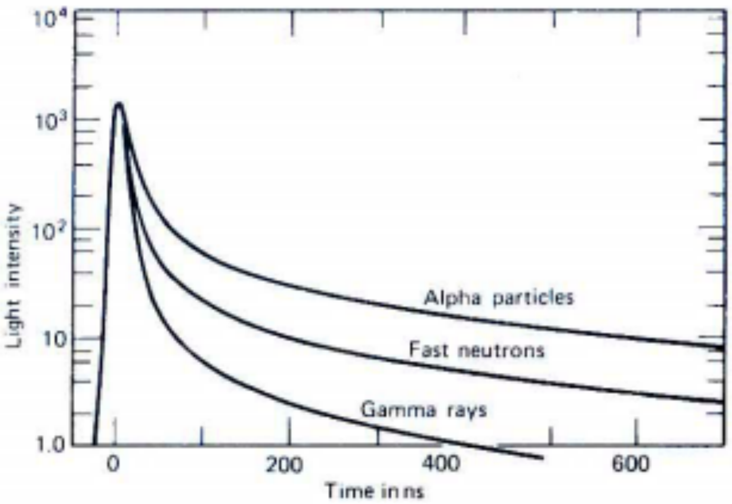
Response for E_n > 20 MeV



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

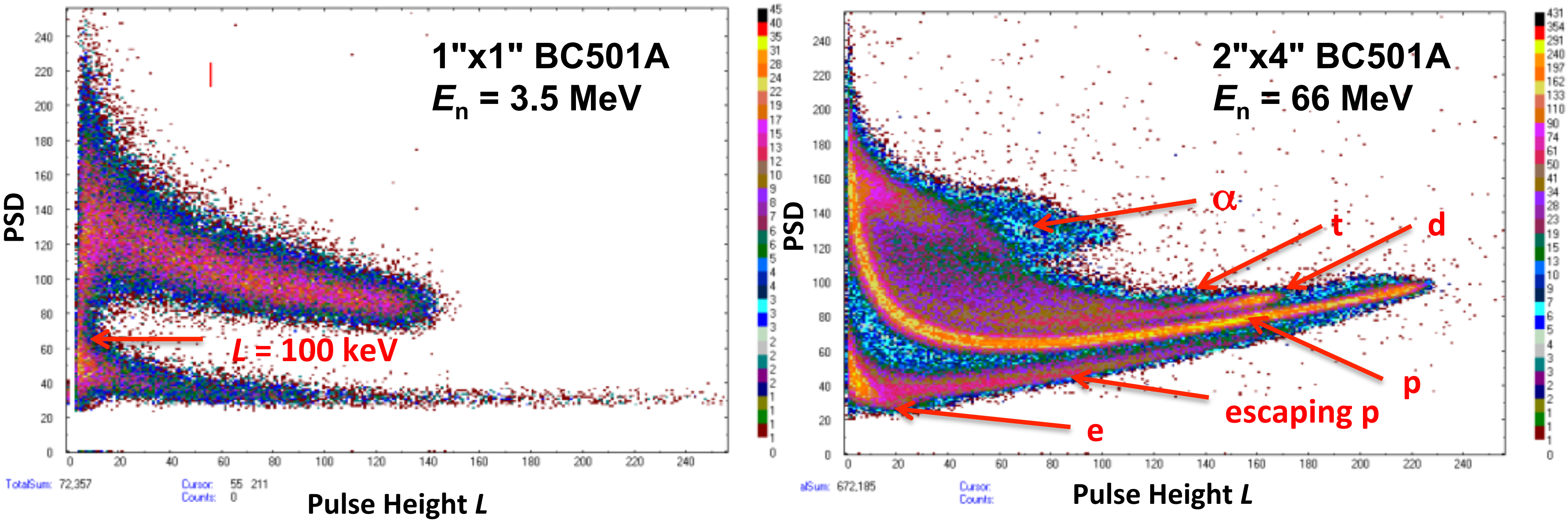
- **Strong contributions from break-up reactions:**
  ⇒ correlation of charged particles from individual interactions!
- **Data libraries (ENDF, JEFF) have only emission tables:**
  ⇒ general-purpose MC codes are not adequate: MCNPX, Geant4

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



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

⇒ Photon-induced events must be excluded

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

Pulse-Height Resolution

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

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

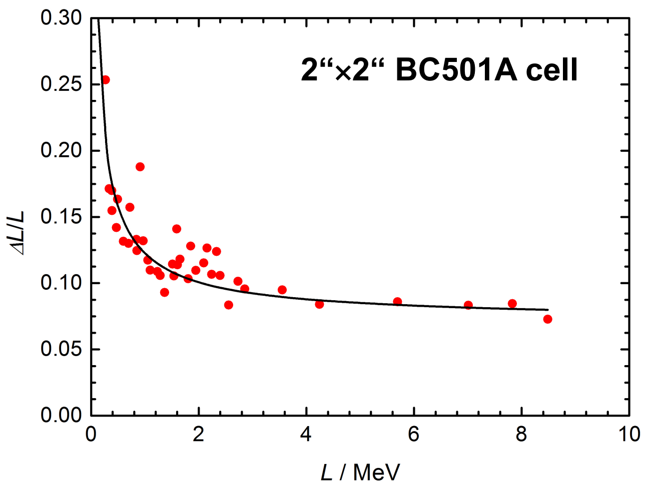
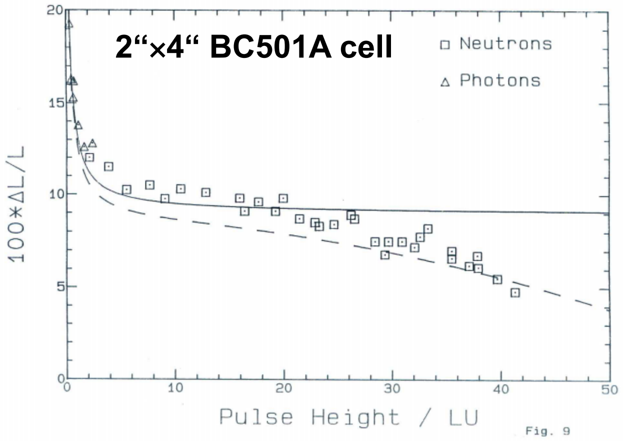


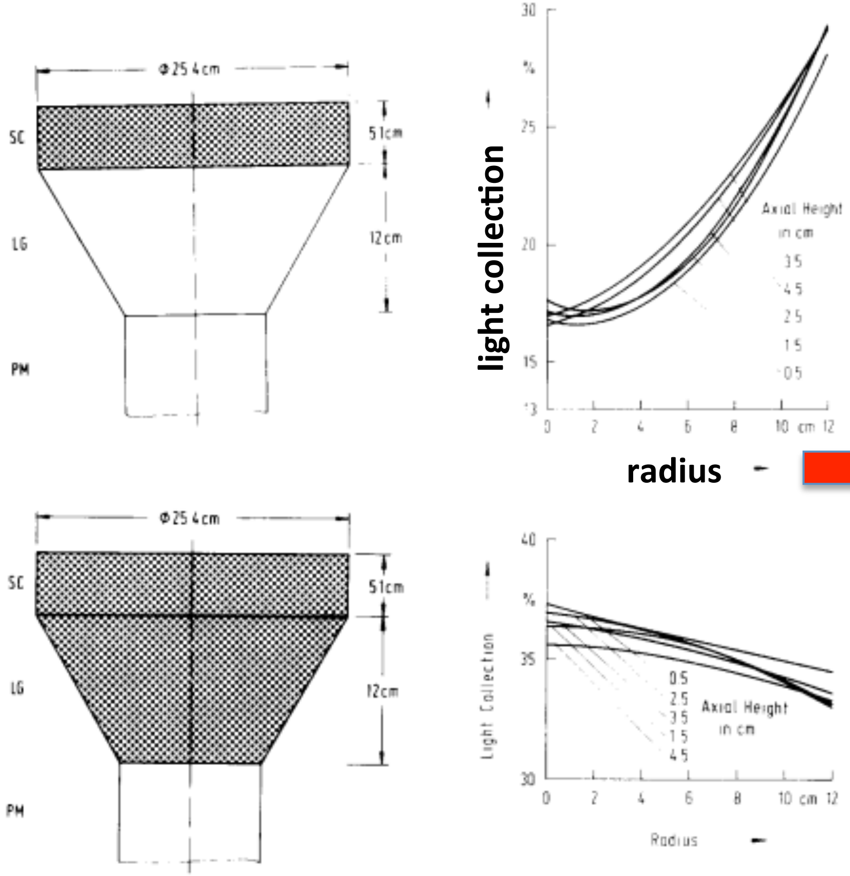
Fig. 2

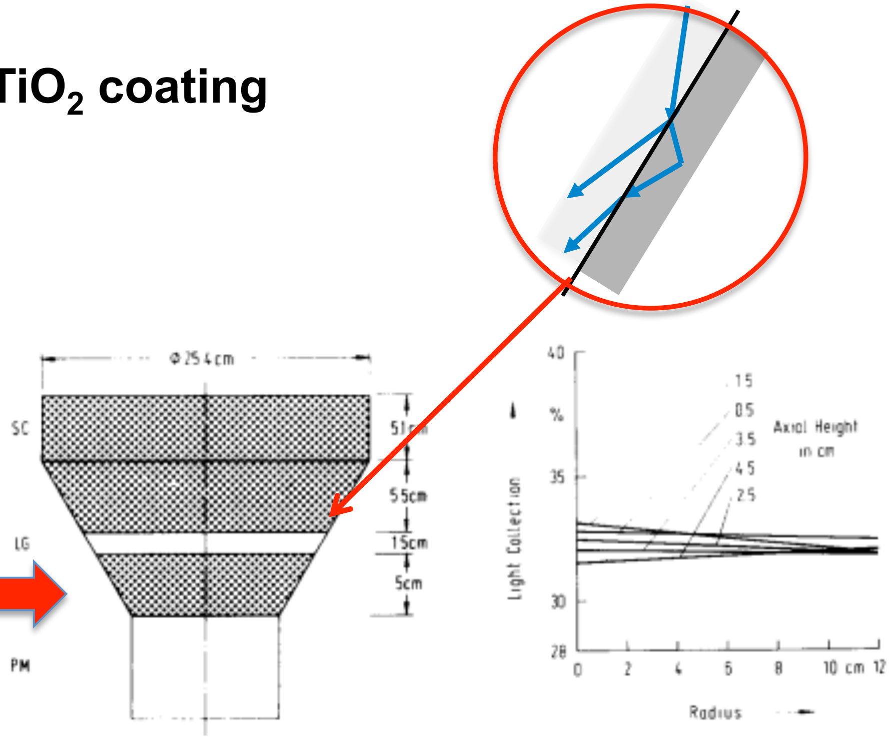
- **Elongated cells for high-energy neutrons:**
  - **Long tracks**
  - ***A* depends on neutron energy E_n**
- **Optimisation important for spectrometry**
  - **Small cells (diameter ≈ depth)**
  - **Partially coated light guides**
- **Unfolding: $\Delta E_n/E_n \approx 0.2 \cdot \Delta L/L$**



Optimization of the Pulse-Height Resolution

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



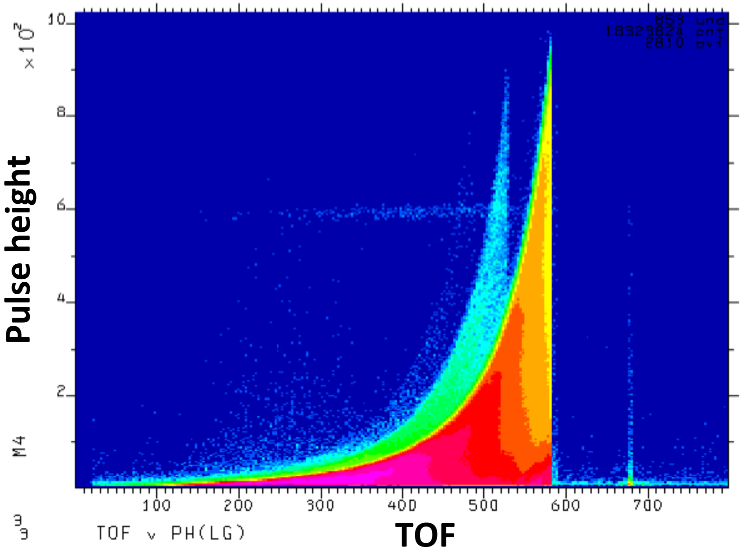


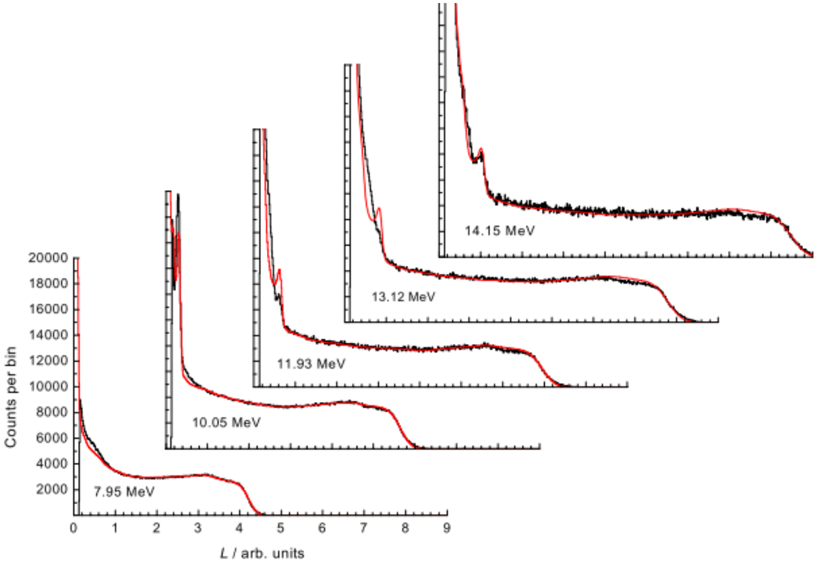
Ref. H. Schölermann et al. NIM 169 (1980) 25-31

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

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: $(\mathrm{d}R_\Phi/\mathrm{d}L)(E_n)$**
- **This works up to 60-70 MeV**

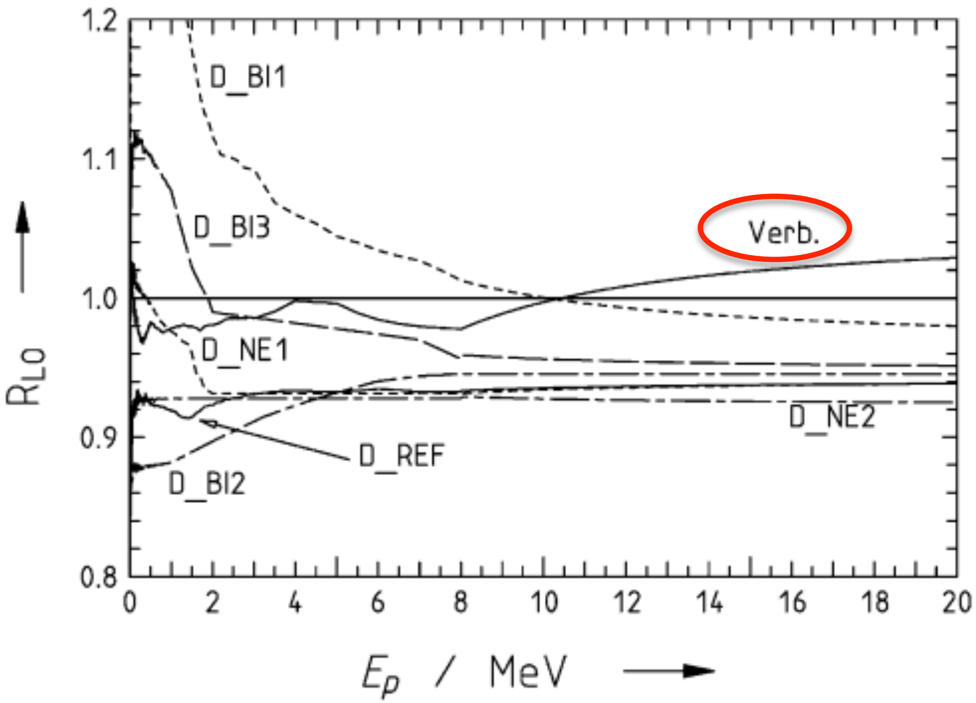




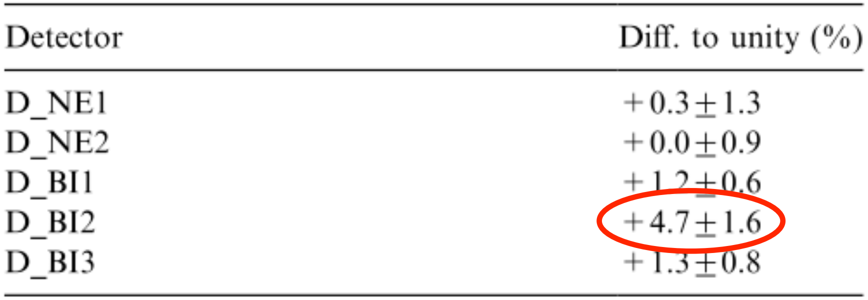
Results

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



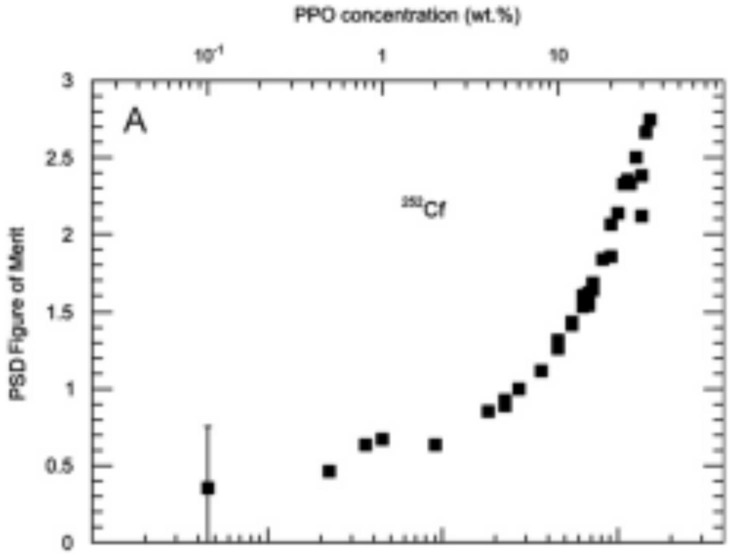
Detector	Diff. to unity (%)
D_NE1	+0.3±1.3
D_NE2	+0.0±0.9
D_BI1	+1.2±0.6
D_BI2	+4.7±1.6
D_BI3	+1.3±0.8

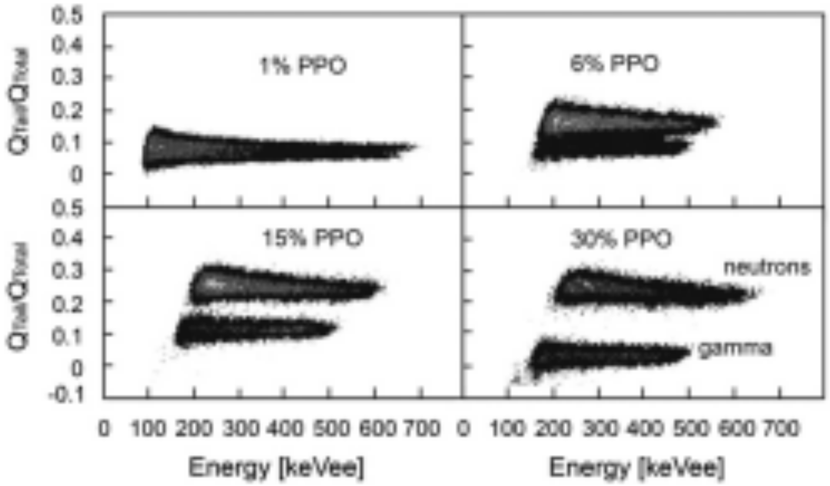
Ref.: D. Schmidt *et al*., NIMA476 (2002) 186-189

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

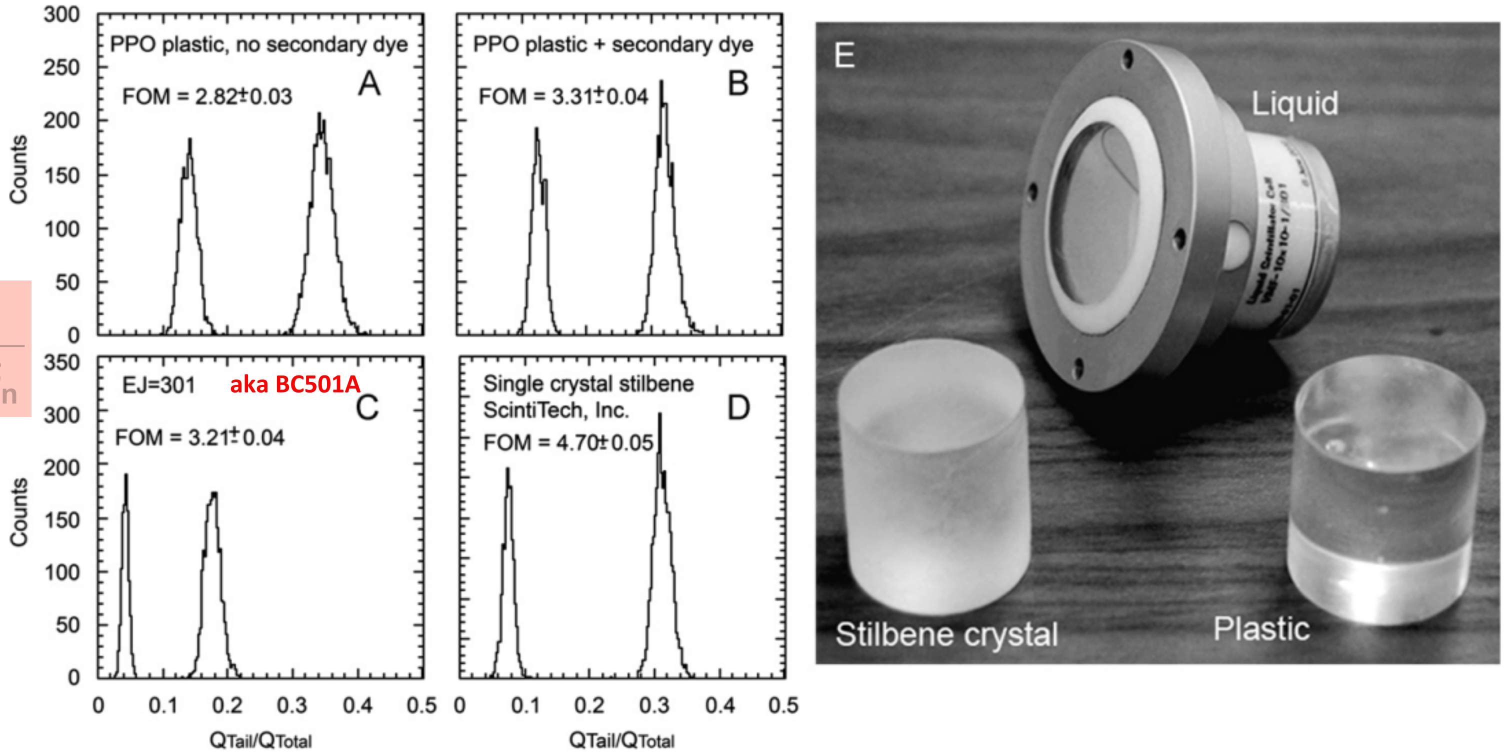




Ref.: N. Zaitseva *et al.*, NIMA668 (2012) 88.93

Commercial Plastic Scintillator with PSD: EJ299-33

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



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

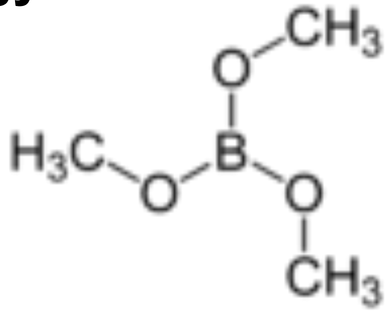
- **PSD properties as good as for liquid or crystal scintillator**
- **Secondary solute improves QE**
- **Practical advantages: non-toxic, non-flammable, no container,**
  all shapes, sizes ≤ 15 cm

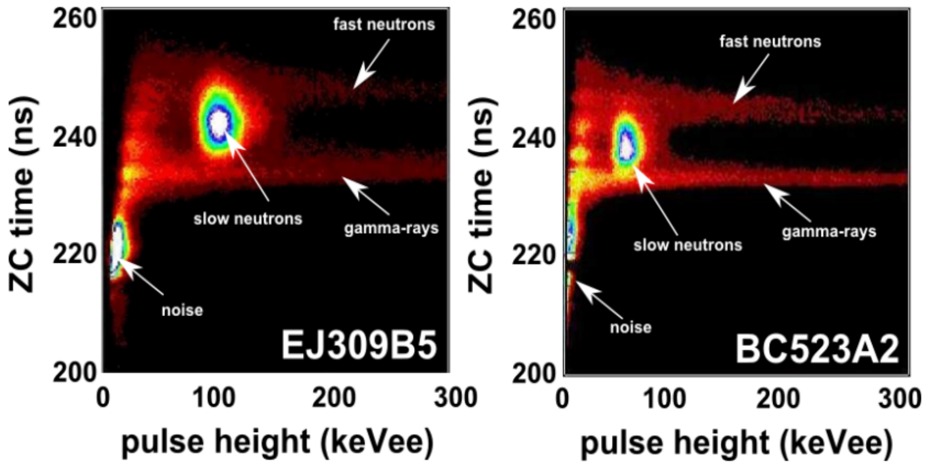
Boron-Loaded Liquid Scintillators

- 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!

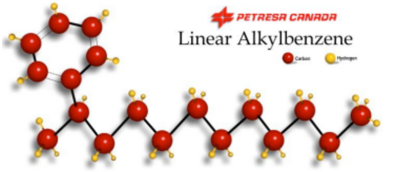




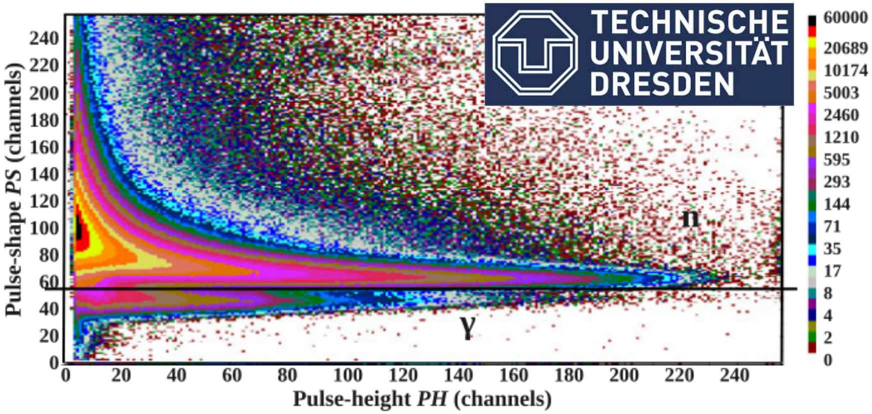
Ref.: J. Iwanowska *et al.*, JINST 7 (2012) C4004 (FNDA2011)

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

‘Unconventional’ Liquid Scintillators: LAB for SNO+



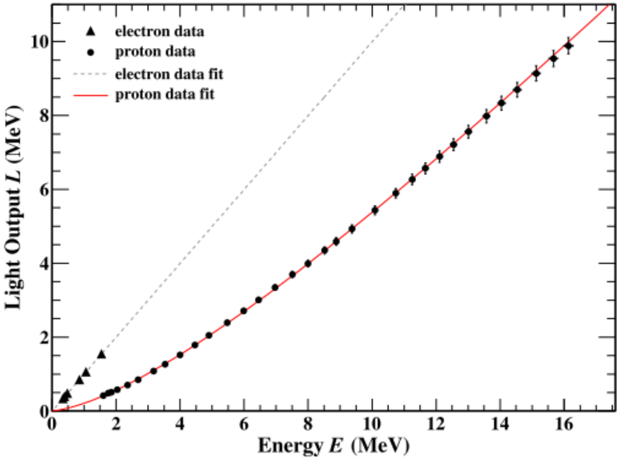
- **SNO+: $0\nu2\beta$ decay of ^{130}Te, …**
- **Scintillator: 780 t (LAB + 2 g/l PPO)**
- **Quenching data required for background model**



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

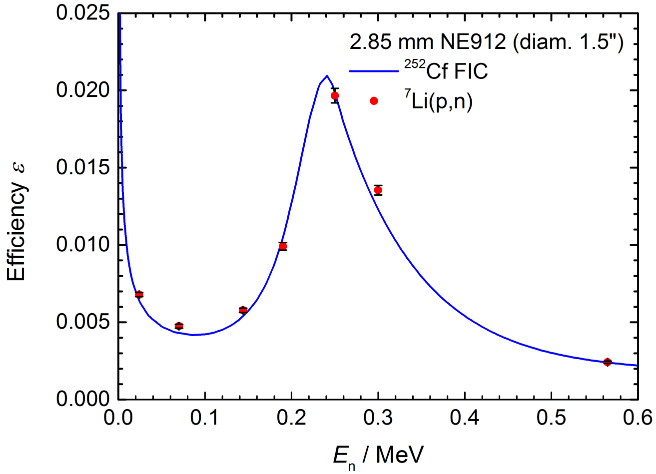
⇒ Important for the background model

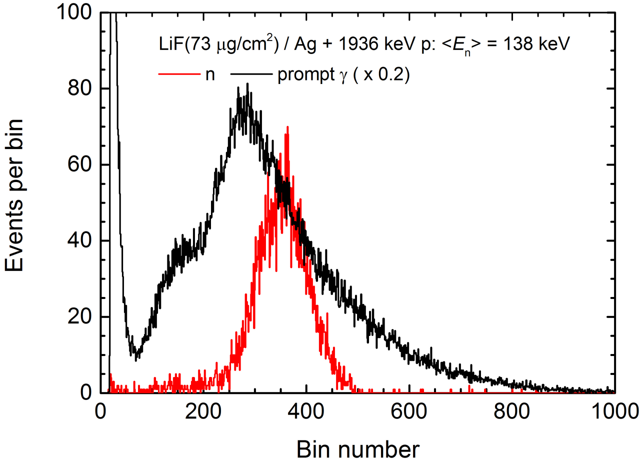


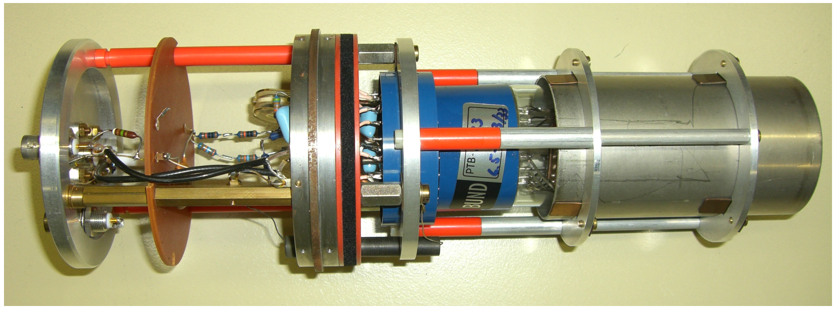
Inorganic Scintillators: ^{6}LiGlass

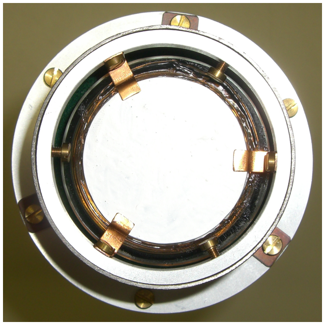
Ce^{3+} activated lithium silicate glass

- 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





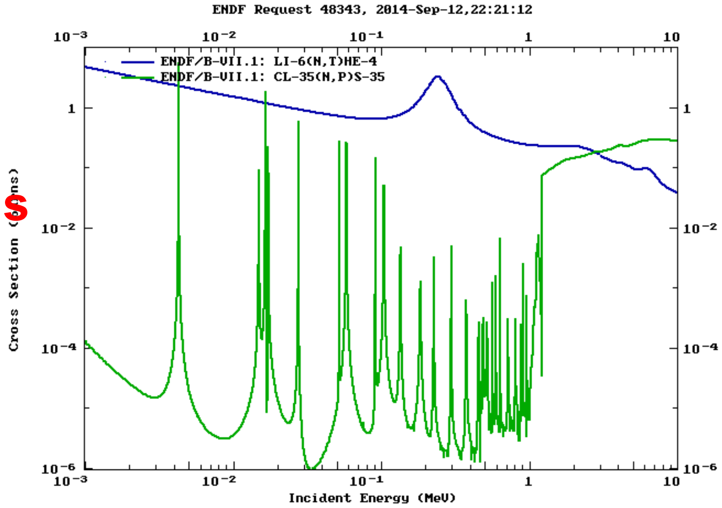


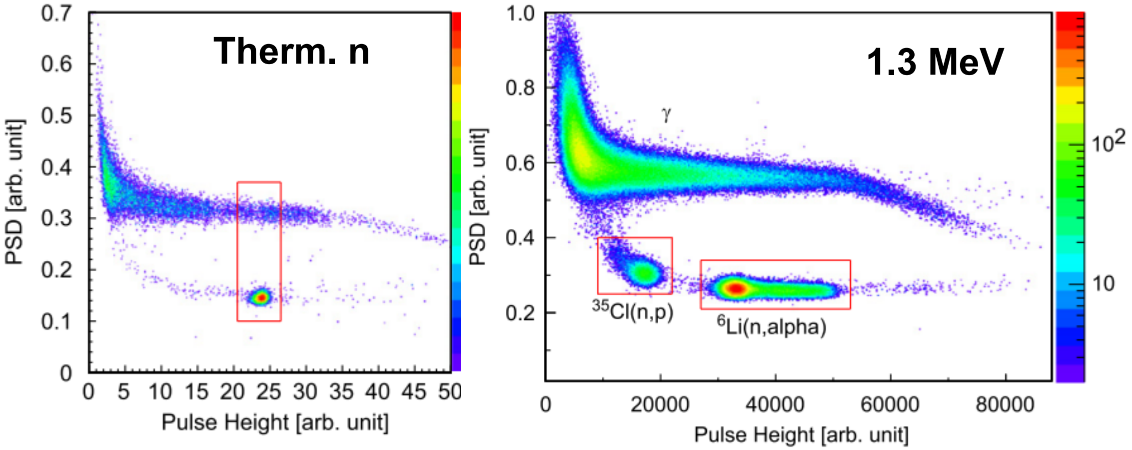


Novel Inorganic Materials: CLYC

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: Δt < 800 ps
- Cracky crystals
- Small sizes: ∅ < 2"
- Expensive material





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