

Neutron Detection

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Neutrons

Particle Properties 2004

n

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Mass $m = 1.0086649156 \pm 0.0000000006$ u

Mass $m = 939.56536 \pm 0.00008$ MeV [a]

$m_n - m_p = 1.2933317 \pm 0.0000005$ MeV
 $= 0.0013884487 \pm 0.0000000006$ u

Mean life $\tau = 885.7 \pm 0.8$ s

$$c\tau = 2.655 \times 10^8 \text{ km}$$

Magnetic moment $\mu = -1.9130427 \pm 0.0000005 \mu_N$

Electric dipole moment $d < 0.63 \times 10^{-25}$ e cm, CL = 90%

Mean-square charge radius $\langle r_n^2 \rangle = -0.1161 \pm 0.0022$
fm² (S = 1.3)

Electric polarizability $\alpha = (11.6 \pm 1.5) \times 10^{-4}$ fm³

Magnetic polarizability $\beta = (3.7 \pm 2.0) \times 10^{-4}$ fm³

Charge $q = (-0.4 \pm 1.1) \times 10^{-21}$ e

Mean $n\bar{n}$ -oscillation time $> 8.6 \times 10^7$ s, CL = 90% (free n)

Mean $n\bar{n}$ -oscillation time $> 1.3 \times 10^8$ s, CL = 90% [e] (bound n)

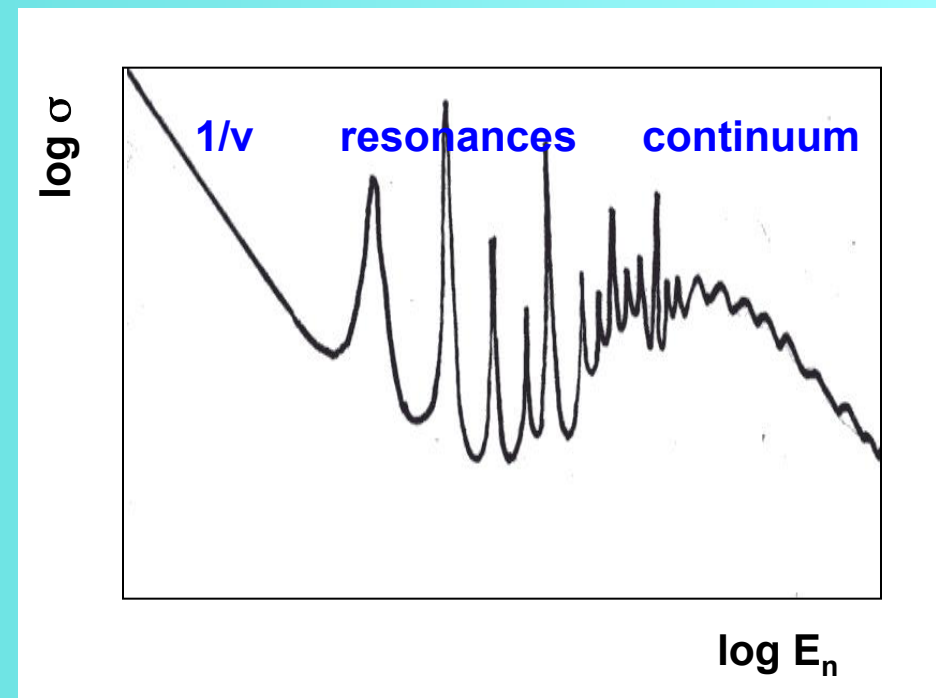
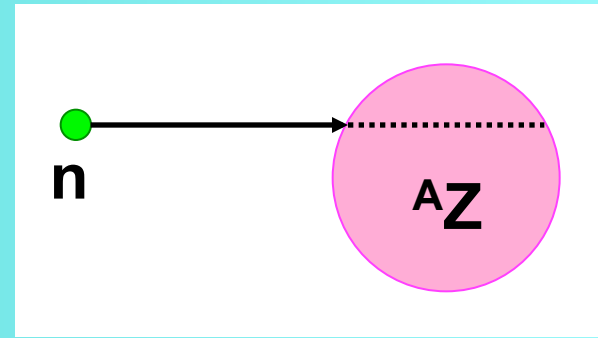
- Proposed: E. Rutherford, 1920
- Discovery: J. Chadwick, 1932
- Neutron reactions: E. Fermi and others, 1934-1935
- Compound nucleus model: N. Bohr, G. Breit-E. Wigner, 1936
- Neutrons in astrophysics: G. Gamow, 1937
- Neutron induced fission: O. Hahn, F. Strassmann, L. Meitner, O. Frisch, 1939
- Chain reaction: E. Fermi, 1942

Nuclear neutron reactions

➤ Reaction channels:

- elastic scattering: (n,n)
- inelastic scattering: $(n,n' \gamma)$
- radiative capture: (n,γ)
- multiplication: $(n,xn\gamma)$
- charged particle production: $(n,p\gamma)$, $(n,\alpha\gamma)$, ...
- fission: $(n,xn^{A_1Z_1}n^{A_2Z_2})$
- ...

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{cap}} + \dots$$



➤ No Coulomb barrier

➤ Reaction thresholds

➤ Energy dependence

➤ No predictive models

Common reactions used for neutron detection at low energies:

Elastic scattering:

- $n + {}^1\text{H} \rightarrow n + {}^1\text{H}$
- $n + {}^2\text{H} \rightarrow n + {}^2\text{H}$ (abund.=0.015%)

Charged particle:

- $n + {}^3\text{He} \rightarrow {}^3\text{H} + {}^1\text{H} + 0.764 \text{ MeV}$ (abund.=0.00014%)
- $n + {}^6\text{Li} \rightarrow {}^4\text{He} + {}^3\text{H} + 4.79 \text{ MeV}$ (abund.=7.5%)
- $n + {}^{10}\text{B} \rightarrow {}^7\text{Li}^* + {}^4\text{He} \rightarrow {}^7\text{Li} + {}^4\text{He} + 0.48 \text{ MeV } \gamma + 2.3 \text{ MeV}$ (abund.=19.9%,
b.r.=93%)

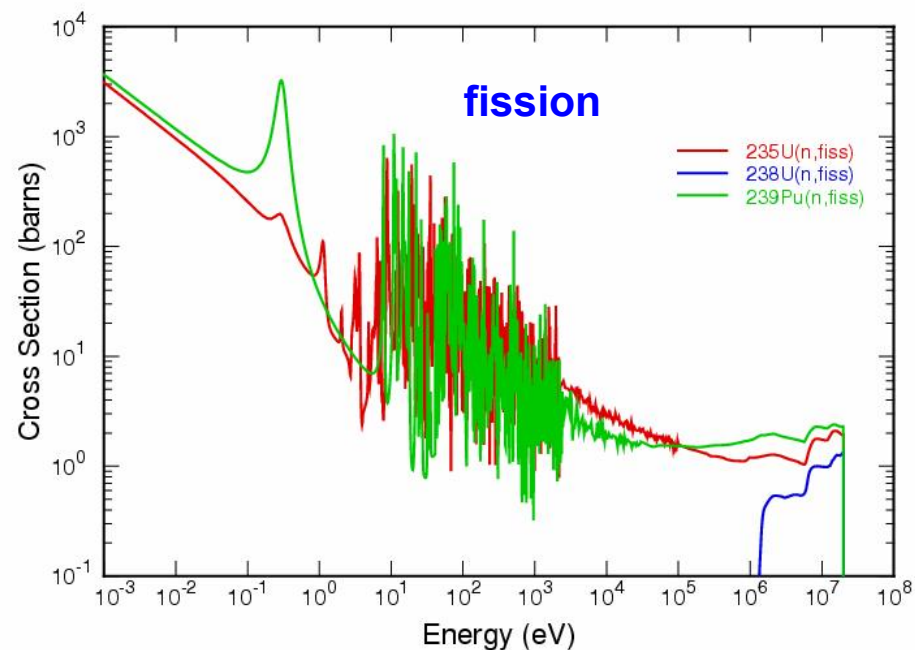
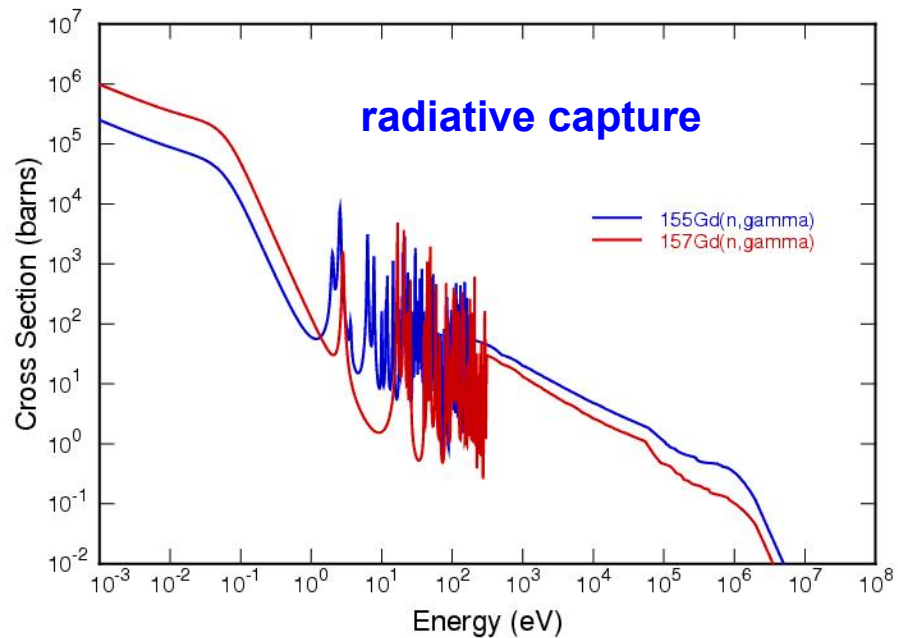
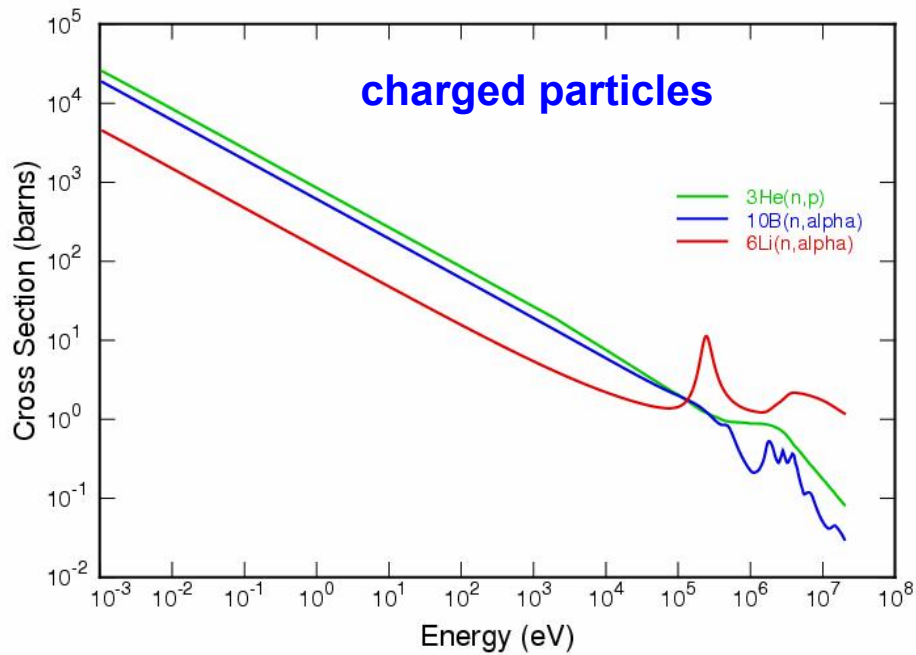
Radiative capture:

- $n + {}^{155}\text{Gd} \rightarrow {}^{156}\text{Gd}^* \rightarrow \gamma\text{-ray} + \text{CE spectrum}$ (abund.=14.8%)
- $n + {}^{157}\text{Gd} \rightarrow {}^{158}\text{Gd}^* \rightarrow \gamma\text{-ray} + \text{CE spectrum}$ (abund.=15.7%)

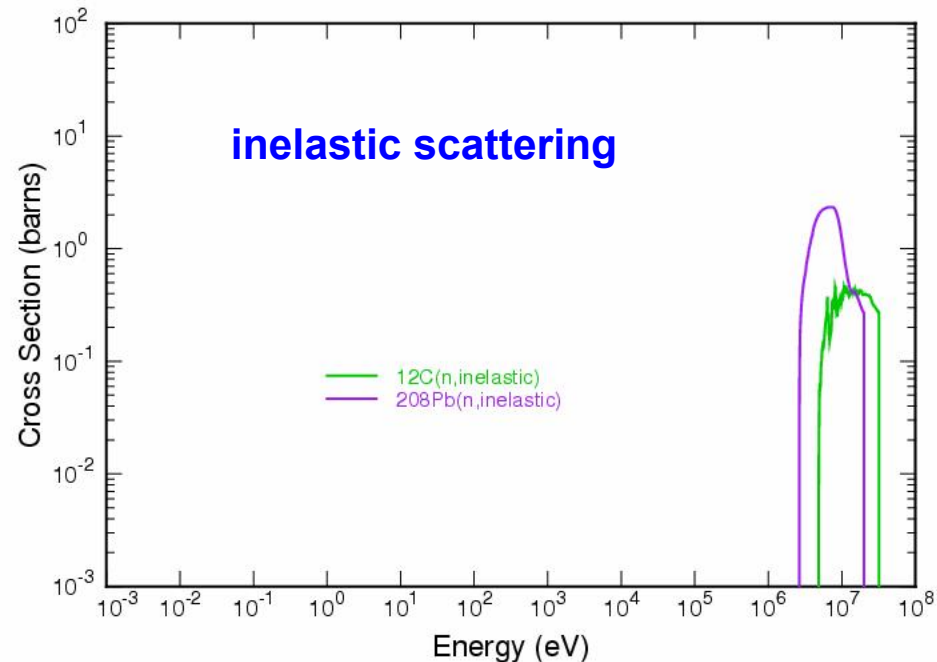
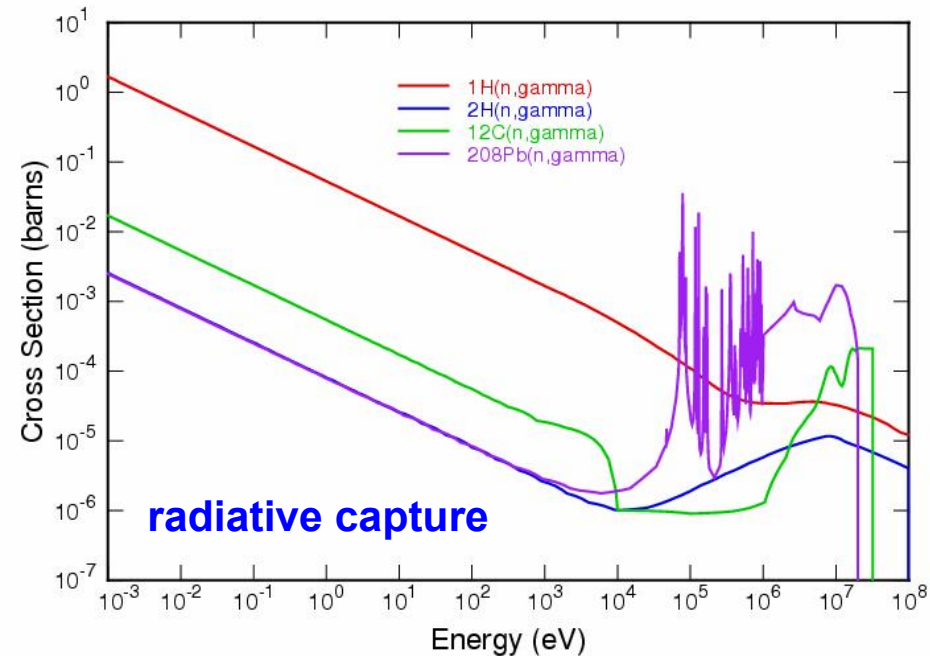
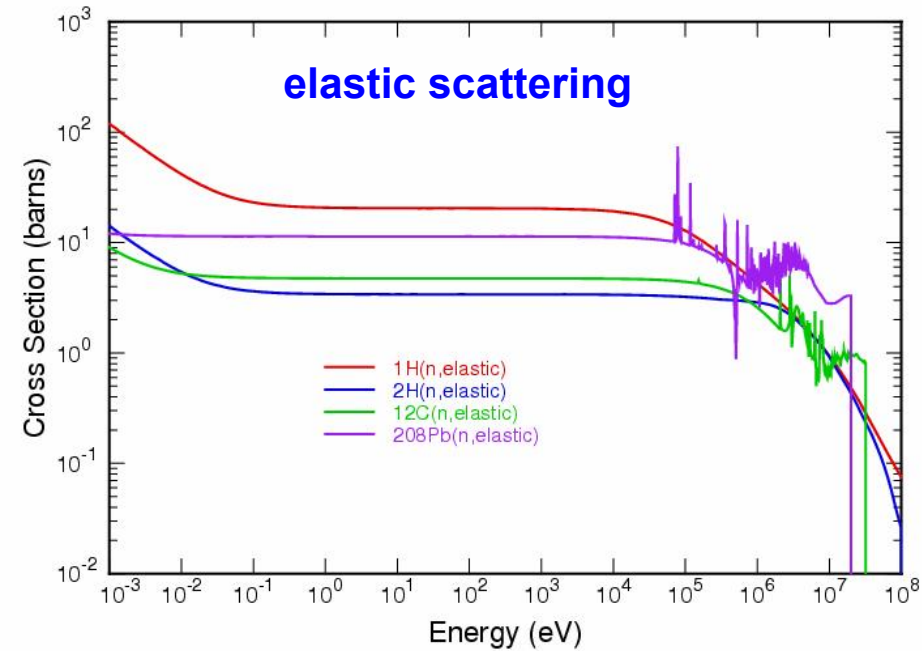
Fission:

- $n + {}^{235}\text{U} \rightarrow \text{fission fragments} + \sim 160 \text{ MeV}$
- $n + {}^{239}\text{Pu} \rightarrow \text{fission fragments} + \sim 160 \text{ MeV}$
- $n + {}^{238}\text{U} \rightarrow \text{fission fragments} + \sim 160 \text{ MeV}$

Cross section energy dependence of useful reactions



Cross section energy dependence of moderators



Neutron detectors:

Counters (only identification):

- Moderated
- Not moderated

Spectrometers (energy determination):

- Recoil
- Charged particle reaction
- Time of Flight
- Slowing down

Physical form:

- Gas: ionization and proportional chambers
- Liquid: scintillators
- Solid: scintillators, semiconductor

Active material:

- Self-detecting
- Loaded
- Lined

Miscellanea of detectors:

- Li glass scintillator: $\text{Li}_2\text{O} + \text{SiO}_2 + \dots$
- Li crystal scintillator: $\text{LiI}(\text{Eu})$, LiF
- Li + $\text{ZnS}(\text{Ag})$ scintillator
- Li + thermo-luminescent material
- Gd crystal scintillators: $\text{Gd}_2\text{O}_2\text{S}(\text{Pr})$,...
- BAs semiconductor

Gas-filled chamber

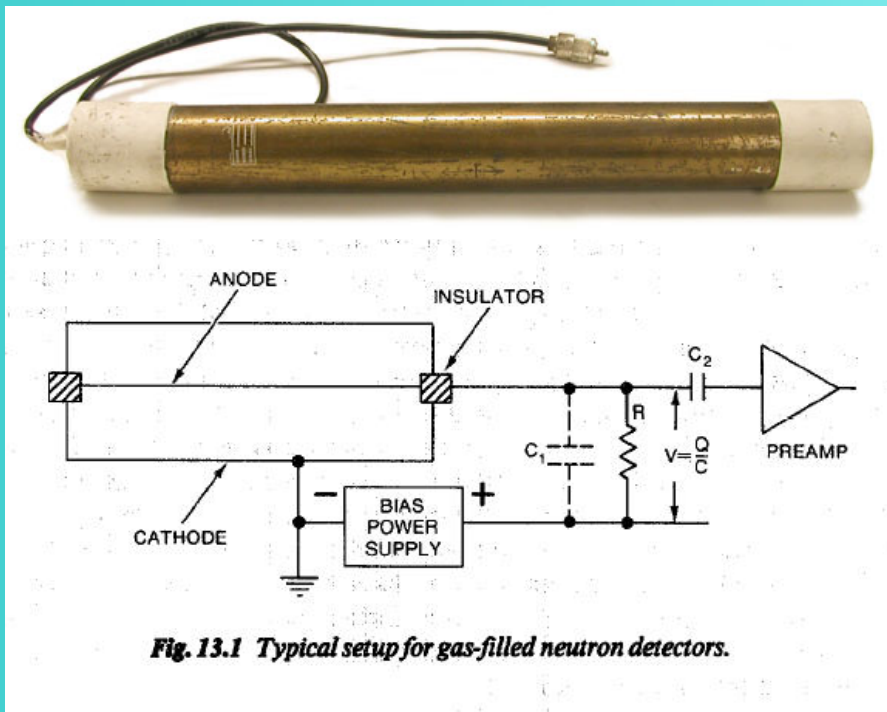


Fig. 13.1 Typical setup for gas-filled neutron detectors.

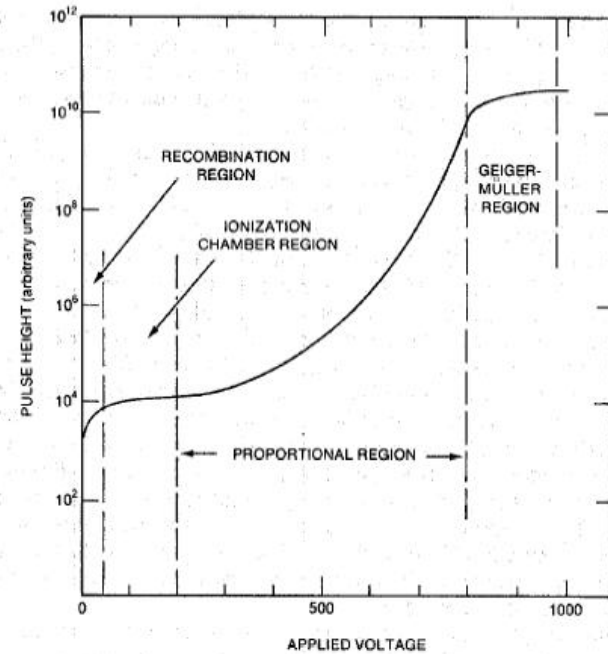


Fig. 13.3 Pulse-height vs applied-voltage curves to illustrate ionization, proportional, and Geiger-Mueller regions of operation.

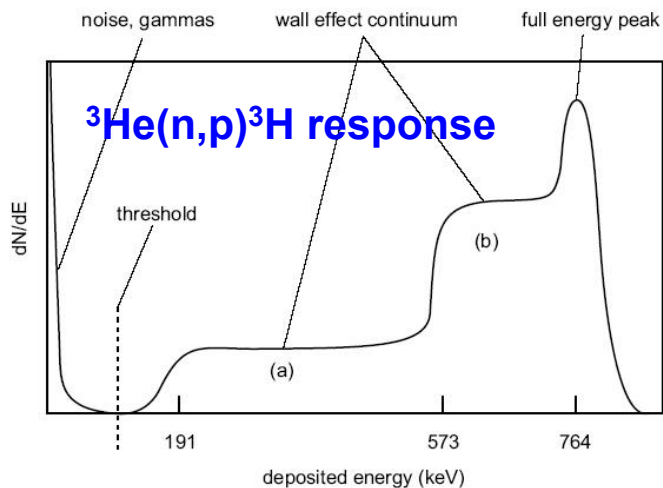


Figure 1: Expected pulse height spectrum from a ^3He tube. The two steps in the spectrum are caused by one of the reaction products hitting the detector wall. In area (a), the triton energy is fully deposited, but the proton only deposited a fraction of its energy, and vice versa in area (b).

Gases:

- H_2 (recoil)
- ^3He (reaction)
- ^4He (recoil)
- BF_3 (reaction)

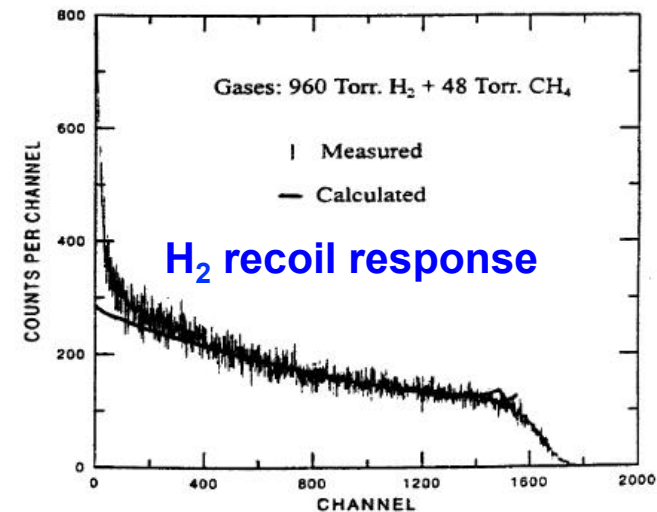
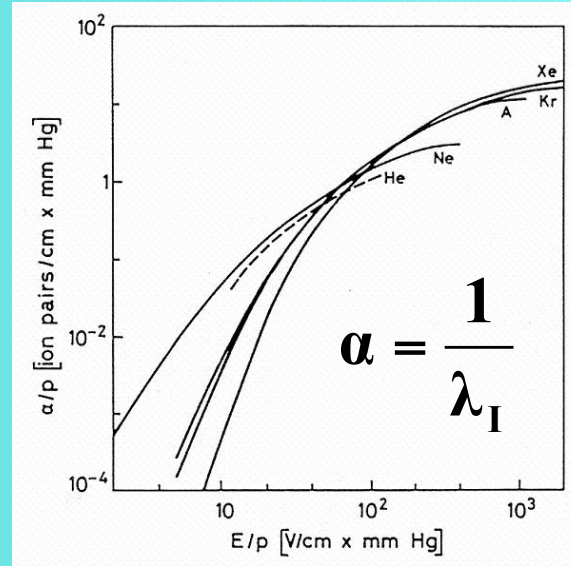
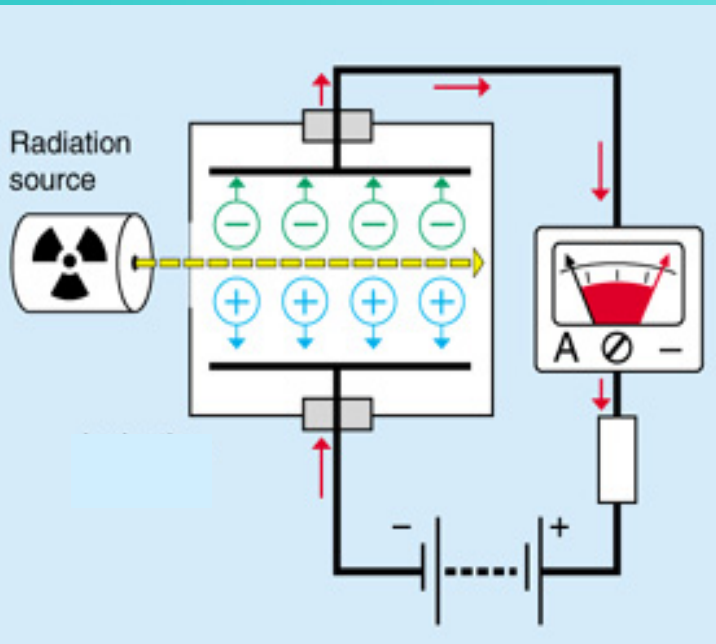


Fig. 1. Measured and calculated pulse height distributions for 0.565 MeV neutrons incident on a cylindrical proportional counter (active volume 38mm diameter \times 178 mm). From Ref.

Gaseous ionization detectors

Townsend coefficient

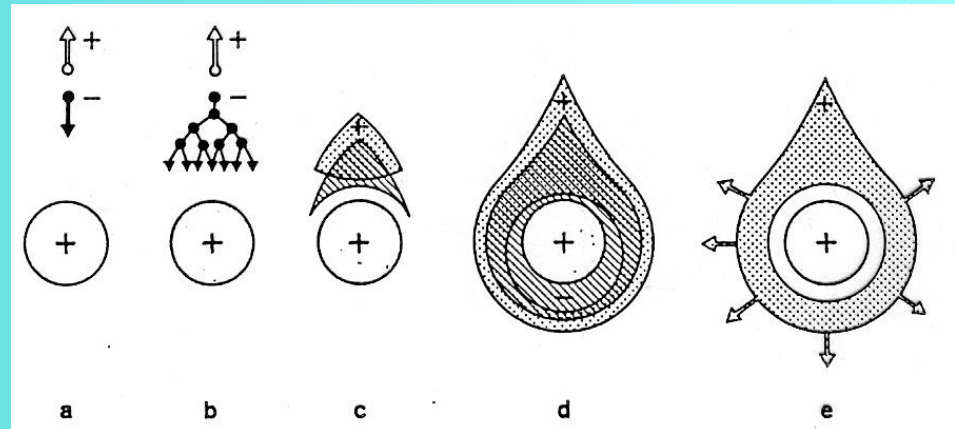
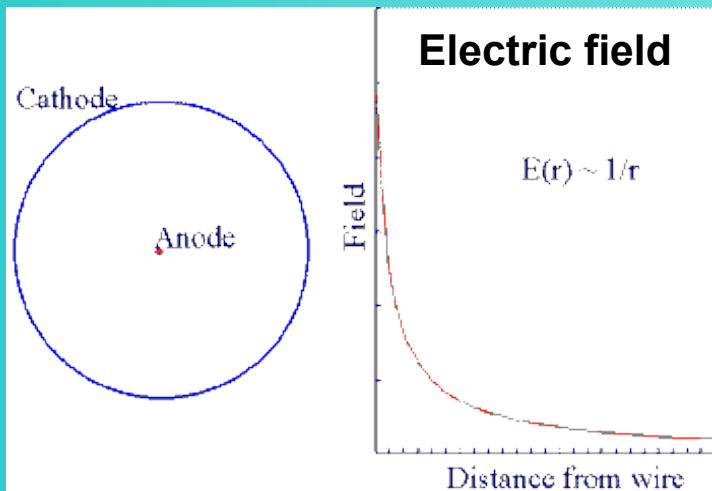


Multiplication

$$M = e^{\int \alpha(x) dx}$$

Cylindrical configuration

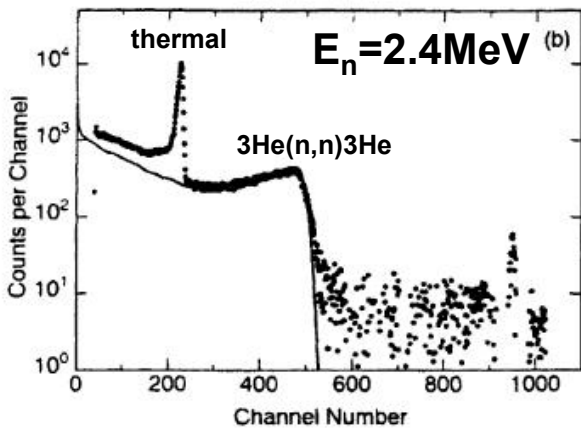
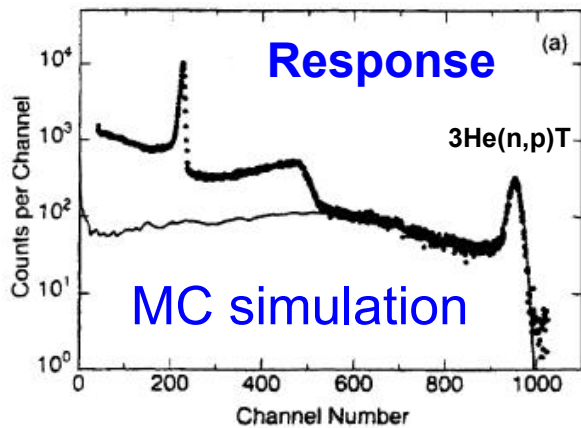
Electron drift and avalanche formation



^3He chambers



NIMA422 (1999) 69



Efficiency

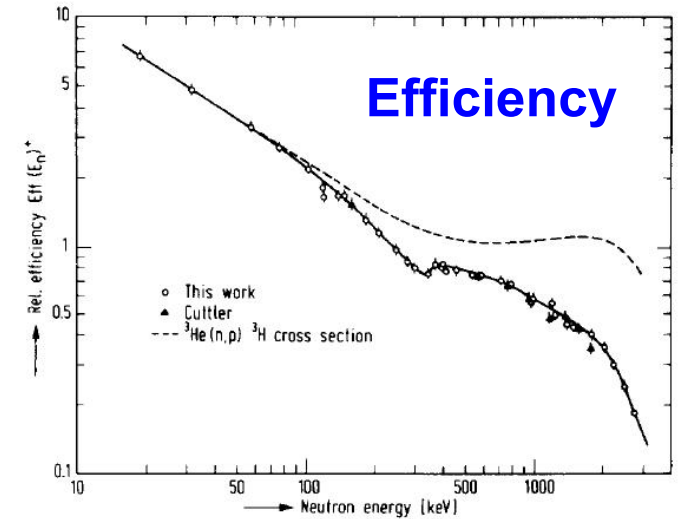


Fig. 7. Relative efficiency of the ^3He fast neutron spectrometer, normalized to previous measurements¹⁵⁾, along with the $^3\text{He}(n,p)^3\text{H}$ cross section

NIM144 (1977) 253

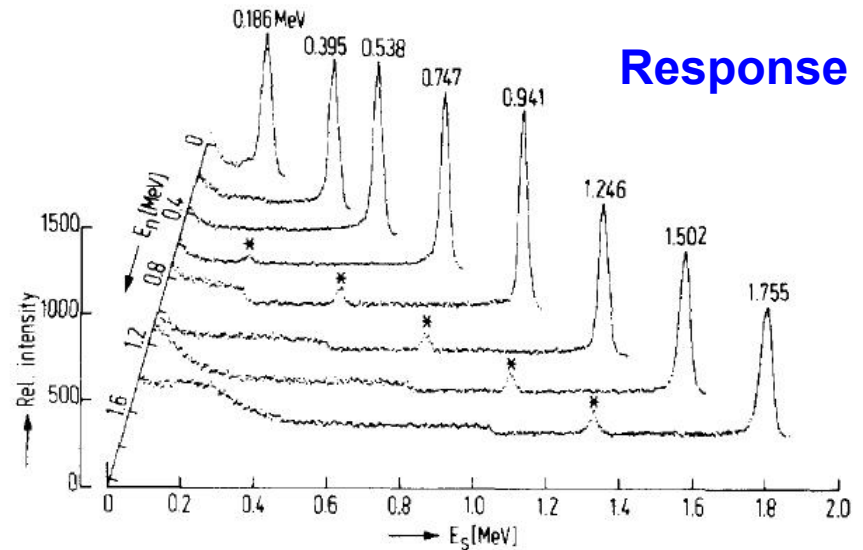
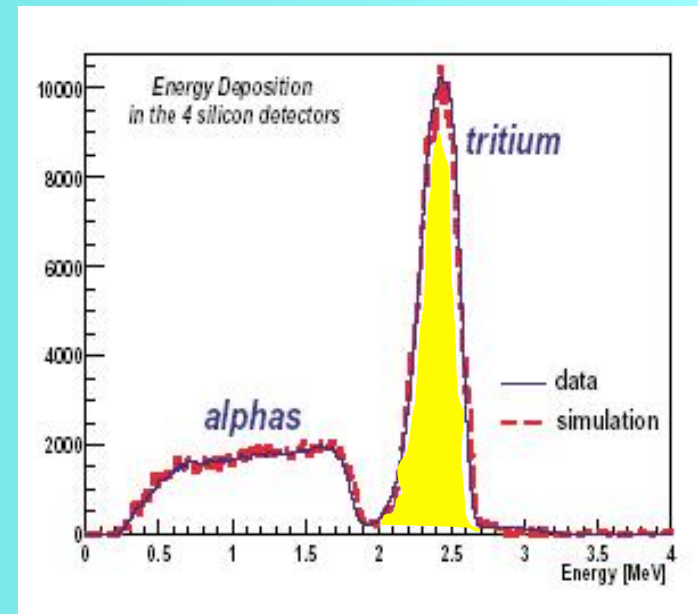
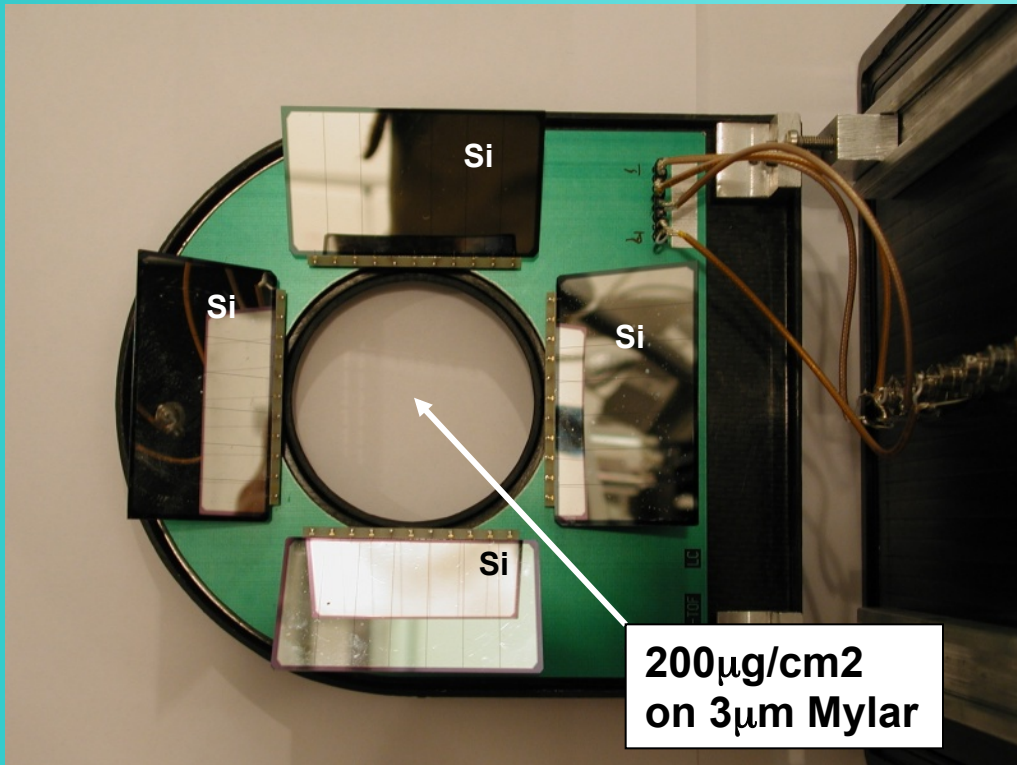


Fig. 2. Response of the ^3He ionization chamber to monoenergetic neutrons produced by the $^7\text{Li}(p,n)^7\text{Be}$ reaction. E_n is the

Foil with deposit + Si-detector

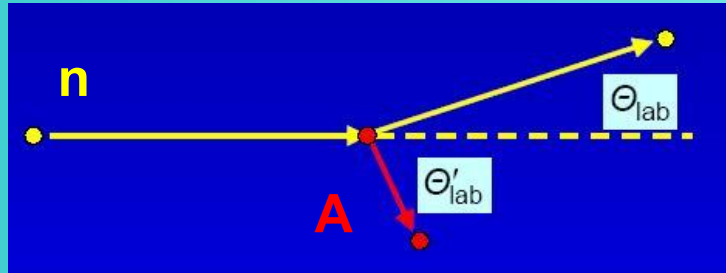
• Reaction: $n + {}^6\text{Li} \rightarrow \text{t} + \alpha$



NIMA517 (2004) 389

Neutron scattering

s-wave ($l=0$) elastic scattering:



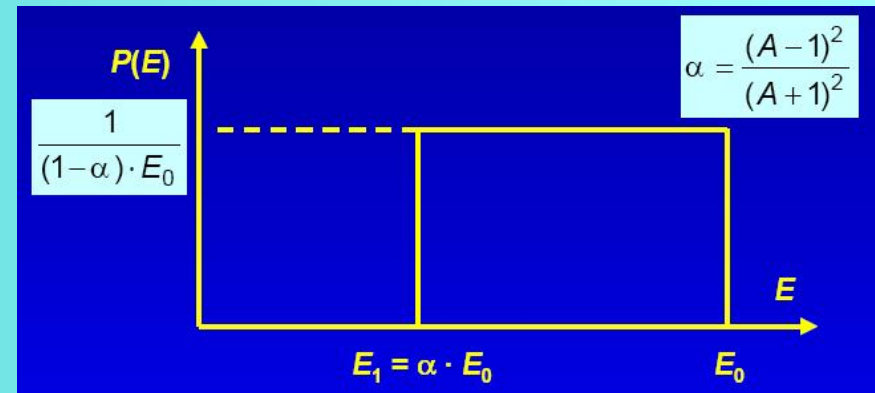
Energy-momentum conservation:

$$\frac{E}{E_0} = \frac{A^2 + 1 + 2A \cdot \cos \Theta_{\text{CMS}}}{(A + 1)^2}$$

There is a minimum neutron energy (maximum recoil energy) after the collision dependent on A:

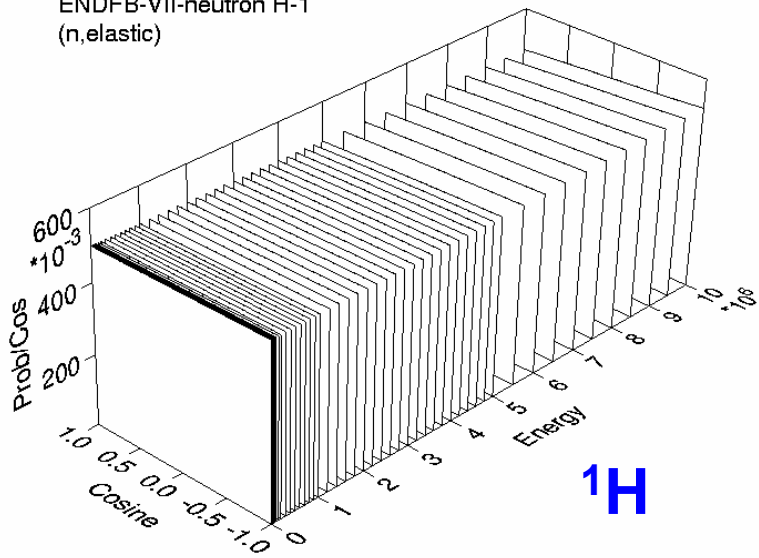
$$\left[\frac{E}{E_0} \right]_{\text{min}} = \frac{(A - 1)^2}{(A + 1)^2} = \alpha$$

Isotropic in CMS:



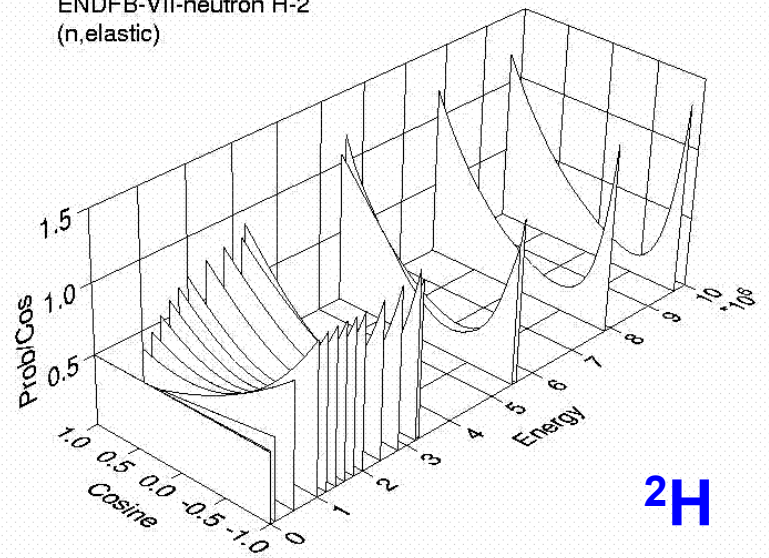
1- α : H (1.0), D(0.89), C(0.28), Fe(0.069), Pb(0.019)

ENDFB-VII-neutron H-1
(n,elastic)



^1H

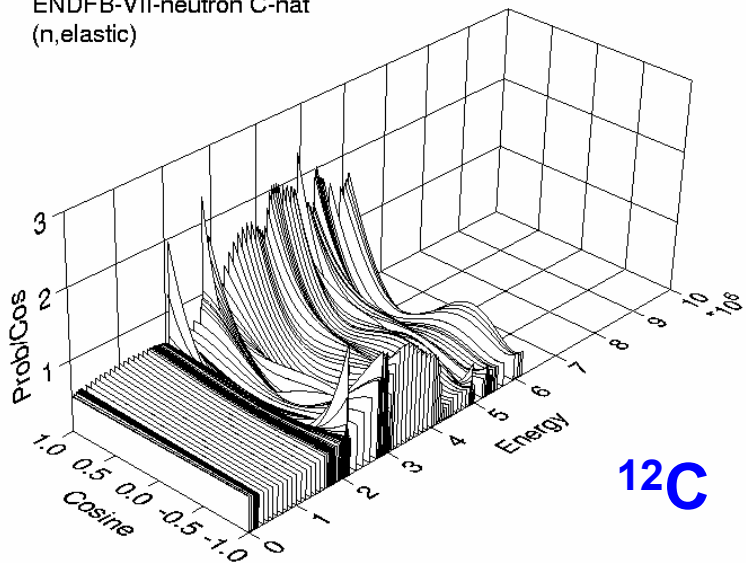
ENDFB-VII-neutron H-2
(n,elastic)



^2H

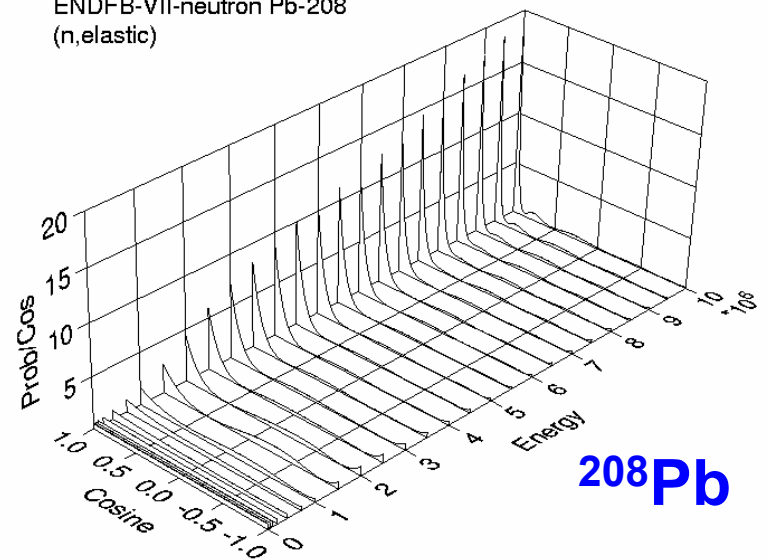
ELASTIC SCATTERING ANGULAR DISTRIBUTION

ENDFB-VII-neutron C-nat
(n,elastic)



^{12}C

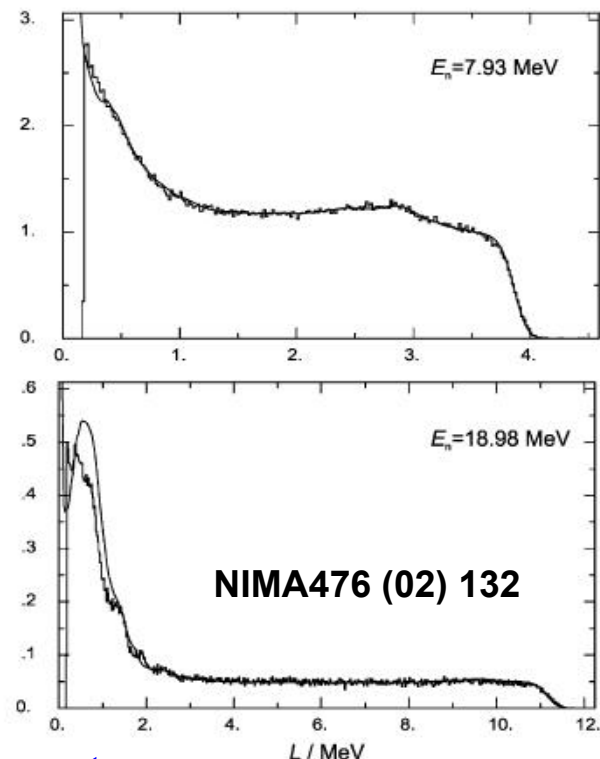
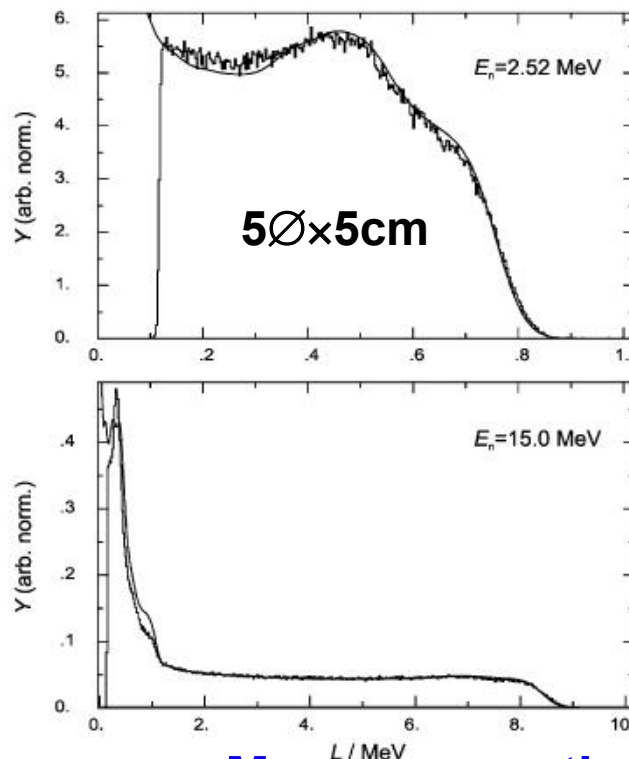
ENDFB-VII-neutron Pb-208
(n,elastic)



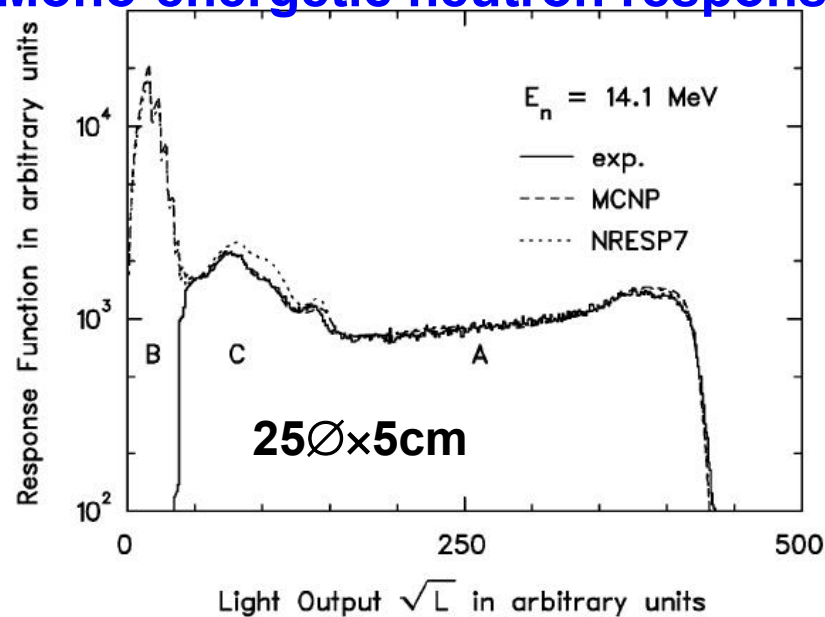
^{208}Pb

BC501/NE213 liquid scintillators

$C_1H_{1.212}$
 $\rho = 0.874\text{g/cm}^3$
 $n (@425\text{nm}) = 1.53$
 $\tau = 3.2 (32.3, 270) \text{ ns}$

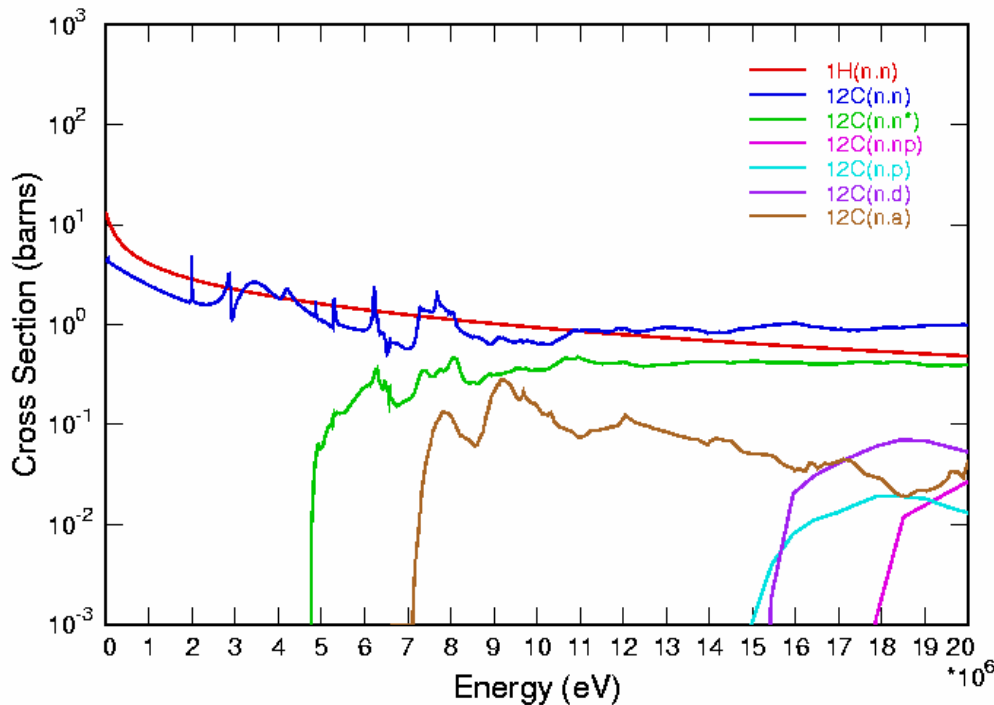


Mono-energetic neutron response

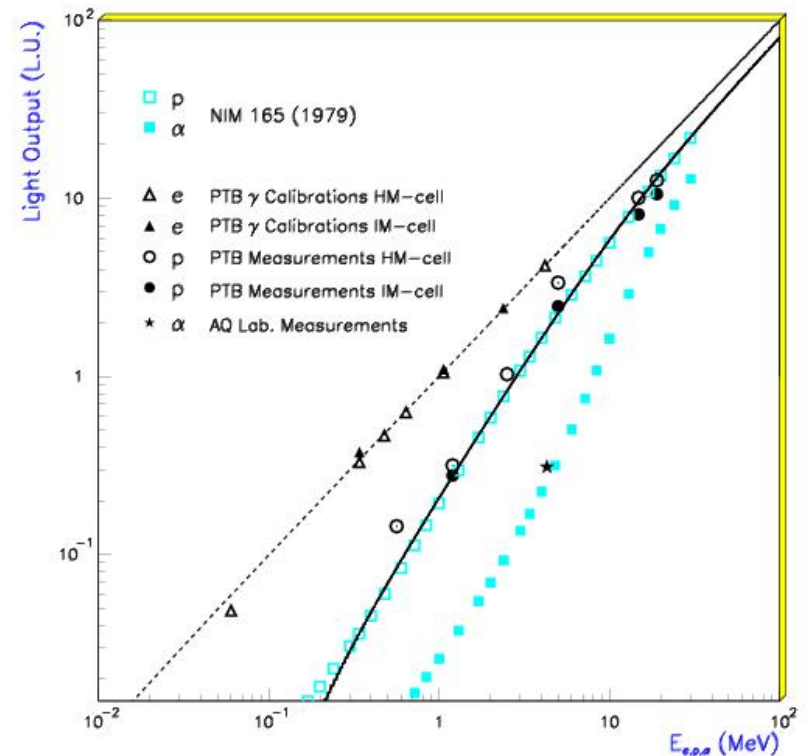


Monte Carlo simulations of neutron interactions and detectors

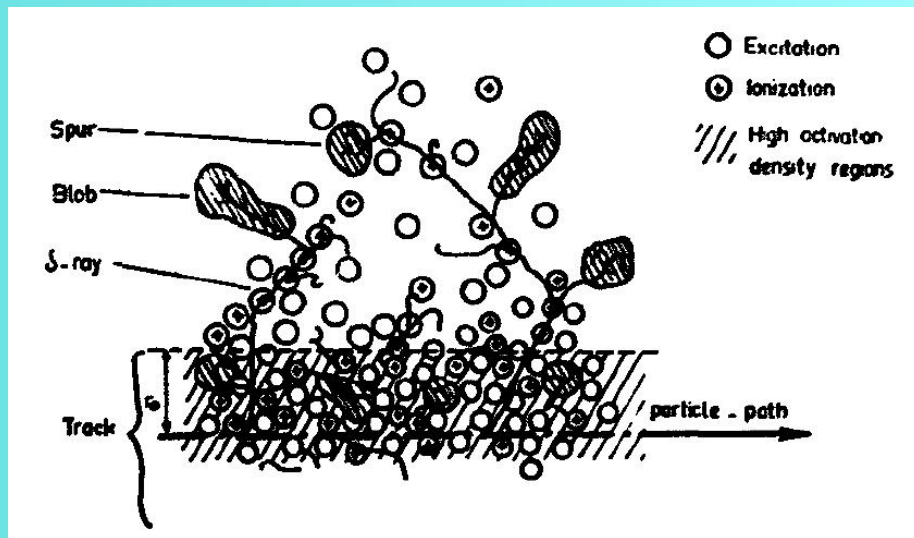
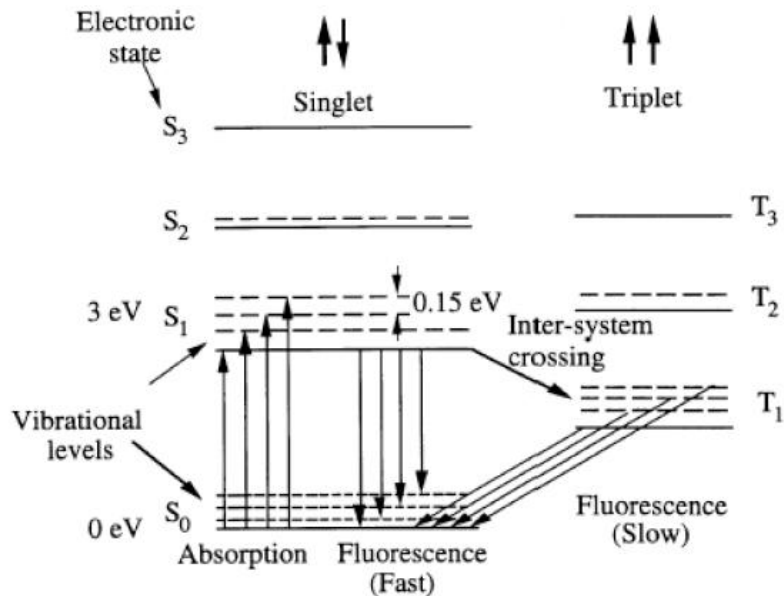
- Birth of modern MC approach
- General purpose codes: MCNP, GEANT, ... and specific codes: NRESP, SCINFUL, ...



- Requires nuclear reaction data
- May require material response (light production, ...)

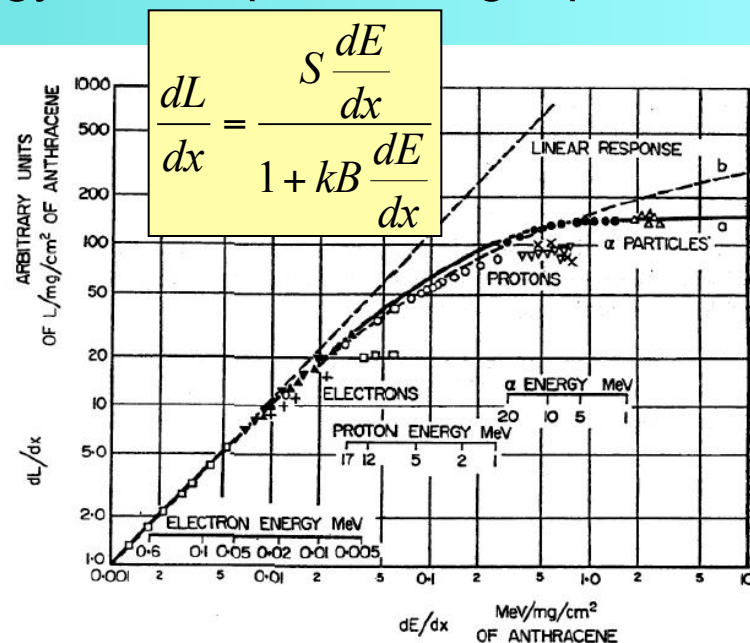
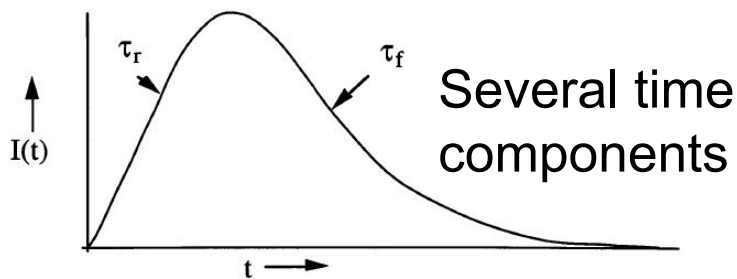


Luminescence in organic materials



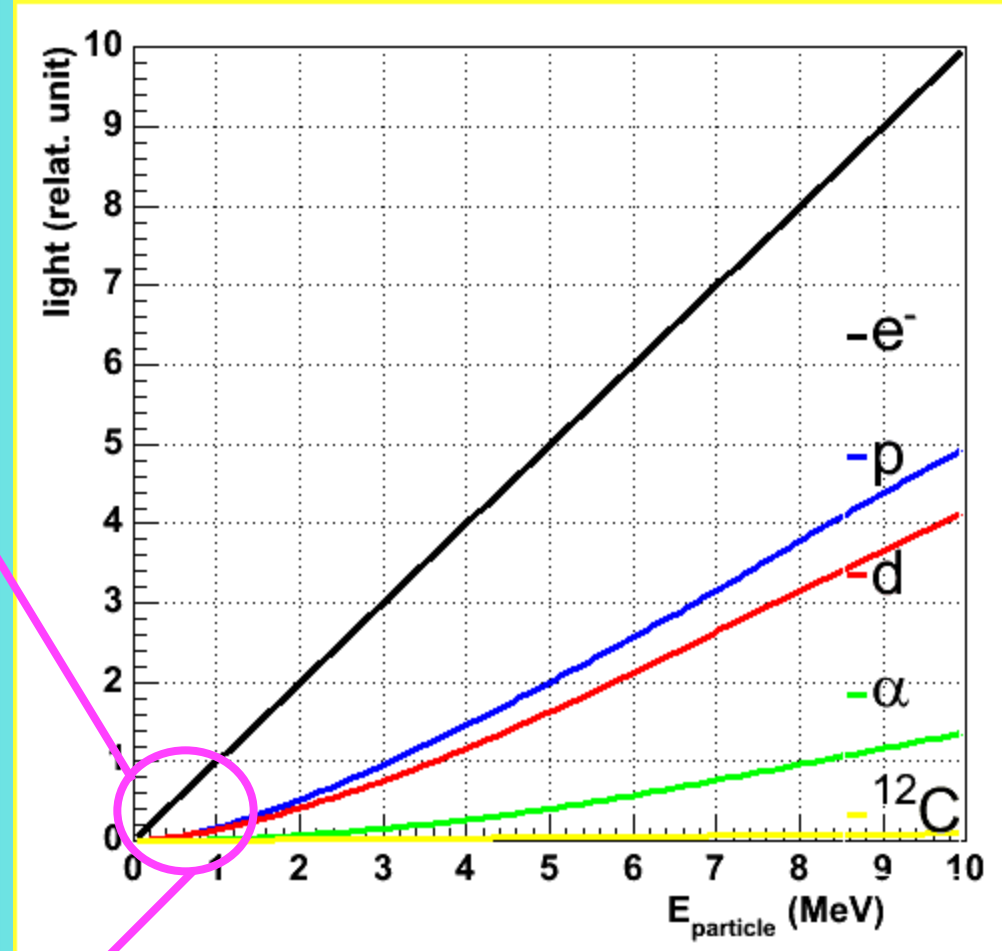
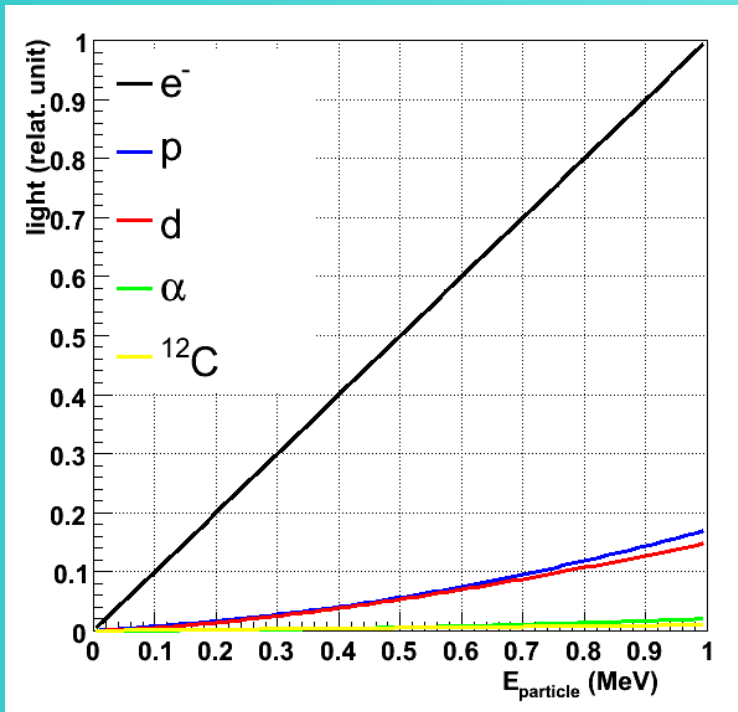
The non-radiative transfer mechanism between excited centers induces an energy-loss dependent light production ...

... and a varying time distribution



Light production curves:

p, α , ^{12}C in NE213: Dekempeneer et al. NIM A256 (1987) 489
d in NE230: Croft et al. NIM A316 (1992) 324

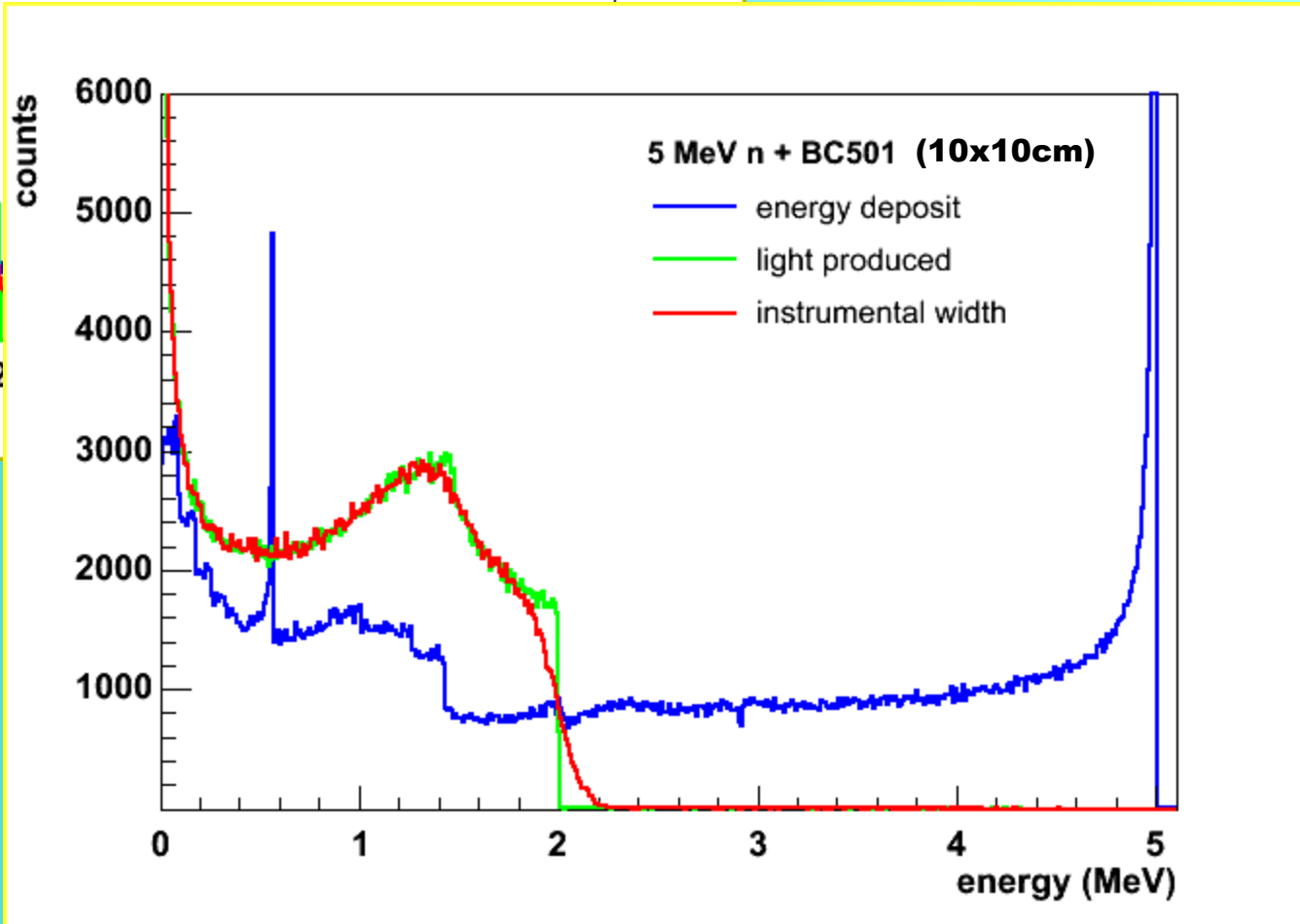
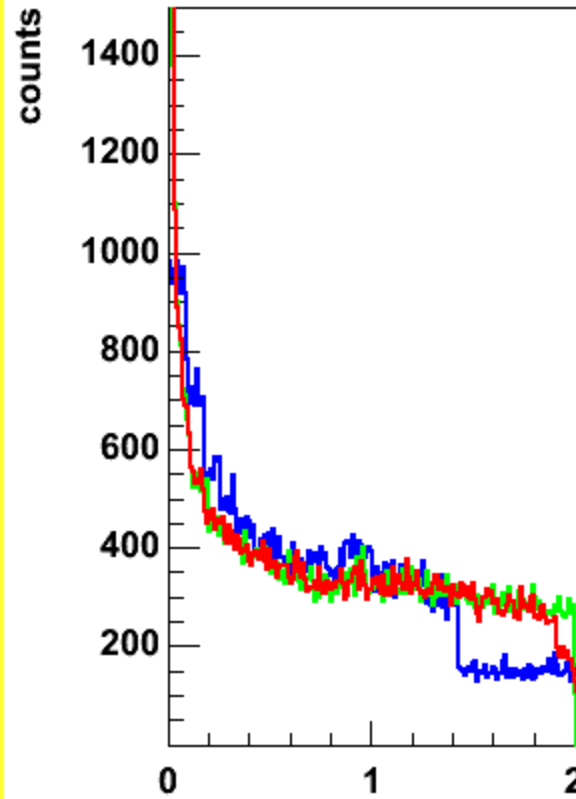


(In reality there is some dependence on chemical composition, fabrication, age, ...)

Simulations with
GEANT3/GCALOR →

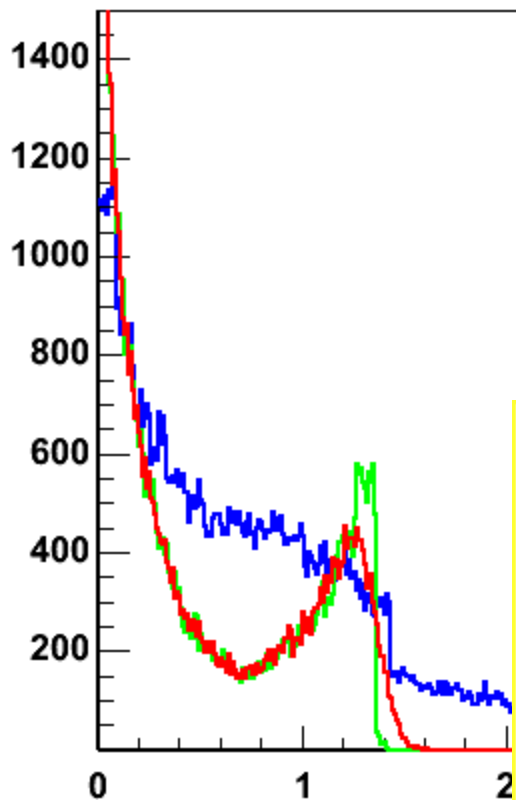
$$\Delta L = L(E) - L(E - \Delta E)$$

(assumed same α and ^{12}C light curves in BC501 & BC537)

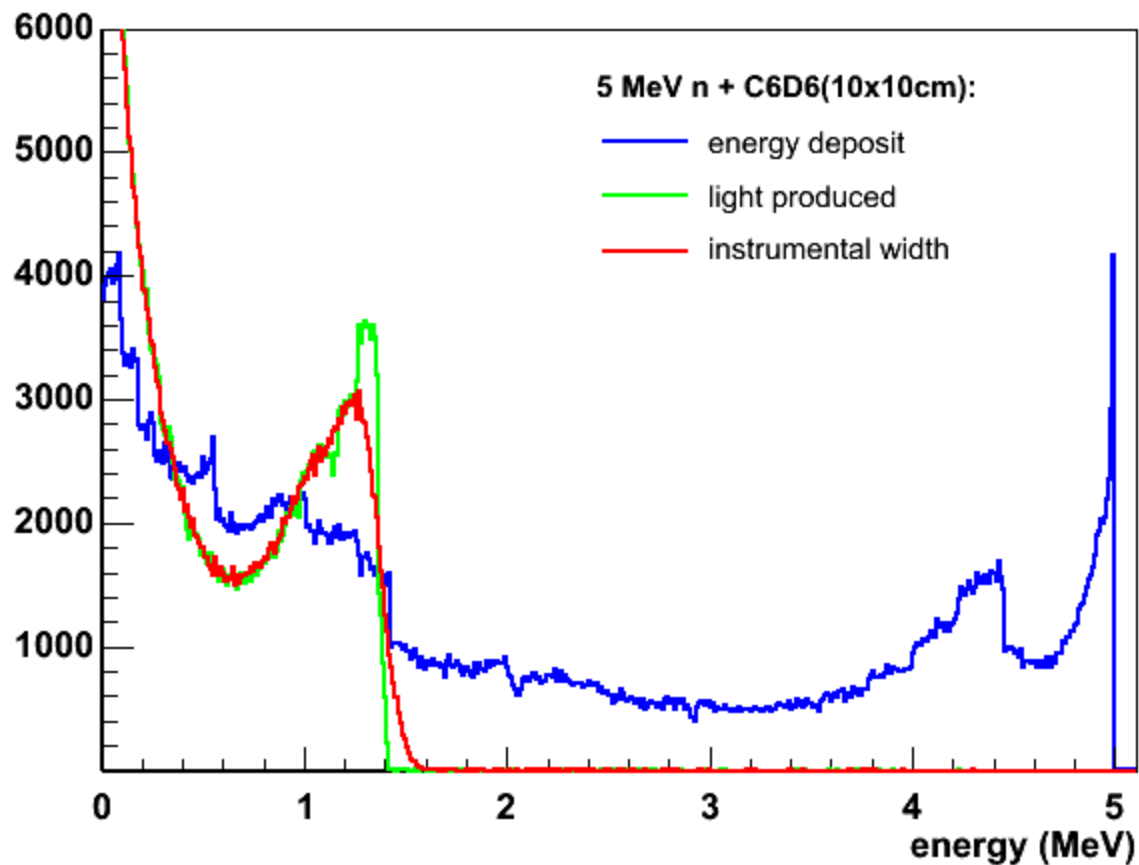


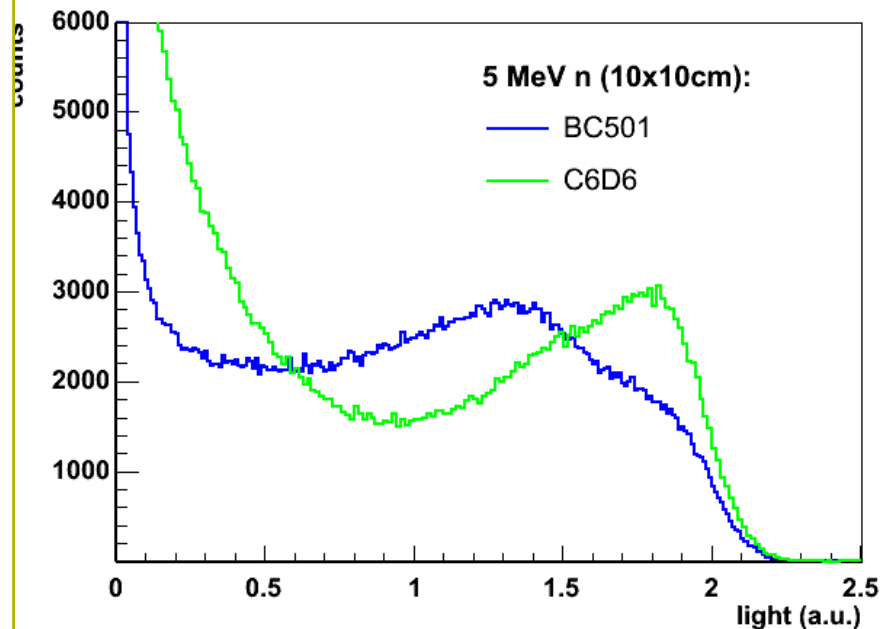
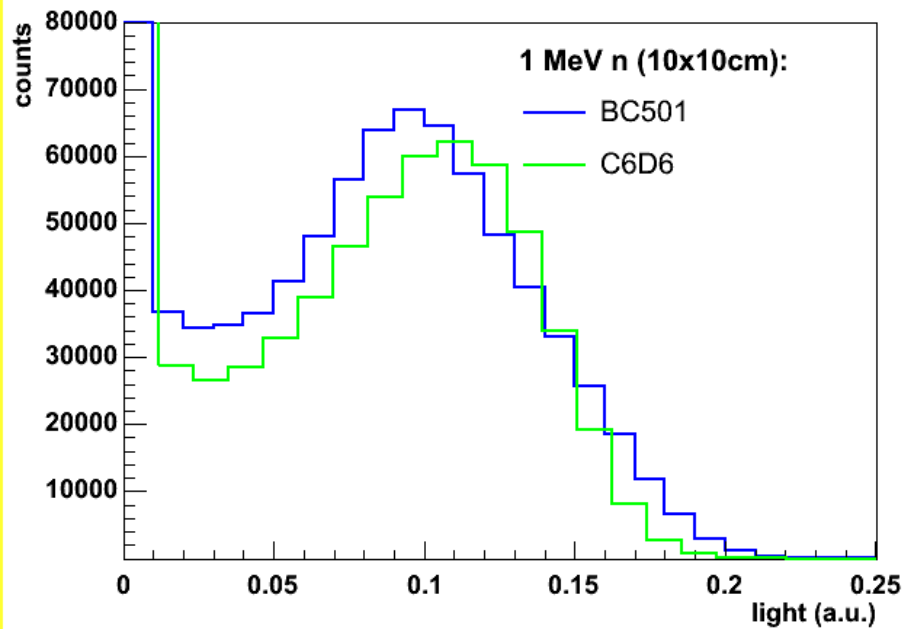
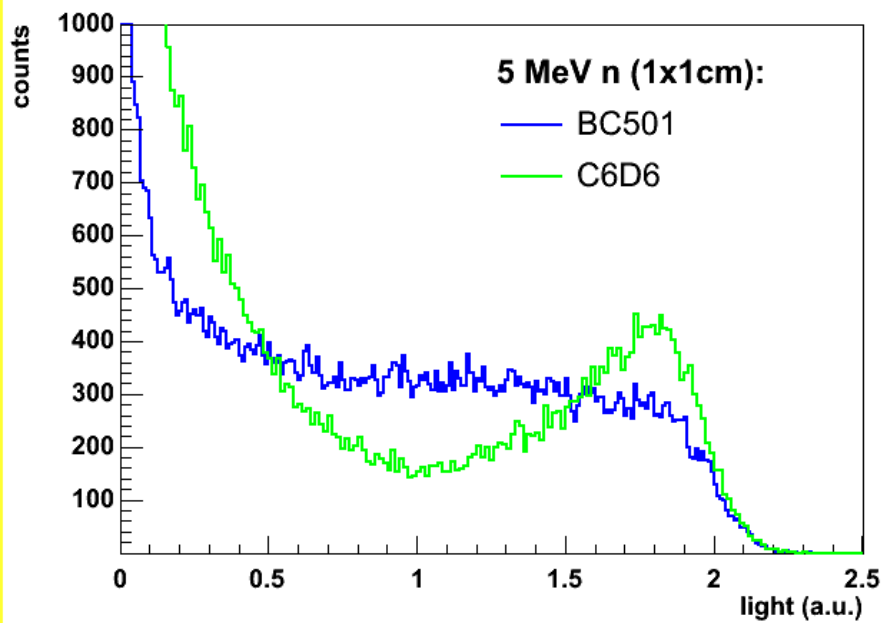
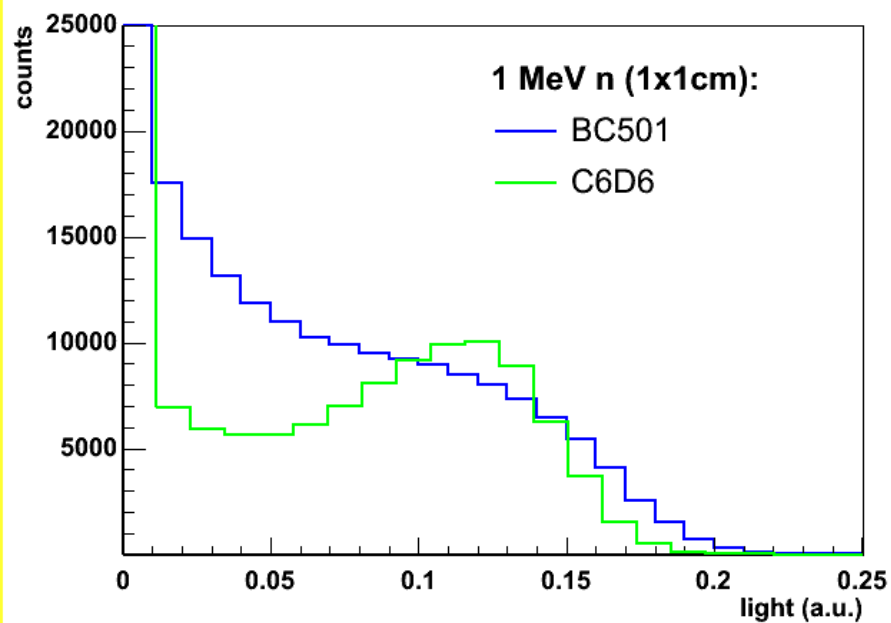
Simulation with
GEANT3/GCALOR

counts



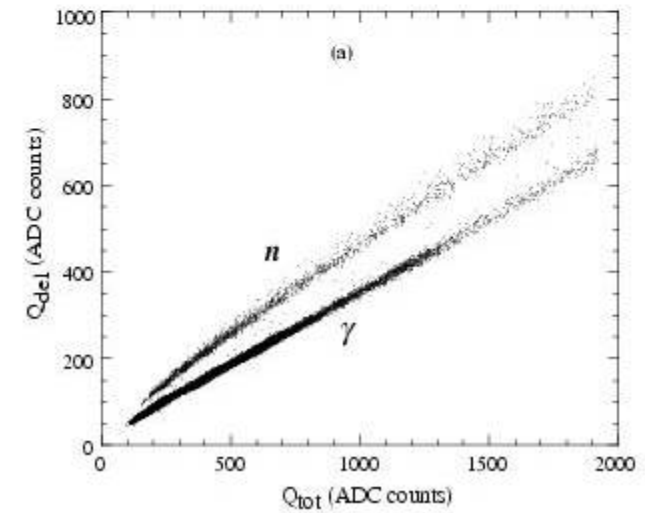
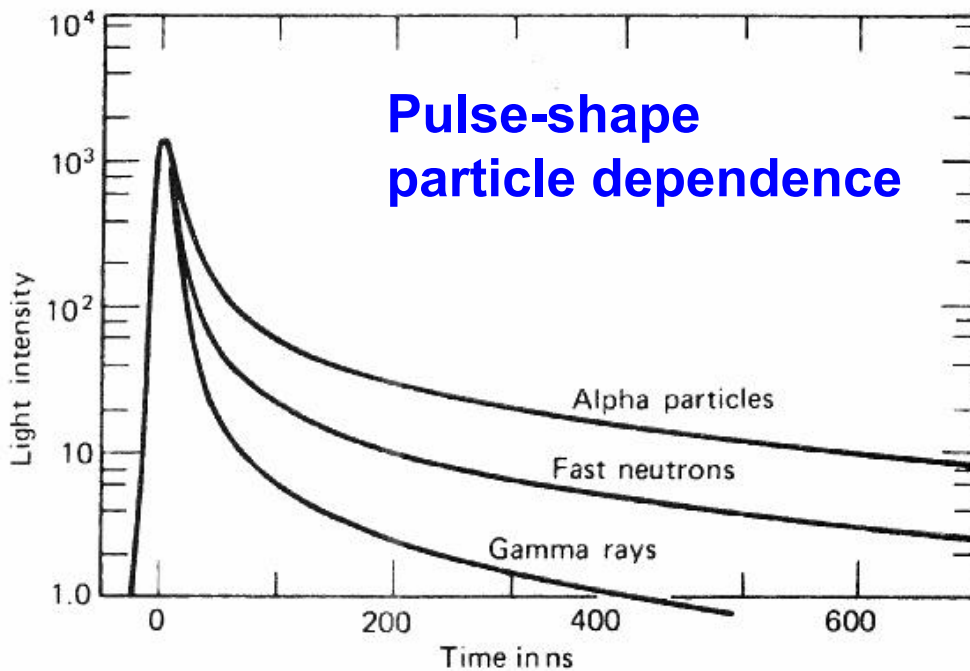
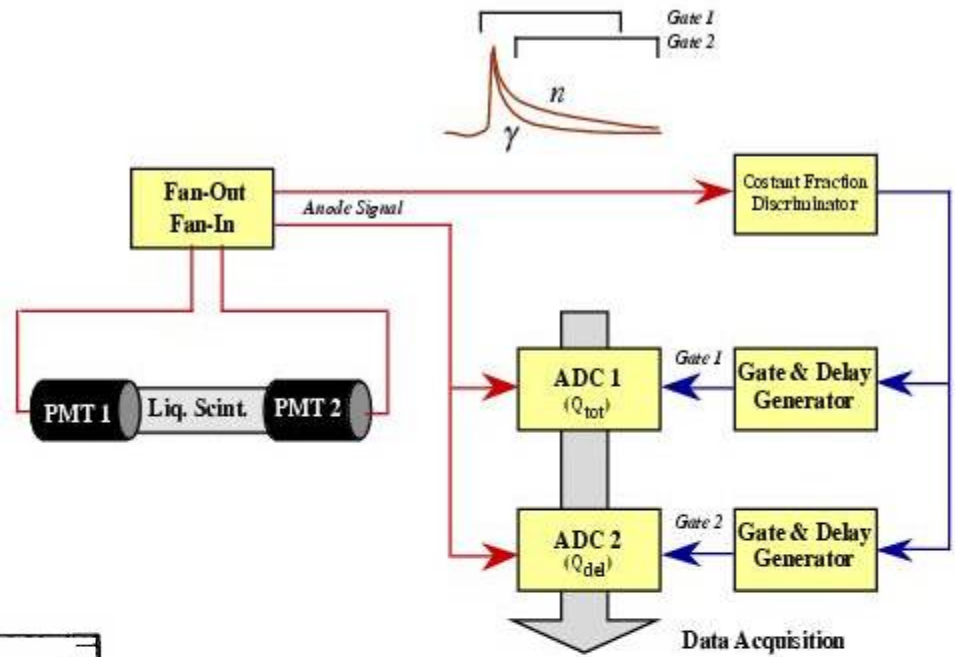
counts





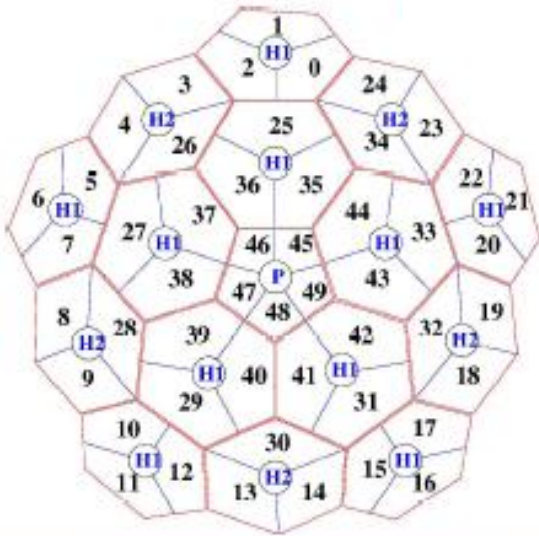
BC501/NE213

Pulse Shape Discrimination



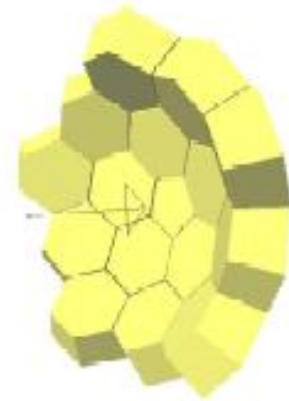
Multi-detector: Neutron Wall (EUROBALL)

BC501 liquid scintillator



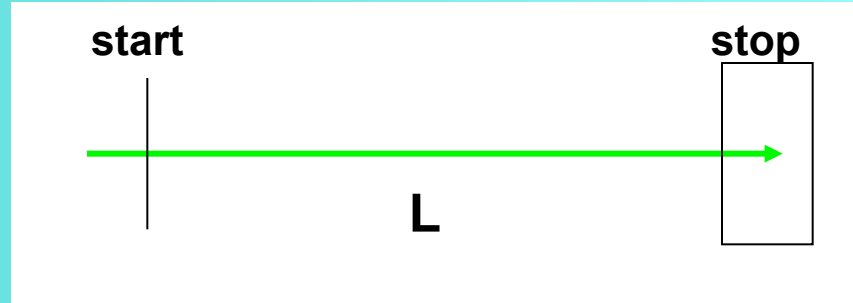
$$\frac{\Delta\Omega}{4\pi} = 25\%$$

$$\varepsilon_{\text{int}} = 50\%$$



Time of Flight Spectrometer

$$E_n = \frac{1}{2} m_n \frac{L^2}{t^2}$$



Start Time: time-pulsed origin, accompanying radiation, ...
(not the neutron)

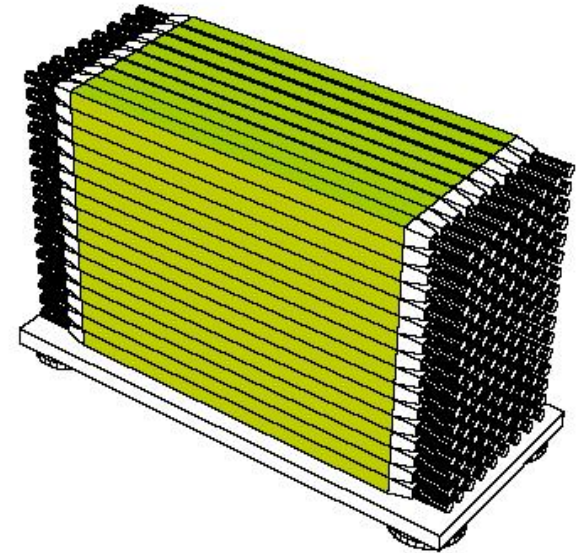
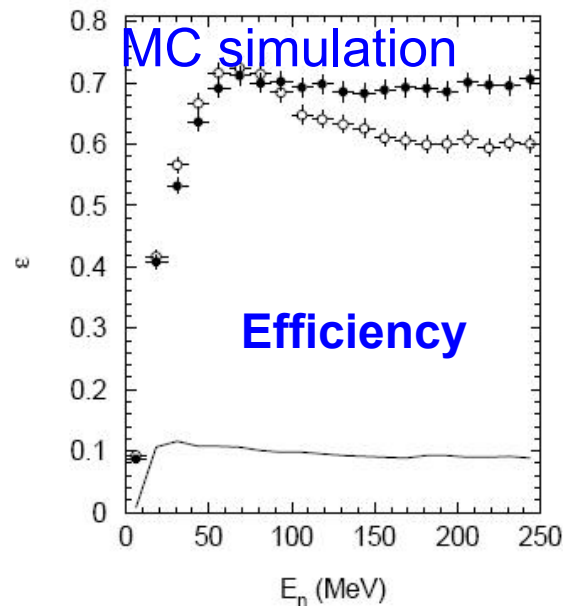
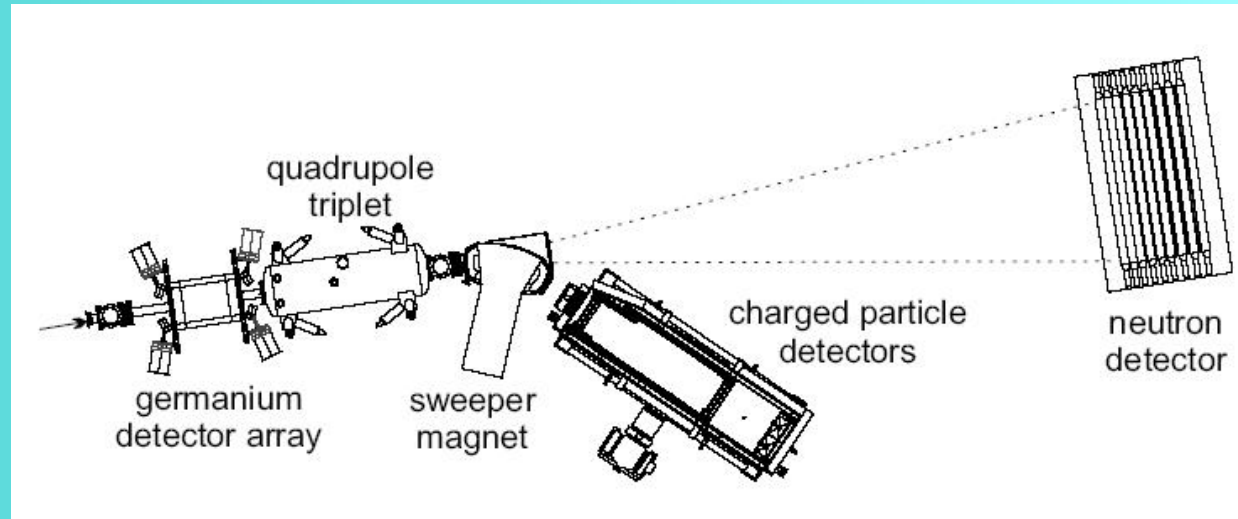
Stop Time: neutron detector

Energy resolution:
$$\frac{\Delta E}{E} = 2 \sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

- Long flight path, short detectors, good time resolution

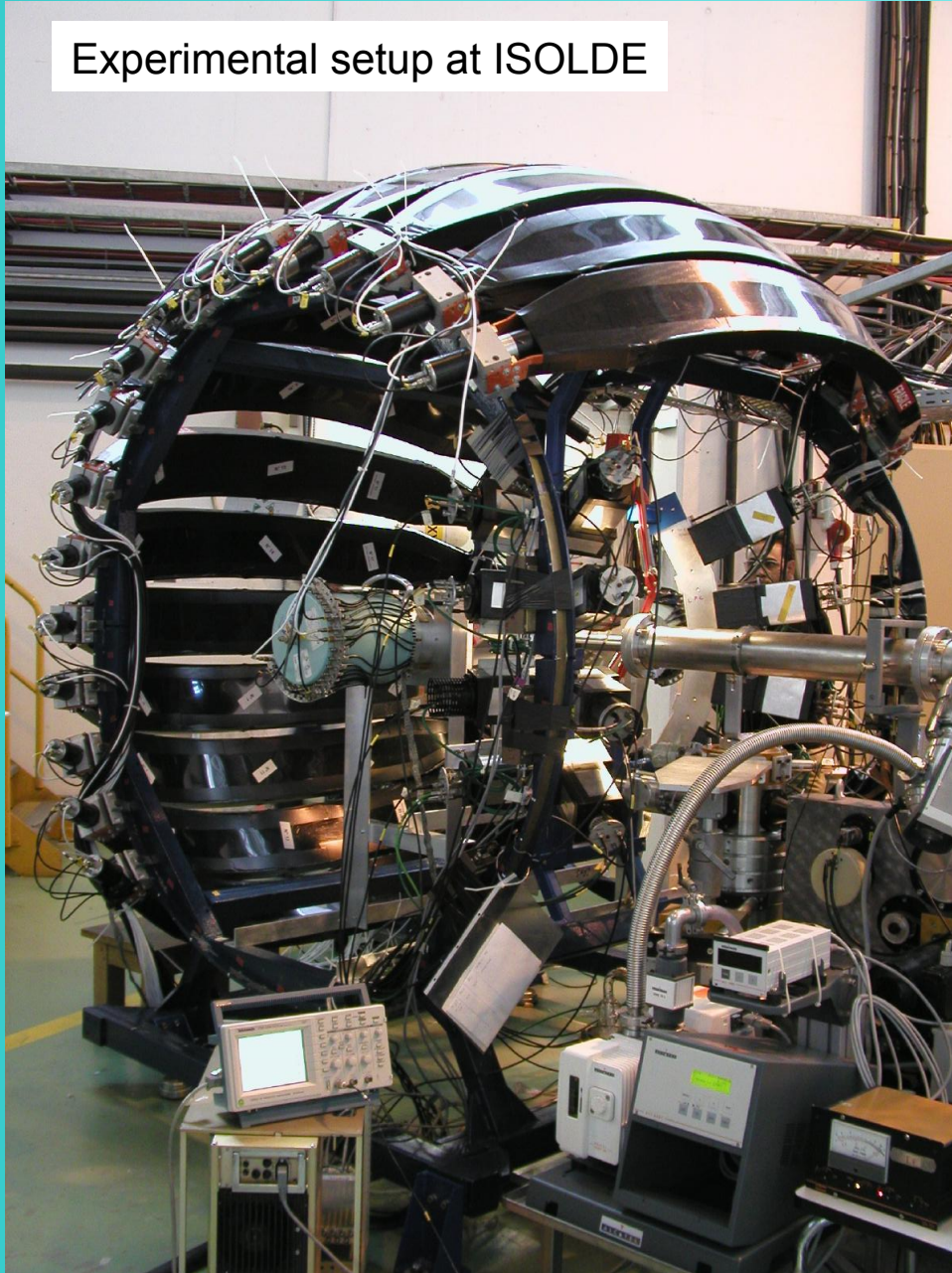
ToF spectrometer: MoNA (NSCL-Michigan)

144 bars
200x10x10 cm³
plastic scintillators+
iron converters



ToF spectrometer: TONERRE (LPC-Caen)

Experimental setup at ISOLDE

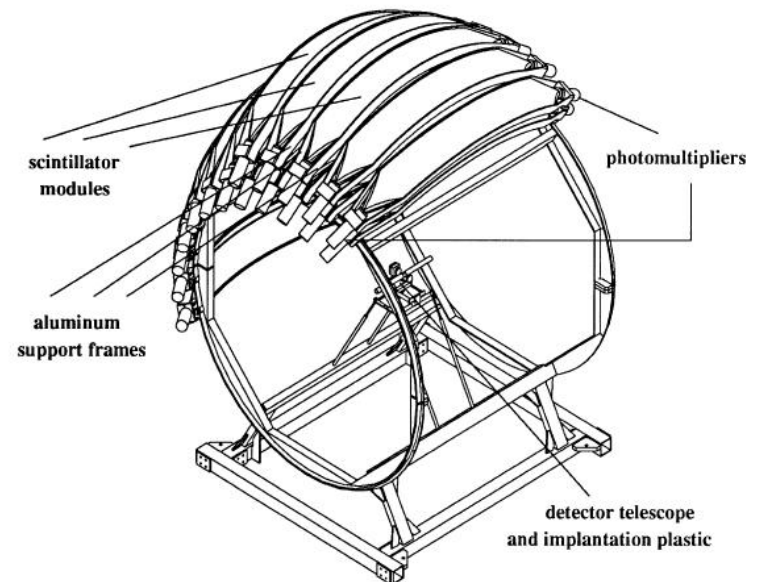


BC400 Plastic scintillator

$$\frac{\Delta\Omega}{4\pi} = 50\%$$

$$\varepsilon_{\text{int}} = 25\%$$

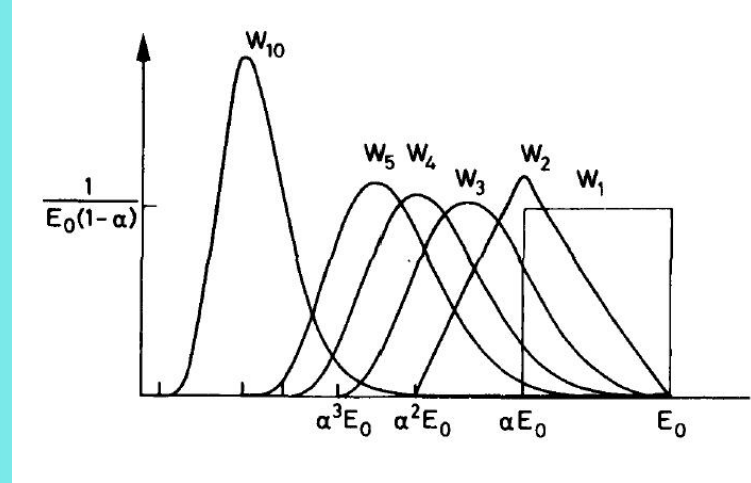
$$\frac{\Delta E}{E} = 10\%$$



Neutron moderation:

After many collisions:

Nucleus	$1-\alpha$	ξ	N (1MeV→ 25 meV)
^1H	1	1	18
^2H	0.889	0.725	24
^4He	0.640	0.425	41
^{12}C	0.284	0.158	111
^{56}Fe	0.069	0.035	500
^{208}Pb	0.019	0.010	1823



Slowing-down parameter:

$$\xi = \left\langle \ln \frac{E_0}{E} \right\rangle = 1 + \frac{(A-1)^2}{2A} \ln \frac{A-1}{A+1}$$

Number of collisions to reach an energy:

$$N = \frac{\ln E_0 / E_f}{\xi}$$

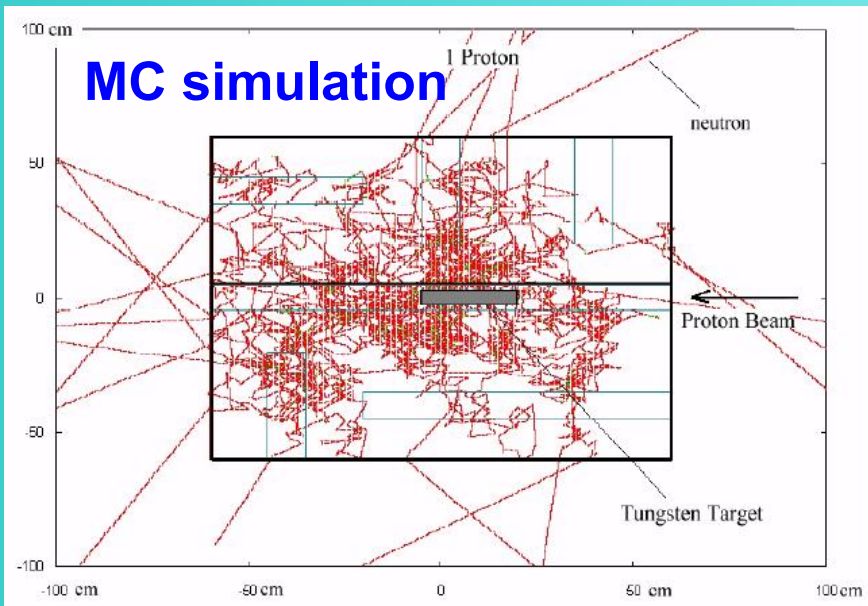
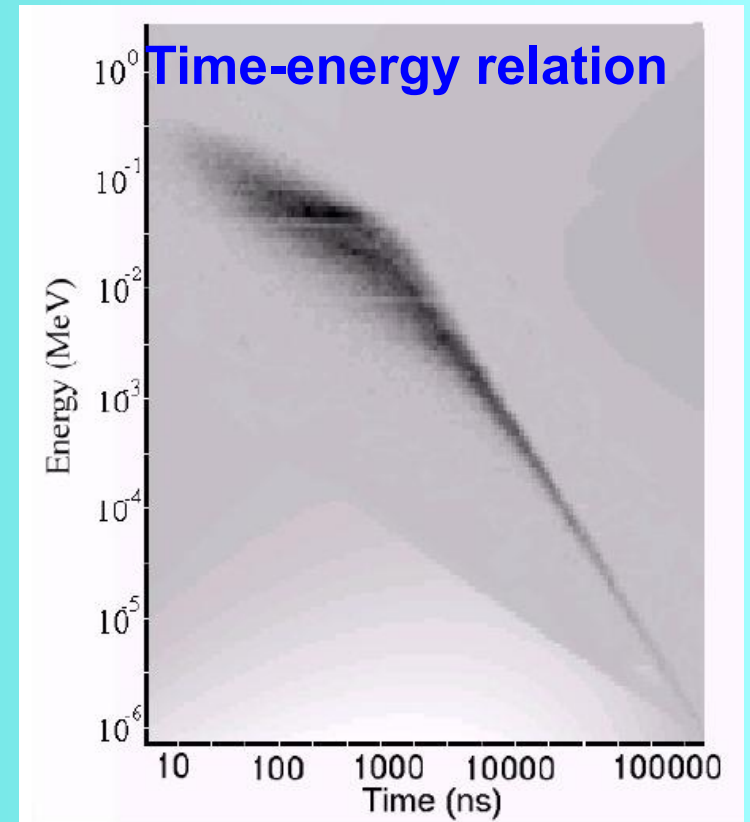
Slowing-down time: $t = \sqrt{\frac{K}{E_f}} - t_0 : K(\xi, \sigma_{\text{ela}}); t_0(E_0, \xi, \sigma_{\text{ela}})$

Slowing Down Spectrometer: LSDS (LANL-Los Alamos)



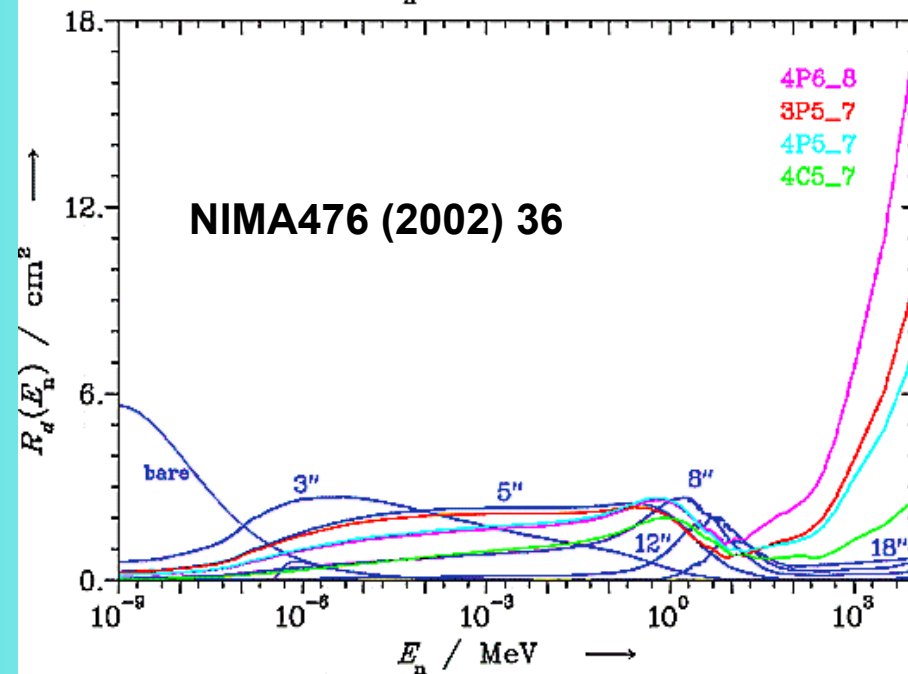
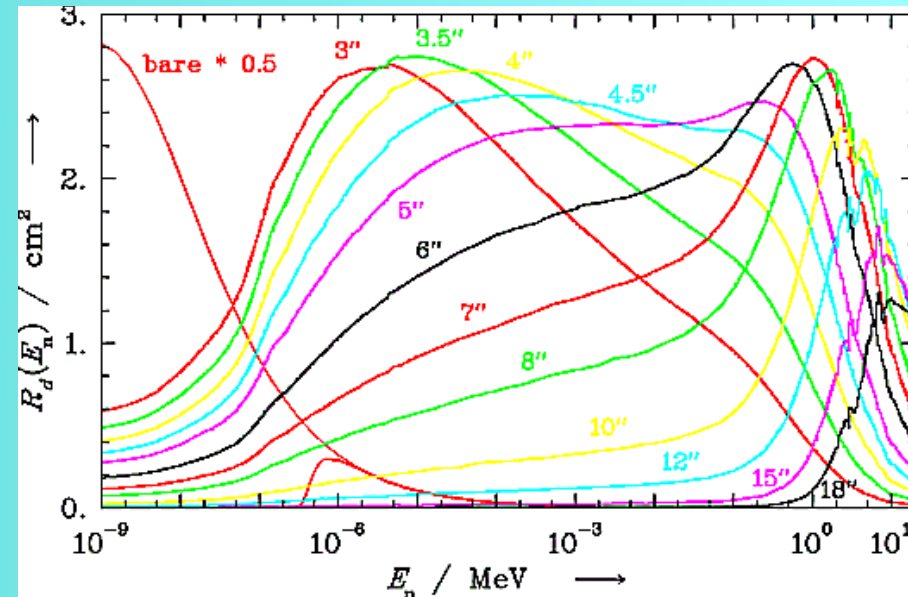
Lead block +
sample+counters

$$\langle E \rangle = \frac{K}{(t + t_0)^2} \quad \frac{\Delta E}{E} = 30\%$$

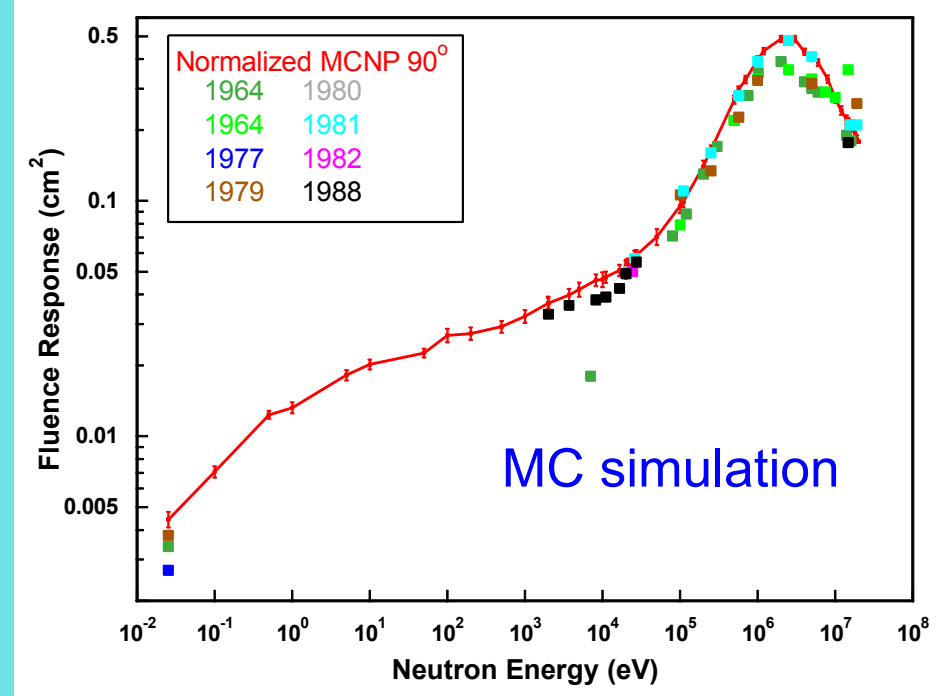
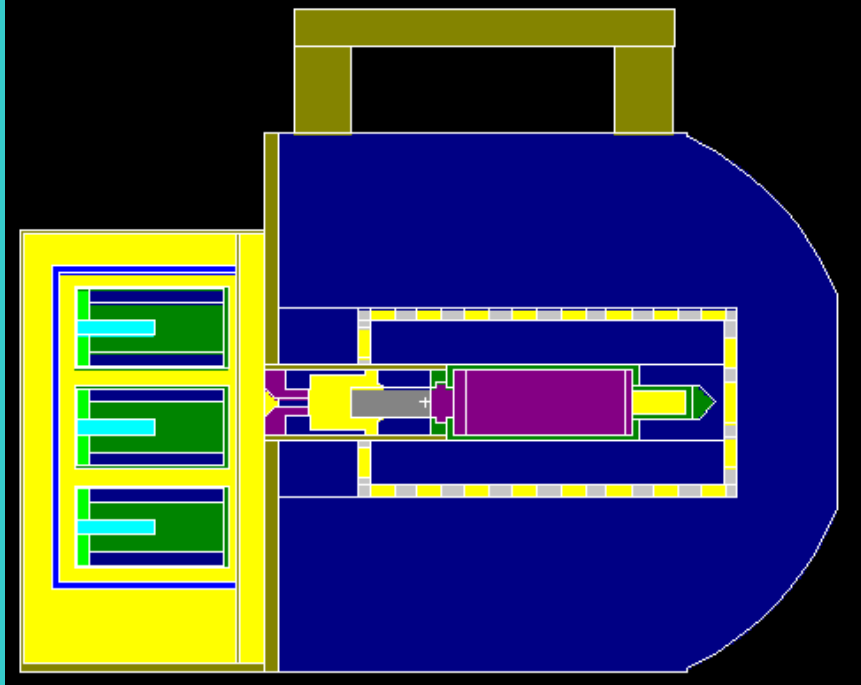


Bonner spheres: NEMUS (PTB-Braunschweig)

Polyethylene sphere + ^3He proportional counter



Monte Carlo simulations of neutron detectors



... allow to obtain spectrometric information

Deconvolution (unfolding):

Given the **response** of an apparatus as a function of a parameter, what is the distribution of **parameter** values which produces a measured **data** distribution?

Inverse (linear) problem: $\mathbf{d} = \mathbf{R} \cdot \mathbf{p}$; $d_i = \sum_j R_{ij} \cdot p_j, \forall i$

Solution is NOT: $\mathbf{p} = \mathbf{R}^{-1} \cdot \mathbf{d}$

Use statistical inference:

- not-unique solution ($\sigma_{\mathbf{d}}$)
- “*a priori*” information
- several methods:

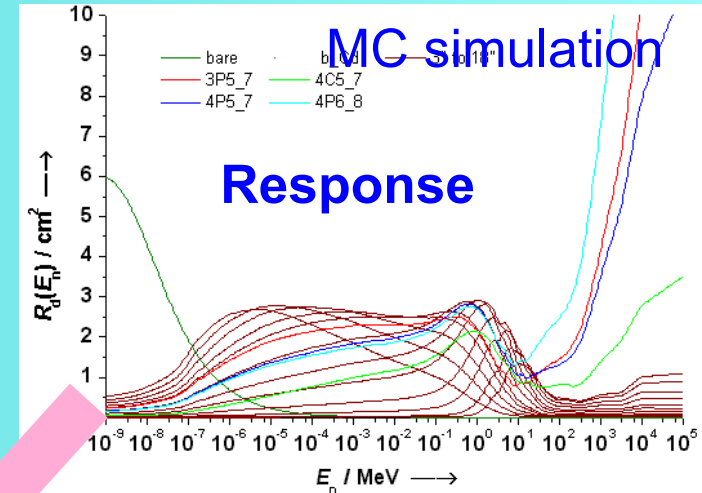
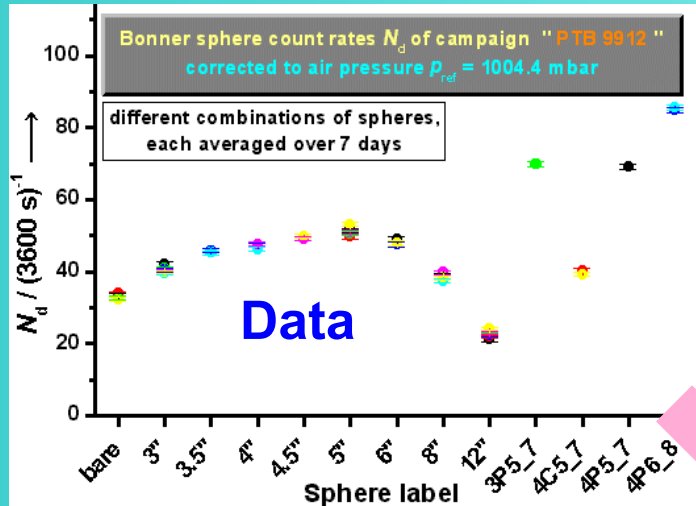
Linear regularization (LR): $\mathbf{p} = (\mathbf{R} + \lambda \mathbf{H})^{-1} \cdot \mathbf{d}$

Maximum Entropy (ME): $p_j^{(m+1)} = p_j^{(m)} \exp\left(\frac{1}{\lambda} \sum_i \frac{R_{ij}}{\sigma_i^2} \left(d_i - \sum_k R_{ik} p_k^{(m)}\right)\right)$

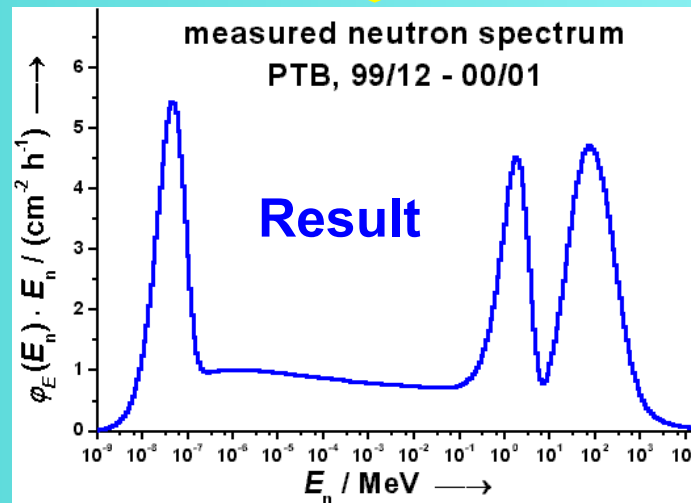
Expectation Maximization (EM): $p_j^{(m+1)} = \frac{1}{\sum_i R_{ij}} \sum_i \frac{R_{ij} p_j^{(m)} d_i}{\sum_k R_{ik} p_k^{(m)}}$

Deconvolution

Bonner spheres measurements



MAXED



The Long Counter

Uni-directional,
flat-efficiency

Moderator+shielding
+BF₃

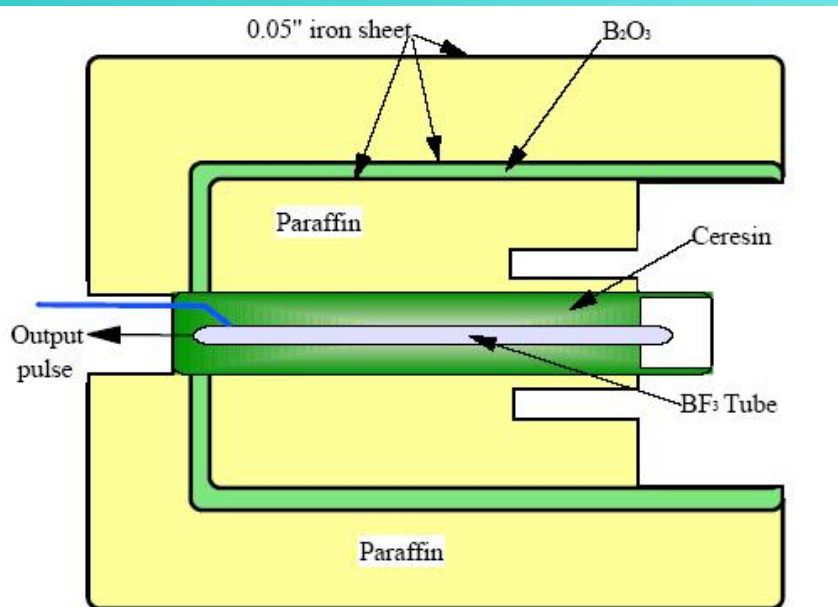
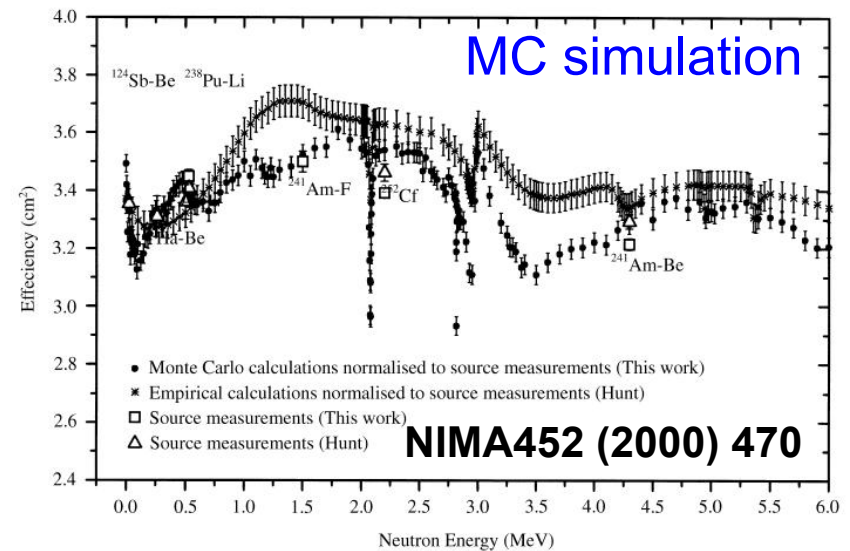
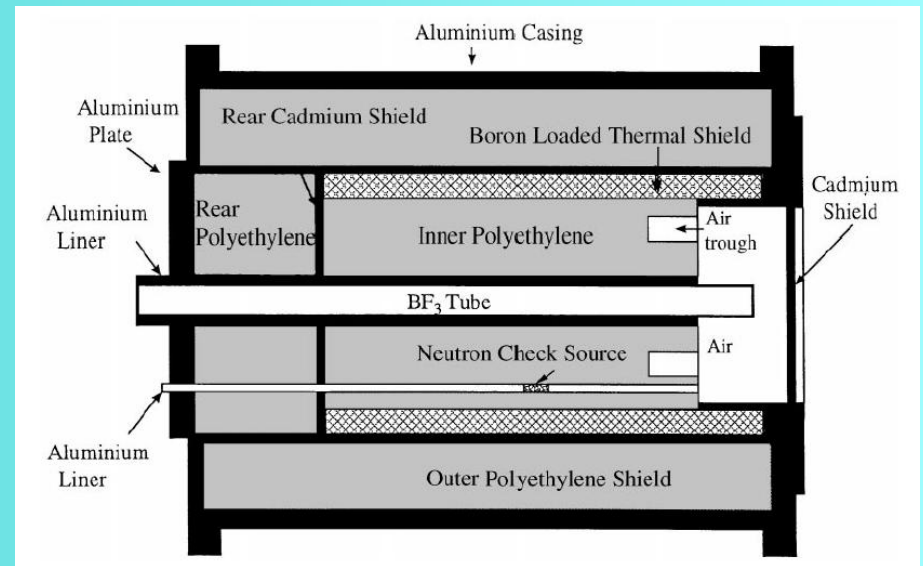


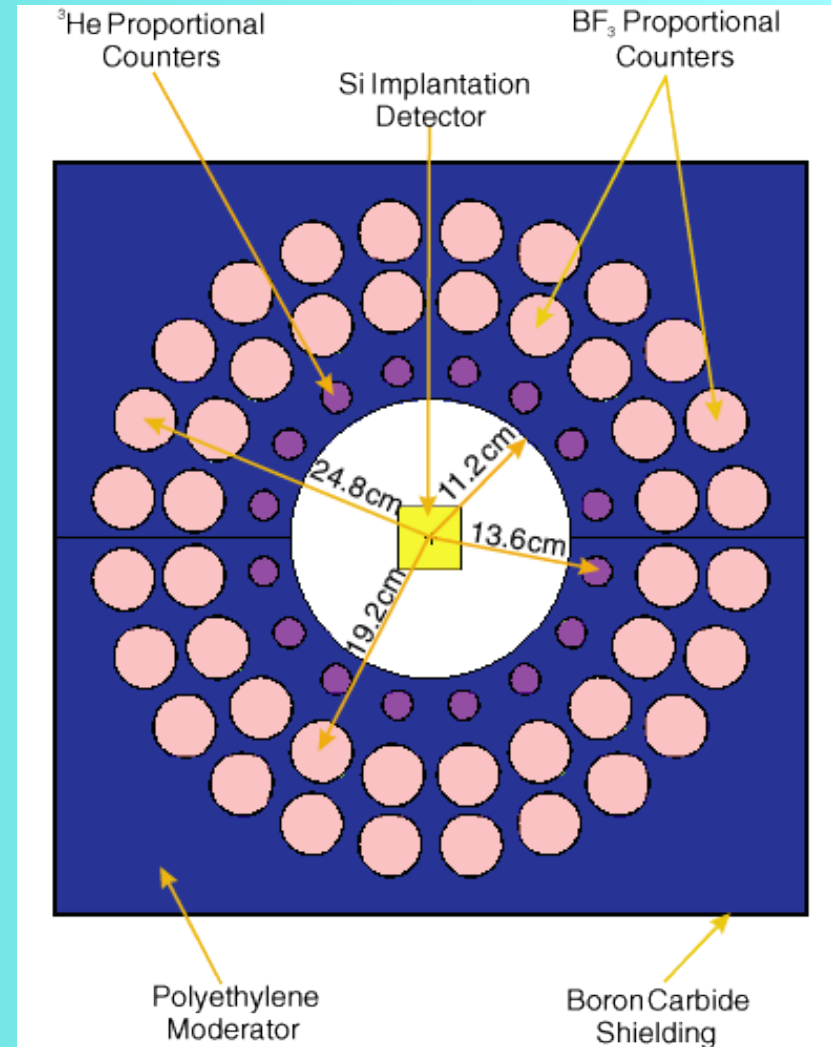
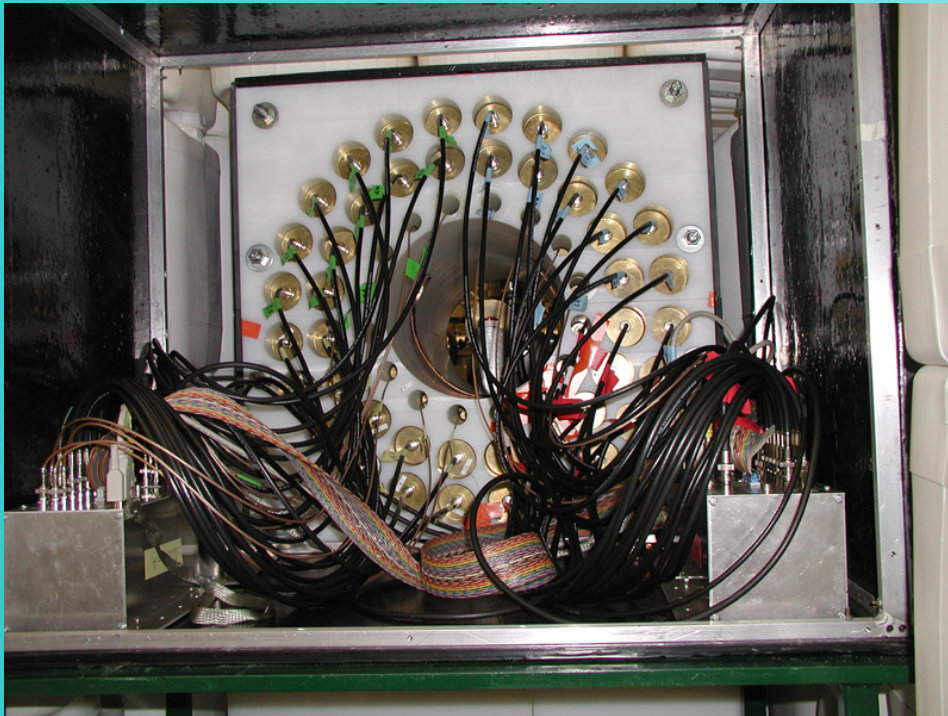
Figure 7-16. Long Counter



Moderated cylindrical array: NERO (NSCL-Michigan)

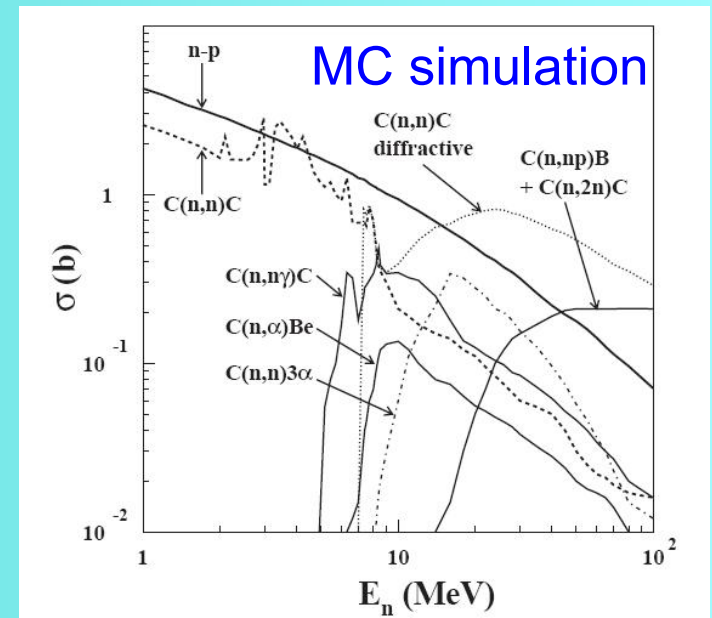
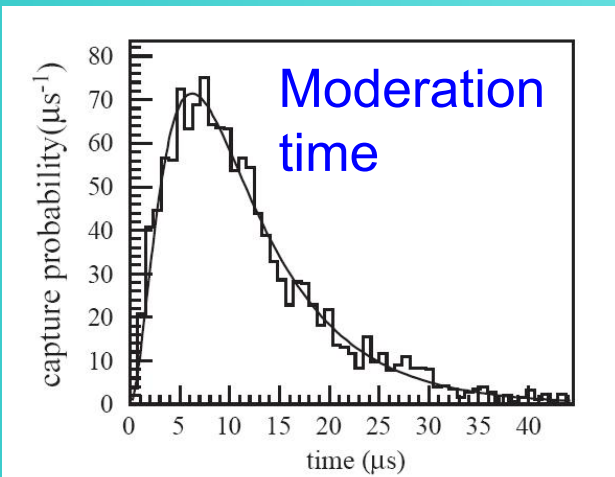
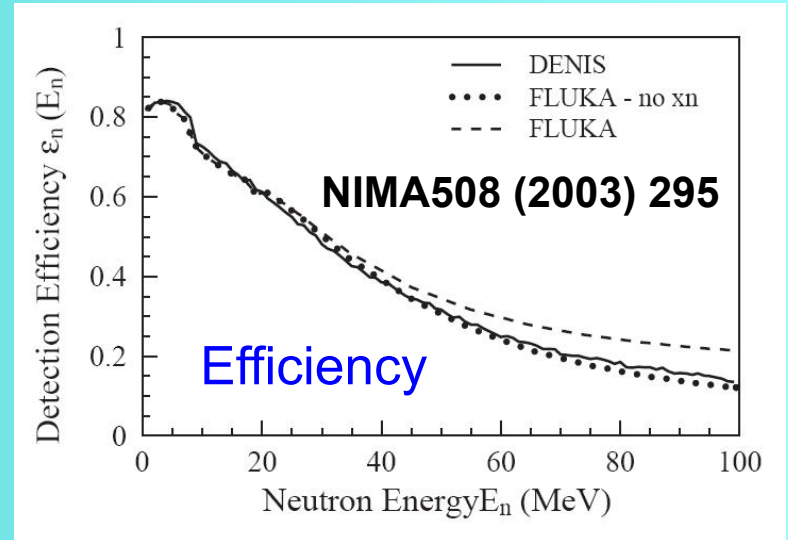
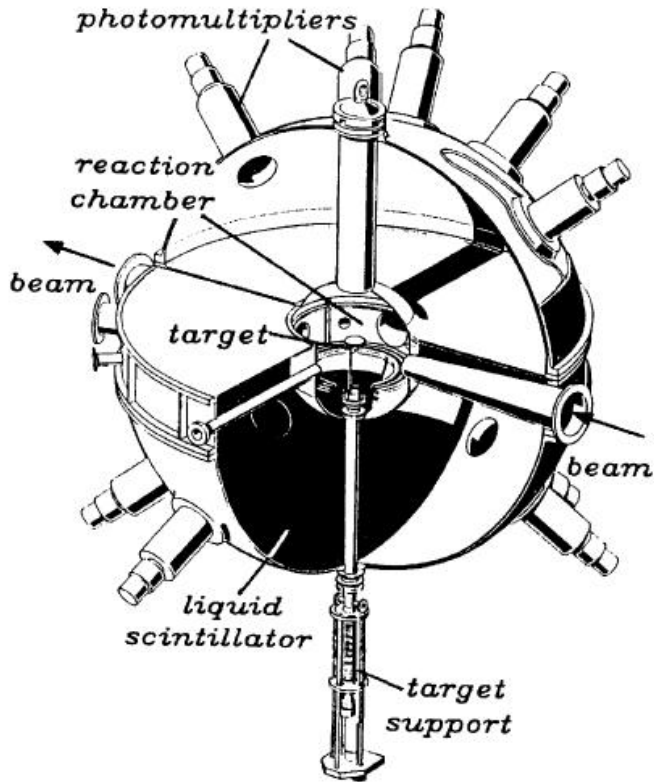
Polyethylene block (60x60x80cm³)
16 ³He and 44 BF₃ proportional
counters

$$\varepsilon = 40 \%$$



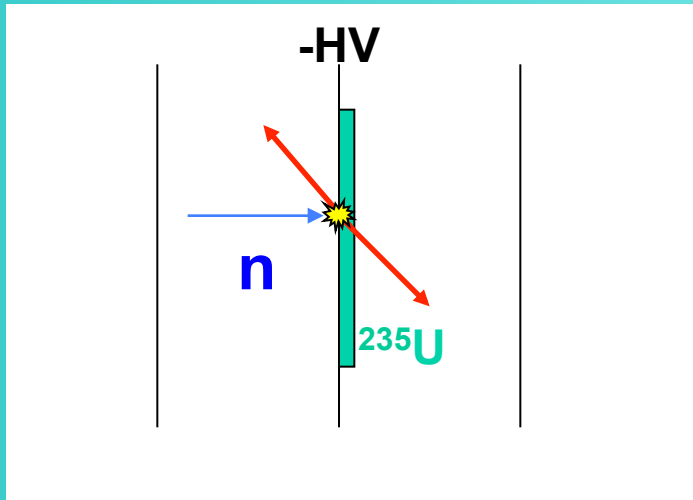
Berlin Neutron Ball

1.5 m³ 0.4% Gd-loaded liquid scintillator



Fission chamber:

U, Pu + gas chamber



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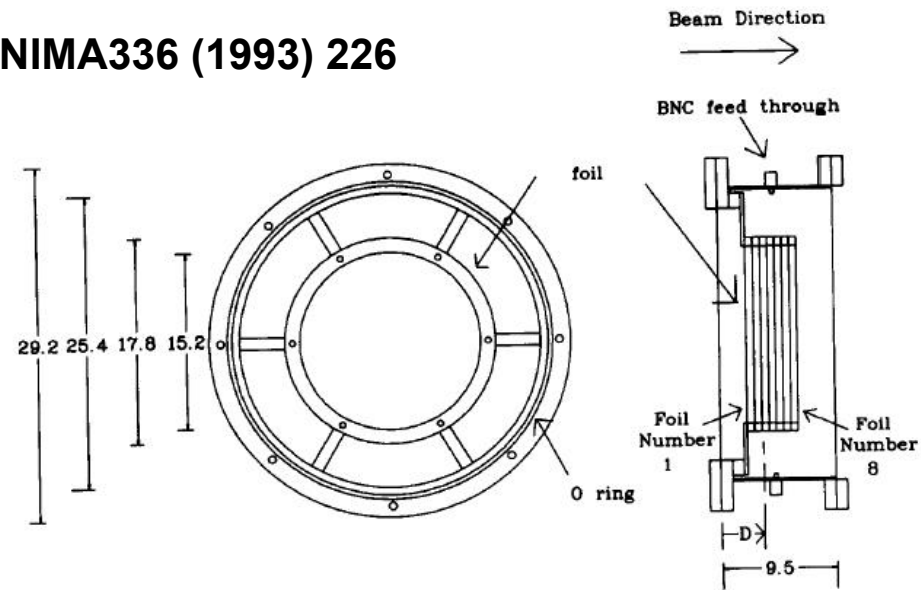


Fig. 1. Schematic diagram of the ionization chamber housing. Dimensions are in centimeters.

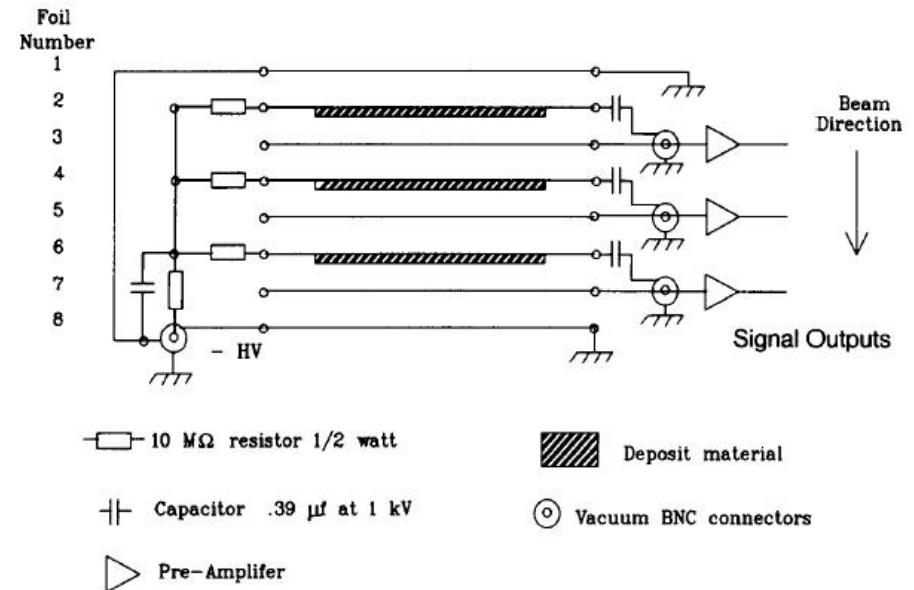
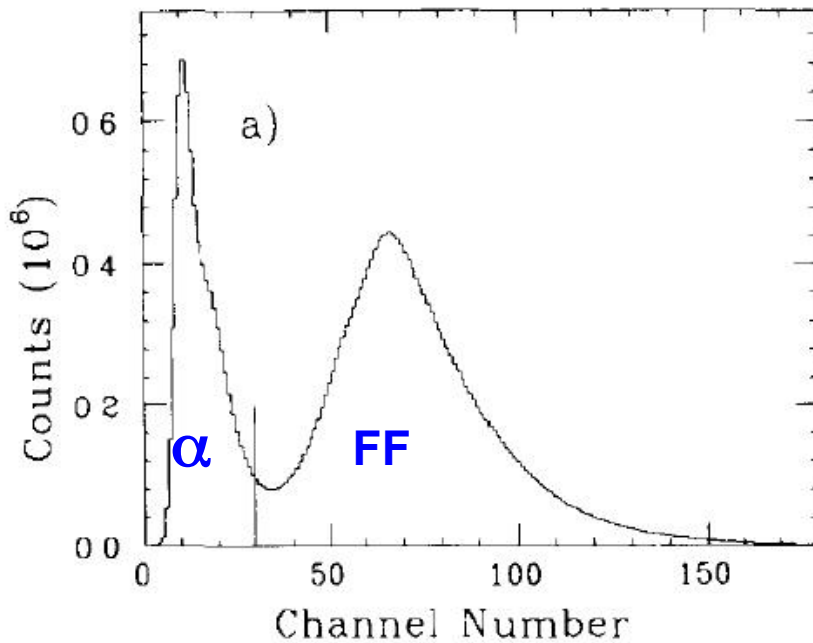


Fig. 2. Electrical wiring diagram of the ionization chamber.