Neutron Detection

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Neutrons

Particle Properties 2004

n

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

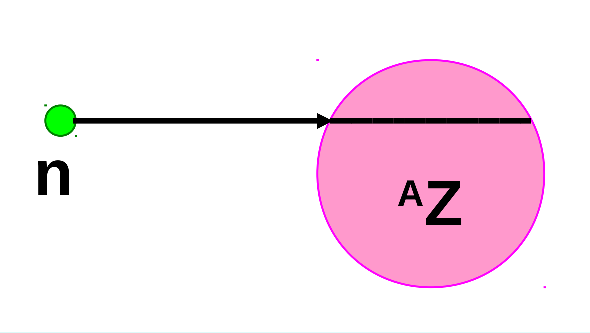
Mass $m = 1.0086649156 \pm 0.0000000006$ u
Mass $m = 939.56536 \pm 0.00008$ MeV [a]
$m_n - m_p = 1.2933317 \pm 0.0000005$ MeV
$= 0.0013884487 \pm 0.0000000006$ u
Mean life $\tau = 885.7 \pm 0.8$ s
$c\tau = 2.655 \times 10^8$ km
Magnetic moment $\mu = -1.9130427 \pm 0.0000005\ \mu_N$
Electric dipole moment $d < 0.63 \times 10^{-25}\ e$ cm, CL = 90%
Mean-square charge radius $\langle r_n^2 \rangle = -0.1161 \pm 0.0022$ fm^2 (S = 1.3)
Electric polarizability $\alpha = (11.6 \pm 1.5) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (3.7 \pm 2.0) \times 10^{-4}$ fm^3
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)

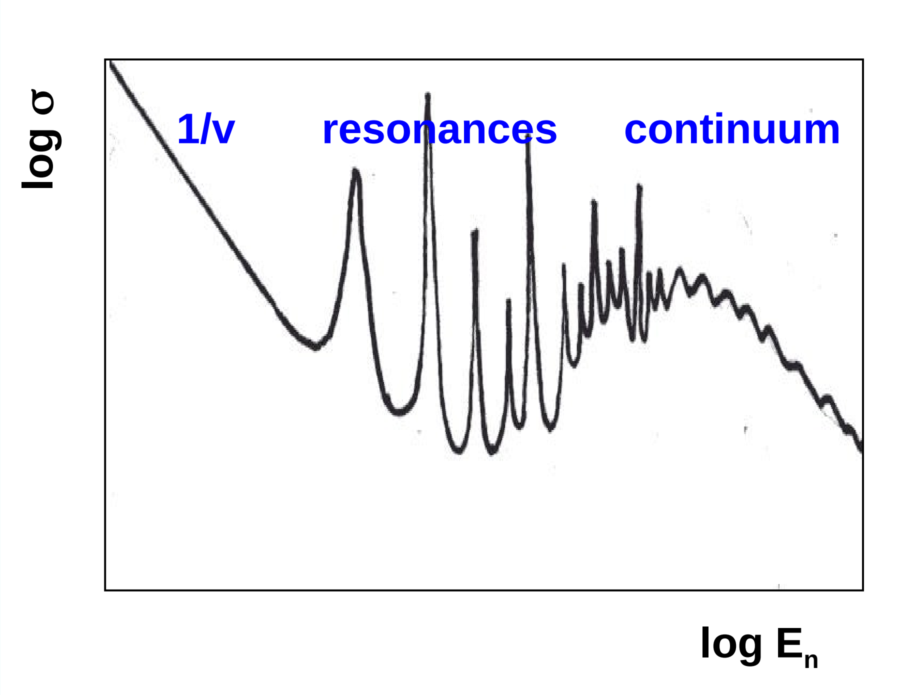
- **Proposed: E. Rutherford, 1920**
- **Discovery: J. Chadwick, 1932**
- **Neutron reactions: E. Fermi and others, 1934-1935**
- **Compound nucleus model: N. Bohr, G. Breit-E. Wigner,1936**
- **Neutrons in astrophysics: G. Gamow, 1937**
- **Neutron induced fission: O. Hahn, F. Strassmann, L. Meitner,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

Nuclear neutron reactions

- **Reaction channels:**
  - **elastic scattering: (n,n)**
  - **inelastic scattering: (n,n'γ)**
  - **radiative capture: (n,γ)**
  - **multiplication: (n,xnγ)**
  - **charged particle production: (n,pγ), (n,$\alpha\gamma$), …**
  - **fission: (n,xn^{A1}Z1^{A2}Z2)**
  - **…**

$$\sigma_{tot} = \sigma_{el} + \sigma_{cap} + \ldots$$





- **No Coulomb barrier**
- **Reaction thresholds**
- **Energy dependence**
- **No predictive models**

Common reactions used for neutron detection at low energies:

Elastic scattering:

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

Charged particle:

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

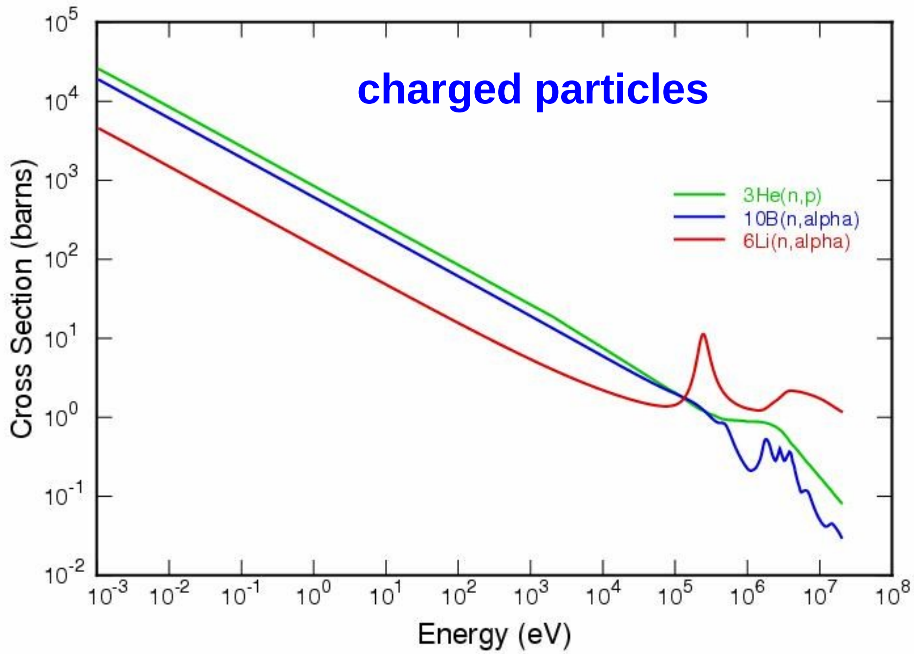
Radiative capture:

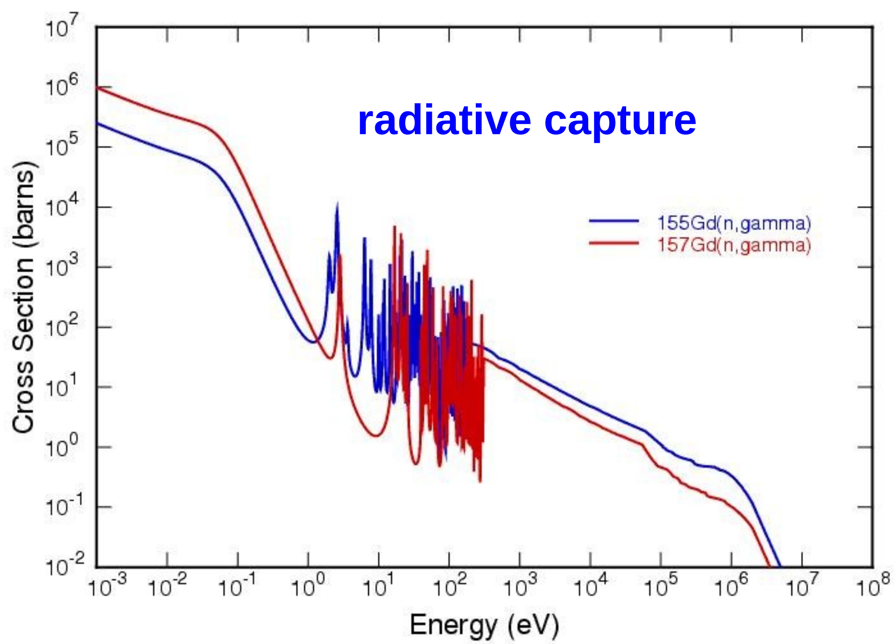
- $n + {}^{155}Gd \rightarrow {}^{156}Gd^{*} \rightarrow \gamma$-ray + CE spectrum (abund.=14.8%)
- $n + {}^{157}Gd \rightarrow {}^{158}Gd^{*} \rightarrow \gamma$-ray + CE spectrum (abund.=15.7%)

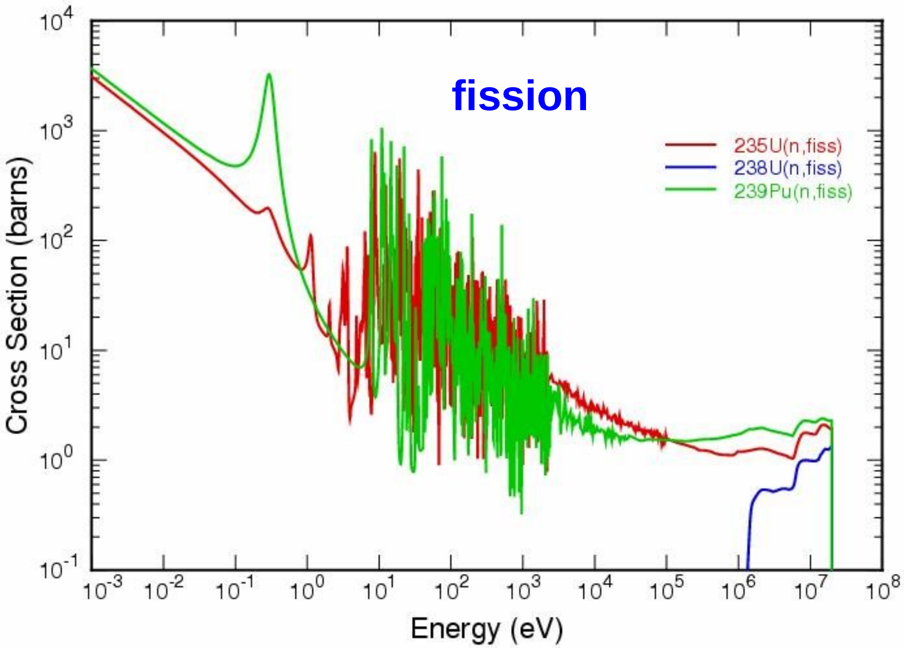
Fission:

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

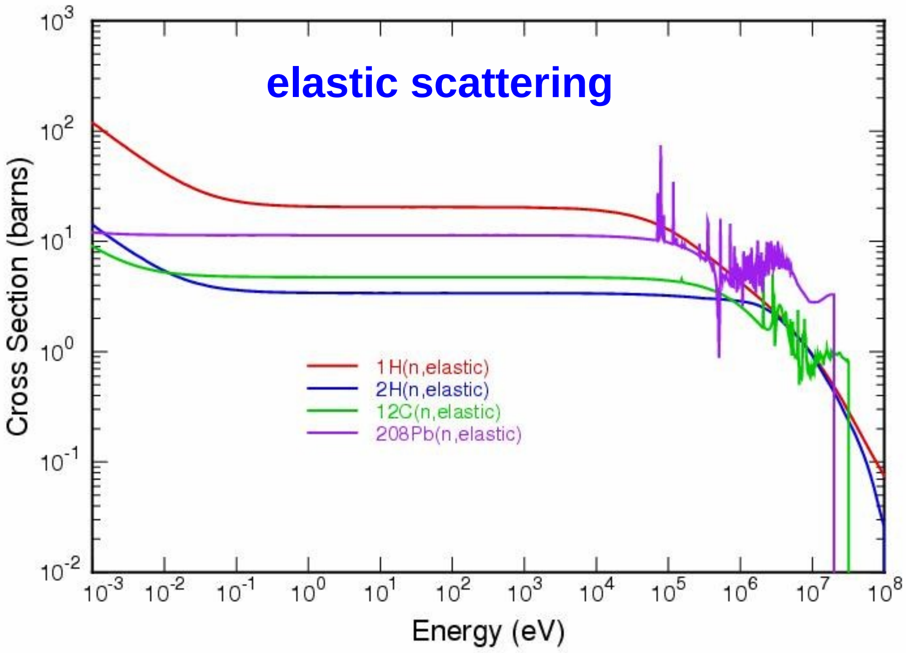
Cross section energy dependence of useful reactions

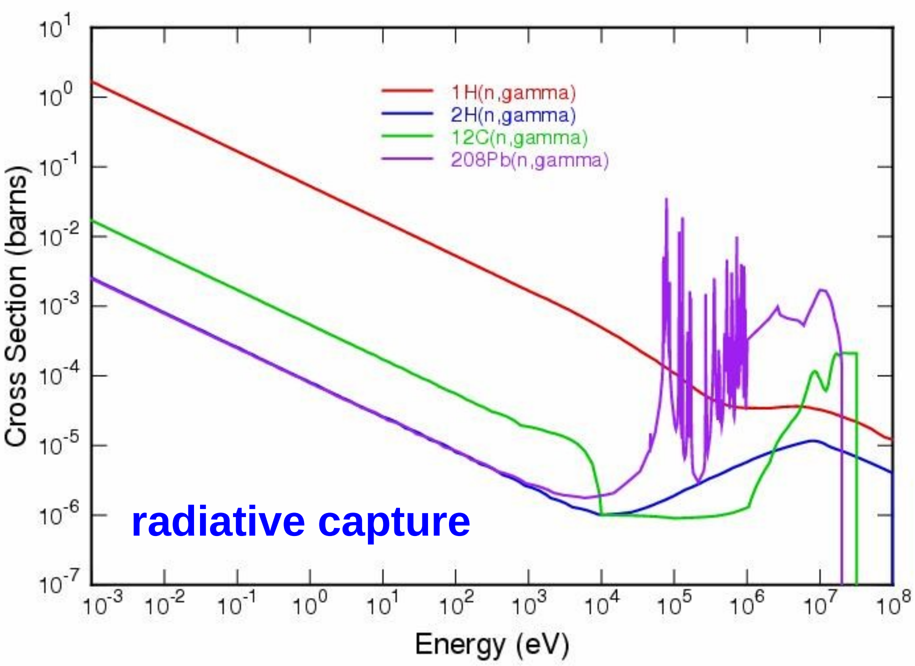


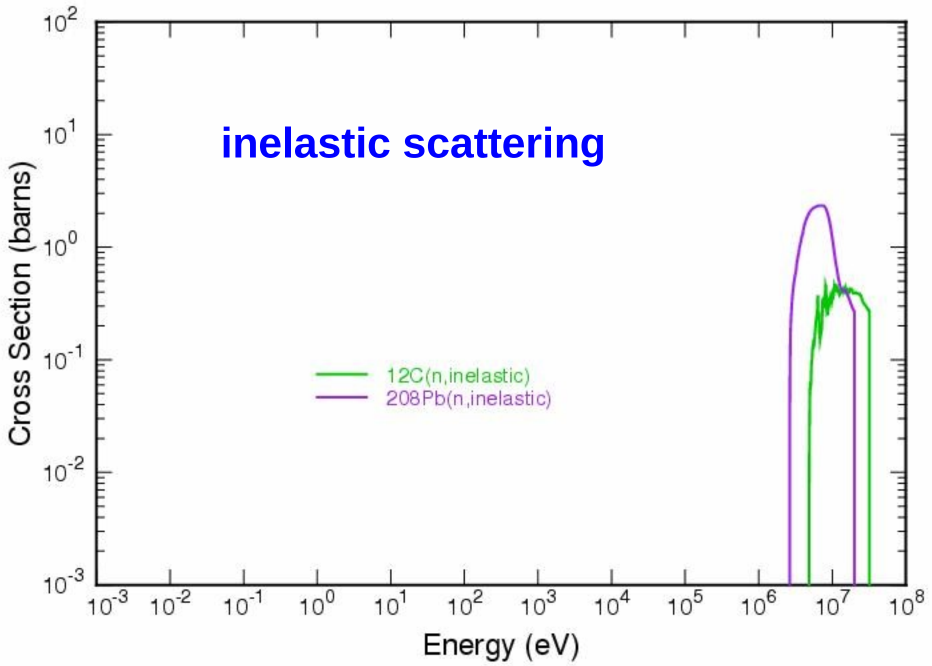




Cross section energy dependence of moderators







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: Li_2O + SiO_2 +…
- Li crystal scintillator: LiI(Eu), LiF
- Li + ZnS(Ag) scintillator
- Li + thermo-luminiscent material
- Gd crystal scintillators: Gd_2O_2S(Pr),…
- BAs semiconductor

Gas-filled chamber

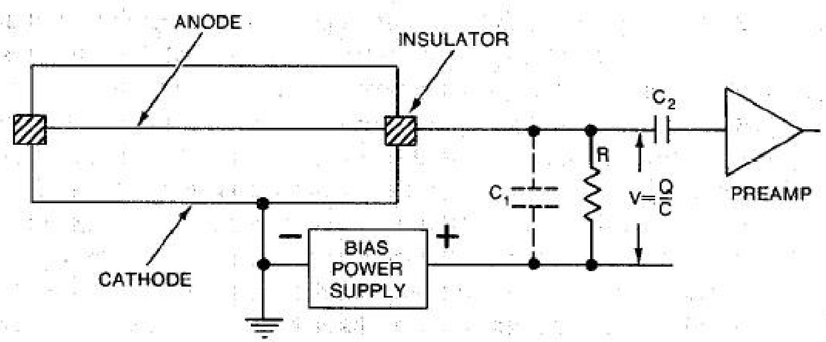


Fig. 13.1 *Typical setup for gas-filled neutron detectors.*

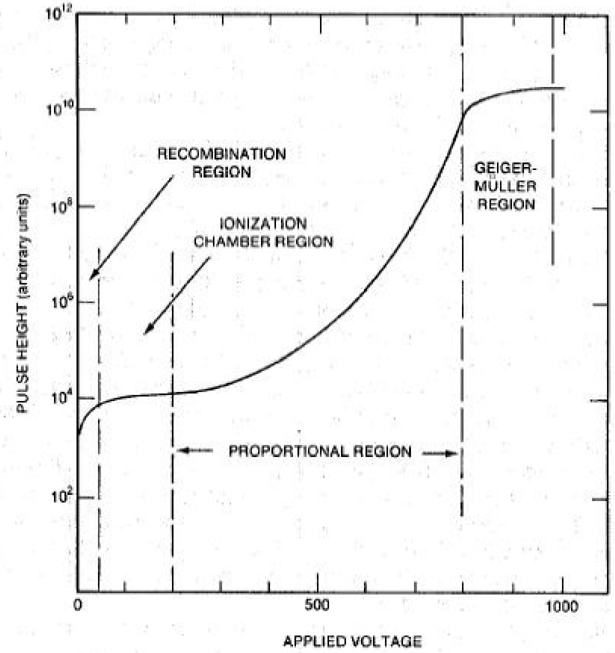


Fig. 13.3 *Pulse-height vs applied-voltage curves to illustrate ionization, proportional, and Geiger-Mueller regions of operation.*

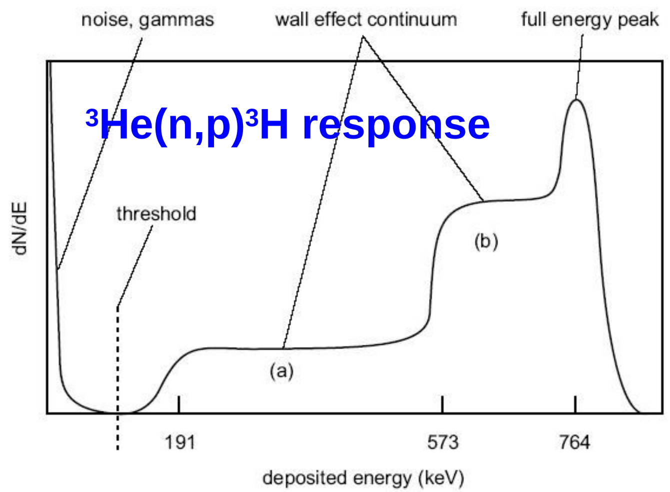


Figure 1: Expected pulse height spectrum from a ^3He tube. The two steps in the spectrum are caused by one of the reaction products hitting the detector wall. In area (a), the triton energy is fully deposited, but the proton only deposited a fraction of its energy, and vise versa in area (b).

Gases:

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

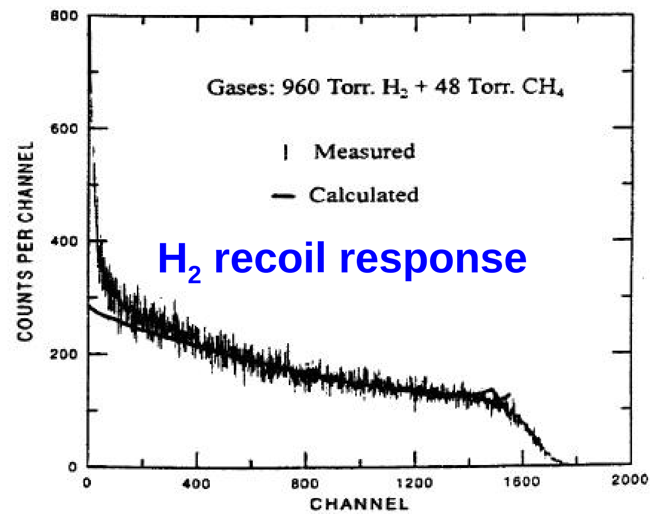
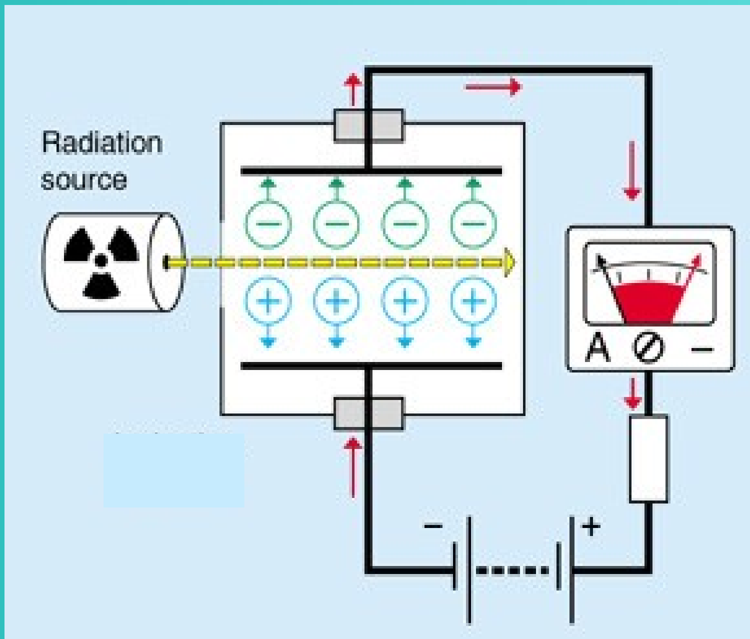
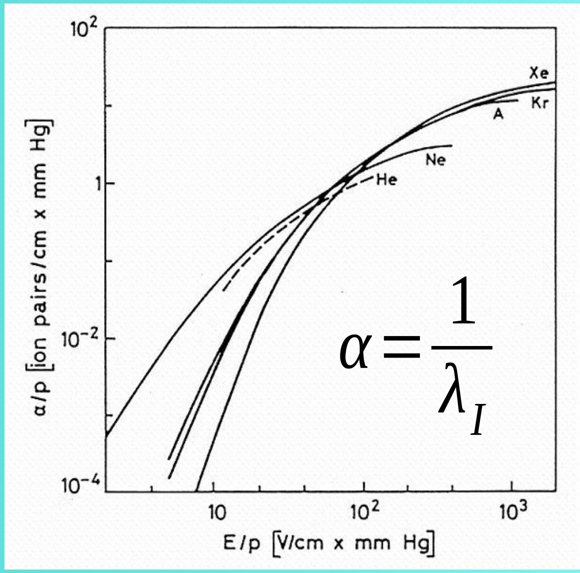


Fig. 1. Measured and calculated pulse height distributions for 0.565 MeV neutrons incident on a cylindrical proportional counter (active volume 38 mm diameter × 178 mm). From Ref.

Gaseous ionization detectors



Townsend coefficient

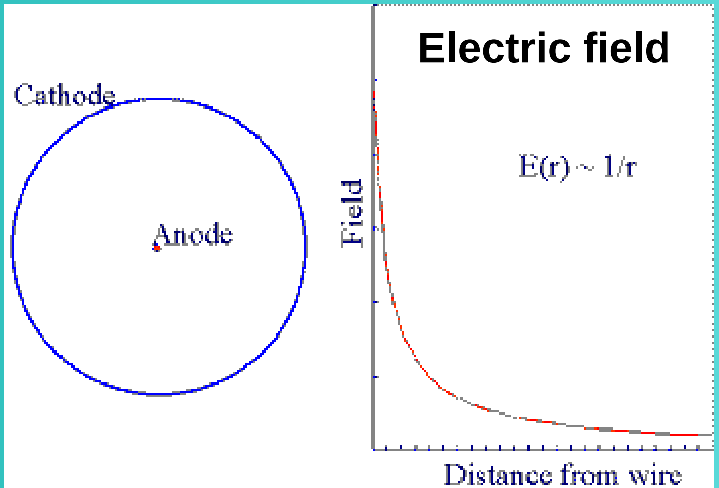


$$\alpha = \frac{1}{\lambda_I}$$

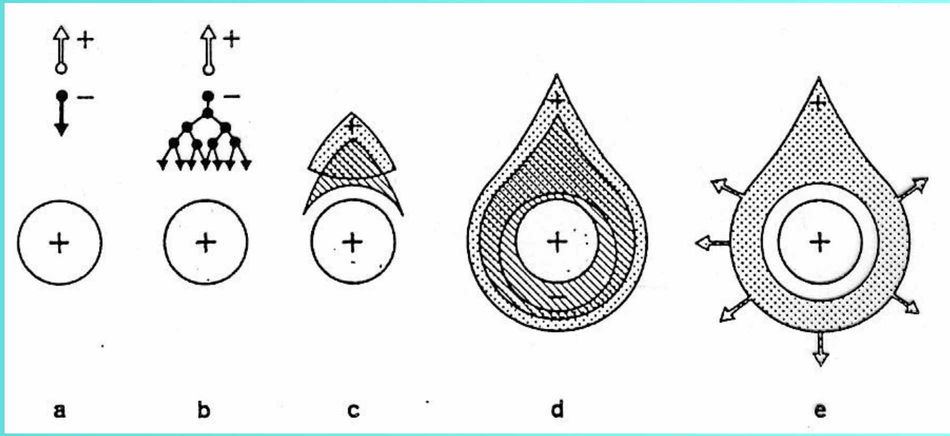
Multiplication

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

Cylindrical configuration

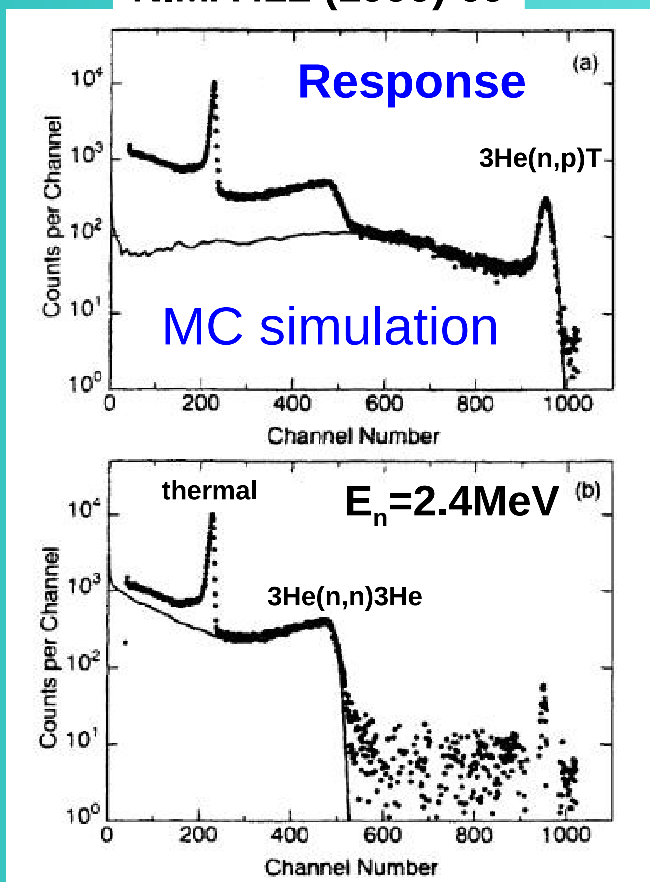


Electron drift and avalanche formation



^{3}He chambers

NIMA422 (1999) 69



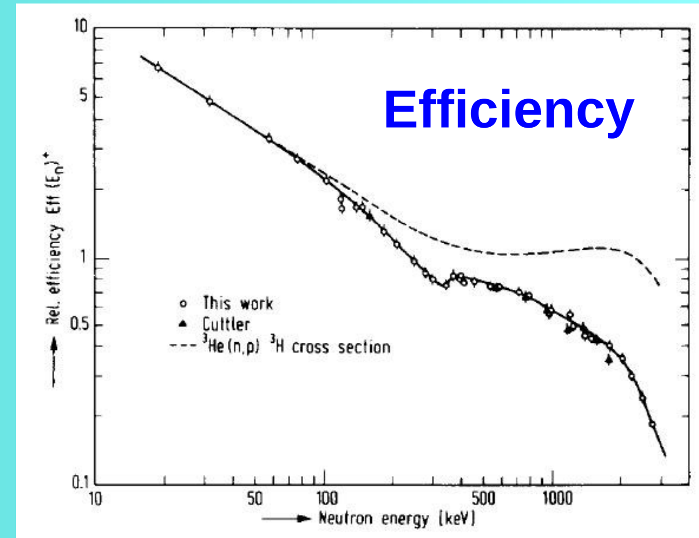


Fig. 7. Relative efficiency of the ^{3}He fast neutron spectrometer, normalized to previous measurements[15], along with the $^3He(n,p)^3H$ cross section

NIM144 (1977) 253

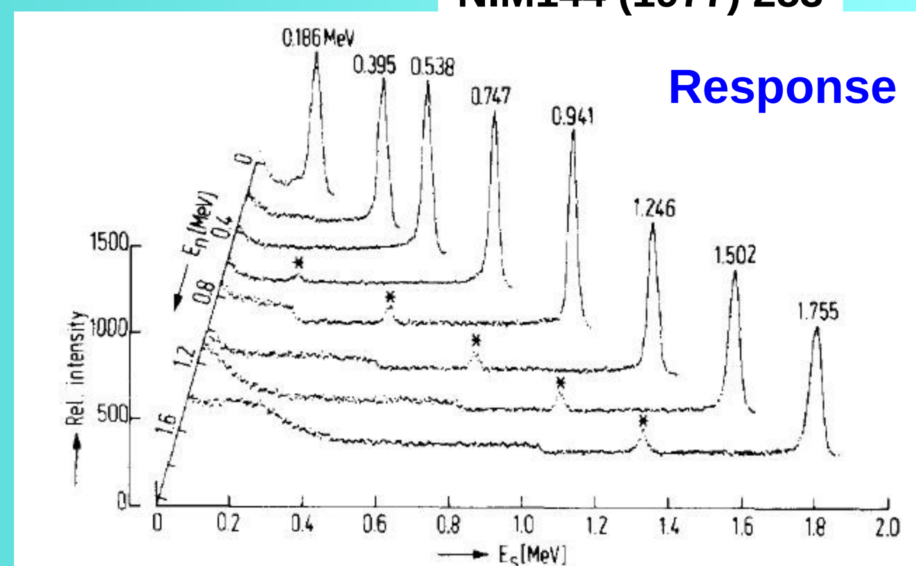
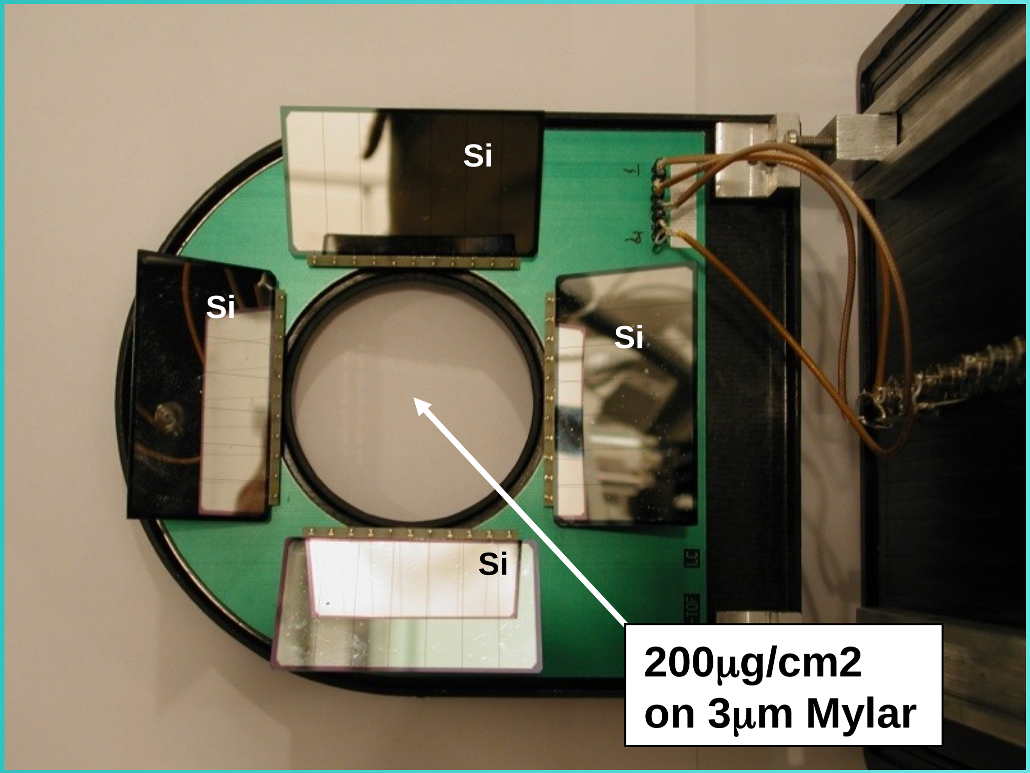
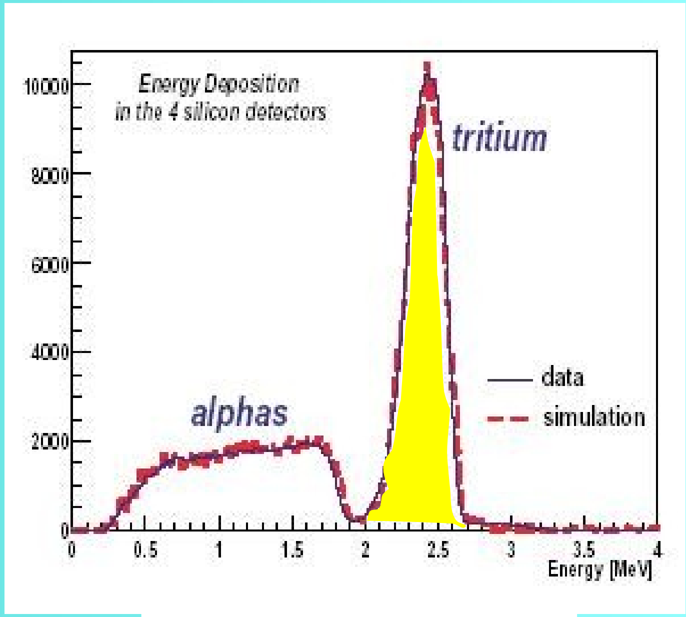


Fig. 2. Response of the ^{3}He ionization chamber to monoenergetic neutrons produced by the $^7Li(p,n)^7Be$ reaction. E_n is the

Foil with deposit + Si-detector

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

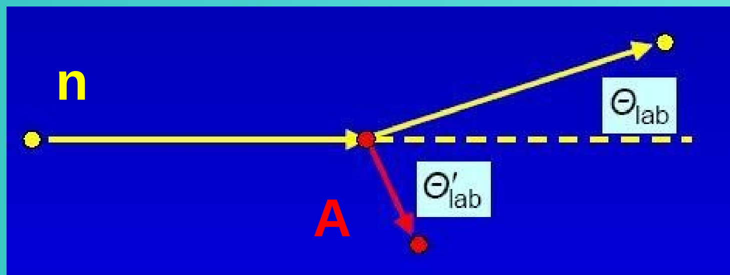




NIMA517 (2004) 389

Neutron scattering

s-wave (l=0) elastic scattering:



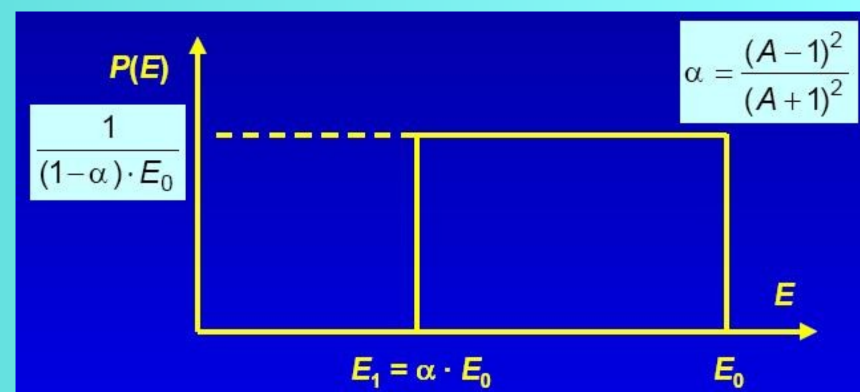
Energy-momentum conservation:

$$\frac{E}{E_0} = \frac{\left[A^2 + 1 + 2A \cdot \cos\Theta_{CMS}\right]}{(A+1)^2}$$

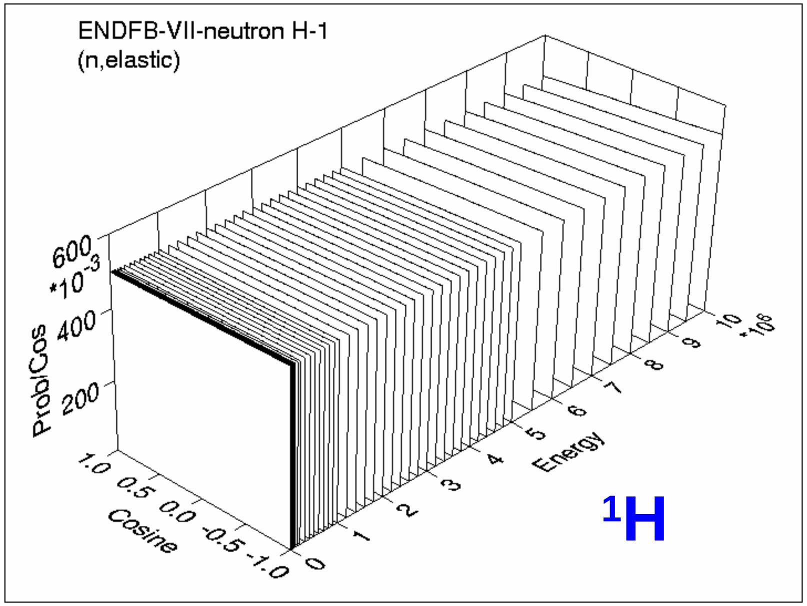
There is a minimum neutron energy (maximum recoil energy) after the collision dependent on A:

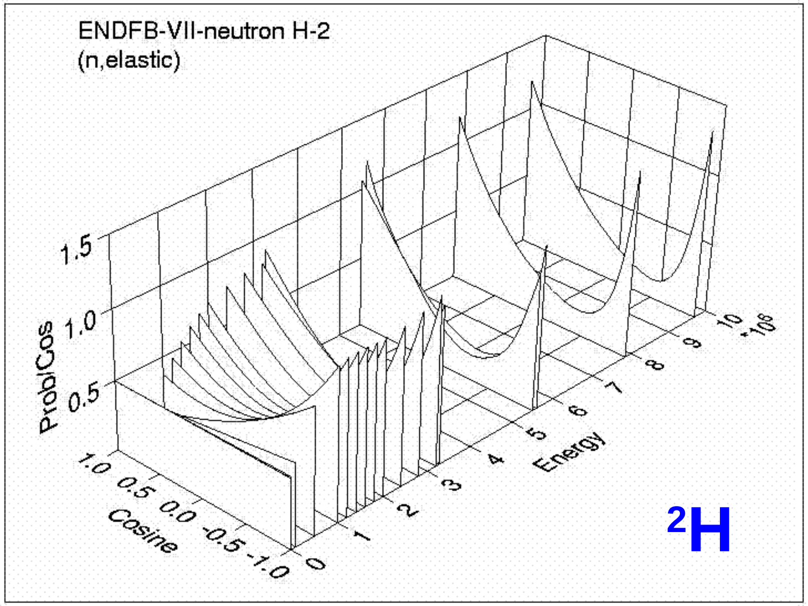
$$\left[\frac{E}{E_0}\right]_{\text{min}} = \frac{(A-1)^2}{(A+1)^2} = \alpha$$

Isotropic in CMS:

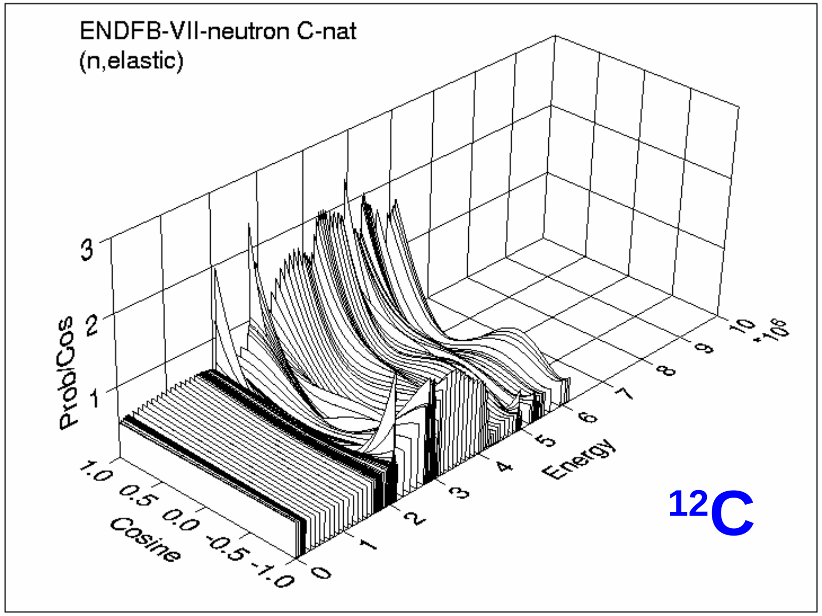


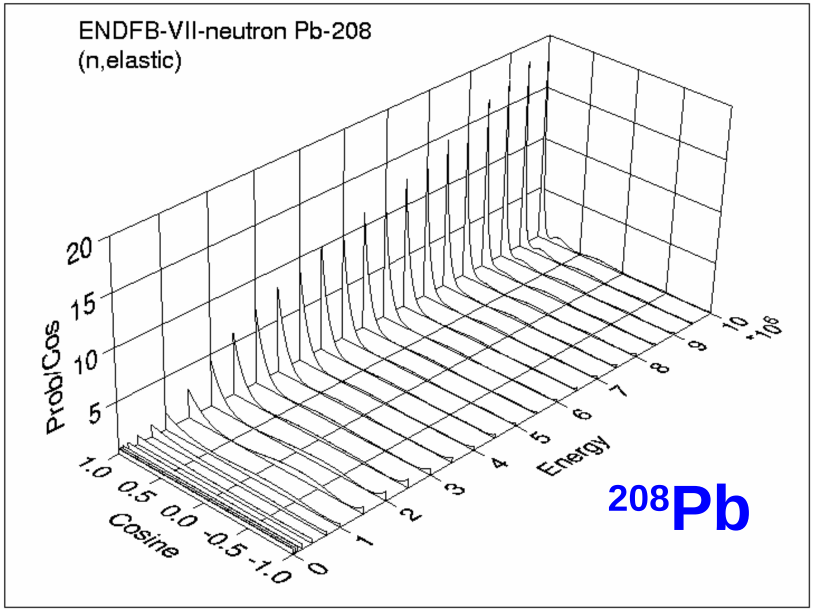
1-α: H (1.0), D(0.89), C(0.28), Fe(0.069), Pb(0.019)





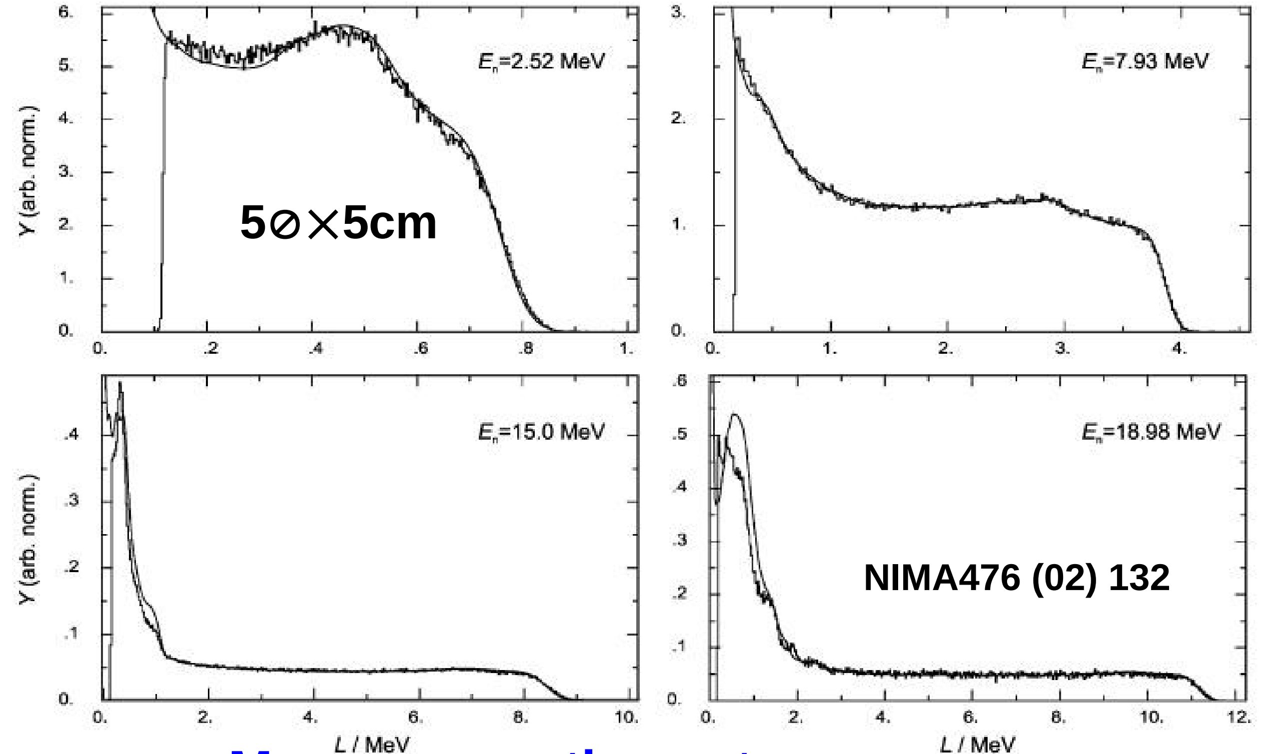
ELASTIC SCATTERING ANGULAR DISTRIBUTION



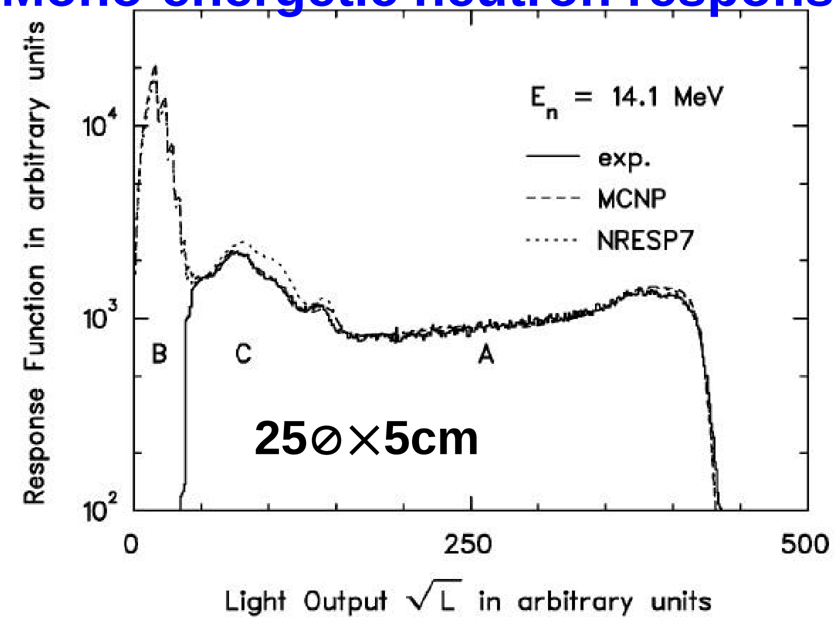


BC501/NE213 liquid scintillators

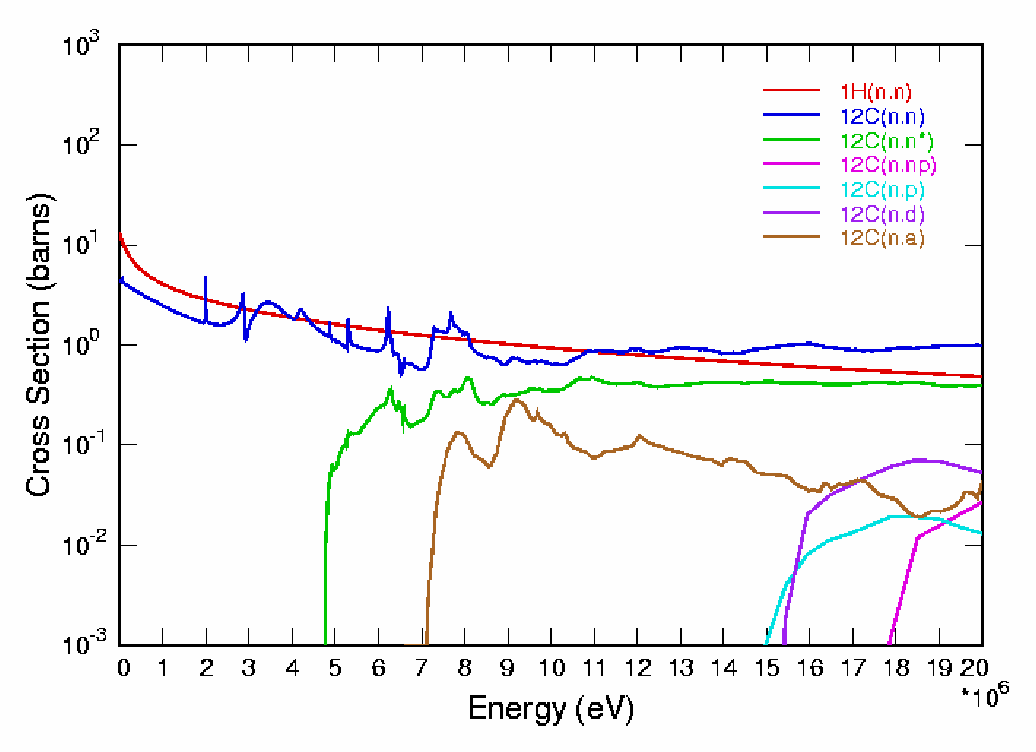
$C_1H_{1.212}$
ρ = 0.874g/cm^3
n (@425nm) = 1.53
τ = 3.2 (32.3, 270) ns



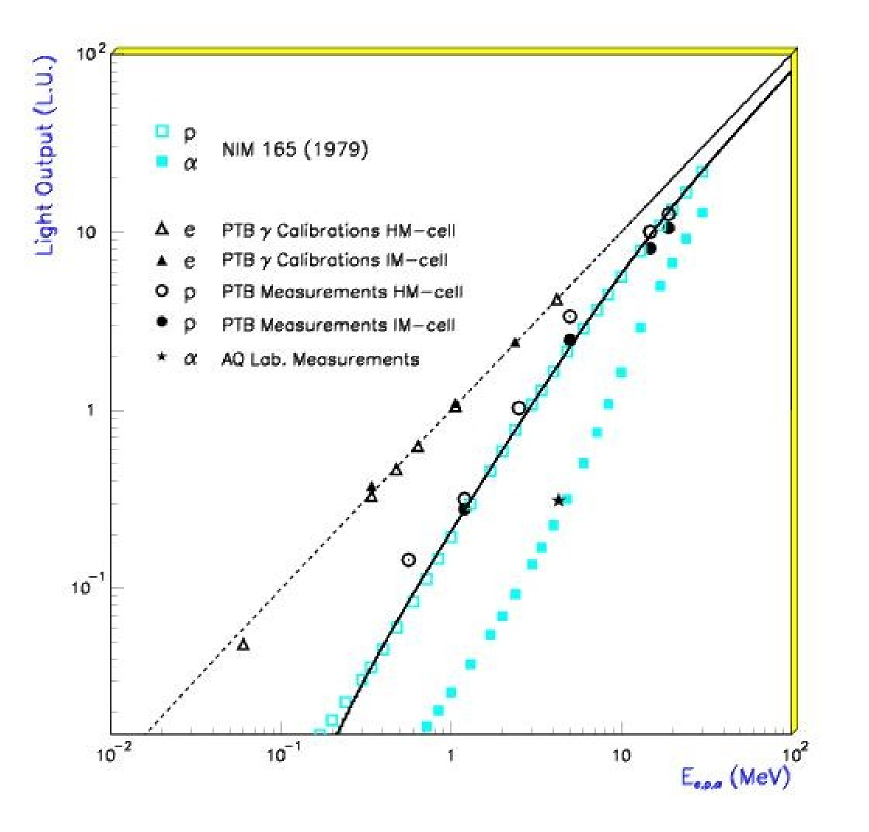
Mono-energetic neutron response



Monte Carlo simulations of neutron interactions and detectors

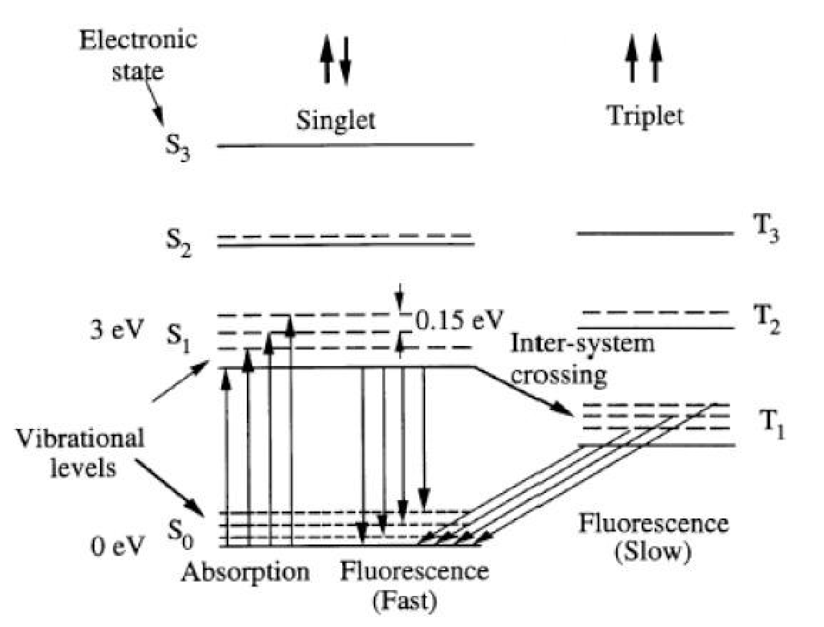


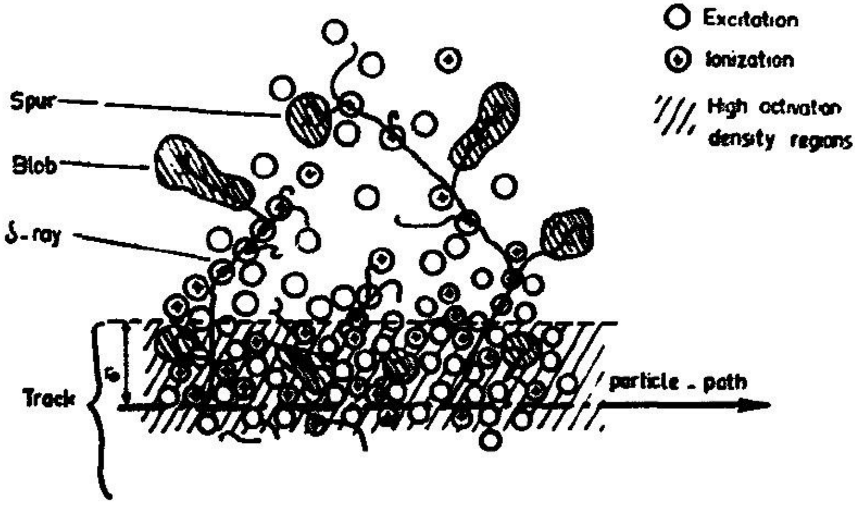
- Birth of modern MC approach
- General purpose codes: MCNP, GEANT, … and specific codes: NRESP, SCINFUL, …



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

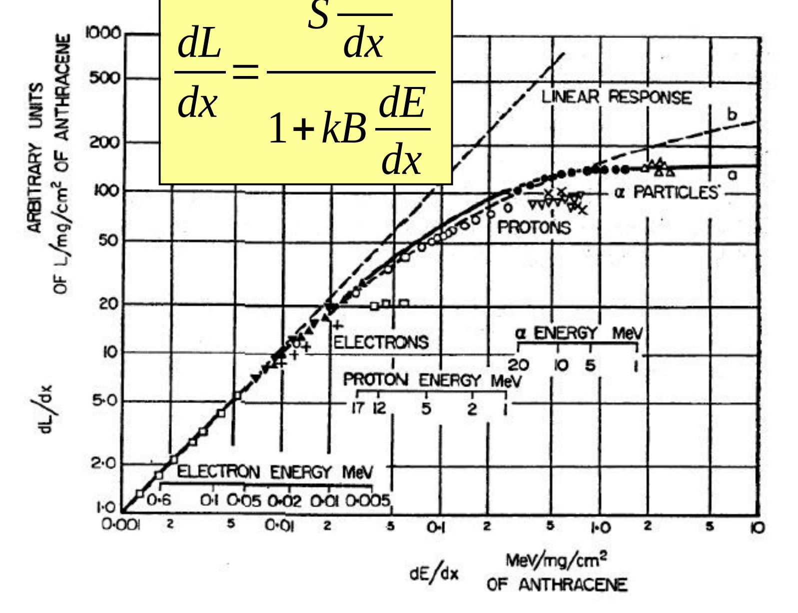
Luminescence in organic materials



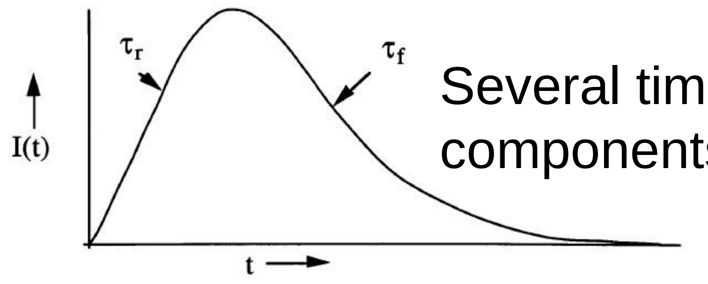


The non-radiative transfer mechanism between excited centers induces an energy-loss dependent light production …

$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$



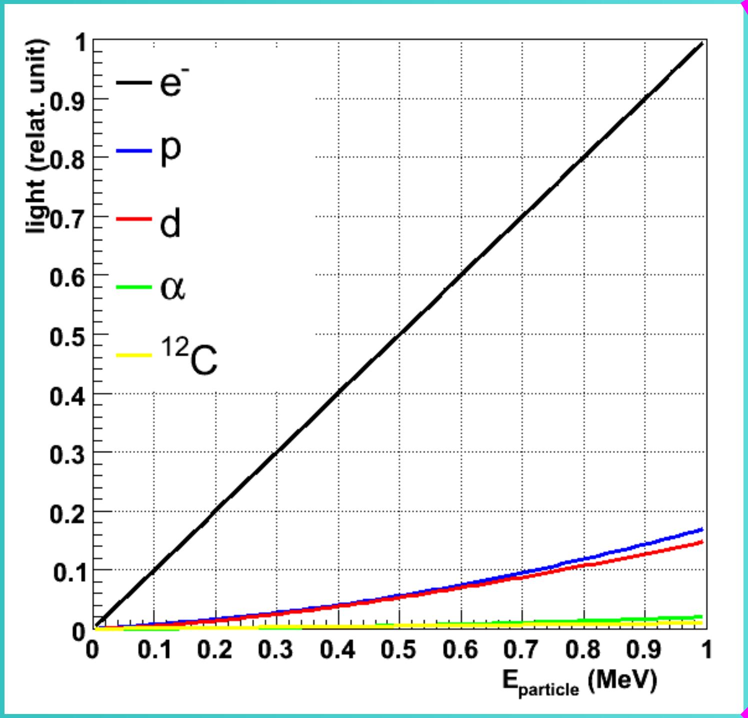
… and a varying time distribution

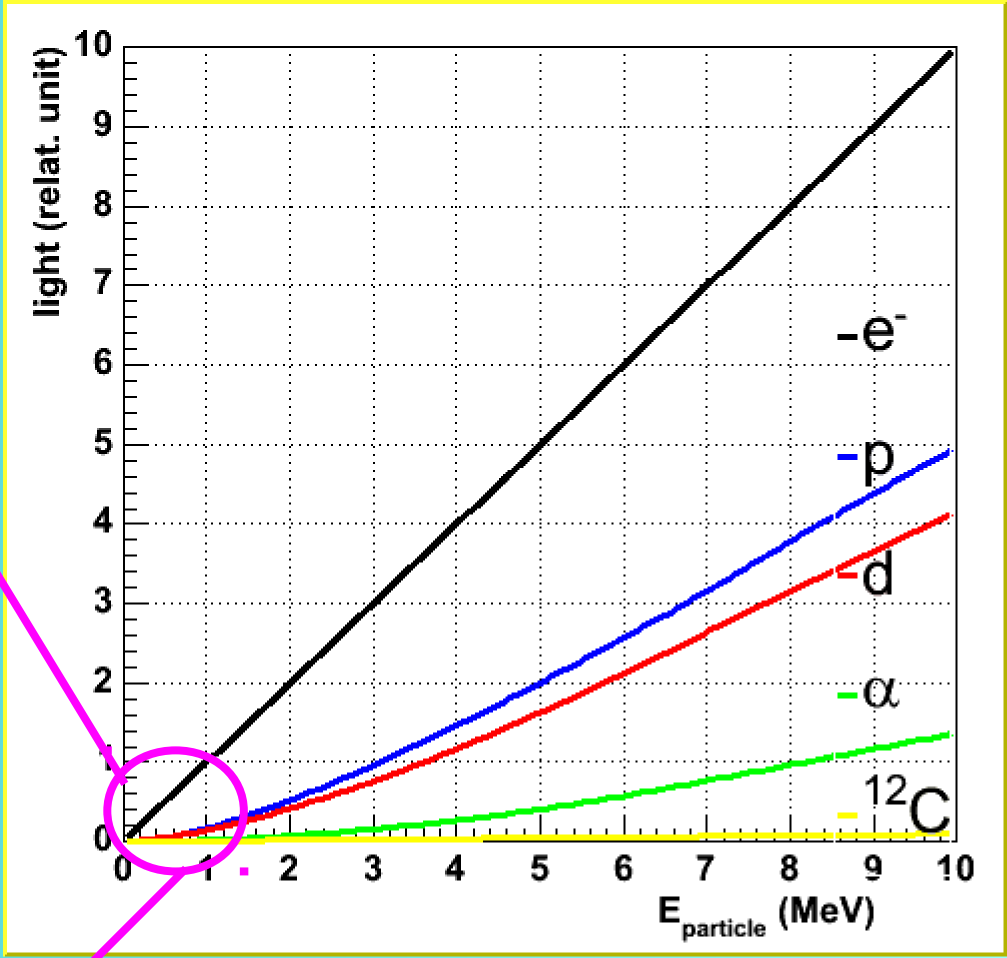


Several time components

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



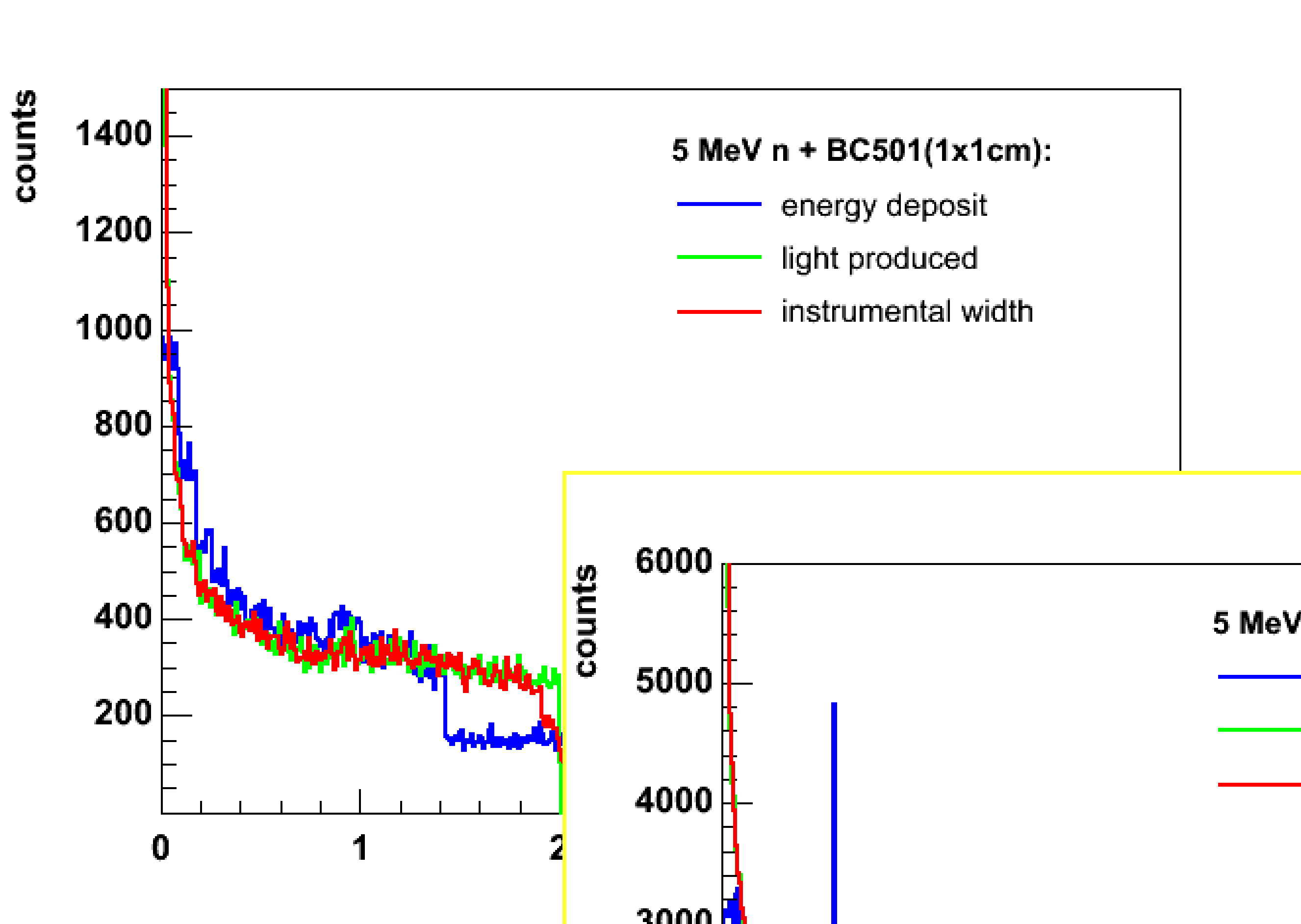


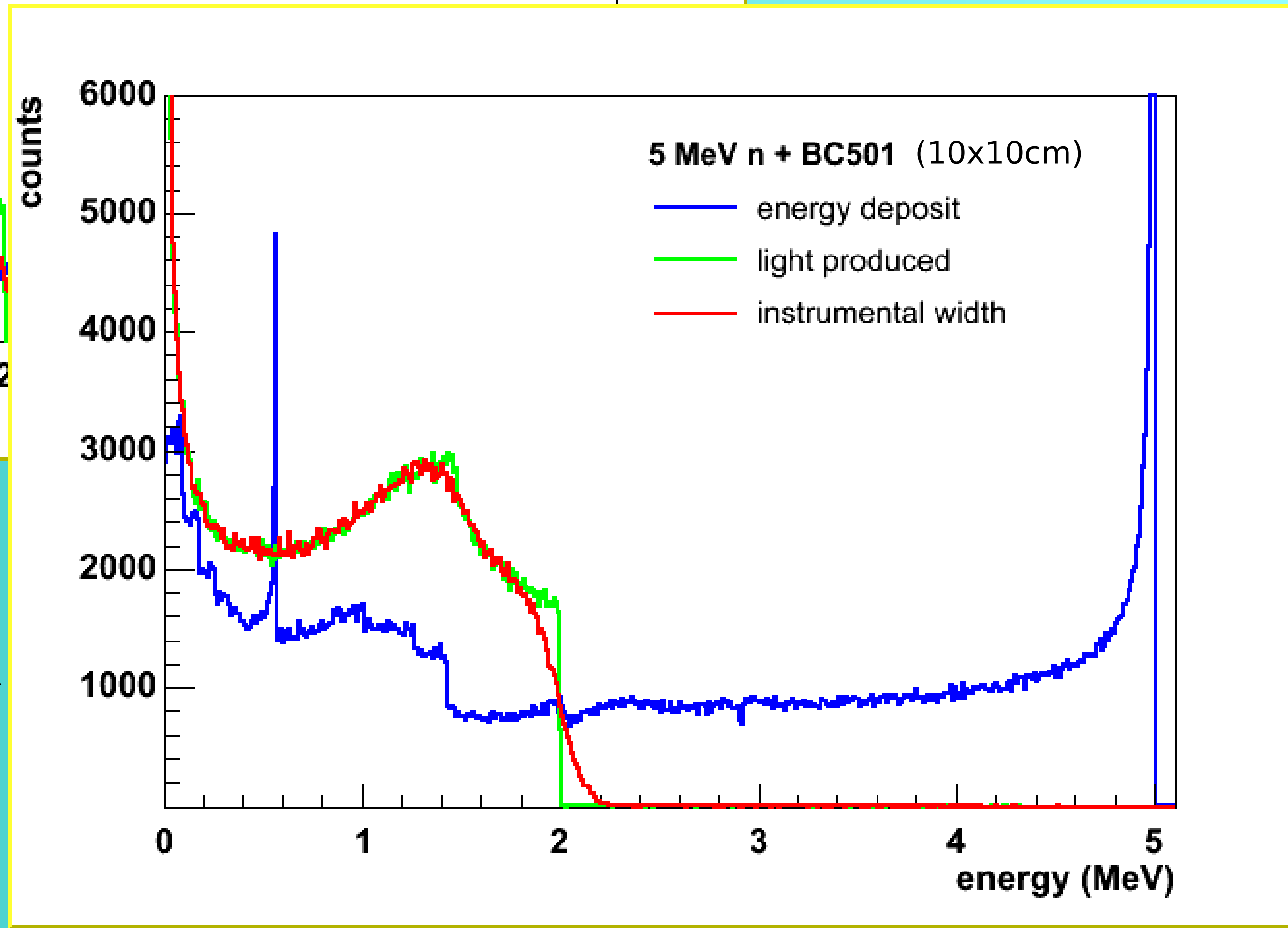
Simulations with GEANT3/GCALOR ➔

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

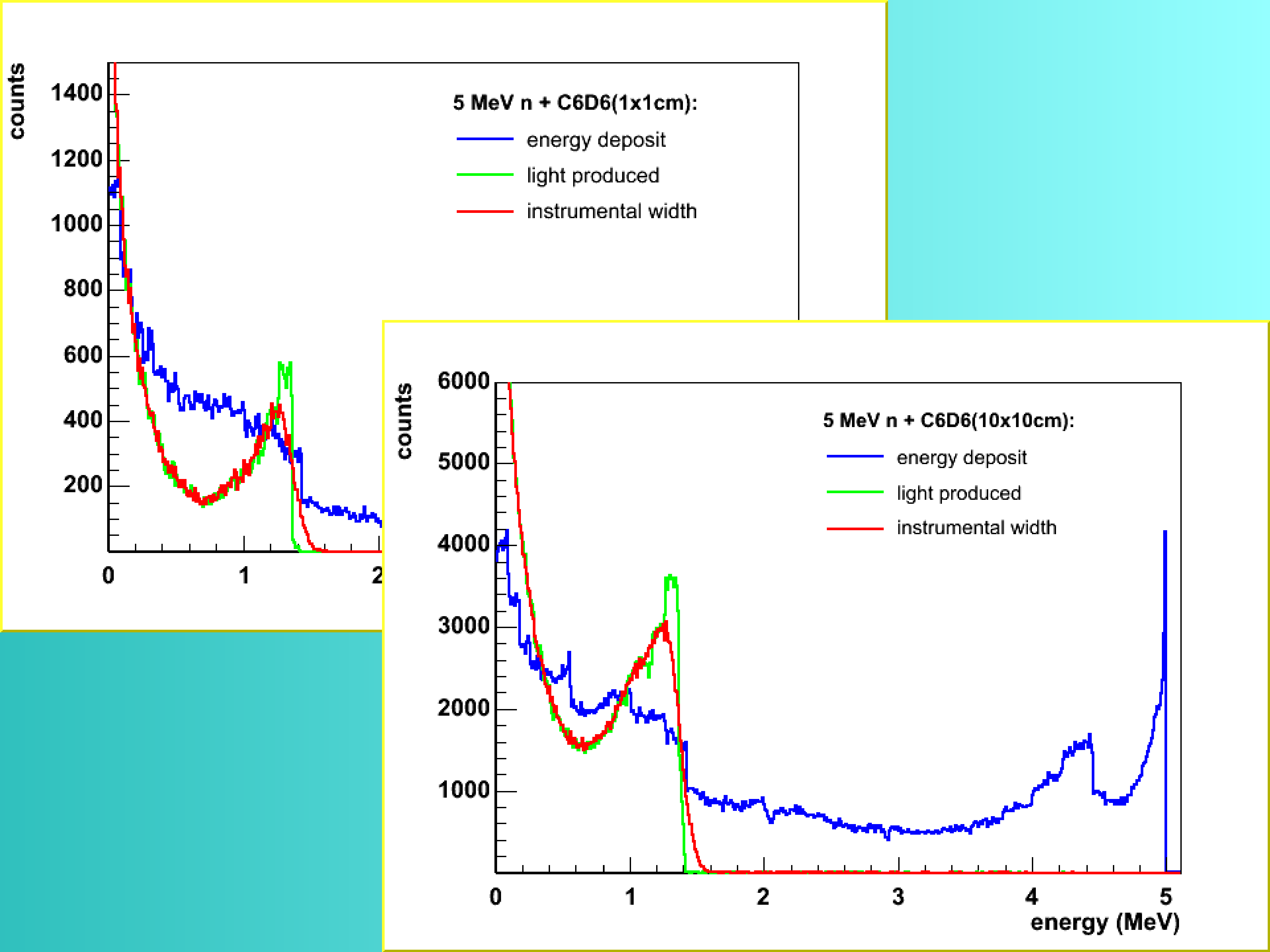
(assumed same α and ^{12}C light curves in BC501 & BC537)

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

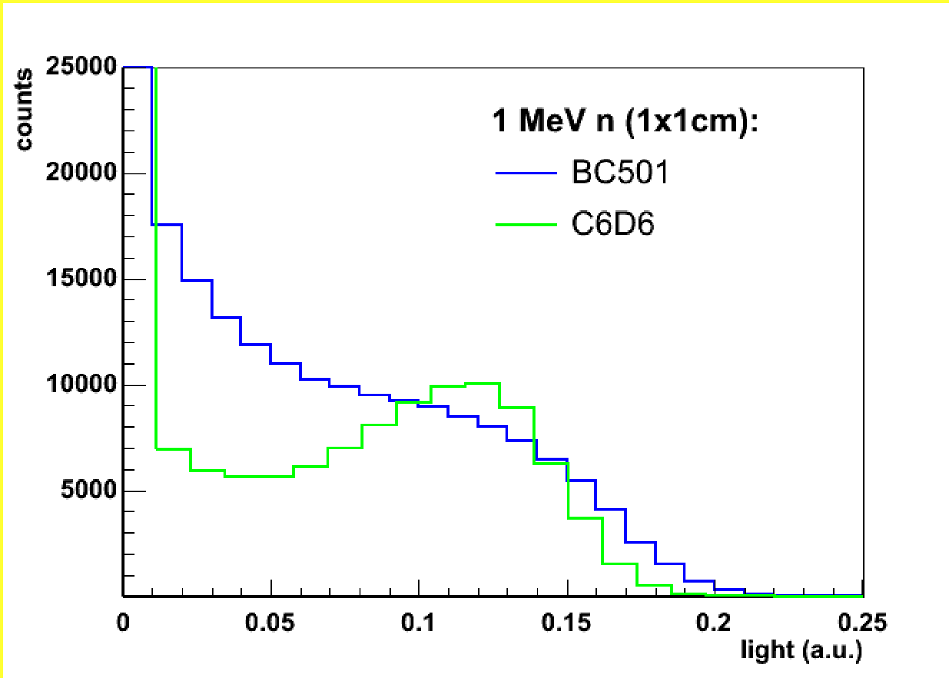


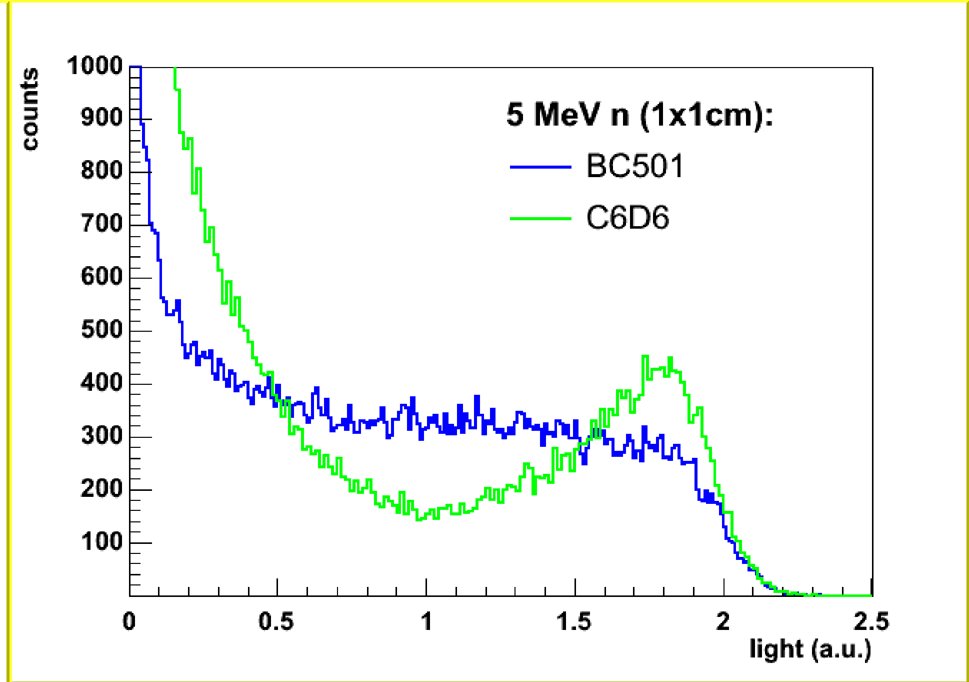


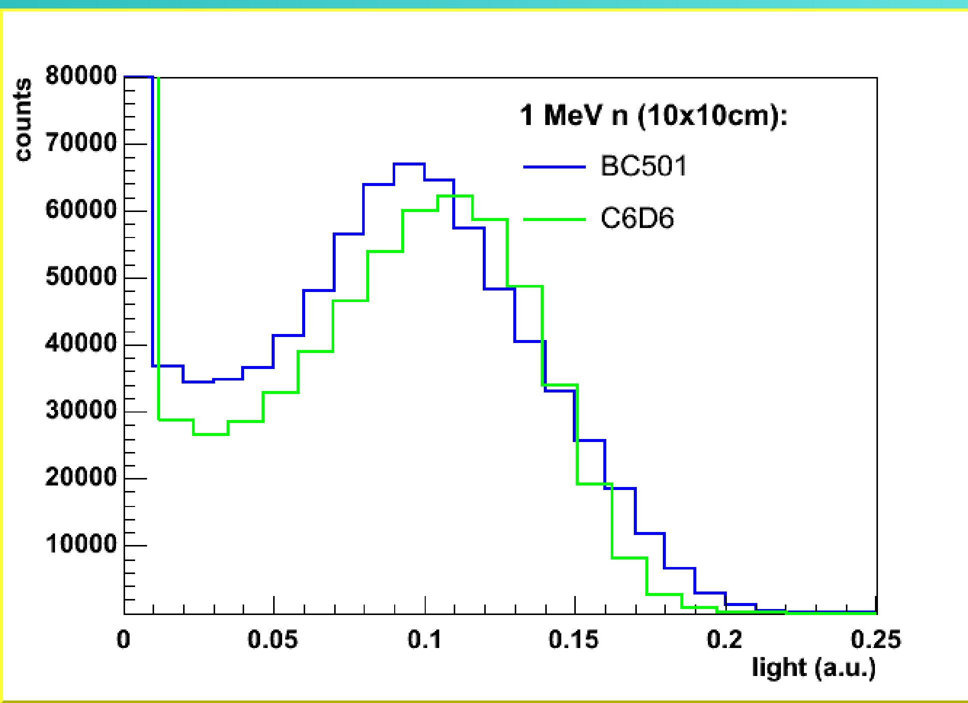
Simulation with GEANT3/GCALOR

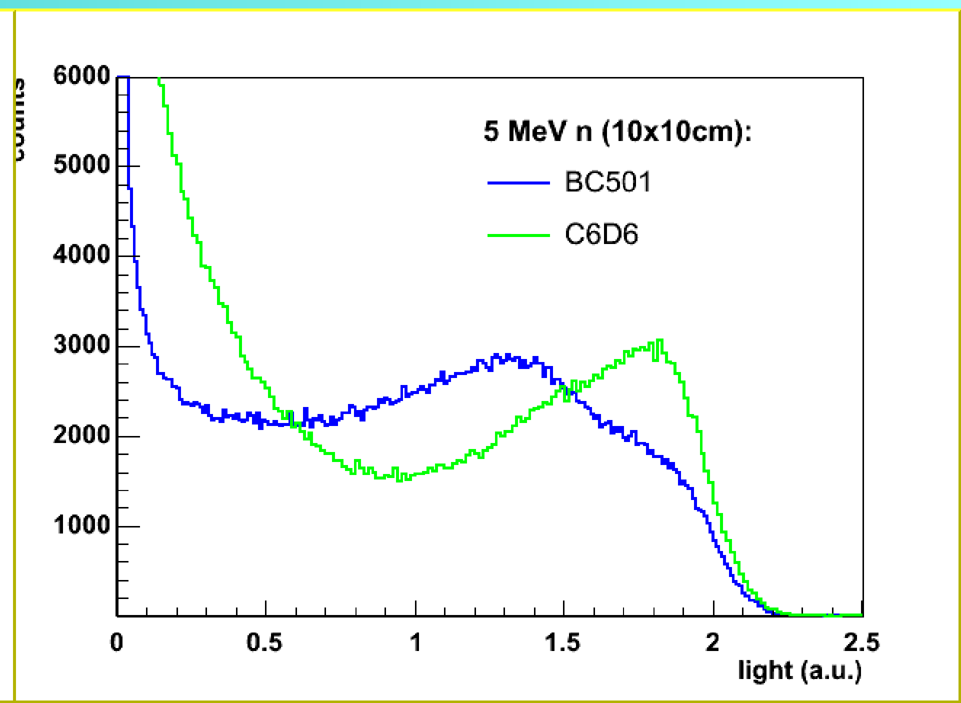


5 MeV n + C6D6(1x1cm):
energy deposit
light produced
instrumental width
counts
1400
1200
1000
800
600
400
200
0
1
2
5 MeV n + C6D6(10x10cm):
energy deposit
light produced
instrumental width
counts
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
energy (MeV)


1 MeV n (1x1cm):
BC501
C6D6
counts
25000
20000
15000
10000
5000
0
0.05
0.1
0.15
0.2
0.25
light (a.u.)

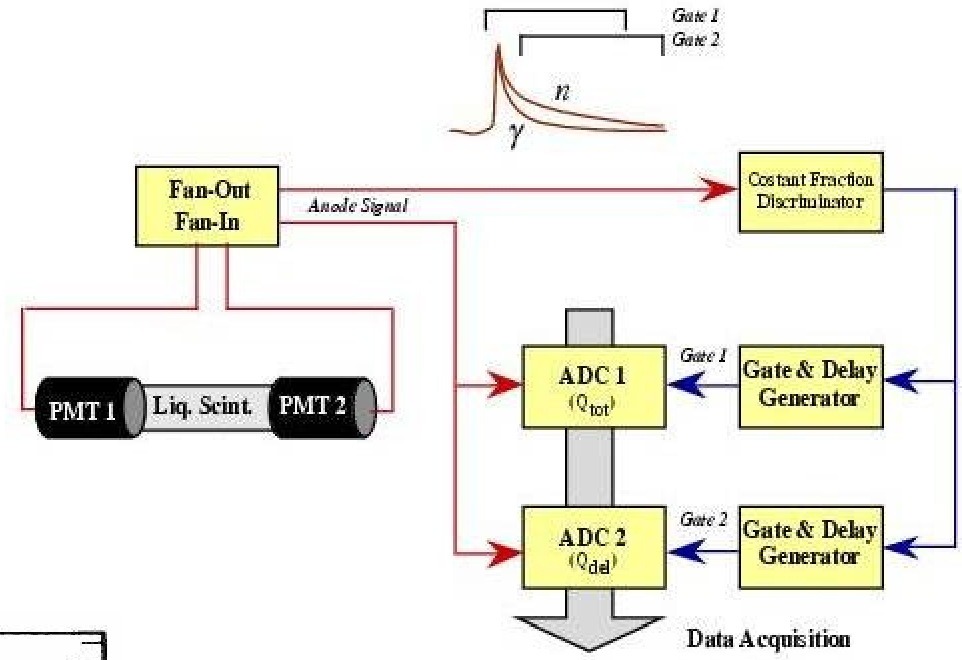

5 MeV n (1x1cm):
BC501
C6D6
counts
1000
900
800
700
600
500
400
300
200
100
0
0.5
1
1.5
2
2.5
light (a.u.)


1 MeV n (10x10cm):
BC501
C6D6
counts
80000
70000
60000
50000
40000
30000
20000
10000
0
0.05
0.1
0.15
0.2
0.25
light (a.u.)

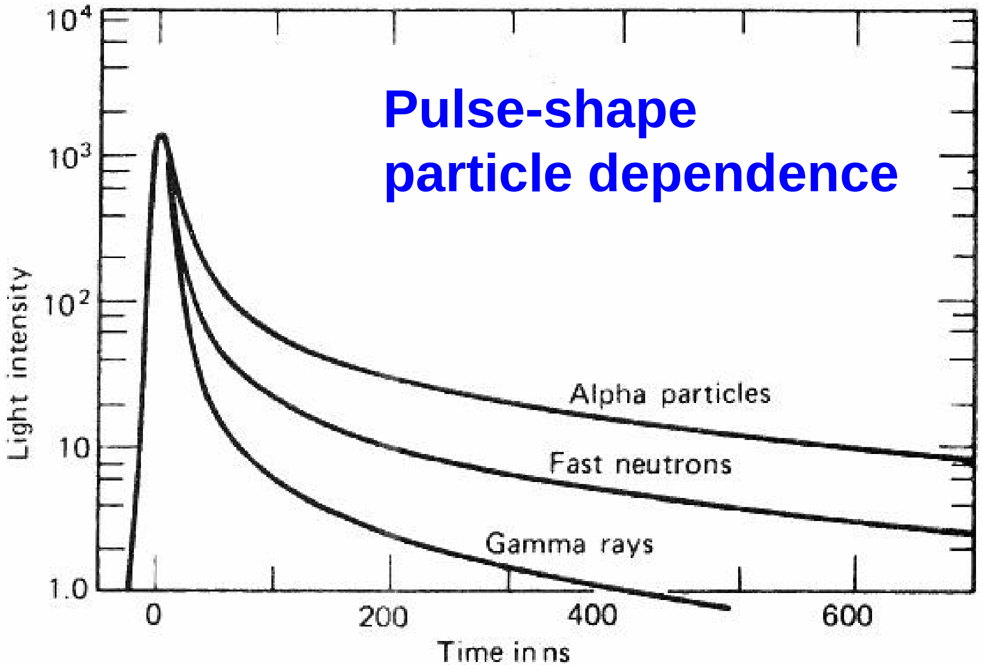

5 MeV n (10x10cm):
BC501
C6D6
6000
5000
4000
3000
2000
1000
0
0.5
1
1.5
2
2.5
light (a.u.)

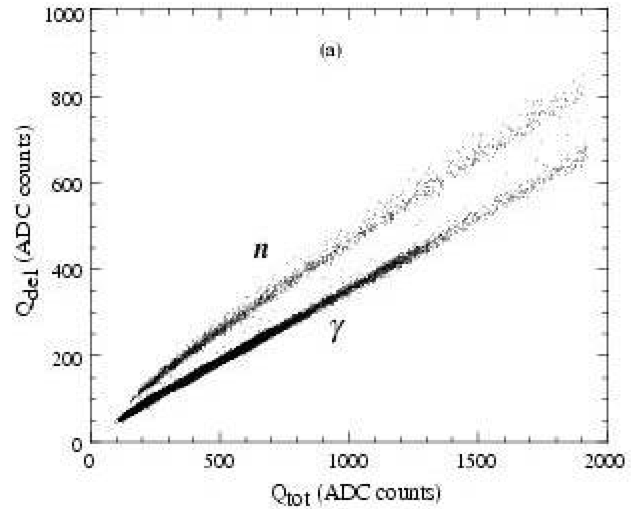
BC501/NE213

Pulse Shape Discrimination



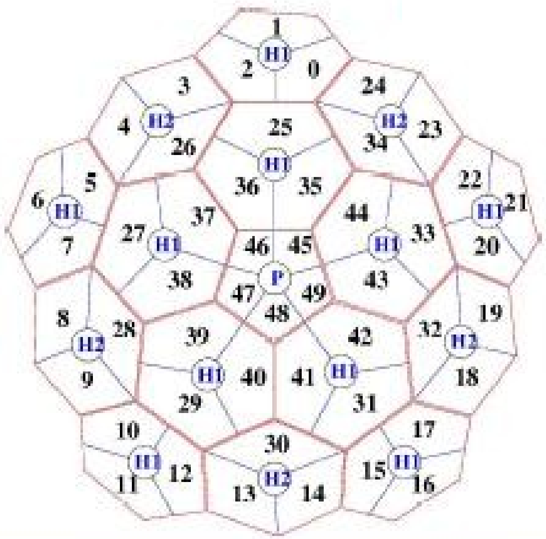
Pulse-shape particle dependence





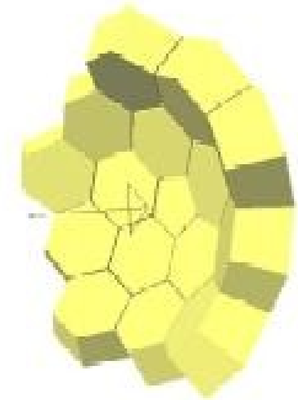
Multi-detector: Neutron Wall (EUROBALL)

BC501 liquid scintillator



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

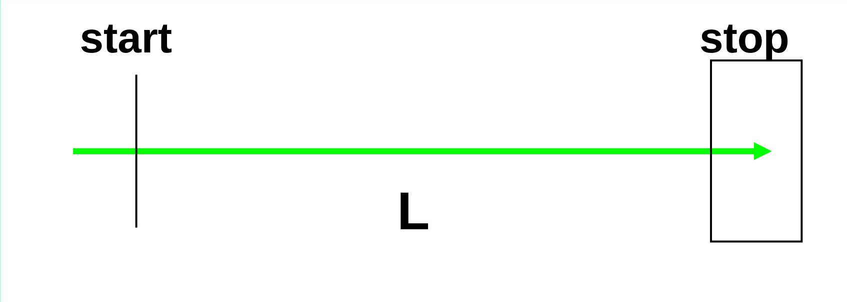
$$\varepsilon_{int} = 50\ \%$$



Johan Nyberg, AGATA meeting Orsay, 2004-06-22

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

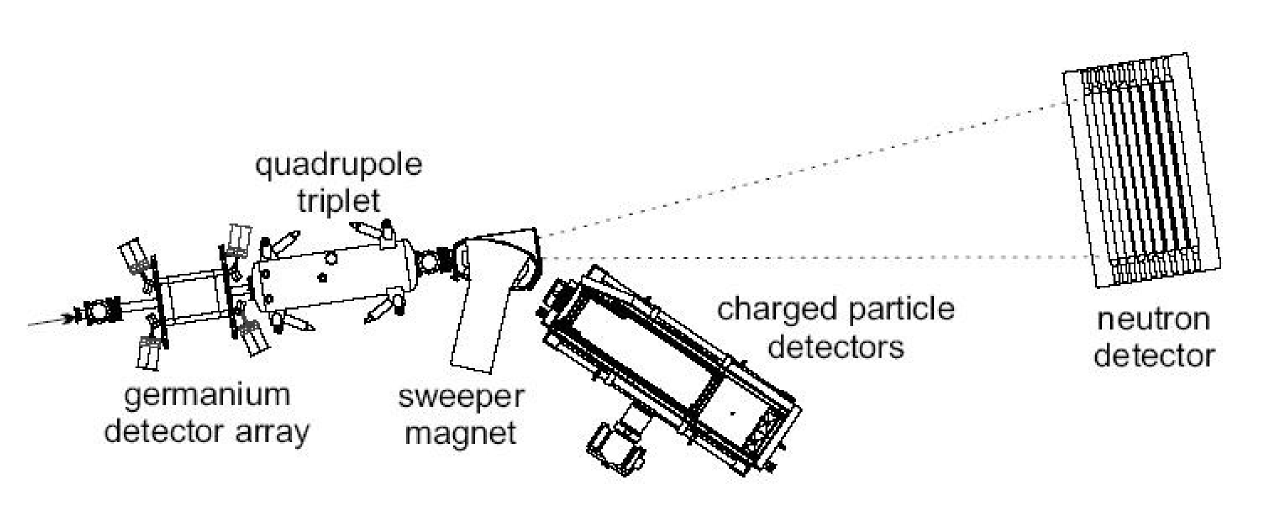
Energy resolution:

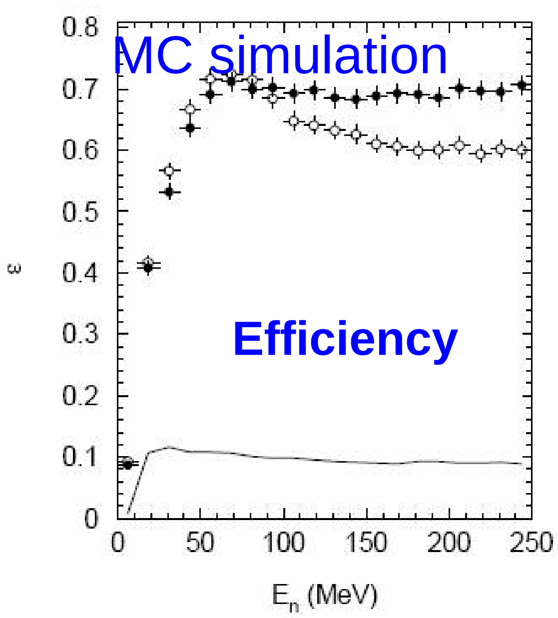
$$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

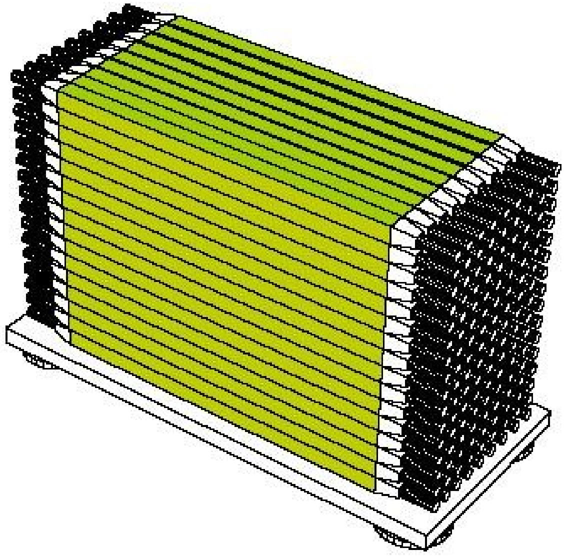
- **Long flight path, short detectors, good time resolution**

ToF spectrometer: MoNA (NSCL-Michigan)

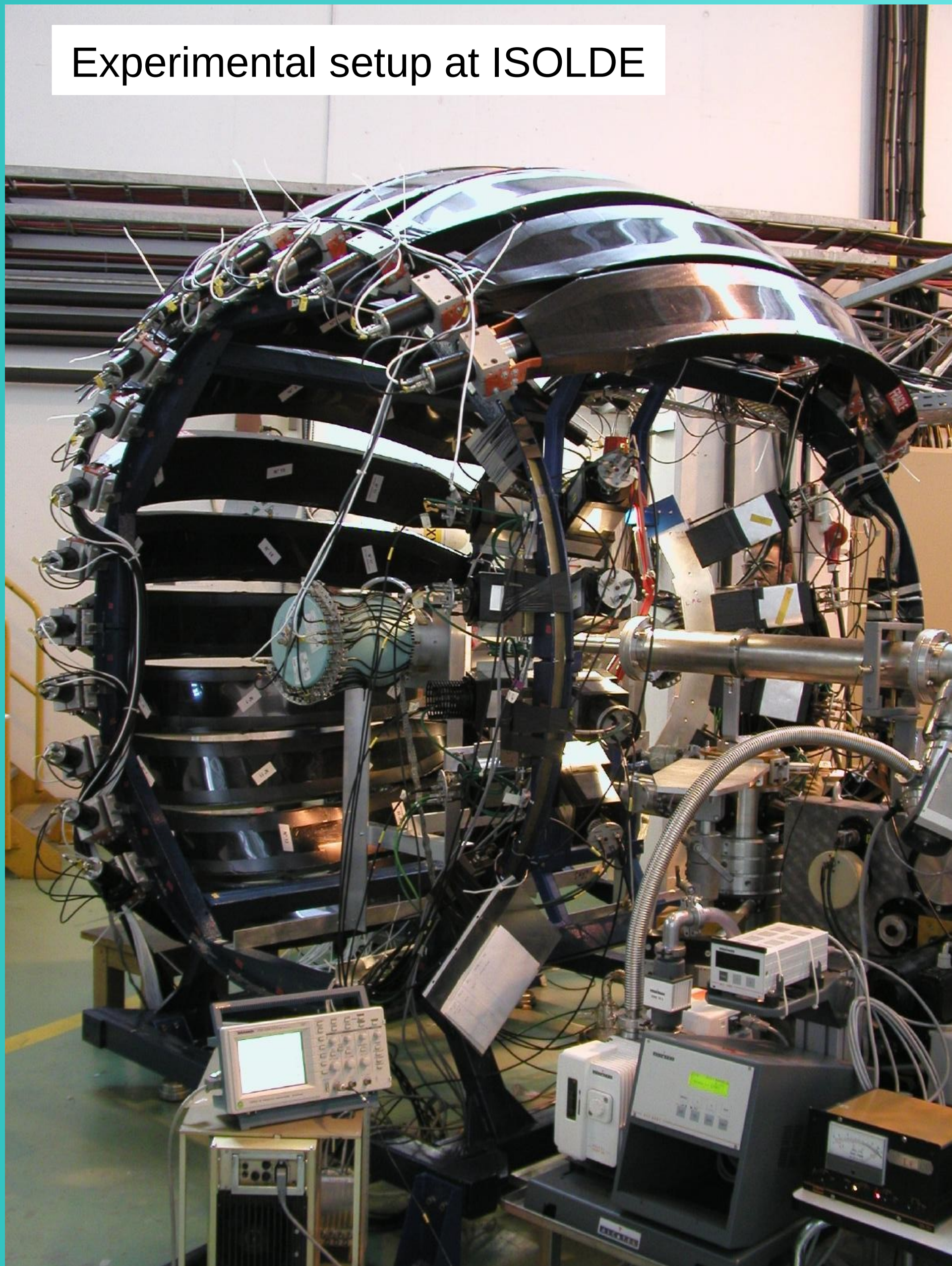
144 bars
200x10x10 cm^3
plastic scintillators+
iron converters







ToF spectrometer: TONERRE (LPC-Caen)

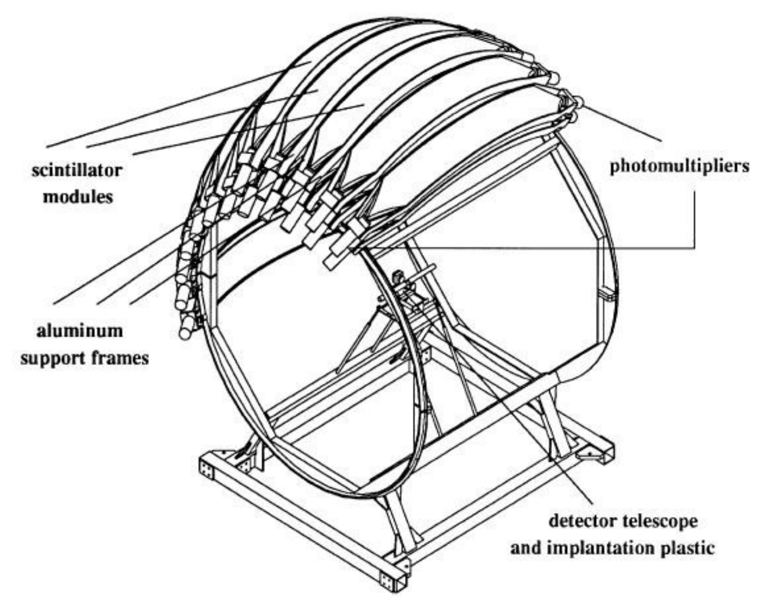


BC400 Plastic scintillator

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

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

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



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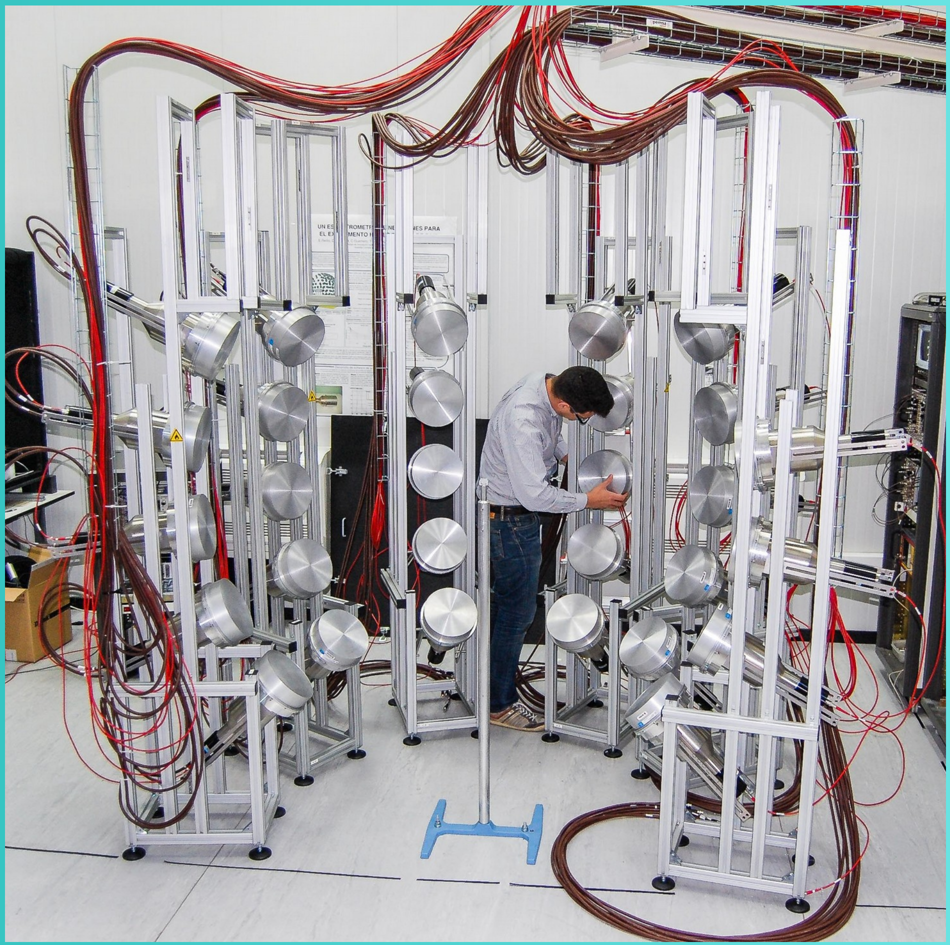
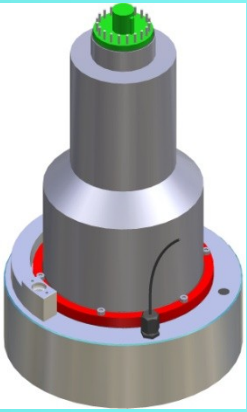
ToF spectrometer: MONSTER (CIEMAT, VECC, JYFL, UPC, IFIC)





Ø=20cm x L=5cm

$$\frac{\Delta\Omega}{4\pi} > 5\text{-}10\ \%$$

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

Digital DAQ 14bits & 1 Gsample/s

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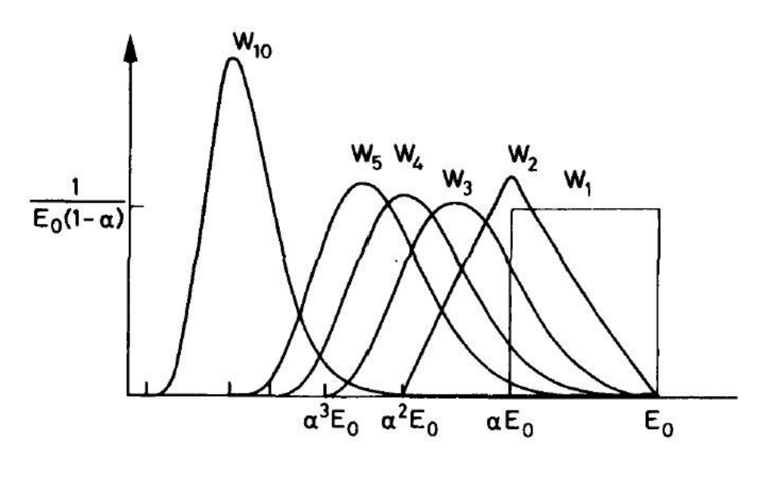
Neutron moderation:

After many collisions:

Nucleus	1-α	ξ	N (1MeV→ 25 meV)
^{1}H	1	1	18
^{2}H	0.889	0.725	24
^{4}He	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:

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

Number of collisions to reach an energy:

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

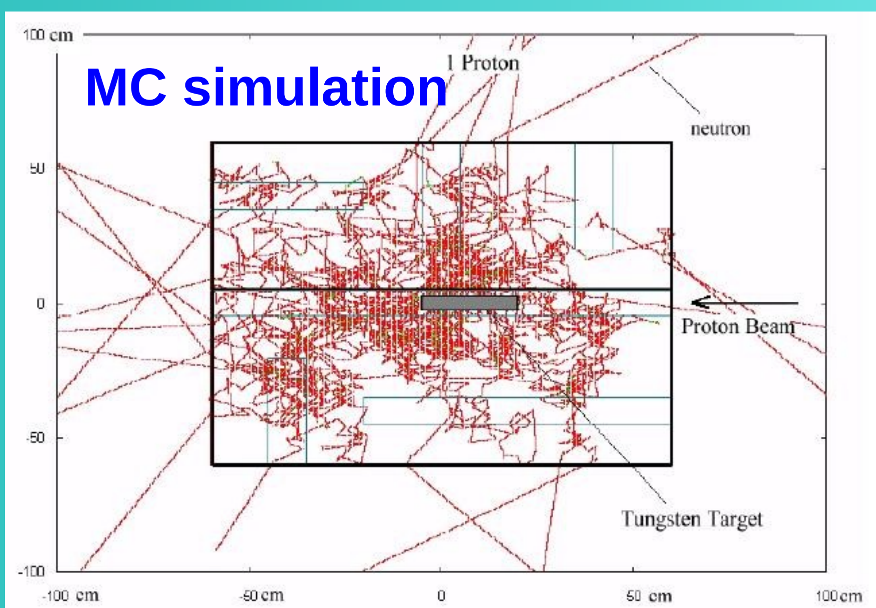
Slowing-down time: $$t = \sqrt{\frac{K}{E_f}} - t_0 \quad : \quad K(\xi, \sigma_{ela});\ t_0(E_0, \xi, \sigma_{ela})$$

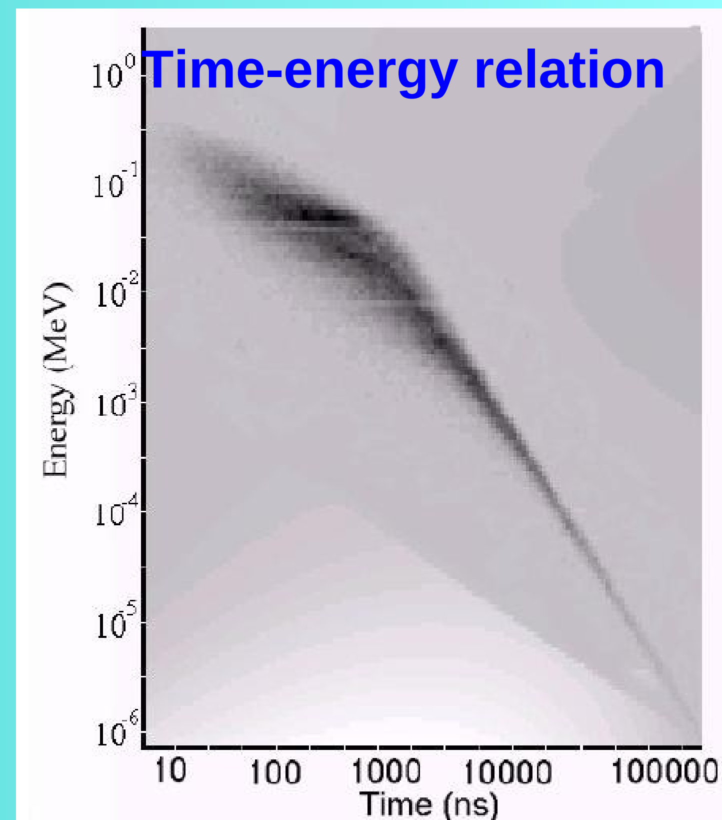
Slowing Down Spectrometer: LSDS (LANL-Los Alamos)

Lead block + sample+counters

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

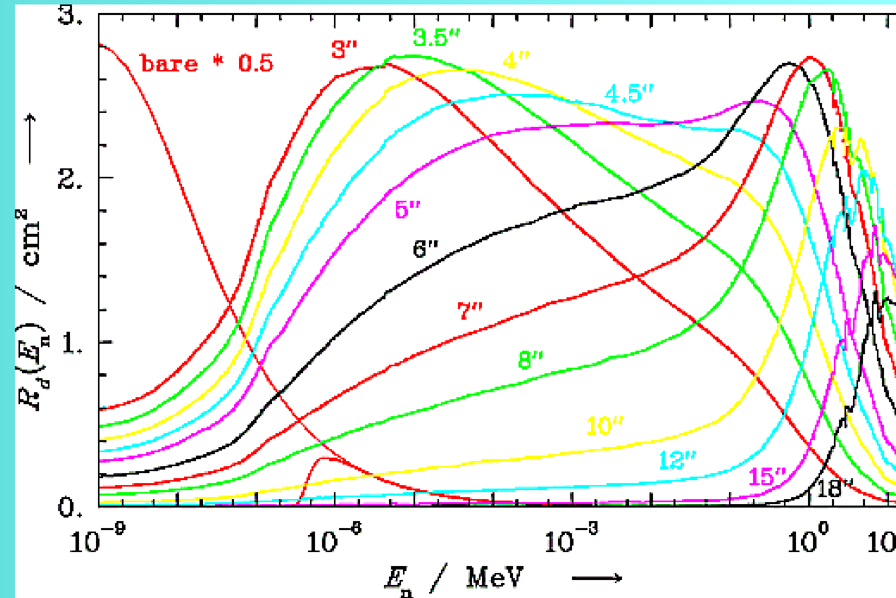
$$\frac{\Delta E}{E} = 30\ \%$$

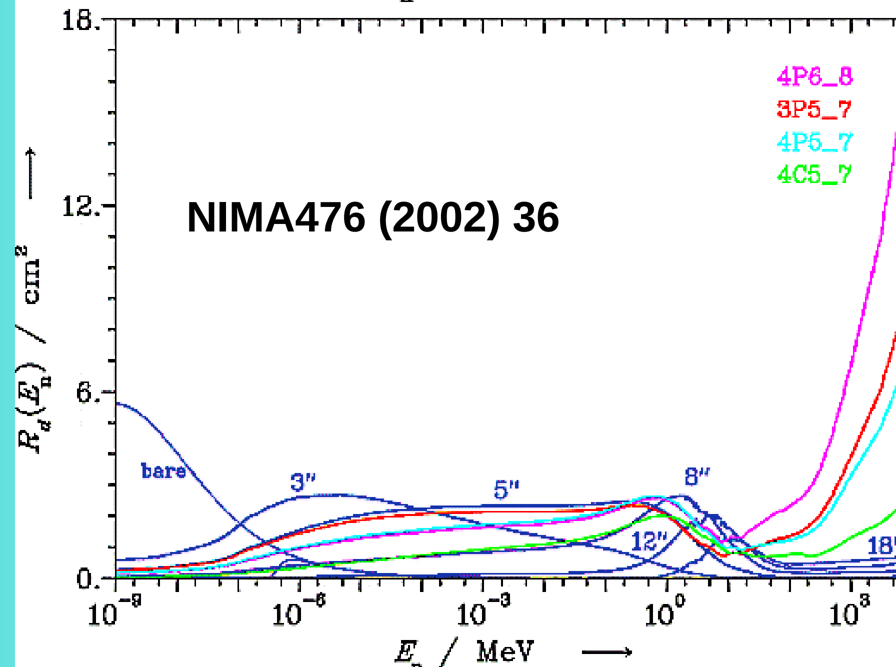




Bonner spheres: NEMUS (PTB-Braunschweig)

Polyethylene sphere +
³He proportional counter





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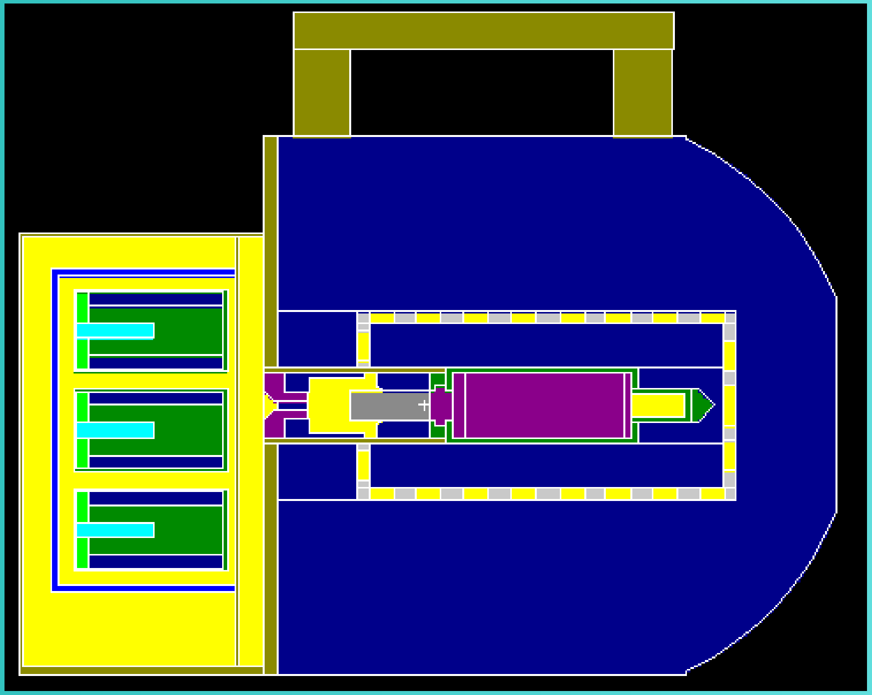
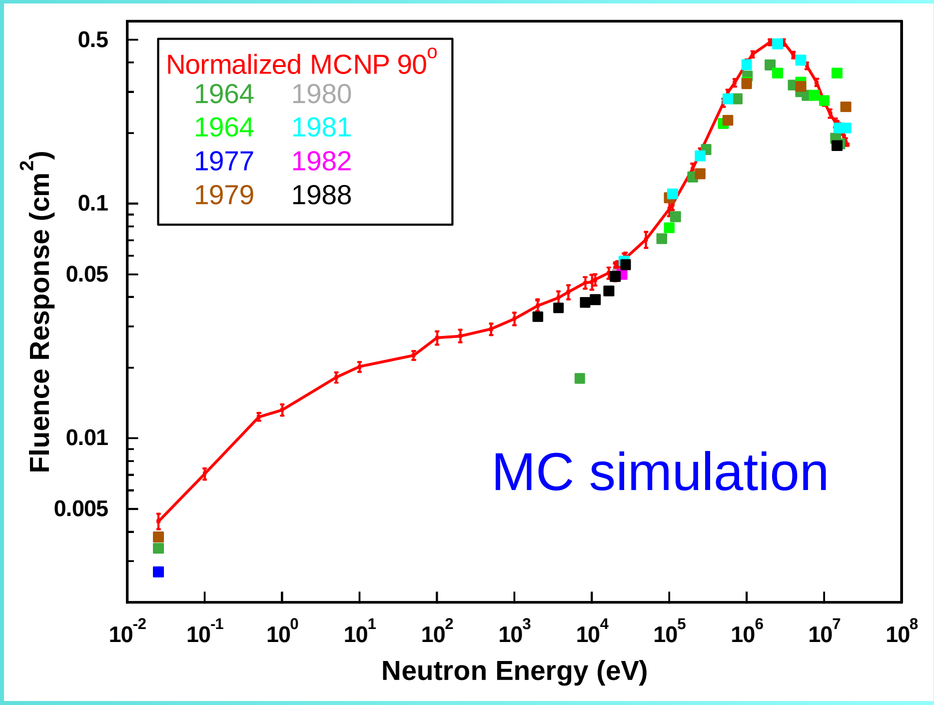
Monte Carlo simulations of neutron detectors





… 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: $d = R \cdot p \; ; \quad d_i = \sum_j R_{ij} \cdot p_j \; , \; \forall i$

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

Use statistical inference:

- not-unique solution (σ_d)
- "*a priori*" information
- several methods:

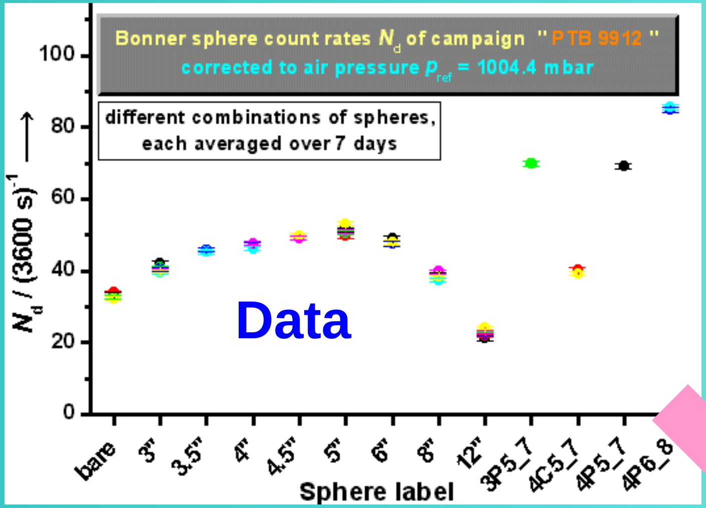
Linear regularization (LR): $p = \left(R + \lambda H \right)^{-1} \cdot d$

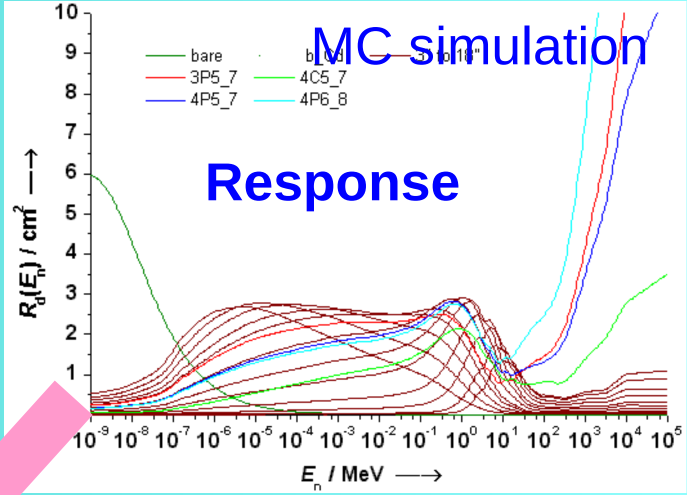
Maximum Entropy (ME): $p_j^{(m+1)} = p_j^{(m)} \exp\left(\frac{1}{\lambda} \sum_i \frac{R_{ij}}{\sigma_i^2} \left(d_i - \sum_k R_{ik} p_k^{(m)} \right) \right)$

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

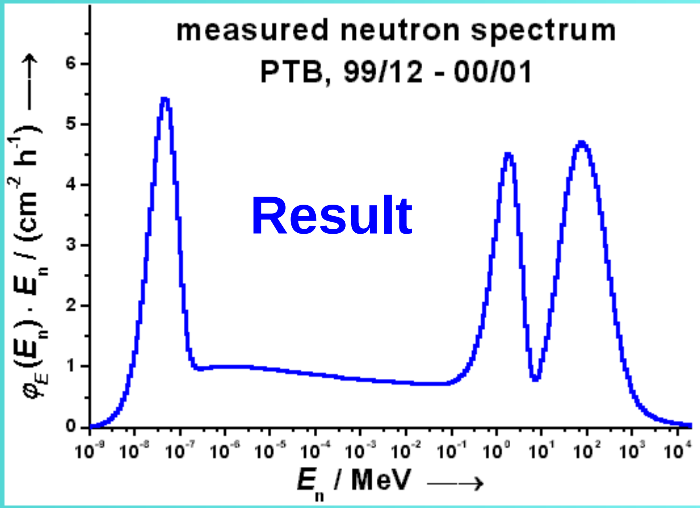
Deconvolution

Bonner spheres measurements





MAXED



The Long Counter

Uni-directional,
flat-efficiency

Moderator+shielding +BF_3

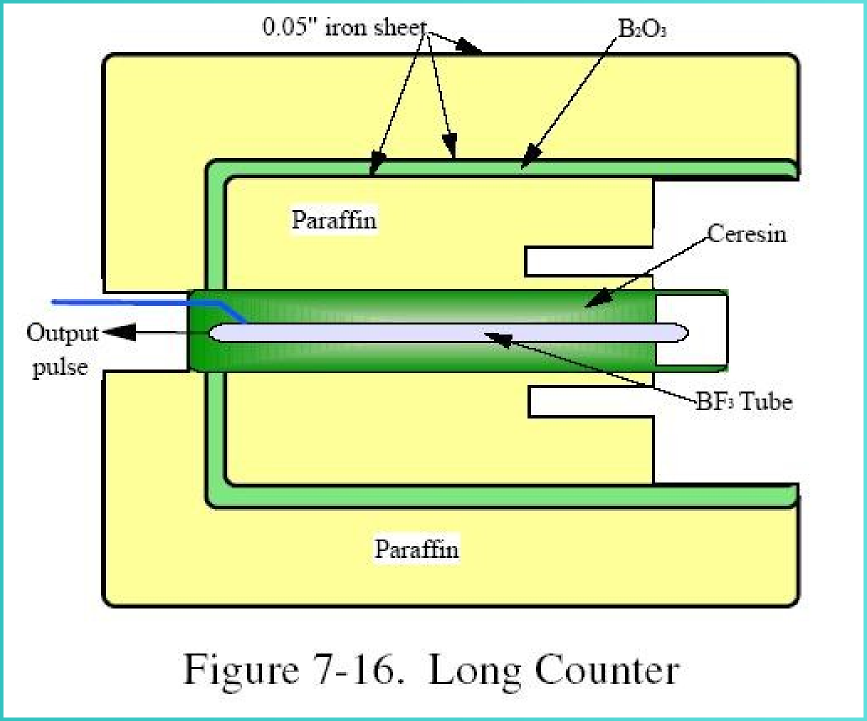
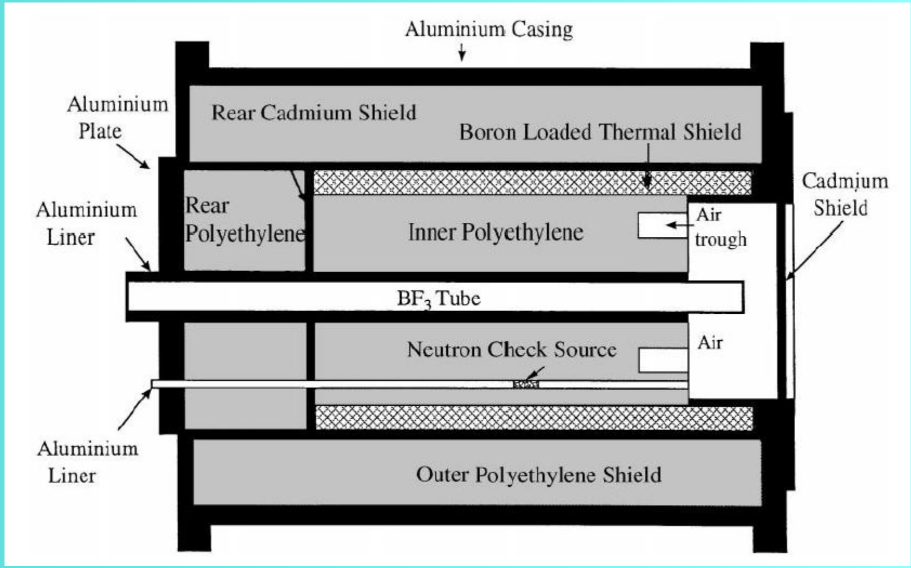
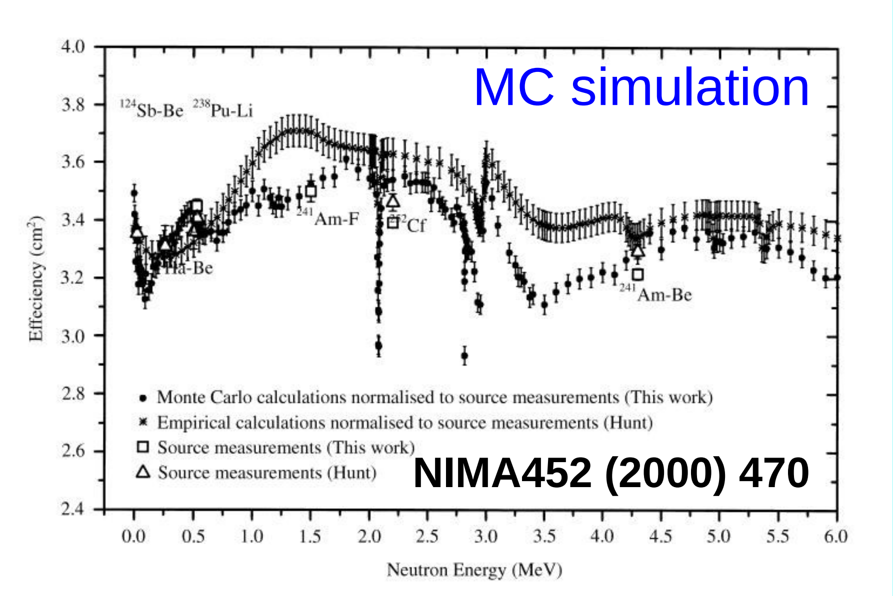


Figure 7-16. Long Counter

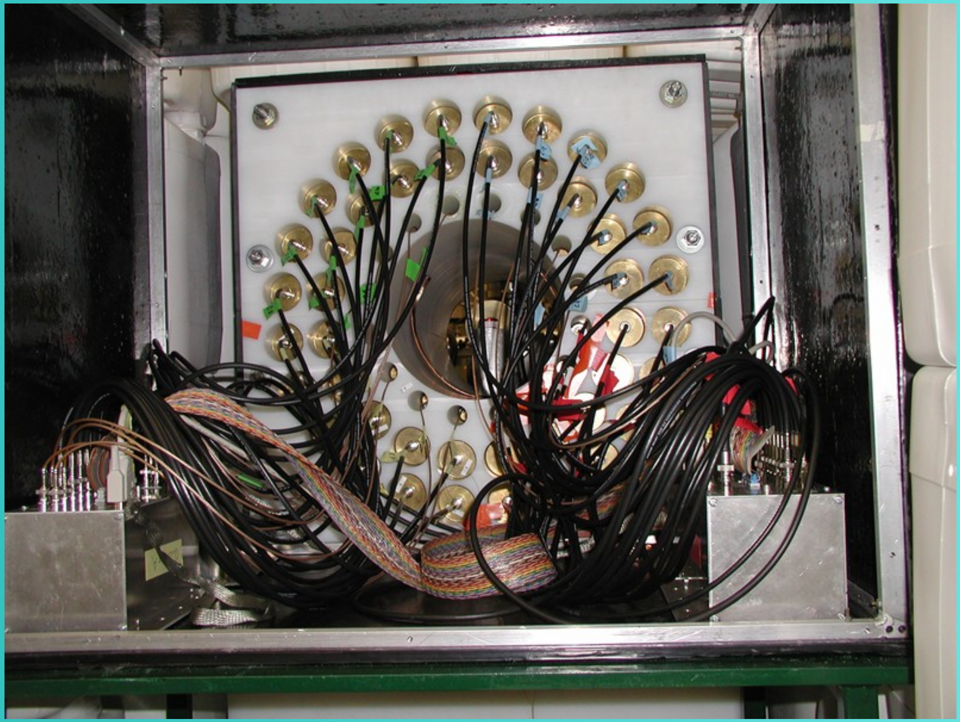


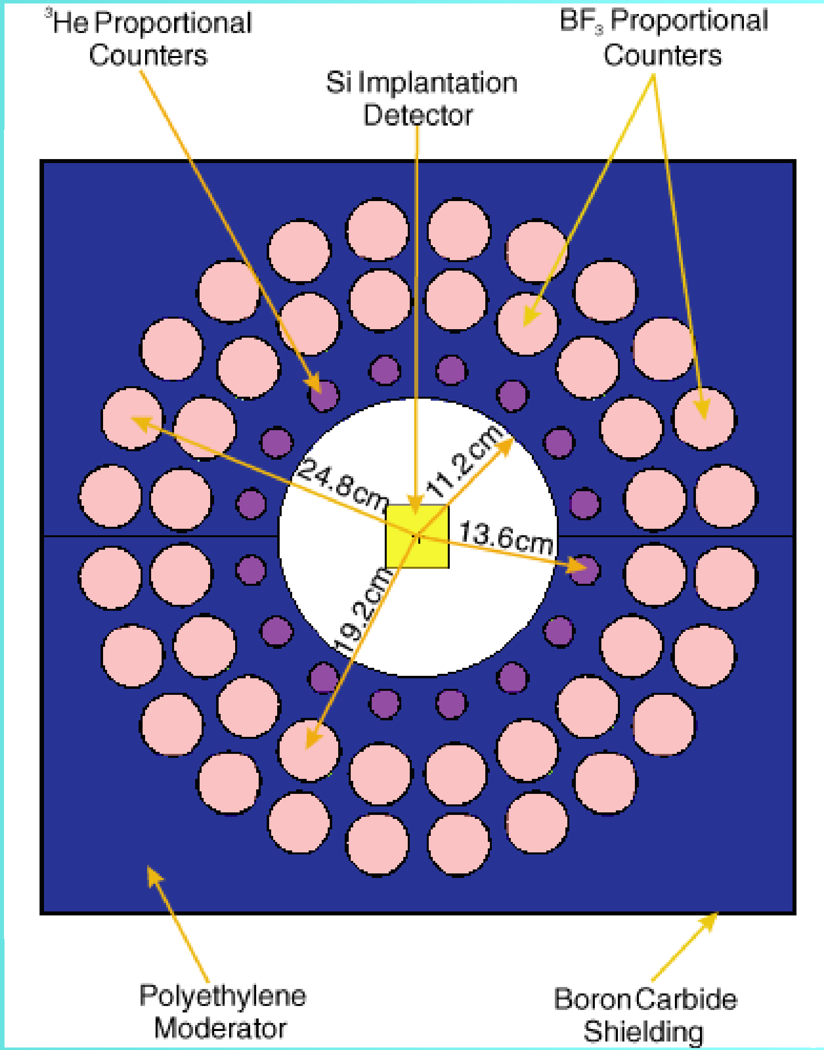


Moderated cylindrical array: NERO (NSCL-Michigan)

Polyethylene block (60x60x80cm^3)
16 ^{3}He and 44 BF_3
proportional counters

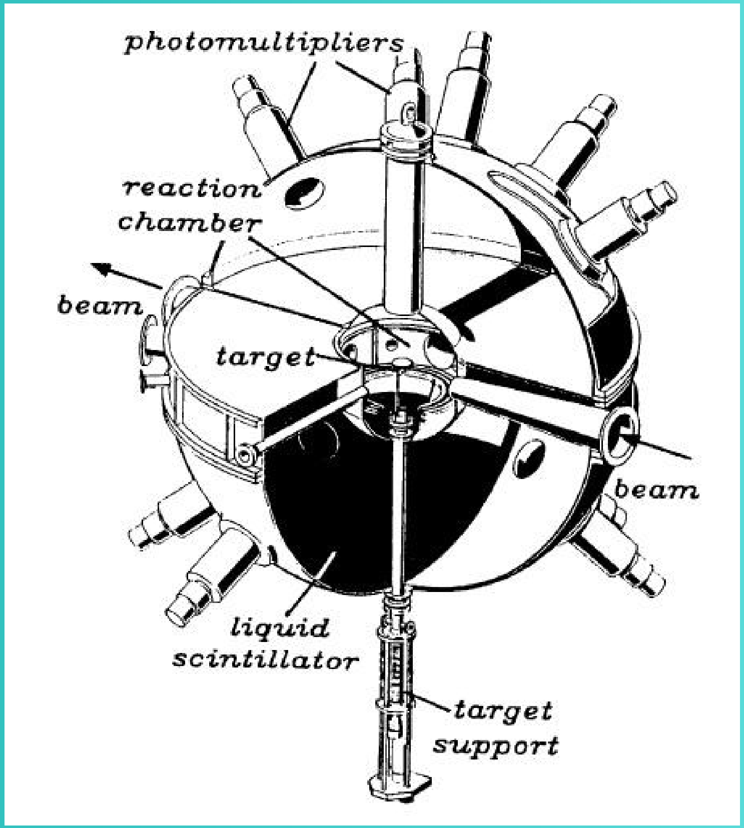
$$\varepsilon = 40\ \%$$

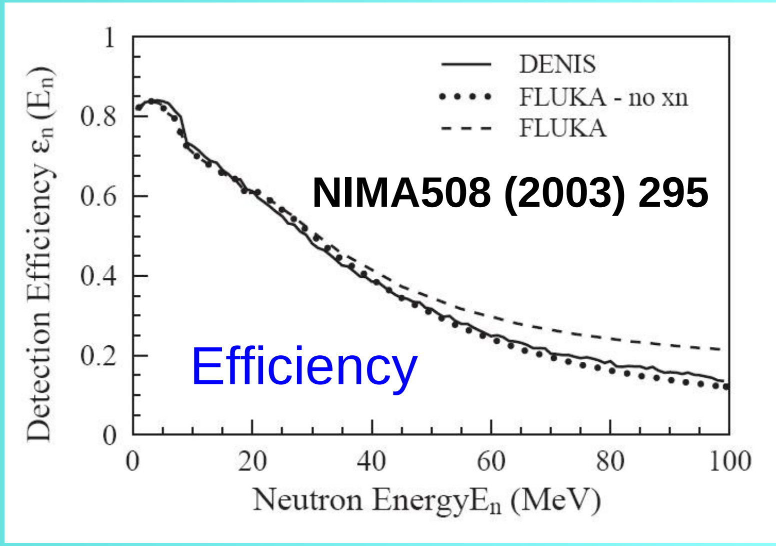


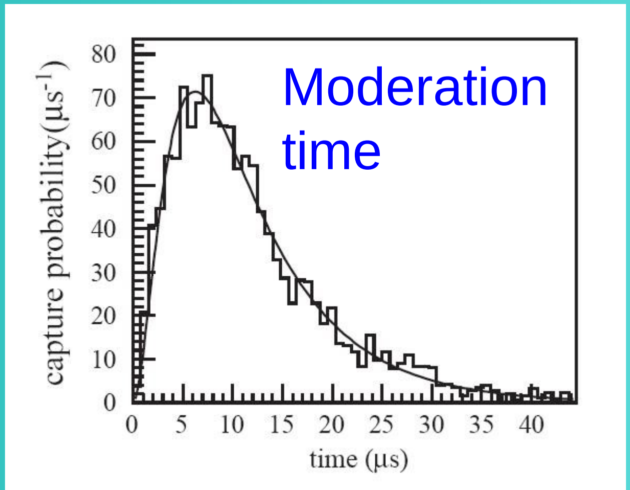


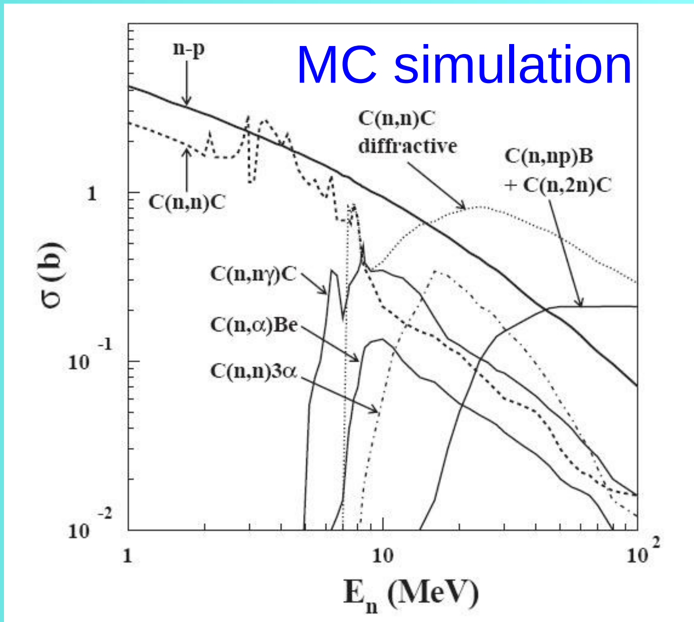
Berlin Neutron Ball

1.5 m³ 0.4% Gd-loaded liquid scintillator



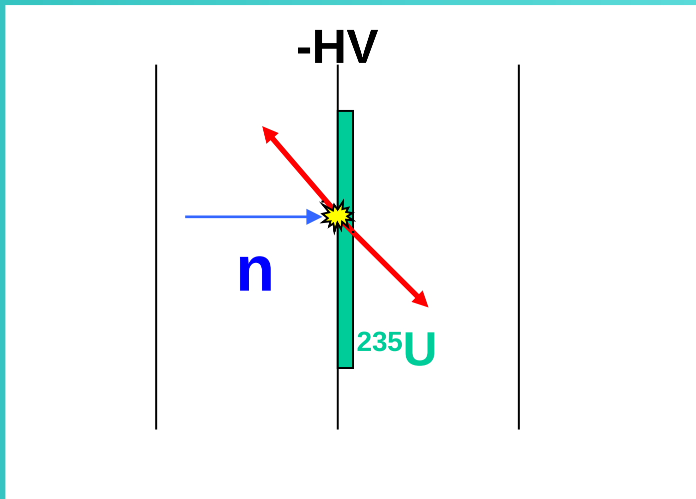






Fission chamber:

U, Pu + gas chamber



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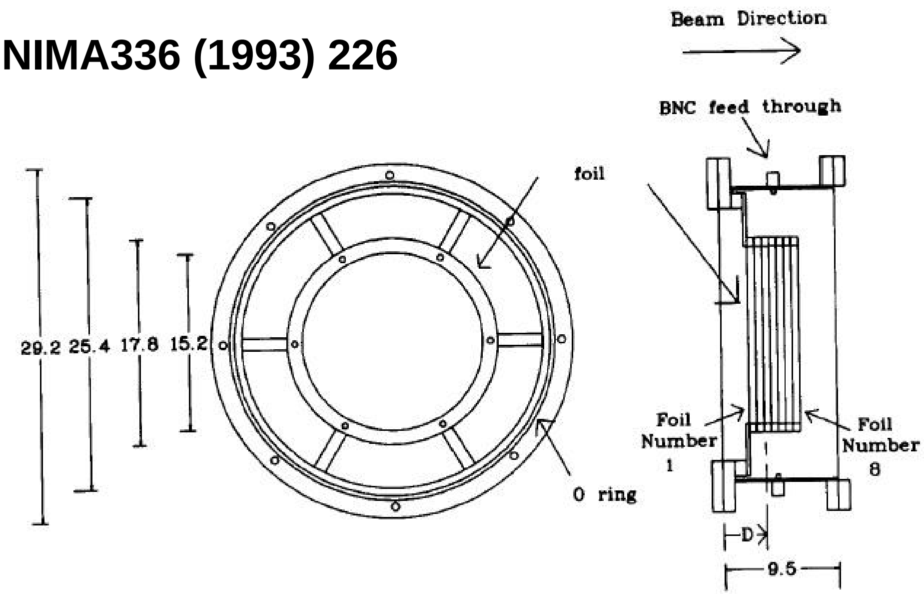
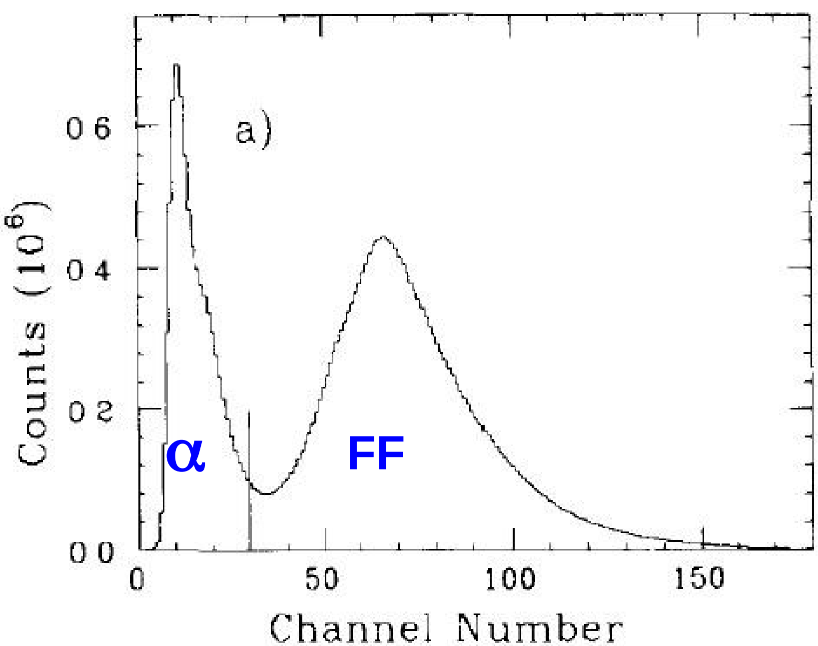


Fig. 1. Schematic diagram of the ionization chamber housing. Dimensions are in centimeters.



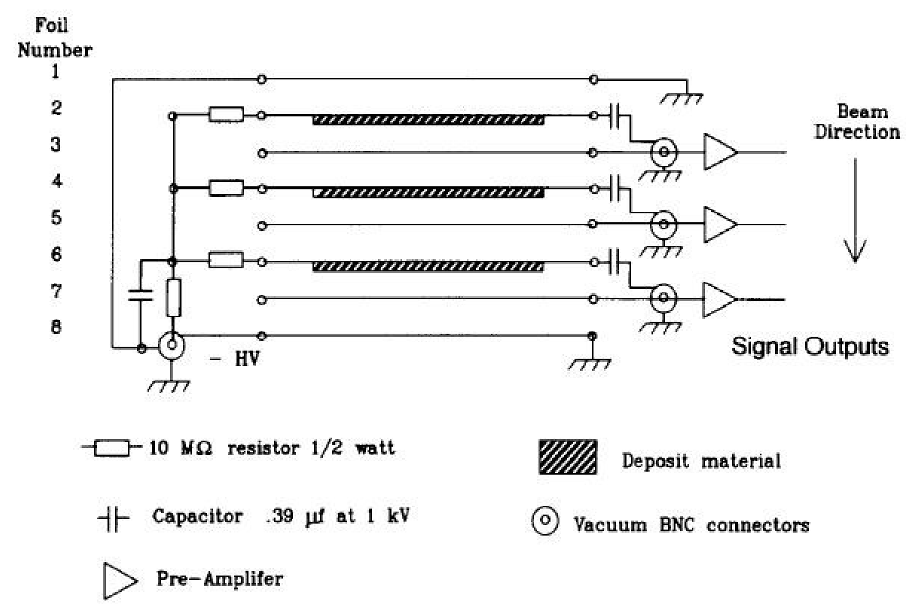


Fig. 2. Electrical wiring diagram of the ionization chamber.