# Neutron Detection

*J.L. Tain*

Jose.Luis.Tain@ific.uv.es
http://ific.uv.es/gamma/

Instituto de Física Corpuscular

C.S.I.C - Univ. Valencia

# Neutrons

**Particle Properties 2004**

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

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

$c\tau = 2.655 \times 10^8$ 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**

# 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,αγ), …
- fission: $(n,xn^{A1}Z1^{A2}Z2)$
- …

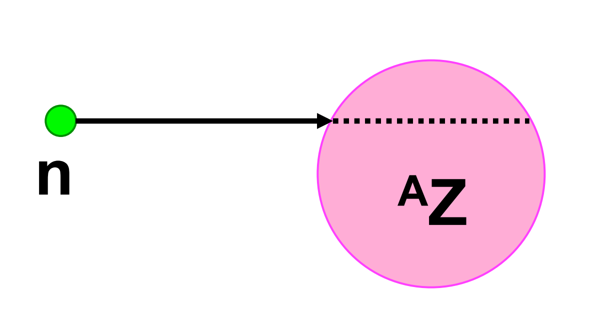
$$\sigma_{tot} = \sigma_{el} + \sigma_{cap} + \dots$$

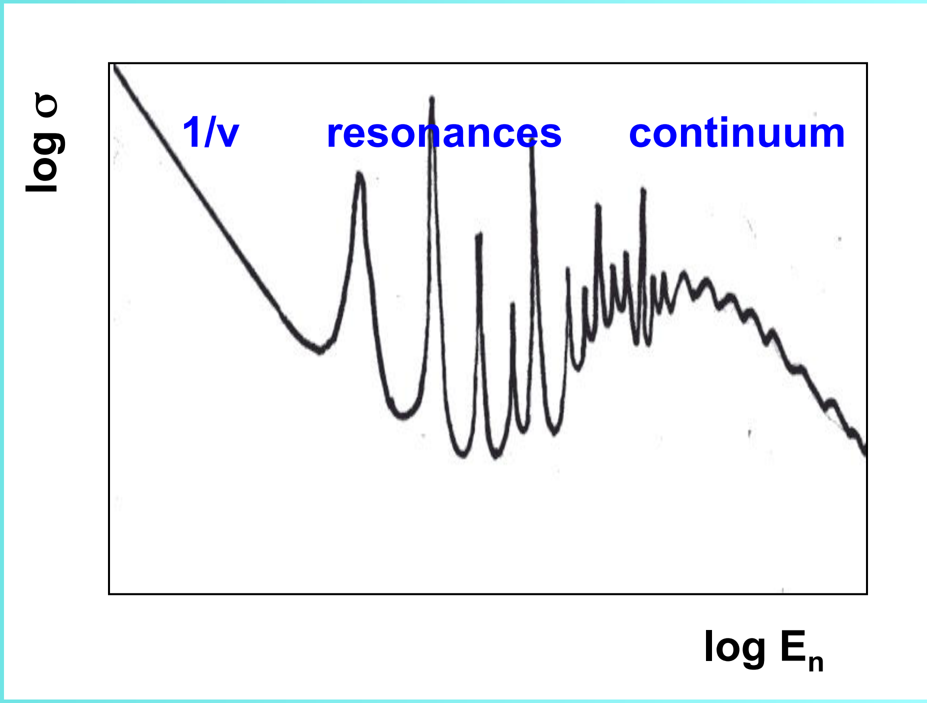
✦ No Coulomb barrier

✦ Reaction thresholds

✦ Energy dependence

✦ No predictive models



**Common reactions used for neutron detection at low energies:**

**Elastic scattering:**

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

**Charged particle:**

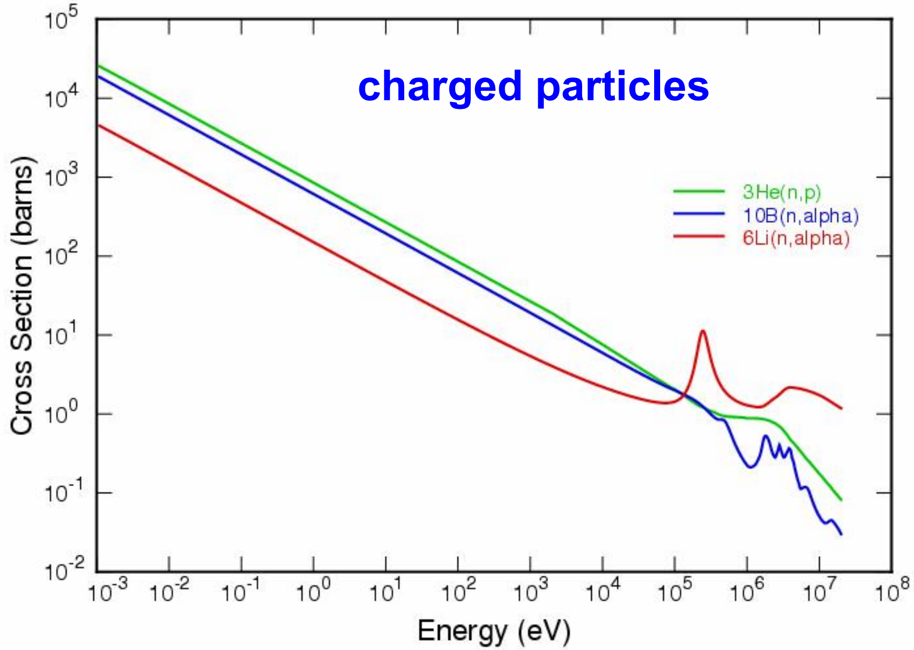
- $n + {}^{3}He \rightarrow {}^{3}H + {}^{1}H + 0.764$ MeV (abund.=0.00014%)
- $n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.79$ MeV (abund.=7.5%)
- $n + {}^{10}B \rightarrow {}^{7}Li^{*} + {}^{4}He \rightarrow {}^{7}Li + {}^{4}He + 0.48$ MeV $\gamma$ +2.3 MeV (abund.=19.9%, b.r.=93%)

**Radiative capture:**

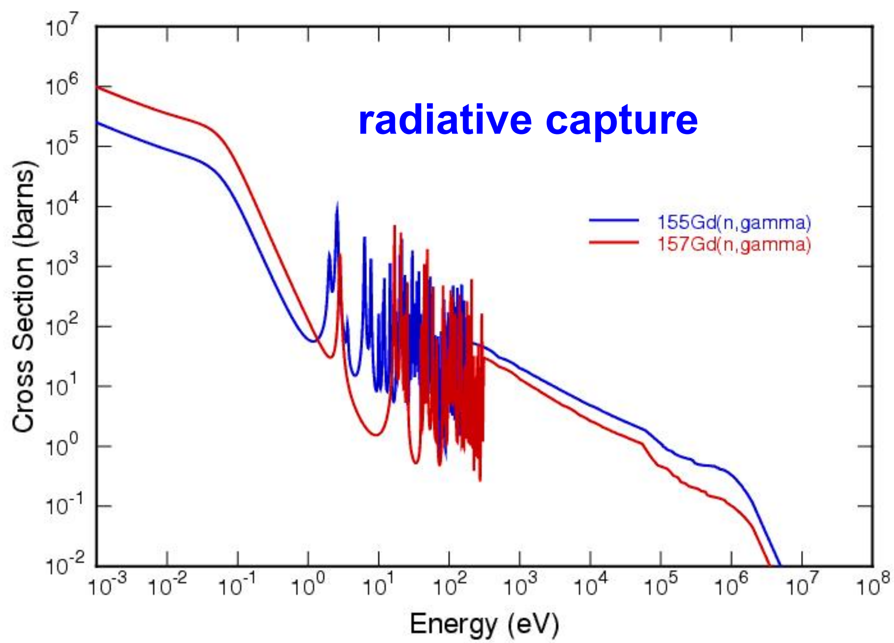
- $n + {}^{155}Gd \rightarrow {}^{156}Gd^{*} \rightarrow \gamma$-ray + CE spectrum (abund.=14.8%)
- $n + {}^{157}Gd \rightarrow {}^{158}Gd^{*} \rightarrow \gamma$-ray + CE spectrum (abund.=15.7%)

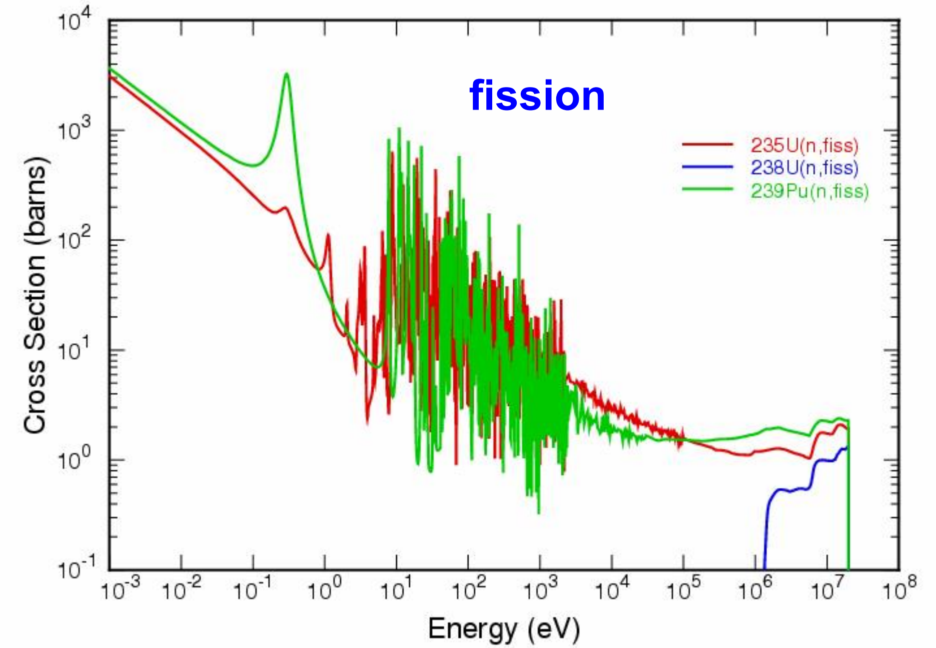
**Fission:**

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

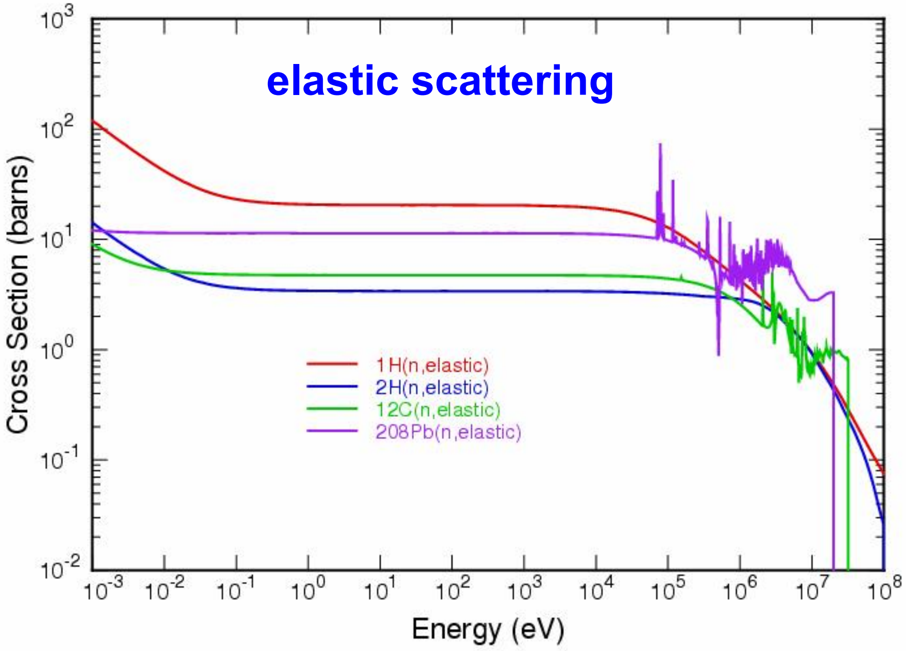


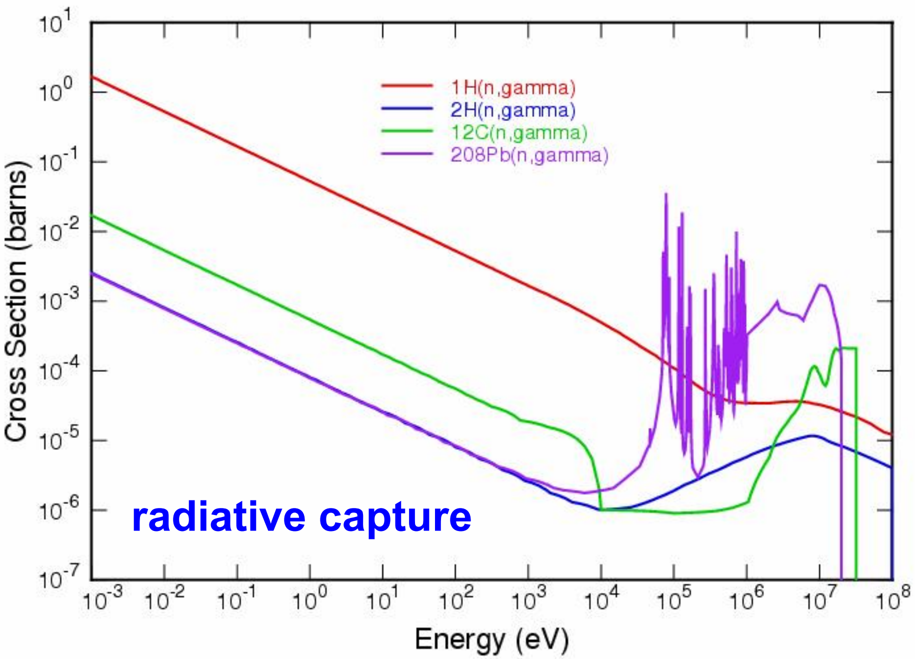

# Cross section energy dependence of useful reactions

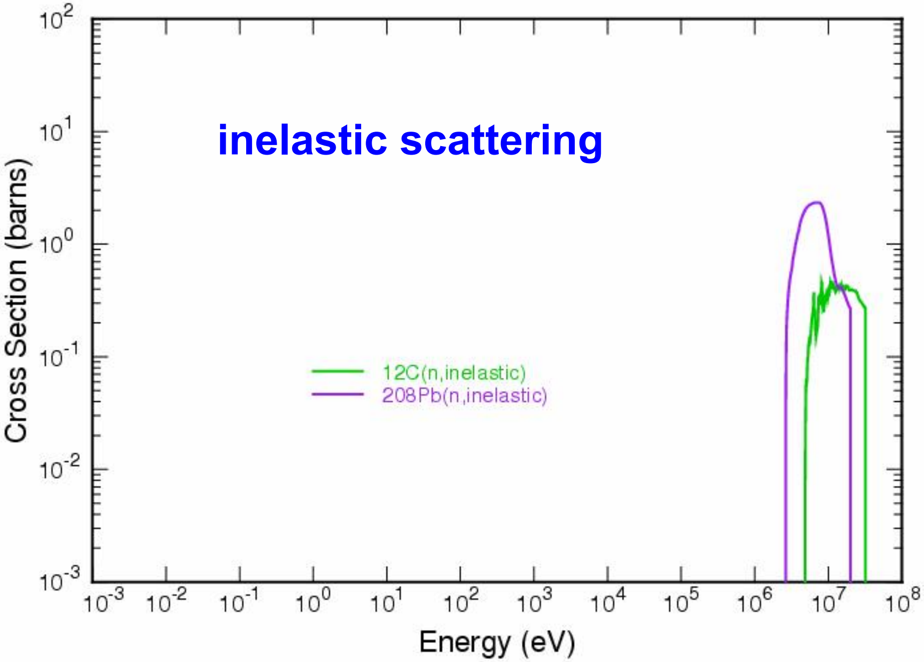


# Cross section energy dependence of moderators



# 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

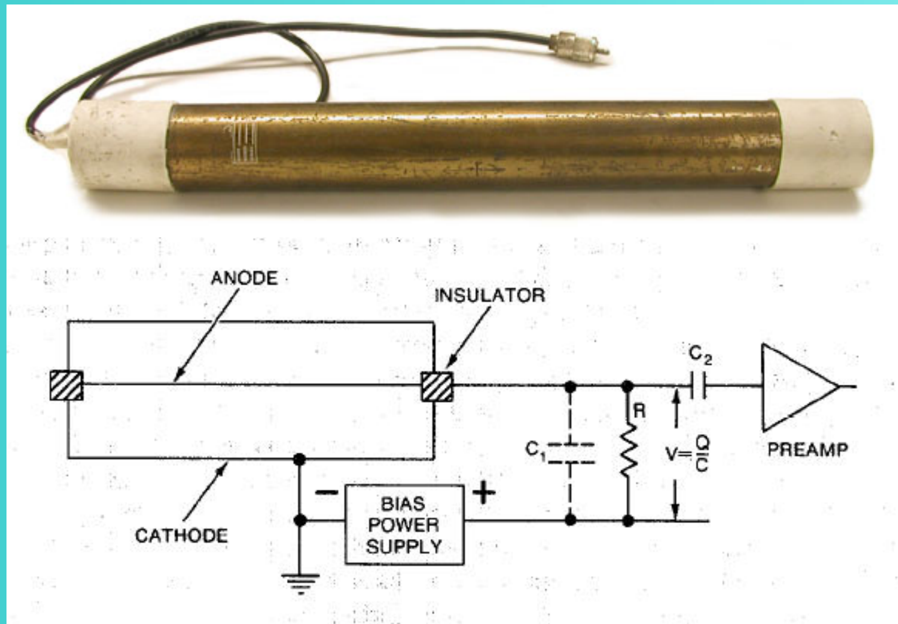



**Fig. 13.1** *Typical setup for gas-filled neutron detectors.*

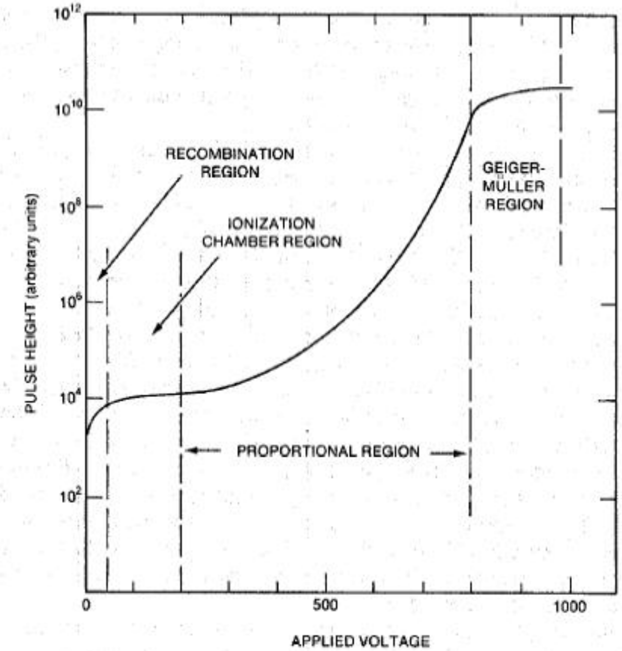



**Fig. 13.3** *Pulse-height vs applied-voltage curves to illustrate ionization, proportional, and Geiger-Mueller regions of operation.*

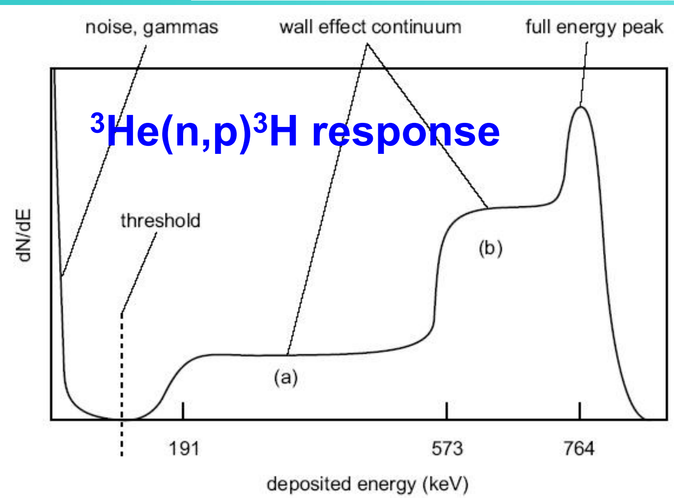



Figure 1: Expected pulse height spectrum from a $^3He$ tube. The two steps in the spectrum are caused by one of the reaction products hitting the detector wall. In area (a), the triton energy is fully deposited, but the proton only deposited a fraction of its energy, and vise versa in area (b).

## Gases:

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

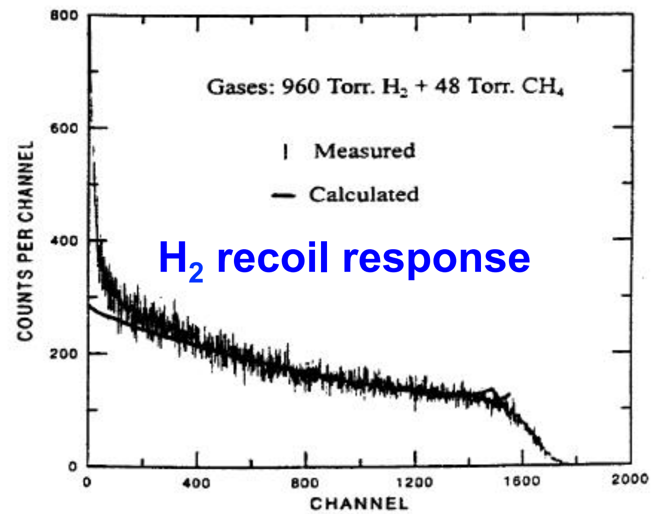



Fig. 1. Measured and calculated pulse height distributions for 0.565 MeV neutrons incident on a cylindrical proportional counter (active volume 38 mm diameter × 178 mm). From Ref.

# $^{3}$He chambers

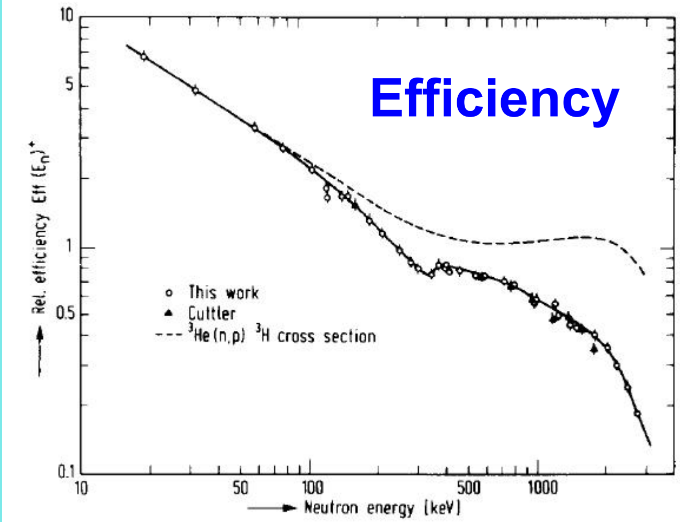
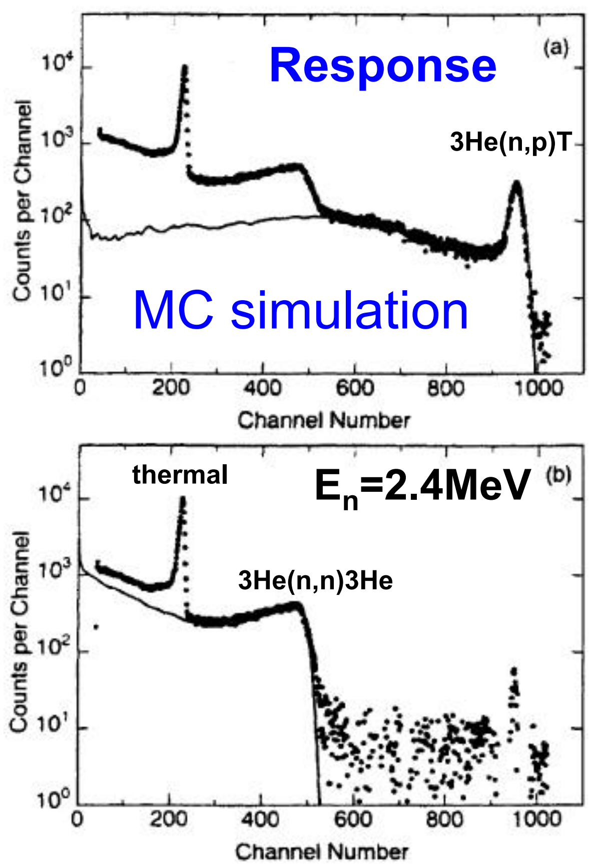



Fig. 7. Relative efficiency of the $^{3}$He fast neutron spectrometer, normalized to previous measurements[15]), along with the $^{3}$He(n,p)$^{3}$H cross section

NIMA422 (1999) 69




NIM144 (1977) 253

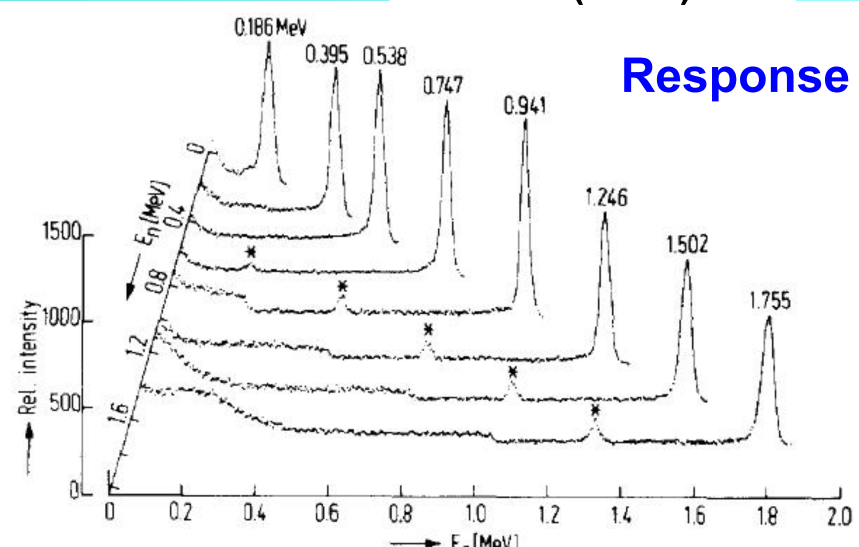
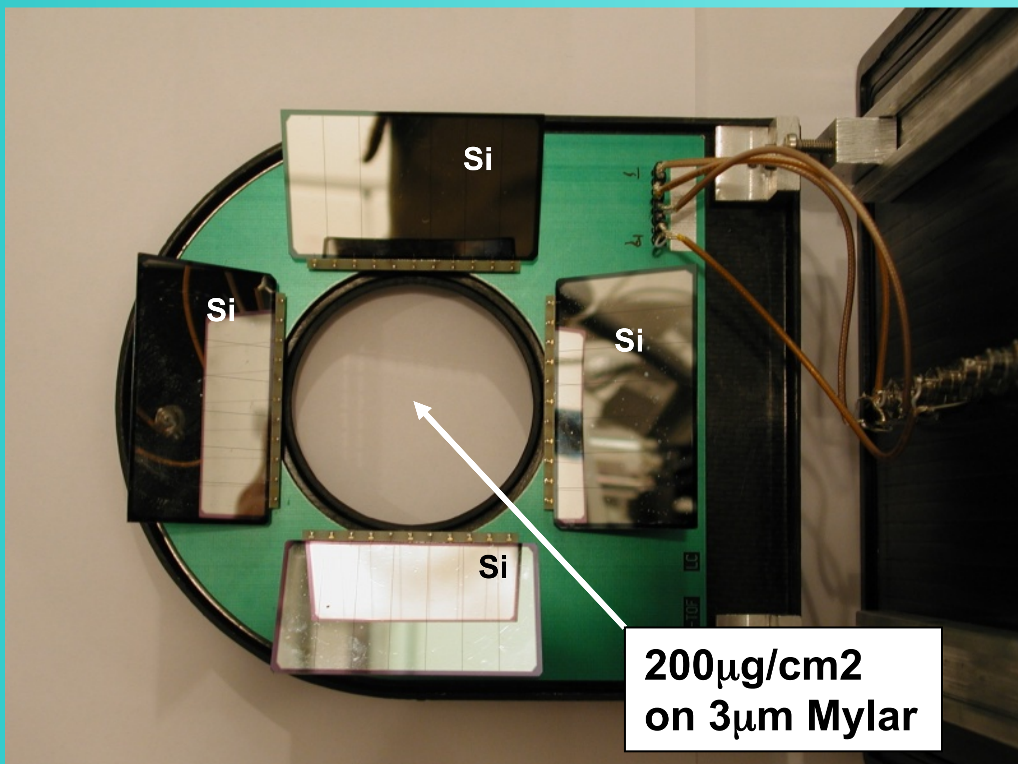
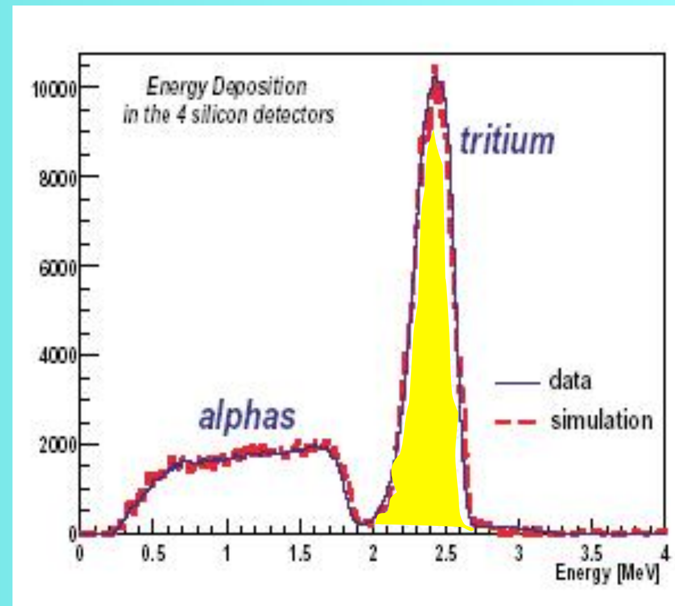



Fig. 2. Response of the $^{3}$He ionization chamber to monoenergetic neutrons produced by the $^{7}$Li(p,n)$^{7}$Be reaction. $E_n$ is the

# Foil with deposit + Si-detector

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

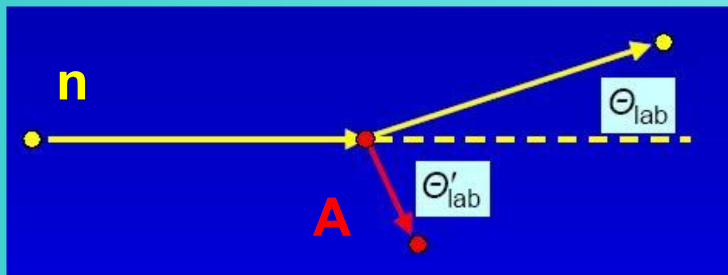



NIMA517 (2004) 389

# Neutron scattering

s-wave (l=0) elastic scattering:



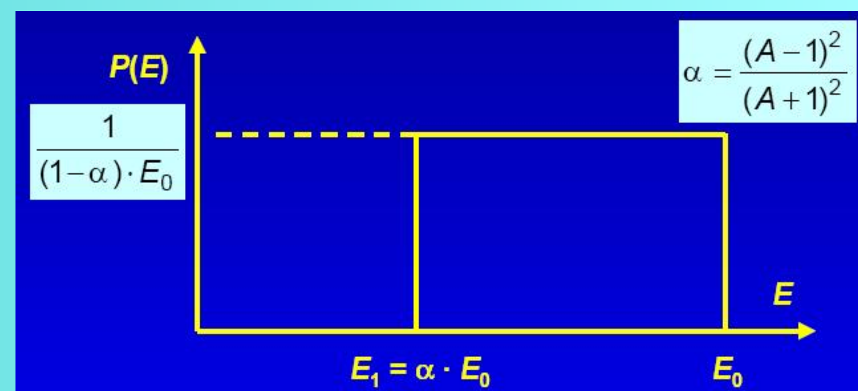

Energy-momentum conservation:

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

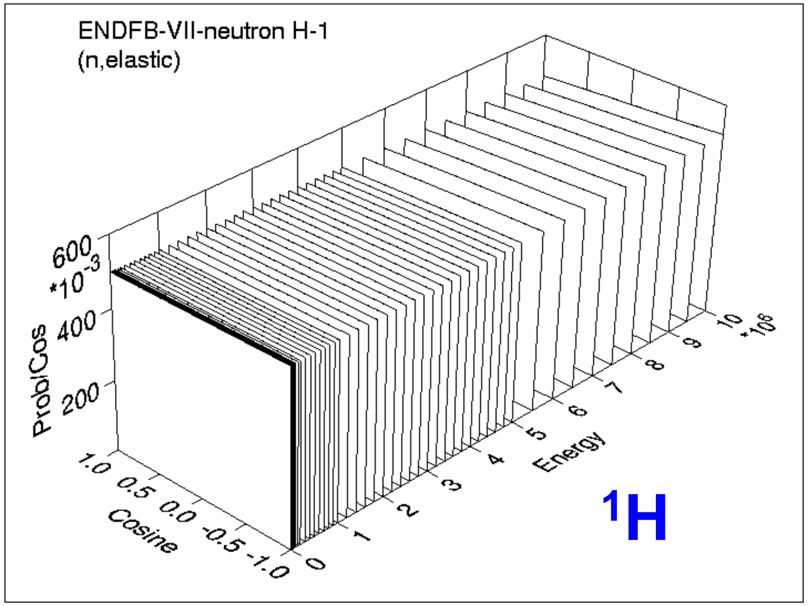
There is a minimum neutron energy (maximum recoil energy) after the collision dependent on A:

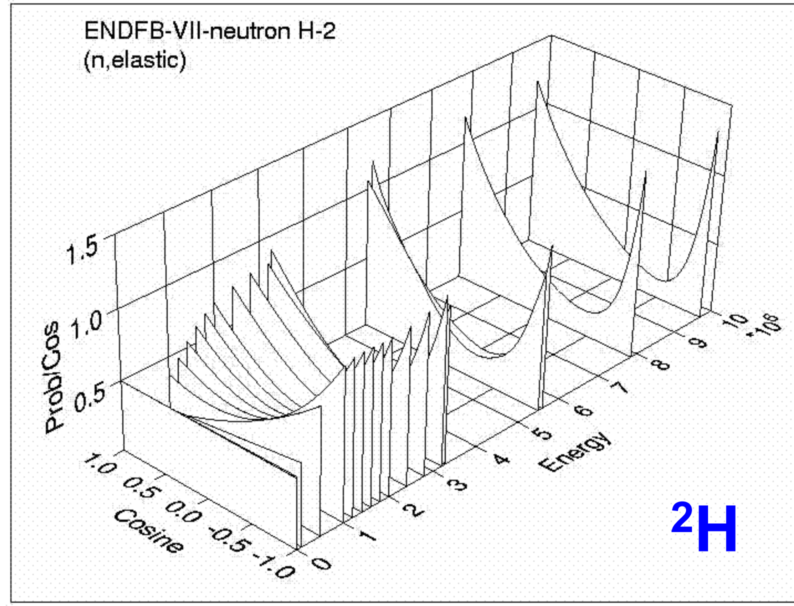
$$\left[\frac{E}{E_0}\right]_{\mathbf{min}} = \frac{(A-1)^2}{(A+1)^2} = \alpha$$

Isotropic in CMS:

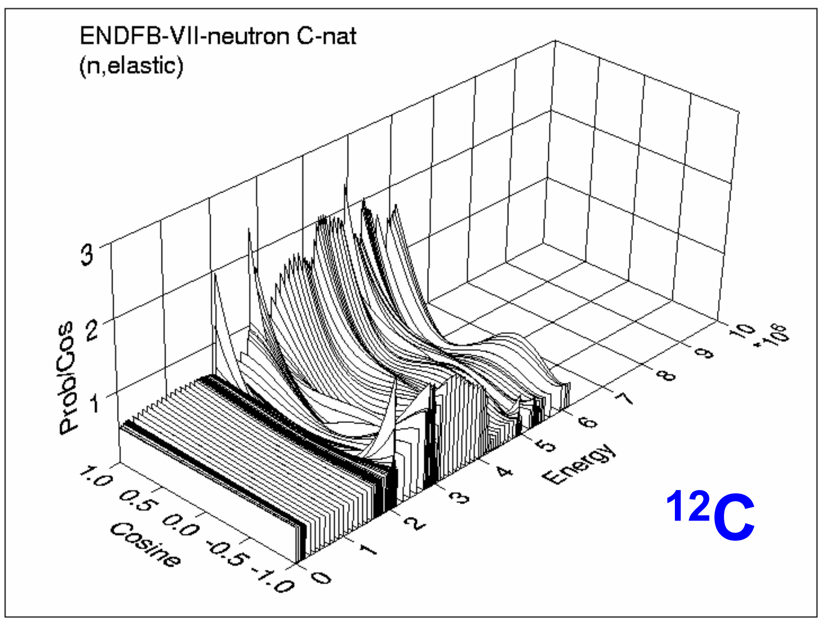


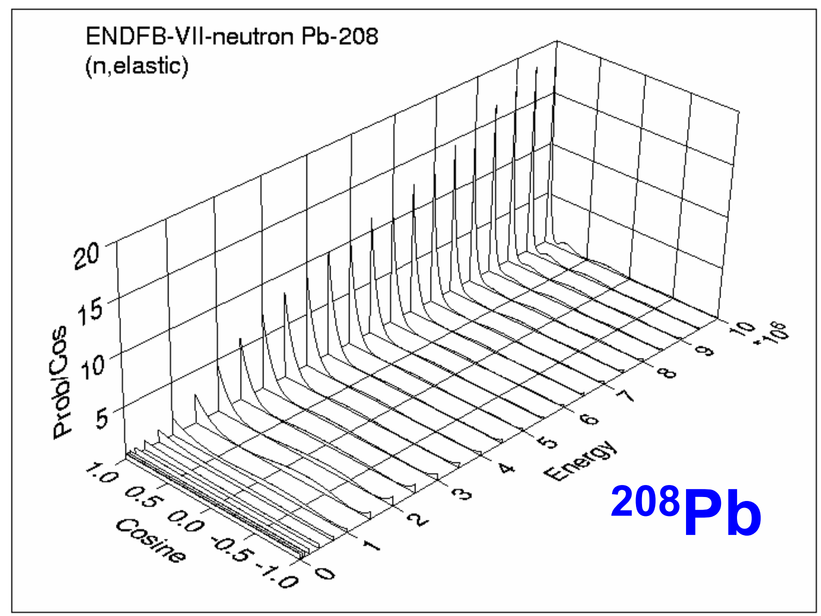

**1-$\alpha$:** H (1.0), D(0.89), C(0.28), Fe(0.069), Pb(0.019)



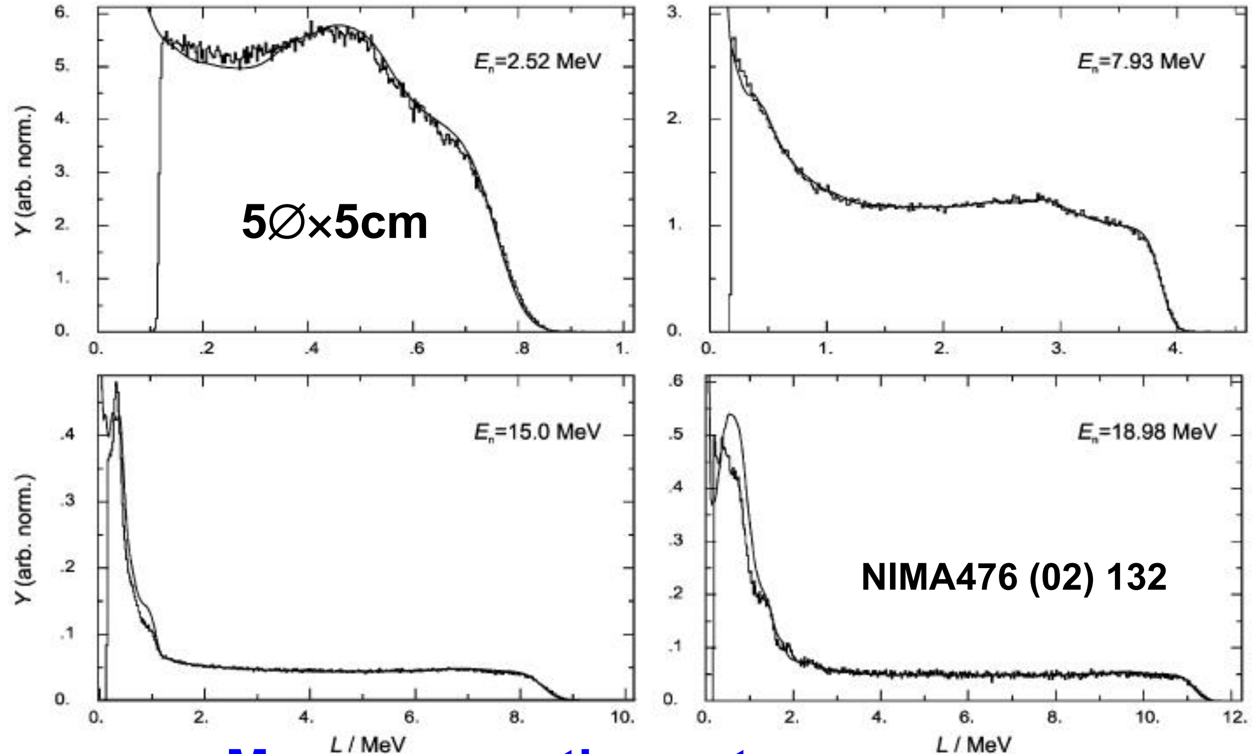

# ELASTIC SCATTERING ANGULAR DISTRIBUTION



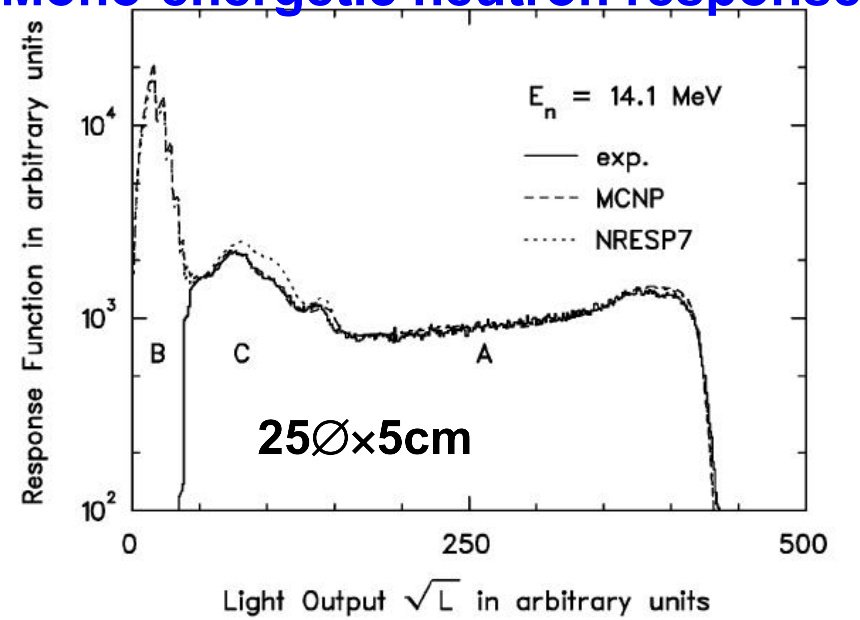



# BC501/NE213 liquid scintillators

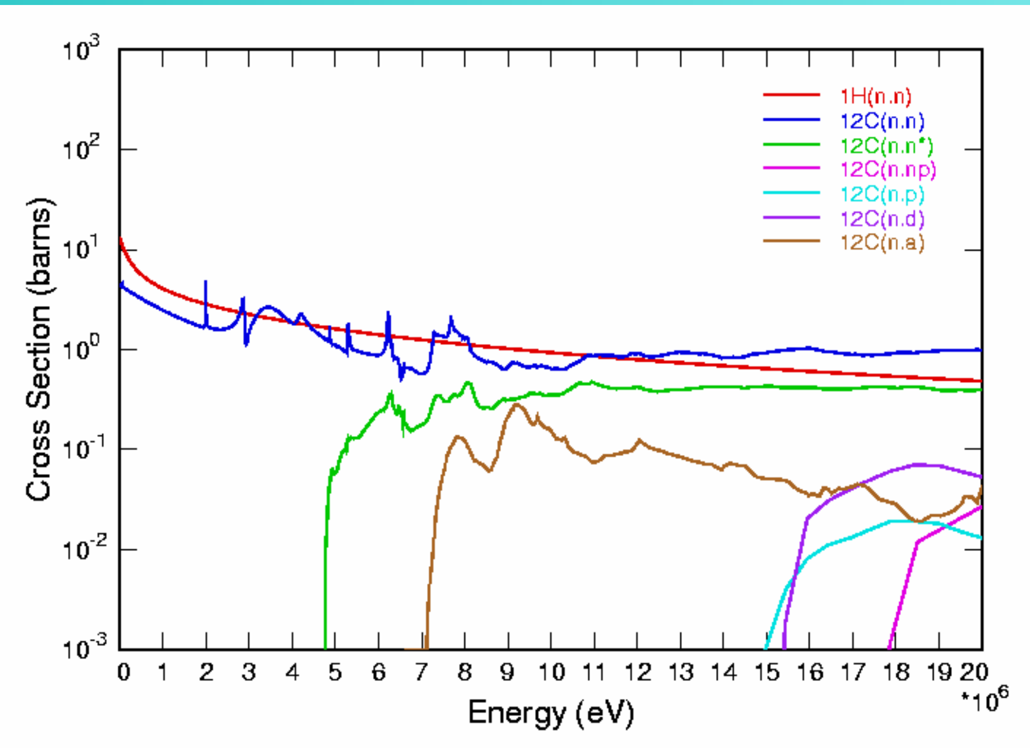
$C_1H_{1.212}$
$\rho$ = 0.874g/cm$^3$
n (@425nm) = 1.53
$\tau$ = 3.2 (32.3, 270) ns



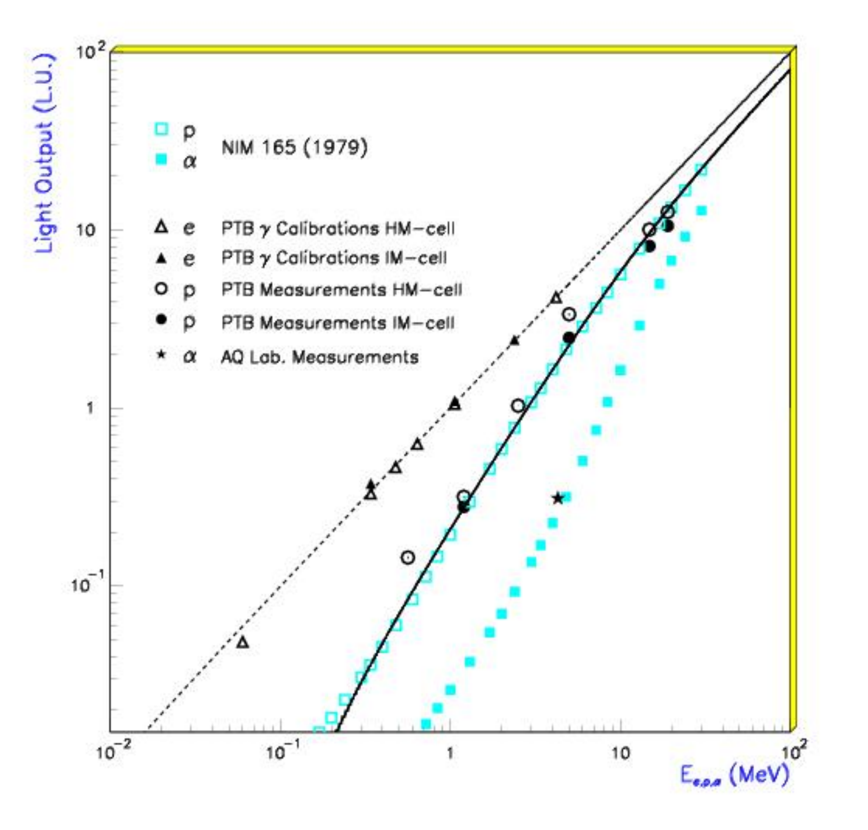

**Mono-energetic neutron response**



# Monte Carlo simulations of neutron interactions and detectors

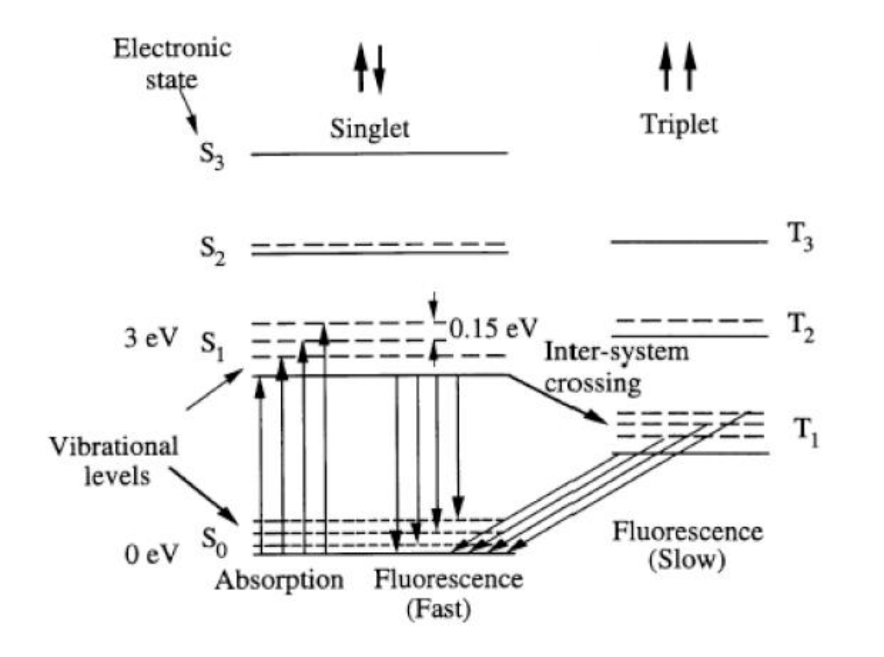


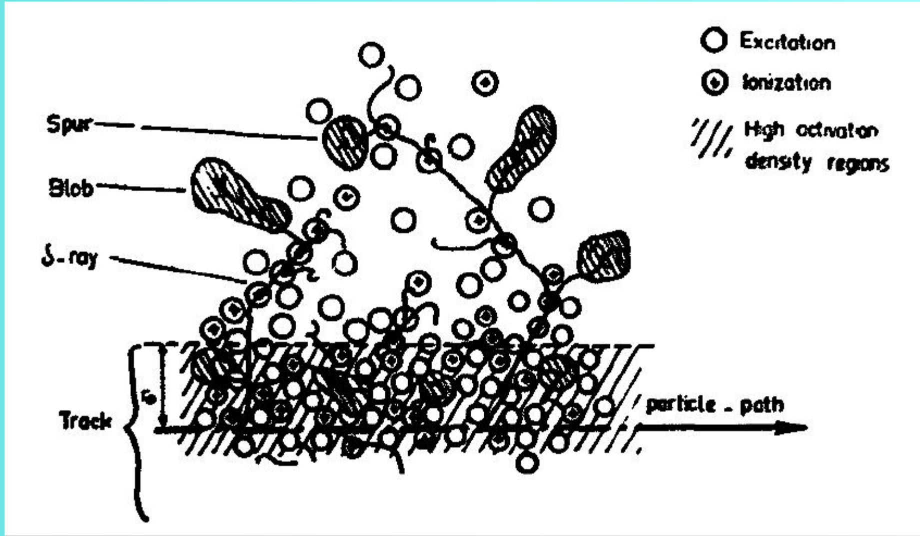

- Birth of modern MC approach
- General purpose codes: MCNP, GEANT, … and specific codes: NRESP, SCINFUL, …




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

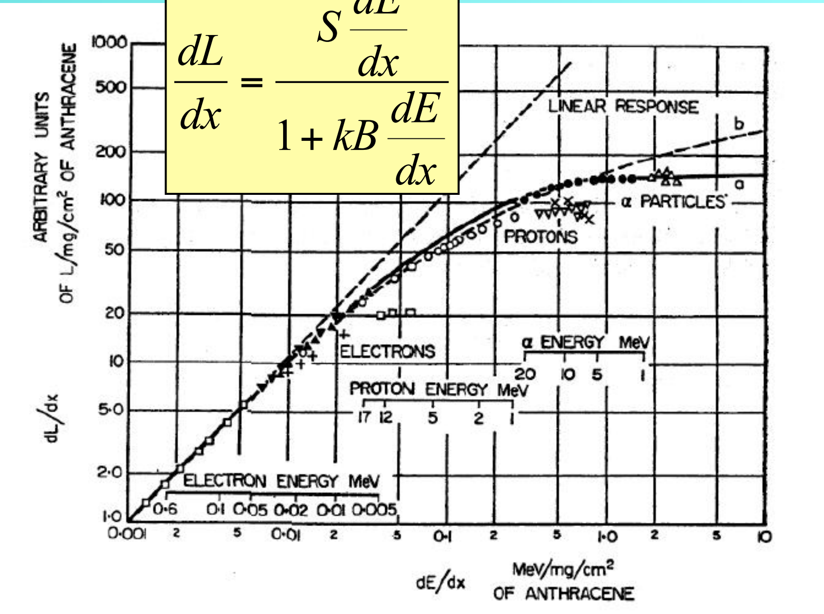
# Luminescence in organic materials



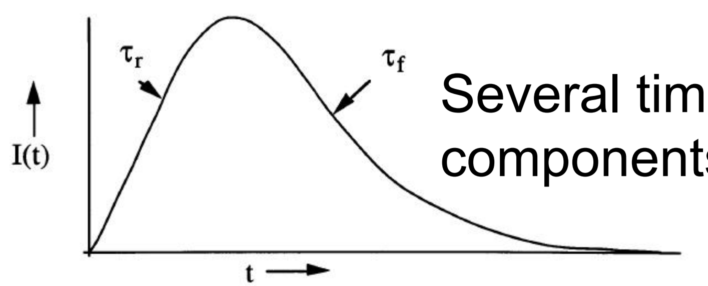




The non-radiative transfer mechanism between excited centers induces an energy-loss dependent light production …

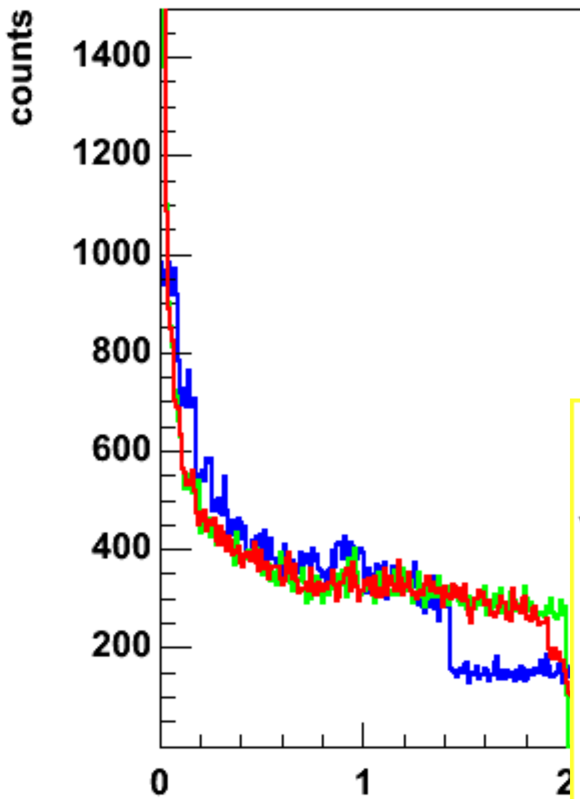
$$\frac{dL}{dx} = \frac{S\,\frac{dE}{dx}}{1 + kB\,\frac{dE}{dx}}$$

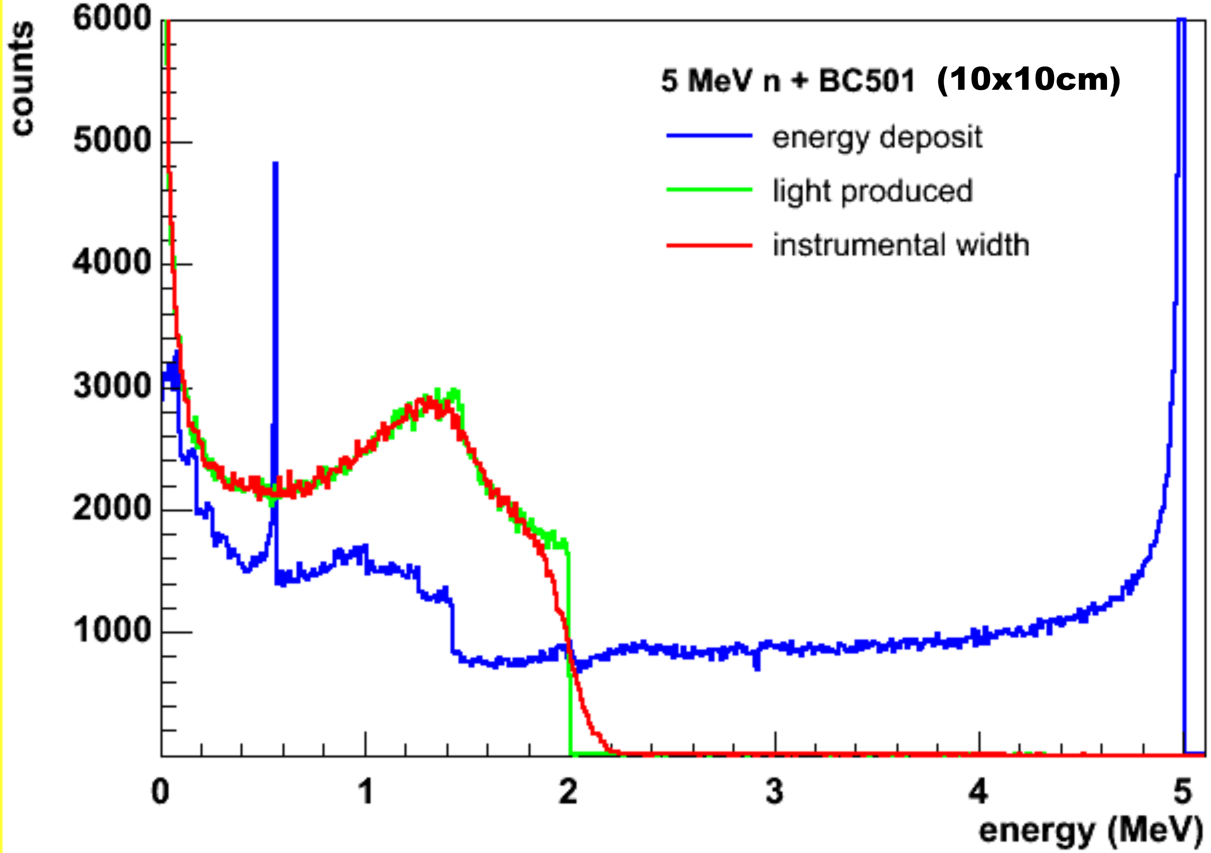



… and a varying time distribution

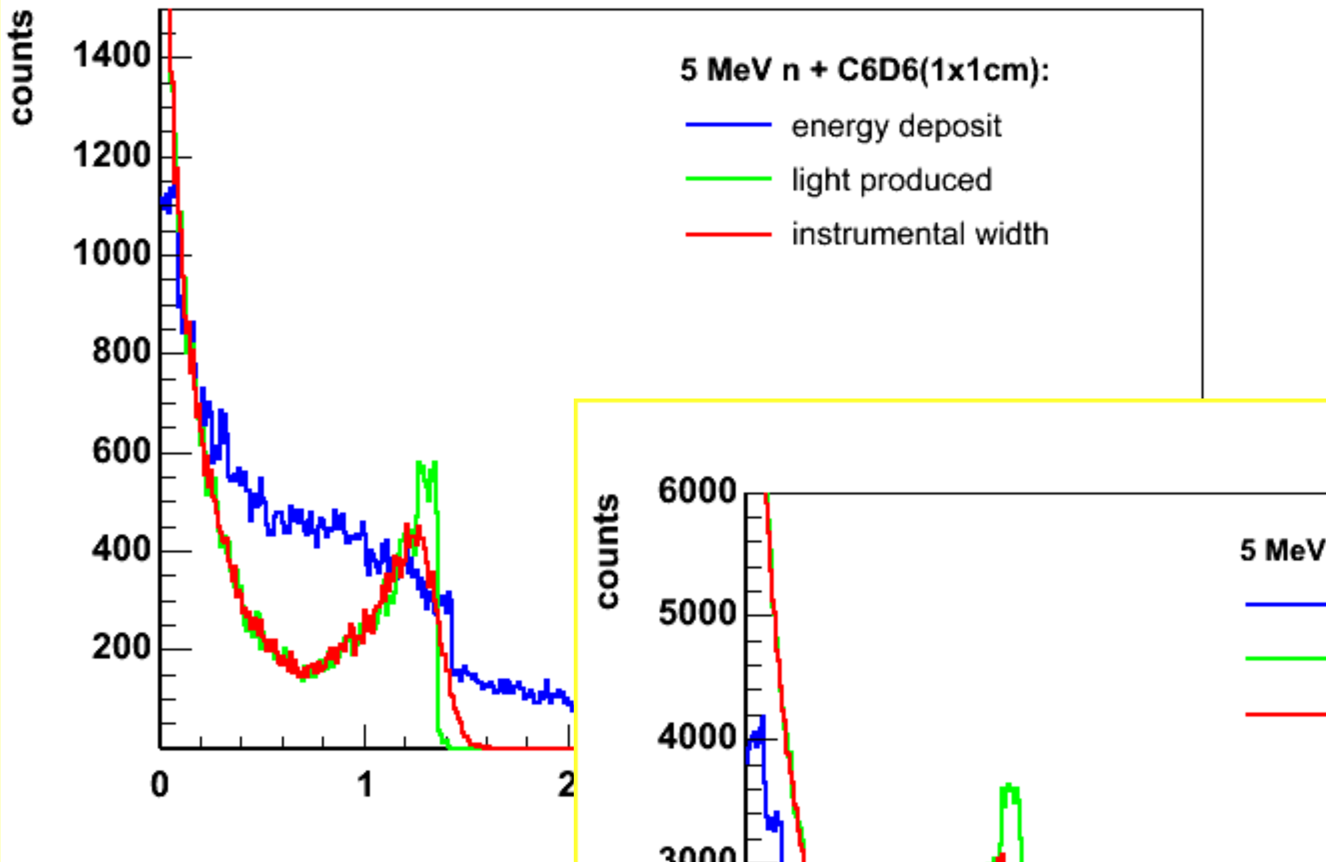


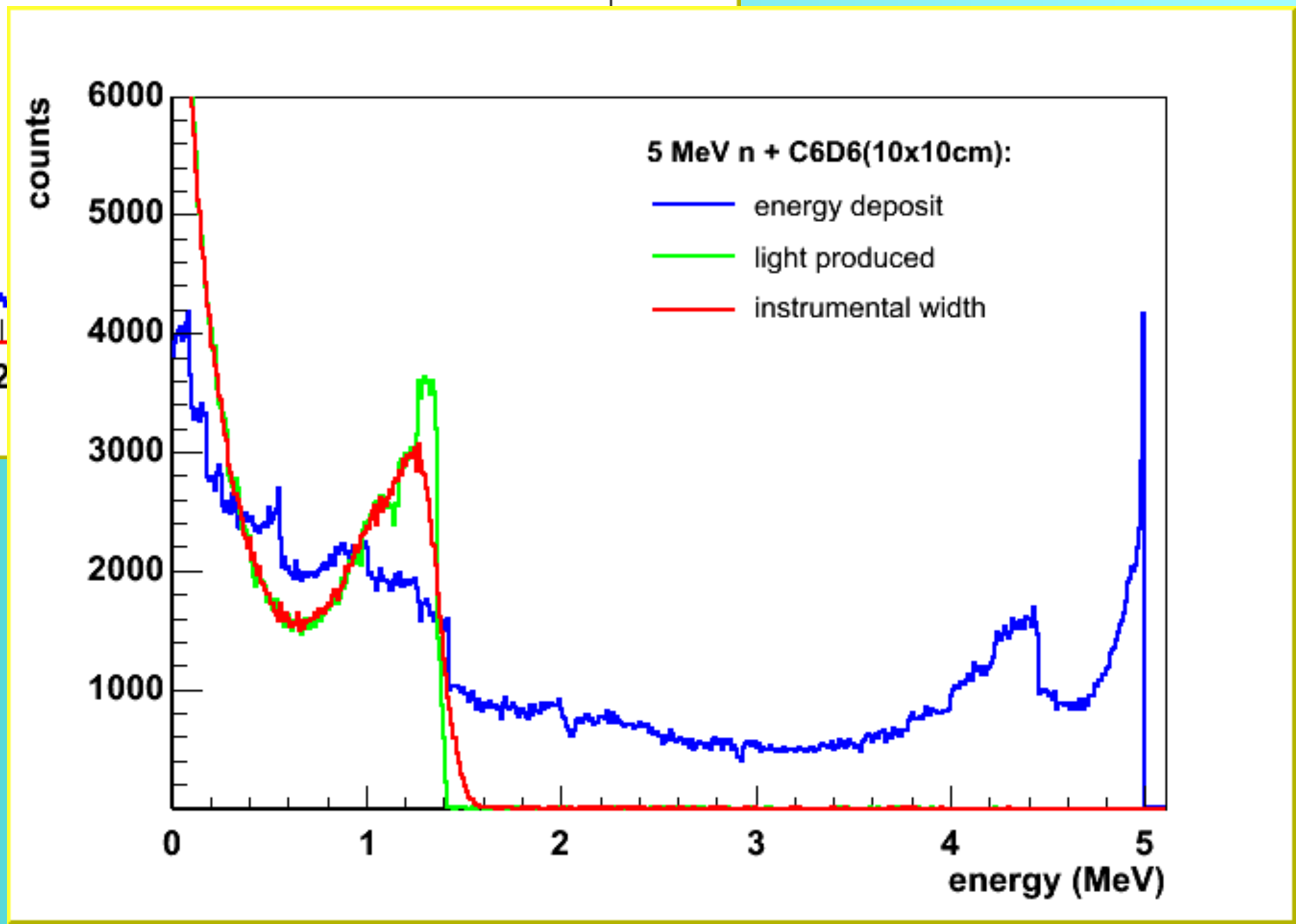

Several time components

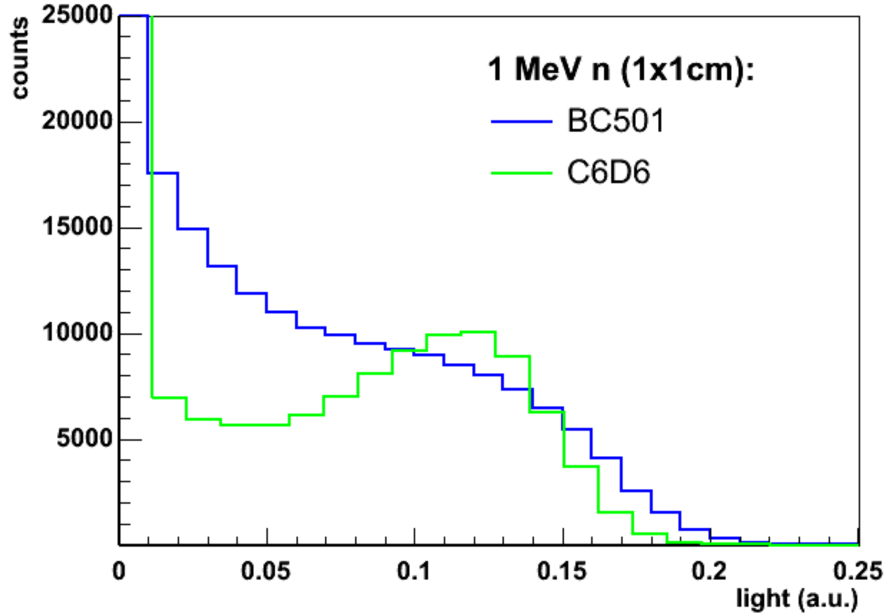


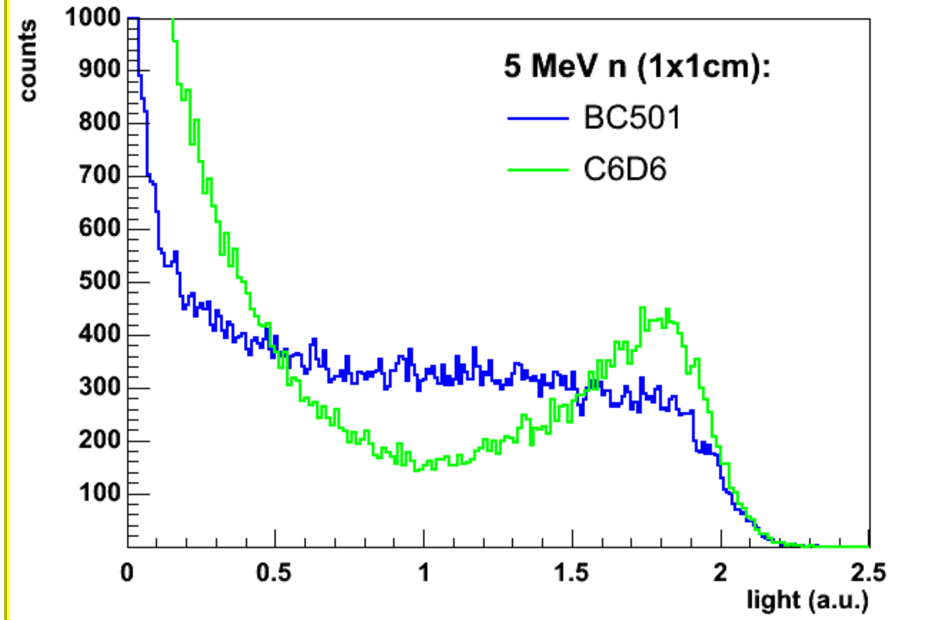



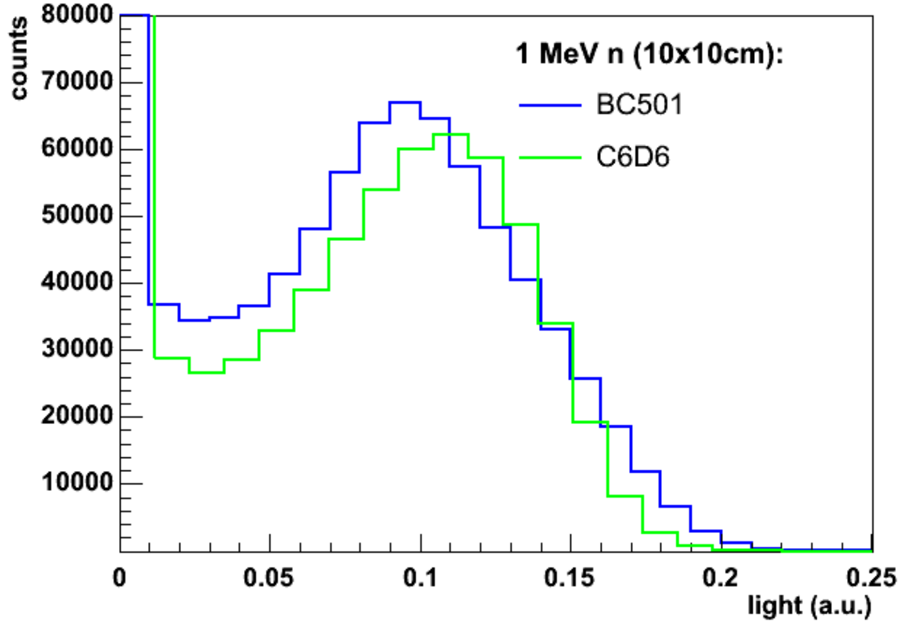

**Simulation with GEANT3/GCALOR**

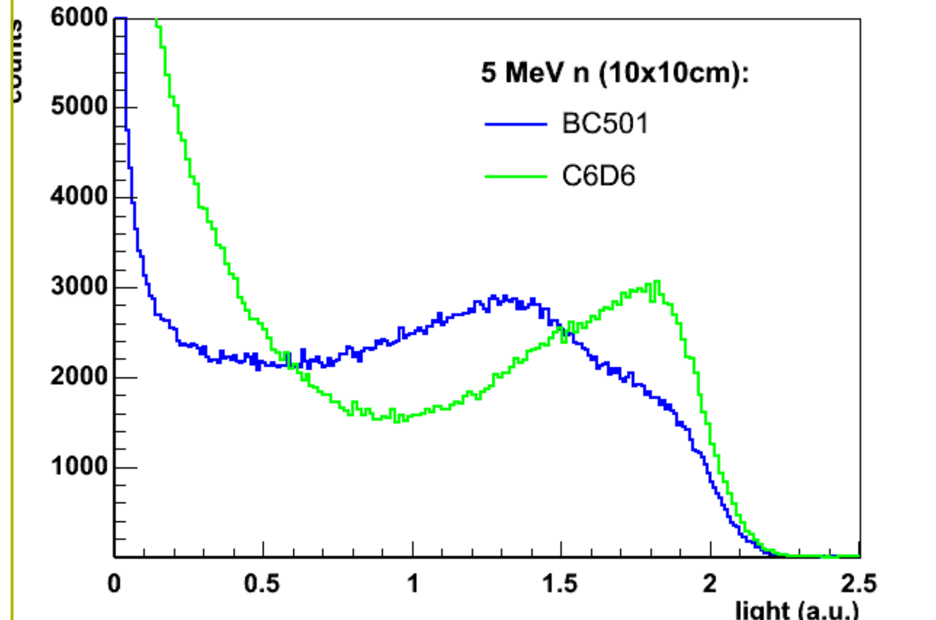

counts
1400
1200
1000
800
600
400
200
0
1
2
5 MeV n + C6D6(1x1cm):
energy deposit
light produced
instrumental width


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


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

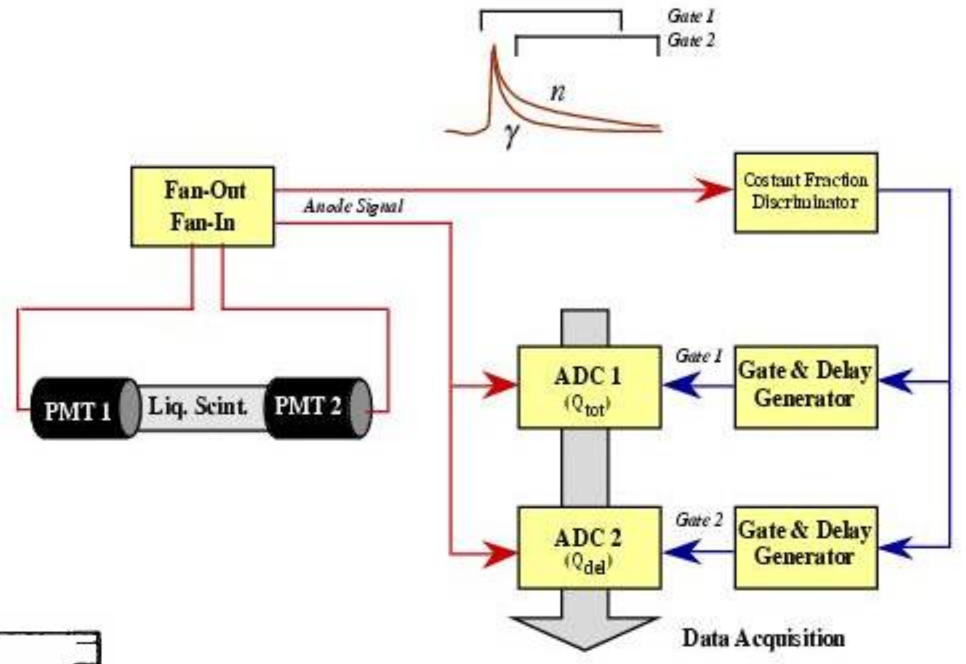

5 MeV n (1x1cm):
BC501
C6D6
counts
light (a.u.)
1000
900
800
700
600
500
400
300
200
100
0
0.5
1
1.5
2
2.5


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

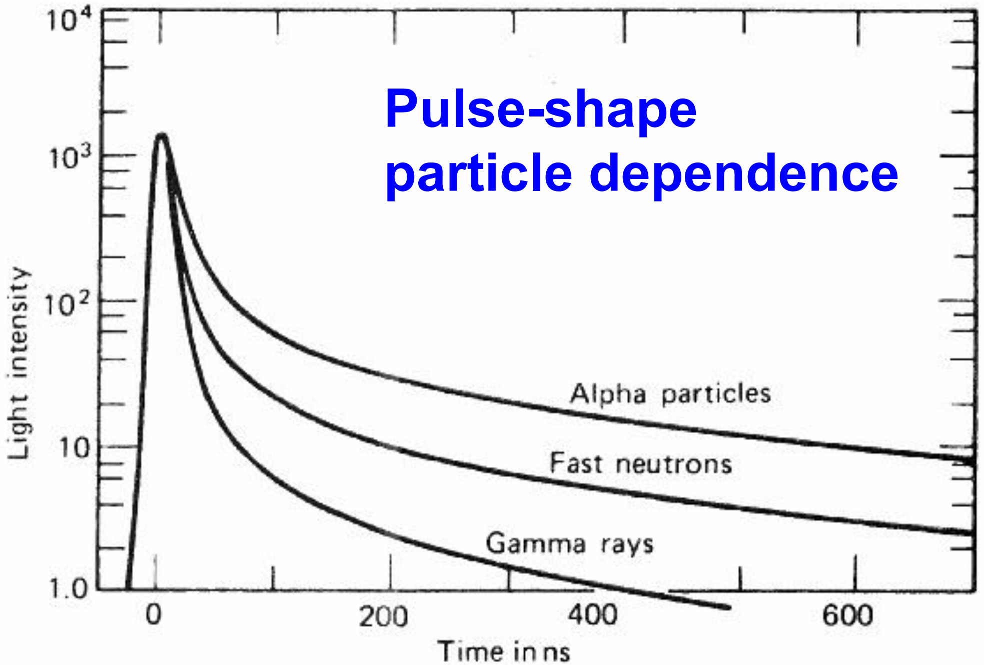

5 MeV n (10x10cm):
BC501
C6D6
light (a.u.)
6000
5000
4000
3000
2000
1000
0
0.5
1
1.5
2
2.5

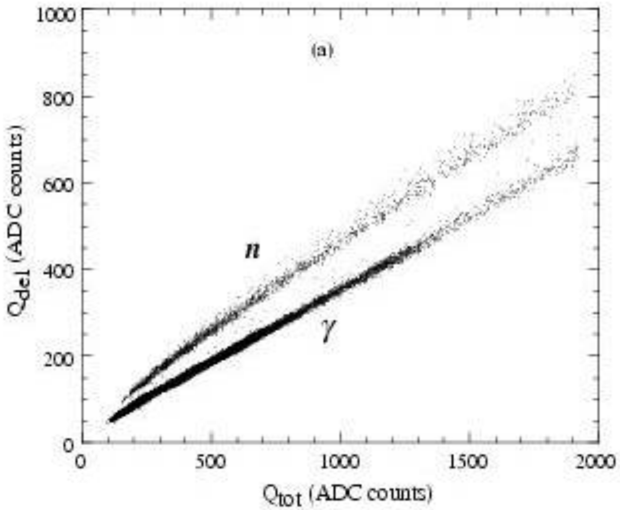
# BC501/NE213

## Pulse Shape Discrimination

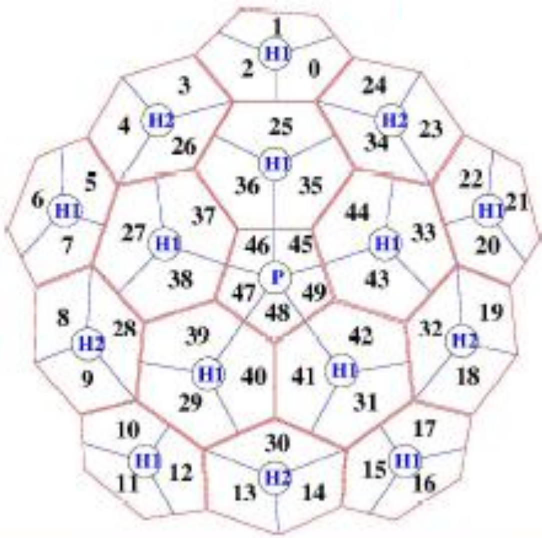



**Pulse-shape particle dependence**



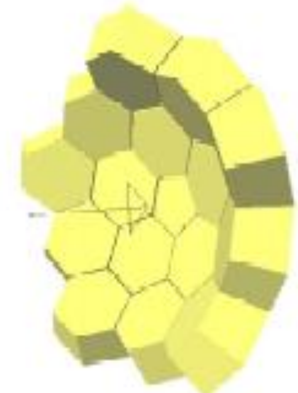
# Multi-detector: Neutron Wall (EUROBALL)




**BC501 liquid scintillator**

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

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

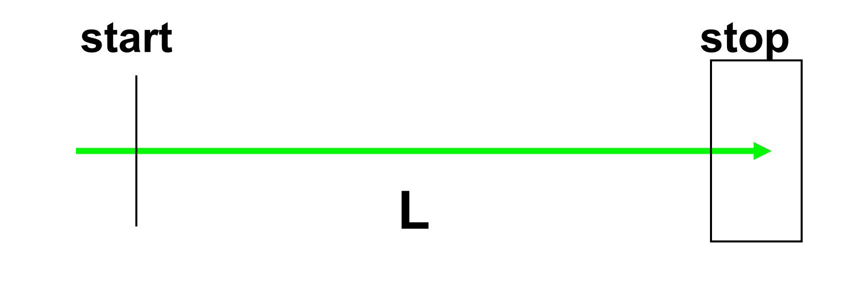




Johan Nyberg, AGATA meeting Orsay, 2004-06-22

# 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)

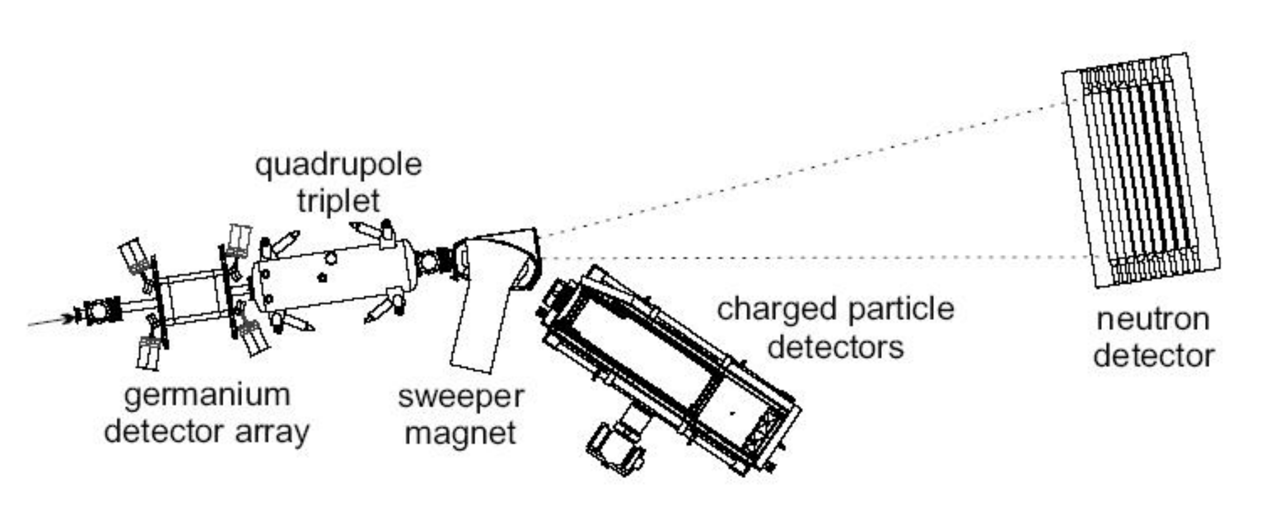
**Stop Time**: neutron detector

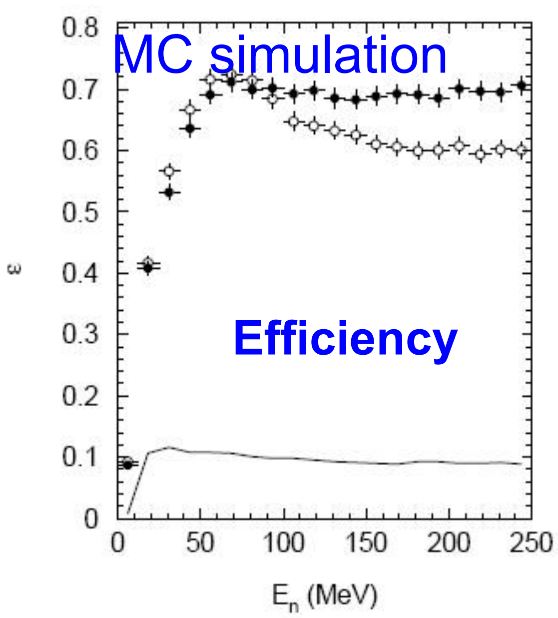
**Energy resolution:** $$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

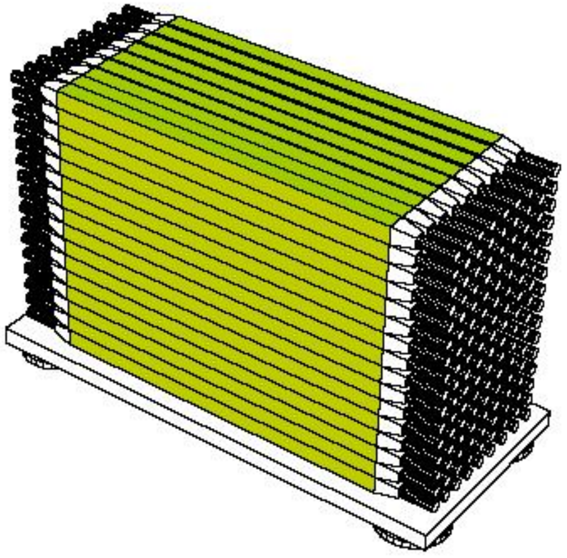
✦ **Long flight path, short detectors, good time resolution**

# ToF spectrometer: MoNA (NSCL-Michigan)

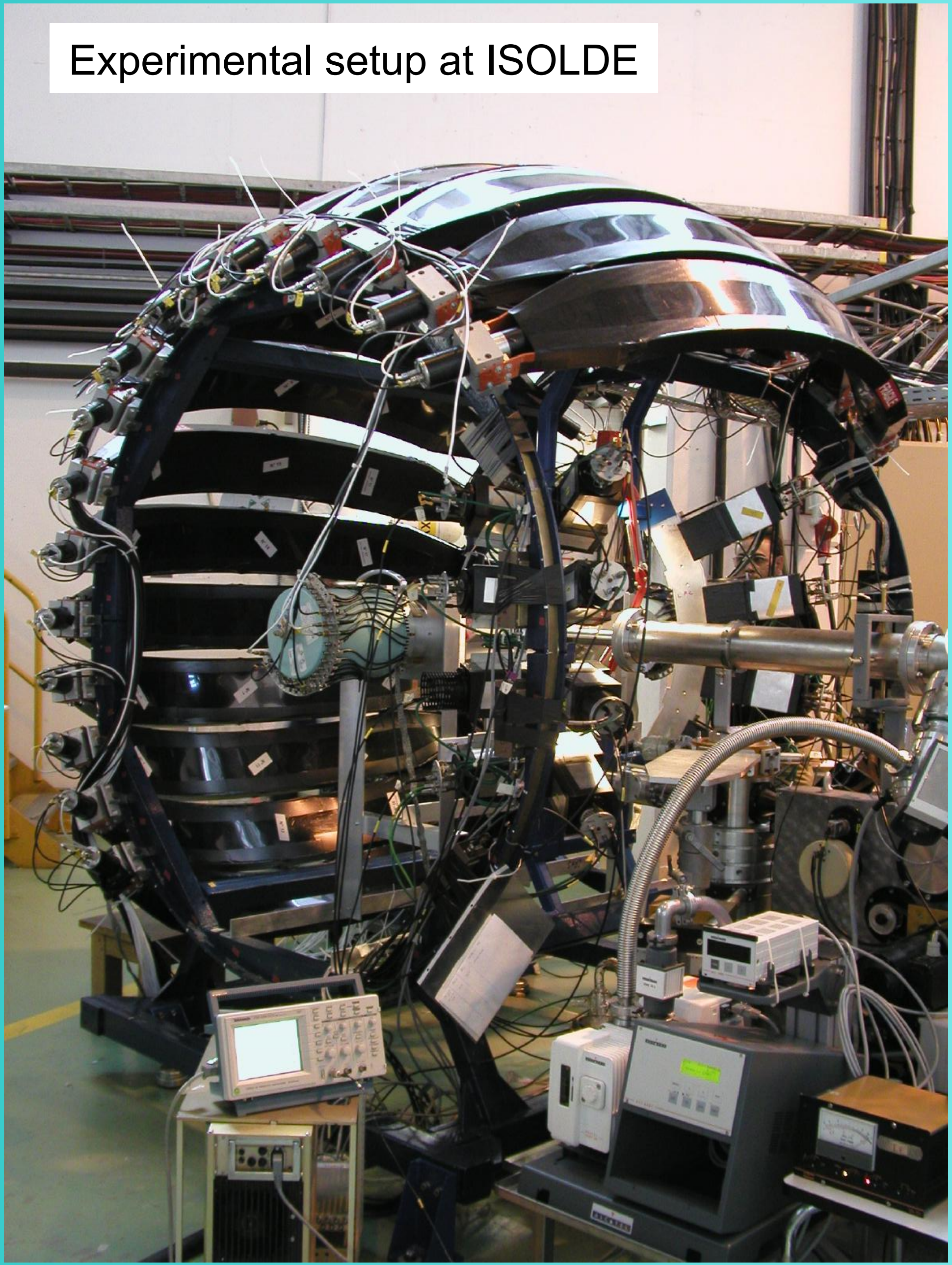
**144 bars**
**200x10x10 cm$^3$**
**plastic scintillators+**
**iron converters**



# ToF spectrometer: TONERRE (LPC-Caen)

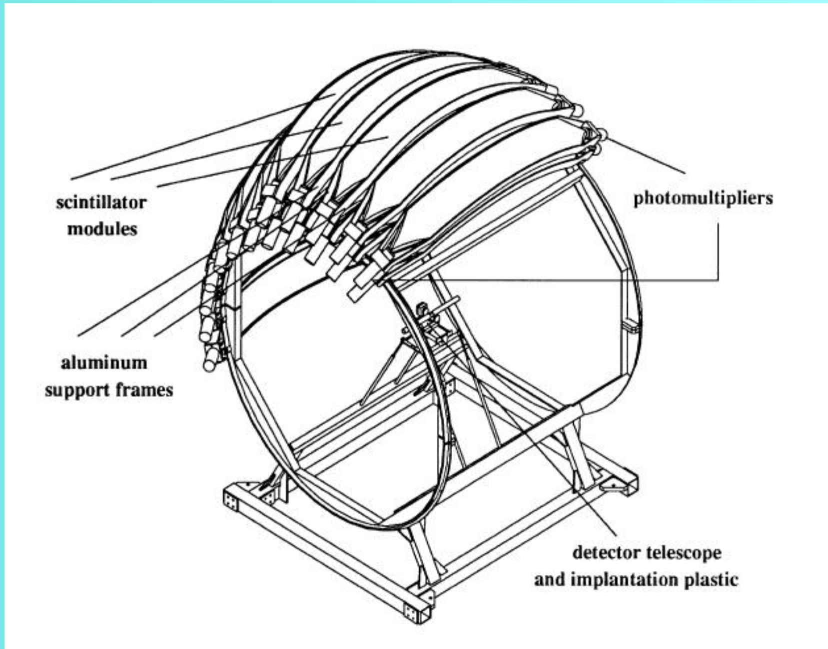



**BC400 Plastic scintillator**

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

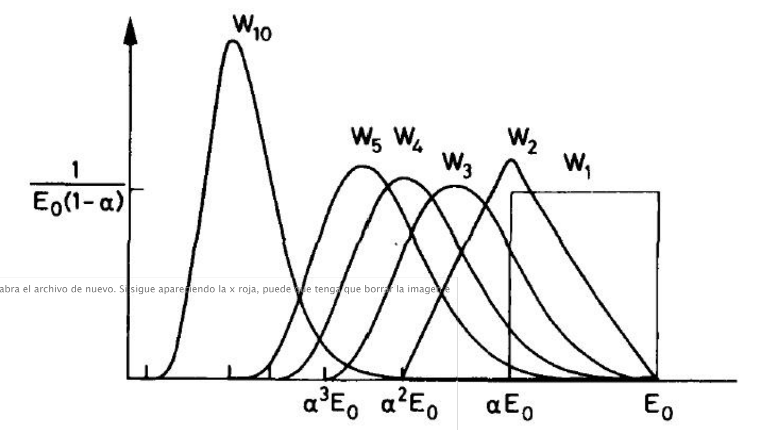
$$\varepsilon_{\text{int}} = 25\ \%$$

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




NIMA 455 (2000) 412

# 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:

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

Number of collisions to reach an energy:

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

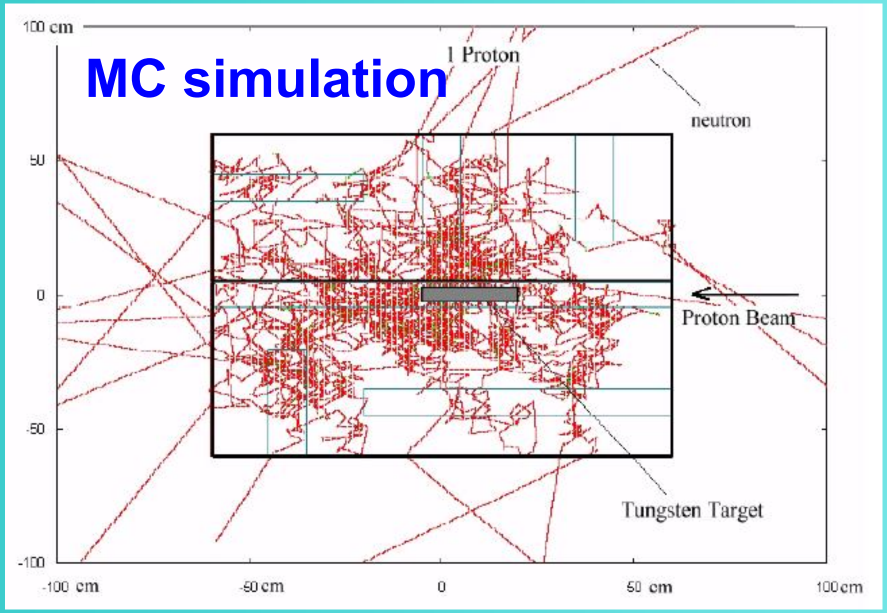
Slowing-down time: $$t = \sqrt{\frac{K}{E_f}} - t_0 : \quad K(\xi, \sigma_{ela}); t_0(E_0, \xi, \sigma_{ela})$$

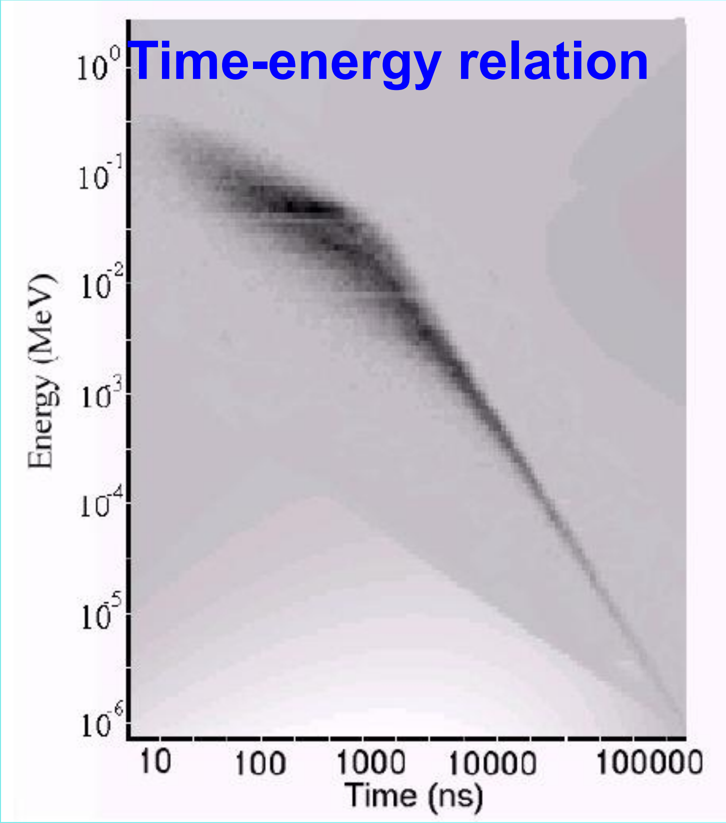
# Slowing Down Spectrometer: LSDS (LANL-Los Alamos)

**Lead block + sample+counters**

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

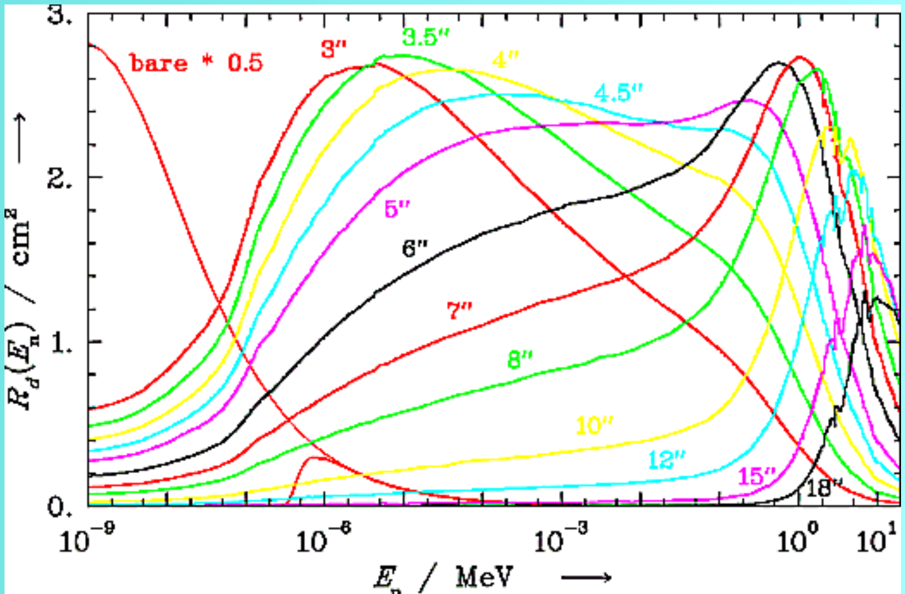
$$\frac{\Delta E}{E} = 30\ \%$$

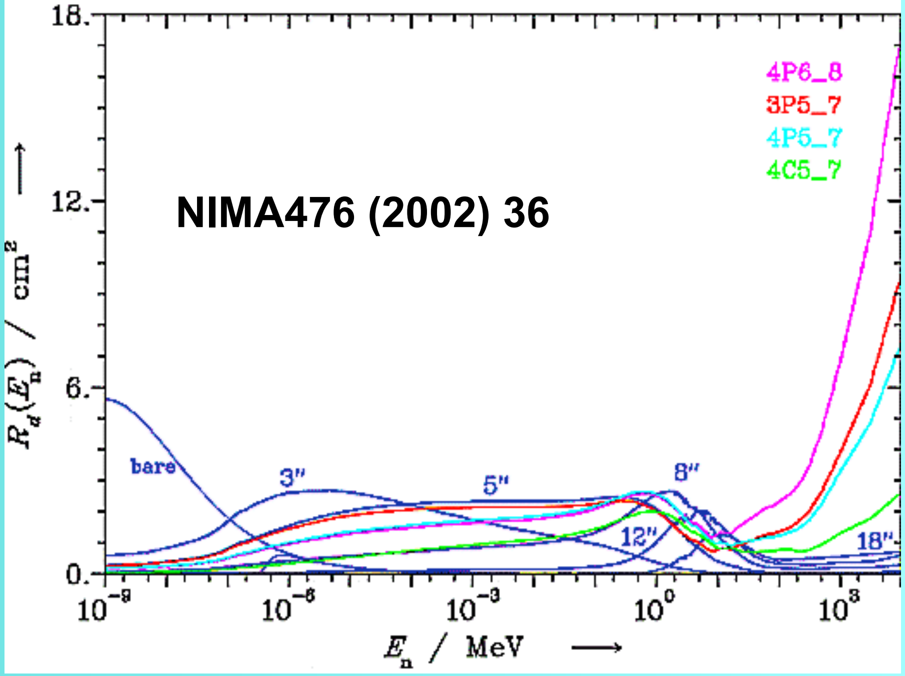


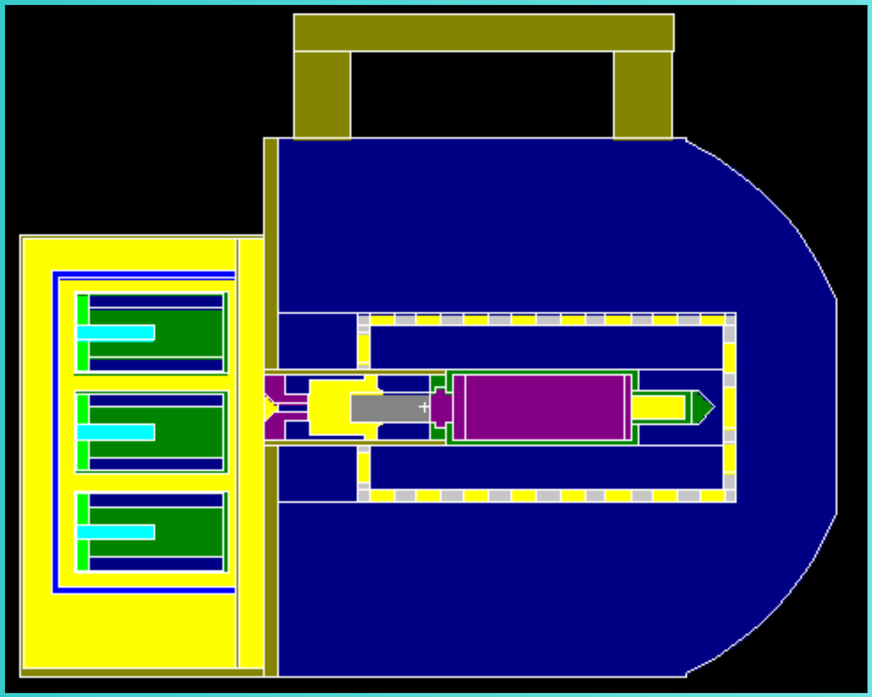
# Bonner spheres: NEMUS (PTB-Braunschweig)

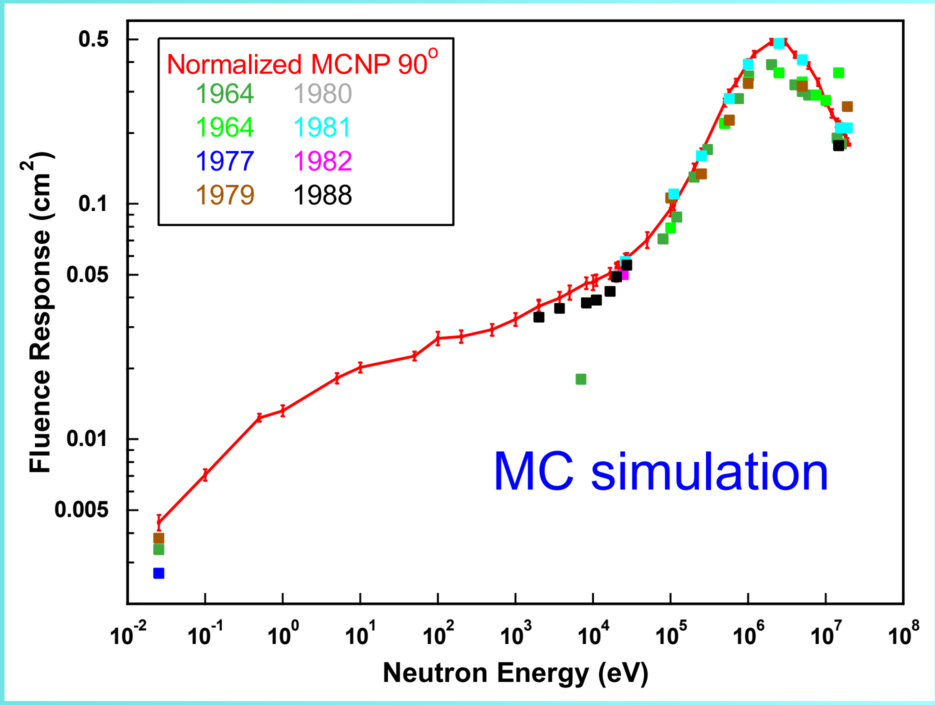
**Polyethylene sphere +**
**$^{3}$He proportional counter**



# 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: $\mathbf{d} = \mathbf{R} \cdot \mathbf{p}\,; \qquad d_i = \sum_j R_{ij} \cdot p_j\,, \forall i$

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:

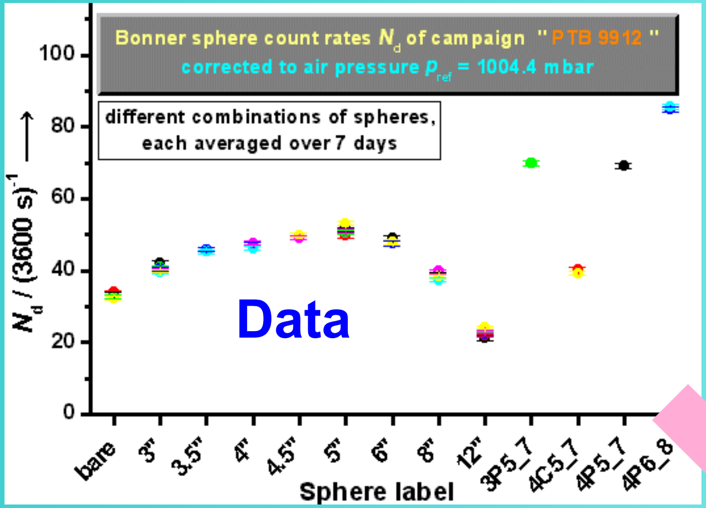
Linear regularization (LR): $\mathbf{p} = (\mathbf{R} + \lambda \mathbf{H})^{-1} \cdot \mathbf{d}$

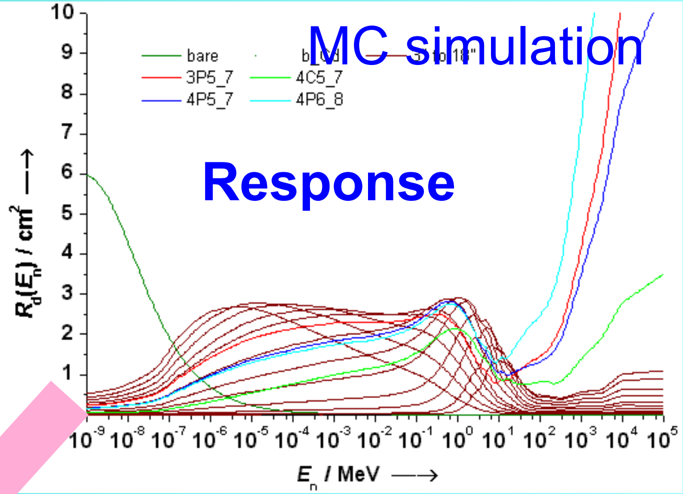
Maximum Entropy (ME): $$p_j^{(m+1)} = p_j^{(m)} \exp\left( \frac{1}{\lambda} \sum_i \frac{R_{ij}}{\sigma_i^2} \left( d_i - \sum_k R_{ik} p_k^{(m)} \right) \right)$$

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

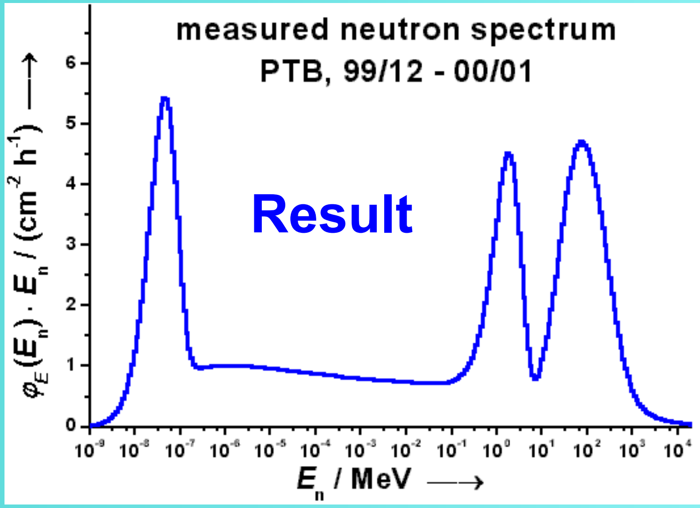
# Deconvolution

## Bonner spheres measurements




MAXED



# The Long Counter

Uni-directional,
flat-efficiency

**Moderator+shielding +$BF_3$**

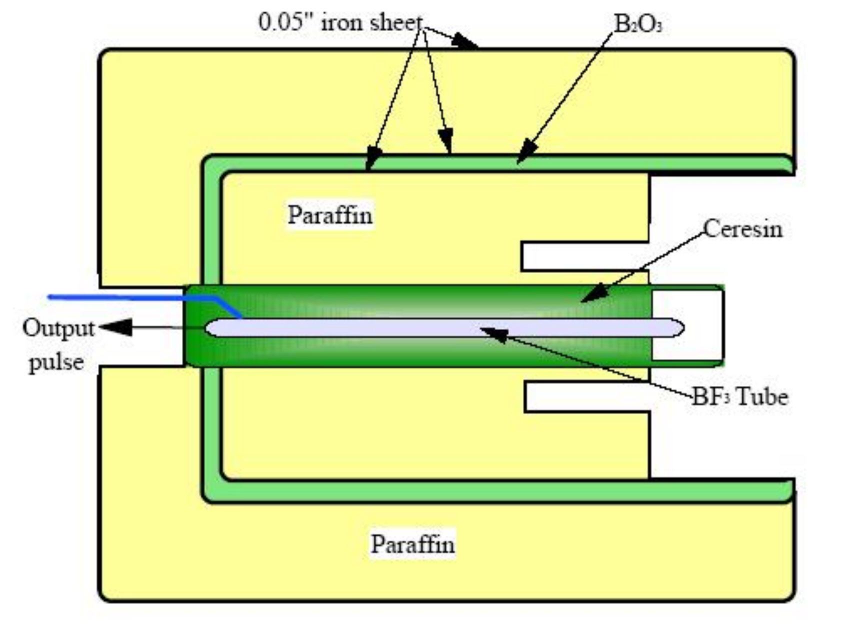
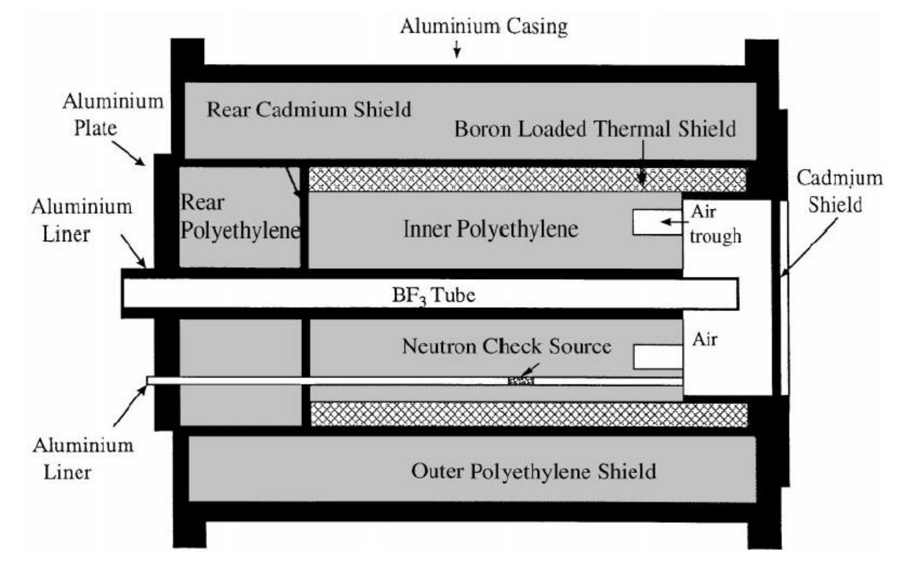
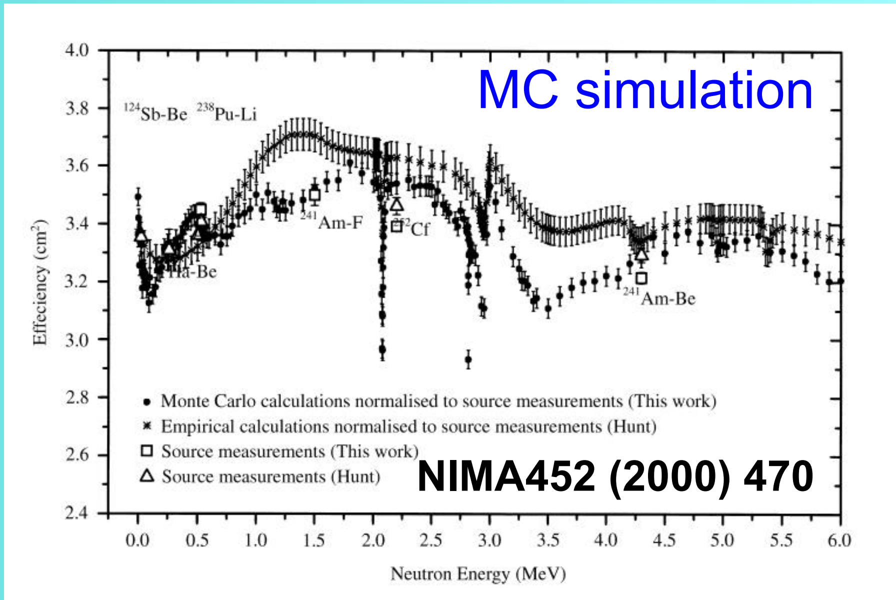



Figure 7-16. Long Counter

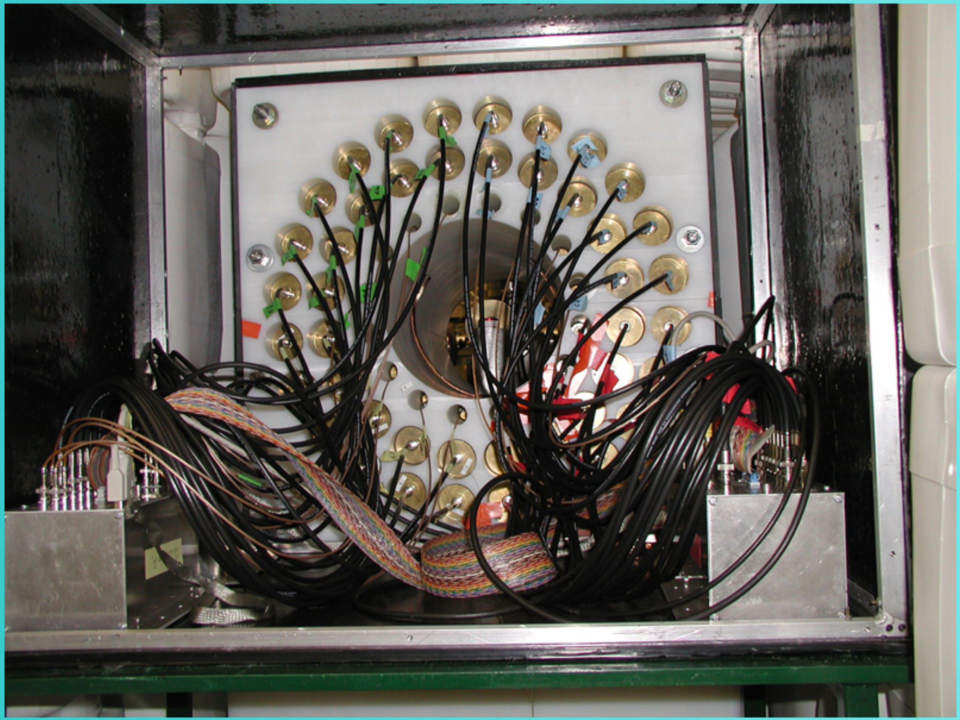


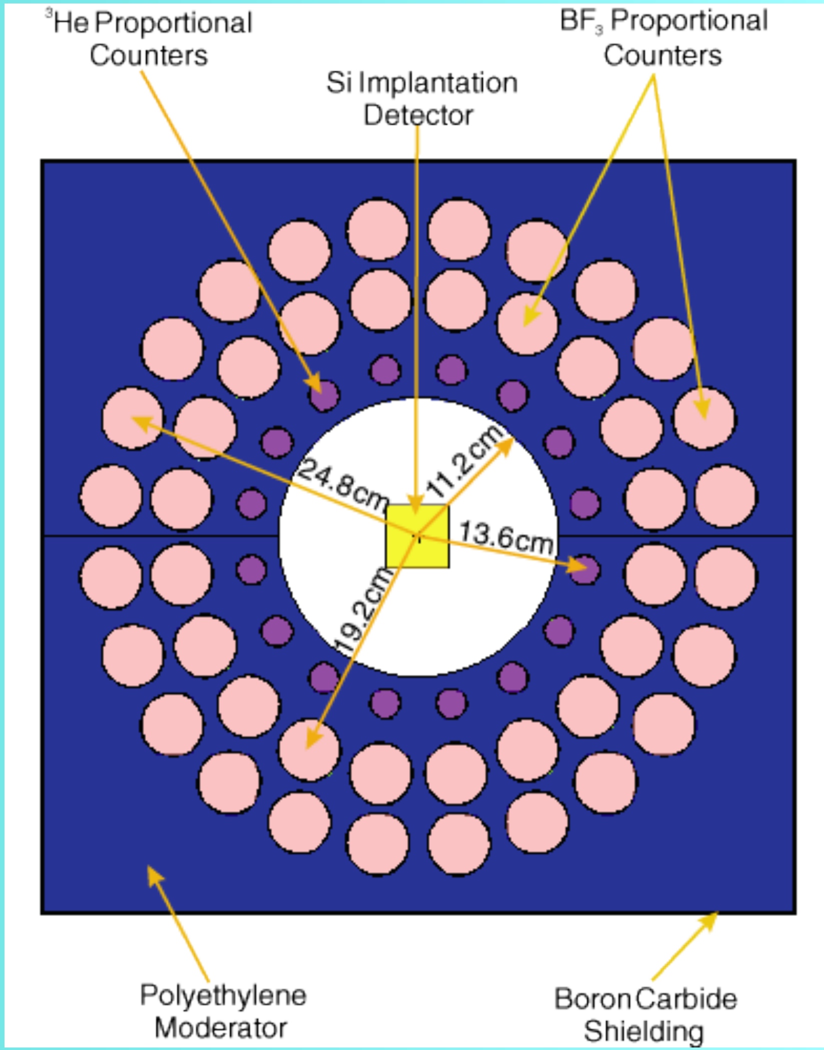



# Moderated cylindrical array: NERO (NSCL-Michigan)

**Polyethylene block (60x60x80cm$^3$)**
**16 $^3$He and 44 $BF_3$ proportional counters**

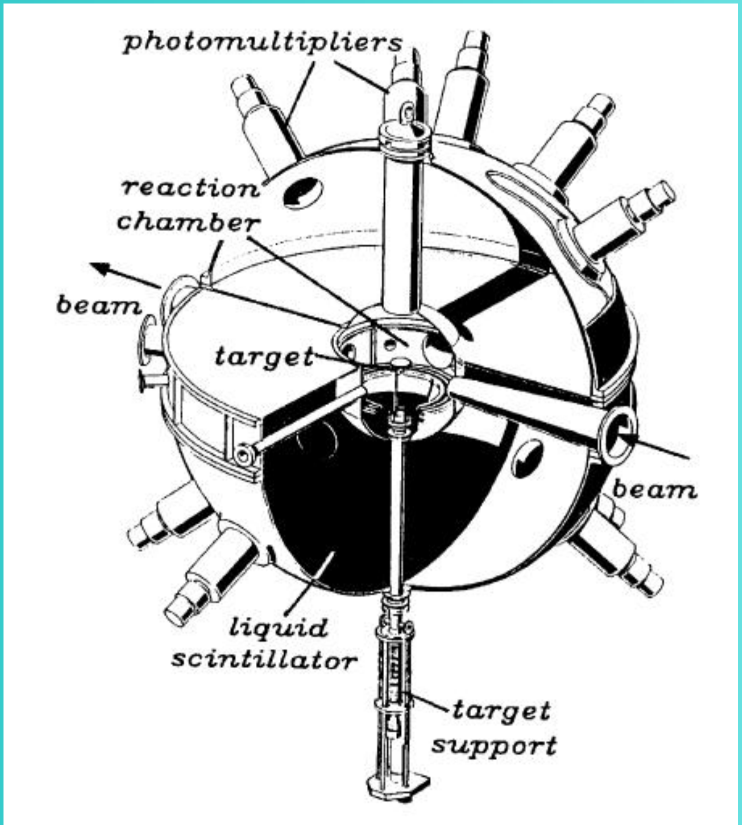
$$\varepsilon = 40\ \%$$

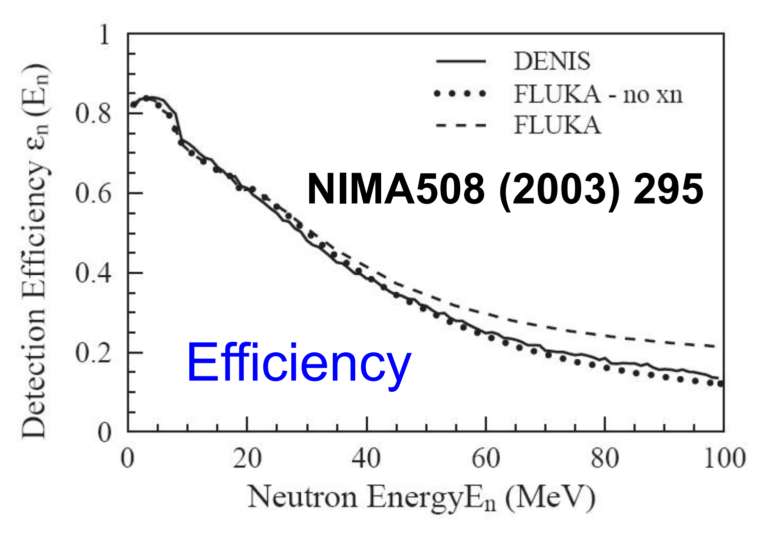


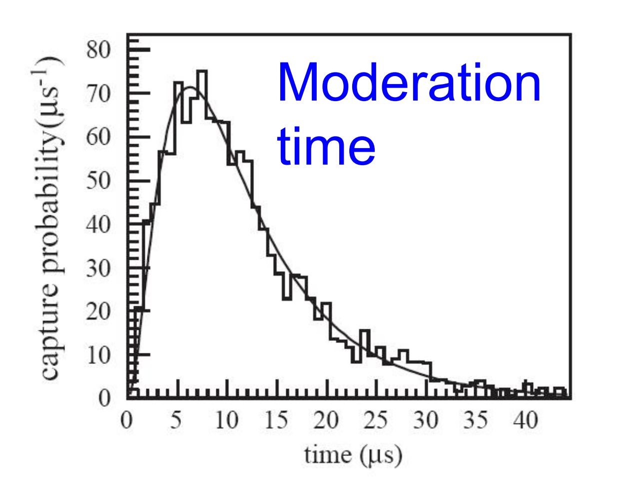


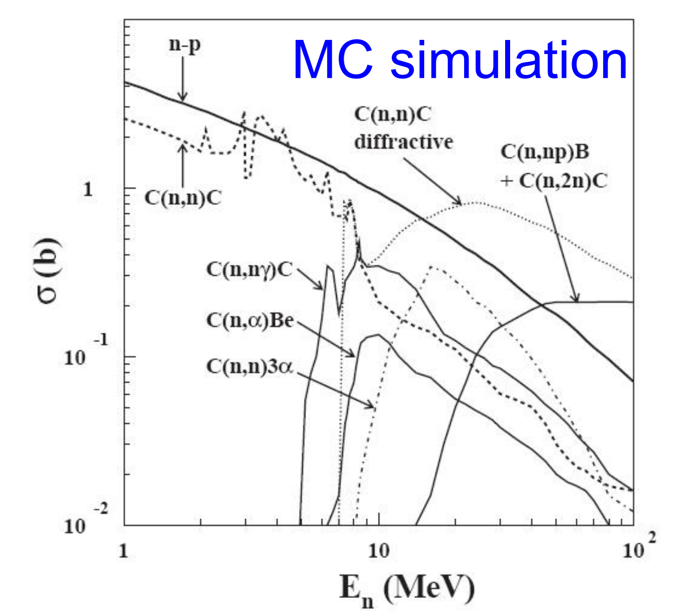
# Berlin Neutron Ball

## 1.5 m$^3$ 0.4% Gd-loaded liquid scintillator



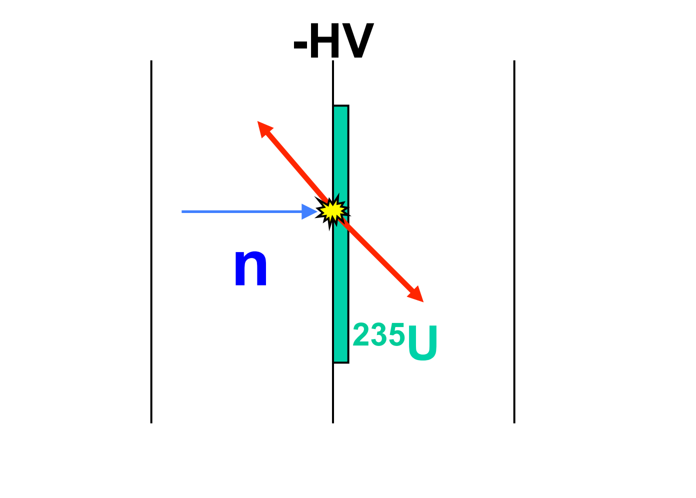



# Fission chamber:

## U, Pu + gas chamber




NIMA336 (1993) 226

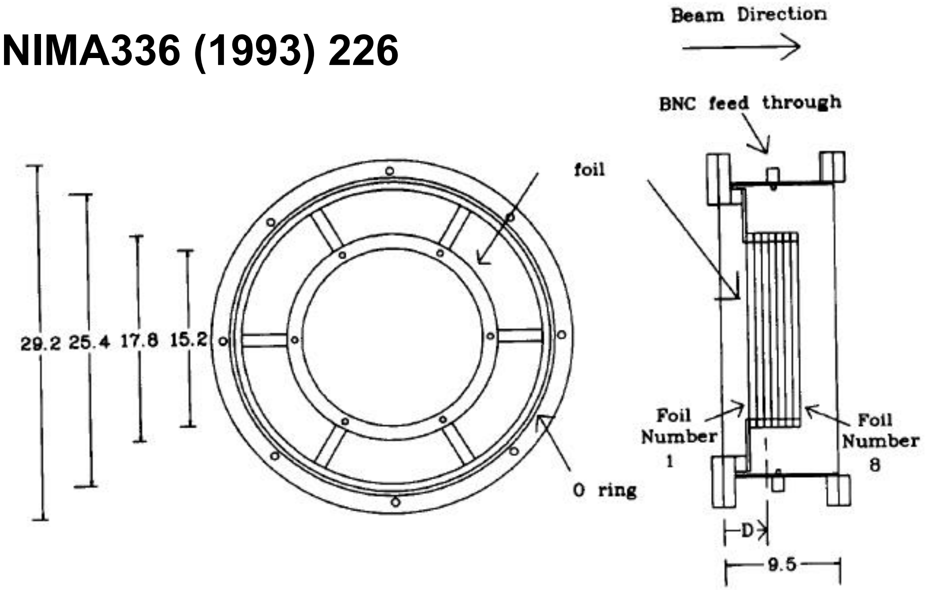
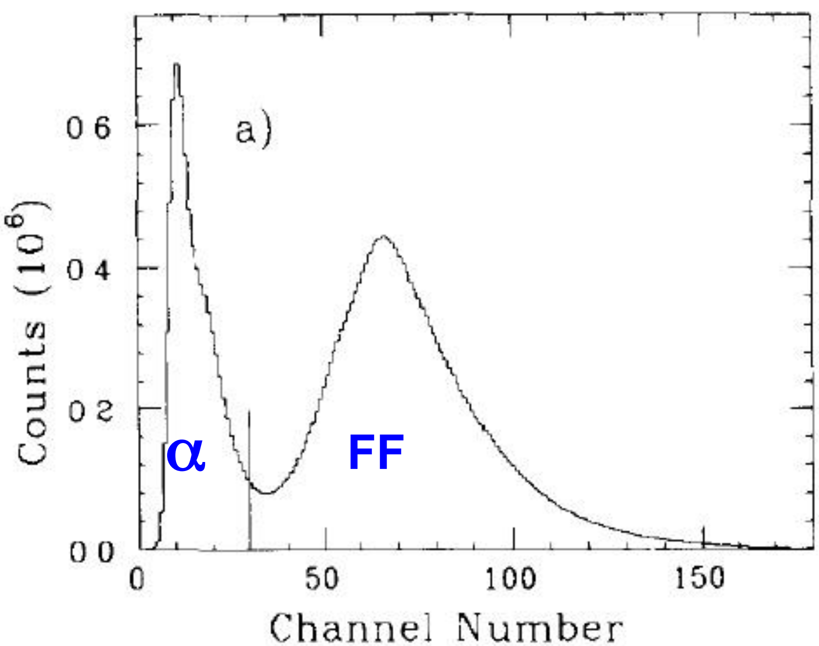



Fig. 1. Schematic diagram of the ionization chamber housing. Dimensions are in centimeters.



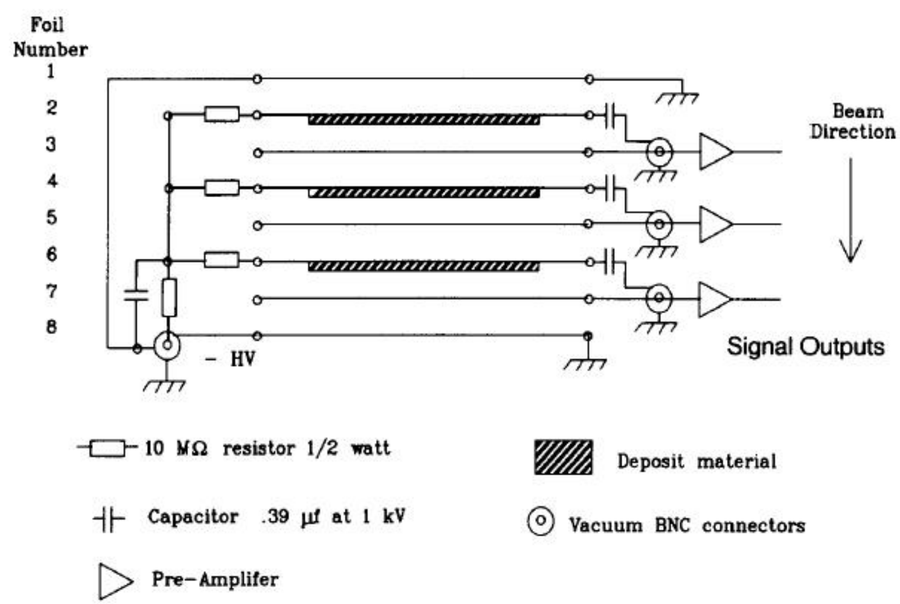




Fig. 2. Electrical wiring diagram of the ionization chamber.