Chapter 11:
Neutrons detectors

Contents

- Principles of neutrons detection
- Slow neutron detection methods
- Fast neutron detection methods

Introduction

- Neutrons are uncharged particles → cannot be directly detected
- Neutrons are generally detected trough nuclear reactions with atomic nuclei → emission of charged particles (proton, α, fission fragments,…) that can be detected
- Neutron reaction cross sections are very energy dependent → two energy domains are considered → slow neutrons ($E < 0.5$ eV) and fast neutrons ($E > 0.5$ eV)

Slow neutrons

- Materials used for neutrons detection
- Neutrons sensitive proportional counters
- Neutrons sensitive scintillators
- Neutrons detectors based on fission
- Neutrons detectors for nuclear power plants

Slow neutron detection: Choice of materials

- Cross section of the reaction must be large → efficient detectors with reasonable dimensions
- Generally → intense field of γ rays → discrimination against these γ rays must be considered in the material choice
- Importance of the Q value (liberated energy) → for Q ↗ → energy given to the reaction products ↗ → easier is the discrimination against the γ rays using amplitude discrimination
- Distances travelled by the reaction products has also importance (for slow neutrons in solids: a few tenths of mm; in gas: several cm)

Important reactions for neutron detection (1)

- Boron reaction: ^{10}B(n,α) →

$$^{10}_{5}B +^{1}_{0} n \rightarrow \begin{cases} ^{7}_{3}Li +^{4}_{2} \alpha & Q = 2.792 \text{ MeV (ground state)} \\ ^{7}_{3}Li^{*} +^{4}_{2} \alpha & Q = 2.310 \text{ MeV (excited state)} \end{cases}$$

- When thermal neutrons (E≈0.025 eV) → 94% to Li* and 6% to Li → Q very large → impossible to extract information about neutron energy
- Also net momentum is zero → for instance for the excited state →

$$\begin{aligned} E_{Li} + E_{\alpha} &= Q \\ m_{Li} v_{Li} &= m_{\alpha} v_{\alpha} \end{aligned}$$

➡ $E_{Li} = 0.84 \text{ MeV} \quad \text{and} \quad E_{\alpha} = 1.47 \text{ MeV}$

Important reactions for neutron detection (2)

- Lithium reaction ^{6}Li(n,α) →

$$ {}^6_3Li + {}^1_0 n \rightarrow {}^3_1 H + {}^4_2 \alpha \qquad Q = 4.78 \text{ MeV} $$

$$ \Rightarrow \quad E_H = 2.73 \text{ MeV} \quad \text{and} \quad E_\alpha = 2.05 \text{ MeV} $$

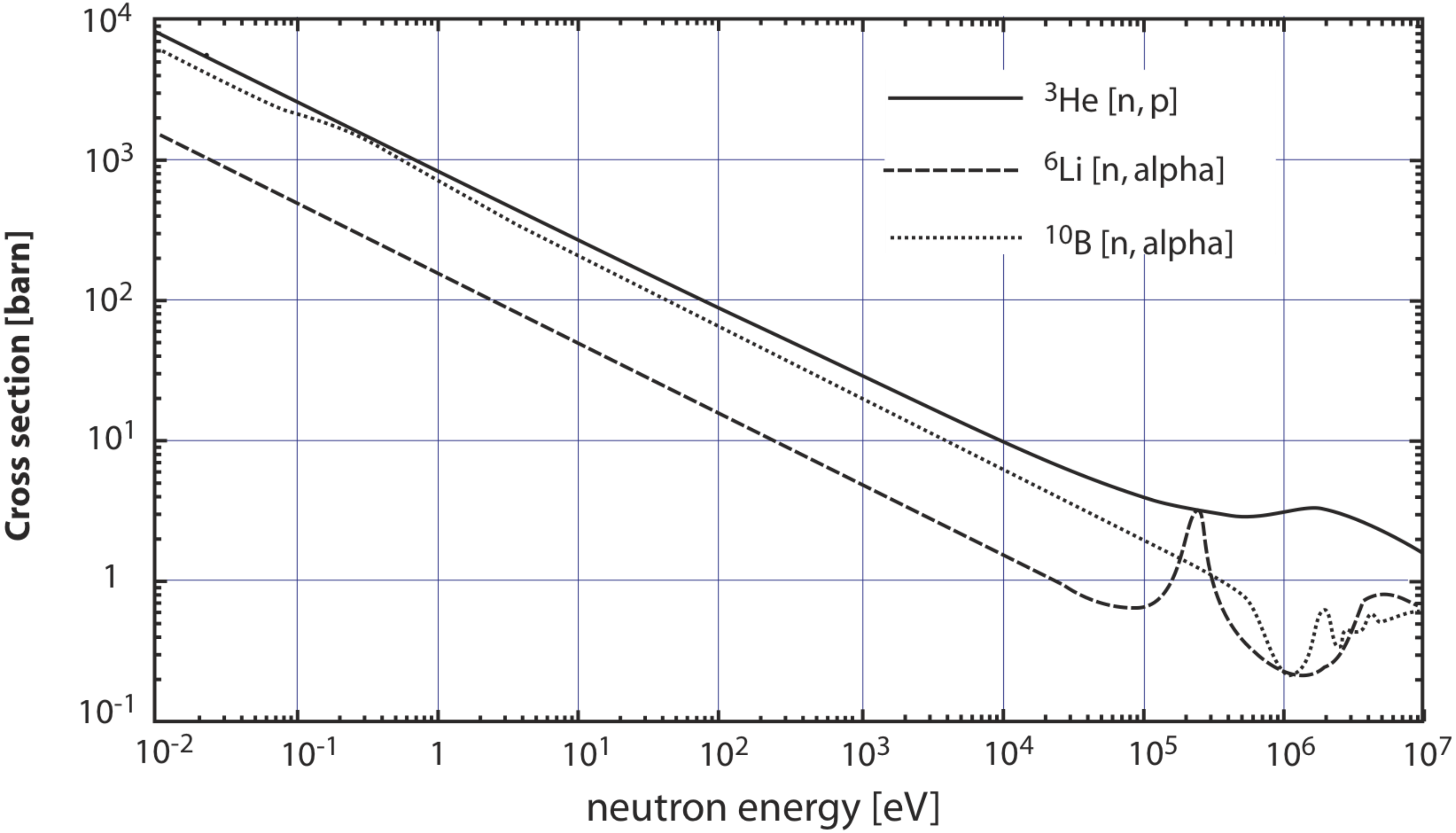
- Helium reaction ^{3}He(n,p) →

$$ {}^3_2He + {}^1_0 n \rightarrow {}^3_1 H + {}^1_1 p \qquad Q = 0.764 \text{ MeV} $$

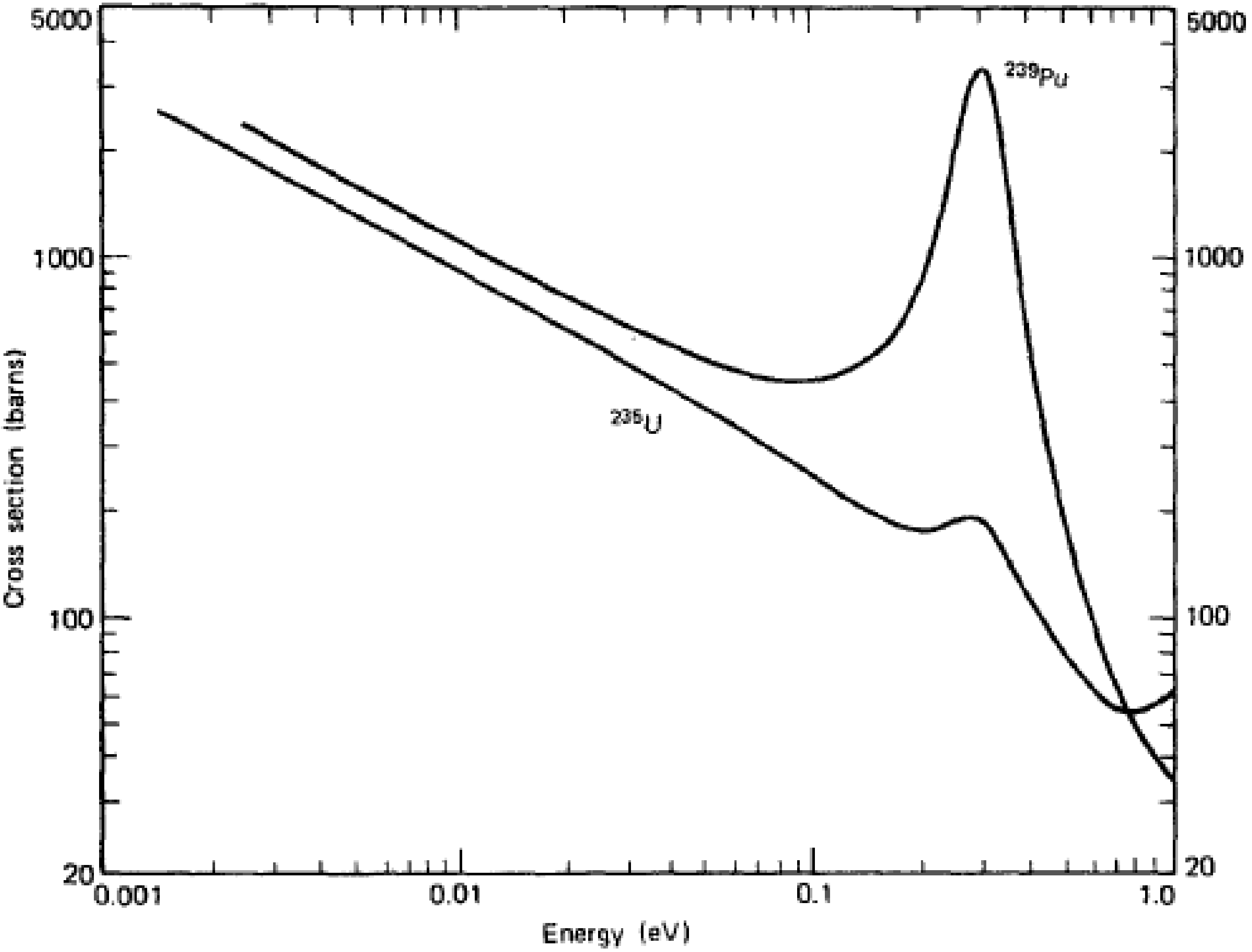
$$ \Rightarrow \quad E_p = 0.573 \text{ MeV} \quad \text{and} \quad E_H = 0.191 \text{ MeV} $$

- Gadolinium (^{157}Gd) neutron capture (255000 barns) → electrons emission
- Neutron-induced fission reactions (^{233}U, ^{235}U, ^{239}Pu) → large Q value (≈ 200 MeV)

Cross sections for various reactions (1)



Cross sections for various reactions (2)

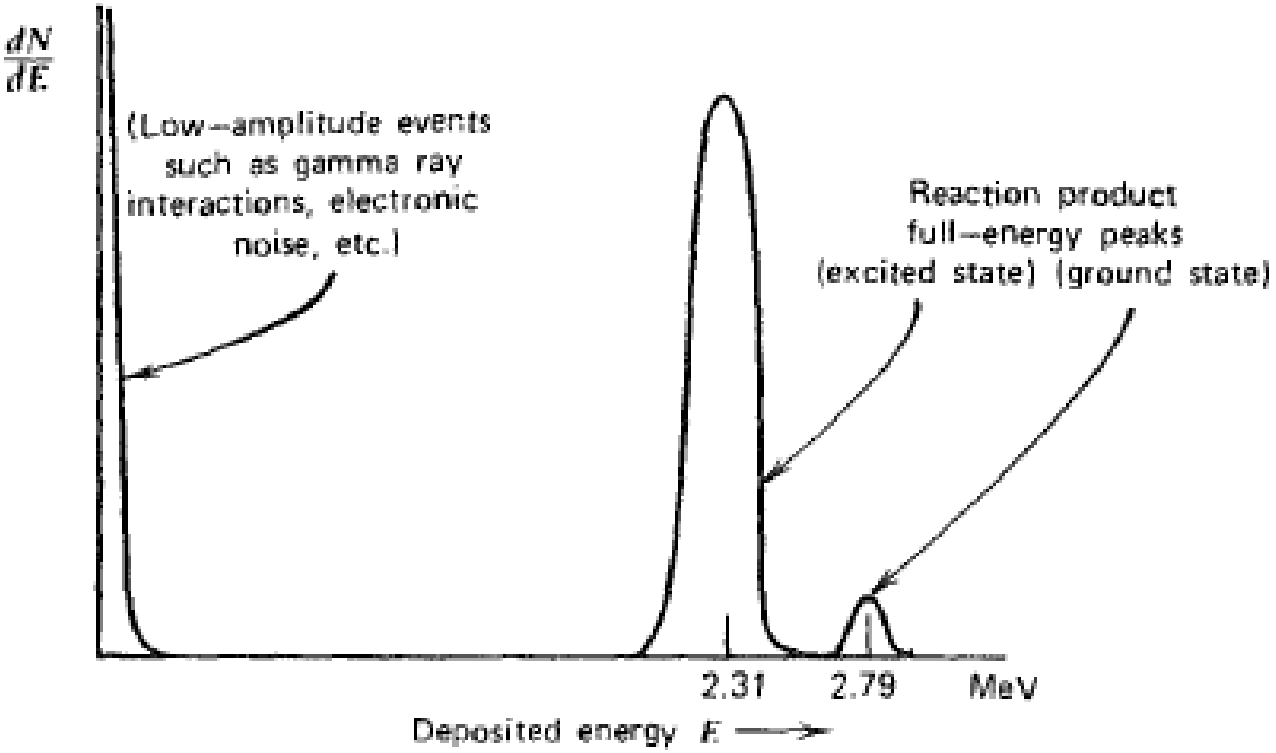


Proportional tubes for neutron detection

- Generally BF_3 gas or ^{3}He gas are used (no gas with Li because stable lithium-containing gas does not exist)
- Both have good γ ray discrimination (better for BF_3 due its larger Q) ↔ γ rays can interact with the walls → production of electrons, but the energy loss of electrons in gas is small (≈2keV/cm) → these pulses are much smaller that neutron pulses
- Poor time resolution → time of flight of reaction products
- BF_3 is highly toxic and very corrosive; because slightly electronegative, cannot work at pressure > 1 bar → poor chamber gas; significant degradation after 10^{10}-10^{11} counts due to contamination of electrodes by molecular dissociation products
- ^{3}He tubes can work at pressures of several bars → excellent proportional counters; long tube life; **very** expensive

Up to a few years, ^{3}He tube was preferentially used but very expensive to manufacture → use of BF_3 ↗

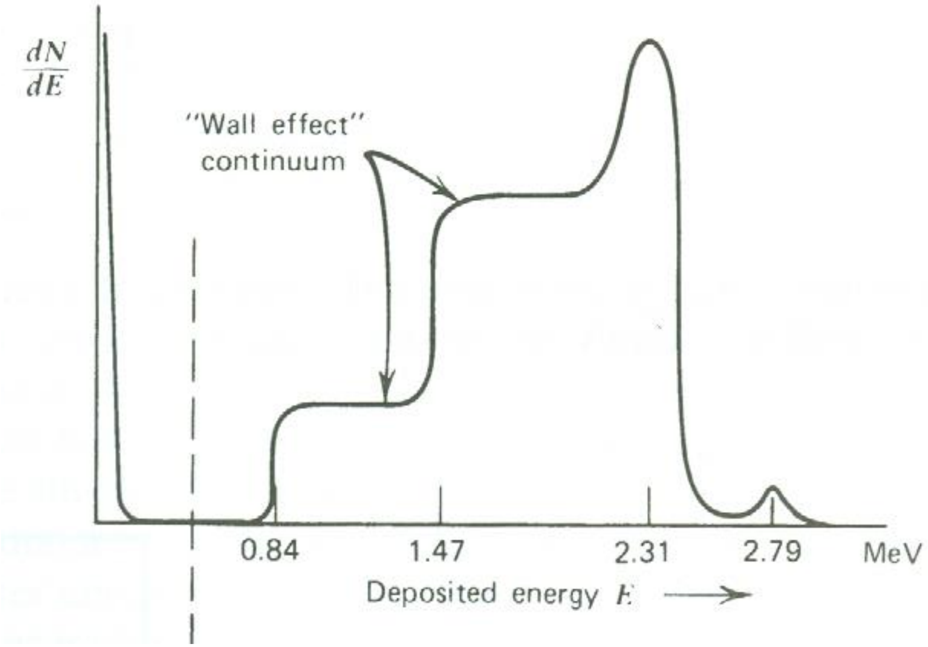
Ideal spectrum for a BF_3 counter



- For large size counter → reaction products are created far from the walls and leave all their energy in the counter gas
- Ratio between the 2 peaks → 94:6

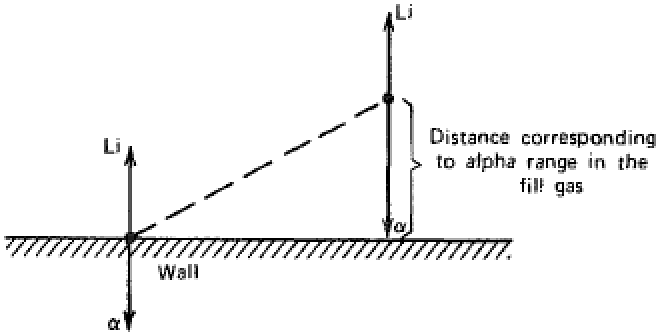
Wall effect for BF_3 (1)

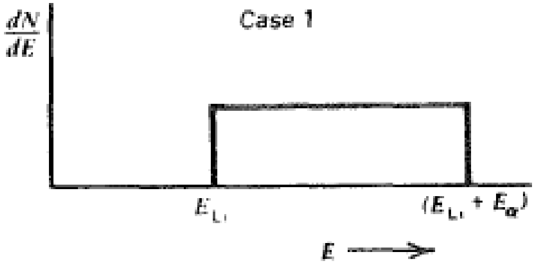
- If the size of the detector is similar to the range of α and Li (typical range of α in BF_3: 1 cm) → interactions with the walls of the detector
- A part of the available energy is deposited inside the walls → modification of the spectrum → « wall effect »



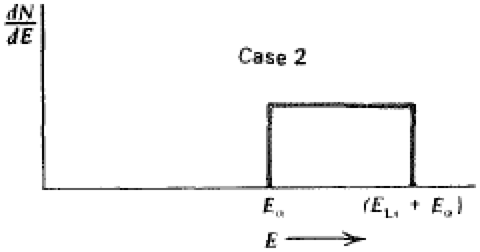
Wall effect for BF_3 (2)

1. The α and Li atoms are emitted in opposite directions → if the α interacts with a wall (only a part of its energy is deposited - uniformly – inside the detector) → the Li atom deposits all its energy in the gas → the deposited energy varies between E_{Li} and $E_{Li} + E_\alpha$





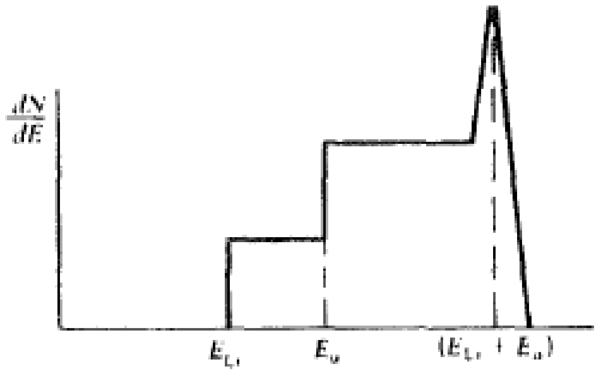
2. If conversely the Li interacts with a wall → the α deposits all its energy in the gas → the deposited energy varies between E_α and $E_\alpha + E_{Li}$



Wall effect for BF_3 (3)

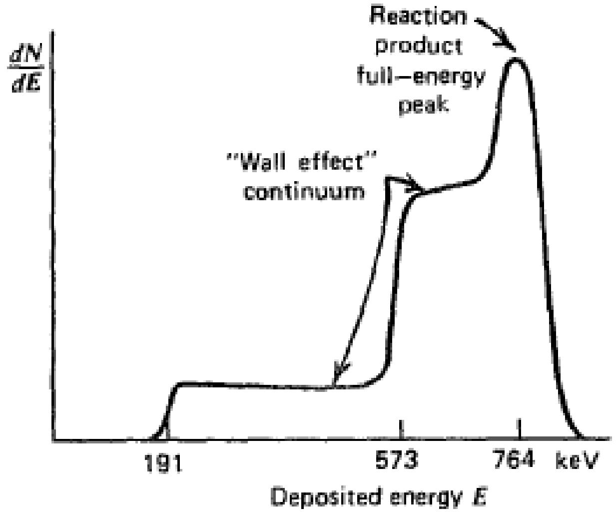
3. If the α and Li are created « far away » from the walls → no escape → total absorption peak at $E_\alpha + E_{Li}$

4. The combination of these ≠ processes gives the final spectrum



^{3}He counter

- Exactly the same principle than for BF_3
- However → smaller Z than BF_3 → the ranges of tritium and proton are large → wall effect more important at given pressure and size



Neutron sensitive scintillators (1)

- Use of Li as scintillator → lithium iodide doped with europium - LiI(Eu) → after reaction of neutron with lithium → tritium and α atoms interacts « classically » with the scintillator
- LiI chemically similar to NaI
- With 0.1% doping of Eu as activator → intrinsic efficiency ≈ 35% of the one of NaI(Tl)
- The lifetime of the luminescence centers ≈ 0.3 μs (for NaI(Tl): ≈ 0.23 μs) → good time resolution
- Large size crystals → no wall effect → total absorption peak
- Disadvantage → the scintillating crystal is sensitive to γ rays → they deposit all their *E* → γ discrimination less effective

Neutron sensitive scintillators (2)

- Other scintillating materials exist
- Li dispersed inside a scintillating matrix of zinc sulfide doped with silver - ZnS(Ag) – and with small thickness ≈ 0.6 mm (material only available as polycrystal → due to interfaces → auto-absorption of its luminescence light → restricted size → only valid for detection of heavy particles) → due to small thickness → good discrimination against γ
- B loaded plastics
- Liquid scintillators containing Li or Gd → discrimination between neutrons and γ rays as a function of the pulse shape
- …

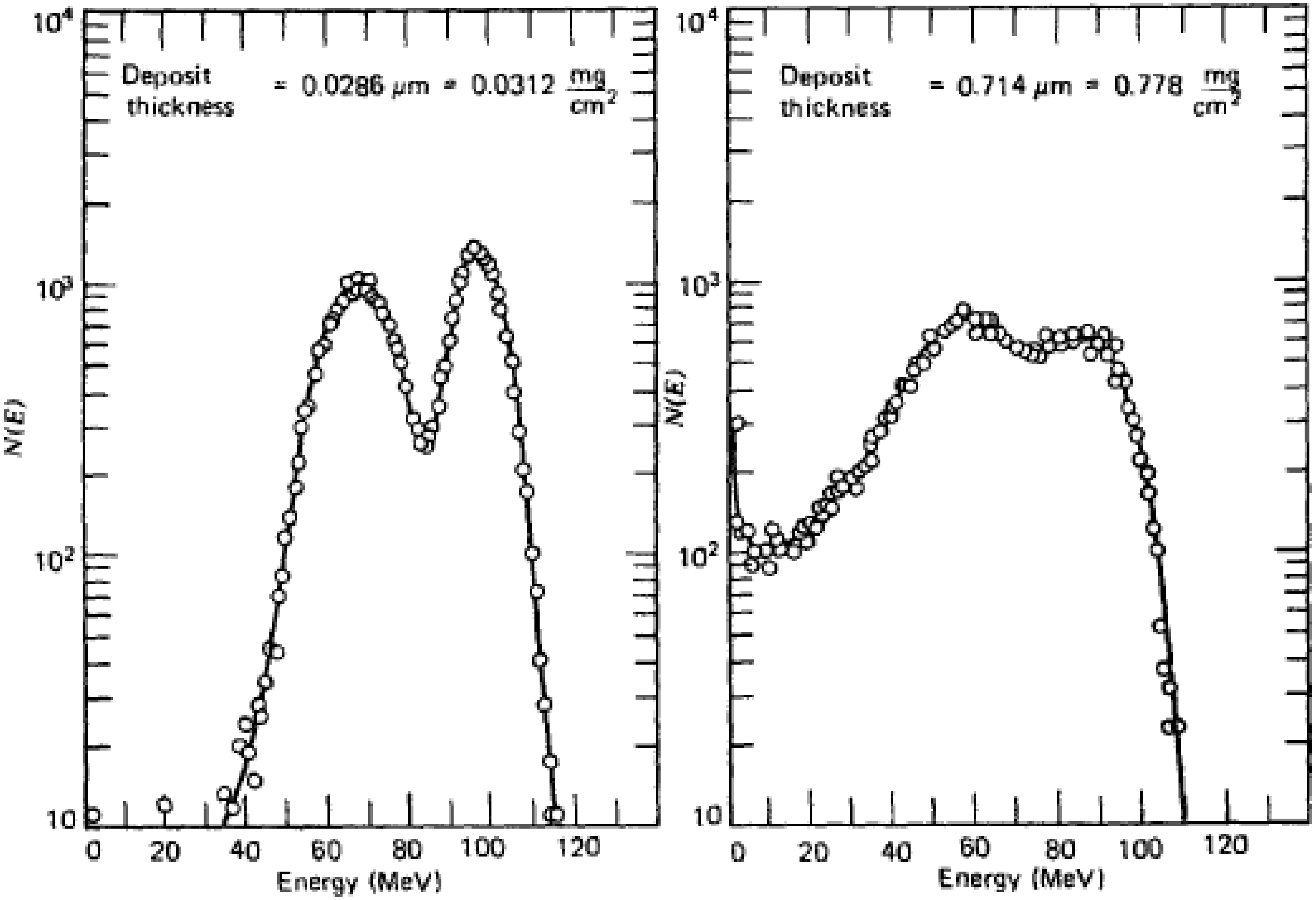
Neutron detectors based on fission reactions

- Fission reactions convert slow neutrons into ionizing reaction products that be conventionally detected → 200 MeV energy is available → typically about 160 MeV to the fission fragments
- Large deposited energy → negligible background
- Due to physical/chemical properties that are unfavorable → impossible to incorporate fission media inside a gas
- Solution → gas detector that has its inner surface coated with fissile medium

Ionization chamber with fissile coating

- Most popular detector → « classical » ionization chamber that has its inner surface coated with fissile medium → possibility to use it in current or pulse mode
- In pulse mode → the measured spectrum depends on the thickness of fissile coating
- Roughly → light and heavy fragments have distributions centered at 100 MeV and 70 MeV
- For a thin fissile coating → we well observe a characteristic spectrum with double humps at 70 and 100 MeV
- For a large fissile coating → ↗ of the detection efficiency but energy absorption inside the coating itself → distorsion of the spectrum

Ionization chamber with UO_2 coating



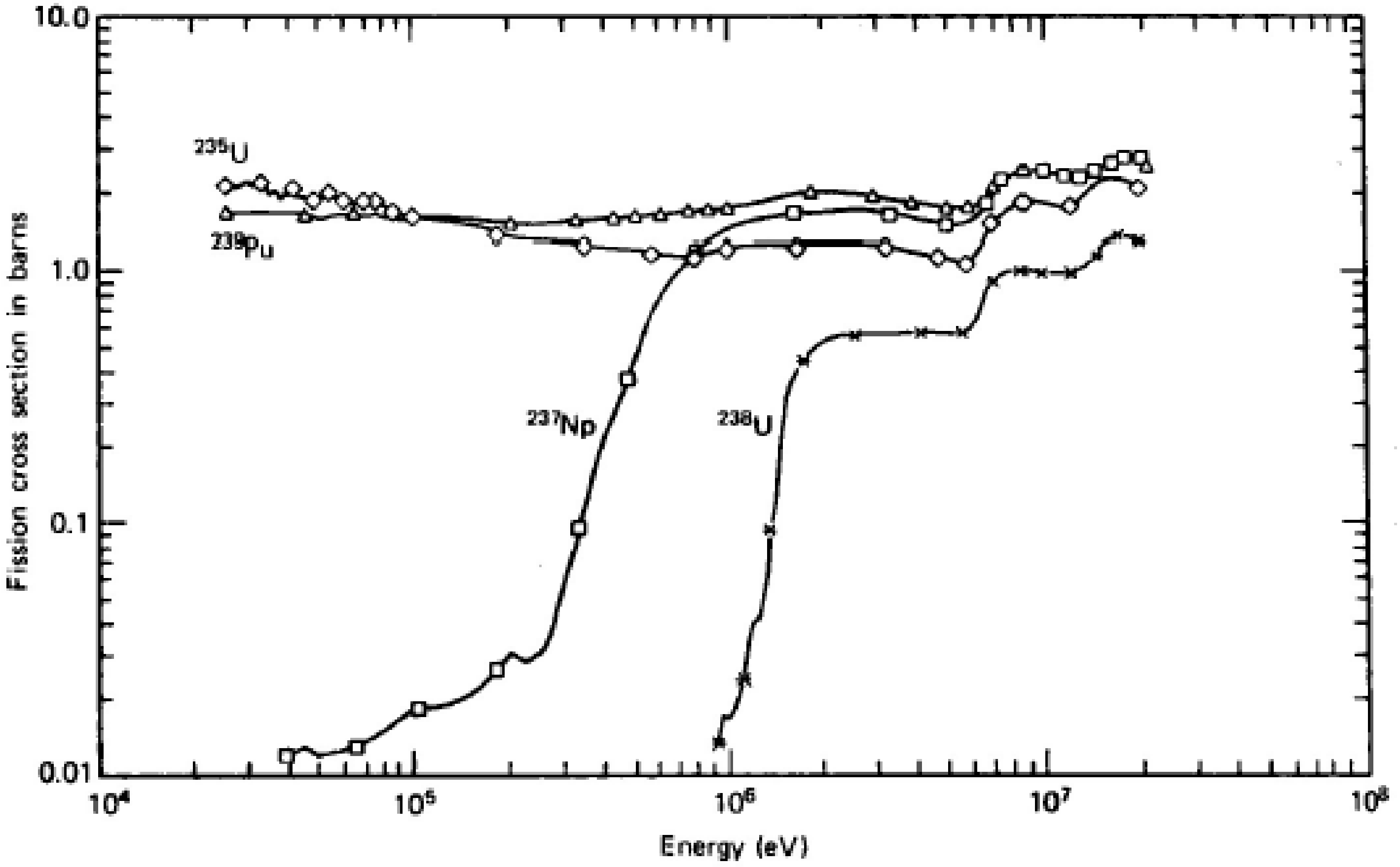
Other detectors based on fission reaction

- Proportional counter that has its inner surface coated with fissile medium (^{235}U or ^{239}Pu) → ^{235}U or ^{239}Pu lined proportional tubes

- Remark → with ^{238}U or ^{237}Np → measure of fast neutrons

- Scintillators containing fissile material

Fission cross sections

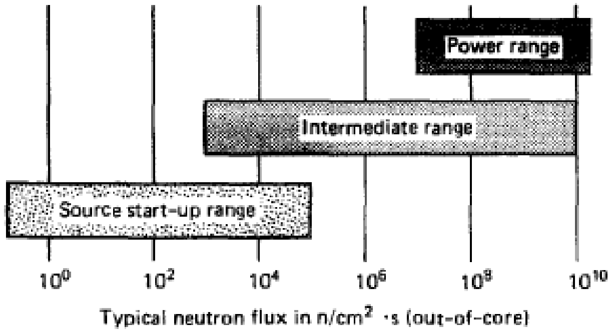


Neutron detectors for nuclear reactors (1)

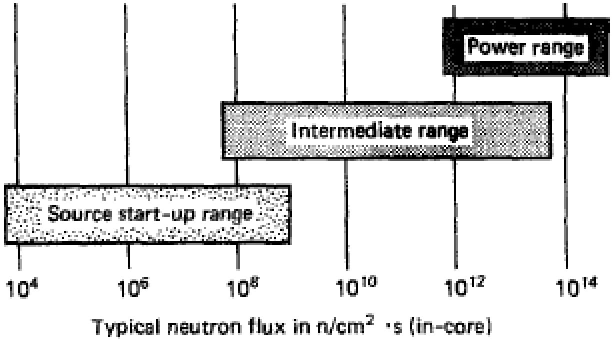
- In thermal nuclear reactors → fission induced by slow neutrons → reactor control and safety system generally based on slow neutrons detection
- Extreme conditions → specifically designed detectors
- Majority of neutron sensors are gas-filled type → advantages: γ–ray discrimination, long-term stability, resistance to radiation damage
- Scintillation detectors are less suitable: high γ–ray sensitivity and spurious events induced in the photomultiplier
- Semiconductors are very sensitive to radiation damage → never used in reactor environment

Neutron detectors for nuclear reactors (2)

- Two categories of detectors as a function of fluxes ranges
- In-core detectors (fluxes in 10^4-10^{14} $cm^{-2}s^{-1}$ range) and out-of-core detectors (0-10^{10} $cm^{-2}s^{-1}$)
- Out-of-core detectors are used outside the PWR core



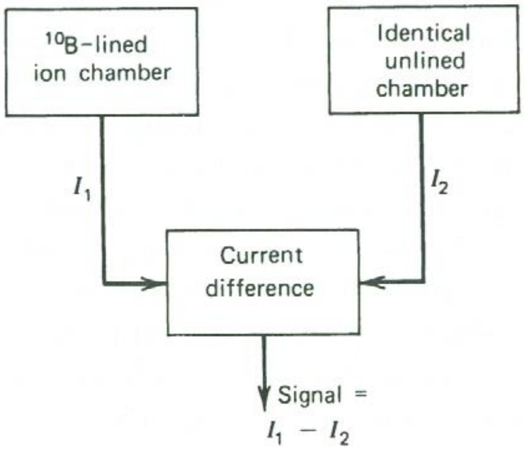
- In-core detectors are used inside the core of BWR and PWR



Out-of-core detectors

- Gas detectors as previously explained may be used as out-of-core detectors
- The pulse mode is limited to rates of 10^7 events per second → for higher fluxes (full operation reactor) → the current mode is used → problem: no γ discrimination
- Another possibility: the use of the fluctuation mode → signal $\propto$ $\overline{\sigma_I^2(t)}$ → allows discrimination
- Another solution → use compensated ion chamber

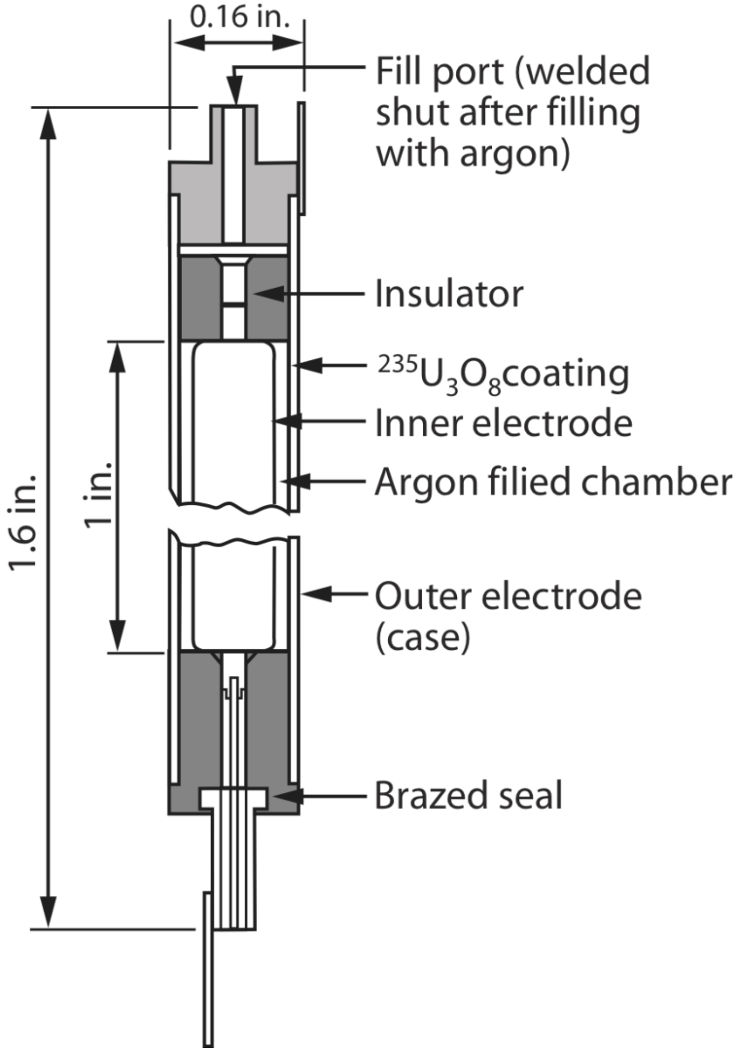
compensated ion chamber (CIC)



- We consider first → an ionization chamber with the inner surface is coated with boron operating in current mode → the measured current (I_1) is the addition of the current due to interactions of neutrons in le B and to γ in the walls and in the gas
- Second we measure the I_2 current in a « normal » chamber and thus due to interactions of γ rays in the walls and in the gas
- The ≠ of these 2 currents gives the current only due to neutrons

Example of in-core ionization chamber

- Typical fission chamber with ^{235}U used in BWR neutron monitoring system
- Use in current mode
- Argon at high pressure → the range of the fission products < the size of the chamber
- Fissile material is consumed → reduction of sensitivity (after 1 year: reduction of 50%)
- To compensate this effect → use of a mixture of fissile and fertile isotopes (^{238}U and ^{239}Pu) or (^{234}U and ^{235}U)



In-core detectors : Self-powered detectors (1)

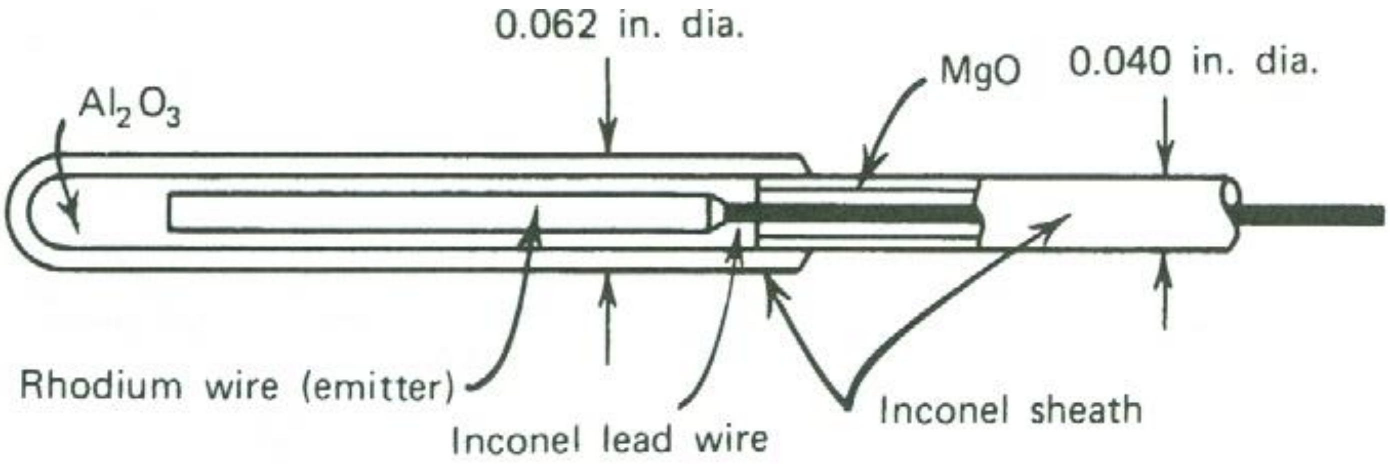
- This detector incorporates material with high cross section for neutron capture leading to subsequent β or γ emission
- If β emission → the e^- current is directly measured (without bias voltage → self-powered detector) → current $\propto$ to the neutrons capture rate
- If γ emission → γ rays interact by photoelectric, Compton or pair creation effect → creation of secondaries e^- → current
- ≠ names exist → detector of Hilborn (inventor in 1964), β emission detector, collectron, PENA detector (« Primary Emission, Neutron Activation »)

In-core detectors : Self-powered detectors (2)

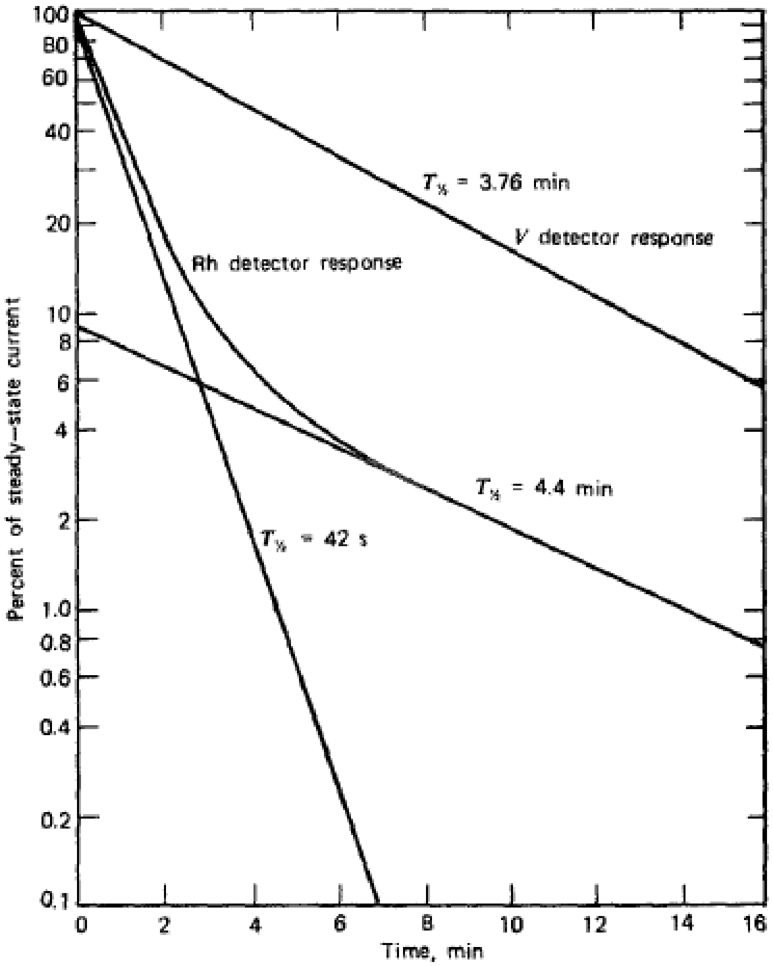
- Advantages of self-powered detectors → small size, small cost and simple lower down electronics
- Disadvantages → small output current, obligatory use in current mode, slow time response
- For direct emission of β → we choose material with a cross section of electronic capture not too small (to avoid a too weak sensitivity) and not too large (to avoid a too quick consumption of the matertial), with high energy β (to avoid auto-absorption inside the material) and with a life time of the activated isotope weaker as possible (to reach a fast response) → rhodium or vanadium (that is generally chosen because of its slow consumption)
- For the emission of e^- via γ rays→ use of ^{59}Co (σ_{cap} = 37 barn) → faster signal but weaker sensitivity than for a direct β emission

In-core detectors : Self-powered detectors (3)

Emitter		σ thermal neutrons [barns]	T 1/2 [s]	beta end point energy [MeV]	Typical sensitivity A/(n/cm^2.s)
Vanadium	$^{51}_{23}V$	4.9	225	2.47	5 10^{-23}
Rhodium	$^{103}_{45}Rh$	139 11	44 265	2.44	2.44 10^{-21}



In-core detectors : Self-powered detectors (4)



Disintegration of ^{52}V and ^{104}Rh

Fast neutron detection

1. Detection after moderation

2. Detection based on fast neutrons reactions and neutron spectroscopy

Detection after moderation (1)

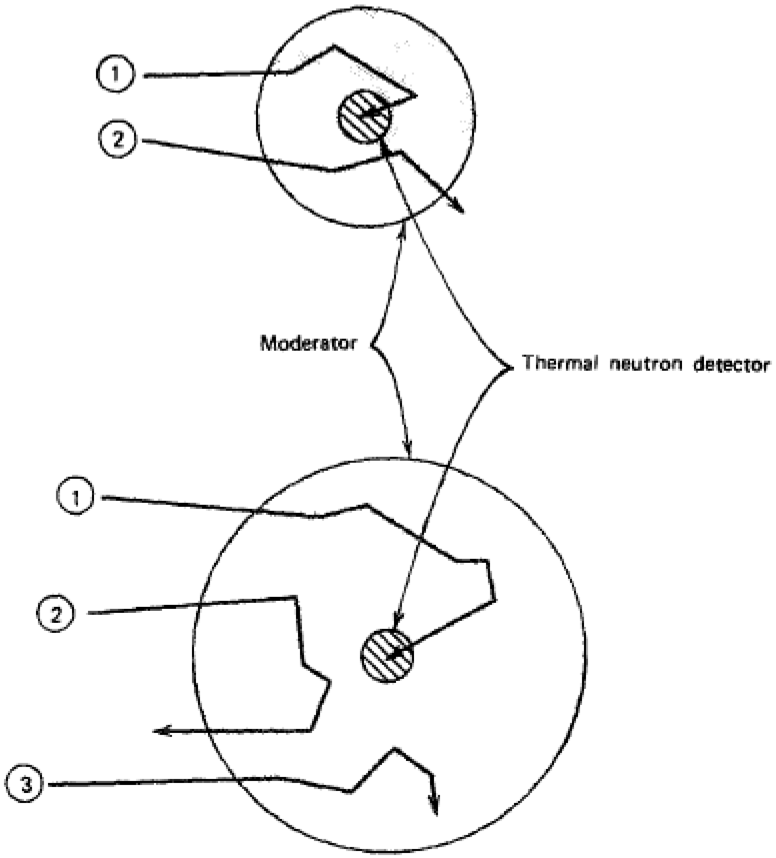
- The detector is surrounded by moderator → few centimeters of hydrogen-containing material (generally polyethylene or paraffin)
- Neutron loses important fraction of its kinetic energy before reaching the detector sensitive to slow neutrons (see before)
- The optimum thickness of moderator depends on the energy of the neutrons flux →
  - For small energy neutrons (keV) → if the moderator is too thick → absorption of the thermalized neutrons inside the moderator → signal loss
  - For high energy neutrons (MeV) → if the moderator is too thin → neutrons are not enough slowing down → are not detected
  - For neutrons with energy > 10 MeV → the detector response strongly ↘ → difficult to use it on this form

Detection after moderation (2)

1. Moderated and detected neutrons
2. Neutrons partially moderated → escape without reaching detector
3. Neutrons absorbed in the moderator

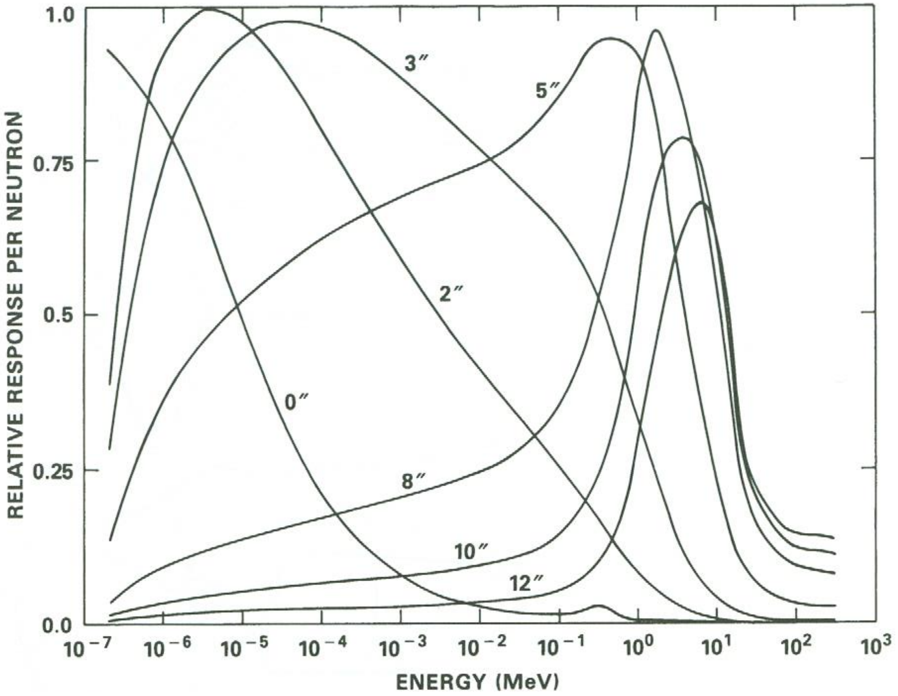
Size of the moderator is important:

Size ↗ → ↘ of process 2 but ↗ of process 3



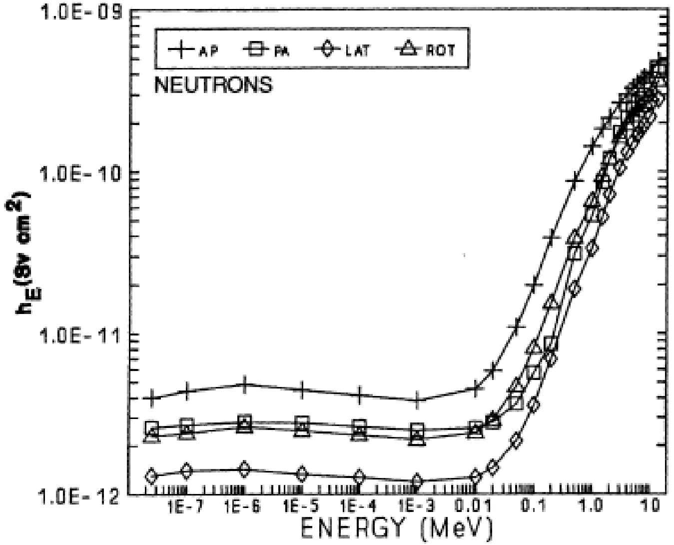
Bonner sphere (1)

- Spherical detector composed of a small LiI scintillator at the center of a moderator sphere made in polyethylene
- As a function of the detector size → the response varies



Sphère de Bonner (2)

- For a sphere with 12 inches diameter → the response curve for this configuration has a very similar shape compared with the dose equivalent (thus in a biological medium) per neutrons as a function of energy → coincidence but very useful



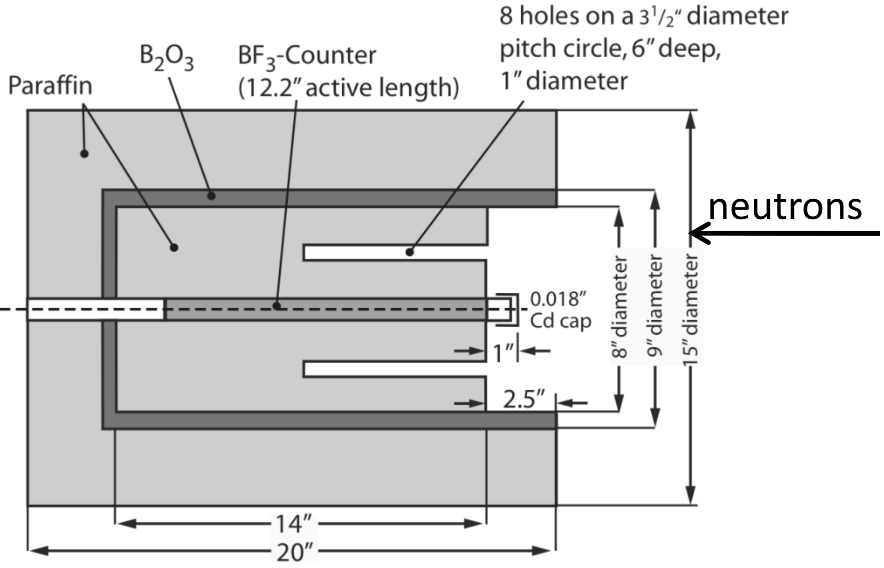
- The efficiency of the detector is large for neutrons with a large biological importance and small for neutrons with small importance → biological weighting automatically include

Example of Bonner sphere

Fuji Electric NSN10014 neutron dosimeter

Long counter (1)

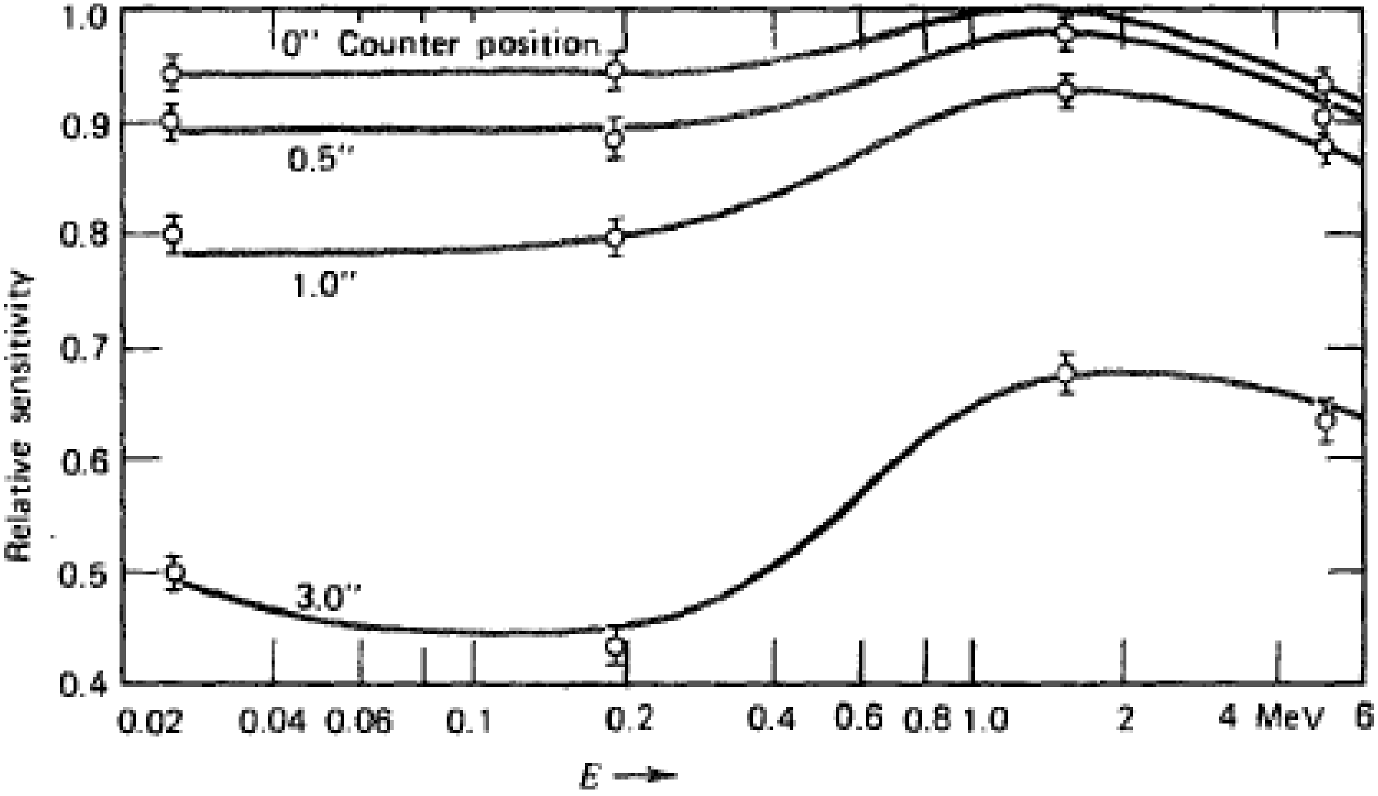
Detection efficiency more or less independent from the neutron energy by choosing a right geometry → only sensitive for neutrons incident on the right-hand face



Neutrons ⫽ to the axis penetrate some distance before moderation → distance ↗ when E↗ → if tube long enough → counting rate independent on the neutron E ↔ some moderated neutrons will arrive to the counter

Neutrons not ⫽ are moderated in the outer annulus of paraffin → subsequently captured in the B_2O_3 → no count

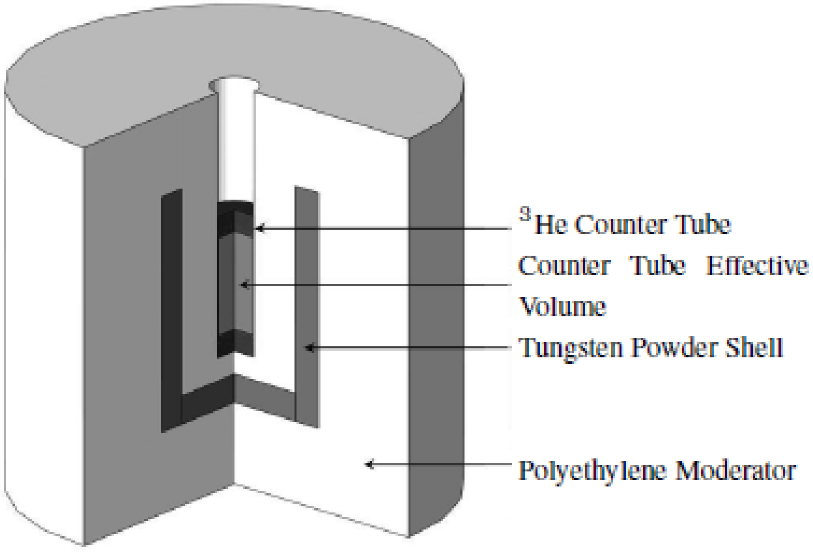
Long counter (2)



Parameter: displacement of the detector in relation to the entrance surface

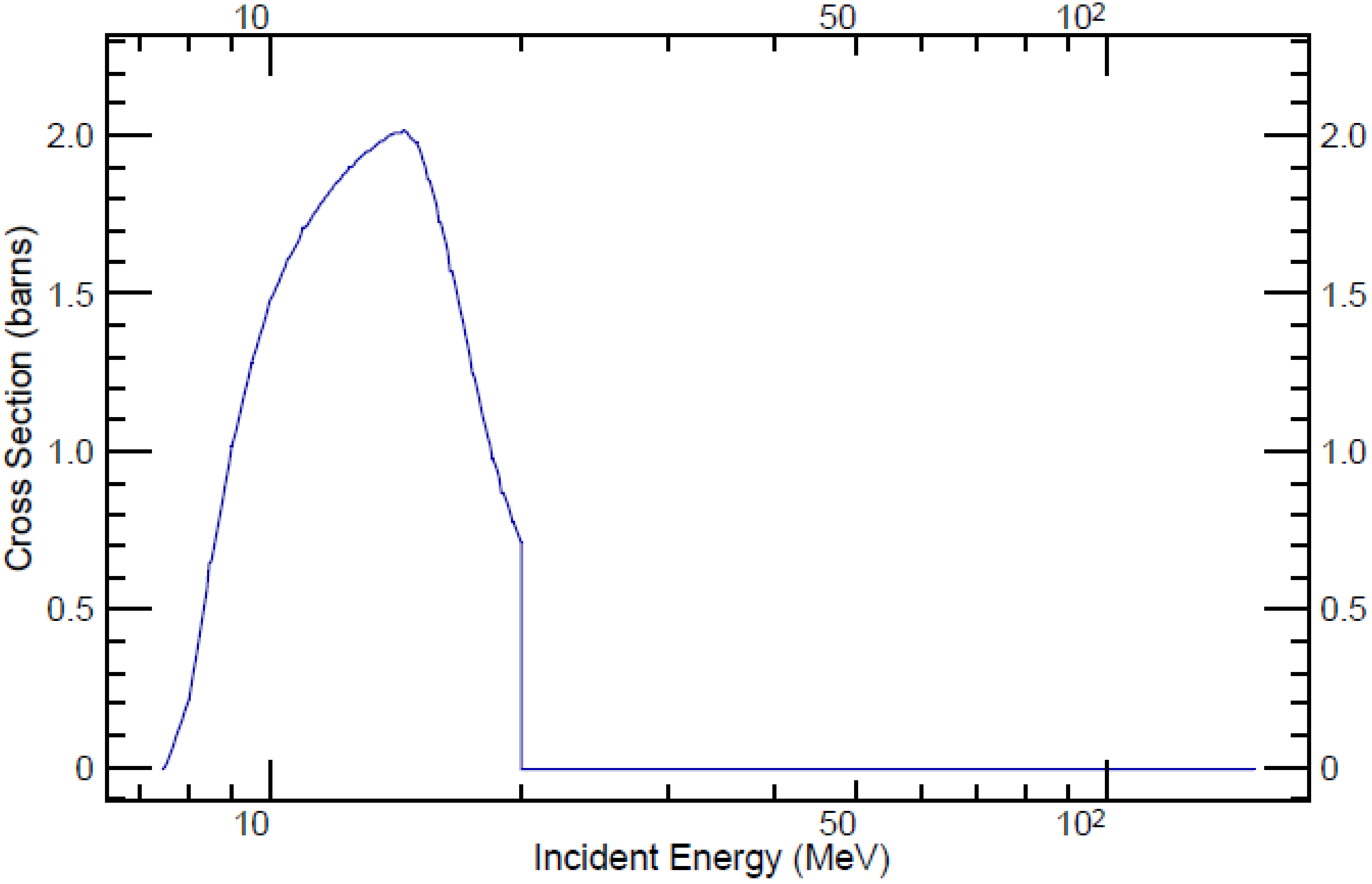
Fast neutron detection (E>10 MeV)

The insertion of a heavy metal layer (tungsten) in the moderator extends the response function to GeV because of nuclear reactions of high energy neutrons in the layer (reaction (n,2n)) → Wendi-II detector



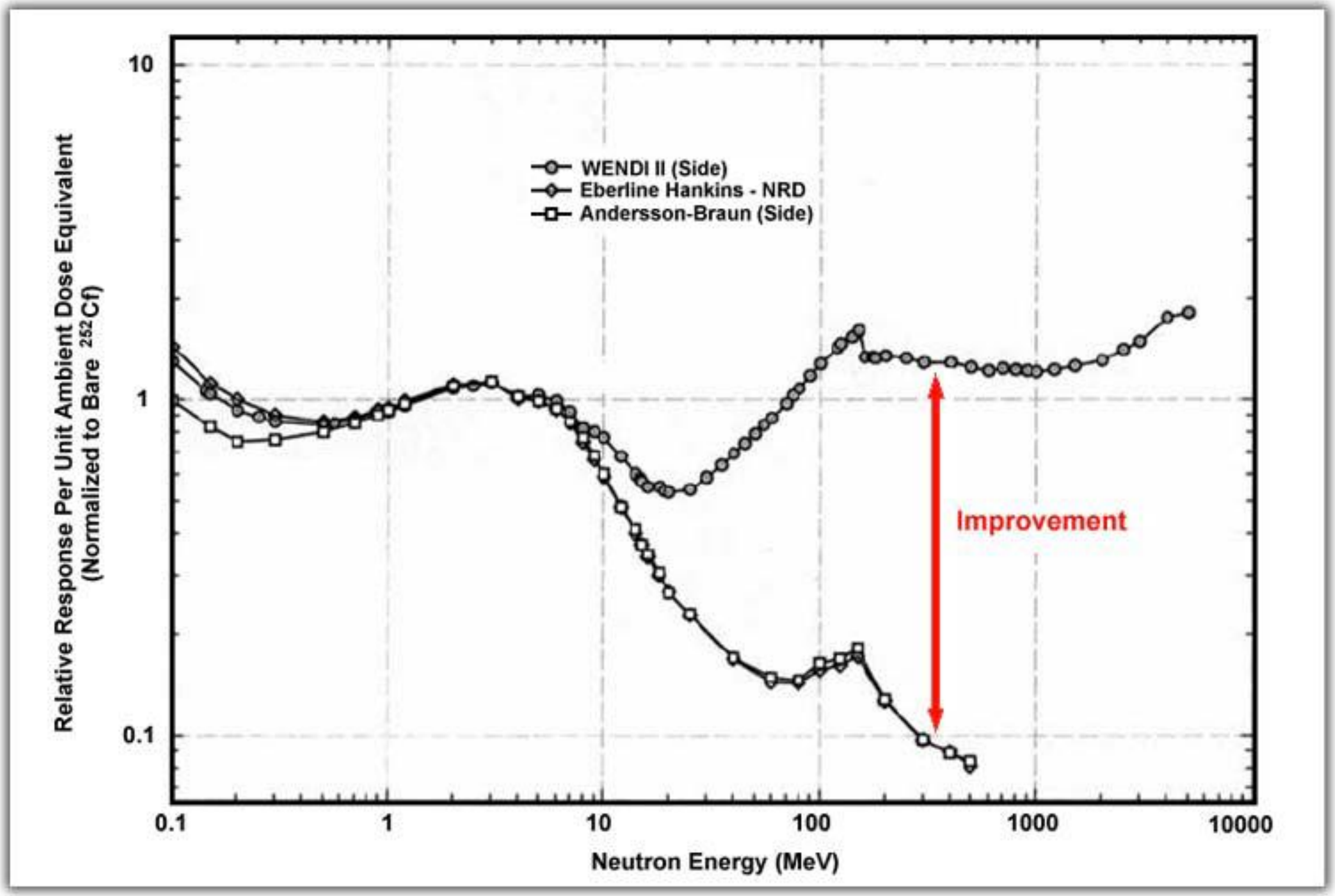
FHT 762 Wendi-II from Thermo Fisher Scientific

Reaction (n,2n) for the tungsten (^{184}W)



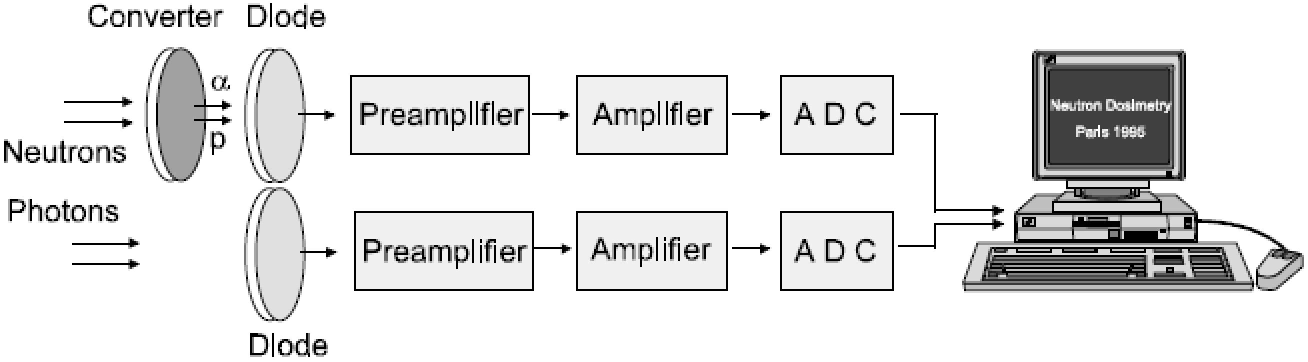
http://www.nndc.bnl.gov/exfor/endf00.jsp

Response of Wendi-II



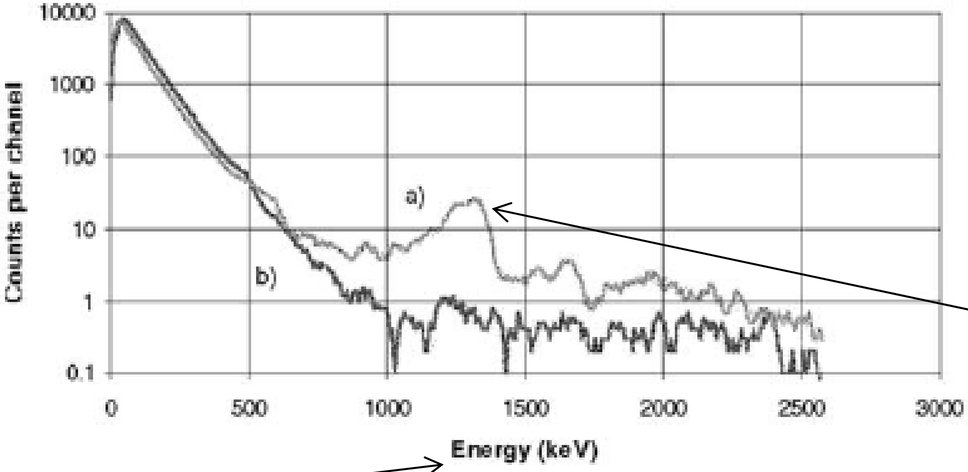
Neutrons detectors with diodes (1)

- Neutrons detectors based on the used of 2 diodes
- Diode 1 (called neutron diode): covered with an organic medium (plastic: PE,…) doped with ^{10}B (≈ $10^{13}/cm^3$ B atoms) → sensitive to neutrons and γ
- Diode 2 (called γ diode): "nude" → no sensitive to neutrons and sensitive to γ
- The 2 diodes are side by side and $\perp$ to ionizing radiations (neutrons + γ)



Neutrons detectors with diodes (2)

- Thermal n interact with 1 in 2 ways →
  1. H(n,n)p → emission of protons
  2. $^{10}B(n,\alpha)^{7}Li$ → emission of α
- The ≠ between signals from diodes 1 et 2 allows to discriminate the contribution due γ from the contribution due to neutrons



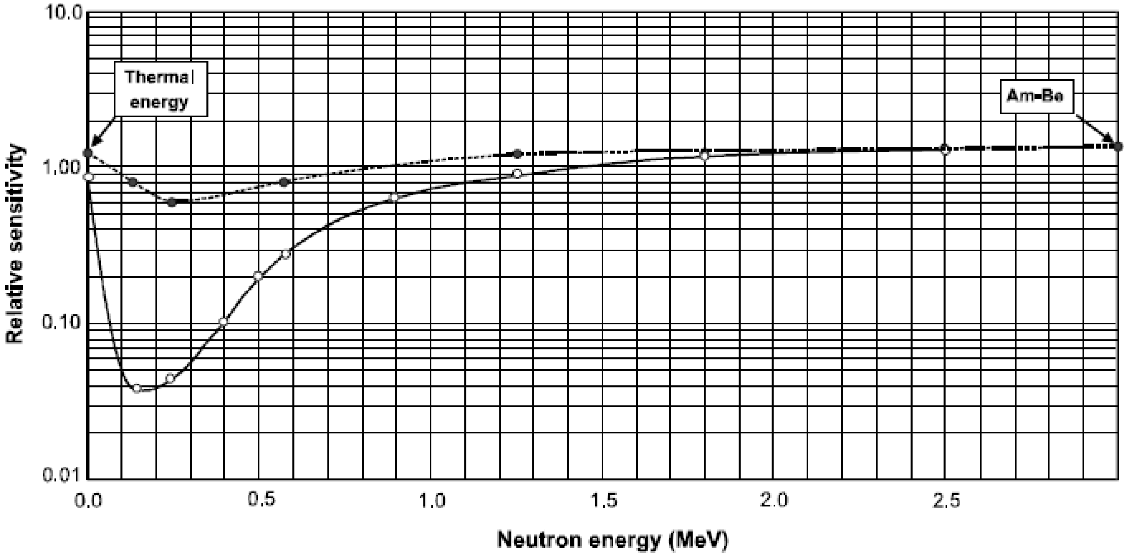
a) Diode 1
b) Diode 2

Pic α

Measured spectrum

Neutrons detectors with diodes (3)

- If the size of the plastic coating is large → important moderation of high energy neutrons → it is possible to study neutrons with high *E*
- The quantity of ^{10}B is chosen to obtain a response to thermal neutrons equal to the response to fast neutrons



Neutrons detectors with diodes (4)

- For very high E (*E* > 10 MEV) → addition of Pb → reaction (n,2n)

- To improve the precision for a large range of *E* → system with 3 or 4 diodes with ≠ coatings → multi-elements detector (Saphydose detector)

Saphydose Detector of Saphymo

Detection based on fast neutrons reactions (1)

- Problems for detectors based on moderation → no information on neutrons energy and detection process slow (thermalization by multiple collisions then diffusion of thermal neutrons)
- Solution → direct use of nuclear reactions for fast neutrons → charged reactions products → detection
- Kinetic energy of the reaction product = Q + incident neutron kinetic energy (E_n) → if $E_n \gg Q$ → we obtain neutron energy
- Advantage: fast detection process
- Disadvantage: weak cross sections → small efficiency

Detection based on fast neutrons reactions (2)

- Two « types » of detectors based on fast neutrons reactions →

1. Use of reactions ^{6}Li(n,α) or ^{3}He(n,p) → same detectors as previously for which the α or proton energy have to be precisely measured

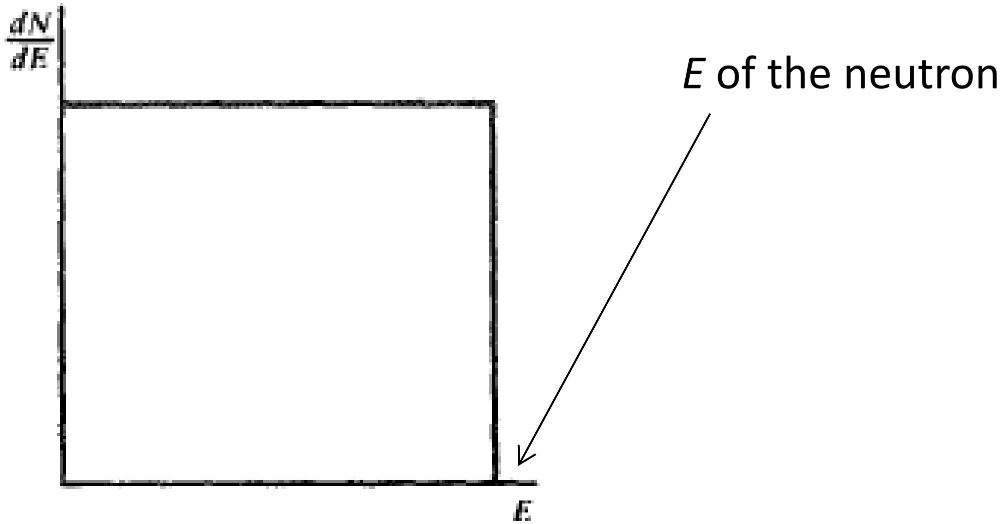
2. Use of the elastic diffusion reaction → measure of the recoil energy of the nucleus implied in neutron-nucleus reaction

Detectors based on the elastic diffusion

- To maximize energy transfer → diffusion with light elements → hydrogen, deuterium, helium
- Hydrogen is very popular → recoil proton → detector called “recoil proton detector“
- Elastic diffusion → $Q = 0$ → the energy of the recoil proton can be equal to the energy of the incident neutron
- Practically →
  - Organic scintillators
  - Proportional counter
  - recoil proton telescope

Organic scintillators for neutrons detection (1)

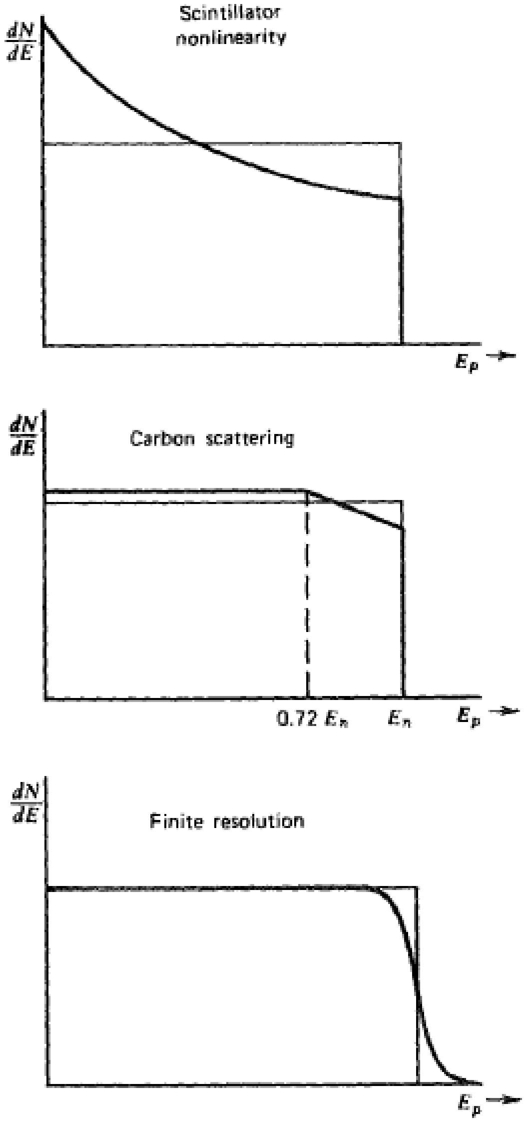
- Organic scintillators contain hydrogen → large possible selection → use for instance of stilbene allowing a good γ discrimination
- In first approximation → all energies given to the proton are equiprobable (in reality → $T_c = E\cos^2\theta_r$) → the measured energy spectrum of the protons is considered as rectangular

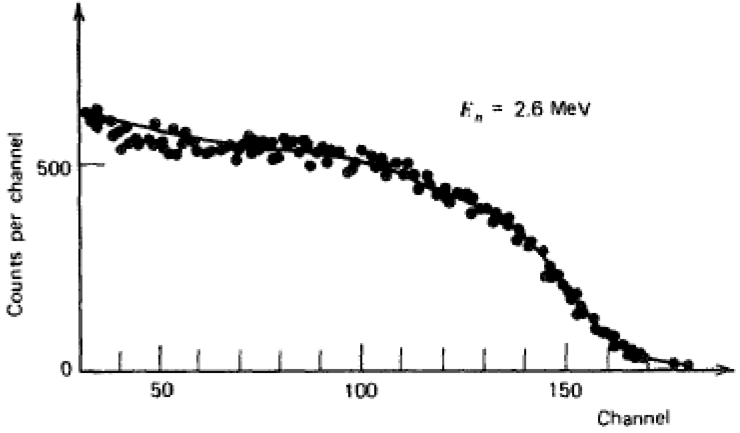


Organic scintillators for neutrons detection (2)

- Deviations in comparison with a rectangular spectrum:
  - Non-linearity of the light response of the scintillator
  - Wall effect if the scintillator is small in comparison to the protons range
  - Multiple scattering for the incident neutron if the scintillator is not small
  - Scattering with the carbon of the scintillator → a neutron can lose 0-28 % of its *E* due to an elastic scattering with C → direct effect is weak due to the bad response of scintillator for large *dE/dx* but neutron having a collision with C and having afterwards a collision with H has an *E* that is only 72-100 % of its initial *E*
  - Resolution of the detector (photoelectrons statistics,…)

Organic scintillators for neutrons detection (3)

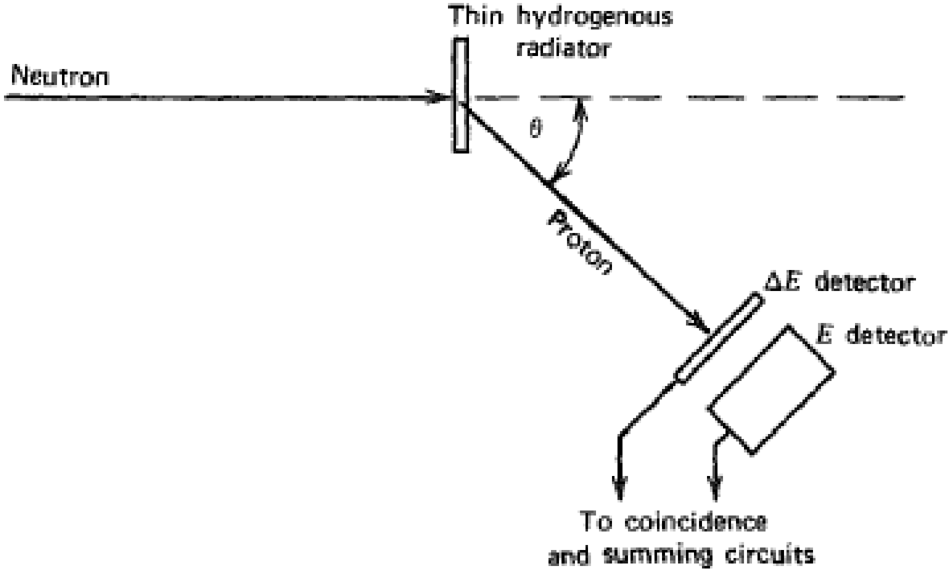




Proportional counters for neutrons detection

- Proportional counters containing hydrogen, a gas rich in hydrogen as methane (CH_4) or helium
- Gas → small density → small efficiency
- Wall effect is important
- The purity of the gas is very important → if impurity → can reach to large deviations
- Use less convenient than scintillators

Recoil proton telescope



- Monoenergy incident neutrons are scattered in a thin film (< than the protons range) rich in H
- As $T_c = E\cos^2 \theta_r$ → precise energy for the proton at a given angle → energy peak
- Extremely small efficiency (1 event for 10^5 neutrons)