Neutron Detectors

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1. Introduction
2. Nuclear reactions in neutron detection
3. Slow neutron detectors
4. Fast neutron detectors

Section 1

Introduction

1. Introduction

Neutron detectors

- Neutrons are detected through nuclear reactions
    - Charged particles are produced and their energy loss detected
    - Cross section changes rapidly with energy
- Together with neutrons, photons are always produced
    - Important the discrimination between photons and neutrons

- Active detectors: Detects the pulse generated by secondary particles
- Passive detectors: Activation method where the neutron is detected "a posteriori" through the gamma decay of nuclei excited by neutrons

Section 2

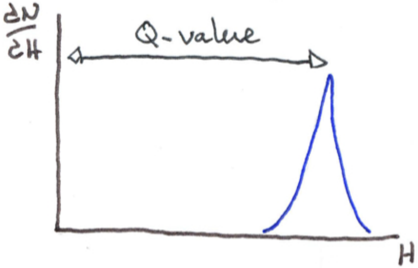
Nuclear reactions in neutron detection

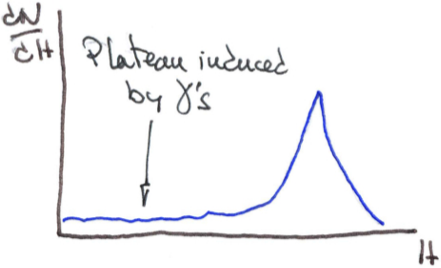
2. Nuclear reactions in neutron detection

Nuclear reactions in neutron detection

- Nuclear reactions for neutron detection should present the following characteristics:
    - High cross section. $\sigma \propto \frac{1}{v}$,
        - ★ This will allow to build small detectors
        - ★ Possibility to use gas as active media
    - High Q-value. (energy liberated by the reaction)
        - ★ Q-value determines the energy of the products
    - Ability to discriminate γ. Neutrons are often accompanied by γ's
    - Detector should be large enough to contain reaction products. If not neutron can be confused with γ's

Nuclear reactions in neutron detection





Reactions

$$A + n \rightarrow 1 + 2 \qquad E_n << m_A$$

Energy conservation $E_1 + E_2 = Q$

Momentum conservation $p_1 = p_2$

$$\sqrt{2m_1E_1} = \sqrt{2m_2E_2}$$

$$E_1 = \frac{Q}{1 + \frac{m_2}{m_1}} \qquad E_2 = \frac{Q}{1 + \frac{m_1}{m_2}}$$

Reaction	Q	Energies
^{10}B + n → ^{7}Li +α ^{10}B + n → ^{7}Li* +α	2.792 MeV (6%) 2.310 MeV (94%)	E_{Li}= 1.01 MeV, E_α=1.78 MeV E_{Li}=0.84 MeV, E_α=1.47 MeV
^{6}Li + n → ^{3}H +α	4.78 MeV	$E_{^3H}$=2.73 MeV, E_α=2.05 MeV
^{3}He + n → ^{3}H + p	0.764 MeV	$E_{^3H}$=0.191 MeV, E_p=0.191 MeV
^{235}U + n → p.F. +n	~200 MeV	~165 MeV available for fission products

Nuclear reactions in neutron detection

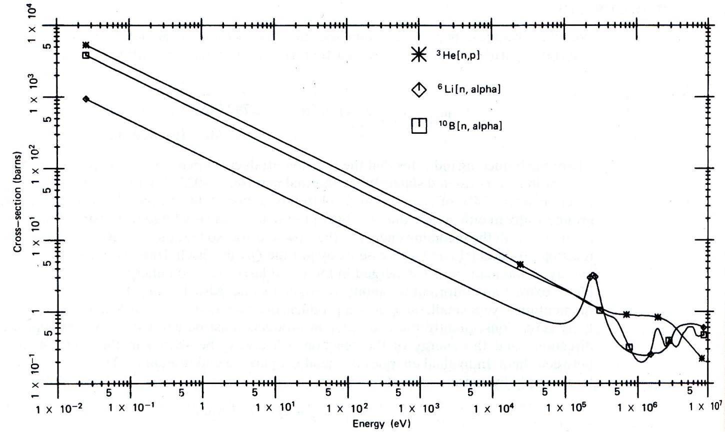
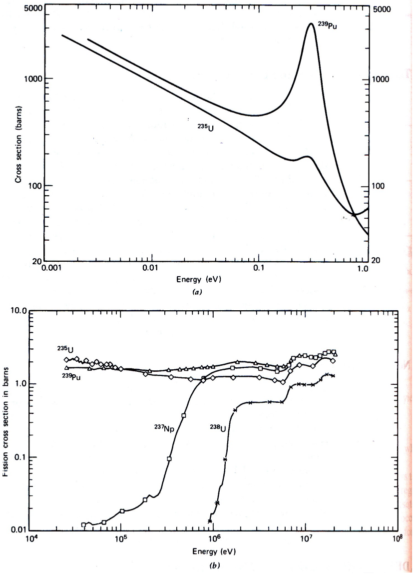


Figure 14.1 Cross section versus neutron energy for some reactions of interest in neutron detection.

Nuclear reactions in neutron detection



Section 3

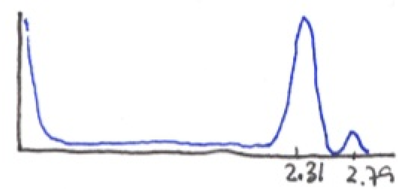
Slow neutron detectors

3. Slow neutron detectors

- Boron-10 based detectors
- Lithium-6 based detectors
- Helium-3 based detectors
- Fission chambers

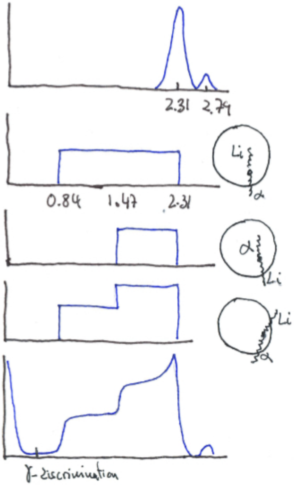
Boron-10 based detectors: gaseous BF_3

- Proportional chamber filled with BF_3
  - BF_3 is used as target and as proportional gas
  - Signal obtained from Li and α energy deposition
- Natural isotopic abundance of ^{10}B is 10%
  - It can be enriched up to 90%
  - Usually used with 50% enrichment
- Large detectors (>1 cm = range of α particles)
  - Energy deposition from both Li and α are detected



Gaseous BF$_3$

- Small detectors → wall effect
  - One of the particles is not fully absorbed in the detector and escapes.



- Li is fully absorbed and α escapes

$$E_{min} = E_{Li} = 0.84\,\text{MeV}$$

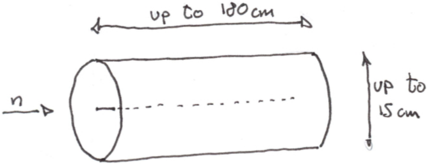
- α is absorbed and Li escapes

$$E_{min} = E_{\alpha} = 1.47\,\text{MeV}$$

- γ's can be easily discriminated (low energy deposition)
- Spectra does not give any information about n energy (only about the detector geometry)
- Only rates can be measured

Gaseous BF_3: Practical details

- Cylindrical shape



- HV ~ 2000-3000 V
- M ~ 100-500
- Pressure ~ 0.1-0.8 atm. At higher pressures → bad proportionality
- Pulses ~ 3-5 μs → Slow detector
- Efficiency

$$\varepsilon(E) = 1 - e^{-\Sigma(E)L}$$

- After $10^{11} - 10^{12}$ hits:
  - Degradation of the performances
  - "Burning" of ^{10}B

BF_3 detector: Example

Let's compute the expected efficiency for a BF_3 proportional counter with the following characteristics: $L = 30\,cm$, $P = 80\,kPa$, $\sigma = 3840$ barns and $T = 300\,K$.

$$\text{1 molecule } BF_3 = \text{1 atom B}$$
$$\text{1 mol } BF_3 = N_A \text{ atoms B}$$

$$pV = nRT$$
$$\frac{n}{V} = \frac{p}{RT} N_A = \text{atoms/m}^3$$

$$\Sigma = \frac{p}{RT} N_A \sigma = 7.42\,m^{-1}$$

$$\varepsilon(E) = 1 - e^{-\Sigma(E)L} = 1 - e^{-7.42\times 0.3} \simeq 0.89$$

Other ^{10}B detectors

- Boron-lined detectors: ^{10}B deposited in walls
  - Most suitable proportional gas can be used (i.e. faster timing)
  - One of the products completely lost

- Doped scintillators: Normal scintillators doped with ^{10}B to make them sensitive to neutrons
  - B_2O_3 used as dopant
  - Small tiles because of opaqueness

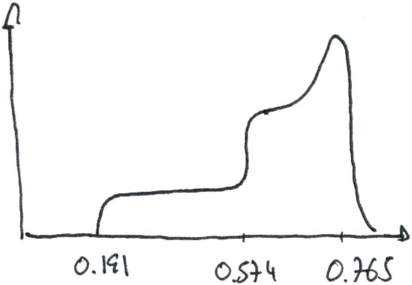
- Compensated chambers

Lithium-6 detectors

- No proportional gas containing Li → No possibility to build proportional chamber
- Advantages of Li:
  - Large Q-value → better γ discrimination
  - Products goes to ground state → only 1 peak
- More common applications with scintillators:
  - LiI(Eu): quite similar to NaI(Tl)
    $\sim$ 35% light output of NaI(Tl)
    $\tau = 0.3\,\mu s$
    Same scintillation efficiency for electrons(γ) and HF (n)
    Worse γ/n separation than gas detectors
    Highly hygroscopic
  - Li in a matrix of ZnS(Ag). For a thickness of ~6 nm ε ~25-30% for 0.1 eV neutrons
  - LiF + ZnS in thin layers (good γ discrimination)
  - Liquid scintillation loaded with ~0.15% Li

Helium-3 based detectors

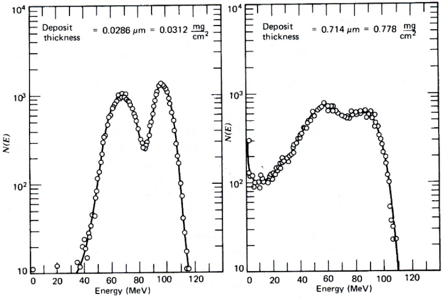
- Can be used only in a proportional counter. ^{3}He cannot be solidified
- Same characteristics as in $^{10}BF_3$ counters → Wall effect



  - It can operate at higher pressures → better detection efficiency
  - low Q → worse γ discrimination

Fission chambers

- Small ionization chambers (or scintillators) with walls covered with fissible material
  - $Q > 200$ MeV/fission → ~160 MeV as KE in fission fragments
  - Most usual gas → Argon
  - Plateau current proportional to neutron flux
  - Pulse Height depends on thickness of the material
- For slow neutrons: ^{235}U, ^{239}Pu
- For fast neutrons: ^{237}Np, ^{238}U



Section 4

Fast neutron detectors

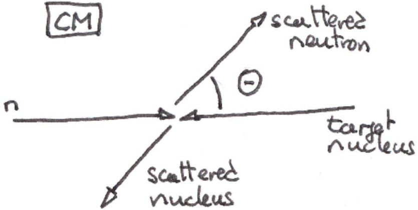
4. Fast neutron detectors
    Fast neutron scattering
    Moderation
    Helium-3 based detectors
    Lithium-6 based detectors
    Proton recoil detectors
    Activation foils

Fast neutron detectors

- Detection techniques described so far do not work with fast neutrons
  - cross section decreases
  - for ^{3}He a bit better in 1-10 MeV region
- Counting techniques
  - Moderation: Energy loss in CH_2 through elastic scattering till n becomes slow/thermal
- Spectroscopy
  - Loaded scintillation: time of flight techniques, pulse shape discrimination
  - Proton recoils in neutron scattering
  - Activation foils

Fast neutron elastic scattering

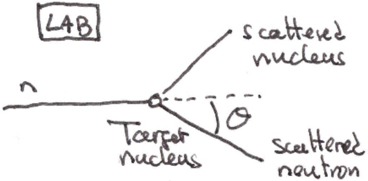
- Energy transfer from neutron to recoil nucleus with Q=0
- Elastic scattering occurs with light nucleus (mainly H)
- if $E_n << 939$ MeV not needed relativistic kinematics



In CM frame

$$E_R = \frac{2A}{(1+A)^2}(1-\cos\Theta)E_n$$

$$\cos\theta = \sqrt{\frac{1-\cos\Theta}{2}}$$



In lab frame

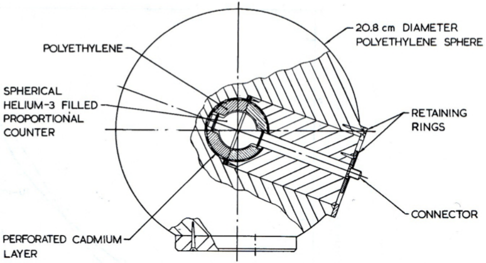
$$E_R = \frac{4A}{(1+A)^2}\cos^2\theta\, E_n$$

Neutron Moderation

- Basic idea: Thermal neutron detector surrounded by a hydrogen rich material
  - Incident neutron looses its energy in the material(CH_2)
  - Few cm thick:

    The thinner the detector → the less energy lost

    The thicker the detector → the less probability to reach the sensitivity area
  - There is an optimal thickness for monoenergetic neutrons
- Typical detectors: BONNER SPHERES

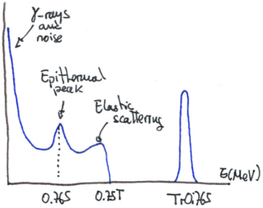


Helium-3 detectors

- ^{3}He can be used as fast neutron detector
- Pulse height spectrum shows some features
  - Full energy peak
  - Continuum from elastic scattering

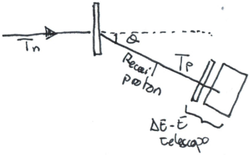
$$E_R^{max} = \frac{4A}{A^2+1} E_n \quad \rightarrow \quad A = 3 \rightarrow E_R^{max} = 0.75 E_n$$

  - Epithermal peak at 765 keV coming from neutron moderation in the walls of the detectors
- Wall effects arise if tube dimensions are not large wrt ranges of secondary particles



Proton recoil detectors

- Based on proton recoil detection from elastic scattering.
- Two types or application: Proton recoil scintillators and proton recoil telescopes



- Organic (lots of H) scintillators are used in neutron spectroscopy.
  - Full proton recoils can be caught in these scintillators
  - Drawbacks: nonlinearity response, multiple neutron scattering, other nuclear reactions
- Proton recoil telescope will take profit of the relation between the energy of the scattered proton and the energy of the incident neutron

$$T_p = T_n \cos\theta$$

Activation foils

- Neutrons can be detected by the radioactivity induced in various elements
- A threshold energy exists for the required nuclear reaction

$$M_1 + M_2 \rightarrow M_3 + M_4 \qquad E_{th} = -Q\left(1 + \frac{M_1}{M_3 + M_4 - M_1}\right)$$

- Activity induced in a foil depends on
  - Neutron fluence at energies above threshold
  - The energy-dependent cross section for the reaction

Reaction	Threshold
^{115}In(n,n')^{115m}In	0.5 MeV
^{58}Ni(n,p)^{58}Co	1.9 MeV
^{27}Al(n,p)^{27}Mg	3.8 MeV
^{56}Fe(n,p)^{56}Mn	4.9 MeV
^{59}Co(n,α)^{56}Mn	5.2 MeV
^{24}Mg(n,p)^{24}Na	6.0 MeV
^{197}Au(n,2n)^{196}Au	8.6 MeV