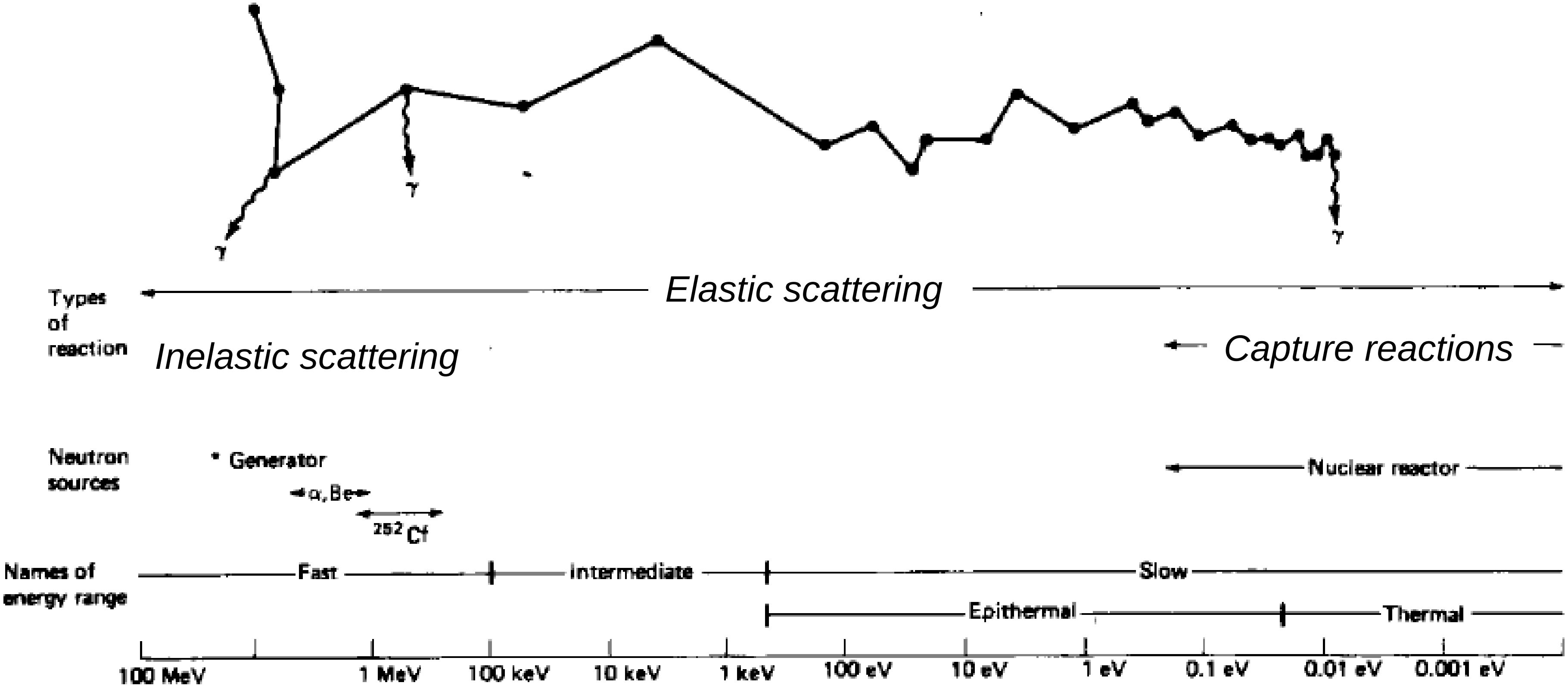
Neutron detection

Neutron properties:

- $M = 939.56\ \mathrm{MeV}$
- $\tau = 886.7\ \mathrm{s}$
- $\mu = -1.91\ \mu_N$
- $d < 0.97 \times 10^{-25}\ \mathrm{e\text{-}cm}$
- $q = 0$

- *Neutrons are neutral, carry no electric charge*
- *no Coulomb interaction with electrons or nuclei*
- *Strong interaction range $r \sim 10^{-15}$ m => small number of interactions*

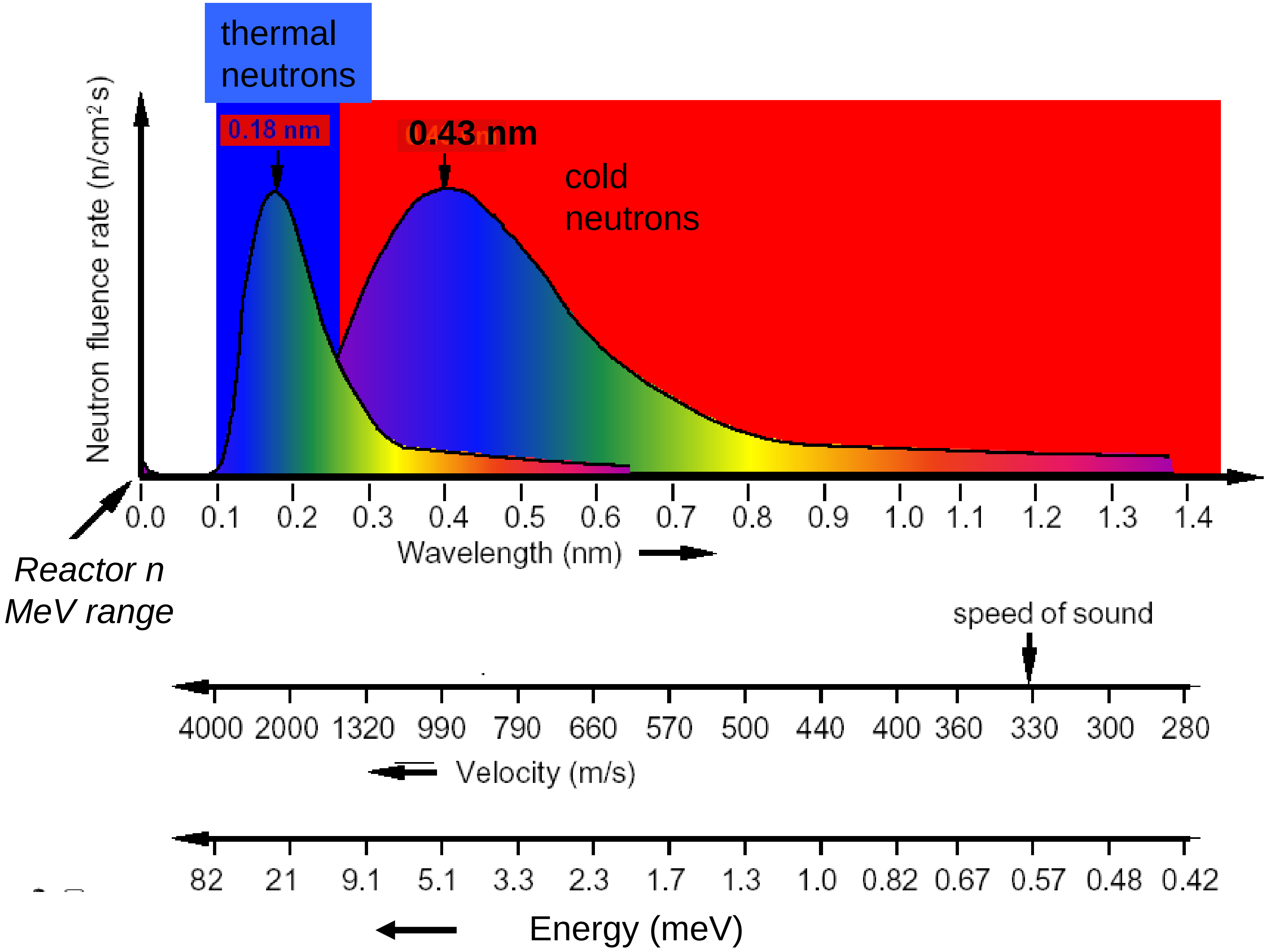
Neutrons – some definitions



Cold neutrons	**< 1 meV**
Slow (thermal)	**< 0.5 eV**
Epi-thermal	**0.5 eV - 50 keV**
Fast	**> 50 keV**
High energy	**> 1 MeV**

- **Ultra-cold neutrons: μeV**

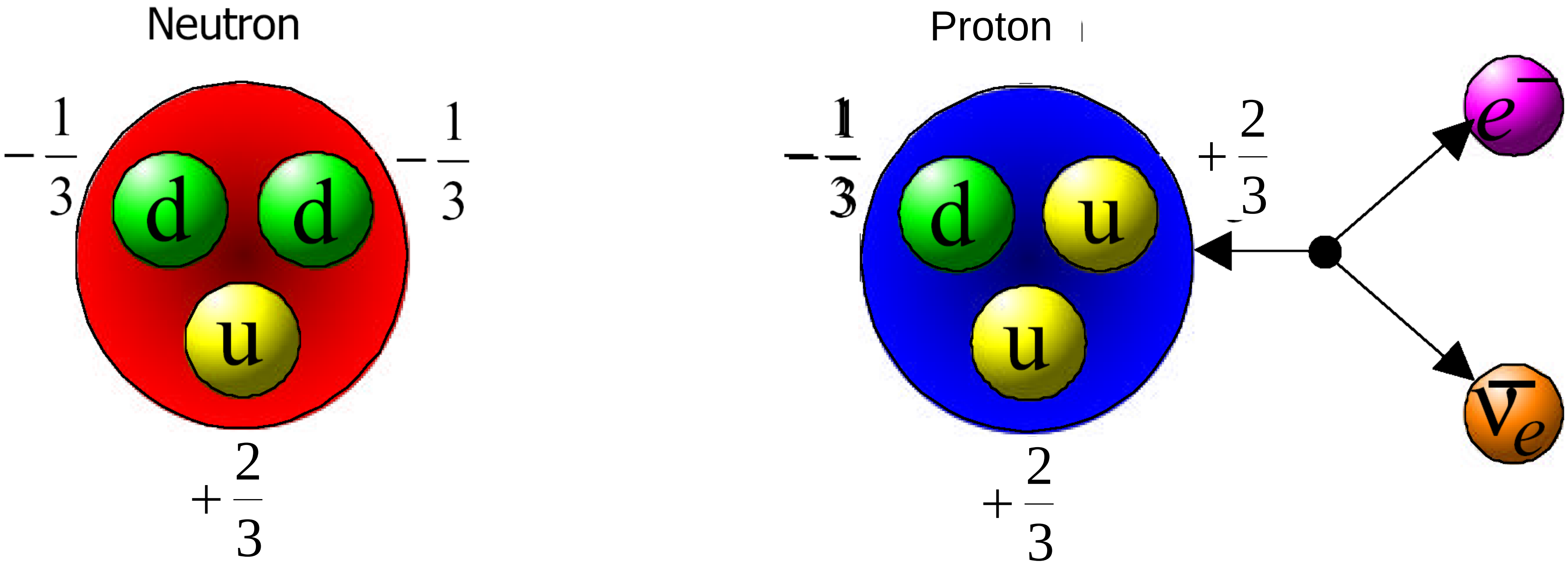
Neutrons – more definitions



How to detect neutrons?

β - decay of free neutron:

$$n \rightarrow p + e^{-} + \bar{\nu}_{e}$$



Half-life: 10 min 14 sec

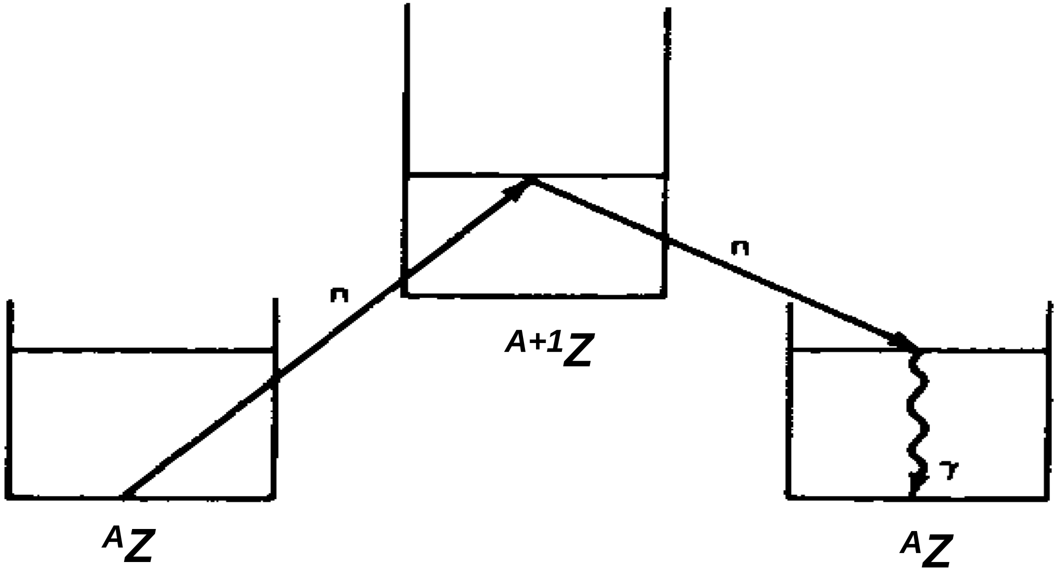
Methods for neutron detection

Detection methods for neutrons

- *Elastic scattering: A(n,n)A*
  main mechanism for energy loss of neutrons in MeV range.

- *Inelastic scattering: A(n,n´)A*, A(n,2n´)B*
  Energy for excited state (Q-value) must be available (> MeV range).

Inelastic excitation



Methods for neutron detection

Nuclear reactions and processes:

- *Radiative neutron capture: $n+(Z,A) \rightarrow \gamma + (Z,A+1)$*

  i. cross section increases tremendeously at low neutron energies
  $\sigma \sim 1/v$ -> slow down neutrons, moderation, create thermal neutrons.
  ii. resonances of capture cross section cause huge fluctuations.
  resonances are specific for isotops.

- *nuclear reactions: (n,p), (n,d), (n,α), (n,t), $(n,\alpha p)$*
  neutrons are captured and charged particles are emitted, again $\sigma \sim 1/v$,
and resonances may occur

- *fission: (n,f), only heavy elements, most likely at thermal energies*

- *hadronic shower*

Neutron moderation

Elastic scattering
-> Neutrons lose kinetic energy and change momentum
Moderation

Center of Mass system:

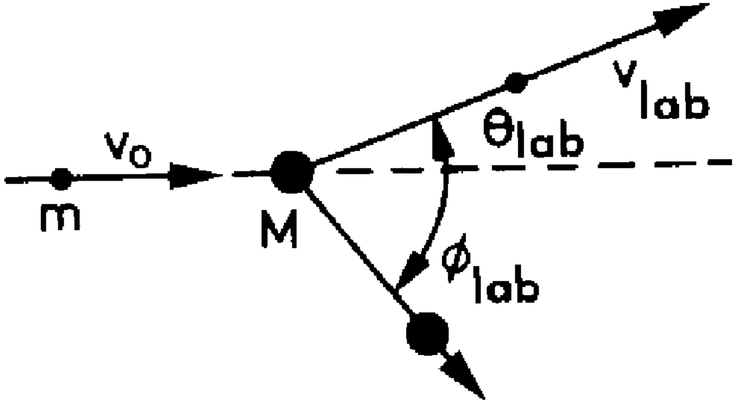
Neutron: $v_{cm} = \frac{A}{A+1} v_0$

recoil nuclei: $V = \frac{1}{A+1} v_0$

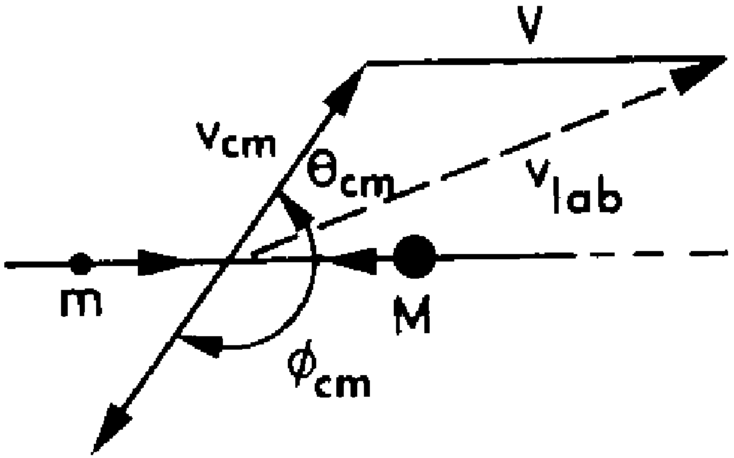
Elastic scattering, kinematics:

$$v_{lab}^2 = v_{cm}^2 + V^2 - 2 v_{cm} V \cos(\pi - \theta_{cm})$$

LAB SYSTEM



CM SYSTEM



Neutron moderation

Via elastic scattering neutrons loose kinetic energy (moderation).

$$\text{Center of Mass system: Neutron: } v_{cm} = \frac{A}{A+1} v_0 \quad \text{recoil nuclei: } V = \frac{1}{A+1} v_0$$

$$\text{Elastic scattering, kinematics: } v_{lab}^2 = v_{cm}^2 + V^2 - 2 v_{cm} V \cos\theta_{cm}$$

$$v_{lab}^2 = \left(\frac{A}{A+1}\right)^2 v_0^2 + \left(\frac{1}{A+1}\right)^2 v_0^2 - 2\frac{A}{(A+1)^2} v_0^2 \cos\theta_{cm}$$

θ_{cm} scattering angle CM-system

$$\frac{E}{E_0} = \left(\frac{v_{lab}}{v_0}\right)^2 = \frac{A^2 + 1 + 2A\cos\theta_{cm}}{(A+1)^2}$$

$$\text{Energy range of scattered neutrons: } \left(\frac{A-1}{A+1}\right)^2 E_0 < E < E_0$$

$$\text{largest energy transfer with proton: } A = 1, \quad 0 < E < E_0$$

$$\text{energy transfer for lead: } A = 208, \quad (207/209)^2 E_0 < E < E_0$$

Neutron moderation

Energy distribution of scattered neutrons at energies E_n<15 MeV
Is dominated isotropic s-wave scattering

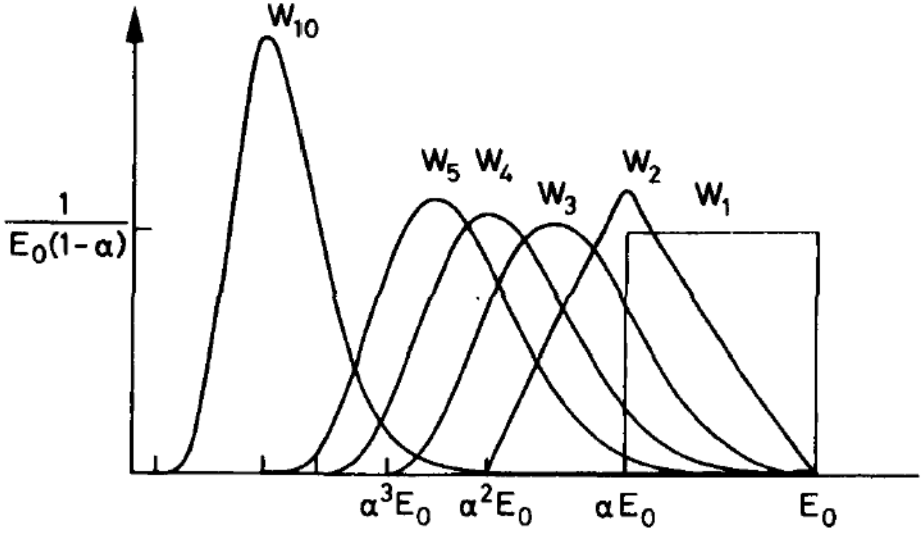
$$dw = \frac{d\Omega}{4\pi} = 2\pi \sin\theta_{cm} \frac{d\theta_{cm}}{4\pi} = \frac{1}{2} \sin\theta_{cm} d\theta_{cm}$$

$$\frac{dE}{E_0} = 2\frac{A}{(A+1)^2} \sin\theta_{cm} d\theta_{cm}$$

$$\frac{dw_1}{dE} = \frac{(A+1)^2}{4A}\frac{1}{E_0} = \frac{1}{E_0(1-\alpha)}$$

$$\text{with } \alpha = \left(\frac{(A-1)}{(A+1)}\right)^2$$

Monoenergetic neutron energy is changed into constant energy distribution after first scattering.



after two scatterings :

$$\frac{dw_2}{dE} = \int_E^{E_0} d\varepsilon \frac{dw_1}{d\varepsilon}\frac{1}{\varepsilon(1-\alpha)} = \frac{1}{E_0(1-\alpha)^2}\ln\frac{E_0}{E} \qquad \alpha E_0 < E < E_0$$

$$\frac{dw_2}{dE} = \int_{\alpha E_0}^{E/\alpha} d\varepsilon \frac{dw_1}{d\varepsilon}\frac{1}{\varepsilon(1-\alpha)} = \frac{1}{E_0(1-\alpha)^2}\ln\frac{E_0}{E} + 2\ln\alpha \qquad \alpha^2 E_0 < E < \alpha E_0$$

Neutron moderation

Energy distribution of scattered neutrons
at energies E_n<15 MeV isotropic s-wave scattering dominates

$$dw = \frac{d\Omega}{4\pi} = 2\pi \sin\theta_{cm} \frac{d\theta_{cm}}{4\pi} = \frac{1}{2}\sin\theta_{cm} d\theta_{cm}$$

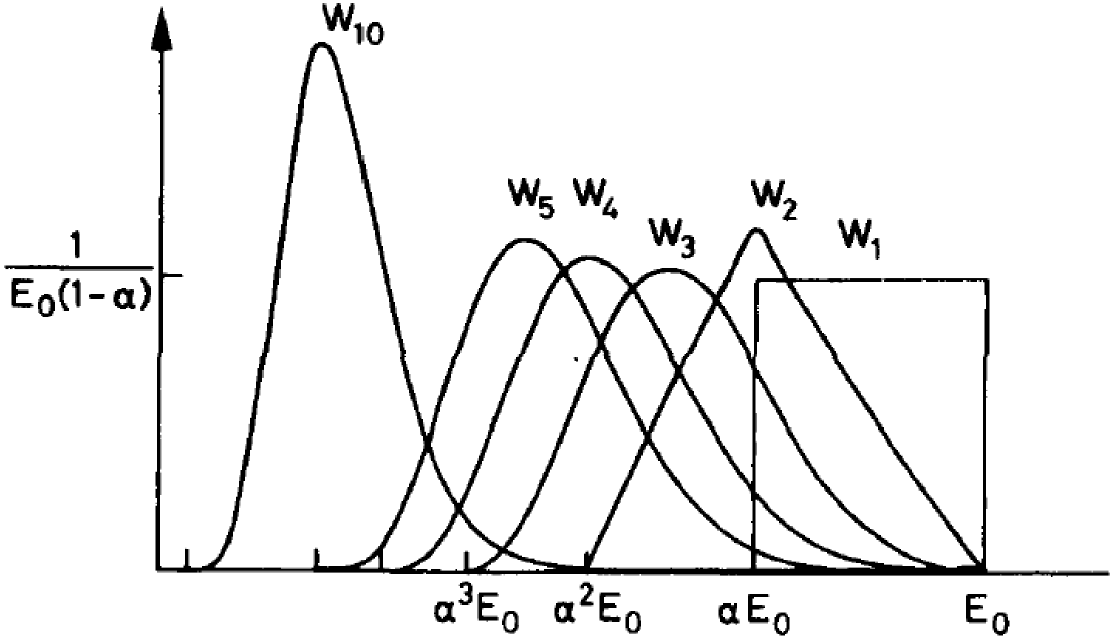
$$\frac{dE}{E_0} = 2\frac{A}{(A+1)^2}\sin\theta_{cm} d\theta_{cm}$$

$$\frac{dw_1}{dE} = \frac{(A+1)^2}{4A}\frac{1}{E_0} = \frac{1}{E_0(1-\alpha)}$$

$$\text{with } \alpha = \left(\frac{(A-1)}{(A+1)}\right)^2$$

General solution for hydrogen :

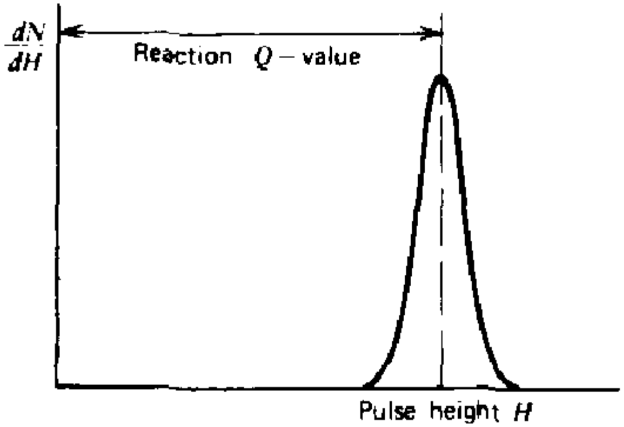
$$\frac{dw_n}{dE} = \frac{1}{E_0(n-1)!}\left(\ln\frac{E_0}{E}\right)^{n-1}$$



example: neutron 1 MeV is moderated down to 1/40 eV
In carbon ^{12}C 111 collisions are needed.
In hydrogen ^{1}H 17.5 collisions are needed.

Specific nuclear reactions for neutron detection

Reaction Q-value determines energy of reaction products for thermal neutrons.



- **^{10}B(n,α)^{7}Li Reaktion**

^{10}B + n -> ^{7}Li + α **Q-value: 2.792 MeV**
ground state 6%

^{10}B + n -> ^{7}Li * + α **Q-value: 2.310 MeV**
excited state 94%

$$E_{Li} + E_{\alpha} = Q = 2.31 \text{ MeV}$$

$$m_{Li} v_{Li} = m_{\alpha} v_{\alpha}$$

$$\sqrt{2 m_{Li} E_{Li}} = \sqrt{2 m_{\alpha} E_{\alpha}}$$

Cross section at thermal energies: σ = 3840 barn !!!

Cross section ~ 1/v

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

Specific nuclear reactions for neutron detection

- ***$^{6}Li(n,\alpha)$ reaction***

$^{6}Li + n \rightarrow {}^{3}H + \alpha$

Q-value: 4.78 MeV

Energy of reaction products: E_{3H} = 2.73 MeV E_{α} = 2.05 MeV

Cross section: σ = 940 barn (therm. neutron)

- ***$^{3}He(n,p)$ reaction***

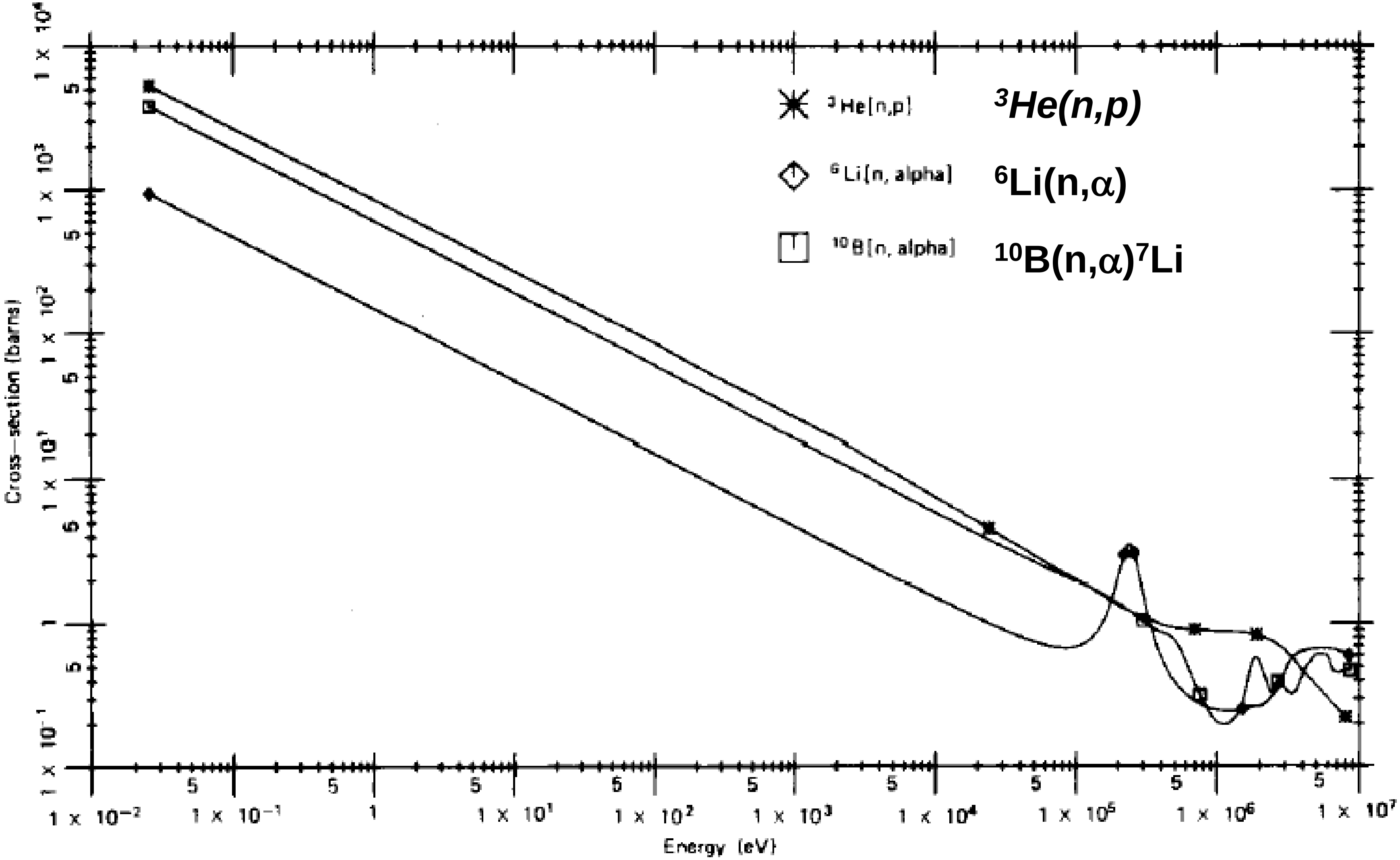
$^{3}He + n \rightarrow {}^{3}H + p$

Q-value: 0.764 MeV

Energy of reaction products: E_{3H} = 0.573 MeV E_{p} = 0.191 MeV

Cross section: σ = 5330 barn (therm. neutron)

Cross sections

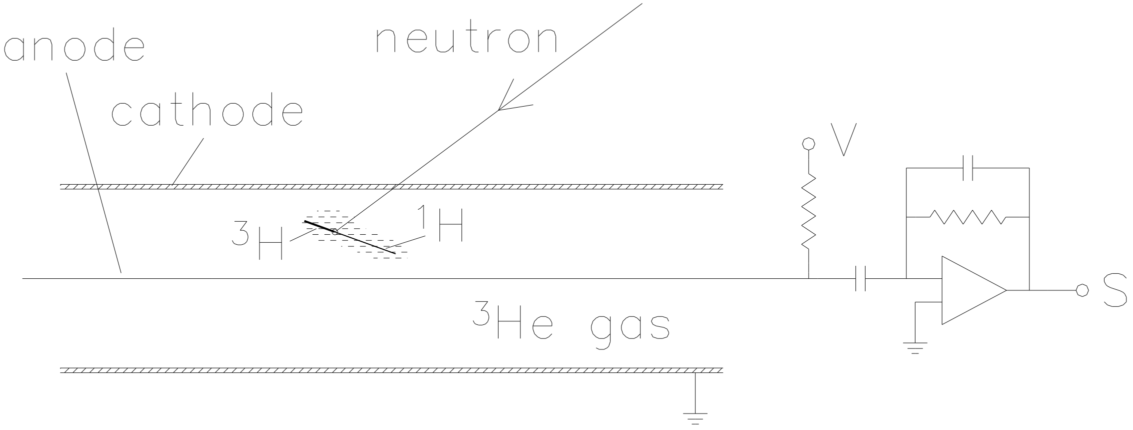


^{3}He(n,p)

^{6}Li(n,α)

^{10}B(n,α)^{7}Li

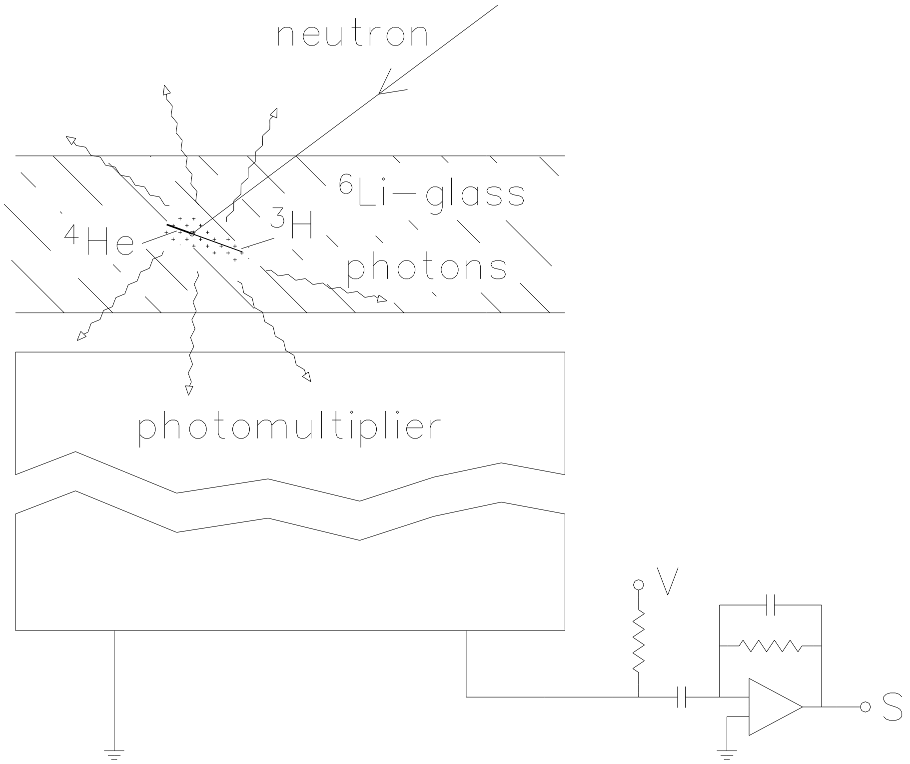
Neutron detection example: ^{3}He gas counter



$$n + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + {}^1\mathrm{H} + 0.76\,\mathrm{MeV}$$

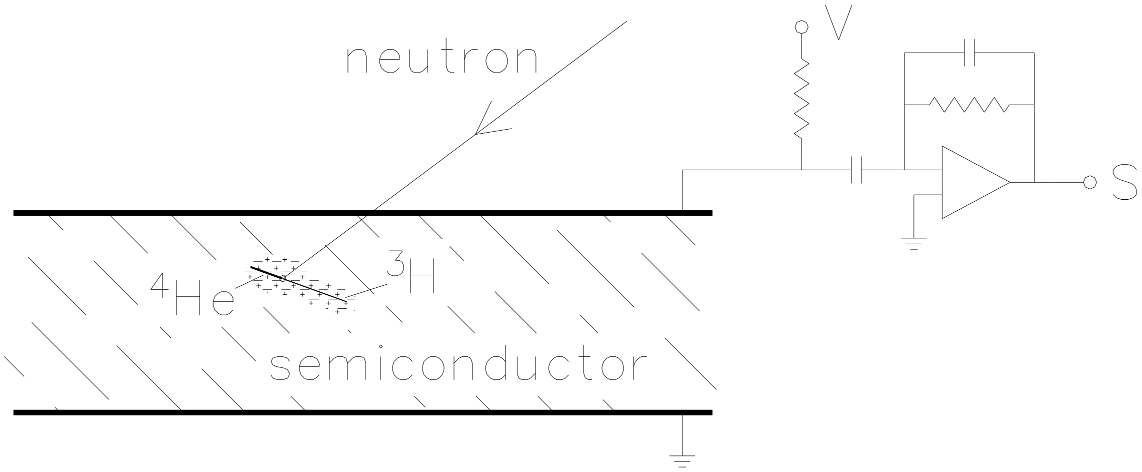
~25,000 ions and electrons produced per neutron (~4×10^{-15} Coulomb)

Neutron detection with scintillation detectors



$$n + {}^6\text{Li} \rightarrow {}^4\text{He} + {}^3\text{H} + 4.79\ \text{MeV}$$

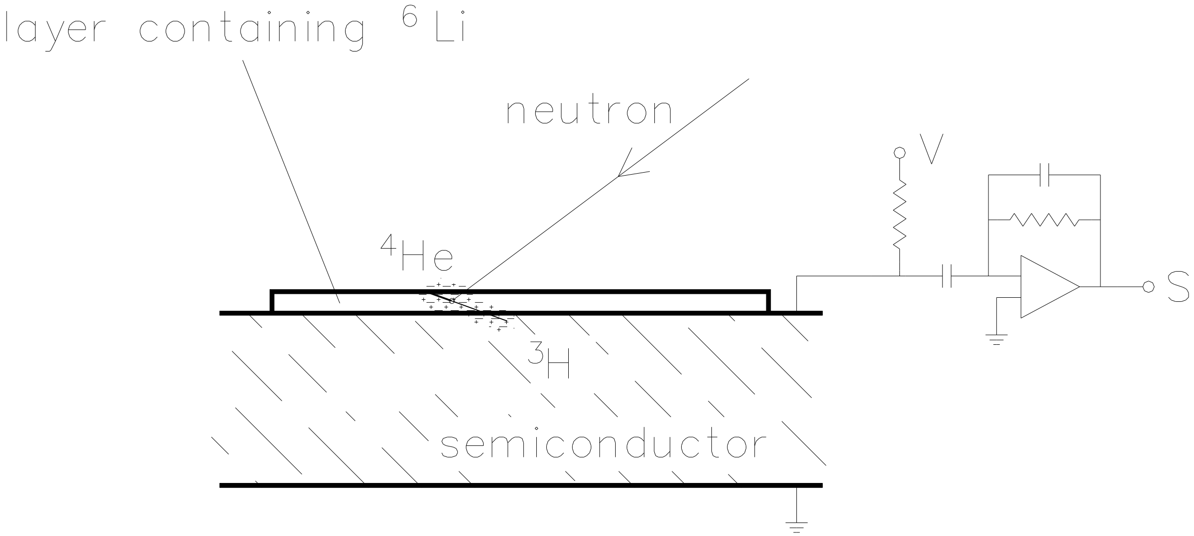
Neutron detection semiconductor



$$n + {}^{6}\text{Li} \rightarrow {}^{4}\text{He} + {}^{3}\text{H} + 4.79\ \text{MeV}$$

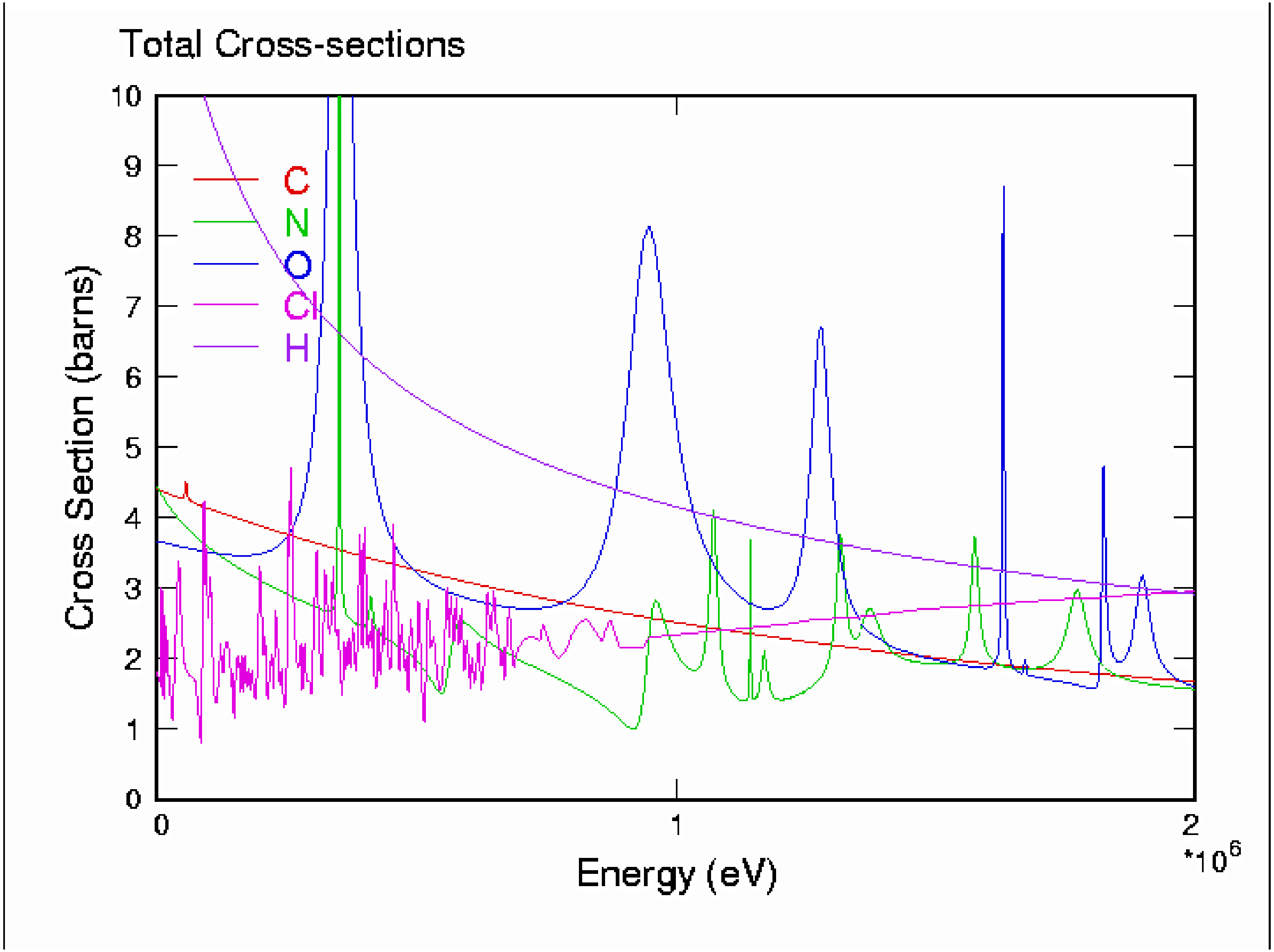
But standard device semiconductors do not contain enough neutron-absorbing nuclei to give reasonable neutron detection efficiency.

Coating with neutron absorbers

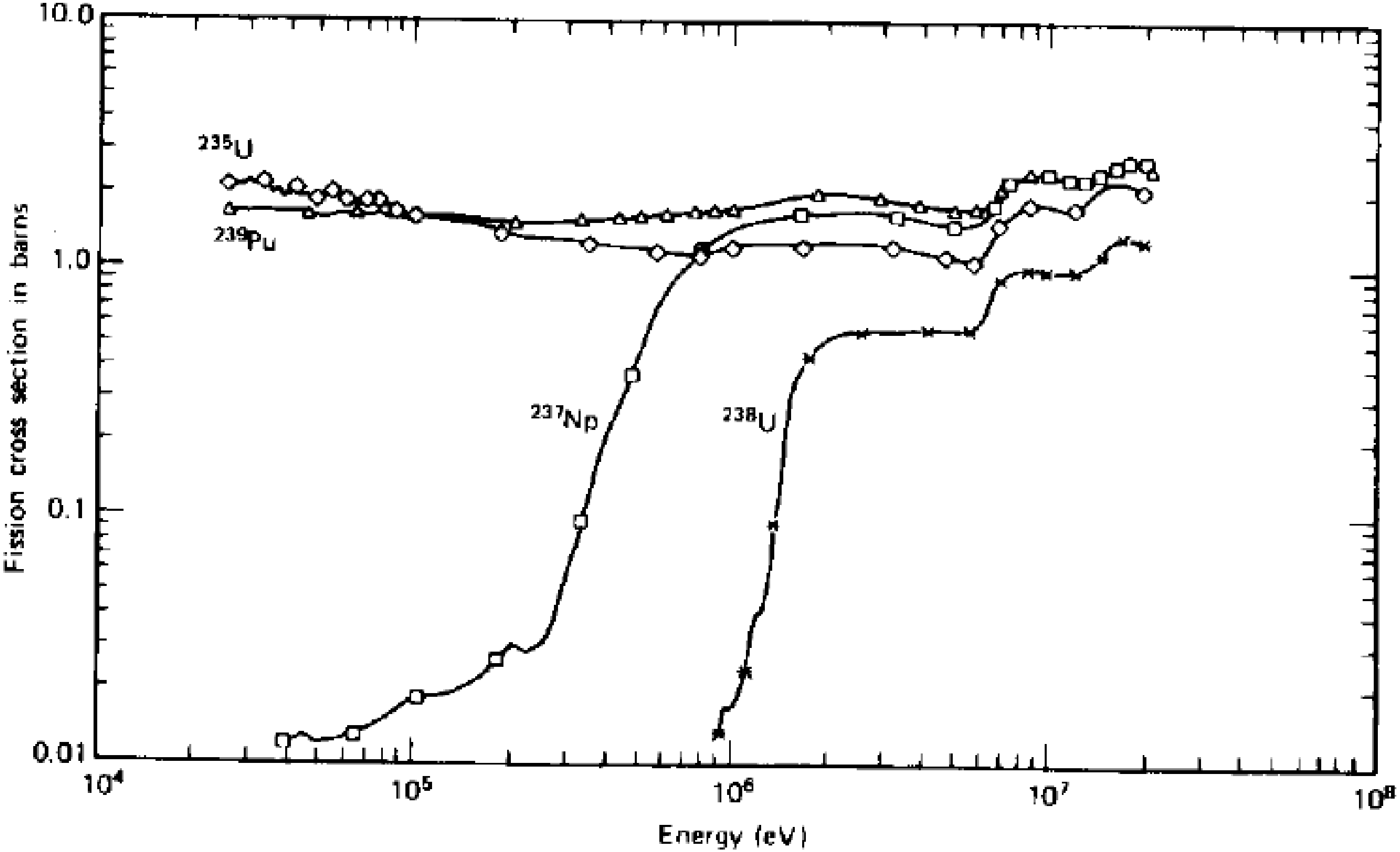


- Layer must be thin (a few microns) for charged particles to reach detector
  - detection efficiency is low
- Most of the deposited energy doesn’t reach detector
  - poor pulse height discrimination

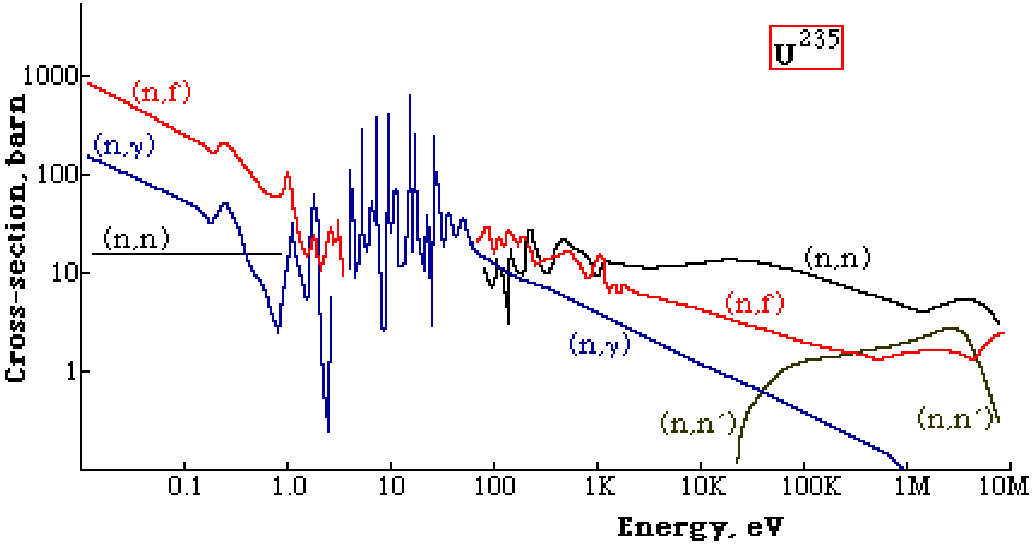
Neutron cross sections

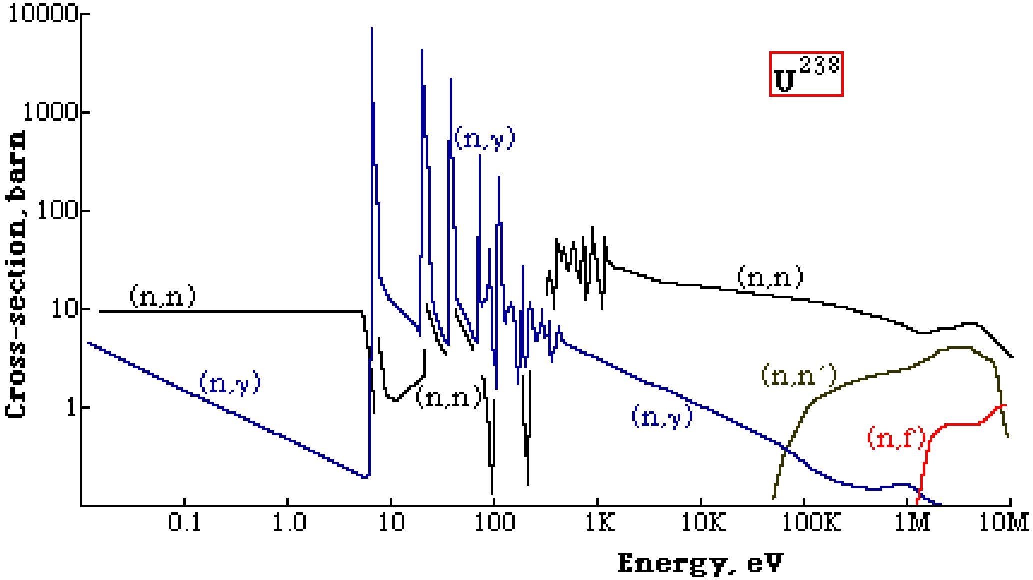


fission and fast neutrons



Neutron induced fission





Fission fragment distribution