TRAINING COURSE ON:
NEUTRON DOSIMETRY, RADIOBIOLOGY AND INSTRUMENTATION

Neutron interactions with matter

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Wed. 24/6/2015, 10:00 – 11:00 am

11:30 -12:30 am

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THE ABSORBED DOSE

- Energy imparted ε:

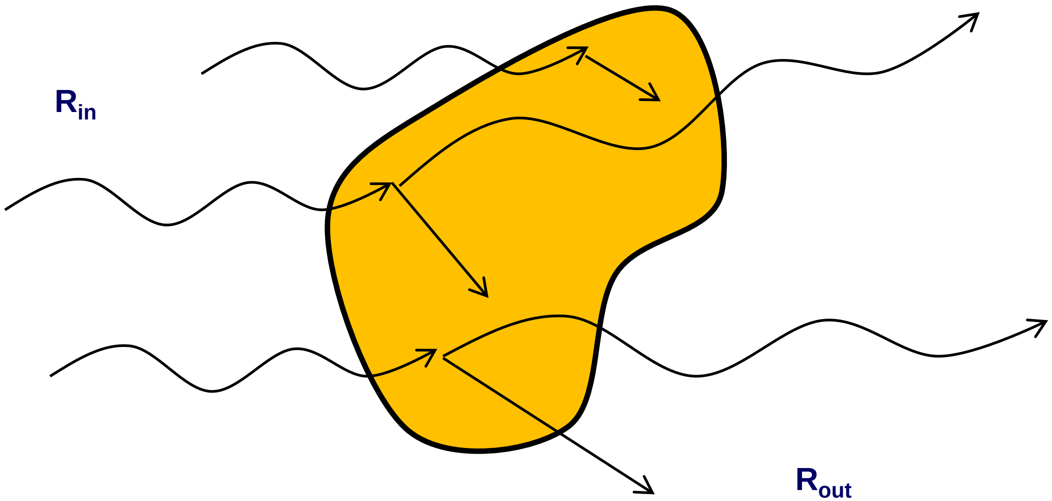
$$\varepsilon = R_{in} - R_{out} + \sum Q$$

  - R is radiant energy, Q is the change of the rest mass energy of a nucleus.
  - Unit joule (J)

- Absorbed dose D:

$$D = \frac{d\bar{\varepsilon}}{dm}$$

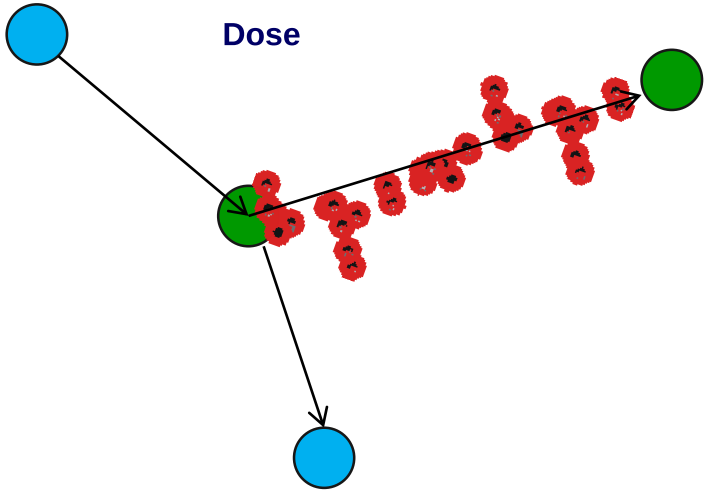
  - Unit gray (Gy)

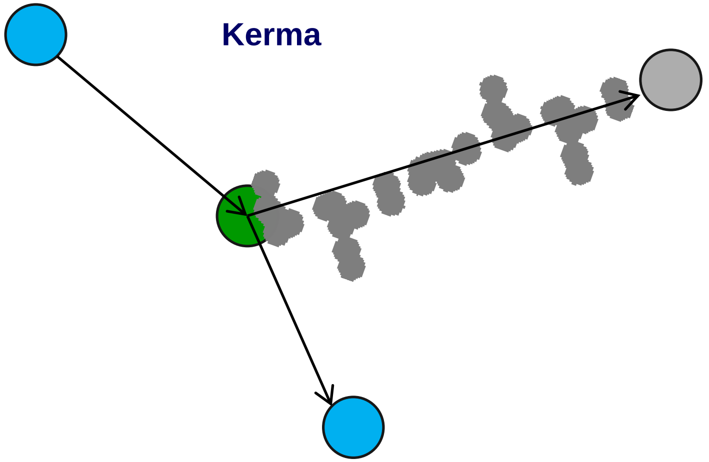


THE KERMA

$$K = \frac{dE_{tr}}{dm}$$

- where dE_{tr} is the sum of initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles in a material of mass dm (ICRU33);
- Unit: gray (Gy)





Energy is deposited locally at the interaction point: no secondary particle transport!

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PARTICLE FLUENCE

- The spectral distribution of particle radiance is defined as:

$$p_E = \frac{d^4N}{da\, d\Omega\, dE\, dt} = v\, n(\vec{r}, \Omega, E)$$

✓ v=particle velocity;

✓ n=particle density (number of particles N per unit volume).

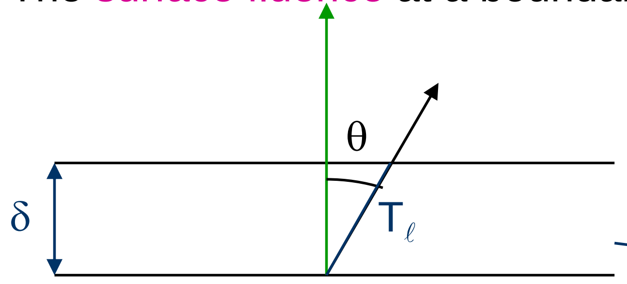
- The particle fluence averaged over a region of volume V can be estimated as:

$$\Phi = \int_V \int_\Omega \int_E \int_t v\, n(\vec{r}, \Omega, E)\, dt\, dE\, d\Omega \frac{dV}{V} = \frac{\int\int nv\, dt\, dV}{V} = \frac{\int nds\, dV}{V} = \frac{T_\ell}{V}$$

✓ nds is a “track-length density”;

✓ T_ℓ sum of track lengths.

- The surface fluence at a boundary crossing is, for one particle of weight w:



$$\Phi_S = \lim_{\delta \to 0} w \frac{T_\ell}{V} = w \frac{\delta / |\cos\theta|}{S\delta} = \frac{w}{S|\cos\theta|}$$

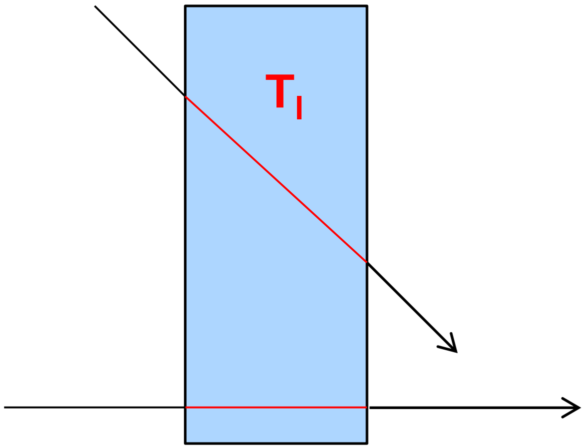
Infinitely thin region of volume Sδ

PARTICLE FLUENCE

- The reaction rate is defined as:

$$R = N_{TOT} \int \sigma_E \Phi_E dE$$

- Cross section is defined for an infinitely thin target



- the longest T_l is the higher the particle contribution to the fluence is,
- since the particle comes across a higher number of nuclei along its path inside the target.

RP QUANTITIES – ICRP 26

- ICRP 26 (1997) accounted for the different qualities of ionizing radiation through the quality factor Q;
- The dose equivalent H was defined as:

$$H = DQN$$

  - → D is the absorbed dose;
  - → N included any factor which could modify the risk from radiation dose.
- ICRP 26 did not specify any factor N and the dose equivalent was later changed to (e.g. ICRU 51):

$$H = QD$$

- The unit of dose equivalent is the sievert (Sv) ($1\ Sv = 1\ J\ kg^{-1}$)

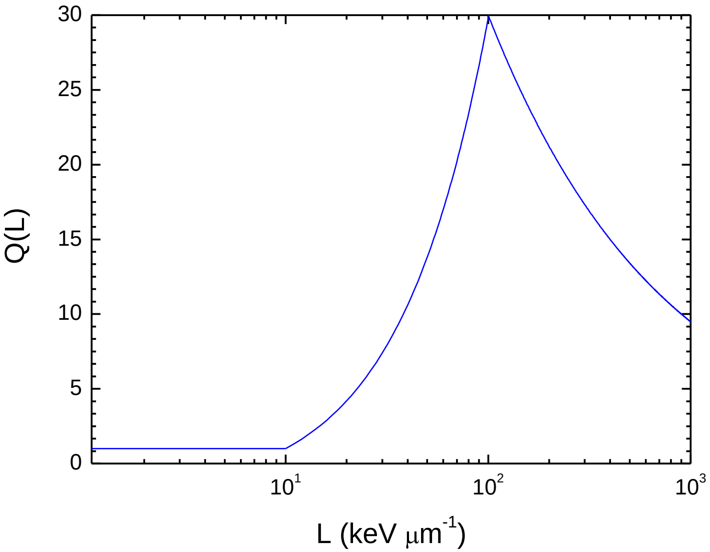
QUALITY FACTOR

- A dependence of Q on LET (L) was given by ICRP;
- The quality factor Q at a point in tissue is:

$$Q = \frac{1}{D}\int_L Q(L) D_L \, dL$$

- ICRP 60 (1991) specified the following Q(L) relation in water (overkilling effect accounted for):

$$Q(L) = \begin{cases} 1 & L \geq 10 \text{ kev } \mu m^{-1} \\ 0.32\ L - 2.2 & 10 \leq L \leq 100 \\ \dfrac{300}{\sqrt{L}} & L \geq 100 \end{cases}$$



QUALITY FACTOR

- When the D(L) relation cannot be assessed, $\overline{Q}$ were recommended as the ratio of the maximum value of H in depth in tissue and D at the corresponding maximum depth.

Radiation	$\overline{Q}$
X, γ, electrons	1
Neutrons, protons, single charged particles with mass > 1 amu	10
Alphas, multiple charged particles	20

QUANTITIES BASED ON THE DOSE EQUIVALENT

- Dose equivalent rate:
  - ✓ Units: J kg^{-1} s^{-1}; special unit: Sv s^{-1};

$$\dot{H} = \frac{dH}{dt}$$

- Mean absorbed dose in a specified tissue or organ:
  - ✓ m_T mass of the organ or tissue;
  - ✓ D absorbed dose in the mass element dm

$$D_T = \frac{1}{m_T} \int_{m_T} D dm$$

- Mean quality factor:
  - ✓ Q quality factor in the mass element dm

$$Q_T = \frac{1}{m_T D_T} \int_{m_T} Q D dm = \frac{1}{m_T D_T} \int_{m_T} \int_L Q(L) D_L dL dm$$

QUANTITIES BASED ON THE DOSE EQUIVALENT

- Effective dose equivalent :
  - ✓ w_T tissue weighting factors

$$H_E = \sum_T w_T D_T Q_T$$

$$\sum_T w_T = 1$$

ICRP 103

Table B.1. ICRP Recommendations for tissue weighting factors in *Publication 26* (1977) and *Publication 60* (1991b).

Tissue	Tissue weighting factor, w_T	
	1977 *Publication 26*	1991 *Publication 60*[2,3]
Bone surfaces	0.03	0.01
Bladder		0.05
Breast	0.15	0.05
Colon		0.12
Gonads	0.25	0.20
Liver		0.05
Lungs	0.12	0.12
Oesophagus		0.05
Red bone marrow	0.12	0.12
Skin		0.01
Stomach		0.12
Thyroid	0.03	0.05
Remainder	0.30[1]	0.05
TOTAL	1.0	1.0

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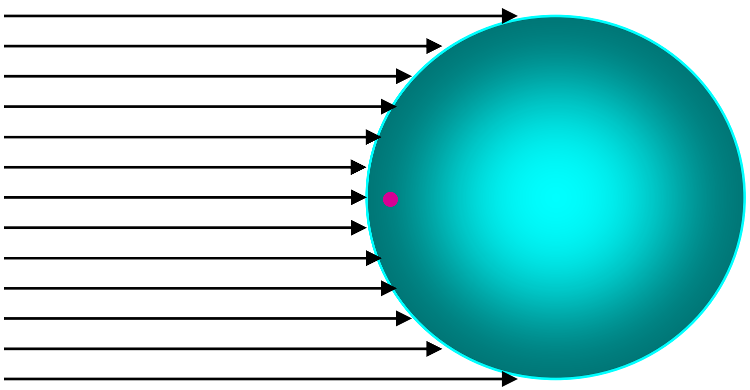
OPERATIONAL QUANTITIES

- The operational quantities defined by ICRU 51 are:
  - ✓ the ambient dose equivalent, $H^*(d)$;
  - ✓ the directional dose equivalent, $H'(d,\Omega)$;
  - ✓ the personal dose equivalent $H_p(d)$.

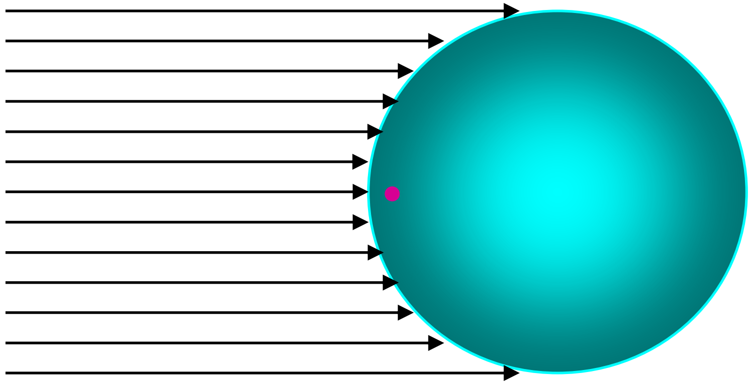
- Their values are "taken as sufficiently precise assessments of effective dose or skin dose, respectively, especially if their values are below the protection limits"(ICRP 103).
- They should give a reasonable conservative estimate of the RP quantities.
- Area monitoring: $H^*(d)$ and $H'(d,\Omega)$;
- Individual monitoring: Hp(d).



- ICRU sphere:
  - ✓ Tissue-equivalent;
  - ✓ Mass composition: oxygen 76.2%, 11.1% carbon, 10.1% hydrogen; 2.6% nitrogen.
  - ✓ 30 cm in diameter;
  - ✓ Density = 1 g cm^{-2};

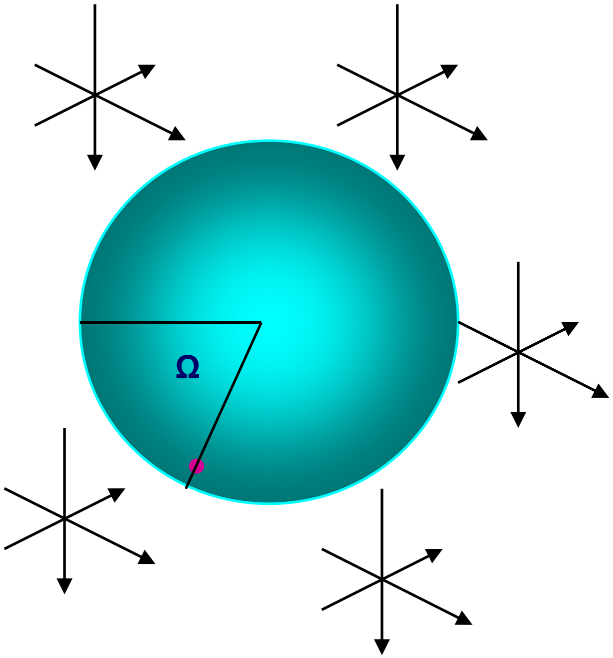
AMBIENT DOSE EQUIVALENT

- The ambient dose equivalent *H*(d)*, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded and aligned field, in the ICRU sphere, at a depth *d* on the radius opposing the direction of the aligned field(ICRU 51).
  - ✓ currently recommended *d*=10 mm, *H*(10)*;
  - ✓ weakly penetrating radiation:
    - → skin *d*=0.07 mm;
    - → eye *d*= 3 mm.

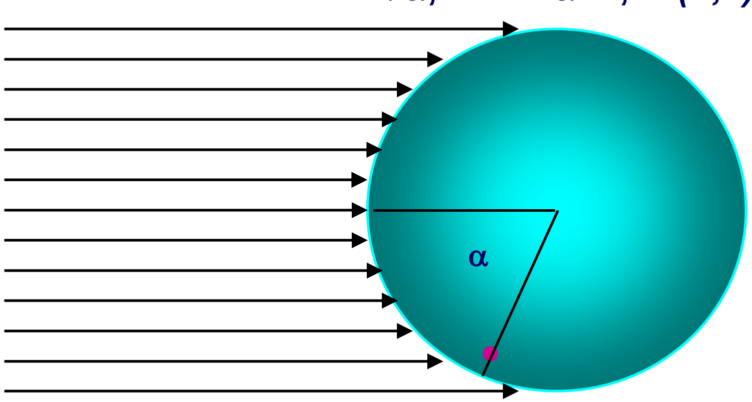


DIRECTIONAL DOSE EQUIVALENT

- The directional dose equivalent *H'(d,Ω)*, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field, in the ICRU sphere, at a depth *d* on the radius in a specified direction Ω (ICRU 51).
  - ✓ strongly penetrating radiation, currently recommended *d*=10 mm;
  - ✓ weekly penetrating radiation:
    - → skin *d*=0.07 mm;
    - → eye *d*= 3 mm.



Unidirectional field: Ω→α, when α=0, *H'(d,0)=H'(d)=H*(d)*.



PERSONAL DOSE EQUIVALENT

- The directional dose equivalent, $H_p(d)$, is the dose equivalent in soft tissue, at an appropriate depth *d*, below a specified point in the body(ICRU 51).
  - ✓ Strongly penetrating radiation *d*=10 mm;
  - ✓ weekly penetrating radiation:
    - → skin *d*=0.07 mm;
    - → eye *d*= 3 mm.
- H_p(d) can measured with a detector worn on the surface of the body and covered with an appropriate thickness of TE material;
- The calibration of a dosimeter is generally performed under simplified conditions and on an appropriate phantom:
  - ✓ ISO phantom: slab phantom (30×30×15 cm^3) filled with water, PMMA walls 10 mm in thickness, excluding the front wall which is 2.5 mm in thickness.

ICRP 60 & ICRP 103

- The mean absorbed dose in the region of an organ or tissue T is:

$$\overline{D}_T = \frac{\int_T D(x,y,z)\rho(x,y,z)dV}{\int_T \rho(x,y,z)dV}$$

- where:
  - ✓ V is the volume of the tissue region T;
  - ✓ D is the absorbed dose at a point (x,y,z) in that region;
  - ✓ ρ is the density at this point.

EQUIVALENT DOSE

- The equivalent dose in an organ or tissue T is:

$$H_T = \sum_R w_R D_{T,R}$$

- where:
  - ✓ w_R is the radiation weighting factor for radiation R.
- Unit: sievert (Sv)

RADIATION WEIGHTING FACTORS

ICRP Publication 103

Table B.3. Radiation weighting factors[1] (ICRP 1991b).

Type and energy range[2]	Radiation weighting factors, w_R
Photons, all energies	1
Electrons and muons, all energies[3]	1
Neutrons, energy < 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, energy>2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

[1] All values relate to the radiation incident on the body or, for internal sources, emitted from the source.
[2] The choice of values for other radiations is discussed in paragraph A14 in ICRP (1991b).
[3] Excluding Auger electrons emitted from nuclei bound to DNA (see paragraph A13 in ICRP 1991b).

Table B.4. Radiation weighting factors[1] in the 2007 Recommendations.

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous curve as a function of neutron energy (see Fig. B.4 and Eqn. B.3.16)

[1] All values relate to the radiation incident on the body or, for internal sources, emitted from the source.

RADIATION WEIGHTING FACTORS - NEUTRONS

$$w_R = \begin{cases} 2.5 + 18.2\, e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0\, e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leqslant E_n \leqslant 50 \text{ MeV} \\ 2.5 + 3.25\, e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases} \quad \text{(B.3.16)}$$

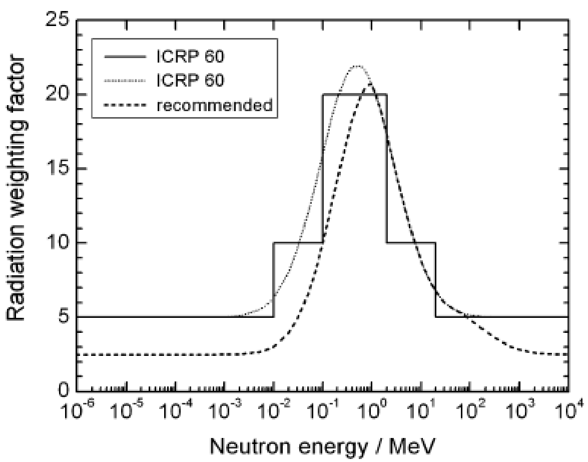


Fig. B.4. Radiation weighting factor, w_R, for neutrons versus neutron energy. Step function and continuous function given in *Publication 60* (ICRP 1991b) and function adopted in the 2007 Recommendations.

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EFFECTIVE DOSE

- The equivalent dose in an organ or tissue T is:

$$E = \sum_T w_T \sum_R w_R D_{T,R} = \sum_T w_T H_T$$

- where:
  - ✓ w_R is the radiation weighting factor for radiation R;
  - ✓ w_T is the the tissue weighting factor for tissue T.
- Unit: sievert (Sv)

Table B.2. Tissue weighting factors, w_T, in the 2007 Recommendations.

Organ/Tissue	Number of tissues	w_T	Total Contribution
Lung, stomach, colon, bone marrow, breast, remainder	6	0.12	0.72
Gonads	1	0.08	0.08
Thyroid, oesophagus, bladder, liver	4	0.04	0.16
Bone surface, skin, brain, salivary glands	4	0.01	0.04

NEUTRON INTERACTIONS WITH SOFT TISSUE

- Neutrons below about 20 MeV:
  - ✓ Thermal neutrons (0<E<0.5 eV);

$$\frac{\Phi(E)dE}{\Phi} = \frac{E}{kT} e^{-E/kT} \frac{dE}{kT}$$

    - ✓ Φ total fluence
  - ✓ Epithermal neutrons (0.5 eV<E<100 keV);
  - ✓ Fast neutrons (100 keV<E<20 MeV);
  - ✓ Intermediate-energy neutrons (20 MeV<E<a few GeV)

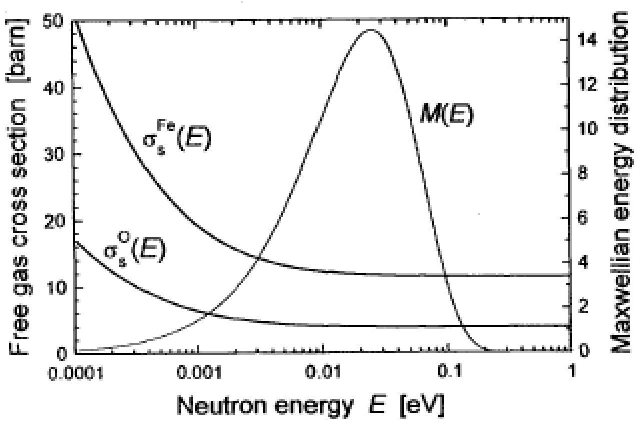
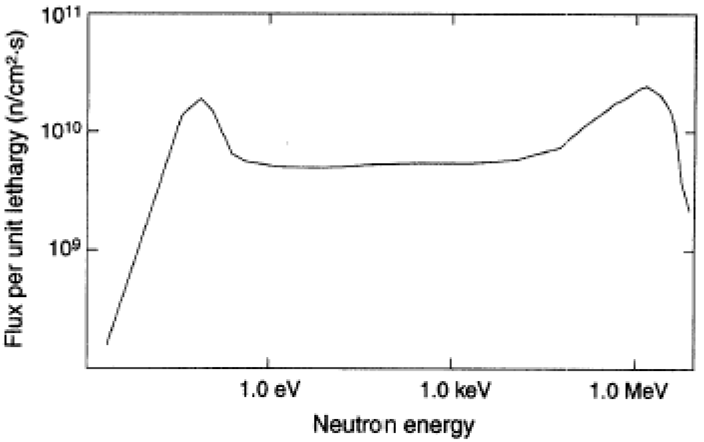
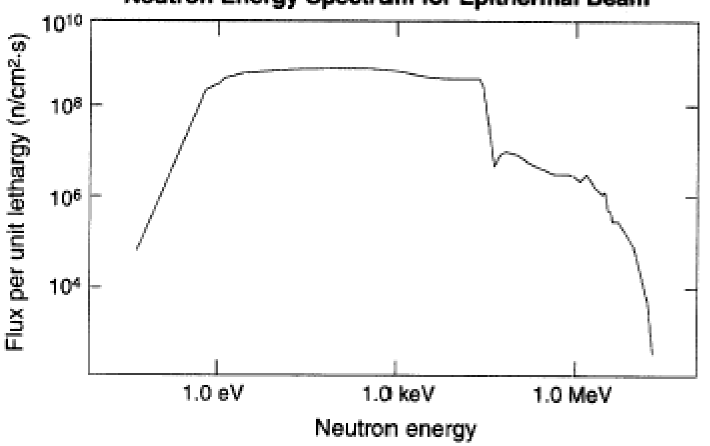


Fig. 4.1. Example of the free gas scattering cross sections and the Maxwellian distribution.

From: K. Drodowicz, IAEA report 1838/PN (1999)





NEUTRON INTERACTIONS WITH SOFT TISSUE

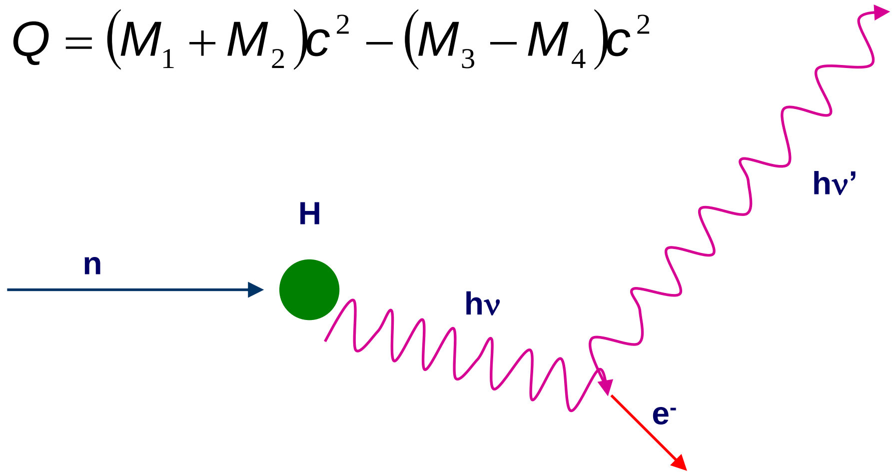
- Soft tissue:

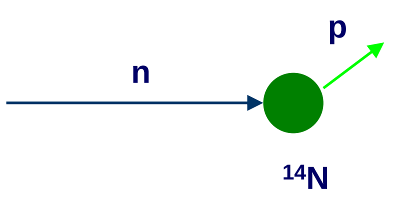
Element	Weight percent
H	10.2
C	12.3
N	3.5
O	72.9
Na	0.08
Mg	0.02
P	0.2
S	0.5
K	0.3
Ca	0.007

THERMAL NEUTRONS

Element	Reaction	Q (MeV)	Cross section
H	$^{1}H(n,\gamma)^{2}H$	2.223	332 mb
C	$^{12}C(n,\gamma)^{13}C$	4.946	3.4 mb
N	$^{14}N(n,\gamma)^{15}N$	10.833	75 mb
N	$^{14}N(n,p)^{14}C$	0.626	1.81 b
O	$^{16}O(n,\gamma)^{17}O$	4.143	0.178 mb

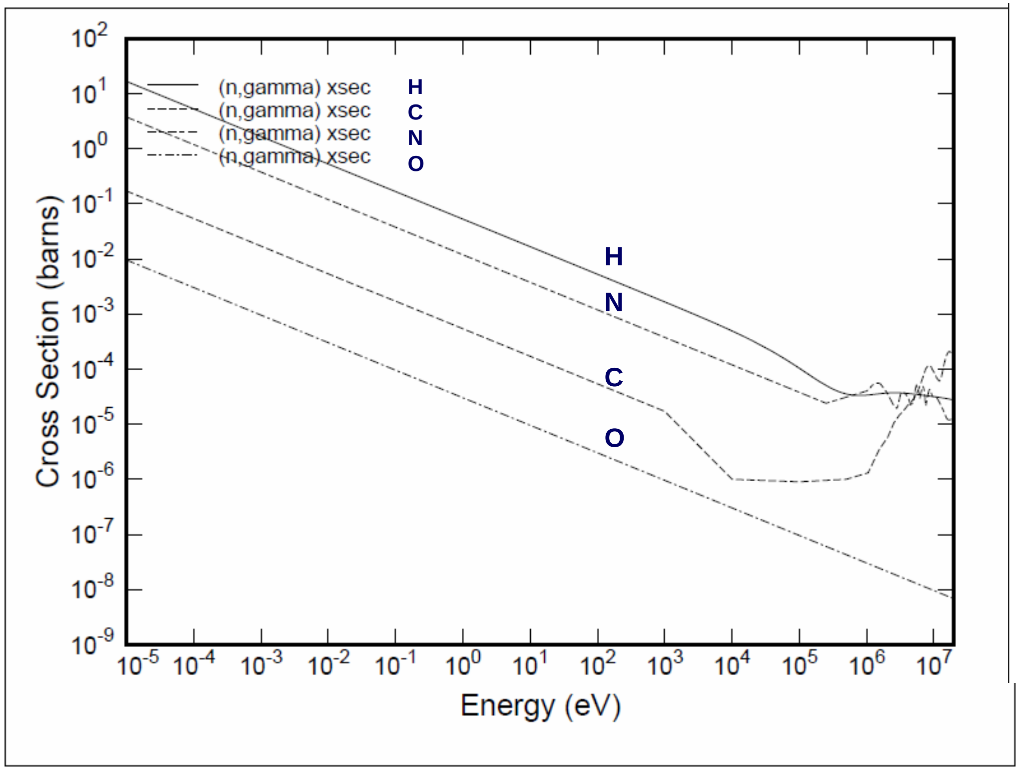
$$Q = (M_1 + M_2)c^2 - (M_3 - M_4)c^2$$

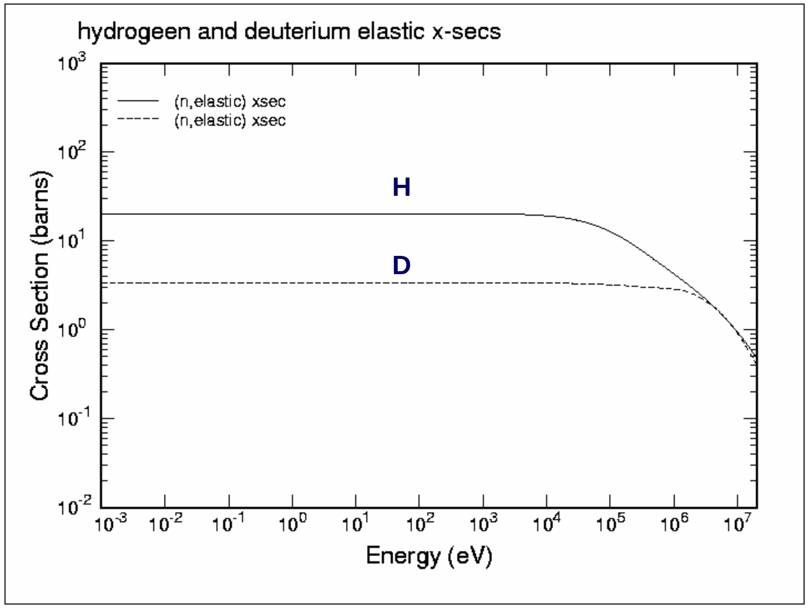




EPITHERMAL NEUTRONS

- Neutron absorption cross sections depend on 1/v;
- Elastic scattering occurs and recoil nuclei can contribute to the absorbed dose.





FAST NEUTRONS

- Elastic scattering occurs and recoil nuclei contribute to the absorbed dose.

$$E_R = \frac{4A}{(A+1)^2}\left(\cos^2 \vartheta\right)E_n$$

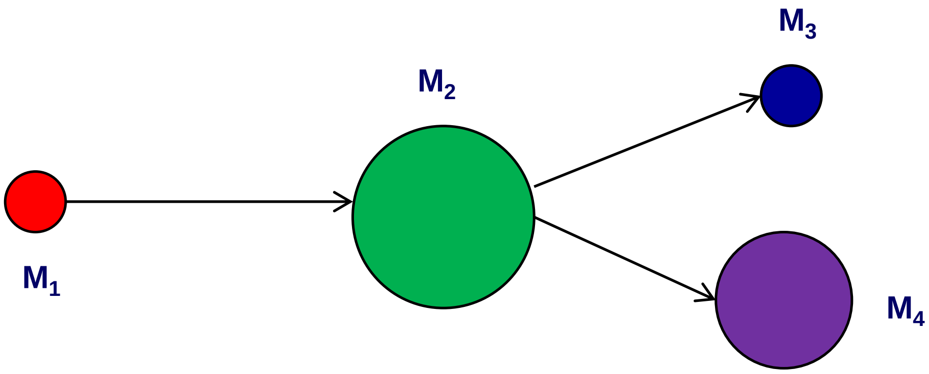
Target Nucleus	$E_{R,max}/E_n$
H	1
C	0.284
N	0.249
O	0.221

- where A is the target nucleus mass (M_2 below)

- Inelastic reactions:

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

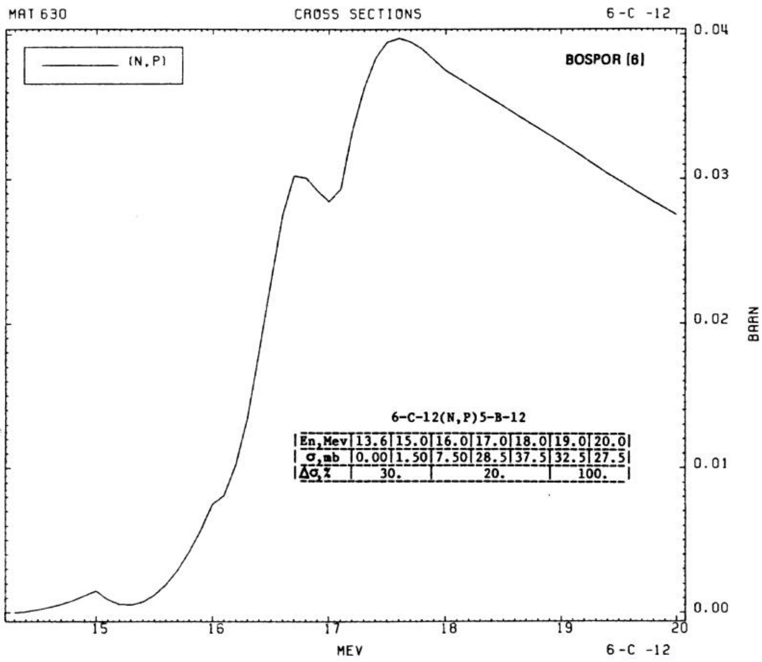
$$E_{th} = -Q\left(\frac{M_1 + M_2}{M_2}\right) \qquad M_2 >> Q/c^2$$



FAST NEUTRONS

- Some inelastic reactions:

Target Nucleus	Reaction	Q (MeV)	Threshold Energy (MeV)
C	$^{12}C(n,\alpha)^{9}Be$	-5.70122	6.18044
C	$^{12}C(n,p)^{12}B$	-12.58665	13.64462
C	$^{12}C(n,2n)^{11}C$	-18.72201	20.29569
N	$^{14}N(n,\alpha)^{11}B$	-0.15816	0.16955
N	$^{14}N(n,2n)^{13}N$	-10.55345	11.31363
O	$^{16}O(n,\alpha)^{13}C$	-2.21561	2.35534
O	$^{16}O(n,p)^{16}N$	-9.63815	10.24595
O	$^{16}O(n,2n)^{15}O$	-15.66384	16.65162



$^{12}C(n,p)^{12}B$

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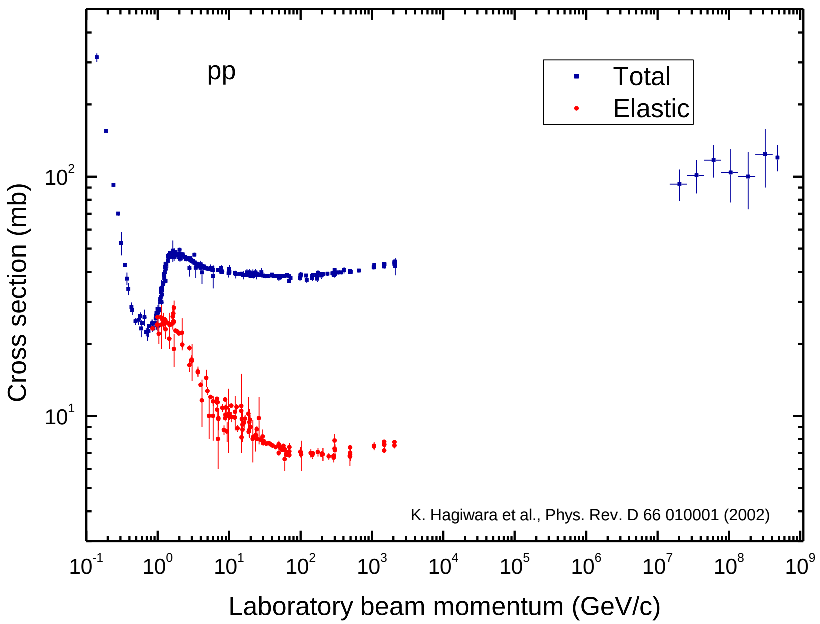
SECONDARY RADIATION AT INTERMEDIATE AND HIGH ENERGIES

- The main mechanisms for secondary hadron production from particles other than ions at intermediate energies (from about 50 MeV up to a few GeV) will be outlined.
- It should be underlined that for particle momenta higher than a few GeV/c, the hadron-nucleus cross section tends to its geometric value:

$$\sigma_{hN} \cong \pi r^2 = \pi (r_0 A^{1/3})^2 = 45 A^{2/3} \text{ mb}$$

- The interaction length scales with:

$$\lambda_{hN} = \frac{1}{\frac{N}{\rho}\sigma_{hN}} \cong 37 A^{1/3} \text{ g cm}^{-2}$$



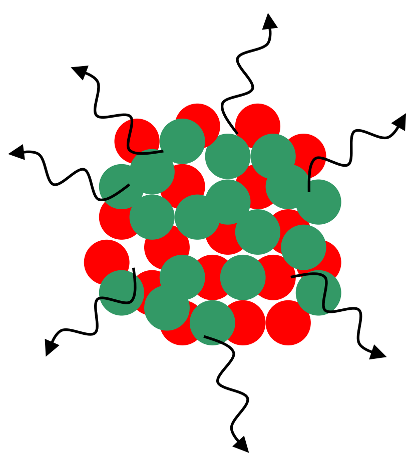
- References:

  - ✓ Ferrari, A. and Sala, P.R. The Physics of High Energy Reactions. Proceedigs of the Workshop on Nuclear Reaction Data and Nuclear Reactors Physics, Design and Safety, International Centre for Theoretical Physics, Miramare-Trieste (Italy) 15 April-17 May 1996, Gandini A. and Reffo G., Eds.World Scientific, 424-532 (1998).
  - ✓ ICRU 28.

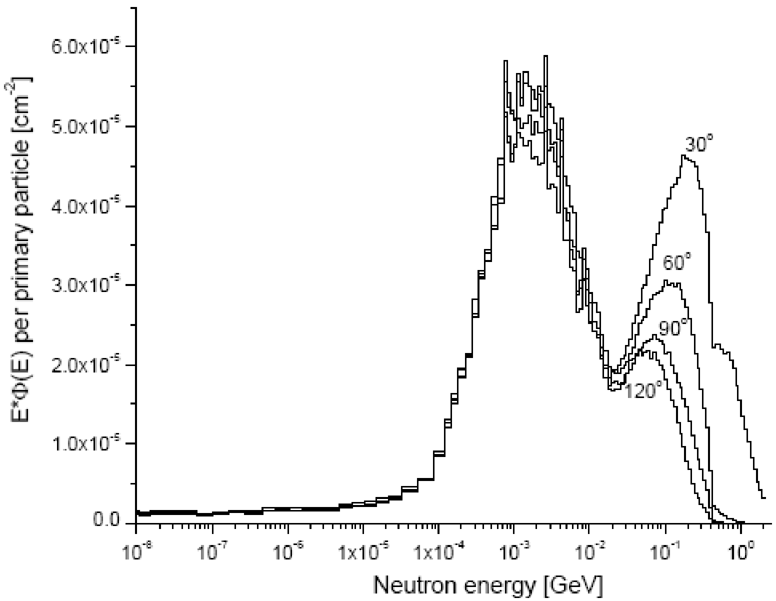
INTRANUCLEAR CASCADE

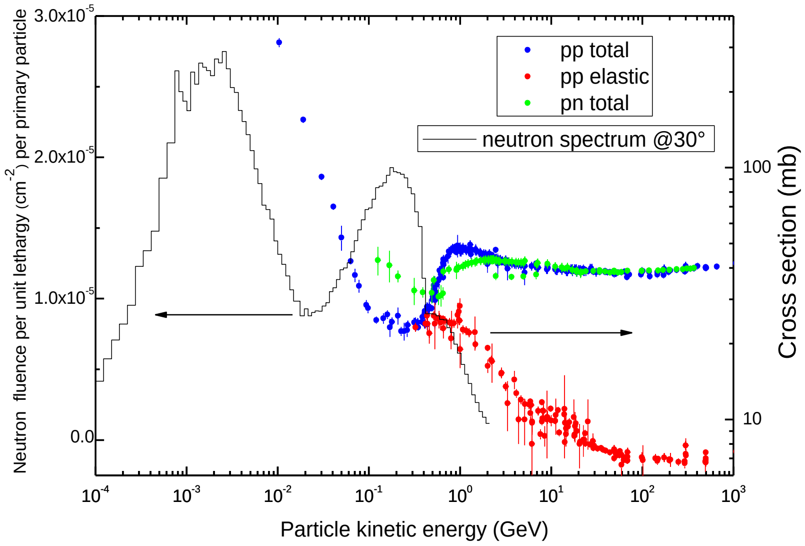
- Intermediate energy reactions can be described through the intranuclear cascade model. Its main steps are:
  - ✓ direct hadron-nucleon interactions (10^{-23} s);
  - ✓ pre-equilibrium stage;
  - ✓ nuclear evaporation (10^{-19} s);
  - ✓ de-excitation of the residual nucleus.

- Secondary particles can interact with other nuclei giving rise to an extra-nuclear cascade.



INTRANUCLEAR CASCADE

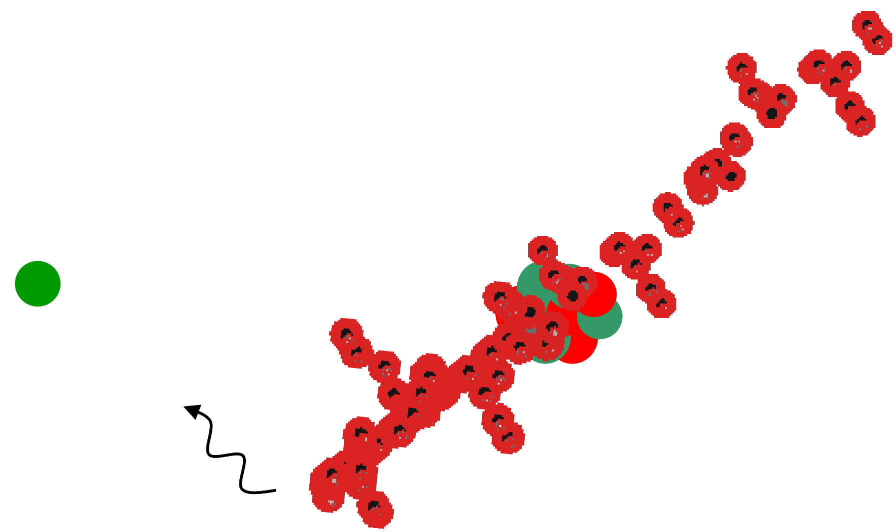




Neutron spectral fluence [EΦ(E)] per primary hadron from 40 GeV/c protons/pions on a 50 mm thick silver target, at emission angles of 30°, 60°, 90° and 120°. Agosteo et al. NIM B 229 (2005) 24-34.

PRINCIPLES OF NEUTRON DETECTION (I)

- Neutrons are detected through:
  - → secondary charged particles
    - → generated via elastic or inelastic reactions with nuclei.



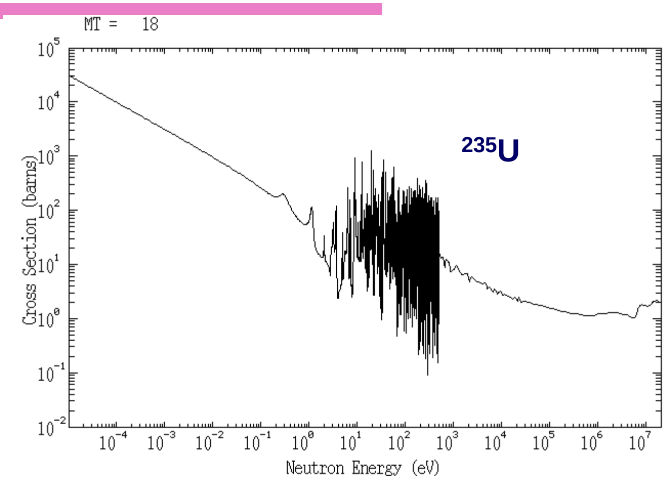
PRINCIPLES OF NEUTRON DETECTION (II)

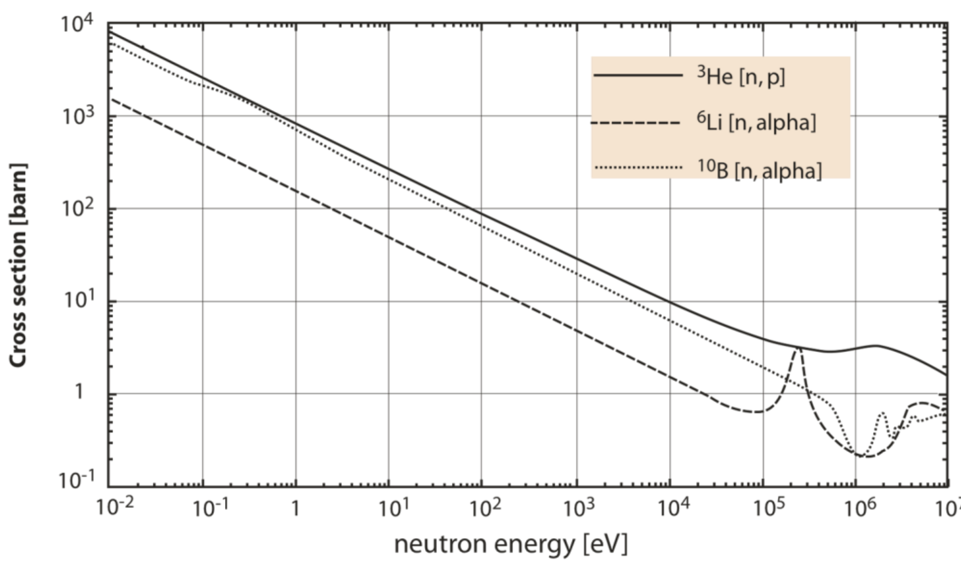
- Generally, the interactions exploited for neutron detection can be classified according to neutron energy:
  - Thermal neutrons: nuclear exoenergetic (Q>0) reactions with high cross section values;
  - Epithermal neutrons: nuclear exoenergetic (Q>0) reactions and elastic reactions;
  - Fast neutrons: nuclear reactions both exo- and endoenergetic (threshold reactions) and elastic reactions;
  - High-energy neutrons (from 20-50 MeV up to a few GeV): inelastic reactions.

- Neutron detectors:
  - ✓ gas detectors;
  - ✓ activation detectors;
  - ✓ solid state detectors (scintillators (also liquid), semiconductors, superheated emulsions, track detectors, TLDs, etc.);

THERMAL NEUTRONS

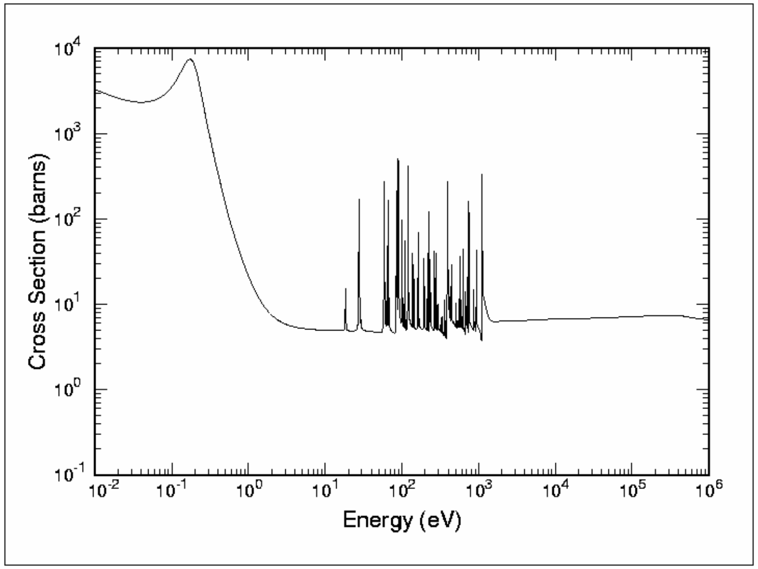
- The nuclear reactions exploited mainly for thermal neutron detection are:
  - ✓ $^{10}B(n,\alpha)^{7}Li$ (Q = 2.79 MeV) ;
  - ✓ $^{3}He(n,p)^{3}H$ (Q = 764 keV) ;
  - ✓ $^{6}Li(n,\alpha)^{3}H$ (Q = 4.78 MeV);
  - ✓ $^{157}Gd(n,\gamma)$
  - ✓ fission reactions;
  - ✓ activation.





EPITHERMAL NEUTRONS

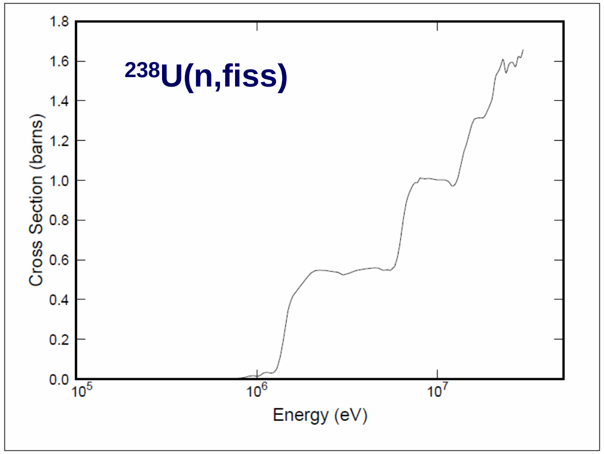
- The fast and epithermal neutron component can be discriminated from the thermal (slow) one by covering a thermal neutron detector with a cadmium layer (cadmium cut-off: about 0.5 eV);
- Neutrons down to a few tens keV can be detected with recoil proton detectors (the signal must be higher than the electronic noise);
- Activation techniques can be employed by using combinations of different materials.

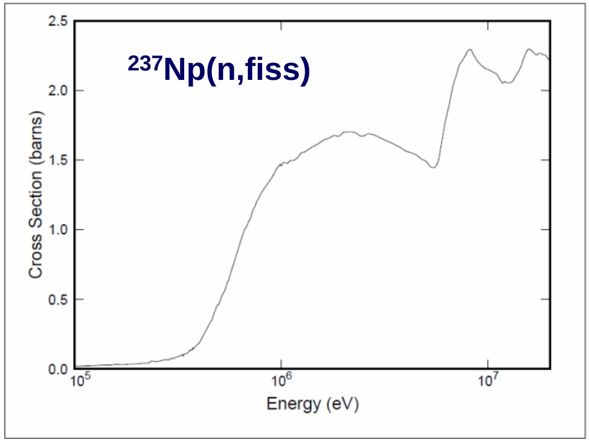


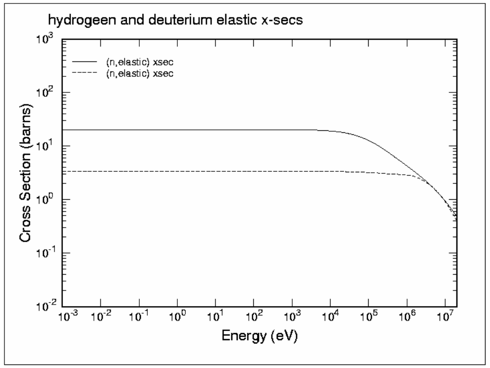
FAST NEUTRONS

- Still the following reactions can be exploited with a lower efficiency:
  - ✓ $^{3}He(n,p)^{3}H$;
  - ✓ $^{6}Li(n,\alpha)^{3}H$;
    - → the energy deposited in the detector is that of the impinging neutron + the Q-value.
- Elastic scattering on:
  - ✓ Hydrogen ($E_{R,max}=E_n$);
  - ✓ ^{3}He ($E_{R,\ max}=0.75\ E_n$);
  - ✓ ^{4}He ($E_{R,\ max}=0.64\ E_n$).
- Activation reactions (Q<0);
- ^{238}U and ^{237}Np fission;
- Neutron moderation.

- The neutron spectrum is reconstructed by unfolding the experimental data.

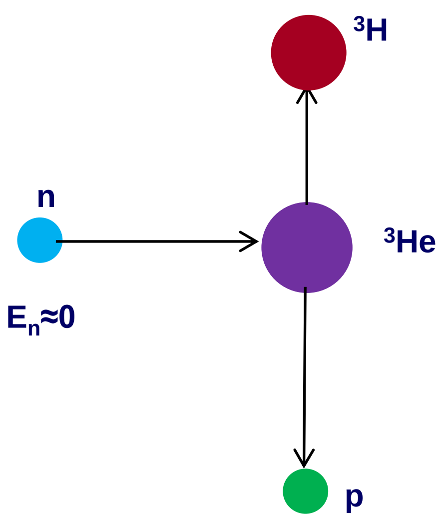






DETECTORS BASED ON THE ^{3}He REACTION

- Secondary particles from neutron capture on ^{3}He are generated through:
  - ✓ n + ^{3}He $\rightarrow$ ^{1}H + ^{3}H (Q = 764 keV);
  - ✓ σ(0.025 eV) = 5316 b;
  - ✓ E_p = 573 keV; E_{H-3} = 191 keV.
- Gas detectors: proportional counters mainly;
- Gas pressure up to several atm. ^{3}He mixed to Ar for minimizing the wall effect.



$$E_p + E_t = Q$$

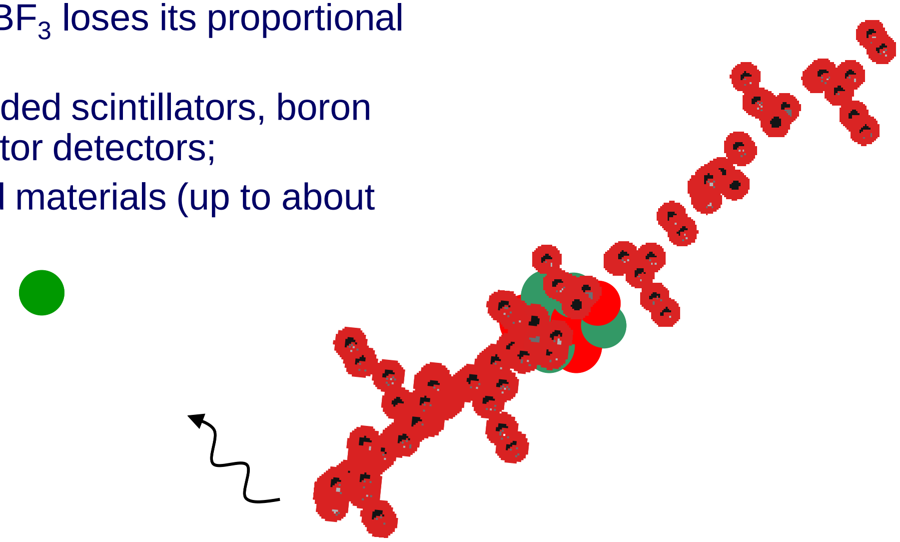
$$\sqrt{2 m_p E_p} = \sqrt{2 m_t E_t}$$

$$E_t = \frac{m_p}{m_p + m_t} Q = \frac{1}{4} 764 \text{ keV} = 573 \text{ keV}$$

$$E_p = \frac{m_t}{m_p + m_t} Q = \frac{3}{4} 764 \text{ keV} = 191 \text{ keV}$$

DETECTORS BASED ON THE ^{10}B REACTION

- Secondary particles from neutron capture on ^{10}B are generated through the following channels:
  - ✓ n + ^{10}B → α + ^{7}Li (ground state) – 6%;
  - ✓ n + ^{10}B → α + (^{7}Li)* (excited state) → α + ^{7}Li + γ (480 keV) – 94% ;
  - ✓ for the most probable channel:
    - → E_{α} = 1.47 MeV; $E_{Li\text{-}7}$ = 0.84 MeV;
  - ✓ σ(0.025 eV) = 3842 b;
- The most common detector based on the ^{10}B reaction is the BF_3 proportional counter;
  - → Low gas pressure (0.5-1.0 atm), since BF_3 loses its proportional properties at high pressure;
- Boron-lined proportional counters, boron-loaded scintillators, boron converters coupled to track and semiconductor detectors;
- All these detectors may employ ^{10}B enriched materials (up to about 90%).



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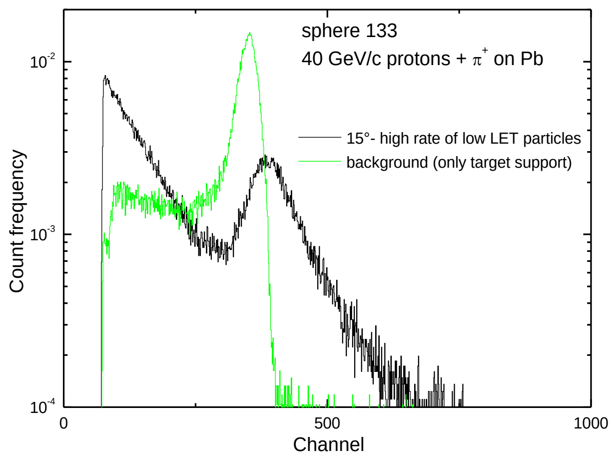
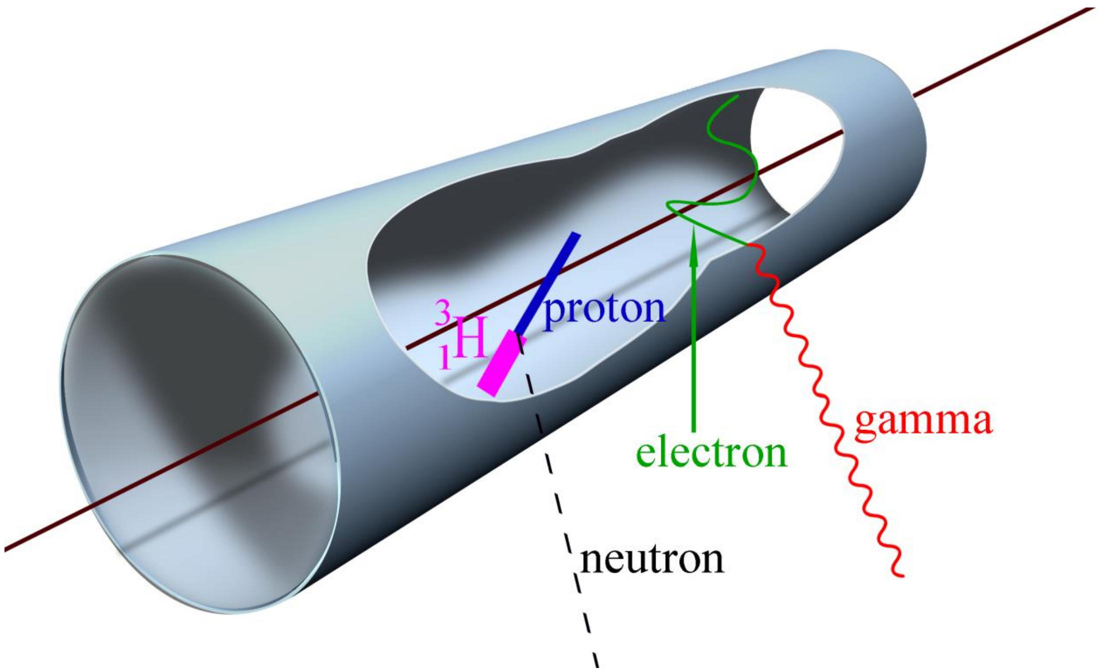
NEUTRON PROPORTIONAL COUNTERS (I)

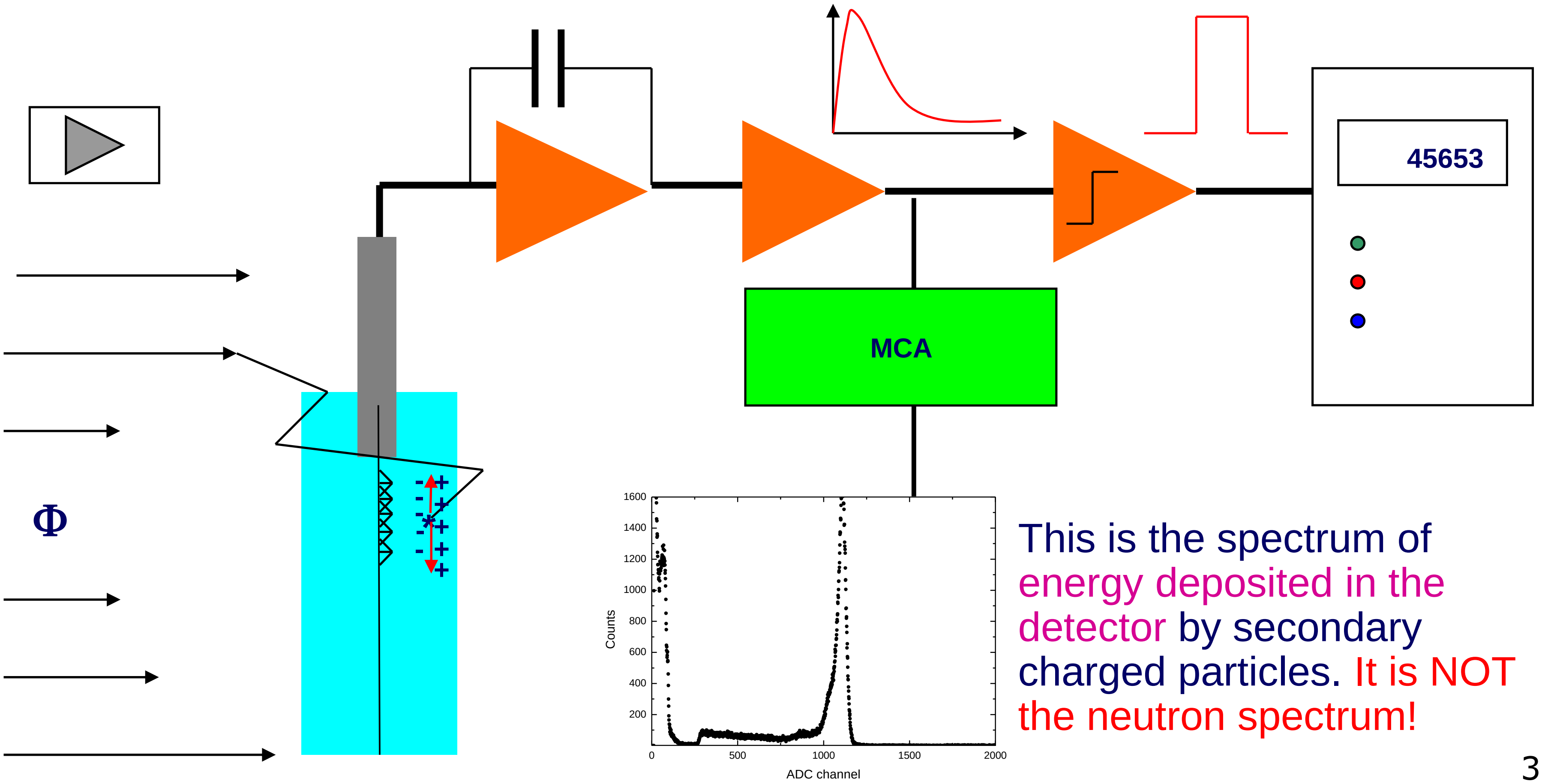
- Gamma rays can interact in the walls and produce electrons in the gas, but the energy loss of electrons is small (≈ 2 keV/cm), so that these pulses are much smaller than those due to neutrons;
- A pulse amplitude threshold can thus eliminate most gamma interactions.





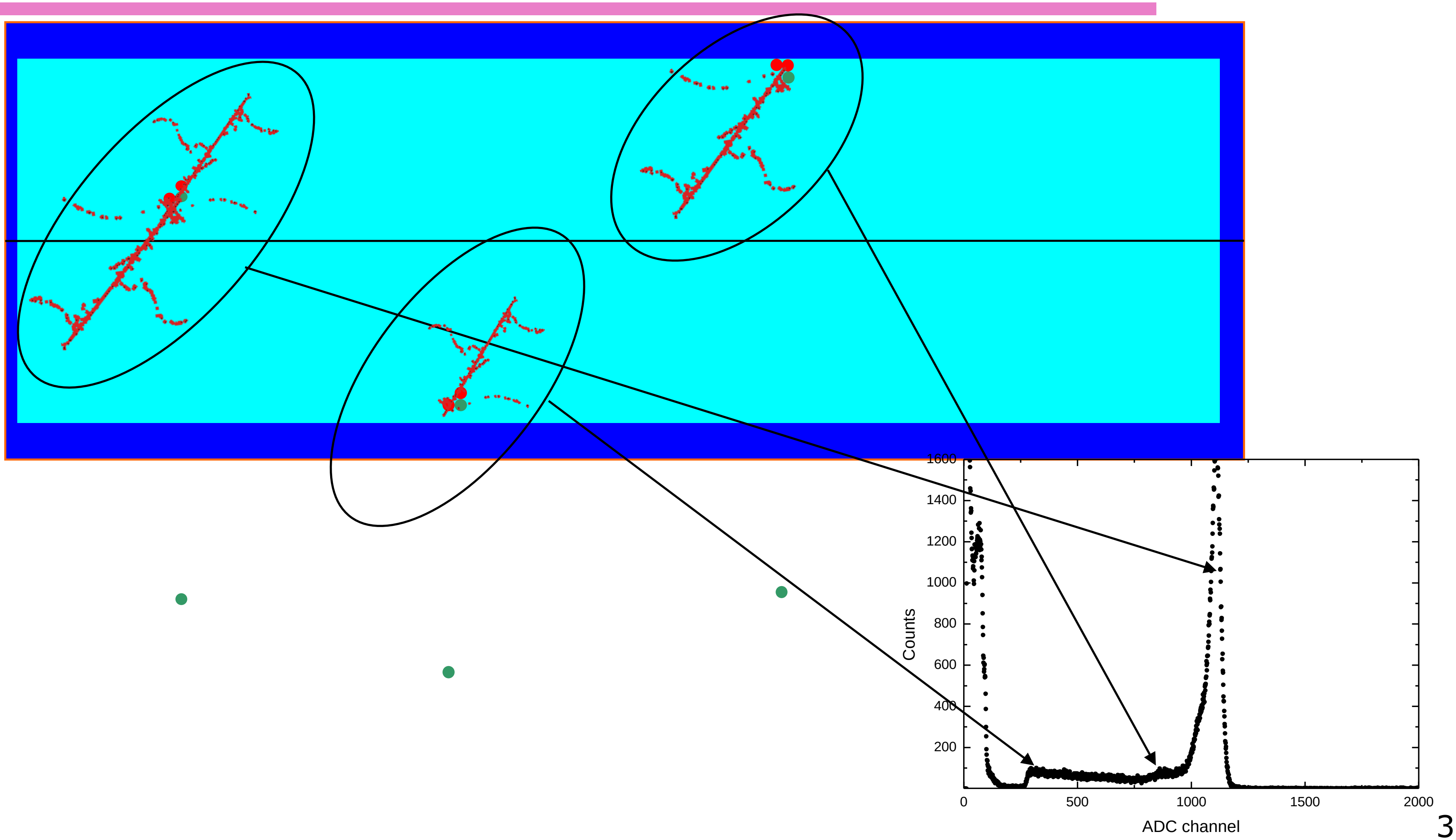
Courtesy Marco Silari, CERN

NEUTRON PROPORTIONAL COUNTERS (II)

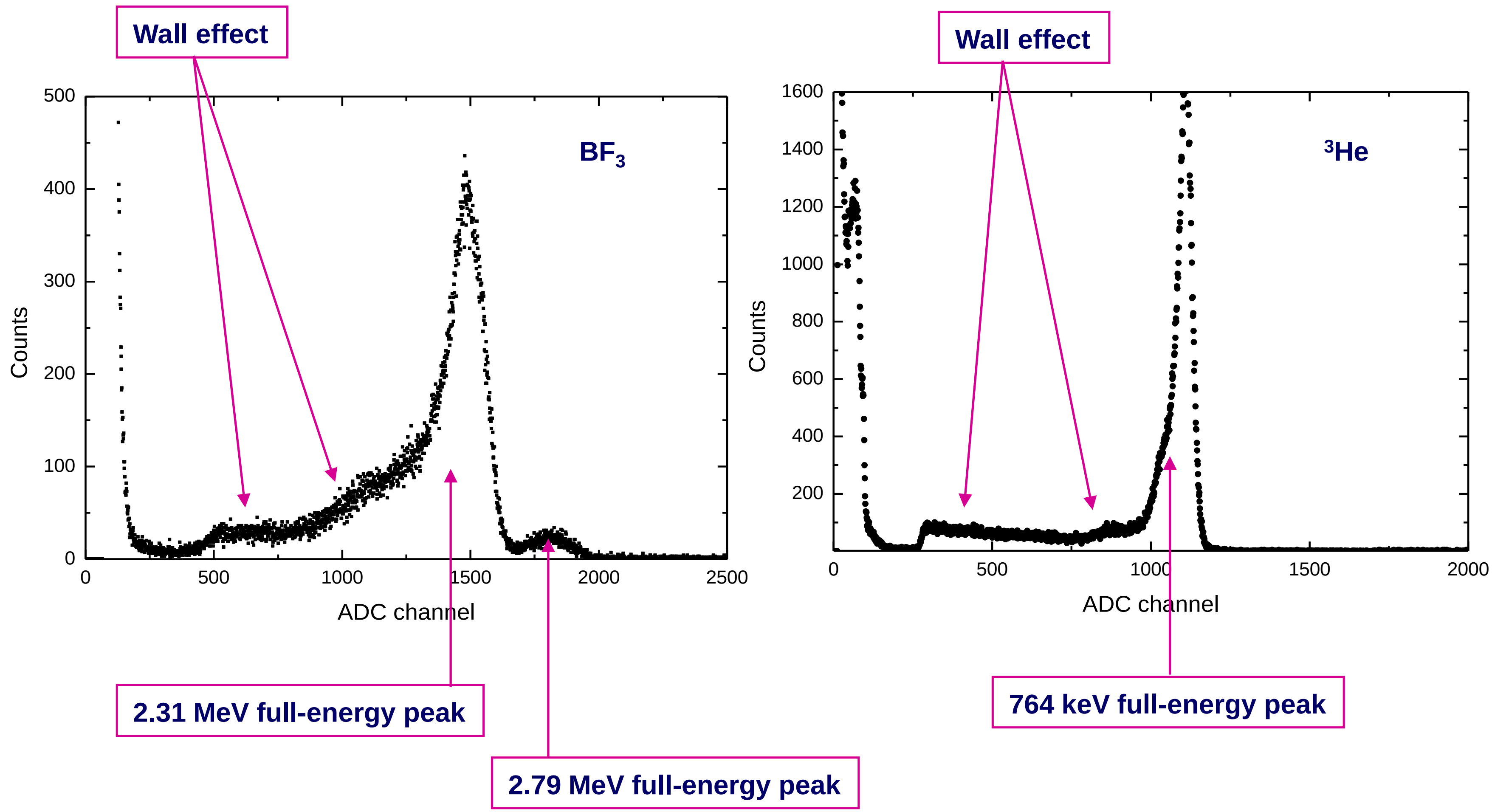


This is the spectrum of energy deposited in the detector by secondary charged particles. It is NOT the neutron spectrum!

THE WALL EFFECT

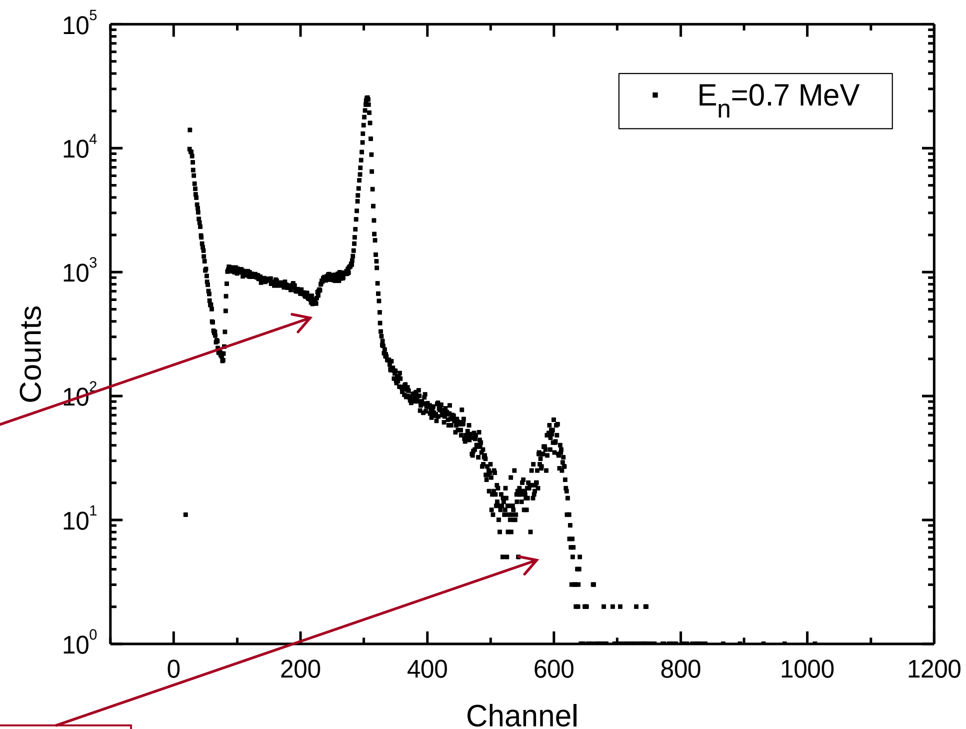


BF_3 AND ^{3}He SPECTRA OF DEPOSITED ENERGY



^3He SPECTRUM OF DEPOSITED ENERGY: FAST NEUTRONS

700 keV monoenergetic neutrons from the $^7Li(p,n)$ reaction@ LNL



Thermal and epithermal neutrons scattered on the room walls and floor

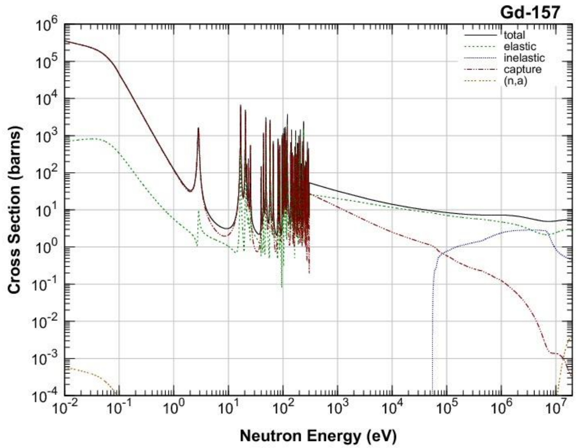
700 keV neutrons
Deposited energy in ^3He: Q+700 keV=764+700 keV =1464 keV

DETECTORS BASED ON THE ^{6}Li(n,α) REACTION

- Secondary particles from neutron capture on ^{6}Li are generated through:
  - ✓ $n + {}^{6}Li \rightarrow \alpha + {}^{3}H$ (Q = 4.78 MeV);
  - ✓ $\sigma(0.025\ eV) = 938\ b$;
  - ✓ $E_{\alpha} = 2.05$ MeV; $E_{H\text{-}3} = 2.73$ MeV.
- Scintillators: LiI(Eu), Li containing glass scintillators, optical fibers;
- TLDs: the contribution of photons can be assessed by employing a pair of detectors enriched in ^{7}Li and ^{6}Li.

DETECTORS BASED ON THE ^{157}Gd(n,γ) REACTION

- Neutron absorption on ^{157}Gd leads to the emission of prompt gamma ray (390 lines) and conversion electrons (444 discrete energies):
  - ✓ σ(0.025 eV) = 255,000 b;
  - ✓ conversion electrons are more effective for neutron detection, since they are directly ionizing;
  - ✓ the most significant conversion electron energy is 72 keV (yield per absorbed neutron 0.39)
- Gd converters are employed for neutron detection and imaging (very thin converters, since the 72 keV electron range in Gd is 20.7 µm;
- Liquid scintillators: prompt gamma ray background is significant.



Additional Slides

Lethargy plots

- Conservative in terms of area for semi-logarithmic plots

$$\int_{E1}^{E2} f(E)dE = \int_{E1}^{E2} E\, f(E)dE/E = \int_{E1}^{E2} E\, f(E)d(\ln E) = \ln 10 \int_{E1}^{E2} E\, f(E)\, d(\log E)$$

- Therefore:

$$f(E)dE = Ef(E)d(\ln E) \quad \text{and}: \; Ef(E) = \frac{f(E)dE}{d(\ln E)}$$

- Histogram:

$$E_i f_i(E) = \frac{f_i(E)\times(E_{i+1}-E_i)}{\ln E_{i+1} - \ln E_i} = \frac{f_i(E)\Delta E}{\ln(E_{i+1}/E_i)}$$

- Lethargy (definition):

$$u = \ln\frac{E_0}{E} = \ln E_0 - \ln E$$

$$du = -\frac{dE}{E}$$

$$F(u)du = -F(E)dE$$

$$F(u) = EF(E)$$