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Neutron interactions and dosimetry

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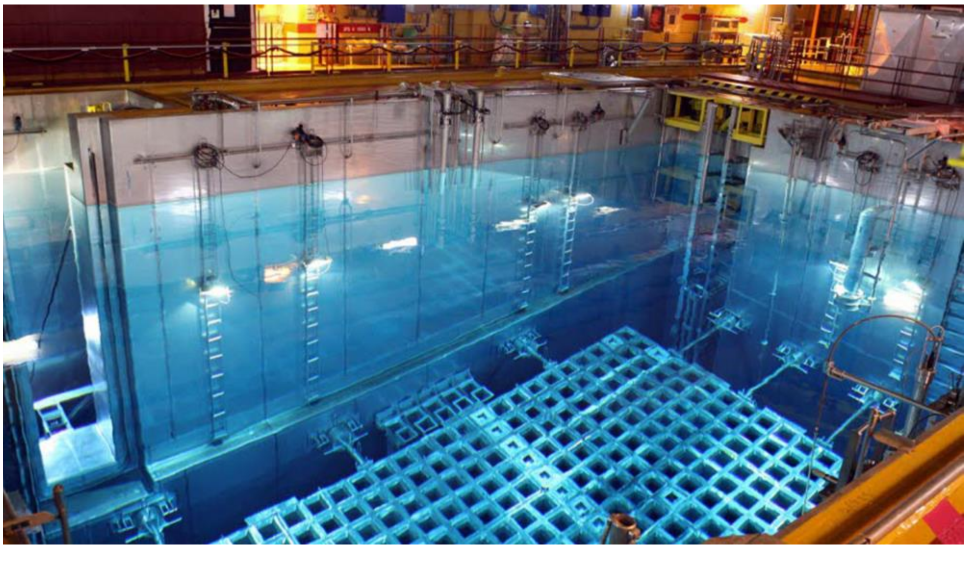
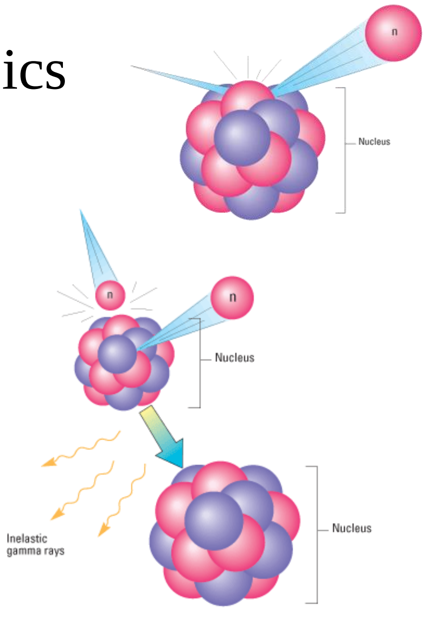
Fuel rod cooling pond



Topics

1. Neutron interactions
   1. Scattering
   2. Absorption
2. Neutron dosimetry
3. Applications



The neutron

- Uncharged particle, mass close to that of proton
- Unstable as free particle; disintegrates into a proton, an electron and an antineutrino ($t_{1/2}$=12 min)
- Do not interact with electrons
- Only nuclear interactions; complex cross sections
- Neutron attenuation similar to that for photons

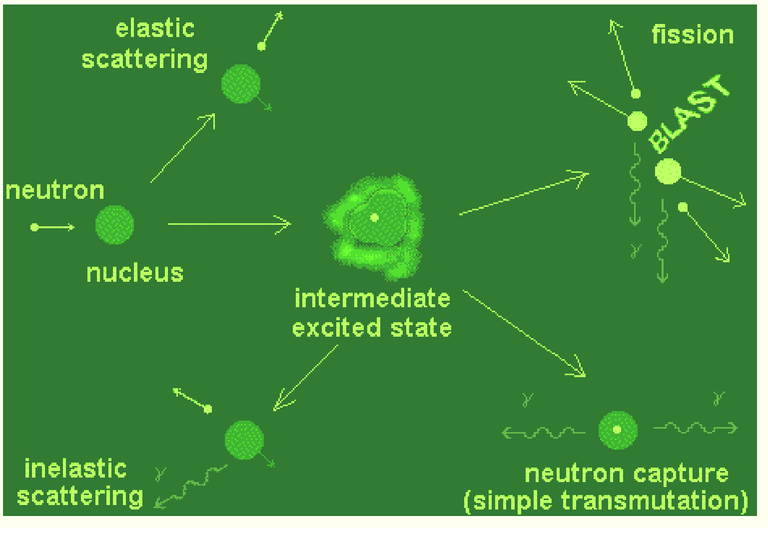
Neutron reactions

$$X + n \rightarrow b + Y$$

- (n,n) Elastic scattering
- (n,n’) Inelastic scattering
- (n,p) Absorption
- (n,α) Absorption
- (n,f) Fission

- Thermalization of neutrons: Collisions with nuclear targets until in thermal equilibrium

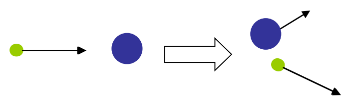
Figure 1: Most likely interactions between nuclei and neutrons



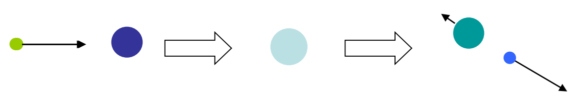
Neutron interactions

- Principally two types of interaction with matter:

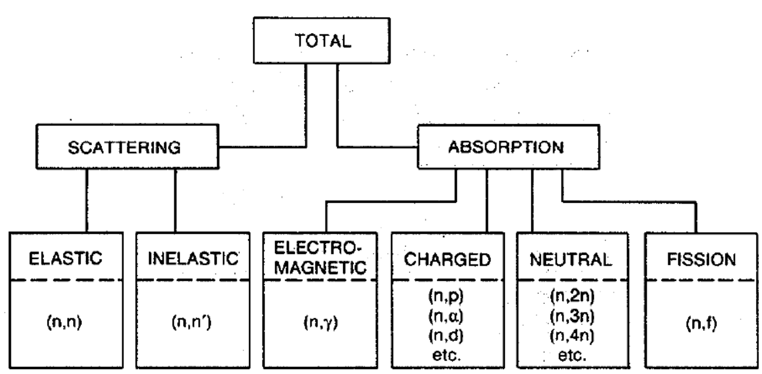
1. *Scattering*: Elastic
   Inelastic



2. *Absorption*: creation of compound nucleus, deexcitation yields p, α, fission products

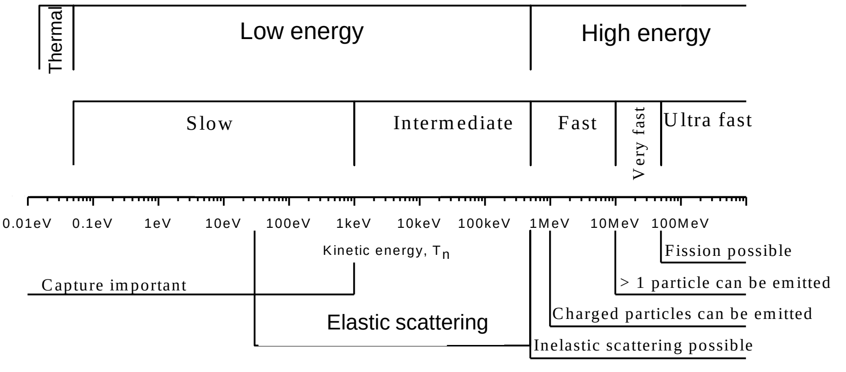


Interactions



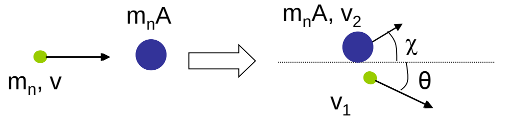
Interactions

- Cross section depends on: - Kinetic energy T_n
  - Nuclear structure



Neutron moderation 1

- Elastic scattering against nucleus – energy of neutron after scattering:



$$E_{\max} = \frac{1}{2}(m_n A)v^2_{2,\max} = 4\frac{Am_n^2}{(m_n + Am_n)^2}T_0$$

$$= 4\frac{A}{(A+1)^2}T$$

- Hydrogen rich absorbers most effective

Neutron moderation 2

- It may be shown that, after *n* interactions, the *average* neutron energy is:

$$T_n = T_0 \left[\frac{A^2 + 1}{(A+1)^2} \right]^n \qquad \Rightarrow n = \ln\left(\frac{T_n}{T_0}\right) \Big/ \ln\left[\frac{A^2 + 1}{(A+1)^2} \right]$$

Table 12-1. Average number of collisions required to reduce a neutron's energy from 2 MeV to 0.025 eV by elastic scattering

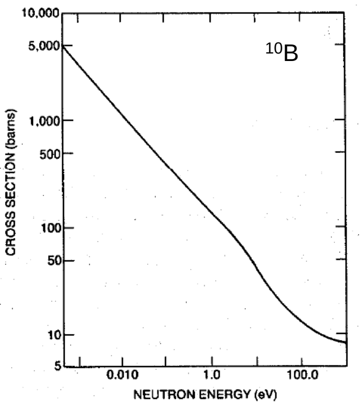
Element	Atomic Weight	Number of Collisions
Hydrogen	1	27
Deuterium	2	31
Helium	4	48
Beryllium	9	92
Carbon	12	119
Uranium	238	2175

Low energies, T_n < 500 keV

- “Potential” (1) and “resonance” (2) elastic scattering:
  1: Scattering on the nuclear ’surface’
  2: Neutron absorbed, but reemitted
  For (1): virtually constant cross section

- At thermal energies, the neutron is captured and the compound nucleus deexcites via e.g. γ emission
  cross section ~ $1/v_n$

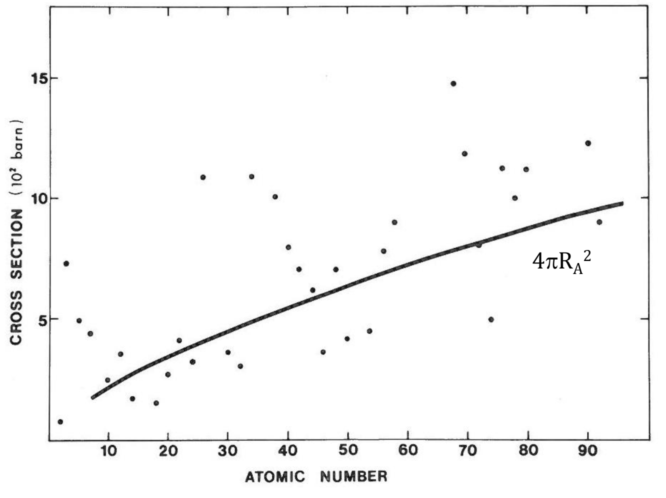
"1/v" cross section



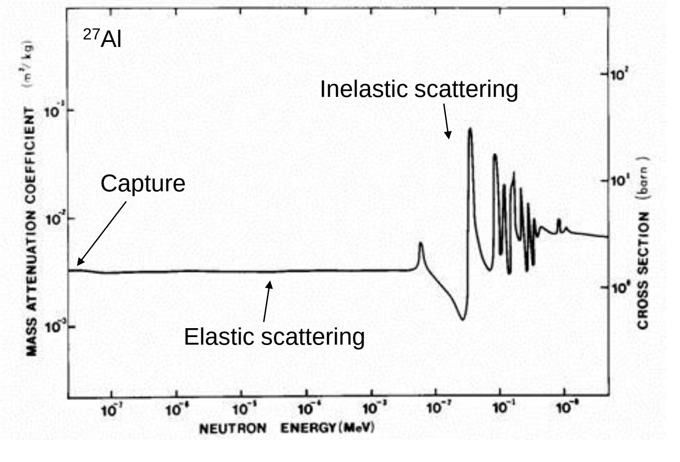
Elastic scattering

- Potential elastic scattering
  - Discontinuities in neutron's potential energy curves due to the nuclear surface interaction (considered as reflections)
    $\sim 4\pi R_A^2$
- Resonance scattering
  - Parts of the incident wave passing through the nuclear surface, resonance scattering occurs with large prob. only for specific wave-lengths

Potential elastic scattering



Cross section



Thermal neutrons

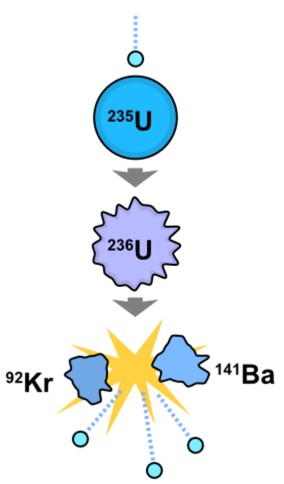
- For neutrons in thermal equilibrium with surroundings:

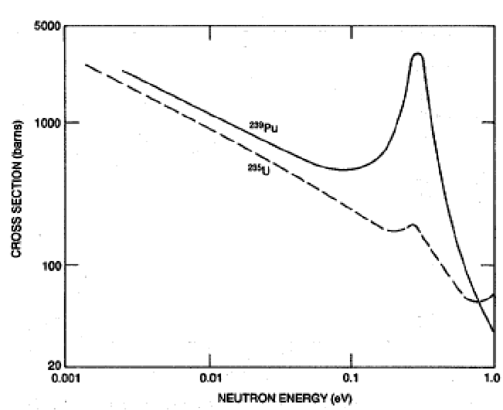
  T_n=kT=0.025 eV at T=293 K

  (k: Boltzman constant)

- ^{235}U has a high cross section for capture of thermal neutrons – gives fission

Fission





High energy neutrons, $T_n > 0.5$ MeV

- Inelastic: (n, nγ), threshold kinetic energy ~ 0.5 MeV
- Occurs at given energies: *resonances*
- Capture reacions: (n, p), (n, α)
- Emission of more than one particle:
  (n, np), (n, nα) (threshold ~ 10 MeV)
- Complicated cross sections

Absorption

X + n → b + Y

- (n,γ) , (n,b), (n,α), (n,f).....
- Conservation of mass and kinetic energy

$$T_X + m_X c^2 + T_n + m_n c^2 = T_b + m_b c_2 + T_Y + m_Y c^2$$

- The Q-value

$$Q = m_X c^2 + m_n c^2 - m_b c_2 - m_Y c^2$$

signifies if a reaction releases (exoergic) or needs energy (endoergic)

Absorption

- Neutron absorption (particle emission)

  X+n→C→b+Y

  b= p, n’, d, α, 2n, 2p, np

- Radiative capture

  X+n→Y*→Y+γ

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Table 9.2 Exoergic Neutron-Particle Reactions

Reaction	Q (*MeV*)	*Thermal Cross Section (b)*
$^{3}He(n,p)^{3}H$	0.77	5330
$^{6}Li(n,\alpha)^{3}H$	4.64	940
$^{10}B(n,\alpha)^{7}Li$	2.78	3840
$^{14}N(n,p)^{14}C$	0.63	1.8
$^{33}S(n,p)^{33}P$	0.75	0.002
$^{35}Cl(n,p)^{35}S$	0.62	0.5

Table 9.3 Endoergic Neutron-Particle Reactions

Reaction	Q (*MeV*)	*Threshold (MeV)*	*Cross Section 14 MeV (b)*
$^{12}C(n,\alpha)^{9}Be$	−5.7	6.2	
$^{16}O(n,p)^{16}N$	−9.6	10.2	
$^{16}O(n,d)^{15}N$	−9.9	10.5	0.04
$^{16}O(n,\alpha)^{13}C$	−2.2	2.3	
$^{32}S(n,p)^{32}P$			0.23
$^{54}Fe(n,p)^{54}Mn$			0.35
$^{56}Fe(n,p)^{56}Mn$			0.11

Data from Refs. 6–9 and 21.

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Neutron attenuation

- For a narrow neutron beam:

$$N = N_0 e^{-\mu x}$$

- μ is the attenuation coefficient:

$$\mu = \rho \frac{N_A}{A} \sigma$$

- Note: the cross section σ may show extreme variations over small energy range
  - If Q positive: $(\mu_{tr}/\rho) > (\mu/\rho)$
  - If Q negative: $(\mu_{tr}/\rho) < (\mu/\rho)$

$$(\mu/\rho)_{tot} = (\mu/\rho)_{n\gamma} + (\mu/\rho)_{es} + (\mu/\rho)_{nb}$$

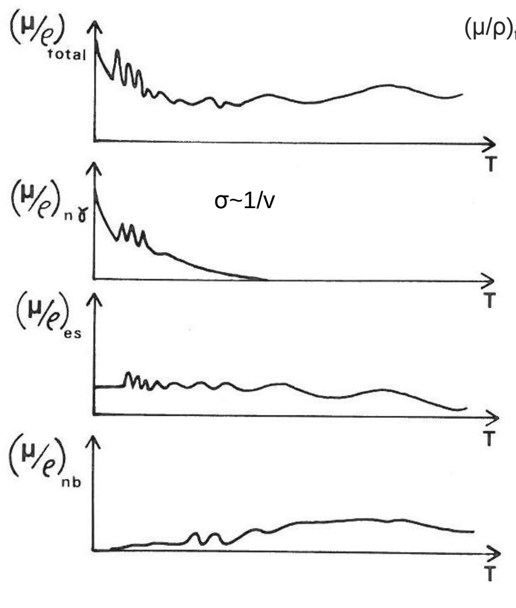

Figure 9.19 An illustration of the relationship between neutron attenuation coefficients for a typical medium mass nucleus is shown. Notice that the curve for the total coefficient is the sum of the other curves. Adapted from Ref. 11.

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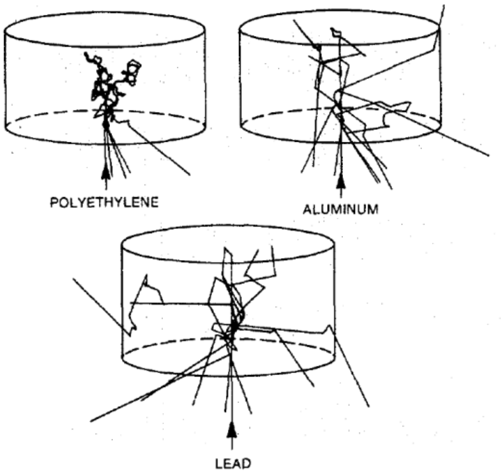
Monte Carlo simulations



Theoretical dosimetry

KERMA factor F_n:

- $K_n = \Phi F_n = \Phi\ E_n(\mu_{tr}/\rho)_{tot}$
- At CPE: $D = K_n = \Phi F_n$

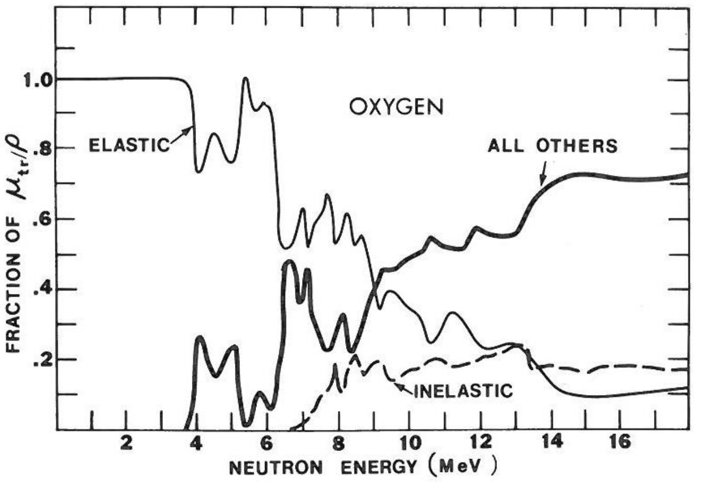


Figure 8.14 The fraction of the energy transfer from a neutron beam to an oxygen absorber is shown for various reactions as a function of neutron energy (25). Notice that the elastic scattering contribution dominates at lower energies. Adapted from Ref. 22.

Important interactions in tissue

- $^{14}N(n,p)^{14}C$ σ_N: 1.84 x 10^{-24} cm^2/atom
- $^{1}H(n,\gamma)^{2}H$ σ_H: 3.32 x 10^{-25} cm^2/atom

- $N_H \sim 41\ N_N$ in tissue…

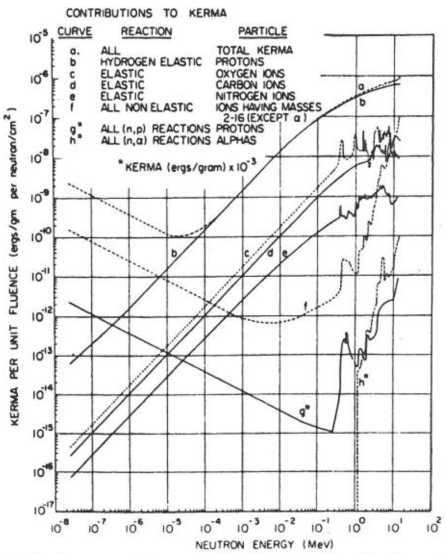


FIGURE 16.1. Kerma per unit fluence contributed by various interactions in a small mass of tissue in free space, as a function of incident neutron energy. Note that curves *g* and *h* are displaced downward by the factor 10^{-3}. (Auxier et al., 1968. Reproduced with permission from J. A. Auxier and Academic Press.)

γ+n mixed-field dosimetry

- (n,γ) – always important
- (γ,n) – important for energy (≥ 10 MeV)

- Three categories of dosimeters
  - Neutron dosimeters (insensitive to γ-rays)
  - γ-ray dosimeters (insensitive to neutrons)
  - n+ γ dosimeters (comparable sensitive to n and γ)

Mixed field dosimetry

- $Q_{n,\gamma} = AD_\gamma + BD_n$

A & B: response per unit of absorbed dose in tissue for γ rays and neutrons, respectively

- *Paired* dosimeters may help estimating D_γ and D_n, e.g.:
  - Tissue Equivalent (TE) ion chamber (A~B) and TLD (B<A)

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Neutron detectors

- High cross section for the desired reaction
- High abundance of target nuclide

- Principle:
  - (n, α) or (n,p) reaction
  - Fission reaction

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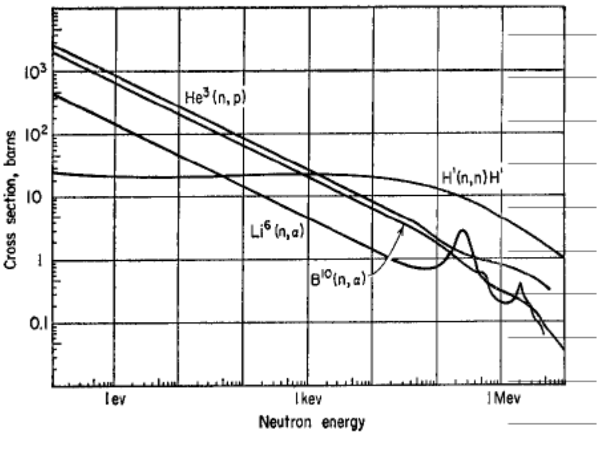
BF_3 counter

- Ion chamber with BF_3 gas
  - $^{10}B+n \rightarrow {}^{7}Li+ \alpha+2.792$ MeV (6%)
  - $^{10}B+n \rightarrow {}^{7m}Li+ \alpha+2.314$ MeV (94 %)

    $\rightarrow {}^{7m}Li+\gamma+0.478$ MeV

Boron cross section



Neutron sources

- Nuclear fission reactors
  Neutron energies ~ 2 MeV
- Accelerators
  Protons on a thick Be target etc.
- Radioactive sources
  Be(α,n) + ^{239}Pu, ^{241}Am, ^{226}Ra, ^{210}Po

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Radioactive sources

- (α,n) reaction
- ^{241}AmBe: $^{9}Be + ^{4}He \rightarrow ^{12}C + n + 5.7$ MeV
  - $T_{½}(^{241}Am)=460$ y
- ^{226}RaBe
  - $T_{½}(^{226}Ra)=1600$ y
- ^{239}PuBe
  - $T_{½}(^{239}Pu)=24000$ y

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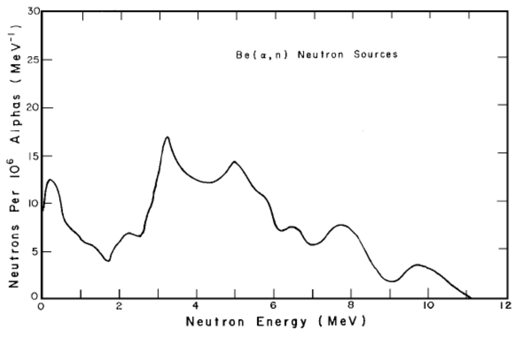
Neutron sources: AmBe



Figur 4: Neutronspektrum från en AmBe-källa

Neutron generators: Accelerators

- Advantage
  - Can be turned off
  - One single energy
- Production in two stages
  - Acceleration
  - Neutron producing reaction
- Some common reaction:
  - $T(d,n)^4He$, Q=17.6 MeV → E_n=14 MeV
  - $D(d,n)^3He$, Q=3.3 MeV → E_n= 2.5 MeV
  - $^7Li(d,n)^8Be$, Q=15 MeV
  - $^9Be(d,n)^{10}B$, Q=4.4 MeV
  - E_n >100 MeV → Spallation

Nuclear reactors

- Power reactors and research reactors
- Neutron flux is very high (10^{15} n/cm^{2}s)
- Energy spectrum 1-7 MeV
- Fission by thermal neutron → Fission → fast neutrons → Slowing down → fission by thermal neutrons
- Research reactors: Neutrons can be extracted for research

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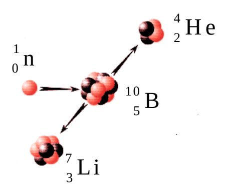
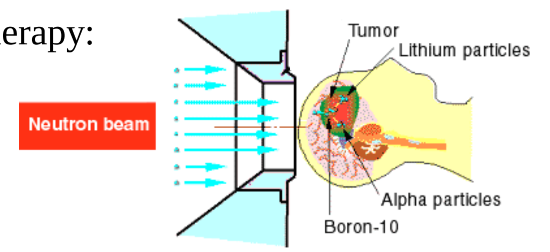
Boron neutron capture therapy

- Thermal neutrons are effeciently captured by ^{10}B
- Result is an unstable nucleus which desintegrates ^{7}Li og ^{4}He (+ kinetic energy and a photon)



- May be used for therapy:



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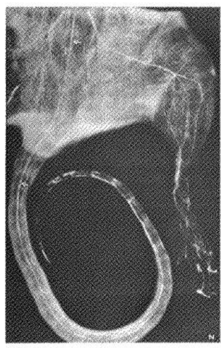
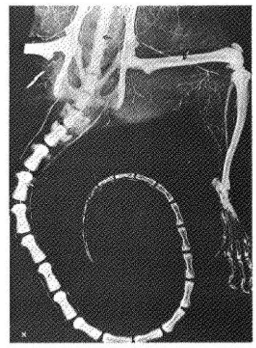
Neutron radiography vs. X-ray



Neutron radiography



X-ray

Dose equivalent

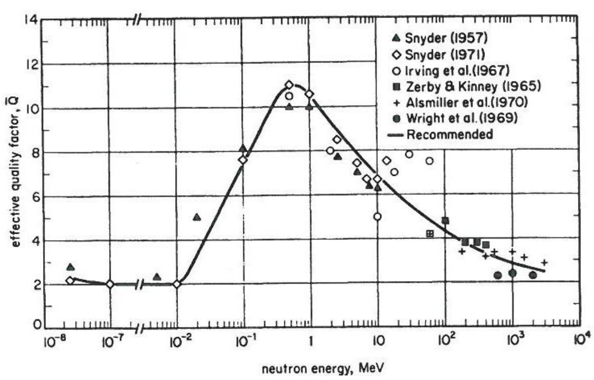


FIGURE 16.6. Quality factors for neutrons, that is, the maximum dose equivalent divided by the absorbed dose at the same depth in the body. The curve represents the recommendation of the ICRP. (ICRP, 1971. References in the figure are given in that report. Reproduced with permission from Pergamon Press, Ltd.)