Neutrons

Classification of neutrons by energy

Thermal:	E < 1 eV (0.025 eV)
Epithermal:	1 eV < E < 10 keV
Fast:	> 10 keV

Neutron sources	***Neutron energies***
Reactors	neutrons in the few keV to several MeV
Fusion reactions	14 MeV
Large accelerators	Hundreds of MeV

Energy Deposition by Neutrons

- Neutrons are generated over a wide range of energies by a variety of different processes.

- Like photons, neutrons are uncharged and do not interact with orbital electrons.

- Neutrons can travel considerable distances through matter without interacting.

- Neutrons will interact with atomic nuclei through several mechanisms.
    - Elastic scatter
    - Inelastic scatter
    - Nonelastic scatter
    - Neutron capture
    - Spallation

- The type of interaction depends on the neutron energy

Cross Sections

- Because mass attenuation coefficients, μ/ρ (cm^2/g) have dimensions of cm^2 in the numerator, they have come to be called "***cross sections***".
- Cross sections do not represent a physical area, but a ***probability of an interaction.***
- Cross sections usually expressed in the unit, barn: (10^{-24} cm^2)
- The atomic cross sections can be derived from the mass attenuation coefficient.

Photons

Cross sections are attenuation coefficients, expressed at the atom level (Probability of interaction per atom)

N_A = atom density (#atoms/cm^3) $\qquad N_A = \frac{\rho}{A} N_0$

σ_A = atomic cross section (cm^2/atom)

$N_0 = 6.02 \times 10^{23}$ atoms/mole

ρ = g/cm^3

A = g/mole

$$\mu = N_A \sigma_A$$

$$\mu = \frac{\rho}{A} N_0 \sigma_A$$

$$\frac{\mu}{\rho} = \frac{N_0 \sigma_A}{A} \qquad \sigma_A = \left(\frac{\mu}{\rho}\right)\left(\frac{A}{N_0}\right)$$

Neutron Cross Sections

Analogous to photons

- Neutrons interact by different mechanisms depending on the neutron energy and the material of the absorber
    - Scattering
        - elastic
        - inelastic
    - Capture
- Each energy loss mechanism has a cross section
- Neutron cross sections expressed in barns (1 barn = 10^{-24} cm^2).
- These cross sections depend on the neutron energy and the absorber

Moderation: slowing down of fast neutrons

Fast neutrons lose energy in a series of scatter events, mostly elastic scatter.

Lower energy neutrons:
- scattering continues
- probability of capture increases (capture cross sections increase at lower energies)

Thermal Neutron Cross Sections

Nuclide	***Cross section (barns)***
^{10}B	3837
^{11}B	0.005
^{12}C	0.0035
^{1}H	0.33
^{14}N	1.70
^{35}Cl	43.6
^{23}Na	0.534
^{157}Gd	254,000
^{153}Gd	0.02

Cross Sections

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Total cross sections for neutrons with hydrogen and carbon as a function of energy

- For hydrogen the contributors to the total cross section are elastic scatter (predominant) and neutron capture (σ = 0.33 barns at thermal neutron energy).

- For carbon, the cross section is complex due to the different nuclear states possible that may enhance or suppress elastic or inelastic scatter at particular neutron energies.

Neutron Interactions

Elastic scatter: The most important process for slowing down of neutrons.

- Total kinetic energy is conserved
- E lost by the neutron is transferred to the recoiling particle.
- Maximum energy transfer occurs with a head-on collision.
- Elastic scatter cross sections depend on energy and material.

$$Q_{\max} = \frac{4mME_n}{(M+m)^2}$$

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TABLE 9.4. Maximum Fraction of Energy Lost, Q_{max}/E_n from Eq. (9.3), by Neutron in Single Elastic Collision with Various Nuclei

Nucleus	Q_{max}/E_n
$^{1}_{1}H$	1.000
$^{2}_{1}H$	0.889
$^{4}_{2}He$	0.640
$^{9}_{4}Be$	0.360
$^{12}_{6}C$	0.284
$^{16}_{8}O$	0.221
$^{56}_{26}Fe$	0.069
$^{118}_{50}Sn$	0.033
$^{238}_{92}U$	0.017

Inelastic scatter

- The neutron is absorbed and then re-emitted
- The nucleus absorbs some energy internally and is left in an excited state.

e.g., $^{14}N(n,n')^{14}N$ $E_\gamma = \sim 10$ MeV

- De-excitation emits a gamma ray.
- In tissue, inelastic scatter reactions can occur in carbon, nitrogen and oxygen.

Nonelastic scatter

- Differs from inelastic scattering in that a secondary particle that is not a neutron is emitted after the capture of the initial neutron.

e.g., $^{12}C(n,\alpha)^{9}Be$ $E_\gamma = 1.75$ MeV

- Energy is transferred to the tissue by the alpha particle and the de-excitation gamma ray.

Neutron capture

- Same as nonelastic scatter, but by definition, neutron capture occurs only at low neutron energies (thermal energy range is < 0.025 eV).
- Capture leads to the disappearance of the neutron.
- Neutron capture accounts for a significant fraction of the energy transferred to tissue by neutrons in the low energy ranges.

e.g., $^{14}N(n,p)^{14}C$ Q = 0.626 MeV $E_p = 0.58$ MeV

$^{1}H(n,\gamma)^{2}H$ Q = 2.2 MeV $E_\gamma = 2.2$ MeV

- The hydrogen capture reaction is the major contributor to dose in tissue from thermal neutrons. Because the gamma is fairly energetic, the dose to tissue will depend on the volume of tissue irradiated.
- Boron Neutron Capture

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{7}_{3}Li + 0.48\,MeV\,\gamma$$ Q = 2.31 MeV

$E_\alpha = 1.47$ MeV
$E_{Li} = 0.84$ MeV

Spallation

- In this process, after the neutron is captured, the nucleus fragments into several parts. Only important at neutron energies in excess on 100 MeV. (cross sections are higher at 400-500 MeV).

- The dose to tissue comes from the several neutrons and de-excitation gamma rays which are emitted.

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