Neutrons

1932: Chadwick discovers the neutron
1935: Goldhaber discovers $^{10}B(n,\alpha)^7Li$ reaction
1936: Locher proposes boron neutron capture as a cancer therapy
1939: Nuclear fission in ^{235}U induced by low-energy neutrons shown to release ***several*** neutrons. Suggests that a self-sustaining chain reaction is possible.
Dec. 2, 1942: E. Fermi; U. Chicago, first uranium fission reactor goes critical.

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

Sources of Neutrons

Reactors: Fission Neutrons

E.g., $${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{147}_{57}La + {}^{87}_{35}Br + 2\ {}^{1}_{0}n \quad Q = 195\,MeV$$

Average distribution of energy among products released by fission of ^{235}U

(after Turner J. E. *Atoms, Radiation, and Radiation Protection*, 2nd ed. New York: Wiley-Interscience, 1995. Table 9.5)

Kinetic energy of charged fission fragments	162 MeV
Fission neutrons	6
Fission gamma rays	6
Subsequent beta decay	5
Subsequent gamma decay	5
Neutrinos	11
Total	**195 MeV**

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Criticality

When, on average, one neutron of the several neutrons released per fission reaction, causes another fission reaction.

$$k_{eff} = \frac{N_{(i+1)}}{N_i}$$

N_i = # of neutrons in a "generation"

critical if $k_{eff} = 1$
subcritical if $k_{eff} < 1$
supercritical if $k_{eff} > 1$

- Moderator: slows down the fast fission neutrons so they can react with another ^{235}U

- Control rods contain boron or cadmium (high cross section for thermal neutrons)

Accelerator neutron sources

Reactions used to produce monoenergetic neutrons with accelerated protons (p) and deuterons (d) (after [Turner], Table 9.1)	
Reaction	*Q value (MeV)*
$^{3}H(d,n)^{4}He$	17.6
$^{2}H(d,n)^{3}He$	3.27
$^{12}C(d,n)^{13}N$	– 0.281
$^{3}H(p,n)^{3}He$	– 0.764
$^{7}Li(p,n)^{7}Be$	– 1.65

- Light metals used as targets to minimize Coulomb repulsion
- Exothermic reactions require only a modest energy accelerator, few hundred keV.
- The endothermic reactions require more substantial accelerators.

Examples:

$${}_{1}^{2}H + {}_{1}^{3}H \rightarrow {}_{3}^{4}He + {}_{0}^{1}n$$

Q = 17.6 MeV
neutron energy ~ 14 MeV

$${}_{3}^{7}Li + {}_{1}^{1}H \rightarrow {}_{4}^{7}Be + {}_{0}^{1}n$$

Q = - 1.64 MeV
neutron energies vary

Accelerated protons must supply additional energy to make this reaction proceed.

Isotopic Neutron Sources

(α,n) Neutron Sources (after [Turner], Table 9.2)		
Source	*Average neutron energy (MeV)*	*Half-life*
^{210}PoBe	4.2	138 d
^{210}PoB	2.5	138 d
^{226}RaBe	3.9	1600 y
^{226}RaB	3.0	1600 y
^{239}PuBe	4.5	24100 y

Alpha source + light metal

$${}^{4}_{2}He + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + {}^{1}_{0}n \qquad Q = 5.78 \text{ MeV}$$

Light metals minimize Coulomb repulsion

Neutron and recoil nucleus share Q and KE of incoming alpha particle.

Neutrons have a ***continuous energy spectrum.***

E.g., ${}^{239}_{94}Pu$ emits alpha particles of ~ 5.1 MeV

PuBe sources used to provide neutrons to “start” reactors.

Photoneutron reactions

- Photon brings enough energy to drive reaction.
- Photoneutron sources emit monoenergetic neutrons (if a single energy photon comes in).
- Requires photons of > several MeV.

(γ,n) Neutron Sources (after [Turner], Table 9.3)		
Source	*Neutron energy (MeV)*	*Half-life*
^{24}NaBe	0.97	15.0 h
^{24}NaD$_2$O	0.26	15.0 h
^{116}InBe	0.38	54 min
^{124}SbBe	0.024	60 d
^{140}LaBe	0.75	40 h
^{226}RaBe	0.7 (maximum)	1600 y

<u>Δ values</u>

$^{206}_{82}Pb \rightarrow ^{205}_{82}Pb + ^{1}_{0}n$ **-23.79 → -23.77 + 8.07**

neutron binding energy = 8.09 MeV

- Energy needed to remove neutron = 8.09 MeV
- If a 10 MeV photon is used to "drive" this reaction, the products share the excess energy: 1.91 MeV.
- E_n = hν – binding energy
- E_n = 1.90 MeV

Cross Sections

- Because mass attenuation coefficients 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

Attenuation coefficient, expressed at the atom level
Probability of interaction per atom

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

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.

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Fig. 24.3 in Hall, Eric J. *Radiobiology for the Radiologist*, 5th ed. Philadephia PA: Lippincott Williams & Wilkins, 2000.

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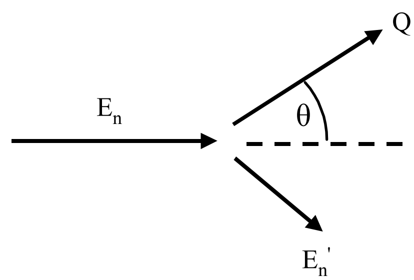
Neutron Interactions

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.

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



Maximum fraction of energy lost (Q_{max}/E_n)
by a neutron in a single elastic collision with
various nuclei (from [Turner], Table 9.4)

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.

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

- 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.

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

- 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.

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

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

- 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.

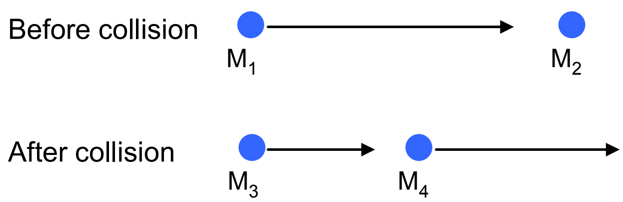
Spallation

- 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.

Threshold Reactions

Q is negative, endothermic reaction.
Threshold energy, E_{th}, must be supplied.

Incoming particle (M_1) must bring enough energy to overcome ***negative Q threshold*** and to provide enough energy to satisfy conservation of momentum requirements.



Schematic of a head-on collision producing a nuclear reaction in which the identity of the particles can change.
(after [Turner], Fig. 9.7)

- Particle M_1 strikes M_2 (at rest).
- Identities of particles change: M_3 and M_4 are created.
- Q value is negative
- Conservation of energy: $E_1 = E_3 + E_4 + Q$
- Conservation of momentum: $p_1 = p_3 + p_4$

$$E_{th} \geq -Q\left(1+\frac{M_1}{M_3+M_4-M_1}\right)$$

Smallest possible E to satisfy the equation is the Threshold Energy, E_{th}.

Example: $^{32}S(n,p)^{32}P$ Q = - 0.93 MeV

E_{th} = 0.957 MeV

In practice, the ***Coulomb Barrier*** adds energy to E_{th} for reaction to occur.

Application:
^{32}S exists in human hair.
^{32}P activity induced by neutrons (> 3.2 MeV) can be used as a measure of the individual's exposure following criticality accidents.

Neutron Activation

- Extremely useful property of neutrons.
- Neutron capture creates a new isotope (same element)
- Sensitive tool for elemental analysis

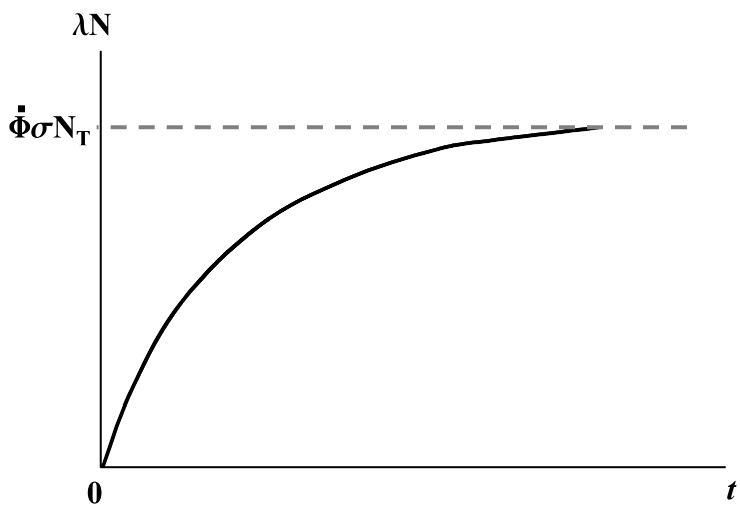
Creation of a nuclide N

$$\lambda N = \Phi \sigma N_T (1 - e^{-\lambda t})$$

Activity = production – loss by decay

N_T = # of target atoms
σ = cross section (barns: 10^{-24} cm^2)
Φ = fluence rate ($n/cm^2\ s$)
t = start of the irradiation

$\Phi \sigma N_T$ = saturation activity $\quad t \rightarrow \infty$



Buildup of induced activity λN during neutron irradiation at constant fluence rate.
(after [Turner], Fig. 9.8)

Example:
Gold activation used as a measure of thermal neutron fluence

^{197}Au (100% abundance)
σ = 98.8 barns
$^{197}Au + n \rightarrow {}^{198}Au$ $t_{1/2}$= 2.7 days

$$\lambda N = \Phi \sigma N_T (1 - e^{-\lambda t})$$

Alternatively, neutron activation can be used to measure the amount of an element present.

Gamma emission energies are element-specific and can be used to identify trace amounts

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