Illinois Institute of Technology

PHYSICS 561

RADIATION BIOPHYSICS

Lecture 2: Radioactivity

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Stable and Unstable Elements

- Every element has ≥1 unstable isotope, i.e. one that undergoes radioactive decay
- Most elements with Z < 92 have at least one stable isotope
- We'll examine radioactivity in terms of the transitions under which an atom decays
- Radioactivity has various influences on biological tissue:
  - Ionization of biological macromolecules
  - Indirect effects, often via free radicals
  - Medical applications: therapy, diagnostics, . . .

Radioactivity

- Nuclear Stability
- Mass Decrement
- Alpha Emission
- Negative Beta Emission
- Positive Beta Emission
- Electron Capture
- Spontaneous Fission

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Rules

- Stable nuclei of even Z more numerous than odd Z.
- Stable nuclei of even N more numerous than odd N.
- Stable nuclei of even A more numerous than odd A.
- In general, stable nuclei of even A have even Z. Some exceptions exist, however, such as ^{2}H, ^{6}Li, ^{10}B, and ^{14}N
- Only two stable structures are known for which Z is greater than N: ^{3}He and ^{1}H
- Examining what happens to the N/Z ratio in a typical alpha decay:

$$
\begin{array}{rll}
 & {}^{236}Ra \rightarrow & {}^{222}Rn + \alpha + \gamma + Q \\
Z = & 88 & 86 \text{ (number of protons)} \\
N = & 138 & 136 \text{ (number of neutrons)} \\
N/Z = & 1.5682 & 1.5814
\end{array}
$$

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Mass Energy of α - Particle

Ignoring binding energy

$2 * m_o c^2$(neutron) $\approx$ 1978 MeV
$2 * m_o c^2$(proton) $\approx$ 1976 MeV

Mass Energy = 3954 MeV
Kinetic Energy ~ 4 MeV

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Beta Decays

Negative Electron Decay

$$^{A}X \rightarrow {}^{A}Y + \beta^{-} + \overline{\nu} + Q$$

Positive Electron Decay

$$^{A}X \rightarrow {}^{A}Y + \beta^{+} + \nu + Q$$

$$(p \rightarrow n)$$

Spontaneous annihilation

$$\beta^{+} + e^{-} \rightarrow 2\gamma$$

$$0.511 \ MeV + 0.511 \ MeV = 1.022 \ MeV$$

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Energy - Wavelength Relationship for Photons

$$E = \frac{hc}{\lambda}$$

$$E(eV) = \frac{12398.4}{\lambda}$$ for λ in eV

$$E(MeV) = \frac{.0123984}{\lambda}$$ for λ in MeV

$$\lambda\left(\mathring{A}\right) = \frac{.0123984}{E(MeV)} = \frac{.0123984}{0.511} = 2.46\ pm$$

for the photons emitted in a positron annihilation $= .0246\ \mathring{A}$

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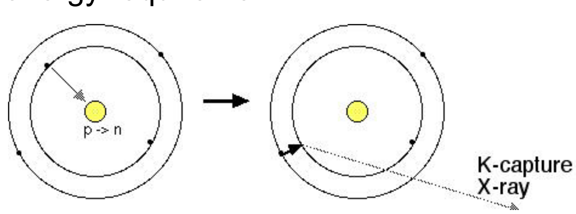
Electron Capture

Neutron-deficient species can capture an electron from an inner shell of the atom. Unlike conventional positron decays, for which the energy difference Q must be at least

$2m_0c^2 = 0.511$ MeV,

the electron-capture process has no minimum energy requirement.



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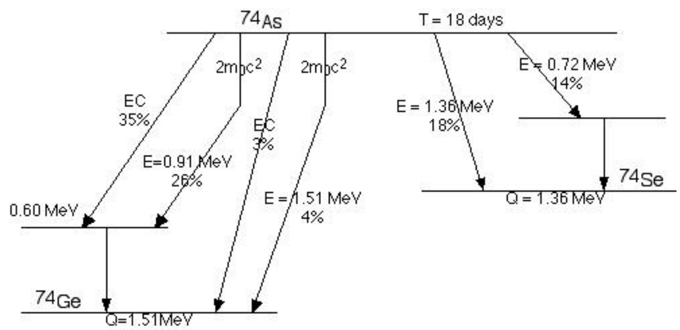
Charting Decay Schemes

We can sometimes find multiple pathways, each with multiple steps, as with ^{74}As here (this is fig. 3.4, p. 37, in Alpen)



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Nomenclature for Nuclei

Incorporates

- Atomic Number
- Atomic Mass Number
- Neutron Number

$${}^{A}_{Z}Chemical\ Symbol$$

$$Simplified\ form:$$

$${}^{A}Chemical\ Symbol$$

$${}^{238}U$$

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Law of Radioactivity

- Rate of disappearance is proportional to the quantity of original nuclide remaining:

$$\frac{dN}{dt} \propto N$$

$$\frac{dN}{dt} = -\lambda N \qquad (\lambda \geq 0)$$

$$N = N_o \;\; at \;\; t = 0 \;\; (\text{" boundary condition"})$$

$$N = N_o e^{-\lambda t}$$

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Half-life and activity

Half-life ≡ time at which $N = N_o/2$

$$N = \frac{N_o}{2} = N_o e^{-\lambda t_{1/2}}$$

$$e^{-\lambda t_{1/2}} = \frac{1}{2}$$

$$\ln e^{-\lambda t_{1/2}} = \ln 1/2 = -\ln 2$$

$$\lambda t_{1/2} = \ln 2$$

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

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Exposure:
A More Detailed Definition

Exposure is defined as *charge to which the target material is exposed per unit mass*

Exposure = $\Delta Q/\Delta m$

The unit of exposure to electromagnetic radiation is the *Roentgen*

The Roentgen was defined as 1 esu/cm^3 air at STP

$\rho(air)_{STP}$ = 1.293 $\cdot 10^{-3}$ g/cm^3

1 esu = 3.34 $\cdot 10^{-10}$ Coulomb

So 1R = 3.34 $\cdot 10^{-10}$ C /(1 cm^3 * 1.293 $\cdot 10^{-6}$ kg/cm^3)

i.e. 1 Roentgen = 2.58$\cdot 10^{-4}$ C/kg

Assignment from
Ch. 3 for Next Week

1. Chapter 3, problem 1:

The atomic mass, m, of ^{64}Cu is 63.929757 amu. It undergoes positron decay with a half-life of 12.9 h. The product of this decay is ^{64}Ni. The mass, m, of this product is 63.927956. What is the total energy of the positron and the neutrino resulting from the decay? Is the product liable to be stable or be radioactive? Why?

2. Chapter 3, problem 3

A source of ^{99m}Tc arrives at the laboratory for use at 10 AM on a Monday morning, at which time this daughter product is eluted for diagnostic use. The parent, ^{99}Mo, has a decay constant of 0.01039 h^{-1}. If, after the separation of the daughter, the parent was found to have an activity of 5.0•10^9 Bq, what is the activity of the parent and the daughter the following Thursday at 10 am?

Further Notes on Homework

- No assignment from chapter 4 until next week
- Reminder: Course web page is:
  http://icarus.csrri.iit.edu/radbio/
  - Includes assignments!

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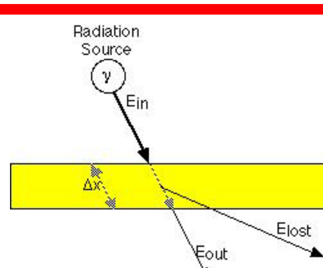
Interactions of Photons with Absorber



Number of photons not transmitted:

$\Delta N = \mu \Delta x N$

μ is the *linear attenuation coefficient*

Units of μ: inverse length

Energies: E_{in}-E_{out} = $E_{transferred}$

$E_{absorbed}$ = amount that stays = (E_{in}-E_{out}) - E_{lost}

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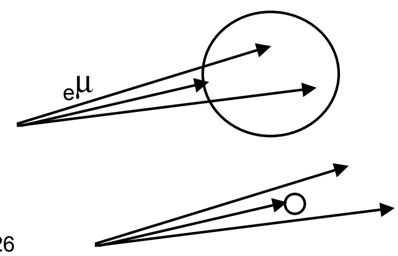
Absorption / Attenuation Coefficients

- Relationships among Attenuation Coefficients:

Coefficient	Symbol	Units
Linear	μ	m^{-1}
Mass	μ/r	$m^2 kg^{-1}$
Electronic	${}_e\mu$	m^2/ e-
Atomic	${}_a\mu$	m^2/ atom



Energy Transferred and Absorbed from Photons by Carbon:

Table 4.2 in book:
Energy Transferred and Energy Absorbed for Incident Photons of Various Energies (for Carbon)

Photon Energy, E_{tot} MeV	Average Energy Transferred, E_{tr} MeV	Average Energy Absorbed, E_{ab} MeV
0.01	0.00865	0.00865
0.10	0.0141	0.0141
1.00	0.440	0.440
10.0	7.30	7.04
100.0	95.63	71.90

Mechanisms of Energy Transfer

Gamma Rays

- Photoelectric scattering:

  Photoelectron KE = $h\nu$ - binding energy

  - Must involve bound electrons
  - Partial cross section $\tau/\rho \propto (h\nu)^u$, roughly:

    u = -3 for low-Z elements

    u = -2.96 for Pb

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Cross Section

- We keep finding quantities that look like L^2 in the numerators of these definitions, so physicists like to describe these as cross-sections, i.e. we think about the effective cross-sectional area of the electron as it interacts with the photon.
- $\tau/\rho \propto E^{-3}$ of the photon (most elements),
- $\tau/\rho \propto E^{-2.96}$ of the photon (for lead)
- But energy = hc/λ, so for most elements $\tau/\rho \propto \lambda^3$

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