Announcements

- Capstone topics are due this week!
- Tuesday – cyclotron tour & exam review
- Nuclear chemistry seminar – 4pm today
- Reactor tour – possibly 1 Nov

Average = 75.9 points
Std. Dev. = 12.3 points
Interaction of radiation with matter

• Ionization
  – primary ionization
  – secondary ionization

• Kinetic energy transfer

• Molecular and atomic excitation

• Nuclear reactions

• Radiative processes
  – Cerenkov
  – bremsstrahlung
particle groupings

• heavy charged particles
  – alphas, fission fragments
• light charged particles
  – beta particles
• uncharged radiations
  – xrays, gamma rays, neutrons
FIG. 6.3. Curves showing relative transmission $\phi/\phi_0$ (or $R/R_0$) as function of absorber thickness $x$. $C_1$ and $C_3$ are average, $C_2$ and $C_4$ maximum range.
TABLE 6.2. Range in water, and average linear energy transfer (LET) values for different radiation

Upper half refers to monoenergetic (accelerated) particles. For β-decay $E_{\text{abs}} = 1/3 E_{\text{max}}$

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Energy (MeV)</th>
<th>Maximum range</th>
<th>Average LET value in water (keV/μm)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>cm air</td>
<td>mm water</td>
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<tr>
<td>Electron</td>
<td>1</td>
<td>405</td>
<td>4.1</td>
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<tr>
<td></td>
<td>3</td>
<td>1400</td>
<td>15</td>
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<tr>
<td></td>
<td>10</td>
<td>4200</td>
<td>52</td>
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<tr>
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<tr>
<td></td>
<td>3</td>
<td>14</td>
<td>0.014</td>
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<td></td>
<td>10</td>
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<td>1.2</td>
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<tr>
<td>Deuteron</td>
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<td>1.7</td>
<td>-</td>
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<td></td>
<td>10</td>
<td>10.5</td>
<td>0.11</td>
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<tr>
<td>Fiss. fragment</td>
<td>100</td>
<td>2.5</td>
<td>0.025</td>
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</table>

$^{226}\text{Ra (α)}$ $E_\alpha$ 4.80 3.3 0.033 145
$^{210}\text{Po (α)}$ $E_\alpha$ 5.30 3.8 0.039 136
$^{222}\text{Rn (α)}$ $E_\alpha$ 5.49 4.0 0.041 134
$^3\text{H (β)}$ $E_{\text{max}}$ 0.018 0.65 0.0055 1.1
$^{35}\text{S (β)}$ $E_{\text{max}}$ 0.167 31 0.32 0.17
$^{90}\text{Sr (β)}$ $E_{\text{max}}$ 0.544 185 1.8 0.10
$^{32}\text{P (β)}$ $E_{\text{max}}$ 1.71 770 7.9 0.07
$^{90}\text{Y (β)}$ $E_{\text{max}}$ 2.25 1020 11 0.07
$^{137}\text{Cs (γ)}$ $E_\gamma$ 0.66 $x_{\mu}$ = 8.1 cm $\text{H}_2\text{O}$ 0.39
$^{60}\text{Co (γ)}$ $E_\gamma$ 1.20-1.30 $x_{\mu}$ = 11.1 cm $\text{H}_2\text{O}$ 0.27
Interaction of heavy charged particles with matter

- Electronic stopping
  - high energy
- Intermediate stopping
  - considerably slower
- Nuclear Stopping
  - near end of range
- Range - average distance traveled
Range of alpha particle
Electronic Stopping

\[ v_l \gg v_e \]

- positive ion
  - stripping of electrons
  - eloss/interaction small
    - many interactions
    - straight line trajectory
- stopping material effects
  - ionization
  - electronic excitation
  - molecular dissociation
Electronic Stopping

$V_1 \gg V_e$

- positive ion
  - stripping of electrons
  - eloss/interaction small
    - many interactions
    - straight line trajectory
- stopping material effects
  - ionization
  - electronic excitation
  - molecular dissociation
Intermediate stopping
\(v_i \approx v_e\) (inner shell)

- electron pickup
- moderate directional change
  (not as much forward momentum)
Nuclear stopping

\[ v_I \approx v_e \] (valence shell)

- ion charge 0,1
- elastic collisions -
  - atom-atom
- large directional changes
  - no longer forward momentum
  - no longer mass asymmetry
- large radiation damage
Energy Deposited along range

![Graph showing specific ionization per mm of air vs. residual range in cm.](image)
Energetics

• maximum energy loss/collision
  \[ \Delta E_{\text{max}} = 4E_0\left(\frac{m_e}{m_i}\right) \]
  6MeV alpha = 3keV

• average energy loss/collision
  ave \( \Delta E \) approx 100-200 eV for 6MeV alpha

• Formation of ion pairs
  radiation -> cation + electron
  approx 30 eV/pair in air
Rate of Energy Loss

\[-\frac{dE}{dx} = \frac{4\pi\gamma^2 z_I^2 e^4 N_{abs} Z_{abs}}{m_e v_I^2} \left[ \ln\left(\frac{2m_e v_I^2}{I}\right) - \ln(1 - \beta^2) - \beta^2 \right] \]

if \(E_i < 100A_i\text{MeV}\) and \(\gamma = 1\)

\[-\frac{dE}{dx} \propto Z^2/v^2 \propto AZ^2/E\]

\[\frac{dE}{dx} \propto AZ^2/E\]

dE/dx increases with A\&Z of ion

dE/dx decreases with E of ion

(at very low E increases when \(\gamma \to 0\))
Range Determinations

• integrate energy loss
• tables/graphs/computer programs
• scaling from protons
• ranges in other absorbers
• ranges in compounds
Scaling from other ions

\[ R(Z_1, A_1, E_1) = \frac{A_1 Z_2^2}{A_2 Z_1^2} R(Z_2, A_2, \frac{A_2}{A_1} E_2) \]

in the case of protons

\[ R(Z, A, E) = \frac{A}{Z^2} R_p \left( \frac{E}{A} \right) \]
Ranges in compounds

\[
\frac{1}{R_{tot}} = \frac{w_1}{R_1} + \frac{w_2}{R_2} + \frac{w_3}{R_3} + \frac{w_4}{R_4} \ldots
\]

where

\( R_i \) = range in element i

\( w_i \) = weight fraction of element i
Ranges in other absorbers

- look it up in energy loss tables (N&S)
  - Computer code (SRIM)
- if ionization potential is not too much different

\[ R_z = 0.173 E_{\alpha}^{3/2} A_z^{1/3} \left( \frac{mg}{cm^2} \right) \]

- use graph to relate to dE/dx of Al
Beta-particle interactions

- ionization
- backscatter
- positron annihilation
- bremsstrahlung
ionization

- removal of atomic electron to form ion pair
Kinetic energy transfer

- impart energy above what was needed to overcome electron binding energy
- inelastic collision with nucleus
backscatter

- single or few large angle scatters
- angles and energies characteristic of absorber
- low E ; High Z
bremsstrahlung

$E_{\text{brem}} / E_{\text{ion}} = E_e Z_{\text{abs}} / 800$

- high $Z$, high $E$
  - shielding should be low $Z$ material
• positron annihilation

- production of two 511 KeV gamma rays
  - (180 degrees apart)
Cerenkov

• \( \beta \) produced faster than speed of light (in medium)
  – shock wave produced as \( \beta \) slows down

• glow in reactor pool
Range - Energy determination

- betas are not monoenergetic - distribution in ranges
- $R(\text{g Al/cm}^2) = 0.543E_{\text{max}}(\text{MeV}) - 0.160$
look it up on graph
Absorption of beta particles

FIG. 6.4. Absorption curve for $^{32}$P $\beta$-radiation showing extrapolated ($C_4$) and average ($C_3$) ranges. The dashed curve is obtained after subtraction of background.
Electromagnetic Radiation

- Photointeracts with electromagnetic fields
- photoelectric effect
- Compton Scattering
- pair production
Photoelectric effect

- $E_e = E_\gamma - BE_e$
- $P = kZ_{\text{abs}}^5 / E_\gamma^{7/2}$
Energy of scattered $\gamma$

- **conserve energy**
  - $E_\gamma = E_\gamma' + E_e$
  - where, $E = [E_o^2 + p^2c^2]^{1/2}$

- **conserve momentum**
  - $E_\gamma/c = E_\gamma'/c \cos \Theta + p_e \cos \Phi$
  - $E_\gamma/c \sin \Theta = p_e \sin \Phi$

- $E_\gamma' = .511E_\gamma/[.511 + E_\gamma(1-\cos \Theta)]$

- $E_{\gamma'}_{\text{min}} = .511E_\gamma/[.511 + 2E_\gamma]$ (backscattered)

- $\rightarrow 0.25 \text{ MeV}$ (high energy $\gamma$)
Compton Scattering

• $P_{cs} = kZ_{abs}/E_{\gamma}$
Backscatter peak

![Graph showing backscatter from shielding]

- Y-axis: Number of \( \gamma \) rays
- X-axis: Energy of \( \gamma \) (MeV)
- Peak at 0.25 MeV
- Backscatter from shielding
Compton edge

\[ E_{CE} = FEP - \text{backscatter} = FEP - 0.25 \text{ Mev} \]
Pair production

- minimum energy needed 1.02 MeV
  (remaining energy into kinetic energy of $e^+/e^-$)

- $P_{pp} = k \log E_g Z^2_{abs}$ (above thresh)
• single escape peak
  \[- E_{\text{det}} = E_\gamma - 511\text{keV}\]
• double escape peak
  \[- E_{\text{det}} = E_\gamma - 2(511\text{KeV})\]
favored means of eloss
16 October

• Reactor tour 7 Nov 2pm
• Capstone projects
  – 4 Nov: abstracts due
  – 20 Nov: paper due

• http://ie.lbl.gov/interact.htm
Review questions

• How much energy is lost when the alpha particle from the decay of $^{239}\text{Pu}$ goes through a 1mg/cm$^2$ nickel absorber?

• How thick of a nickel absorber would you need to stop the alpha particle(s) from the decay of $^{228}\text{Th}$?

• What effect would this have on the beta particles?
16 October

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Electromagnetic Radiation

- Photointeracts with electromagnetic fields
- Photoelectric effect $\rightarrow$ Full Energy Peak
- Compton Scattering $\rightarrow$ Compton edge
  - Backscatter peak
  
  $E_{CE} = FEP - \text{backscatter} = FEP - 0.25 \text{ MeV}$

- Pair production $\rightarrow$ escape peaks
  - Single escape peak ($FEP - 0.511 \text{ MeV}$)
  - Double escape peak ($FEP - 1.022 \text{ MeV}$)
gamma energy spectrum
gamma ray absorption

• attenuation rather than range
• absorption coefficient $\mu$
• $I = I_0 e^{-\mu d}$
• half thickness $d_{1/2} = \frac{.693}{\mu}$
  (thickness that cuts intensity to half)
How much Al would it take to reduce a 10 KeV photon to 1/10 its original intensity?

\[ d_{1/2} = 28 \text{mg/cm}^2 \]

\[ \mu = \frac{0.693}{d_{1/2}} = 2.48 \times 10^{-2} \text{ cm}^2/\text{mg} \]

\[ I = I_0 e^{-\mu d} \]

\[ 0.1I_0 = I_0 e^{-0.0248d} \]

\[ \ln(0.1) = -0.0248d \]

\[ d = 92.8 \text{mg/cm}^2 \]
critical absorption of X-rays
Interactions of neutrons with matter

• nuclei rather than atomic electrons
  – Z=0
• probability for interaction lower than $\beta,\gamma$
  – long range
• Neutron thermalization
• capture
  – gamma or charged particle emission
• elastic and inelastic scattering

\[ \delta E = E_i - E_f \]

\[ \delta E_{\text{max}} = \frac{4AE_o}{(A+1)^2} \]

– equal prob of \( \delta E \) from 0 to max

\[ \langle E_f \rangle = E_o \left[ 1 - \frac{2A}{(A+1)^2} \right] \]

• thermalized when \( \langle E_n \rangle = \frac{3}{2} kT \approx 0.04 \text{eV} \)

\[ n = \frac{\ln \left( \frac{E_o}{E} \right)}{1 - \left[ \frac{(A-1)^2}{2A} \right] \ln \left[ \frac{A+1}{A-1} \right]} + 1 \]

• absorption : \( \sigma = f(1/e) \)
Neutron Detection

• interact via scattering and nuclear reactions
  – (rather than atomic ionization or excitation)
• ->Detect result of reaction
  – charged particles and gamma rays
• thermal neutrons
• $^{10}\text{B} \ (n,\alpha) \ ^7\text{Li}$ - BF$_3$ - wall counter

\[ n \rightarrow \alpha \text{ CF}_4 \]
• $^3\text{He}(n,p)^3\text{H}$ - gas counters
• $^6\text{Li}(n,\alpha)$ - Lil
• fissionable material
• energy of charged particle close to Q-value
  • fast neutrons must be moderated first
• gamma discrimination
Energy information

• spectroscopy
  – \((n, \gamma) : E_\gamma > Q\)
  – large, dense crystal (BaF, LiF)

• recoil angle

• time of flight
  – \(E = 1/2mv^2\)

• semiconductor sandwich
Detectors based on Light Emission

convert kinetic energy of particle into detectable light

✿ Organic
  – aromatic molecules
  – delocalized electrons in $\pi$ molecular orbitals

✿ Inorganic
  – crystals of alkali halides
  – small activator impurity
Desirable characteristics

- high scintillation efficiency
- linear conversion
- transparent to own $\lambda$
- decay time -> short fast pulse
- manufacturable
- index of refraction near glass
Organic Scintillators
Organic Scintillators

- Absorption: $\pi$-electronic energy levels
  - higher singlet states deexcite to S1 through internal degradation
- Prompt Fluorescence (nsec)
- Phosphorescence from triplet state (slow)
  - intersystem crossing to triplet states
- Delayed fluorescence: $T+T \rightarrow S_1+g$
- Pulse Shape Discrimination
  - density of triplet states
Inorganic Scintillators

Diagram showing the energy levels in inorganic scintillators, with transitions from the valence band to the conduction band, involving activator levels, and emission of light.
Inorganic Scintillators

- crystalline structure
- Promote electron from valance band to conduction band
- deexcites emitting scintillation photon
- Activator modifies band structure
- Phosphorescence: initial excitation to state with forbidden transition to g.s.
- BGO, BaF$_2$ / NaI(Tl), CsI(Tl), CsI(Na)
Pulse Shape Discrimination

![Graph showing pulse intensity for different types of particles: Alpha particles, Fast neutrons, and Gamma rays. The graph plots light intensity against time, with logarithmic scales on the y-axis and linear scales on the x-axis.](image)
Light Collection

• Photomultiplier tubes
• Photocathode: absorb $h\nu$ emit $e^-$
  – Quantum efficiency (e/photon: 20-30%)
• Electron multiplication
  – secondary electron emission ($\delta = \#e_{sec}/\#e_{pri}$)
  – stages (N)
  – gain = $\alpha \delta^N$
• Voltage Sensitive
Photomultiplier Tube (PMT)
Photodiode
(silicon detectors)
• higher quantum efficiency
• insensitive to magnetic fields
• lower power
• more compact
• improved ruggedness
• band gap 1-2 eV (photocathode 3-4eV)
• different wavelength sensitivity
• slower time response
Detection of charged particles

- Gas Detectors
- Semiconductor detectors
- collecting electrons
Gas detectors

• ionization detectors
  – pulse mode
  – current mode

• proportional detectors
  – secondary ionization

• Geiger-Mueller counters
  – considerable increase in number of ultraviolet photons
current mode
pulse mode
proportional counter
INCOMING RADIATION

ANODE

e-

TOWNSEND AVALANCHE

CATHODE
GM counter
Semiconductor detectors

- electron -hole pairs
  - Si : 3.6 eV/pair
  - Ge : 2.9 eV/pair
  (Gas: 20-40 eV/pair; scint: 400-1000eV/pair)
- Diodes (reverse bias)
- pn junctions
- Surface barrier detectors
simplified crystal structure
n-type semiconductor material
p-type semiconductor material

[Diagram showing a p-type semiconductor material with labeled positive ions (+4) and a missing electron labeled as a "hole".]
pn junction
pn junction

<table>
<thead>
<tr>
<th>p-type</th>
<th>n-type</th>
</tr>
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<tbody>
<tr>
<td>○○○○-</td>
<td>+●●●●</td>
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<tr>
<td>○○○○-</td>
<td>+●●●●</td>
</tr>
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Diagram showing the charge distribution at a pn junction.
pn junction reverse bias (no current)