BioEngineering 221/Radiology 221

Production of Radionuclides & Interaction of Radiation with Matter

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Aspects of the Radiotracer

biomolecule + radioactive element = radiotracer

• What modes of radioactive decay are used?
• How do radionuclides decay to produce emissions for imaging?
• How are relevant radionuclides produced?
• How do radionuclide emissions interact in tissue and detectors?
Illustration of Course thus Far and Future

Visualize molecular analog chemically labeled with positron-emitting radionuclide:

$^{18}$F-Fluorodeoxyglucose
Production of Radionuclides
Nuclear transitions & Radioactive Decay

Stimulated transitions

Nuclear reactions

Radionuclide production

Spontaneous transitions

• α decay
• β decay
• γ de-excitation

Increase Energy

Decrease Energy

Molecular Imaging Program at Stanford
Nuclear Transitions

- Adding energy to the nuclei, pushes nuclei to the edge of the valley of stability
- Energy needed for this process
Producing Radioactive Nuclei

- Naturally occurring radioactive isotopes:
  - Typically have long half-life
  - Very heavy elements that are not endogenous to human biology

Use methods to produce radioactive isotopes

Produced through **Nuclear Reactions**
Overview

1. **Reactor-Produced** Radionuclides: Neutron activation and fission products
2. **Accelerator-Produced** Radionuclides: Proton activation and cyclotron
3. Radionuclide **Generators** ($^{99m}$Tc)
A common neutron source

\[ ^{235}_{92}U + n \rightarrow ^{236}_{92}U^* \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + \#n + \#\gamma + \#\nu + E \]

- Stimulated fission is the source of energy in a nuclear power plant
- Production of a statistical # of neutrons enables a chain reaction
- Excited $^{236}\text{U}$ has more than 100 nuclides among its fission products
Fission Yield of U-235

- In general one fragment with A between 130 and 150; and another between 85 and 105
- Fission products with equal masses are least likely
A Nuclear Reactor

- Nuclear reactors have provided large quantities of radioactive isotopes for nuclear medicine
  - Fuel cells contain fissionable material (~4-5% of U-235 by weight)
  - Moderator to slow down the neutrons (water or ‘heavy’ water D_2O)
  - Control rods contain strong neutron absorbers to moderate the reaction
  - Each fission events creates about ~200 MeV of energy, mainly released as heat to moderator
  - Radionuclides are produced in samples surrounding the reactor core
Reactor produced Radionuclides

- Fission products have excess neutrons and thus decay by $\beta^-$ decay
- If a radioactive intermediate has sufficiently long half-life it can be extracted and used as a medical radionuclide

\[
\begin{align*}
^{99}_{39}Y & \longrightarrow ^{99}_{40}Zr & \longrightarrow ^{99}_{41}Nb & \longrightarrow ^{99}_{42}Mo (T_{1/2} = 65.9 \text{ hr}) \\
\beta^{-}, 1.5s & \beta^{-}, 21s & \beta^{-}, 15s & \\
\end{align*}
\]

- $^{99}_{40}$Mo is used to generate $^{99m}_{43}$Tc (More on this in just a bit)
- Also $^{131}$I and $^{133}$Xe produced by neutron activation, these are important for nuclear medicine as well
Reactor produced Radionuclides

Thyroid uptake of radioactive iodine ($\text{I}^{131}$)
Reactor produced Radionuclides

Xe-133 Scintigraphy
Radionuclides by fission

General properties:

- Excess of neutrons, hence $\beta^{-}$ decay
- Products may be carrier free, thus radionuclides have high specific activity by chemical separation
- Lack of specificity in fission products is a drawback
Overview

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Nuclear reactions: proton activation

Proton needs to be energetic to make it to the atomic nucleus, typically 10-20 MeV

➔ Need particle accelerators

• Different kind of particle accelerators
• Most common: cyclotron
Proton acceleration: Cyclotron

- Charged particle in **electric** field: **acceleration**
- Charged particle in **magnetic** field: **change of direction**

→ These principles are combined in a cyclotron.
Proton acceleration: Cyclotron

- Charged particle in **electric** field: **acceleration**
- Charged particle in **magnetic** field: **change of direction**

➤ These principles are combined in a cyclotron.

- Pair of hollow ‘dees’, positioned between poles of magnet
- Ion source at the center
- Electric field between dees
Proton acceleration: Cyclotron

- Particle gains energy in gap between dees
- Upon increased energy, the ion will have a larger radius in the dee
- Electric field is reversed after every transition
Proton acceleration: cyclotron

- When maximum orbital radius is reached, particles are extracted, using targets or a stripping foil
- Cyclotron produce in general smaller quantities of radioactivity than nuclear reactors due to
  - Lower beam intensities
  - Lower cross section
- Special interest are short-lived positron emitters: $^{11}\text{C}$ (20 min), $^{13}\text{N}$ (10 min), $^{15}\text{O}$ (2 min), these require a local cyclotron
- Also $^{18}\text{F}$ (110 min) important, but a regional distribution center is sufficient
Overview

1. **Reactor-Produced** Radionuclides: Neutron activation and fission products
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Radionuclide Generators

- Parent-daughter radionuclide pair contained in apparatus that permits separation
- Most important generator: $^{99}$Mo – $^{99m}$Tc
- Very common because of wide spread Tc use (more than 1850 TBq of $^{99}$Mo required per week)
- Also $^{68}$Ga, $^{82}$Rb, $^{62}$Cu are generator produced
Radionuclide Generators

- Shielded vacuum vial
- Normal saline eluent
- Alumina column
- Lead shield

- Eluant (saline vial)
- Eluate (evacuated vial)
- Aluminium column (99Mo tightly bound, 99mTc loosely bound)
- Lead shielding

Molecular Imaging Program at Stanford
Radiotracers

• Many candidate radionuclides, yet relatively small number of practical radionuclides because of following considerations:
  • **Type** and **energy** of emissions and the branching ratio: ideally no other processes than γ-emission at energies 50-600 keV
  • Physical **half-life of radionuclide**:
    • If too short: no time for preparation
    • If too long: high radiation contamination for disposal and most of the activity emitted outside of examination time
  • **Specific activity**: need as many as possible radioactive molecules in a sample; must not be biologically pertering
  • **Radionuclidic purity**: fraction of the radioactivity in the desired form, i.e. no contaminants
  • **Cost and complexity**: ease of production
## Radiotracers

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Decay Mode</th>
<th>Principal Photon Emissions</th>
<th>Half-Life</th>
<th>Primary Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$C</td>
<td>$\beta+$</td>
<td>511 keV</td>
<td>20.4 min</td>
<td>Imaging</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>$\beta+$</td>
<td>511 keV</td>
<td>9.97 min</td>
<td>Imaging</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>$\beta+$</td>
<td>511 keV</td>
<td>2.03 min</td>
<td>Imaging</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>$\beta+$</td>
<td>511 keV</td>
<td>110 min</td>
<td>Imaging</td>
</tr>
<tr>
<td>$^{32}$P</td>
<td>$\beta-$</td>
<td>—</td>
<td>14.3 d</td>
<td>Therapy</td>
</tr>
<tr>
<td>$^{67}$Ga</td>
<td>EC</td>
<td>93, 185, 300 keV</td>
<td>3.26 d</td>
<td>Imaging</td>
</tr>
<tr>
<td>$^{82}$Rb</td>
<td>$\beta+$</td>
<td>511 keV</td>
<td>1.25 min</td>
<td>Imaging</td>
</tr>
<tr>
<td>$^{89}$Sr</td>
<td>$\beta-$</td>
<td>—</td>
<td>50.5 d</td>
<td>Therapy</td>
</tr>
<tr>
<td>$^{99m}$Tc</td>
<td>IT</td>
<td>140 keV</td>
<td>6.02 hr</td>
<td>Imaging</td>
</tr>
<tr>
<td>$^{111}$In</td>
<td>EC</td>
<td>172, 247 keV</td>
<td>2.83 d</td>
<td>Imaging</td>
</tr>
<tr>
<td>$^{123}$I</td>
<td>EC</td>
<td>159 keV</td>
<td>13.2 hr</td>
<td>Imaging</td>
</tr>
<tr>
<td>$^{125}$I</td>
<td>EC</td>
<td>27-30 keV x rays</td>
<td>60.1 d</td>
<td>In vitro assays</td>
</tr>
<tr>
<td>$^{131}$I</td>
<td>$\beta-$</td>
<td>364 keV</td>
<td>8.04 d</td>
<td>Therapy/imaging</td>
</tr>
<tr>
<td>$^{153}$Sm</td>
<td>$\beta-$</td>
<td>41, 103 keV</td>
<td>46.7 hr</td>
<td>Therapy</td>
</tr>
<tr>
<td>$^{186}$Re</td>
<td>$\beta-$</td>
<td>137 keV</td>
<td>3.8 d</td>
<td>Therapy</td>
</tr>
<tr>
<td>$^{201}$Tl</td>
<td>EC</td>
<td>68-80 keV x rays</td>
<td>3.04 d</td>
<td>Imaging</td>
</tr>
</tbody>
</table>
Production of Radionuclides: Major Takeaways

1. Naturally abundant radionuclides are long-lived, not generally useful for nuclear medicine studies

2. Produce short-lived radionuclides via stimulated transitions: ex. neutron activation or fission in reactor, proton activation in cyclotron

3. Work horse isotope Tc-99m eluted from Mo-99 product in radionuclide generator

4. Radionuclide chemically labeled to biological analog, which predetermines application, specificity, and so much
Interaction of Radiation with Matter
Interactions of rad. with matter: How it fits in

• Why is understanding interaction of radiation with matter important for imaging in nuclear medicine?
• Emissions from radioactive nuclei are too high in energy & too small to be seen with the naked eye
• We observe their existence only through the effects they produce in matter
• Effects caused by various forces and interactions the nuclear emissions experience as they traverse a material

Example: Scintillation Detector
Range of $^{18}\text{F}$ positrons in water

- FWHM $\sim 0.1$ mm
- FWTM $\sim 1$ mm, average $\sim 0.6$ mm
- Average range $^{82}\text{Rb}$ $\sim 4.3$ mm
Interactions of rad. with matter: How it fits in

- The forces and interactions that nuclear emissions experience can also alter the state of the emissions.
- This can directly impact imaging, ex. Compton scatter in PET:
Interactions of rad. with matter: How it fits in

- The forces and interactions that nuclear emissions experience can also alter the state of the emissions

(a) Scatter Correction  (b) No Scatter Correction  Difference (b)-(a)/(b)
Intro: interaction of radiation with matter

• Examples of highly penetrating radiation?

**Rank in order of penetrating power:**

1. Neutrino
2. Neutron
3. Photon
4. Electron
5. Alpha

any pattern?
Intro: interaction of radiation with matter

• Incoming radiation interacts with the *electrons* or the *nucleus* of the material it encounters

Tissue penetration dependent on:
1. Type of Radiation
2. Interaction Material (and thickness)
Intro: interaction of radiation with matter

- Important for detection of radiation, assessing radiation damage, analyzing radiation therapy
- density $\rho$ and atomic number $Z$ of the interacting matter is important
- Interactions are statistical in nature:

$$P_{\text{int}} = 1 - e^{-\mu x}$$

- $\mu$ = attenuation coefficient (1/cm)
- $x$ = distance travelled
- $1/\mu = \text{mean free path}$
- Many particles per unit length so low variations in average numbers
Interaction of radiation with matter

Distinction between three types:

1. **Heavy charged particles:**
   - Short, well defined range
   - Collisional losses (at Nuc Med energies)

2. **Light charged particles:**
   - Longer, largely varying paths
   - Collisional and some radiative losses

3. **Photons**
   - Rayleigh Scatter (non-ionizing)
   - Photo-electric Effect
   - Compton Scatter
   - Pair Production

**Interaction of ionizing radiations will ultimately result in a cascade of lower energy electrons**
Intro: interaction of radiation with matter

- Charged particles undergo two primary energy transfer mechanisms:
  - Collisional Energy Transfers
  - Radiative Energy Transfers
I: Collisional losses

Collisional losses

(ionization)

• When incoming radiation has a lot of kinetic energy, it may ionize the material; i.e. we have ionizing radiation

• Alternative: excitation of the atom (elastic)
II: Radiative losses

Competing process: Radiative loss

Charged particle interacts with the electric field of the nucleus, loses energy, emits a *Bremsstrahlung* photon.
II: Bremsstrahlung

Results in a continuum of energies produced:

![Graph showing the distribution of photon energies produced by Bremsstrahlung](image)

- **K-shell Emissions**
II: Bremsstrahlung

X-ray CT Imaging exploits bremsstrahlung to visualize anatomy
I: Heavy Charged Particles

- Interact mainly through Coulomb interaction with atomic electrons
- Range is short: 10 MeV proton loses all its energy in only 0.25 mm copper
- *Inelastic* scattering: # particles in ≠ # particles out:
  \[ \alpha + Z \rightarrow \alpha + Z^+ + e^- \]
- Energy transferred to the atom
- Ionizing radiation: target becomes ionized, may yield biological damage
- Other interaction may be elastic scattering from nucleus, or nuclear reactions
II: Light Charged Particles: Electrons/Positrons

• Electrons behave similarly as heavy charged particles
• Lose energy through interactions with atomic electrons, however:
  • More energy is transferred in a collision
  • Secondary electrons may become ionizing: \textit{delta-rays}
  • Path subject to large variations
• Q: What about positrons?
  A: exactly the same, except for \textit{annihilation} after thermalization
Bremsstrahlung vs Collisional Losses

• Okay – so there are two competing processes: Collisional and radiative energy transfers
• Which is dominant?
• Relatively more Bremsstrahlung at higher or lower energies?
• Relatively more Bremsstrahlung at high Z or low Z?
II: Radiative vs. collisional losses

\[
\frac{\text{Loss}_{\text{Bremsstrahlung}}}{\text{Loss}_{\text{collision}}} \approx \frac{ZE_{\beta}^{\text{max}}}{3000}
\]

- Radiative losses more prominent for increasing particle energy and increasing absorber \( Z \)
- Radiative losses more prominent for increasing particle energy
Are radiative (bremsstrahlung) or collisional losses more dominant for charged particles at energies relevant to nuclear medicine imaging studies?

\[
\frac{\text{Loss}_{\text{Bremsstrahlung}}}{\text{Loss}_{\text{collision}}} \approx \frac{ZE_{\beta}^{\text{max}}}{3000}
\]
Are radiative (bremsstrahlung) or collisional losses more dominant for charged particles at energies relevant to nuclear medicine imaging studies?

\[
\frac{\text{Loss}_{\text{Bremsstrahlung}}}{\text{Loss}_{\text{collision}}} \approx \frac{ZE_{\beta}^{\text{max}}}{3000}
\]

- Z for tissue is low H20 ~7.4
- Energy range for nuclear medicine studies ~0.1-0.5 MeV

Very small fraction of energy transferred from interaction of charge particles in tissue result in radiative yields, and dose is predominantly locally deposited.
II: Compare particle tracks

- Heavy charged particles travel in “straight lines, energy deposited locally
- Electrons undergo large angle deflections

1. e- mass much lower
2. e- charge lower
3. e- experience large angle deflections (bremsstrahlung)
Specific ionization

- Specific ionization: number of ion pairs per distance
- The value is energy dependent

![Graph showing ion pairs per mm against energy (keV)]

- Electrons
  - More ion/pairs for lower energy, so larger ionization density towards the end of a particle track
Specific ionization

- More energy deposited towards the end of track
- **Bragg Peak**, in particular for alpha particles
Proton Therapy
Particle Range

- Range of heavy particles (ex. Alpha particles & protons)
Particle Range

- Range of electrons/positrons
- More spread than heavy particles

![Graph illustrating the range of particles detected vs. absorber thickness, showing a steep decrease at lower absorber thickness indicating the extrapolated range and background.](image)
Particle Range

- Range of electrons/positrons
- Strongly energy dependent

Electrons in water
## Stopping power and Range

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Stopping Power</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(MeV cm/g)</td>
<td>(MeV/cm)</td>
<td>(g/cm²) (cm) (um)</td>
</tr>
<tr>
<td>1 MeV proton</td>
<td>Air 0.00120</td>
<td>222 0.266</td>
<td>0.00287 2.39 23900</td>
</tr>
<tr>
<td>1 MeV electron</td>
<td></td>
<td>1.66 0.00199</td>
<td>0.0490 408 408x10⁶</td>
</tr>
<tr>
<td>1 MeV proton</td>
<td>Water 1.00</td>
<td>260 260</td>
<td>0.00246 0.00246 24.6</td>
</tr>
<tr>
<td>1 MeV electron</td>
<td></td>
<td>1.85 1.85</td>
<td>0.437 0.437 4370</td>
</tr>
<tr>
<td>1 MeV proton</td>
<td>Tungsten 19.3</td>
<td>63.5 1220</td>
<td>0.0122 0.00063 6.34</td>
</tr>
<tr>
<td>1 MeV electron</td>
<td></td>
<td>1.02 19.6</td>
<td>0.768 0.0399 399</td>
</tr>
</tbody>
</table>

- Density is crucial
- Stopping power decreases as Z/A
- Electrons about 2 orders of magnitude **larger range**
- Source NIST pstar andestar: 
  http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
Heavy and Light Charged Particles: Takeaways

• Interaction of Radiation in Matter in two categories:
  • Charged Particles
    • Heavy Charged Particles
    • Electrons/Positions
  
• Also two primary energy transfer mechanisms for charged particles:
  • Collisional Energy Transfers
    • Inelastic Coulomb scattering
    • Elastic nuclear interactions
  • Radiative Energy Transfers
    • Bremsstrahlung
Photon Interactions

Photons are highly penetrating electromagnetic radiation
Interaction of radiation with matter

Distinction between three types:
1. Heavy charged particles:
   • Short, well defined range
   • Collisional losses (at Nuc Med energies)
2. Light, charged particles:
   • Longer, largely varying paths
   • Collisional and some radiative losses
3. Photons
   • Rayleigh Scatter (non-ionizing)
   • Photo-electric Effect
   • Compton Scatter
   • Pair Production
Photon Interactions

• For a photon to deposit energy, energy needs to be transferred to an electron first

Two processes most relevant at Nuclear Medicine Energies:
1. Photoelectric absorption
2. Compton Scatter

Important: the electron that receives energy from the photon will deposit energy in the material (i.e. ionize the material)
Photons: Photo-Electric Absorption

1. **Photon absorbed by atom**
2. Atom emits *photoelectron*, with energy:
   \[ E_{pe} = E_y - BE \text{ (BindingEnergy)} \]
3. Photo-Electron now is ionizing
4. An higher shell electron fills the vacancy and emits an X-Ray photon
III: Photons: Compton Scatter

1. **Photon scattered by electron**
2. Electron overcomes the binding energy and gets ejected:
   \[ E_e = E_\gamma - E'_\gamma - E_{\text{binding}} \]
3. Scattered -*unbound*- electron deposits energy
III: Photons: Compton Scatter

1. Photon scattered by electron

\[ E_{sc} = E_0 / \left[ 1 + \left( E_0 / 0.511 \right) \left( 1 - \cos \theta \right) \right] \]

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Photon Energy (keV)</th>
<th>( E_{sc}^{min} ) (keV)</th>
<th>( E_{re}^{max} ) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{125}\text{I})</td>
<td>27.5</td>
<td>24.8</td>
<td>2.7</td>
</tr>
<tr>
<td>(^{133}\text{Xe})</td>
<td>81</td>
<td>62</td>
<td>19</td>
</tr>
<tr>
<td>(^{99m}\text{Tc})</td>
<td>140</td>
<td>91</td>
<td>49</td>
</tr>
<tr>
<td>(^{131}\text{I})</td>
<td>364</td>
<td>150</td>
<td>214</td>
</tr>
<tr>
<td>(\beta^+) (annihilation)</td>
<td>511</td>
<td>170</td>
<td>341</td>
</tr>
<tr>
<td>(^{60}\text{Co})</td>
<td>1330</td>
<td>214</td>
<td>1116</td>
</tr>
<tr>
<td>—</td>
<td>(\infty)</td>
<td>255.5</td>
<td>—</td>
</tr>
</tbody>
</table>
III: Photons: Compton Scatter

![Graph showing Compton scatter probability for different photon energies (10 keV, 100 keV, 500 keV, 1 MeV, 5 MeV) as a function of scattering angle (θ) in degrees. The probability decreases with increasing angle and energy.](image)
III: Photons: Compton Scatter

- Scatter more forward for higher energies
- Electron obtains most energy when photon backscatters (most energy transfer)
How Angular Dependency Matters in PET

(One Example)
Photons: Rayleigh Scatter

1. Elastic scatter of a photon off the entire atom

- 10% of interactions at 30 keV (in soft tissue) - mammography
- 5% of interactions at 70 keV (in soft tissue) - X-ray imaging
- Interaction probability goes up with $\sim Z^3$
- **Non-ionizing!**
III: Photons: Other processes

- **Pair production**: higher energy photons are able to create electron-positron pairs ($E > 1.022$ MeV), this process quickly becomes dominant ($\sim Z \log(E)$).
Photon interactions

- Interactions alter emissions from the radionuclide carefully selected for a molecular probe for imaging
- It is important to know how likely these interactions will affect emissions

Simple Experiment to Extract this Parameter

\[
\frac{I}{I_0} = \exp(-\mu x)
\]

\( \mu \) is the probability of interaction per unit path length (1/cm)
Photon Probability of Interaction

\( \tau = \text{photoelectric absorption} \)
\( \sigma = \text{Compton Scatter} \)
\( K = \text{Pair production} \)
Dominant Photon Interactions Z vs. E

Different processes dominant at different energies

- Photoelectric absorption
- Compton scattering
- Pair production
Photon interactions

- **Rayleigh Scatter**: coherent scatter whereby the photon changes direction, can be significant at low energies
- **Photoelectric**: $\gamma \rightarrow$ photoelectron (-BE). Probability $\sim Z^4/E^3$
- **Compton Scatter**: $\gamma \rightarrow \gamma' + e'$. Probability $\sim Z/E$
- **Pair production**: higher energy photons are able to create electron-positron pairs (E>1.022 MeV), this process quickly becomes dominant ($\sim Z \log(E)$)
How Photons Deposit Energy in Matter

- Interactions of photons and charged particles with matter are coupled
- Secondary electrons ionize and deposit dose
A look forward: The Scintillation process

1. **Gamma** interaction
   - Photoelectric Absorption
   - Compton Scattering

2. Photo- or Compton **electron** deposits energy in scintillator
   - Ionization
   - Excitation of Medium

3. Scintillator atoms get excited
   - Thermalization of charge carriers

4. Scintillator atoms de-excite by emitting optical photons

**one** gamma photon yields **one** electron, but **many** optical photons
### Photon interactions

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Air ($\rho = 1.2 \times 10^{-3}$ g/cm$^3$)</th>
<th>$\text{H}_2\text{O}$ ($\rho = 1$ g/cm$^3$)</th>
<th>Tungsten ($\rho = 19$ g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Attenuation (10$^{-3}$ cm$^2$/g)</td>
<td>Mean free path (10$^6$ cm)</td>
<td>Total mean free path (cm)</td>
</tr>
<tr>
<td>140</td>
<td>2.57</td>
<td>0.324</td>
<td>6030</td>
</tr>
<tr>
<td>C</td>
<td>135</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>PE</td>
<td>0.67</td>
<td>1.24</td>
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<tr>
<td>511</td>
<td>0.20</td>
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<td>86.2</td>
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<tr>
<td>PE</td>
<td>0.01</td>
<td>64.4</td>
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<td>1000</td>
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<td>13100</td>
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<tr>
<td>C</td>
<td>63.6</td>
<td>0.013</td>
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</tr>
<tr>
<td>PE</td>
<td>0.003</td>
<td>311</td>
<td></td>
</tr>
</tbody>
</table>

- Higher energy results in higher mean free path
- Mean free path = average distance between interactions
- Air almost no attenuation
- In water Compton dominant at $E > 140$ keV
- In tungsten Compton dominant at $E > 500$ keV
- $Z_{\text{eff}}$ air = 7.6; $Z_{\text{eff}}$ H$_2$O = 7.4