INTRODUCTION TO IONIZING RADIATION (Attix Chapter 1 p. 1-5)

- Ionizing radiation: Particle or electromagnetic radiation that is capable of ionizing matter. IR interacts through different types of “collision events”: ionizations, excitations and dissociations.

- The energy transferred to an atom to cause ionization is on the order of 10 to 15 electron volts (eV), for water 13 eV.

- What is the energy of a photon to be able to transfer 10 eV of energy? Answer:
  \[ E_\gamma = \hbar \nu = \frac{hc}{\lambda} \]
  Photon Energy
  \[ \lambda = \frac{(1.24 \text{ keV} \cdot \text{nm})}{E_\gamma} \]
  Photon Wavelength

  \( \nu \) is the frequency, \( \hbar \) is Planck’s constant. For example: for 10 eV transferred the photon must have had a wavelength of:
  \[ \lambda = \frac{1.24 \text{ keV} \cdot \text{nm}}{10 \text{ eV}} = 124 \text{ nm} \]

  Therefore, UV radiation can also cause ionization.

- Photons of this low energy (or long wavelength) are not normally dealt with in the study of radiological physics because they are so readily absorbed in tissue. However, this energy range is important in causing damage to the skin (skin cancer and tanning).

- An atom doesn’t have to be ionized to result in biological damage to biologically important molecules (water or DNA for example). Enough energy transferred to cause excitation can be sufficient (eg. radiolysis of water). Actually, excitation may result in about the same amount of biological damage as does ionization itself.

Indirectly and directly ionizing radiation

- There are two general classes of ionizing radiation: neutral (uncharged) particles (photons and neutrons) and charged particles.

- Neutral particles don’t directly ionize matter but rather they set in motion fast charge particles which deliver their energy to matter while slowing down. Neutral particles are termed indirectly ionizing radiation. Charged particles are termed directly ionizing radiation.
Indirectly ionizing radiation

- the deposition of energy in matter by indirectly ionizing radiation is a two-step process:
  1. an uncharged particle interacts and sets in motion a charged particle.
  2. the charged particle deposits its energy to matter.

- the interaction of the neutral particle is indeterminate or stochastic. It is as if the particle were traveling through empty space and then suddenly collides at random with an atom (or nucleus or electron - depending on the interaction process).

- Examples of indirectly ionizing radiation are X-rays and gamma rays (photons) and neutrons. X-rays and gamma rays have energies from approximately 100 eV upward (see classifications on page 3 of Attix).
There is many different interactions possible. The following is a bubble chamber photograph of a photon interaction at point A, a so-called “triplet production” whereby a photon interacts and produces two electrons and a positron (positive electron). The charged particles interact almost continuously. As energy is lost the radius of curvature decreases ($r = \frac{mv}{qB}$). The direction of the magnetic field is into the plane.
Directly ionizing radiation

- Charged particles interact almost continuously with the Coulomb field around nuclei and electrons.

- The typical distance between charged particle ionization events is very small. Electrons have a rate of energy loss per unit distance (or stopping power) in unit-density material (1 g/cm$^3$) of ~ 2 MeV/cm at a kinetic energy of a few MeV. Suppose the average energy transferred to the atoms in the material the electrons are traveling through is 20 eV/event. We calculate the number of collision events per cm as follows:

$$\frac{\text{Number of Events}}{\text{cm}} = \frac{2 \times 10^6 \text{ eV/cm}}{20 \text{ eV/event}} = 10^5 \text{ events/cm}$$

Examples of charged particles of interest

<table>
<thead>
<tr>
<th>Particle</th>
<th>Rest Energy (MeV)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron (positron)</td>
<td>0.511</td>
<td>-1 (+1)</td>
</tr>
<tr>
<td>Muon</td>
<td>105.7</td>
<td>±1</td>
</tr>
<tr>
<td>Pion</td>
<td>139.6</td>
<td>±1</td>
</tr>
<tr>
<td>Proton (1(^1)H nucleus)</td>
<td>938.3</td>
<td>+1</td>
</tr>
<tr>
<td>Deuteron (2(^2)H)</td>
<td>1875.6</td>
<td>+1</td>
</tr>
<tr>
<td>((^3)H) Triton</td>
<td>2809.0</td>
<td>+1</td>
</tr>
<tr>
<td>Alpha-Particle (4(^4)He)</td>
<td>3727.4</td>
<td>+2*</td>
</tr>
<tr>
<td>Heavy Ions</td>
<td>Nuclear Mass</td>
<td>+Z*</td>
</tr>
</tbody>
</table>

*) these ions may not be completely ionized (i.e. they still have orbital electrons).

Electrons and Positrons

- positive electrons, called positrons, are the antiparticles of electrons.
- electrons are called beta-particles when emitted from a nucleus.
- they are called knock-on electrons or delta-rays when they are knocked out of an atom by another charged particle.
- an electron kicked out of an atom by an electronic transition in the atom is called an Auger electron.
- electrons may be accelerated by Van de Graff generators, linear accelerators, betatrons, microtrons and TV picture tubes.
Negative Pions
- produced by charged particle collisions with a nucleus.
- negative pions have been used experimentally in radiotherapy.

Protons
- $^1$H nucleus accelerated by a Van de Graff generator or cyclotron.
- Neutron collision with a hydrogen nucleus often results in protons receiving much of the neutron’s kinetic energy.
- proton beams are already used clinically in radiotherapy: prostate cancer and pediatric cancers.
- cyclotron accelerated protons are used to produce exotic radionuclides for nuclear medicine and PET imaging.

Alpha-particles
- $^4$He nucleus.
- emitted from many heavy radionuclides in alpha decay.

Heavy/Light Ions
- have a maximum charge equal to its atomic number, Z.
- It is often agreed today to name ions with $Z > 10$ as heavy ions, and $Z < 10$ as light ions.
- in development for radiotherapy and radiology, in particular in Europe and Japan.
Physical → Chemical → Biological Effects

- the absorption of radiation energy causing excitation and ionization of biologically important matter leads to important changes in cellular biochemistry.

- There are two general physical/chemical actions of ionizing radiations: **indirect action** and **direct action** (not to be confused with directly and indirectly ionizing radiation). See the Figure on page 7.
  - **In direct action** a fast charged particle breaks the bond of a biologically important molecule.
  - **Indirect action** is the production of free radicals in the cell which are highly reactive and cause bonds to be broken.

The free radicals are usually produced by the radiolysis of water. Radiolysis occurs due to excitation and ionization:

\[
\text{fast } e^- \rightarrow H_2O \rightarrow H_2O^+ \rightarrow \dot{H} + \dot{O}H
\]

* denotes a molecule of water in an excited state. \( \dot{H} \) and \( \dot{O}H \) are free radicals. The dot denotes an unpaired electron.

\[
\text{fast } e^- \rightarrow H_2O \rightarrow H_2O^+ + e^-
\]

- The hydroxyl radical \( \dot{O}H \) is responsible for most of the damage to biological molecules.
- The amount of damage from indirect action may be large, however, the amount of unrepairable damage seems to be small.
- The biological effect (chromosomal mutation or cancer for example) may take years to express itself

In summary, biological effects of ionizing radiation occur at all time scales:

<table>
<thead>
<tr>
<th>Process</th>
<th>Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon Interaction</td>
<td>( 10^{-20} - 10^{-18} ) sec (photon passing through atom)</td>
</tr>
<tr>
<td>Fast Electron</td>
<td>( 10^{16} - 10^{18} ) sec (electron passing through cell)</td>
</tr>
<tr>
<td>Ion Radical</td>
<td>( 10^{10} - 10^{11} ) sec (ion radical lifetime)</td>
</tr>
<tr>
<td>Free Radical</td>
<td>( 10^{6} - 10^{8} ) sec (free radical lifetime)</td>
</tr>
<tr>
<td>Chemical Changes due to breaking of bonds</td>
<td>( 10^{4} - 10^{2} ) sec (reaction rate dependent)</td>
</tr>
<tr>
<td>Biological Effects</td>
<td>( 10^{4} - 10^{7} ) sec (depends on effect)</td>
</tr>
</tbody>
</table>
Direct and Indirect Action

- Direct action is the direct damage of biologically important molecules, most usually DNA as shown below.
- Indirect action is the production of free radicals which can diffuse some distance away (about 20 angstroms) from its production site to cause damage.
- For electrons, > 75% of the effects are indirect actions.

Figure from [Hall: Radiobiology for the Radiologist]
Dose, D, and Dose Equivalent H (Chapter 3 III and VI)

- The goal of this course is to lay the foundation for dosimetry which is the determination of dose.

- The absorbed dose, $D$, is a physical quantity relating the amount of energy absorbed by matter $\Delta \varepsilon$ per unit mass, $\Delta m$:

$$D = \frac{\Delta \varepsilon}{\Delta m}$$

- If the mass is too small there will be considerable statistical uncertainty and if it is very large there will be self-absorption.

- The SI unit of dose is the Gray = 1 J/kg and the rad is a historical unit: 1 rad $= 10^{-2}$ Gray (Gy).
• The *dose equivalent*, \( H \), is a measure of the human hazard of long-term exposure to ionizing radiation. It is an operational quantity that can be directly measured in radiation monitoring.

• \( H = DQN \)
  where \( Q \) is a quality factor. The quality factor characterizes the biological effectiveness of the radiation based on the ionization density along the tracks of charged particles in tissue (see later). \( Q \) depends on the type of radiation and its energy. \( Q=1 \) for photons and electrons. \( Q >1 \) for radiation that causes more biological damage.

• \( N \) (currently assigned a value of 1) is the product of all other weighting factors. \( N \) could be used to describe biologically relevant parameters such as age, health status, genetic predisposition, etc.

• *Equivalent dose* and *effective dose* are body related protection quantities that can not be measured directly.

• The equivalent dose \( H_T \) in a tissue or organ \( T \) is given by \( H_T = \sum w_R D_{T,R} \), where \( D_{T,R} \) is the mean absorbed dose from radiation \( R \) in a tissue or organ \( T \), and \( w_R \) is the radiation weighting factor.

• The effective dose \( E \) is the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body, given by \( E = \sum w_T H_T \) where \( w_T \) is the tissue-weighting factor.

• The SI unit of dose equivalent, equivalent dose and effective dose is the Sievert (Sv) and it has the same physical units as dose: 1 Sv = 1 J/kg (hence the name dose equivalent). The historical unit is the rem: 1 rem = 10^{-2} \text{ Sv}.