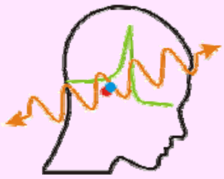
Radiation Physics



RADIATION PHYSICS

Lecture (13)

Interaction of Radiation with Matter

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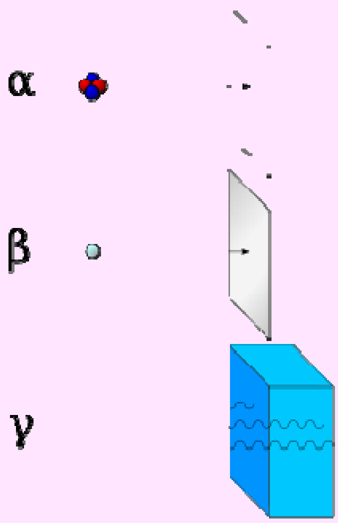
INTERACTION OF RADIATION WITH MATTER

- What happens when this radiation interacts with matter?
- Our main reason for doing this is to find out what happens to the radiation as it passes through matter and also to set ourselves up for considering how it interacts with living tissue and how to detect radiation. Since all radiation detectors are made from some form of matter it is useful to first of all know how radiation interacts so that we can exploit the effects in the design of such detectors.



PHYSICAL CHARACTERISTICS OF THE MAJOR TYPES OF RADIATION

Radiation	Mass	Electric Charge	Velocity
Alpha Particles	relatively heavy	double positive	relatively slow
Beta Particles	about 8,000 times lighter	negative	less than the velocity of light
Gamma Rays	None	None	3×10^8 m/s in free space

We will consider the passage of each type of radiation through matter with most attention given to gamma-rays because they are the most common type used in nuclear medicine.

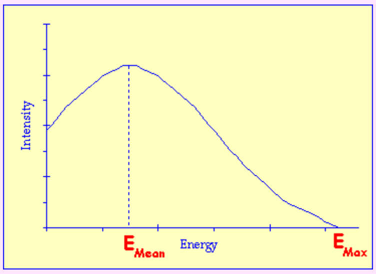
One of the main effects that you will notice irrespective of the type of radiation is that ions are produced when radiation interacts with matter. It is for this reason that it is called ionizing radiation.

ALPHA PARTICLES

- Alpha-particles have a double positive charge and we can therefore will exert considerable electrostatic attraction on the outer orbital electrons of atoms near which they pass. The result is that some electrons will be attracted away from their parent atoms and that ions will be produced. In other words ionizations occur.
- Alpha-particles are quite massive relative to the other types of radiation As a result they travel in **straight lines** through matter.
- **The energy with which they are emitted** is always distinct. For example ^{221}Ra emits an alpha-particle with an energy of 6.71 MeV. Every alpha-particle emitted from this radionuclide has this energy. Another example is ^{230}U which emits three alpha-particles with energies of 5.66, 5.82, 5.89 MeV.
- Finally it is useful to note that alpha-particles are very damaging biologically and this is one reason why they are not used for *in-vivo* diagnostic studies.

BETA PARTICLES

- **Beta-particles** have a negative electric charge. Notice that positrons are not considered here since these particles do not last for very long in matter before they are annihilated.
- Because of their negative charge they are attracted by nuclei and repelled by electron clouds as they pass through matter. The result is ionization.
- The path of beta-particles in matter is often described as being (متعرج) tortuous, since they tend to recoil from atom to atom.
- The energy of beta-particles is never found to be distinct in contrast to the alpha-particles above. The energies of the beta-particles from a radioactive source forms a spectrum up to a maximum energy.

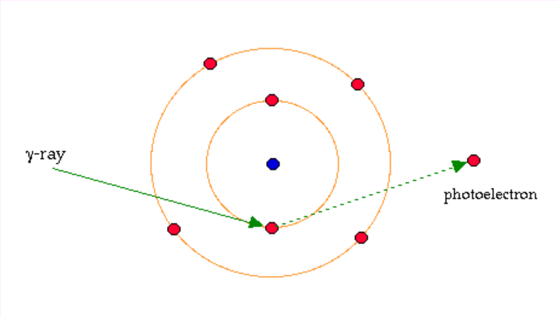


GAMMA RAYS

- **The energies of gamma-rays** emitted from a radioactive source are always distinct. For example ^{99m}Tc emits gamma-rays which all have an energy of 140 keV and ^{51}Cr emits gamma-rays which have an energy of 320 keV.
- **Gamma-rays** have many modes of interaction with matter. Those which have little or no relevance to nuclear medicine imaging are:
  - Mössbauer Effect
  - Coherent Scattering
  - Pair Production
  - Those which are very important to nuclear medicine imaging, are the **Photoelectric Effect** and the **Compton Effect**.
- Note that the effects described here are also of relevance to the interaction of X-rays with matter since X-rays and gamma-rays are essentially the same entities. So the treatment below is also of relevance to radiography.

PHOTOELECTRIC EFFECT

- When a gamma-ray collides with an orbital electron of an atom of the material through which it is passing it can transfer all its energy to the electron and cease to exist.
- On the basis of the Principle of Conservation of Energy we can deduce that the electron will leave the atom with a kinetic energy equal to the energy of the gamma-ray less that of the orbital binding energy. This electron is called a **photoelectron.**



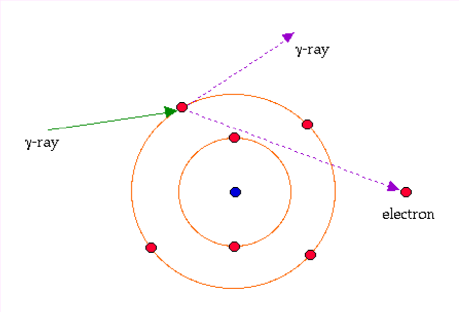
- Note that an ion results when the photoelectron leaves the atom. Also note that the gamma-ray energy is totally absorbed in the process.

- Two subsequent points.
  - Firstly the photoelectron can cause ionizations along its track in a similar manner to a beta-particle.
  - Secondly X-ray emission can occur when the vacancy left by the photoelectron is filled by an electron from an outer shell of the atom.

COMPTON EFFECT

- Gamma-ray transfers **only part** of its energy to a valance electron which is essentially free.
- Notice that the electron leaves the atom and may act like a beta-particle and that the gamma-ray deflects off in a different direction to that with which it approached the atom.
- This deflected or scattered gamma-ray can undergo further Compton Effects within the material.

- Note that this effect is sometimes called **Compton Scattering**.



RADIATION BIOLOGY

- It is well known that exposure to ionizing radiation can result in damage to living tissue.
- What's important in radiation biology is that these interactions may trigger complex chains of biomolecular events and consequent biological damage.
- **Ionizing radiations** lose their energy in matter is by ejection of orbital electrons. The loss of orbital electrons from the atom leaves it positively charged.
- Other interaction processes lead to **excitation** of the atom rather than ionization. Here, an outer valence electron receives sufficient energy to overcome the binding energy of its shell and moves further away from the nucleus to an orbit that is not normally occupied. This type of effect alters the chemical force that binds atoms into molecules and a regrouping of the affected atoms into different molecular structures can result.
- That is, excitation is an indirect method of inducing chemical change through the modification of individual atomic bonds.

Ionizations and excitations can give rise to unstable chemical species called **free radicals**. These are atoms and molecules in which there are unpaired electrons. They are chemically very reactive and seek stability by bonding with other atoms and molecules. Changes to nearby molecules can arise because of their production.

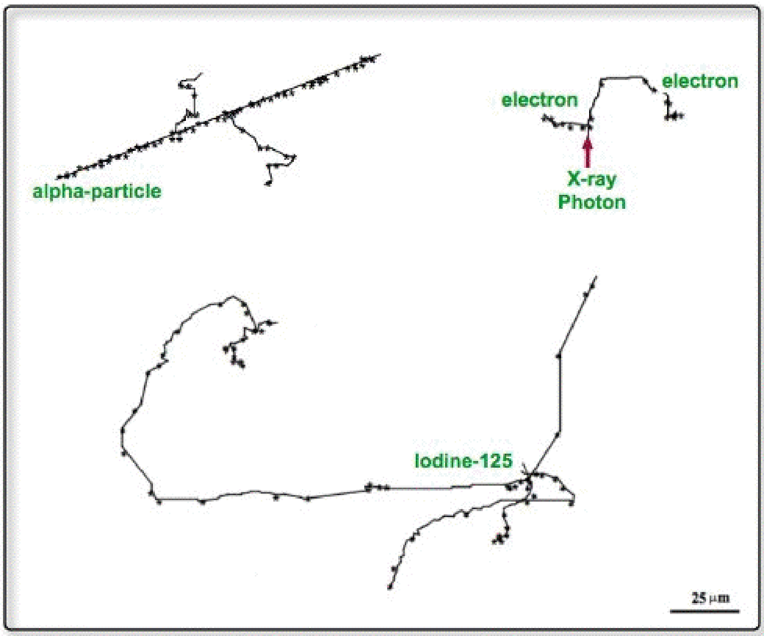
In the case of X- and gamma-ray interactions, the energy of the photons is usually transferred by **collisions** with orbital electrons, e.g. via photoelectric and Compton effects. These radiations are capable of penetrating deeply into tissue since their interactions depend on chance collisions with electrons.

Nuclear medicine imaging is only possible when the energy of the gamma-rays is sufficient for complete emission from the body, but low enough to be detected.

The interaction of **charged particles** (e.g. alpha and beta particles), can be by **collisions** with atomic electrons and also via attractive and repulsive electrostatic forces.

The rate at which energy is lost along the track of a charged particle depends therefore on the **square** of the charge on that particle. That is, **the greater the particle charge, the greater the probability of it generating ion pairs along its track.** In addition, **a longer period of time is available for electrostatic forces to act when a charged particle is moving slowly and the ionization probability is therefore increased as a result.**

The situation is illustrated in the following figure where tracks of charged particles in **water** are depicted. Notice that the track of the relatively massive **α-particle is a straight line**, with a large number of interactions (indicated by the asterisks) per unit length. Notice also that the tracks for electrons are tortuous, and that the number of interactions per unit length is considerably less.



The **Linear Energy Transfer** (**LET**) is defined as the energy released per unit length of the track of an ionizing particle. A slowly moving, highly charged particle, has a substantially higher LET than a fast, singly charged particle.

An alpha particle of 5 MeV energy and an electron of 1 MeV energy have LETs, for instance, of 95 and 0.25 keV/µm, respectively. The ionization density and hence the energy deposition pattern associated with the heavier charged particle is very much greater than that arising from electrons, as illustrated in the figure above.

The energy transferred along the track of a charged particle will vary because the velocity of the particle is likely to be continuously decreasing. Each interaction removes a small amount of energy from the particle so that the LET **gradually increases along a particle track** with a dramatic increase (called the Bragg Peak) occurring just before the particle comes to rest.

The International Commission on Radiation Units and Measurements (**ICRU**) suggest that **lineal energy** is a better indicator of **relative biological effectiveness** (RBE). Although **linear energy** has the same units as LET (e.g. keV/µm), it is defined as the: **ratio of the energy deposited in a volume of tissue to the average diameter of that volume.**

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Source	Effective Dose (mSv/year)	Comment
Cosmic radiation	~0.4	About 100,000 cosmic ray neutrons and 400,000 secondary cosmic rays penetrate our bodies every hour - and it increases with altitude!
Terrestrial radiation	~0.5	Over 200 million gamma-rays pass through our body every hour from sources such as soil and building materials
Internal radiation	~0.3	About 15 million ^{40}K atoms and about 7,000 natural uranium atoms disintegrate inside our bodies every hour, primarily from our diet
Radon and other gases	~1.3	About 30,000 atoms disintegrate inside our lungs every hour as a result of breathing

- The sum total of this *Natural* Background Radiation is about 2.5 mSv per year, with large variations depending on altitude and dietary intake as well as geological and geographical location.

- Its generally considered that repair mechanisms exist in living matter and that these can be invoked following radiation damage at the biomolecular level. These mechanisms are likely to have an evolutionary basis arising as a response to radiation fluxes generated by natural background sources over the aeons. Its also known that quite considerable damage to tissues can arise at quite higher radiation fluxes, even at medical exposures. Cell death and transformations to malignant states can result leading to latent periods of many years before clinical signs of cancer or leukemia, for instance, become manifest.