RADIOACTIVITY - SPONTANEOUS NUCLEAR PROCESSES

OBJECTIVES

At the conclusion of this lesson the trainee will be able to:

1. For α, β and γ decays
   a) Write a typical equation for the production of each type of radiation.
   b) List the physical properties of each type of radiation.
   c) Discuss how each type of radiation interacts with matter.
2. State how to shield against alphas and betas.
3. State how to shield against γ rays and calculate γ ray shielding in terms of ½ value layers.

RADIOACTIVITY - SPONTANEOUS NUCLEAR PROCESSES

The property we know as radioactivity was first observed in 1896 by Becquerel. He was carrying out experiments with fluorescent salts (which contained uranium) and found that some photographic plates had been exposed despite being well wrapped against light.

Later research showed that the "rays" that he had observed were of three distinct types. We now call these alpha particles (α), beta particles (β) and gamma rays (γ). We also know of several other types of rays or emissions but these three are the commonest.

TYPES OF EMISSIONS

All natural nuclides of atomic number greater than 82 are unstable (i.e., radioactive) and eventually decay (or disintegrate) by emitting an alpha particle or a beta particle. The new nuclides formed (daughter nuclides) also decay until a stable nuclide of atomic number 82 or less is formed. Several naturally occurring radioactive nuclides with lower mass number are also known and many other manmade radioactive nuclides have been found.

Alpha Emissions

The alpha particle is emitted, typically, from a heavy nuclide such as U238. This is expressed as:

$$^{238}_{92}U \longrightarrow \alpha + ^{234}_{90}Th$$

Examination of the alpha particle shows it is a helium-4 nucleus so you can write:

$$^{238}_{92}U \longrightarrow ^{4}_{2}He + ^{234}_{90}Th$$

(parent) (α) (daughter)

OR

$$^{A}_{Z}X \longrightarrow \alpha + ^{A-4}_{Z-2}X$$

These equations represent a parent nucleus emitting a fast moving helium-4 nucleus (α particle) and resulting in a new daughter nucleus.

The alpha particle does not have any electrons (remember it is a helium nucleus) and therefore will have a charge of +2e, (usually given simply as +2). The mass of the alpha is 4.0015u and its speed when first emitted is typically a few percent of the speed of light.

Beta Emissions

Beta particles are emitted by neutron-rich nuclides, i.e. a nuclide with too many neutrons. This is a typical example:

$$^{90}_{38}Sr \longrightarrow \beta + ^{90}_{39}Y$$

You may put the mass number and charge number onto the β symbol if desired, giving:

$$^{90}_{38}Sr \longrightarrow ^{0}_{-1}\beta + ^{90}_{39}Y$$

OR $$^{A}_{Z}X \longrightarrow \beta + {}_{Z+1}^{A}X$$

As noted from the above expressions the daughter nuclide from beta decay appears one position higher in the table of the elements. A neutron in the nucleus has changed into a proton so the atomic number goes up one.

The beta particle is a fast moving electron. It has the same mass as any other electron, 0.00054u, and it has the same charge, -1. The speeds of beta particles range from about 90 to 99% of the speed of light. They are very fast!

Gamma Emissions

After an alpha or beta emission the residual nucleus will usually be in an excited state. Excited states must not be confused with the concept of unstable nuclides. Both stable and unstable nuclides can be in an excited state. The mode of de-excitation could be by emission of a suitable particle (α, β, neutron, proton) but in most cases the de-excitation takes place by the emission of one or more gamma photons. The name photon is used to emphasize that gamma radiation has particle-like properties. A typical example is written:

$$^{60}_{27}Co \longrightarrow \beta + ^{60}_{28}Ni^* \text{ (}\beta\text{ emission)}$$

Then $$^{60}_{28}Ni^* \longrightarrow \gamma + ^{60}_{28}Ni \text{ (}\gamma\text{ emission)}$$

The cobalt-60 emits a beta leaving the daughter nickel-60 nucleus in an excited state (indicated by the asterisk). Almost immediately the excited nickel-60 emits γ-rays until it is de-excited. The duration of the excited state is very short, usually less than 10^{-9}s so we usually write the beta and gamma decays as though they are a single event.

$$^{60}_{27}Co \longrightarrow \beta + \gamma + ^{60}_{28}Ni$$

The generalized gamma decay can be written:

$$^{A}_{Z}X^{*} \longrightarrow \gamma + ^{A}_{Z}X$$

As you can see there is no change in Z or A because the gamma ray has no charge and no mass so it cannot affect the charge and mass of the nuclide.

Gamma rays are electro-magnetic radiations like light rays, radio waves and x-rays. A gamma photon has more energy than most x-ray photons which in turn have more energy than ultra violet photons and so on, down to the longest wave length radio waves. Figure 2.1 shows the electromagnetic spectrum. Note that long waves imply low frequencies, low photon energies, and wave like properties. High energy γ-rays are more particle-like in their interactions. The gamma ray speed is the same as that of light in a vacuum.

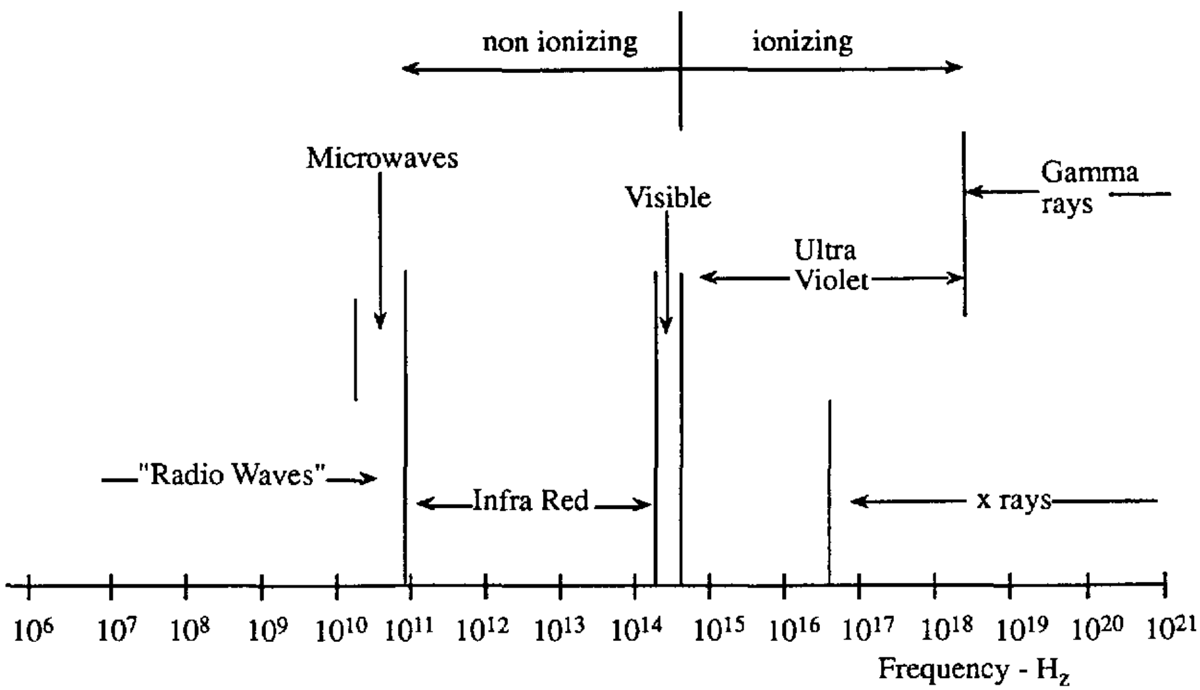

Figure 2.1: Electro Magnetic Spectrum

INTERACTION OF PARTICLES OR RAYS WITH MATTER

Alpha and beta particles are classed as ionizing particles. This is because they carry electric charge which causes the atoms they approach to separate into ions. Each separation creates an ion-pair.

Ionization by Alpha Particles

Alpha particles with their charge of +2 and their mass of 4u create intense ionization. In dry air the alpha causes about 50 000 ion-pairs per centimeter of its path, giving up about 33 eV per pair produced. A 4 MeV alpha travels about 2.5 cm before all its energy is used up. It slows down and stops and becomes a normal helium atom by adopting two electrons from neighbouring atoms.

In liquids or solids the ion-pairs per centimeter is much greater and the distance travelled by the alpha is much less. In general the range (straight line distance) of alpha particles in solid materials is less than 0.1 mm (about the thickness of a sheet of paper).

Ionization by Beta Particles

Beta particles have a charge of -1, a mass of 0.0005u and are travelling very fast (90-99%c). They cause less intense ionization than alpha particles, typically 100 - 300 ion-pairs per centimeter of path in dry air. Because of their small mass the beta particles are deflected easily and do not travel in a straight line. In air their total length of path would be typically 20 m. Beta particles are more penetrating than alphas and will penetrate a sheet of paper. Generally a mm or so of a dense material will be sufficient to stop them.

Gamma Ray Interaction with Atoms

Gamma rays behave differently from alpha and beta particles. First, they have no charge and no mass. Secondly, they do not lose their energies in small, scattered amounts, but give it away in larger chunks when they undergo a reaction. Three of the possible reactions between gamma rays and atoms are described below.

1. The photoelectric effect.

   This gamma ray interaction can take place for gamma rays of low energy. An incident gamma ray reacts with an electron in an atomic orbit. The gamma photon gives all of its energy to an orbiting electron. The gamma ray ceases to exist and the electron is ejected from the atom and behaves like a beta particle. In many materials, the photoelectric effect is not important for photon energies above 0.1 MeV.

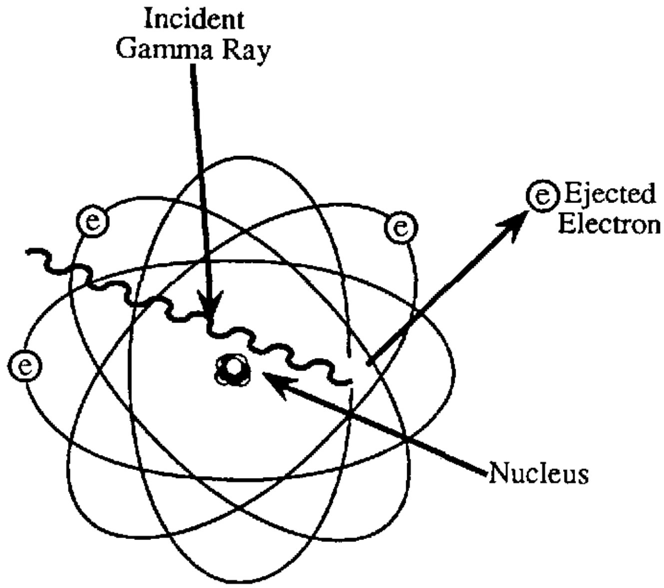

Figure 2.2: Photo Electric Effect

2. The Compton Effect

This gamma ray interaction occurs mainly for gamma photons with energies from about 0.1 to 10 MeV. The incident gamma ray is "scattered" by hitting an electron. The electron in turn is given some of the gamma ray energy and ejected from the atom. This electron is usually more energetic than the photoelectron and will cause ionization exactly like a beta particle.

The scattered gamma ray is really a different gamma ray as the original photon is absorbed and a new one emitted at a lower energy.

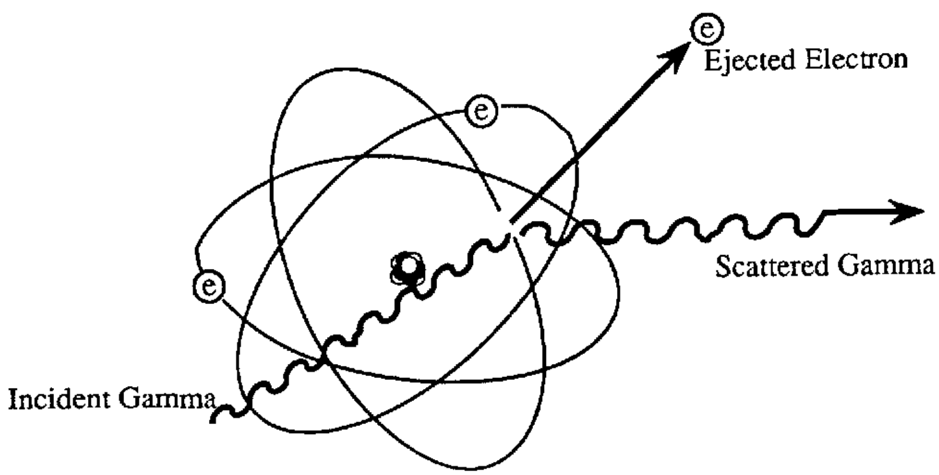

Figure 2.3: Compton Effect

3. Pair Production

This gamma ray interaction always occurs near an atomic nucleus which recoils. The gamma ray gives its energy to the creation of an electron-positron pair. (A positron is a positively charged electron!) The minimum gamma photon energy that can do this is 1.02 MeV (the energy equivalent of 2 electron masses). The process most often happens at higher energies.

The positive and negative electrons created both cause ionization but their fates differ. The positron will meet with another atomic electron and they will "mutually annihilate". Both cease to exist but 2 gamma rays of 0.511 MeV each are created. These gammas will go on and cause one of the other possible gamma ray interactions. The electron will eventually settle down with some accommodating atom and become a normal atomic electron.

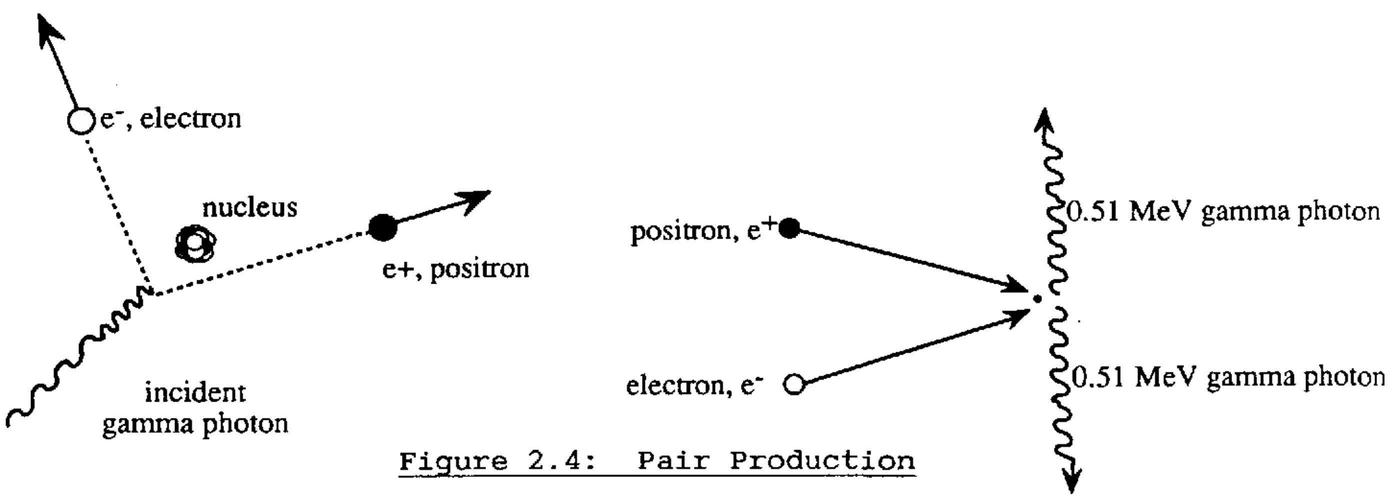

Figure 2.4: Pair Production

Direct and Indirect Ionization

Alphas and betas cause direct ionization. Each ion-pair created takes a small amount of energy and therefore slows the alpha or beta a little bit. Eventually the particle will be stopped. Alphas of a given energy would all travel the same straight line distance (range) in a given material. Similarly betas of a given energy would all have about the same range in a given material. By contrast the gamma rays cannot be assigned a range as they may interact immediately or travel a very long distance between interactions. The gamma ray energy is transferred in large chunks and is deposited in the material by indirect (i.e. secondary) ionizations near each of the interactions.

SHIELDING

It is easy to shield against alphas or betas, we simply need material of thickness equal to or greater than their range.

Shielding against gamma rays is not so easy. No matter how thick the shielding some of the gamma rays can still penetrate. For any particular energy of gammas we can always find the amount of material that will reduce the intensity to half. We call this the half value layer (HVL). Two half value layers would reduce the intensity to ¼ of the original.

As an example, for gamma rays from fission products about 15 cm of water is a half value layer. In the irradiated fuel bays, water is maintained at least 4.5 m (30 HVL's) depth above the fuel. That means that the γ ray intensity reaching the surface of the bay will be reduced by a factor of 2^{30}, that is, it has been halved 30 times. In round numbers that is a reduction of 10^{-9} or one billionth of the original intensity. (You should check these numbers on your calculator.)

Gamma rays are shielded most effectively using materials made from heavy nuclei. Lead is often used where there is very little room for shielding. Where lighter materials (e.g. concrete or water) are used, greater thicknesses are needed.

Type of Radiation	Approximate Mass (AMU)	Charge	Energy Range (MeV)	Remarks
α	4	+2	4 to 8	Very short range, highly ionizing
β	0.0005	-1	0.5 to 3.5	Short Range
γ	0	0	Up to 10 (most below 3)	Long Range

Table 2.1

ASSIGNMENT

1. Using $^{A}_{Z}X$ notation, write equations for Alpha, Beta and Gamma decay.

2. Briefly explain how Alpha, Beta, and Gamma deposit their energy in matter.

3. List the masses and charges for α and β particles.

4. What is ionization?

5. Why is it said that γ rays do not cause direct ionization?

6. Describe methods used to shield against α or β particles.

7. What type of material makes good gamma ray shielding?

8. For a material of half value thickness of 6 cm, shielding 1 MeV gamma rays, calculate the thickness needed to reduce the intensity by 1 000.

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