3 Radioactivity - Spontaneous Nuclear Processes

Becquerel was the first to detect radioactivity. In 1896 he was carrying out experiments with fluorescent salts (which contained uranium) and found that his photographic plates had been exposed despite being well wrapped against light. The penetrating "rays" he discovered were later shown to be of three distinct types: alpha particles (α), beta particles (β), and gamma rays (γ).

3.1 Types of Emissions

All nuclides of atomic number greater than 83 are unstable (that is, 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 83 or less is formed. There are also several naturally occurring radioactive nuclides with mass number less than 83, and many artificial radioactive nuclides have been discovered.

3.1.1 Alpha Emissions

The alpha particle is emitted, typically, from a heavy nuclide such as U-238. This is expressed as:

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

Examination of the alpha particle shows it is a helium-4 nucleus so it is sometimes written:

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$$

(parent) $\rightarrow$ (daughter) + (α)

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

These equations represent a parent nucleus emitting a fast moving α particle (helium-4 nucleus), producing a new daughter nucleus.

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

3.1.2 Beta Emissions

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

$$^{90}_{38}Sr \rightarrow \,^{90}_{39}Y + \beta^{-}$$

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

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

or $$^{A}_{Z}X \rightarrow \,^{A}_{Z+1}X + \beta^{-}$$

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

The beta particle is a very fast moving electron originating in a nucleon inside the nucleus. It has the same mass as any electron, 0.000548 u, and the same charge, -1. The speeds of beta particles range from about 90 to 99% of the speed of light.

3.1.3 Gamma Emissions

An alpha or beta emission usually leaves the disrupted daughter nucleus in an excited state. Excited states are not the same as unstable nuclides. An excited nucleus has excess energy. Both stable and unstable nuclides can be in an excited state. The kind of de-excitation could be emission of a suitable particle (α, β, neutron, or proton) but in most cases, the de-excitation takes place by the emission of one or more gamma photons. The name photon emphasizes that gamma radiation has particle-like properties. A typical example is written:

$$^{60}_{27}\text{Co} \rightarrow \,^{60}_{28}\text{Ni}^{*} + \beta^{-} \qquad (\beta \text{ emission})$$

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

Cobalt-60 emits a beta particle, 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 much less than 10^{-9}s so we usually write the beta and gamma decays as though they are a single event.

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

The generalized gamma decay can be written:

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

As you can see, there is no change in Z or A. The gamma ray has no charge and no mass (it is pure energy) and cannot affect the atomic number or mass number of the nuclide.

Gamma rays are electromagnetic radiation like light rays, radio waves, and x-rays. Changes in charge configuration generate electromagnetic radiation. Different kinds of electromagnetic radiation are distinguished by their photon energy. 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 3.1 shows the electromagnetic spectrum. Low frequencies coincide with low photon energies, long waves, and wave like properties. High-energy gamma rays are more particle-like in their interactions. The speed of all electromagnetic radiation is $c = 3 \times 10^8$ m/s.

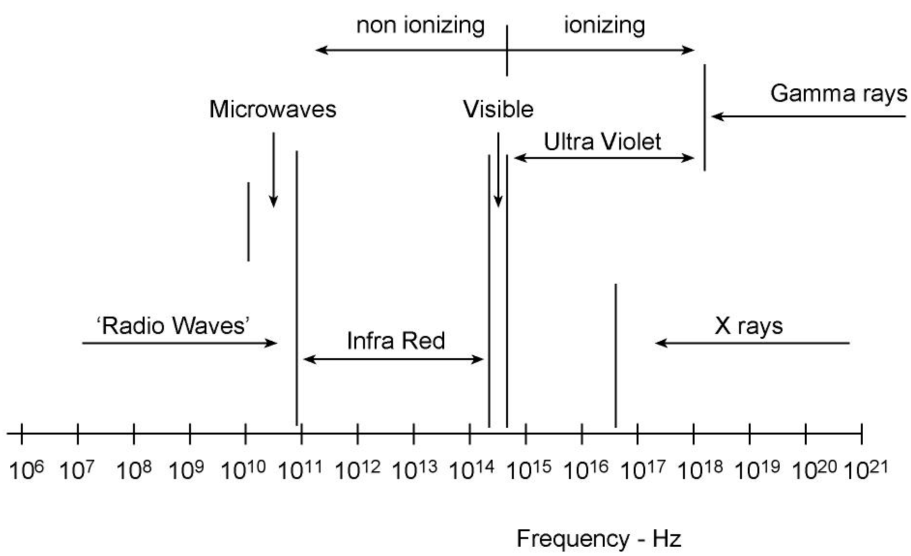

Figure 3.1 – Electro-Magnetic Spectrum

3.2 Interaction of Radiation 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. Gamma rays are said to be indirectly ionizing, as described later in this section. Table 3.1 summarizes the properties of these different kinds of radiation.

3.2.1 Interactions of Alpha Particles

Alpha particles with their charge of +2 and their mass of 4 u create intense ionization. In dry air the alpha generates about 50 000 ion-pairs per centimeter of its path, giving up about 34 eV per pair produced. A 4 MeV alpha dissipates its energy in about 2.5 cm of travel. It slows, stops, and becomes a normal helium atom by adopting two electrons from its surroundings. Near the end of its path, it transfers some energy to neighbouring atoms by atomic excitation.

In liquids or solids, the number of ion-pairs generated per centimeter is much greater so the distance the alpha travels is much less. Typically, the range (straight-line distance) of an alpha crosses the same mass of material in different materials. The alpha particle range in solid materials is generally less than 0.1 mm, about the thickness of a sheet of paper.

3.2.2 Interactions of Beta Particles

Beta particles have a charge of -1, a mass of 0.000 548 u, and travel 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 dry air, their total length of path is typically 20 m. Their actual range might less than half of this. Beta particles are more penetrating than alphas: they will penetrate a sheet of paper. Generally, 1mm or so of a dense material is sufficient to stop them.

Rapid slowing or quick changes in direction cause beta particles to emit X-rays. This process usually accounts for only a few percent of the beta particle energy loss, with most of the energy lost by ionization. This unusual radiation has a suitably unusual name, bremsstrahlung radiation, from the German word for “braking”.

3.2.3 Gamma Ray Interactions with Atoms

Gamma rays do not interact with matter in the same way as alpha and beta particles. They have no charge and no mass and do not lose energy steadily in small, scattered amounts. Instead, they give it away in larger chunks in direct interactions. Three reactions between gamma rays and atoms follow.

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 the orbiting electron and ceases to exist. The electron is ejected from the atom and behaves like a beta particle. The ejected electron is called a photoelectron.

In many materials, the photoelectric effect is not important for photon energies above 0.1 MeV.

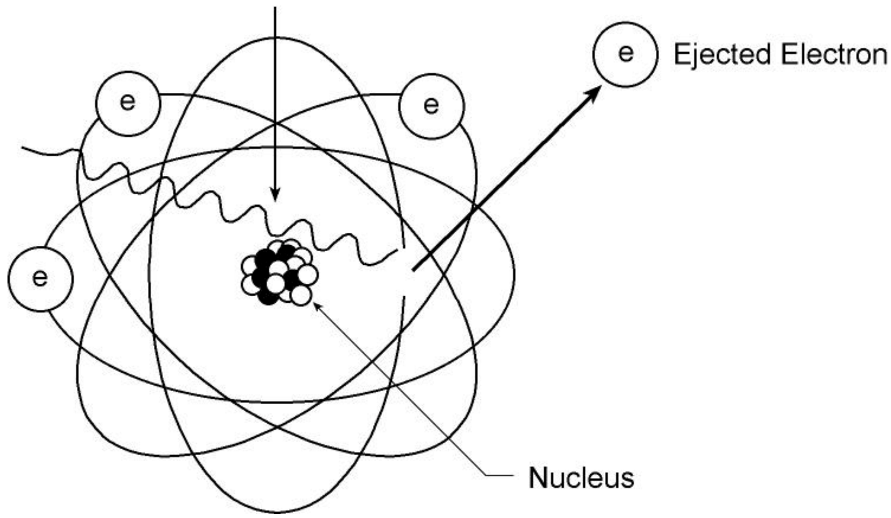

Figure 3.2
Photoelectric Effect

The Compton Effect
This gamma ray interaction is most important for gamma photons with energies between 0.1 and 10 MeV. The incident gamma ray is "scattered" by hitting an electron. The electron receives some of the gamma ray energy and is ejected from the atom. The Compton electron is usually much more energetic than a photoelectron. It causes ionization just as a beta particle does.

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. After a series of such interactions, a low-energy gamma ray is produced, which is then absorbed by the photoelectric effect.

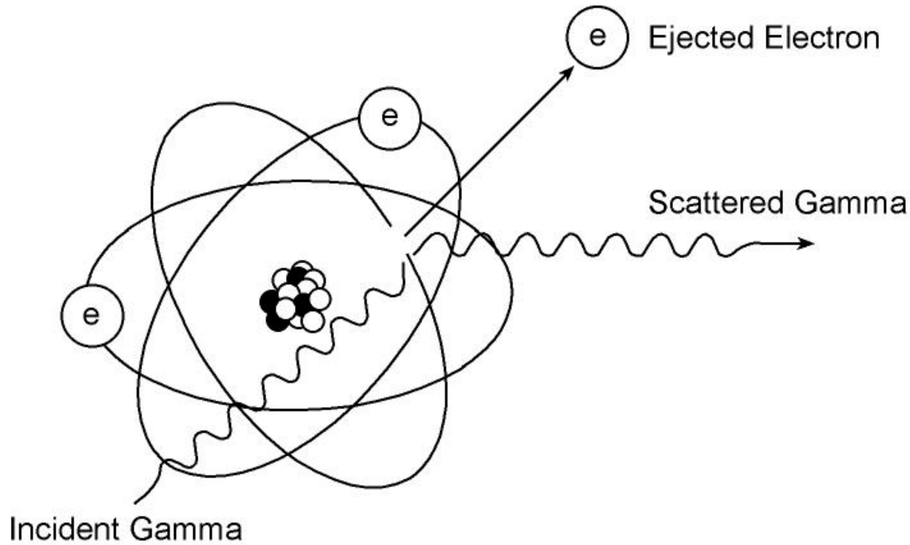

Figure 3.3
Compton Effect

Pair Production
This gamma ray interaction always occurs near an atomic nucleus that 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 for high-energy gamma rays.

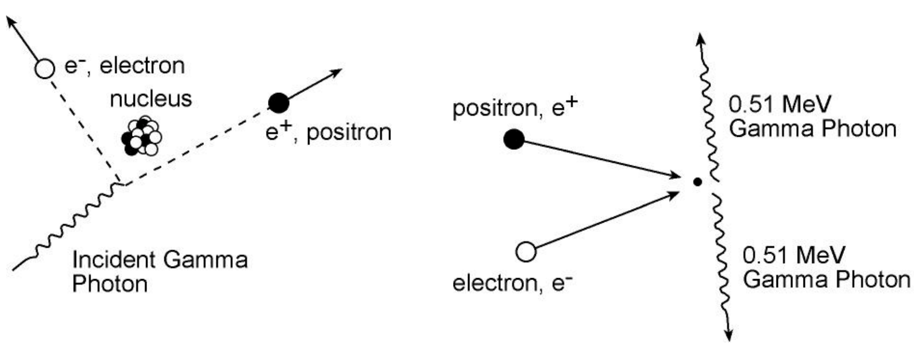

Figure 3.4
Pair Production

The positive and negative electrons created both cause ionization but their fates differ. Once it has slowed, the positron meets with another atomic-electron and they "mutually annihilate". Both cease to exist but two gamma rays of 0.511 MeV each are created.

The 0.511 MeV gamma rays go on and cause one of the other possible gamma ray interactions. The electron eventually settles down with some accommodating atom and become a normal atomic electron.

3.3 Direct and Indirect Ionization

Alphas and betas cause direct ionization. Each ion-pair created takes a small amount of energy and slows the alpha or beta a little bit. Eventually the particle stops. Alphas of a given energy all travel the same straight-line distance (range) in a given material. Similarly, betas of a given energy all have about the same range in a given material. By contrast, the gamma rays do not have a range. 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 interaction sites. A small fraction of the gamma rays may penetrate quite thick materials and emerge on the other side with no loss of energy.

Table 3.1

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

3.4 Shielding

It is easy to shield against alphas or betas; we simply need material of thickness equal to or greater than their range. Shielding materials for betas should not stop them too quickly or the stopping process causes bremsstrahlung radiation (X-ray radiation). This then needs shielding.

Shielding against gamma rays and x-rays is not so easy. No matter how thick the shielding, some of the rays will still penetrate. For any particular photon energy, we can always find the amount of material that cuts the intensity in half. We call this the half value layer (HVL). Two half value layers reduce the intensity to ¼ of the original, and a third reduces it to $^1/_8$.

As an example, for typical 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 HVLs) depth above the fuel. That means that the absorption in the water reduces γ ray intensity reaching the surface of the bay by a factor of 2^{30}. That is, it halves it 30 times. In round numbers $1/2^{30}$ is a reduction of 10^{-9} or one billionth of the original intensity. (You should check these numbers on your calculator.)

Materials containing heavy atoms shield gamma rays most effectively. Lead is often used where space for shielding is limited. Where lighter, less expensive materials (e.g., concrete, or water) are used, greater thickness is needed.

3.5 Summary of Key Ideas

- The three major particles emitted by spontaneous radioactive decay are alpha, beta and gamma.
- Alpha particles are doubly charged helium nuclei, which move slowly when they are emitted. They are emitted from large nuclei such as U-235, U-238 or Thorium.
- Beta particles are electrons. At the time the are emitted they are generally traveling at a speed greater than 90% of the speed of light. They are emitted from a nucleus with too many neutrons. A neutron in the nucleus changes to a proton and a beta particle is emitted.
- Gamma usually accompanies alpha or beta decay. They are photons of electromagnetic energy that travel at the speed of light.
- Alpha and beta particles are directly ionizing radiations. They leave a trail of ionized atoms in their wake.
- Gamma rays are indirectly ionizing radiation, and interact with atoms to generate ions. The three gamma interactions are Compton effect, photoelectric effect and pair production.
- Beta and alpha can be shielded by placing material between the source of the radiation between the source and a person.
- Gamma is the most difficult to shield. The effectiveness of a material in shielding gamma is referred to as a half value

layer; the thickness of material required to reduce the gamma energy by one-half.

3.6 Assignment

1. Using ${}^{A}_{Z}X$ notation, write equations for alpha, beta and gamma decay.

2. Briefly, describe 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.