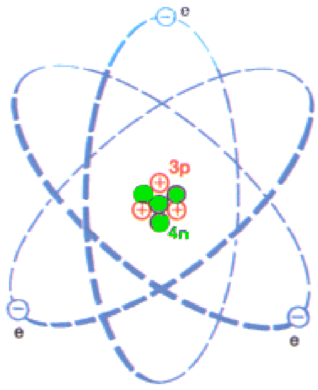
Detection & Measurement of Radioactivity



Lithium atom

All substance are made of atoms. These have electrons (e) around the outside, and a nucleus in the middle. The nucleus consists of protons (p) and neutrons (n), and is extremely small. (Atoms are almost entirely made of empty space!). In some types of atom, the nucleus is unstable, and will decay into a more stable atom. This radioactive decay is completely spontaneous. You can heat the substance up, or subject it to high pressure or strong magnetic fields - in fact, do whatever you like to it - and you won't affect the rate of decay in the slightest. When an unstable nucleus decays, there are three ways that it can do so. It may give out:-

- an **alpha particle** (we use the symbol α)
- a **beta particle** (symbol β)
- a **gamma ray** (symbol γ)

Many radioactive substances emit α particles and β particles as well as γ rays.

Alpha Particles

Alpha particles are made of **2 protons and 2 neutrons**. This means that they have a **charge** of **+2**, and a **mass** of **4** *(the mass is measured in "atomic mass units", where each proton & neutron=1).* Alpha particles are relatively **slow** and **heavy**. They have a **low penetrating power** - you can stop them with just a sheet of **paper**. Because they have a large charge, alpha particles ionize other atoms strongly and have a range of only a few centimetres in air.

Alpha particles are made of 2 protons with 2 neutrons. This means that when a nucleus emits an alpha particle, it loses 2 protons and so its **atomic number decreases by 2**. Also, when a nucleus emits an alpha particle, its **atomic mass decreases by 4** (that's 2 protons plus 2 neutrons). So Americium-241 (an α -source used in smoke detectors), which has an atomic number of 95 and an atomic mass of 241 will decay to Neptunium-237 (which has an atomic number of 93 and an atomic mass of 237). The equation would look like this:-

$$^{241}_{95}\text{Am} \dashrightarrow {}^{237}_{93}\text{Np} + {}^{4}_{2}\alpha$$

Alpha-decay occurs in very heavy elements, for example, Uranium and Radium. These heavy elements have too many protons to be stable. They can become more stable by emitting an alpha particle.

Beta Particles

Beta particles have a charge of **minus 1**, and a mass of about **1/2000th of a proton**. This means that beta particles are **the same as an electron**. They are **fast**, and **light**. Beta particles have a **medium penetrating power** - they are stopped by a sheet of **aluminium** or plastics such as **perspex**. Beta particles ionise atoms that they pass, but not as strongly as Alpha particles do.

It appears strange that when the nucleus contains protons and neutrons, how can an electron come out of a nucleus?

To answer this, we need to know more about protons and neutrons:

Protons & neutrons are made of combinations of even smaller particles, called "quarks". Under certain conditions, a neutron can decay, to produce a proton plus an electron. The proton stays in the nucleus, whilst the electron flies off at high speed.

This means that when a nucleus emits a β - particle,

- the **atomic mass is unchanged**,
- the **atomic number <u>increases</u> by 1**.

This is because a neutron has changed into a proton (almost the same mass - we can ignore the tiny mass of the electron) and thus the number of protons has gone up.

Example: Strontium-90 undergoes β decay and forms Yttrium-90.

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

This isn't the whole story - an almost massless particle called an "anti-neutrino" is also emitted. Furthermore, we are only considering "beta-minus" emission (negatively-charged electrons).

There is another type of beta decay, called "beta-plus", where a positively-charged electron (called a "positron") is emitted, along with a neutrino.

Beta decay occurs in very "neutron-rich" elements, for example, Strontium-90 and Iodine-130. These elements are typically created in nuclear reactors.

These elements have too few protons and too many neutrons to be stable. They can thus become more stable by emitting a beta particle.

Beta particles have a charge of -1, and weigh only a tiny fraction of a neutron or proton. As a result, β particles interact less readily with other atoms than alpha particles. Thus beta particles cause less ionisation than alphas, and have a longer range, typically a few metres in air. In Beta decay, the atomic number increases by one while the atomic mass remains unchanged.

Gamma Rays:

Gamma rays are **waves, not particles**. This means that they have **no mass** and **no charge**. Gamma rays have a **high penetrating power** - it takes a thick sheet of metal such as **lead**, or **concrete** to reduce them significantly. Gamma rays do not directly ionise other atoms, although they may cause atoms to emit other particles which will then cause ionisation.

Gamma rays (γ) are electromagnetic waves, rather like X rays and radio waves. Thus gamma rays have **no mass** and **no charge**.

After a nucleus has emitted an α-particle or a β-particle, it may still have too much energy: we say it is in an "excited state". It can get rid of this energy by emitting a pulse of very high frequency electromagnetic radiation, called a gamma ray. Gamma rays do not pull electrons off atoms they pass, as α-particles and β-particles do. This means that they do not lose much energy as they travel, as they do not interact as much with the matter they pass. Therefore, gamma rays have a **high penetrating power**, and a **very long range**.

It's worth noting that there is no such thing as a pure γ-ray source. Gamma rays are given off by most α-emitters and β-emitters. If we want a source of pure gamma rays, we can get it by using a substance that emits both β and γ, and simply keep it in an aluminium container that stops the β-particles.

Useful gamma sources include Technetium-99m, which is used as a "tracer" in medicine. This is a combined β and γ source, and is chosen because betas are less harmful to the patient than alphas (less ionisation) and because Technetium has a short half-life (just over 6 hours), so it decays away quickly and reduces the dose to the patient. In Gamma decay, both atomic number and atomic mass remain unchanged.

Detection of Radioactivity

Although some forms of electromagnetic energy, such as light and heat, can be detected by the human senses. One of the greatest draw backs to high energy radiation is the inability to detect it. We cannot see, feel, taste, smell, or hear the various forms of ionizing radiation. Fortunately, ionizing radiation interacts with matter which makes detection and measurement possible by utilizing specialized equipment. In this section we want to introduce you to the various ways and means of detecting and measuring ionizing radiation.

Becquerel discovered radioactivity because it left marks on photographic film. However, there are more definitive means commonly used by scientists and technicians who study and work with radiation. The equipment utilized for the detection and measurement of radiation commonly employs some type of substance or material that responds to radiation. Many common methods use either an ionization process or molecular excitation process as a basis. Remember that radiation interacts with matter. For detection and measurement purposes the process of ionization is the most commonly employed technique, based on the principle of charged particles producing ion pairs by direct interaction. These charged particles may collide with electrons, which remove them from their parent atoms, or transfer energy to an electron by interaction of electric fields.

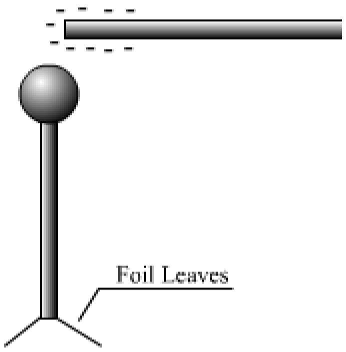
How do you choose a detection device?

Important considerations for choosing a particular type of detection device include the application, the type of radiation, the energy of the radiation, and the level of sensitivity needed. Remember from previous discussion that radiation exists as waveforms with varying energies and may be either particulate or electromagnetic in nature.

There are three types of radiation detection devices:

- The Electroscope
- The Cloud Chamber
- Other Detection Devices

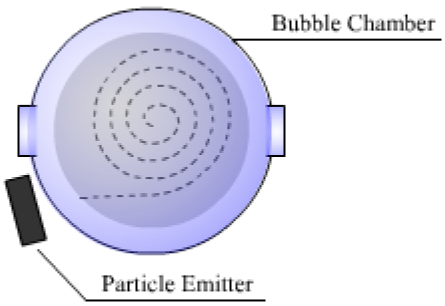
THE ELECTROSCOPE



Marie Curie used an electroscope to study the radioactivity or Uranium ores. The electroscope is a fairly simple device comprised of a metal rod with two thin leaves attached to one end. If the electroscope is given a negative charge, the metal leaves will separate from each other. It is this characteristic that makes the electroscope useful as a detection device. A negatively charged electroscope will discharge when ions in the air remove electrons from it, and consequently, a positively charged electroscope will discharge when it takes electrons from the air around it. The rate of discharge of the electroscope is a measure of ions in the air and can be used as a basis of measurement and detection.

THE CLOUD CHAMBER

A unique device for detection and measurement is the Cloud Chamber, invented by the British physicist Charles Wilson in 1911. The Cloud chamber makes it possible to visually see the path of ionizing radiation thus making it possible to photograph it. The cloud chamber consists of a plastic or glass container, which sits on dry ice. A dark cloth is saturated with alcohol and placed around the inside of the container near the top. A small radioactive material may be suspended from the lid of the container. In the chamber, the alcohol evaporates from the cloth and condenses as it reaches the cold region created by the dry ice at the floor of the container. Just above the floor of the chamber there is a region where the alcohol vapor does not condense unless there are seeds around, so that drops of alcohol can form. This condition



is similar to that of seeding clouds with a chemical to form rain. The idea is that only seeds available in the chamber are those of ions produced by the interaction with radiation. The resulting trail of alcohol droplets can be seen against the black background in the bottom of the chamber.

These are only a few of the devices commonly utilized for purposes of detection and measurement of radioactivity and radiation. It is important to understand that when working with radioactivity/radiation, due to our inability to sense radiation, we need them to assist us in detecting the presence of radiation and we also need them to help monitor the radiation.

OTHER DETECTION DEVICES

Another common device used for detection and measurement is the ionization chamber. The Geiger counter, survey meter, and personal dosimeters work on the basis of the ionization chamber. The principle operation of an ionization chamber is that it will produce an electric current in the presence of a radioactive source. Ionization chambers consist of tubes filled with gas, such as argon. When radiation enters the tube and interacts with the gas, it removes electrons from the gas. The gas atoms become positively charged ions, and the free electrons move through the gas to a wire in the tube, setting up a current. The current is commonly amplified and sent to a recording or counting device. This in response may produce a flash of light, ticking sounds, or an analog readout. Ionization chambers are capable of measuring the amount of radiation by means of measuring the amount of current produced.

Measurement of Radioactivity

For measuring radioactivity, three types of devices are available:

1. Gas-filled tube counters e.g. the Geiger Muller Counter
2. Scintillation Counters
3. Semi-conductor Detectors

1. **The Geiger Counter:** A potential difference just below that required to produce a discharge is applied to the tube (1000 V). Any atoms of the gas struck by the γ-rays entering the tube are ionized, causing a discharge. Discharges are monitored and counted by electronic circuitry and the output is reported as counts/sec or Rontgens/hr or mR/hr.

2. **Scintillation Counters:** Crystals of certain substances e.g. cesium fluoride, cadmium tungstate, anthracine and sodium iodide emit small flashes of light when bombarded by γ-rays. The most commonly used phosphor in scintillation counters is NaI with a minute quantity of thallium added. In the instrument, the crystal is positioned against a photocell which in turn is linked to a recording unit. The number of flashes produced per unit time is proportional to the intensity of radiation. Small portable scintillation counters are available.

3. **Semi-Conductor Detectors:** A semi-conductor is a substance whose electrical conductivity is between that of a metal and an insulator. It is noted that Ge(Li) semi-conductors ate excellent detectors of γ-rays with a resolution ten times higher than NaI (Th) scintillometers. The main disadvantage of these is a lower efficiency for higher energy x-rays. Besides, Ge(Li) semi-conductors need to be cooled by liquid nitrogenand are hence cumbersome and not suitable as field instruments.

Besides the above there are instruments known as γ-ray spectrometers, which can distinguish different energy peaks and hence make it possible to identify the source of radiation.

A Geiger counter will record "counts per minute", but this doesn't tell us what the radioactive substance is actually doing, merely what is reaching the detector. It also tells us nothing about the amount of damage being done to you. Thus we need several different units in order to measure radioactivity.

- The **activity** of a source is measured in **Becquerels** (Bq),
  One Becquerel is one decay per second.
- The amount of radiation that your **cells absorb** is measured in **grays** (Gy),
  One gray is one Joule of energy absorbed by 1kg of your body. This is the **dose** you receive.
- To measure the harm done to you, we need to remember that α particles ionise very strongly, and cause 20 times more cell damage than the same dose of β particles, γ rays or X-rays. We measure the "**dose equivalent**" in **sieverts** (Sv).
- A dose of 1 gray of β-particles, γ-rays or X-rays will give you a dose equivalent of 1 sievert. A dose of 1 gray of α-particles will give you a dose equivalent of 20 sieverts

The sievert is quite a large unit, so we usually work in millisieverts (mSv)
or microsieverts (μSv).

Here's a good way to think of it:
imagine you're out in a rainstorm.
Then the amount of *rain falling* is measured in *Bequerels,*
the amount of *rain hitting you* is measured in *grays,*
and *how wet you get* is measured in *sieverts*.

Our bodies have an activity of around 4000 Bq. The average annual dose in the UK is around 2.5 millisieverts.

Unit of Measuring Radioactivity:

The unit of measuring radioactivity is the Curie (Ci). One Curie is the amount of radiation produced by 1 gm of radium (Ra226). This is equivalent to 2.7x1011 decays per second. For practical measurements this unit is too large and therefore it has been replaced by the SI derived unit, the becquerel (Bq), which equates to one decay per second (therefore 1 Bq = 2.7×10^{-11}Ci and 1 curie is 37 gigabecquerels).

As one might expect, a becquerel is actually a tiny amount of radioactive material, so in practice one usually sees numbers of gigabecquerels. The amount of radioactivity is normally obtained by measuring the radiation produced or by measuring the amount of radioactive material (in grams, say) and using its known properties.

In a fixed mass of radioactive material, the number of becquerels changes with time. In some circumstances, amounts of radioactive material are given after adjustment for some period of time. For example, one might quote a ten-day adjusted figure, that is, the amount of radioactivity that will still be present after ten days. This deemphasizes short-lived isotopes.

Safety Precautions

Some of the principle safety precautions commonly used in working with radioactivity/radiation are time, distance, and shielding. Recall our earlier discussion of the dentist wanting to photograph your teeth. Have you ever wondered why the dentist lays a heavy apron across your chest? The dentist is practicing a means of protection from exposure. In that, they are using distance and shielding from the source of radiation. The concepts of these three principles are fairly simple. The first principle is time. The less time you spend around a radioactive material the less exposure you will receive. The second principle states that the greater the distance away from a radioactive source the lesser your exposure to the radiation. Lastly, if you can protect yourself with some type of material to act as a shielding device you will also reduce your overall exposure.