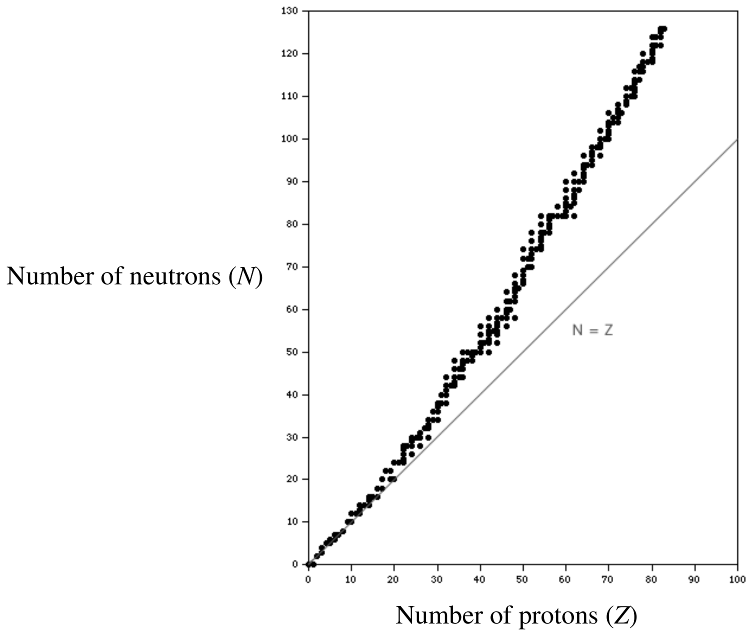
Radioactivity

Stable and Unstable Nuclei

Radioactivity is the spontaneous disintegration of certain nuclei, a random process in which particles and/or high-energy photons are emitted. Nuclei which exhibit this behaviour are *radioactive*, and are described as *unstable* nuclei.

Stable nuclei of low mass have approximately equal numbers of neutrons and protons, whereas stable nuclei of high mass have more neutrons than protons. The relationship between the number of neutrons and protons for stable nuclei is demonstrated below, with black spots representing known stable nuclei.



The increase in ratio of neutrons to protons for stable nuclei is due to the properties of the attractive nuclear force and the repulsive electrostatic force between protons. The attractive 'strong nuclear force' between nucleons acts over very small distances, whereas the electrostatic repulsive force acts over the whole nucleus.

Larger nuclei have their neutrons further apart, meaning they do not exert as strong a pull on each other, whereas the repulsion remains strong. There must therefore be more neutrons compared to protons in order to overcome the repulsion over the larger distances.

Eventually, a point is reached beyond which there are no stable nuclei: nuclei with more than 83 protons are all unstable, as the nucleus is too large for the short range attractive forces of any amount of neutrons to be effective.

Types of Decay of Unstable Nuclei

Unstable nuclei spontaneously decay and emit some form of radiation (the radiation is not necessarily electromagnetic). Some of the possible types of decay are shown below:

- Alpha (α) decay, in which helium nuclei (alpha particles) are emitted.
- Beta minus (β^-) decay, in which electrons (e^-) are emitted.
- Beta plus (β^+) decay, in which positrons (e^+) are emitted.
- Spontaneous fission, in which a nucleus splits into two.

Generally these types of decay can be considered to correspond to three regions on the *N* versus *Z* graph:

- Alpha decay occurs for nuclei with $Z > 83$.
- Beta minus decay occurs above the graph of stable nuclei.
- Beta plus decay occurs below the graph of stable nuclei.
- Spontaneous fission occurs for some nuclei with $Z > 83$.

Alpha Decay

Like atoms, nuclei have discrete energy levels. The spacing of these energy levels is much larger than that of the energy levels of atoms, and is in the MeV range.

An alpha particle (helium nucleus) is particularly tightly bound. If a heavy nucleus is unstable owing to an excess of *nucleons* (protons *and* neutrons) it may decay by emitting an alpha particle. Because the initial and final nuclei are in discrete energy states, the emitted alpha particle also has discrete energy.
The general equation for an alpha decay is given by ${}_{Z}^{A}X \longrightarrow {}_{Z-2}^{A-4}Y + {}_{2}^{4}\alpha$

Beta Decay

Beta minus decay occurs when a nucleus has an excess of *neutrons*, and involves the conversion of a neutron into a proton. This is accompanied by the emission of an electron and an antineutrino.

The general equation for beta minus decay is given by ${}_{Z}^{A}X \longrightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}e^{-} + {}_{0}^{0}\overline{\nu}$

A beta minus particle is an electron, which has a charge number of negative 1.

Beta plus decay occurs when a nucleus has an excess of *protons*, and involves the conversion of a proton into a neutron. This is accompanied by the emission of a positron and a neutrino.

The general equation for beta plus decay is given by ${}_{Z}^{A}X \longrightarrow {}_{Z-1}^{A}Y + {}_{1}^{0}e^{+} + {}_{0}^{0}\nu$

A beta plus particle is a positron, which has a charge number of plus 1.

Particles Involved in Beta Decay

A positron has the same mass as an electron, and opposite charge. It is the antiparticle of an electron, which means under the right conditions a collision between them will cause *annihilation*. This 'annihilation' does not violate conservation of energy – the positron and electron are converted to two gamma rays. This energy cannot be emitted as a *single* gamma ray since momentum must be conserved and only two photons leaving in opposite directions can cancel out the change in momentum.

Before the discovery of the neutrino and antineutrino, it was expected that the electron or positron would retain kinetic energy to account for the mass defect, and conserve the momentum along with the new nucleus. In experiments, however, the emitted electrons and positrons from beta decays are observed to have a *range* of energies and momenta, up to some maxima. The only way this could be accounted for is if there were another particle being emitted.

Neutrinos and antineutrinos are neutral particles with very small mass, which balance this energy and momentum conservation discrepancy. Both neutrinos and antineutrinos have mass and charge numbers of zero, so the total mass number and total charge number (atomic number) on both sides of the equation are equal.

Gamma Decay

Gamma decay occurs when an *excited nucleus* (denoted ${}_{Z}^{A}X^{*}$) decays to its ground state. This can happen after alpha or beta decay, as a nucleus is sometimes left in one of a small number of possible excited states.
Gamma decay results in the emission of one or more high-energy photons (gamma rays). Since the energy levels in nuclei are discrete, gamma photons will have discrete energies.

The general equation for a gamma decay is given by ${}_{Z}^{A}X^{*} \longrightarrow {}_{Z}^{A}X + n\gamma$ where *n* is the number of high-energy photons emitted.

Gamma rays have a mass number and charge number of 0, since they are electromagnetic photons which have neither mass nor charge.

Some Properties of Radioactive Emissions

Some radioactive emissions cause ionisation in matter through which they pass (by either removing or adding electrons from the material). They are collectively called 'ionising radiation'. Some examples of these are shown below:

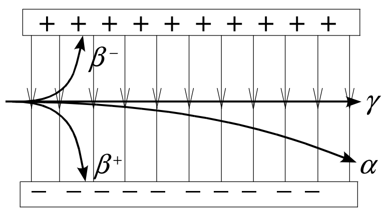
Type of radiation	**Common source**
alpha beta minus beta plus gamma	radioactive nuclei
x-ray	x-ray device
neutron	nuclear reactor
proton	cyclotron

As the radiation ionises atoms it loses kinetic energy, and once all its kinetic energy is lost, it stops. Radiation that ionises less will therefore travel further, that is it will have greater *penetration*. This relationship is demonstrated in the table below, using air as an example for comparison:

	Nature	***Ionisation***	***Penetration in air***
Alpha	Helium nucleus	High	A few cm
Beta	Electron / positron	Medium	Several metres
Gamma	High energy photon	Low	Many metres

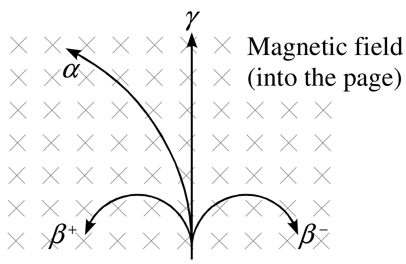
Alpha and beta particles have a charge and are therefore deflected by electric and magnetic fields, whereas gamma radiation is not deflected. The sign of the charge of any given radiation can be determined from the deflection in an electric or magnetic field. Note also that alpha particles, since they are 7294 times the mass of beta particles (even though twice the charge), will deflect significantly less.

The diagrams below show radiation (fired at similar energies) and deflection:



Electric field
(between parallel plates)

Paths of deflection are parabolic



Paths of deflection are circular

The Effects of Ionising Radiation on Living Matter

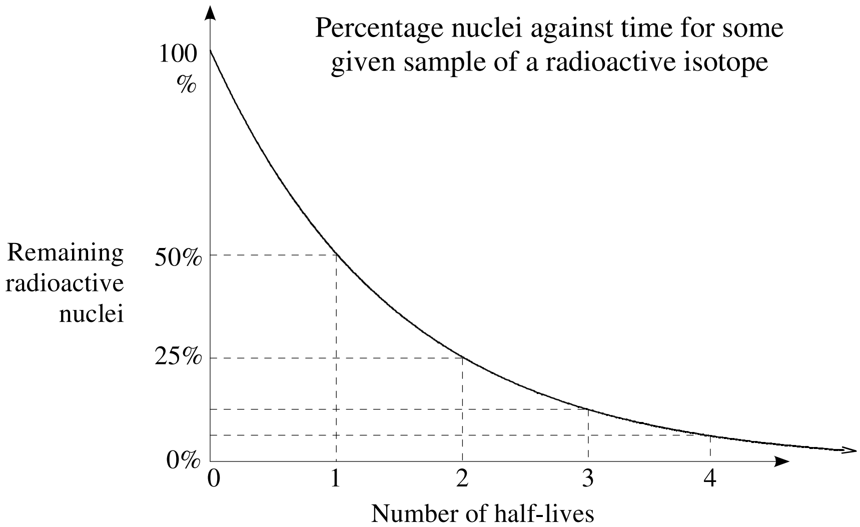
Ionising radiation can break chemical bonds in living matter, and this can kill cells. It can also change the genetic material in cells (for example causing cancer or mutations).

Since ionising radiation can damage living matter, dosages should be minimised wherever possible. The following are some examples of how radiation dosages can be reduced:

- increasing the distance from the source
- limiting the time of exposure
- using adequate shielding (for example wearing a lead apron)

Half-life Activity

The half-life $t_{\frac{1}{2}}$ of a sample of a given isotope is the time required for half of the radioactive nuclei in it to decay. After two half-life periods have passed, a quarter of the radioactive nuclei of that isotope will still remain, and so on. The result of this pattern is that the number of radioactive nuclei in a sample of a given isotope decreases exponentially with time.



Radioactivity is a random process in which at any given time a nucleus has a probability of decaying. This probability is constant for each isotope, therefore the half-life for any given isotope is constant over time. It is independent of both the physical state (e.g. temperature) and the chemical state (e.g. in elemental form or bonded with other elements).

The relationship between number of nuclei *N* and number of half-lives *n* for any given material can be represented by $N = N_0 \left(\frac{1}{2}\right)^n$ where N_0 is the initial number of nuclei.

Sometimes it is useful to calculate the expected half-life from the chance of one particle remaining alive after one unit of time. The relationship $t_{\frac{1}{2}} = \frac{\log \frac{1}{2}}{\log P}$ can be used for this (P is the probability of not decaying, between 0 and 1).

The *activity* of a radioactive substance is the number of radioactive nuclei that decay per unit time. For a given nucleus, the relationship of activity to the number of nuclei is as follows:

- Activity is proportional to the number of radioactive nuclei present, and hence decreases exponentially with time.
- The half-life for the activity is the same as the half-life for the number of radioactive nuclei.

A graph for percentage activity against time would look identical to the graph above.

The unit of activity is the *becquerel* (Bq) and is equal to the number of decays per second.

The relationship between activity *A* and number of half-lives *n* for any given material can be represented by $A = A_0 \left(\frac{1}{2}\right)^n$ where A_0 is the initial activity.

Positron Emission Tomography (PET)

Particles accelerated by cyclotrons are used to manufacture medical radioisotopes, such as fluorine–18 and oxygen–15. These radioisotopes can be used to manufacture chemical compounds known as *radiopharmaceuticals*.

Radioactive fluorine–18 is used to create the radiopharmaceutical 2–fluoro–2–deoxy–D–glucose (known as ^{18}FDG). Biological tissues, such as muscles, take up ^{18}FDG in a similar way to how they take up glucose, the principal fuel for muscle action. This ^{18}F-labelled glucose can be used, for example, to measure the metabolism of glucose in the heart.

As part of certain PET scans, a patient is injected with a serum containing ^{18}FDG, and must lay perfectly still. The body initially treats the ^{18}FDG as glucose and it is concentrated in body tissues that are using glucose as a fuel. For a person laying still, the ^{18}FDG can concentrate within the heart. Cancerous tumours use glucose at greater rates than regular tissue, so ^{18}FDG can also become concentrated within a tumour.

Radioactive oxygen–15 is used to create a radioactive form of water. This radiopharmaceutical becomes part of the blood flowing throughout the patient, making an effective tracer for blood flow.

Positron-electron Annihilation

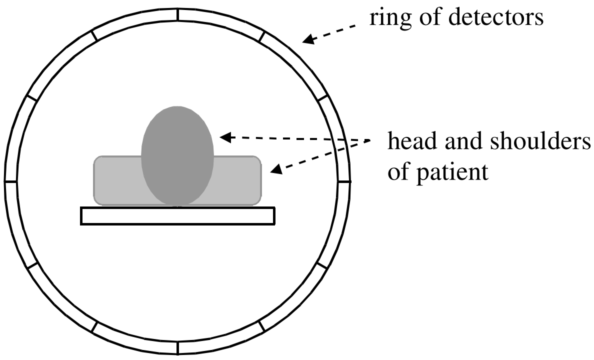
The radioisotopes used in PET all contain too many protons (compared to their number of neutrons), so they undergo beta plus decays, emitting positrons. The positrons interact with electrons present in the surrounding tissue. Commonly, the anti–particles: positions and electrons annihilate each other, converting all their mass into energy. This energy is released as two gamma photons travelling in opposite directions, as discussed in the *Particles Involved in Beta Decay* section of this topic. Using the expression $E = mc^2$, the energy released by the annihilation process can be calculated.

Nearness of PET Facilities to Particle Accelerators

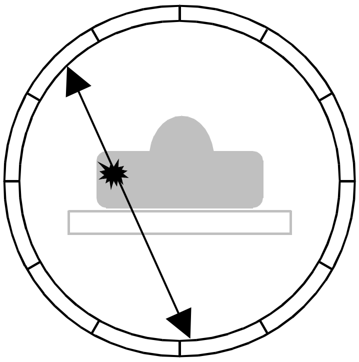
The radioisotopes used in PET scans have short half lives. Fluorine–18 has a half–life of 110 minutes and oxygen–15 has a half–life of 2 minutes. With the half–lives being short, the radioisotopes must be produced near to the PET facilities. The radiopharmaceutical must continue to undergo radioactive decay after it has been ingested by the patient, so this ingestion must occur soon after the radioisotope has been produced. PET facilities therefore need to be located near particle accelerators (such as cyclotrons).

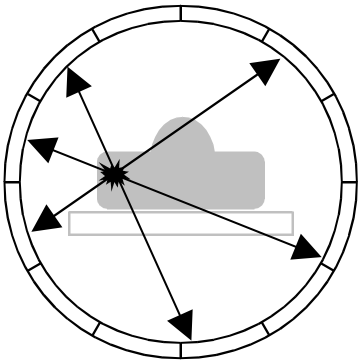
Determining the Location of a Tracer Radioisotope

When a person is undergoing a PET scan they are lying flat, surrounded by a ring of detectors. The diagram below shows this arrangement viewed along the axis of the body:



When a positron–electron annihilation occurs at the location of the radioisotope (for instance where the ^{18}FDG has concentrated within a tumour) the two photons are produced. These travel at 180º to each other forming a *coincidence line*. These photons are detected on opposite sides of the detector ring, as shown below (left):





Multiple coincidence lines allow the location of the tracer radioisotope to be accurately determined, as shown above (right). The ring of detectors moves along the axis of the body, allowing a three–dimensional image to be constructed. Within a full PET scan (taking between 30 minutes and one hour), over a million coincidence lines are found.