Nuclear interactions

Shortly after the discovery of the neutron, *Hideki Yukawa*, a Japanese physicist, postulated a strong force of attraction between nucleons that overcomes the Coulomb repulsion between protons. The existence of the force postulated by Yukawa is now well established and is known as the **strong nuclear interaction**. The force is independent of whether the particles involved are protons or neutrons and at nucleon separations of about 1.3 fm, the force is some 100 times stronger than the Coulomb force between protons. At separation greater than 1.3 fm, the force falls rapidly to zero. At smaller separations the force is strongly repulsive thereby keeping the nucleons at an average separation of about 1.3 fm. ($1 \text{ femtometre} = 10^{-15} \text{ m}$)

7.2 RADIOACTIVE DECAY

7.2.1 Describe the phenomenon of natural radioactive decay.

7.2.2 Describe the properties of α and β particles and γ radiation.

7.2.3 Describe the ionizing properties of α and β particles and γ radiation.

7.2.4 Outline the biological effects of ionizing radiation.

7.2.5 Explain why some nuclei are stable while others are unstable.

7.2.1 NATURAL RADIOACTIVE DECAY

Certain elements emit radiation spontaneously, i.e. without any external excitation; this phenomenon is called **radioactivity**. It was first discovered by the Austrian physicist *Henri Becquerel* in 1896, who found that uranium salts which had been protected from exciting radiations for several months still emitted penetrating radiation seemingly without any loss in intensity. Becquerel discovered that the uranium itself was responsible for this radiation and also that the radiation was independent of pressure, temperature and chemical combination.

This indicated that the radioactive properties of uranium were due to the nucleus of the atom and not to the electronic structure.

7.2.2 THE RADIATIONS (α, β, γ)

Shortly after Becquerel's discovery two physicists working in France, *Pierre and Marie Curie* isolated two other radioactive elements, polonium and radium each of which is several million times more active than uranium. An extremely good account of the Curies' heroic experiments can be found in Madame Curie's biography written by her daughter, Irene. At first it was thought that the radiation emitted by radioactive elements were of the same nature as the X-rays that had been discovered the previous year. However, in 1897, *Rutherford* found that two types of radiation occurred in radioactivity, some of the rays being much more penetrating than the others. He called the less penetrating rays alpha (α) rays and the more penetrating ones beta (β) rays.

In 1900 *Villiard*, also French, detected a third type radiation which was even more penetrating than β-rays. Naturally enough he called this third type gamma (γ) radiation.

Madame Curie deduced from their absorption properties that α-rays consisted of material particles and *Rutherford* showed that these particles carried a positive charge equal to about twice the electron charge but that they were very much more massive than electrons. Then in 1909, in conjunction with *Royds*, *Rutherford* identified α-particles as helium nuclei.

α-particles have a range in air at STP of about 5 cm and are readily stopped by a few sheets thickness of writing paper.

β-particles were soon identified as electrons that have considerable energy. They travel several metres in air before being absorbed. They can also penetrate thin sheets of aluminium.

In 1928 the English physicist *Paul Dirac* predicted the existence of a positively charged electron and in 1932 this particle was found by the American physicist *Carl Anderson*, to be present in cosmic radiation. Then in 1934, the Curie's daughter Irene, along with her husband *Frederic Joliot*, discovered the positively charged electron, now called the **positron** (e+, β^+) , to be present in certain radioactive decay.

γ-rays are not influenced by electric or magnetic fields but can be diffracted by crystals. This indicates that γ-rays consist of short wavelength electromagnetic radiation typically in the range 5-0.05 nm. From the Planck relation, $E = hf$, this means that the photons associated with γ-radiation have very high energies and are therefore

Name	Identification	Charge	Kinetic energy range/MeV	Rest mass/kg	Penetration range
alpha, α	helium nucleus	$+2e$	$2 \rightarrow 10$	6.70×10^{-27}	$\approx$ 4 cm air sheet of thin paper
beta, β^-, β^+	electron/positron	$-e$, $+e$	$0.1 \rightarrow 1.0$	9.11×10^{-31}	$\approx$ 1-3 m in air thin aluminium sheet
Gamma γ	high frequency em radiation (photon)	zero	$10^{-3} \rightarrow 3$	zero	several mm of lead

Figure 704   A summary of radiations and their properties (table)

very penetrating; in fact a considerable thickness of lead is required to stop them.

The energies are given in MeV (1eV = 1.6×10^{-19} J –see 5.1.3)

α-decay

A nucleus of a radioactive element that emits an α-particle must transform into a nucleus of another element. The nucleus of the so-called 'parent' element loses two neutrons and two protons. Therefore the nucleon number (A) changes by 4 and the proton number (Z) by 2. The nucleus formed by this decay is called the 'daughter nucleus'. We may express such a nuclear decay by the nuclear reaction equation

$$\underset{\text{(parent)}}{{}^{A}_{Z}\text{X}} \rightarrow \underset{\text{(daughter)}}{{}^{A-4}_{Z-2}\text{Y}} + \underset{(\alpha\text{-particle})}{{}^{4}_{2}\text{He}}$$

For example the isotope uranium –238 is radioactive and decays by emitting α radiation to form the isotope thorium-234, the nuclear reaction equation being:

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

Or simply

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

Clearly in any nuclear radioactive decay equation, the mass number and proton number of the left-hand side of the equation must equal the mass number and proton number of the right-hand side of the equation.

β^- and β^+ decay (HL only)

In 1950 it was discovered that a free neutron decays into a proton and an electron after an average life of about 17 minutes. Another particle, the **antineutrino** is also emitted in this decay. In order to conserve momentum and energy in β decay, the existence of the neutrino was postulated in 1934 by the Italian physicist *Enrico Fermi*. This particle is extraordinarily difficult to detect. It has zero rest mass so travels at the speed of light; it is uncharged and rarely reacts with matter (Millions upon millions of neutrinos pass through the human body every second). However, in 1956, the neutrino was finally detected. It turns out though, that in β-decay in order to conserve other quantities, it must be an antineutrino and not a neutrino that is involved. (*Conservation laws along with particles and their antiparticles are discussed in detail in Option J*).

The decay equation of a free neutron is

$${}^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\text{e} + \bar{\nu}$$

Or simply

$$\text{n}^0 \rightarrow \text{p}^+ + \text{e}^- + \bar{\nu}$$

$\bar{\nu}$ is the symbol for the antineutrino.

The origin of β- particle is the decay of a neutron within a nucleus into a proton. The nucleon number of a daughter nucleus of an element formed by β^- decay will therefore remain the same as the nucleon number of the parent nucleus. However, its proton number will increase by 1. Hence we can write in general that

$$\underset{\text{(parent)}}{{}^{A}_{Z}\text{X}} \rightarrow \underset{\text{(daughter)}}{{}^{A}_{Z+1}\text{Y}} + \underset{\text{(electron)}}{{}^{0}_{-1}\beta} + \underset{\text{(antineutrino)}}{\bar{\nu}}$$

For example, a nucleus of the isotope thorium-234 formed by the decay of uranium-238, undergoes β- decay to form a nucleus of the isotope protactinium-234. The nuclear reaction equation for this decay is

$${}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\text{e} + \bar{\nu}$$

Or simply

$${}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + \text{e}^- + \bar{\nu}$$

The origin of β+ particles is from the decay of a proton within a nucleus into a neutron. The decay equation of the proton is

$${}^{1}_{1}\text{p} \rightarrow {}^{1}_{0}\text{n} + {}^{+1}_{0}\text{e} + \nu$$

Or simply

$p^+ \rightarrow n^0 + e^+ + \nu$

ν is the symbol for the neutrino.

For example, a nucleus of the isotope ruthenium-90 decays to a nucleus of the isotope technetium-90. The nuclear reaction equation for this decay is

$$^{90}_{44}\mathrm{Ru} \rightarrow {}^{90}_{43}\mathrm{Tc} + {}^{0}_{+1}\mathrm{e} + \nu$$

Or simply

$$^{90}_{44}\mathrm{Ru} \rightarrow {}^{90}_{43}\mathrm{Tc} + \mathrm{e}^+ + \nu$$

Unlike free neutrons, free protons are stable (although current theory suggests that they have an average life of 10^{30} years.). This probably explains why most of the observable matter in the universe is hydrogen.

γ radiation

The source of γ radiation in radioactive decay arises from the fact that the nucleus, just like the atom, possesses energy levels. In α and β decay, the parent nuclide often decays to an excited state of the daughter nuclide. The daughter nuclide then drops to its ground state by emitting a photon. Nuclear energy levels are of the order of MeV hence the high energy of the emitted photon. (Nuclear energy levels are discussed in more detail in topic 11).

7.2.3 IONIZING PROPERTIES OF α, β AND γ RADIATION

As α-particles travel through air, they readily interact with the air molecules by "grabbing" two electrons from a molecule and so becoming a neutral helium atom. This leaves the air molecule electrically charged and the air through which the α-particle are passing is said to be 'ionized'. If the air is situated between two electrodes, the positive ions created by the passage of the α-particles will migrate to the negative electrode and an **ionization current** can be detected.

β-particles and γ radiation may also cause ionization but in this situation the particles of the radiation actually remove electrons from the air molecules by collision with the molecules, thereby creating an electron-ion pair. This phenomenon of ionizing is used in particle detectors such as Geiger tubes and cloud and bubble chambers.

7.2.4 BIOLOGICAL EFFECTS OF RADIATION

It is well known that that X-rays and the radioactive radiations can cause severe damage to living organisms. The mechanism of this damage is not fully understood. However, it seems that when radiation is absorbed by a complex organic molecule, instead of straightforward excitation of the molecule, re-organization of the molecule may take place. For example, two hydroxyl radicals, $(.OH)_2$ may combine to form hydrogen peroxide, H_2O_2. Such re-combinations can have drastic effects particularly in the DNA of cells where this upset in the genetic coding may give rise to mutations in the next generation. Another effect of the upset in the genetic coding in a cell is that it may cause the cells to keep dividing without any check thereby resulting in a cancerous tumour.

Such affects on the genetic coding in cells are nearly always harmful and furthermore there is no safe lower limit of radiation as far as these genetic disturbances are concerned. Since α-radiation is the most readily absorbed of the radiations, this is by far the most harmful. However, one would have to swallow or breathe a radioactive source that emits α-radiation for it to be destructive for, as we have mentioned above, the radiation is readily stopped by about 4 cm of air. Combining the distance that one might be from a radioactive source and the penetrating properties of radiation, suggests that β-radiation is probably the most threatening because it can travel several metres in air but is readily absorbed by body tissue. Most γ radiation is likely to pass through human tissue, but on the other hand it can travel long distances in air.

The effect is essentially the same and the probability of genetic damage increases with increasing intensity and exposure to radiation. Because of this it is vitally important that we are exposed to the minimum of radiation. The effects of the atom bombs dropped on Nagasaki and Hiroshima are still with us and this should be a salutary lesson to all Governments.

The effects of radiation on the whole body have been studied in great detail. The radiation energy absorption by the body of about 0.25 J kg^{-1} causes changes in the blood and may lead to leukaemia; 0.8 –1.0 J kg^{-1} gives rise to severe illness (radiation sickness) with the chance of recovery within about 6 months, whereas about 5 J kg^{-1} is fatal. For this reason, people working in hospital X-ray departments, radioisotope laboratories, outer space and nuclear power stations take great precautions against exposure to radiation.

On the plus side, the controlled use of the radiations associated with radioactivity is of great benefit in the treatment of cancerous tumours (see Option I).

7.2.5 NUCLEAR STABILITY

Figure 705 shows the variation with proton number (Z) of the neutron number (N) (number of neutrons) of the naturally occurring isotopes. The straight line is the plot of the points given by $N = Z$.

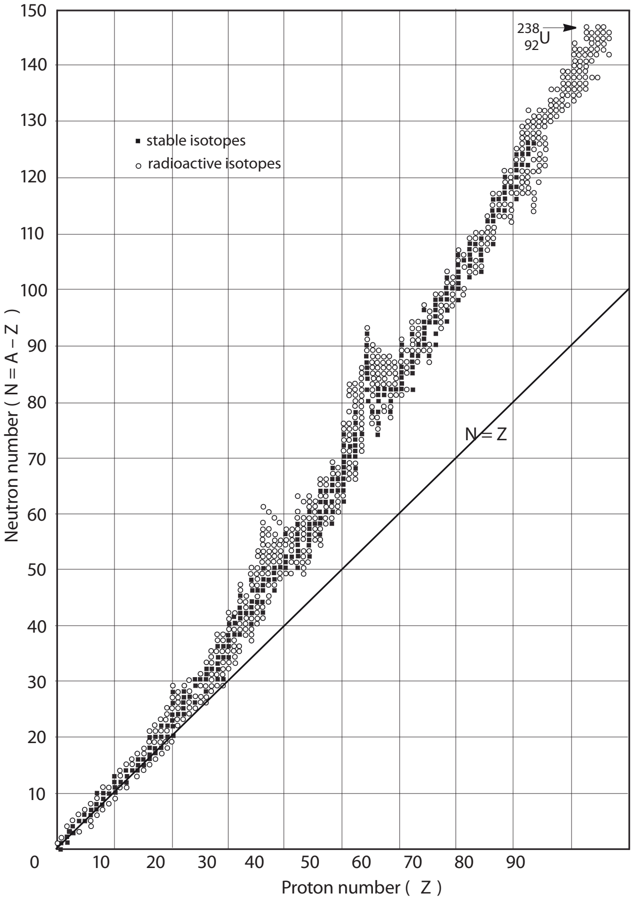


Figure 705 The variation of neutron number with proton number

From Figure 705 we see that for nuclei of the elements with Z less than about 20, the number of protons is equal to the number of neutrons. Above Z = 20, there is an excess of neutrons over protons and this excess increases with increasing Z. We can understand this from the fact that as Z increases so does the electrostatic force of repulsion between protons. To balance this, the number of neutrons is increased thereby increasing the strong nuclear force of attraction between the nucleons. When a proton is added to a nucleus, it will exert roughly the same force of repulsion on the other protons in the nucleus. This is because it is very nearly the same distance from each of the other protons. However, the strong nuclear force is very short range and is only really effective between adjacent neighbours. So as the size of the nucleus increases, proportionally more and more neutrons must be added. Each time protons and neutrons are added, they have to go into a higher energy state and eventually a nuclear size is reached at which the nucleus becomes unstable (a bit like piling bricks on top of one another) and the nucleus tries to reach a more stable state by emitting a nuclear sub-group consisting of two protons and two neutrons i.e. a helium nucleus (α particle).

Consider now a nucleus of the isotope $^{65}_{28}$Ni. This nucleus is unstable because the neutron excess is too great, each neutron added having to go into a higher energy state. To become stable, one of the neutrons will change into a proton by emitting an electron i.e. a β^--particle. On the other hand, a nucleus of the isotope $^{54}_{25}$Mn does not contain enough neutrons to be stable. To become stable, a proton changes into a neutron by emitting a positron i.e. a β^+ particle (positron).

HALF-LIFE

7.2.6 State that radioactive decay is a random and spontaneous process and that the rate of decay decreases exponentially with time.

7.2.7 Define the term *radioactive half-life*.

7.2.8 Determine the half-life of a nuclide from a decay curve.

7.2.9 Solve radioactive decay problems involving integral numbers of half-lives.

7.2.6-8 RADIOACTIVE HALF-LIFE

(This topic is explored in more depth in topic 13 and SL option B)

We have no means of knowing when a particular atom in a sample of radioactive element will undergo radioactive decay. You could sit watching an atom of uranium-238 and it might undergo decay in the next few seconds. On the other hand, you might wait 10^9 years or even longer, before it decayed. However, in any sample of a radioactive element there will be a very large number of atoms. It is therefore possible to predict the probability of decay of a particular atom. What we can say is that the more atoms in a sample, the more are likely to decay in a given time.

The rate of decay of atoms at a given instant is therefore proportional to the number of radioactive atoms of the element in the sample at that instant. As time goes by, the number of atoms of the element in the sample will decrease and so therefore will the rate of decay or activity as it is called. Of course, the number of atoms in the sample will not change since, when an atom of the element decays, it decays into an atom of another element.

Exponential decay

There are many examples in nature where the rate of change at a particular instant of a quantity is proportional to the quantity at that instant. A very good example of this is the volume rate of flow of water from the hole in a bottom of the can. Here the volume rate is proportional to the volume of water in the can at any instant. Rates of change such as this, all possess a very important property, namely that the quantity halves in value in equal increments of time. For example, if the quantity Q in question has a value of 120 at time zero and a value of 60, 20 seconds later, then it will have a value of 30 a further 20 seconds later and a value of 15 another 20 seconds later. If the quantity Q is plotted against time t, we get the graph shown in Figure 706.

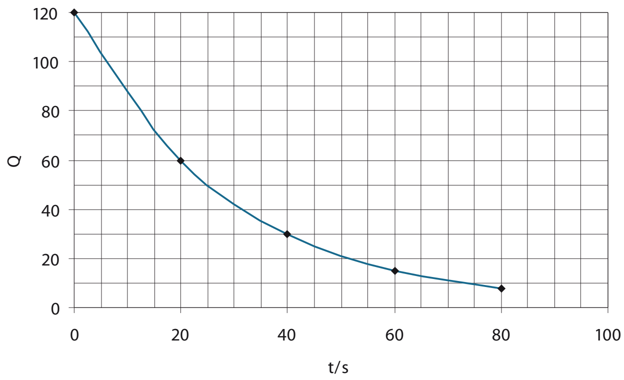


Figure 706 Exponential decay

This type of decay is called an **exponential decay**. The time it takes for the quantity to reach half its initial value is called the **half-life**. Clearly the half-life is independent of the initial value of the quantity and depends only on the physical nature to which the quantity refers. For instance, in the case of water flowing from a can, the half-life will depend on the size of the hole in the can and we might expect it to depend on the temperature of the water and the amount and type of impurities in the water. (*Perhaps here, is a good idea for an experiment to assess the Design criterion in IA*). For radioactive elements, the half-life depends only on the particular element and nothing else.

For the case of a radioactive element its half life is therefore defined as **the time it take the activity of a sample of the element to halve in value or the time it takes for half the atoms in the sample of element to decay.**

The number of atoms that decay in unit time i.e. the activity of the sample, has the SI unit the **becquerel** (Bq).

We also note from the graph, that theoretically it takes an infinite amount of time for the activity of a sample of a radioactive isotope to fall to zero. In this respect, we cannot ask the question "for how long does the activity of a sample last?"

7.2.9 SOLVE PROBLEMS INVOLVING INTEGRAL NUMBER OF HALF-LIVES

Example

A freshly prepared sample of the isotope iodine-131 has an initial activity of 2.0×10^5 B. After 40 days the activity of the sample is 6.3×10^3 Bq.

Estimate the half life of iodine-131.

By plotting a suitable graph, estimate the activity of the sample after 12 days.

Solution

If we keep halving the activity 2.0×10^5, we get 1.0×10^5, 0.5×10^5, 0.25×10^5, 0.125×10^5, 0.065×10^5 ($\approx 6.3 \times 10^3$). So 5 half-lives = 40 days. Hence 1 half-life = 8 days.

Another way of looking at this is to note that the activity of a sample after n half-lives is

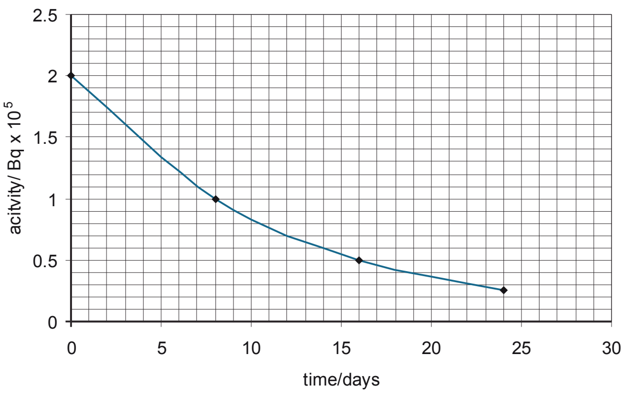
$\frac{A_0}{2^n}$ where A_0 is the initial activity. For this situation we have $2^n = \frac{2.0 \times 10^5}{6.3 \times 10^3} = 32$, giving

$n = 8$.

The data points for a graph showing the variation with time of the activity are shown below:

time/days	activity/Bq
0	2
8	1
16	0.5
24	0.25

So the graph is as follows

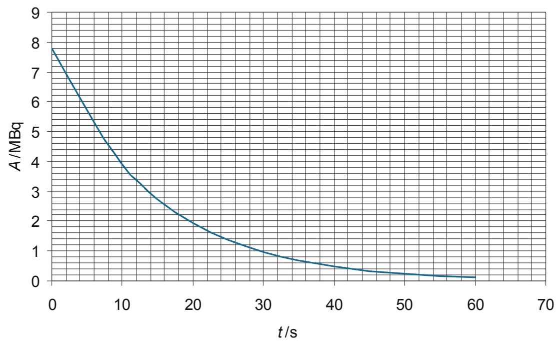


From which we see that after 12 days the activity is 7.0×10^4 Bq.

Exercise 7.2

1. The initial activity of a sample of a radioactive isotope decreases by a factor of $\frac{1}{16}$ after 90 hours. Calculate the half-life of the isotope.

2. The graph below shows the variation with time *t* of the activity *A* of a sample of the isotope xenon-114. Use the graph to determine the half-life of xenon-114.



7.3 NUCLEAR REACTIONS, FISSION AND FUSION

NUCLEAR REACTIONS

7.3.1 Describe and give an example of an artificial (induced) transmutation.

7.3.2 Construct and complete nuclear equations.

7.3.3 Define the term *unified atomic mass unit*.

7.3.4 Apply the Einstein mass–energy equivalence relationship.

7.3.5 Define the concepts of *mass defect*, *binding energy* and *binding energy per nucleon*.

7.3.6 Draw and annotate a graph showing the variation with nucleon number of the binding energy per nucleon.

7.3.7 Solve problems involving mass defect and binding energy.

7.3.1,2 ARTIFICIAL (INDUCED) TRANSMUTATION

So far only **transmutation** of elements has been discussed, i.e.the transformation of one element into another, that takes place through natural radioactivity. In 1919 Rutherford discovered that when nitrogen gas is bombarded with α-particles, oxygen and protons are produced. He surmised that the following reaction takes place:

$$^{4}_{2}\text{He} + ^{14}_{7}\text{N} \rightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{H}$$

After the discovery of this induced transformation, Rutherford working in conjunction with Chadwick, succeeded in producing artificial transmutation of all the elements from boron to potassium (excluding carbon and oxygen) by bombarding them with α-particles.