Radioactivity – an introduction

This Factsheet will explain the nature, properties and effects of radioactive emissions, the concept of half-life and the hazards and benefits of radioactivity.

What is radioactivity?

Radioactivity involves the spontaneous (in other words, occurring without outside interference) emission of an alpha or beta particle from the nucleus of an atom, causing the proton number (see box) of the atom to change. An individual radioactive decay therefore always involves one element changing to another element.

Radioactive decay may also be accompanied by gamma emission. This is how the nucleus rids itself of excess energy if it is in an excited state after emitting an alpha or beta particle.

The properties of alpha and beta particles and gamma rays are shown in Table 1. As the table shows, they differ significantly in their
♦ range – how far they travel, or how easily they are stopped
♦ ionising ability – their ability to "knock" electrons from atoms that they collide with, turning them into ions.
These are important in considering health risks

Table 1. Properties of alpha, beta and gamma radiation.

Type of radiation	Consists of	Range	Ionising Properties
alpha (α)	helium nuclei – i.e. 2 protons + 2 neutrons	5 cm in air – can be stopped by a thick sheet of paper	Highly ionising
beta (β^-)	fast electrons	Up to a few metres in air – can be stopped by a few millimetres of aluminium	Less than α
gamma (γ)	very high frequency (and so high energy) electromagnetic waves	Singificantly reduced by several metres of concrete, or several cm of lead	Weak – much less than β

*Tip: In beta emission, the electron comes **from the nucleus**. It is **not** one of the electrons from the atom.*

What sort of atoms decay?

Atoms that decay radioactively are known as **unstable**; those that do not are **stable**. Atoms may be unstable because:
♦ they are too large (with a larger nucleus than lead)
♦ the balance between protons and neutrons is not right. In small stable atoms, there are roughly the same number of protons and neutrons, whilst in large stable atoms, neutrons always outnumber protons.
This will be covered in more detail in later work on radioactivity.

Atoms – a reminder

An atom contains **protons**, **neutrons**, and **electrons**; the properties of these are shown in the table below.

Particle (symbol)	Mass (atomic mass units)	Charge (units of 1.6×10^{-19}C
proton (p)	1	+1
neutron (n)	1	0
electron (e)	≈ 0	-1

The **nucleus** of the atom contains the protons and neutrons, which are known collectively as **nucleons**. **The nucleus is the only part of the atom involved in radioactivity**.

Two numbers are used to describe the particles in the nucleus:
♦ **A** – the **nucleon number** (or **mass number**)
♦ **Z** – the **proton number** (or **atomic number**)
So, if an atom has A = 13 and Z = 6, then it would have 6 protons, and 7 neutrons (since protons + neutrons = A). **The proton number tells you which element the atom is** – so for example, any atom with proton number 6 is a carbon atom.

We write an atom of element X with nucleon number A and proton number Z as $^A_Z X$ - so an atom of oxygen with 8 protons and 8 neutrons in its nucleus is written $^{16}_8 O$.

♦ **Isotopes** of an element have the same proton number, but different nucleon numbers – so they have the same number of protons but different numbers of neutrons. Common examples of isotopes are $^{14}_6 C$ and $^{12}_6 C$, and $^{35}_{17} Cl$ and $^{37}_{17} Cl$.

Where does radioactivity come from?

Radioactivity comes from both natural and man-made sources. Man-made, "artificial" elements with very large nuclei are always radioactive, but many naturally occurring elements (or particular isotopes of elements) are radioactive too.

This naturally occurring radiation means that we are exposed to a low level of radiation constantly; this is called **background radiation**.

*Sources of background radiation include:*

♦ *rocks, such as granite*
♦ *radon gas, which is formed in the ground*
♦ *cosmic rays, which come from space*
♦ *artificially produced radioisotopes*

Effect of radiaoctive decay on the nucleus – nuclear equations.

- Alpha decay removes 2 protons and 2 neutrons from the nucleus – so Z, the proton number, decreases by 2, and A, the nucleon number, decreases by 4.

- In beta decay, a neutron in the nucleus emits an electron and changes to a proton. So Z increases by 1 and A stays the same.

- Gamma radiation only involves the emission of energy, and so does not change either A or Z.

Radioactive decay can be represented in **nuclear equations**:
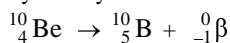
eg: α decay of radon 204:

$$\begin{array}{cccccc} {}^{204}_{86}\text{Rn} & \rightarrow & {}^{200}_{84}\text{Po} & + & {}^{4}_{2}\alpha \end{array}$$
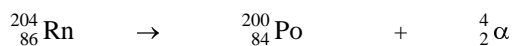
| The atom we start with – radon 204 | The atom produced after decay – polonium 200 | alpha particle |

β decay of beryllium 10:

$$ {}^{10}_{4}\text{Be} \rightarrow {}^{10}_{5}\text{B} + {}^{0}_{-1}\beta $$

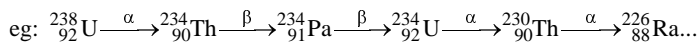The α particle may also be written as ${}^{4}_{2}\text{He}$ (as it is a helium nucleus).

The β particle may also be written as ${}^{0}_{-1}\text{e}$ (as it is an electron)

Tip: *Check your finished equation is right by checking that the A values add up to the same on both sides, and the Z values add up to the same on both sides.*
*Always put the A and Z values on for the emitted particles as well as the atoms. This helps you to make sure you get the equation right.*

Radioactive decay series
In some cases, the atom produced is also radioactive, and so decays in its turn. This process continues until an atom is produced that will not decay. If the initial atom has a large nucleus, then the final, non-radioactive atom in the series will be a stable isotope of lead.

eg: ${}^{238}_{92}\text{U} \xrightarrow{\alpha} {}^{234}_{90}\text{Th} \xrightarrow{\beta} {}^{234}_{91}\text{Pa} \xrightarrow{\beta} {}^{234}_{92}\text{U} \xrightarrow{\alpha} {}^{230}_{90}\text{Th} \xrightarrow{\alpha} {}^{226}_{88}\text{Ra}...$

Artificial radioactivity
Radioactive isotopes can be created by bombarding naturally occurring atoms with particles such as neutrons (used in a nuclear reactor), protons or α particles. Nuclear equations can be written for this type of process in exactly the same way:

eg: ${}^{63}_{29}\text{Cu} + {}^{1}_{0}\text{n} \rightarrow {}^{64}_{29}\text{Cu} \rightarrow {}^{64}_{30}\text{Zn} + {}^{0}_{-1}\beta$
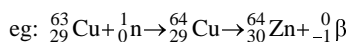
Some artificially produced isotopes decay by emitting a **positron** – which is a particle identical to an electron, except that it is positively charged (in fact, it is the **antiparticle** of the electron). This is known as positron emission, or β^+ decay. In positron emission, a proton emits a positron, thus changing into a neutron, so the proton number decreases by 1, and the nucleon number remains unchanged.

eg: Fluorine is bombarded with α particles to produce sodium –22:

$${}^{19}_{9}\text{F} + {}^{4}_{2}\alpha \rightarrow {}^{22}_{11}\text{Na}$$
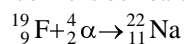
Sodium – 22 then decays by positron emission to form Neon – 22

$${}^{22}_{11}\text{Na} \rightarrow {}^{22}_{10}\text{Ne} + {}^{0}_{1}\text{e}$$
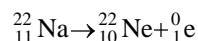
Typical exam question
The following nuclear equation represents the decay of uranium to
thorium: ${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{y}_{z}\text{X}$
(a) Determine the values of y and z   [2]
(b) Identify the particle X   [1]
(c) Q represents the energy released in this reaction. Which two forms does this energy take?   [2]
(d) The thorium also decays by β^- emission forming an isotope of palladium (Pa). Write the nuclear equation for this decay. [2]

(a) y = 238 – 234 = 4 ✓ *z = 92 – 90 = 2* ✓
(b) The particle has 4 nucleons and 2 protons
    It is an alpha particle or He nucleus. ✓
(c) Kinetic energy of the alpha particle ✓ *Gamma radiation* ✓
(d) ${}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa}$ ✓ *+ β* ✓ *+ (energy (γ))*

Decay law and half life
Radioactive decay is a **random** process – it is not possible to predict when a particular nucleus will decay. We can get a picture of how this works using another "random" process – throwing dice.

Imagine you have a large number (say 6000) of normal dice. Each dice represents a radioactive atom, and we will say a dice has "decayed" (to give a stable product) if it shows a 1 when it is thrown. Of course, the dice are not a perfect model – radioactive decay goes on continuously, not just at set time intervals, and may produce radioactive products. However, it is close enough to be useful.

All the dice are thrown. About one sixth of the dice, or about 1000 dice, will show a 1 – so these atoms have decayed.

There are 5000 "undecayed" dice left. They are thrown again – again, about one sixth of them will show a 1, and decay. The decayed dice are removed, and the process is repeated.

The numbers of dice we'd expect to decay on each throw are shown in the table and graph below:

Throw	No. of Decays	Throw	No. of Decays
1st	1000	7th	335
2nd	833	8th	279
3rd	694	9th	233
4th	579	10th	194
5th	482	11th	162
6th	402	12th	135
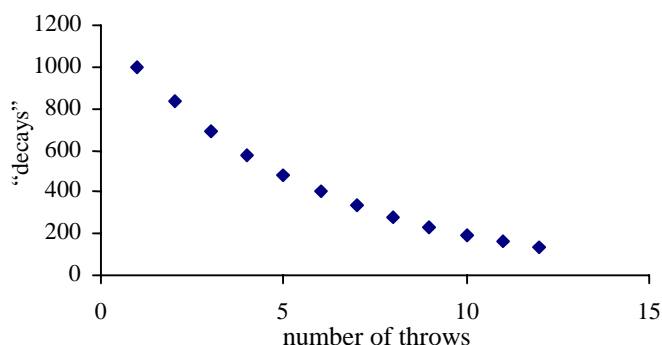
Key points to note:

♦ We can predict that the actual results of throwing the dice would give results very much like these. However, we have no idea which dice will "decay" on any one throw, or how long a particular dice will take to "decay".

♦ The probability of any dice "decaying" is always the same – it is $\frac{1}{6}$. So the number of dice decaying each time will be about $\frac{1}{6}$ of the dice that are left.

♦ The graph produced by the dice has a characteristic shape – it is called an exponential decay curve. (see Factsheet 10 – Exponentials and Logarithms – for more on exponentials)

Radioactivity behaves very much like the dice – there is a constant probability of a nucleus decaying, so the number of nuclei decaying is proportional to the total number of them. The number of decays per second of a sample is called its **activity**, and is measured in bequerels (Bq)

The number of atoms decaying over a given period is a constant fraction of (or is proportional to) the number remaining.

This is expressed in an equation as $A = \lambda N$
where A = activity, λ = decay constant (which is the probability of any given atom of that element decaying in one second) and N = no. of undecayed atoms.

This equation leads to an **exponential decay curve**.

Tip: You must remember that the atoms decaying do not disappear – they change into another element, which may or may not be radioactive.

An exponential decay curve has some very important properties; these will also come up elsewhere in Physics.

♦ Activity never decreases to zero
♦ There is a **constant half life** – for a given radioactive element, the time taken for the activity to halve will always be the same. (So, for example, it would take the same time for activity to decrease from 400 Bq to 200 Bq, as for activity to decrease from 200Bq to 100Bq

♦ The **half-life** in seconds is given by $T_{\frac{1}{2}} = \dfrac{0.69}{\lambda}$, where λ is the decay constant. (This equation will be justified in later studies)

Calculations involving half life
Calculations involving half life may require you to:
♦ determine half-life from a graph
♦ determine half life from count rates
♦ determine count-rates or time, given the half life.
The following examples illustrate these.

Example 1. The table below shows the count rate for a radioactive isotope. The background count rate is 0.6 counts per second.
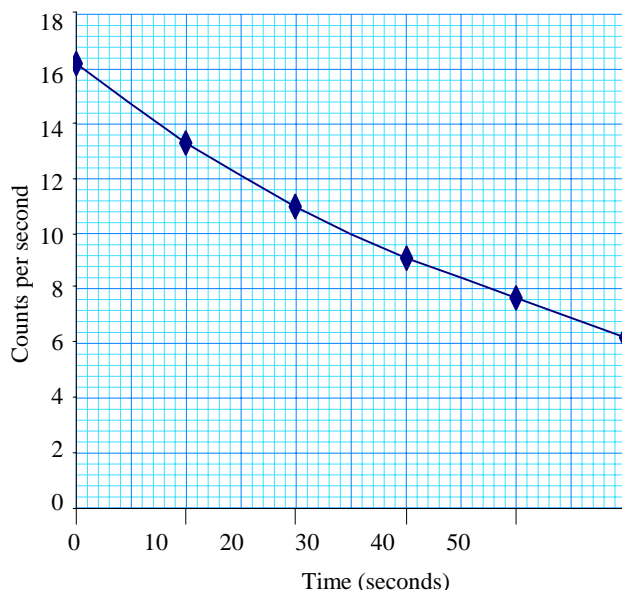
Time (s)	0	10	20	30	40	50
Count rate (counts per second)	16.7	13.8	11.6	9.7	8.2	6.8

Plot a graph of corrected count rate against time and use it to determine the half life of the isotope.

The table below shows the corrected count rates:

Time (s)	0	10	20	30	40	50
Count rate (counts per second)	16.1	13.2	11.0	9.1	7.6	6.2

Now we measure two or more half-lives from the graph. For example, we could choose to find the time taken for the count rate to decline from 16 to 8, and from 14 to 7. We then average the values.

From graph:
  time taken to decline from16 to 8 is 37 seconds.
  time taken to decline from 14 to 7 is 45 – 7.5 = 37.5 seconds.

So our estimate is the average of these values – 37.25=37 sec(2 SF) (since the original data was given to 2 SF, it would not be appropriate to use any greater accuracy in the answer).

---

*Tip: **You must** always **use** corrected count rates **in any half-life calculations. If you are told the background count, use it!***

Example 2. A sample of carbon 14 has an activity of 40 Bq
a) After 17 100 years, the activity of this sample will have fallen to 5Bq. Calculate the half life of carbon 14.

b) After how many more years will the activity of this sample have fallen to approximately 0.078Bq?

a) We need to work out how many half-lives are required for the activity to fall to 5Bq.

$40 \xrightarrow{T_{1/2}} 20 \xrightarrow{T_{1/2}} 10 \xrightarrow{T_{1/2}} 5$

So 17100 years = 3 half-lives.
So half-life = 17 100 ÷3 = 5700 years.

b) 5 → 2.5 → 1.25 → 0.625 → 0.3125 → 0.15625 → 0.078125
So it takes another 6 half-lives = 34 200 years.

Typical Exam Question
The half life of a sample of radioactive material is related to its decay constant by the equation:

$$T_{1/2} = \frac{0.69}{\lambda}$$

(a) Explain the meaning of the symbols:
   (i) $T_{1/2}$ [1]
   (ii) λ [1]
(b) A sample of ^{24}Na has a half-life of 234 hours.
    Calculate the radioactive decay constant for ^{24}Na [2]

(a) (i) $T_{1/2}$: Half-life, the average time for the number of undecayed
        atoms or nuclei to be reduced to half their initial number. ✓
    (ii) λ: Decay constant, the constant of proportionality in the
        relationship: activity $\propto$ number of undecayed atoms ✓
(b) $\lambda = \ln2 /(234 \times 3600)$ ✓ $= 8.2 \times 10^{-7} s^{-1}$ ✓

Typical Exam Question
(a) Sketch a diagram of the apparatus that could be used in
    a school laboratory to determine the half-life of a radioactive
    sample. [3]
(b) State the measurements that are required to accurately
    determine the half-life. [2]
(c) Explain how the measurements would be used to determine
    the half-life for the sample. [3]
(a) Diagram should include radioactive source✓ and GM tube✓
    connected to ratemeter✓
(b) For this sample the count rate should be recorded at intervals of
    10s (5-20s) ✓ for 300s. ✓
(c) Plot a graph of count rate against time✓
    Find, from the graph, the time for the count rate to half ✓
    Repeat using different intervals of halving (1600 to 800, 1000 to
    500 etc.) ✓ Average the results.

Experiments with radioactivity

A **Geiger-Müller tube** (G-M tube) attached to a **ratemeter** is used to detect radioactivity in the school laboratory. It is used to measure the radioactive count-rate per second (which is proportional to the number of emissions per second).

Some errors arise in the use of the GM tube because after it has registered one count, there is a short interval (known as the **dead time**) before it can register another, so any decays occurring in this period are not registered. This problem is most noticeable when the count rate is high.

Radioactive sources for experiments are always supplied in a holder, and have low levels of activity. When not in use, they are stored inside a lead "castle", in a wooden box; accordingly they will prevent no danger when stored. The following **safety precautions** must always be observed when handling radioactive sources:

♦ always lift with forceps
♦ hold so that the open end is directed away from the body
♦ never bring close to the eyes

In all experiments, it is necessary to first measure the **background radiation** for a short time and obtain an average value. This value is then subtracted from all future readings to give the count rate due to the source alone – the **corrected count rate**.

In any experiment aiming to measure the count rate for just one type of radiation (in other words, for just α, just β or just γ), it is necessary to ensure that the other types of radiation do not "interfere":

♦ To obtain γ alone, a cover disc of aluminium over the source will absorb any α or β produced (NB: γ is never produced alone, so this will always be necessary).

♦ An α or β source can be selected that does not emit γ radiation, but it is also necessary to consider any other products in the radioactive decay series; if an α emitter produces a decay product that is also radioactive, the count-rate of the decay product will also be included in any measurements. This is addressed by selecting a source for which all the decay products in the series have much longer half-lives (and so a low, roughly constant activity rate) over the time of the experiment, or much shorter half lives (so almost all of the atoms decay within a very short time-scale).

> **Exam Hint:** *Examination questions about experiments require essential practical details, such as precautions, how frequently measurements are taken and sources of error.*

Absorption of α radiation.
After the background radiation has been measured, the source is intially placed close to the GM tube and the average reading noted over a short period. This is repeated, moving the GM tube away from the source in 5mm steps, until the count rate has returned to the background level (or the corrected count rate is zero. Materials such as paper or metal can be placed between the source and the counter to demonstrate absorption; in this case the GM tube must be less than 5cm from the source.

Absorption of β radiation
The same procedure as for α radiation can be followed, except that the steps by which the GM tube is moved away need to be longer, since the range of β radiation is much greater. Various thicknesses of aluminium foil can be placed between the source and the counter to determine the required thickness for total absorption.

Absorption of γ radiation
Gamma radiation is only absorbed to any extent by lead; the thickness of lead required can be determined in the same fashion as the previously described experiments.

Range of γ radiation in air
Gamma rays are not absorbed to any great extent by air; their intensity falls off with distance according to an inverse square law – in other words, the intensity is inversely proportional to the square of the distance from the source. This gives the equation:

$$I = \frac{k}{d^2} \text{ , where k is a constant.}$$

This is demonstrated by placing a GM tube at various distances from a gamma source and measuring the count rates. The count rates are corrected for background radiation. A graph is then plotted of corrected count rate (y-axis) against $\frac{1}{d^2}$. This should give an approximately straight line.

Errors – resulting in the graph not being exactly a straight line – are due to the source itself having a size – in other words, not being a "point source" to the GM tube, to the GM tube's dead time., and to the random nature of decay.

Measuring half life
After the background count has been measured, the source is placed close to the GM tube. Counts are taken at 10 second intervals, and a graph of corrected count rate (y-axis) against time (x-axis) can be produced. From the graph, a number of values for the half-life can be found; an average of these produces a suitable estimate. (In later work, an alternative, more accurate approach will be used).

Uses of radioactivity
Carbon dating
Carbon-14 is a naturally occurring beta-emitter with a half-life of 5700 years. It is formed in the atmosphere from nitrogen, due to the action of cosmic rays, and becomes incorporated in radioactive carbon dioxide.

During photosynthesis, plants and trees take in carbon dioxide from the atmosphere; this includes carbon-14. The amount of carbon-14 present as a proportion of the total amount of carbon will be, on average, the same in a living plant as in the atmosphere as a whole.

However, when the plant dies, it stops interacting with the atmosphere, so it doesn't acquire any more carbon-14. The activity level then declines exponentially. By measuring the residual activity, it is possible to estimate how many half-lives there have been since the plant died, and hence how long ago it lived.

Carbon-14 is particularly suitable for this use due to:
♦ its presence in all living things
♦ the length of its half life – sufficiently short that changes can be observed over thousands of years, but sufficiently long that there is still significant residual activity after this period.

This method assumes that the proportion of carbon-14 in the atmosphere has stayed the same; this depends on whether the amount of cosmic rays penetrating the atmosphere was the same.

Radioactive tracers
Radioactive tracers are used to follow the path of a compound in a system such as pipelines or the human body. They rely on the fact that radioactive isotopes behave identically to non-radioactive ones in physical and chemical processes. For example, a radioactive tracer can be used to detect a leak in a pipe, since the count-rate will increase where the leak occurs as the pipe will block α and β emissions.

A γ emitter would not be suitable, since the pipe would not block this. Isotopes used for this purpose need to have a suitable half-life, so that the count rate will not become so low as to be almost undetectable during the course of the investigation.

Sterilization
Gamma rays can be used to sterilize medical instruments or keep food fresh for a longer period.

Radiotherapy -cancer treatment
Radiotherapy involves using gamma sources to attack cancer cells. It relies on the cancerous cells being more affected by the radiation than the normal ones, but obviously the normal cells are affected too, so it does produce some unpleasant side effects, like those described in the "Dangers of radioactivity" box. Again, a short half-life is required.

Exam Workshop
This is a typical poor student's answer to an exam question. The comments explain what is wrong with the answers and how they can be improved. The examiner's answer is given below.

Top number $\longrightarrow$ $^{238}_{92}$U **and** $^{235}_{92}$U **are radioactive isotopes of Uranium.**
Bottom number $\nearrow$

(a) State the correct terms, and meanings of, the 'top number' and 'bottom number'.   [4]
top number: number of protons + neutrons ✔
bottom number: number of protons ✔   2/4

> Although the student knows what the numbers mean, s/he has lost out by not giving the correct terms – not reading carefully, perhaps?

(b) Explain the meaning of the term 'isotope'.   [2]
atoms with different numbers of neutrons ✔   1/2

> To obtain both marks, the candidate needs to make it clear that the isotopes have the same number of protons. This could be written down directly, or the candidate could make reference to A and Z.

(c) U-238 decays via α-emission to produce an atom of thorium(Th). Write a nuclear equation to represent this decay.   [3]
$^{238}_{92}$U $\rightarrow$ $^{234}_{90}$Th $+ \alpha$ ✔✔   2/3

> The two marks awarded were for calculation of A and Z for thorium. The candidate needed to indicate the values of Z and A for the α particle to obtain full marks; clearly s/he knew them, since the other calculation was correct.

(d) Uranium-238 has a half-life of 4.5×10^9 years. Calculate the time required for the activity of a sample of Uranium-238 to decrease from 6.04×10^4 Bq to 1.8875×10^3 Bq.
$6.04 \times 10^4 \div 1.8875 \times 10^3 = 32$ ✔
$2 \times 2 \times 2 \times 2 \times 2 = 32$, so 5 half-lives ✔   2/3

> What the candidate has done is correct, and clearly presented. But s/he has missed out on the final mark by not reading the question carefully – it asks for the time in years, not the number of half-lives. The candidate should be surprised not to use all the information.

Examiner's Answers
(a) Top: nucleon / mass number. ✔
It's the no. of nucleons or protons + neutrons in nucleus ✔
Bottom: atomic number / proton number ✔
It's the number of protons in nucleus ✔
(b) Atoms with the same number of protons ✔
but different numbers of neutrons in their nuclei. ✔
c) $^{238}_{92}$U $\rightarrow$ $^{234}_{90}$Th $+ ^4_2\alpha$ (1 each for 234, 90 and 1 for 4 and 2)
d) $6.04 \times 10^4 = 1.8875 \times 10^3 \times 2 \times 2 \times 2 \times 2 \times 2$ ✔(method)
so 5 half-lives ✔. So $5 \times 4.5 \times 10^9 = 2.25 \times 10^{10}$ years ✔

Dangers of radioactivity
Since α radiation is so easily absorbed, it is not dangerous unless the radioactive source is inside the body. Although β radiation is more penetrating, most of its energy is usually absorbed by clothes, and it is easy to protect people further by using aluminium shielding. The greatest danger arises from gamma radiation; although it is not strongly ionising, it can penetrate deeply into the body.

Damage from radiation can include:
♦ radiation burns (like normal burns, but caused by gamma rays)
♦ hair loss
♦ radiation sickness
♦ damage to reproductive organs
♦ delayed effects such as cancer and leukemia
The level of danger depends on the amount of radiation absorbed; people likely to be exposed to radioactive materials, such as workers in nuclear power plants, have their radiation dosage carefully monitored to ensure it does not exceed safe levels.

The hazard represented by a particular radioisotope is therefore dependent on:

♦ the nature of its emissions, and of the emissions of its decay products
♦ its level of activity
♦ its half-life, since long half-life radioisotopes will continue to be highly active for a long period of time, and hence potentially be a danger for this time.

This has implications for the disposal of nuclear waste, which includes long-half-life isotopes. The canisters used to contain nuclear waste need to be resistant to naturally occurring phenomena like landslides or earthquakes, since the contents would still represent a danger for many years to come.

Qualitative Questions

1. Give two sources of background radiation

2. Give two uses for radioactive elements, other than carbon dating.

3. Explain how carbon dating works.

4. Describe the penetrating power of α, β and γ radiation.

5. Explain what is meant by "half-life"

6. Explain what is meant by "activity", and give its units

7. Which form of radiation is potentially the most dangerous to human beings?

8. Explain why γ emission occurs

The answers to these questions may be found in the text.

Quantitative Questions

1. Write nuclear equations for the following decays:

a) β emission from a $^{60}_{27}$Co nucleus to produce Nickel (Ni)

b) α emission from a $^{214}_{84}$Po nucleus to produce Lead (Pb)

c) $^{63}_{29}$Cu absorbs a neutron, then decays by β emission to form zinc (Zn)

2. An isotope has a half-life of 12 hours. Calculate its decay constant.

3. The graph below shows the decline of activity with time for a radioisotope. Calculate its half-life.
    The background count is 2.6.
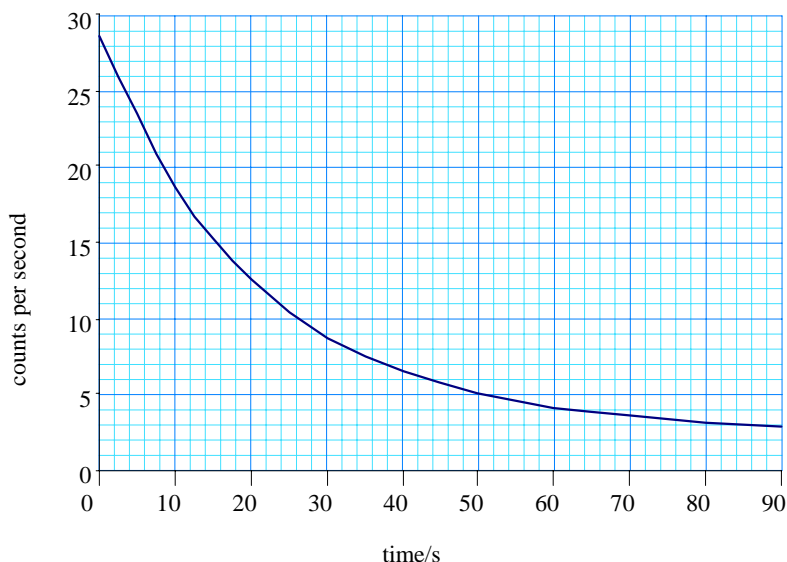
Hint: the background count must be allowed for – so, for example, find the time required for the count to decline from 24 + background to 12 + background.

4. A radioisotope has a half-life of 12 hours.
    Its initial activity is 1.6×10^{12} Bq.
    Find the time required for its activity to decline to 3.125×10^{9} Bq.

5. The activity of a radioisotope declines from 920Bq to 7.1875Bq in 1 hour 10 minutes. Find its half life, giving your answer in minutes.

Answers

1. a) $^{60}_{27}$Co$\rightarrow ^{60}_{28}$Ni$+^{0}_{-1}\beta$

b) $^{214}_{84}$Po$\rightarrow ^{210}_{82}$Pb$+^{4}_{2}\alpha$

c)) $^{63}_{29}$Cu$+^{1}_{0}$n$\rightarrow ^{64}_{30}$Zn$+^{0}_{-1}\beta$

2. 1.60×10^{-5} (3SF)

3. 14 – 15 seconds.

4. 108 hours (or 4 days 12 hours)

5. 10 minutes