RADIOACTIVITY

The knowledge and understanding for this unit is given below.

Ionising radiations

1. Describe a simple model of the atom which includes protons, neutrons and electrons.
2. State that radiation energy may be absorbed in the medium through which it passes.
3. State the range through air and absorption of alpha, beta and gamma radiation.
4. Explain what is meant by an alpha particle, beta particle and gamma ray.
5. Explain the term ionisation.
6. State that alpha particles produce much greater ionisation density than beta particles or gamma rays.
7. Describe how one of the effects of radiation is used in a detector of radiation.
8. State that radiation can kill living cells or change the nature of living cells.
9. Describe one medical use of radiation based on the fact that radiation can destroy cells.
10. Describe one use of radiation based on the fact that radiation is easy to detect.

Dosimetry

1. State that the activity of a radioactive source is measured in becquerels, where one becquerel is one decay per second.
2. State that the absorbed dose D is the energy absorbed per unit mass of the absorbing material.
3. State that the gray Gy is the unit of absorbed dose and that one gray is one joule per kilogram.
4. State that the risk of biological harm from an exposure to radiation depends on:
   a) the absorbed dose
   b) the kind of radiation, e.g. slow neutron
   c) the body organs or tissue exposed.
5. State that a radiation weighting factor,W_R is given to each kind of radiation as a measure of its biological effect.
6. State that the dose equivalent H is the product of D and W_R is measured in sieverts Sv.
7. Carry out calculations involving the relationship $H = DW_R$.
8. Describe factors affecting the background radiation level.

Half life and safety

1. State that the activity of a radioactive source decreases with time.
2. State the meaning of the term ‘half life’.
3. Describe the principles of the method for measuring the half life of a radioactive source.
4. Carry out calculations to find the half life of a radioactive isotope from appropriate data.
5. Describe the safety procedures necessary when handling radioactive substances.
6. State that the dose equivalent is reduced by shielding, limiting the time of exposure or by increasing the distance from the source.
7. Identify the radioactive hazard sign and state where it should be displayed.

Nuclear Reactors

1. State the advantages of using nuclear power for the generation of electricity.
2. Describe, in simple terms, the process of fission.
3. Explain, in simple terms, a chain reaction.
4. Describe the principles of the operation of a nuclear rector in terms of fuel rods, moderator, control rods, coolant and containment vessel.
5. Describe the problems associated with the disposal and storage of radioactive waste.

Units, prefixes and scientific notation

1. Use SI units of all quantities appearing in the above Content Statements.
2. Give answers to calculations to an appropriate number of significant figures.
3. Check answers to calculations.
4. Use prefixes (μ, m, k, M, G)
5. Use scientific notation.

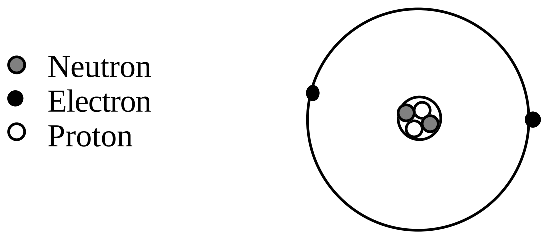
IONISING RADIATIONS

Atoms

Every substance is made up of atoms. Each element is made up of the one kind of atom, sometimes these atoms are combined together to form molecules.
Inside each atom there is a central part called the **nucleus.** The nucleus contains two particles:

protons: these have a positive charge
neutrons: these have no charge.

Surrounding the nucleus are negatively charged **electrons**.
An uncharged atom will have the same number of protons and electrons.
Consider the element helium, which has two neutrons and two protons in the nucleus, and two electrons surrounding the nucleus. This can be represented as:



atom of helium

Ionisation

Atoms are normally electrically neutral but it is possible to add electrons to an atom or take them away. When an electron is added to an atom a negative ion is formed; when an electron is removed a positive ion is formed. **The addition or removal of an electron or electrons is called ionisation.** It is important to remember that the nucleus remains unchanged during this time.

Ionising Radiations

There are some atoms which have unstable nuclei which throw out particles to make the nucleus more stable. These atoms are called **radioactive**. The particles thrown out cause ionisation and are called ionising radiations.
There are three types of ionising radiation:

Alpha particles are the nuclei of helium atoms. They have 2 neutrons and 2 protons in the nucleus and are therefore positively charged.

Symbol: ${}^{4}_{2}\alpha$

Beta particles are fast moving electrons. They are special electrons because they come from within the nucleus of an atom. They are caused by the break up of a neutron into a positively charged proton and a negatively charged electron.

Symbol: ${}^{0}_{-1}\beta$

Gamma rays are caused by energy changes in the nuclei. Often the gamma rays are sent out at the same time as alpha or beta particles. Gamma rays have no mass or charge and carry energy from the nucleus leaving the nucleus in a more stable state.

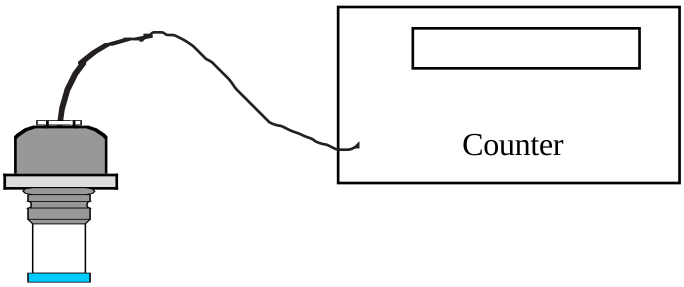
Symbol: γ

Properties of radiation
Alpha particles will travel about 5 cm through the air before they are fully absorbed. They will be stopped by a sheet of paper. Alpha particles produce much greater ionisation density than beta particles or gamma rays. They move much more slowly than beta or gamma radiation.

Beta particles can travel several metres through air and will be stopped by a sheet of aluminium a few millimetres thick. They have a lower ionisation density than alpha particles.

Gamma rays can only be stopped by a very thick piece of lead. They travel at the speed of light and have a very low ionisation density.

Detection of Radiation
A Geiger-Müller (GM) tube is used to detect α, β and γ radiation. If any of these enter the tube, ions are produced resulting in a small current flow. The current is amplified and a counter counts the number of events giving an indication of the level of radioactivity.



Geiger - Müller tube

Effects of radiation on living things
All living things are made of cells. Ionising radiation can kill or change the nature of healthy cells. This can lead to different types of cancer.

Uses of the properties of radiation
Radiation can be used in the treatment of cancer. The radioactive source, cobalt-60 kills malignant cancer cells. The source is rotated around the body centred on the cancerous tissue so the cancerous cells receive radiation all the time. However, as the source is moving the healthy tissue only receives the radiation for a short time and is therefore not damaged.

Radioactive tracers help doctors to examine the insides of our bodies. Iodine-131 is used to see if our thyroid glands are working properly. The thyroid gland controls the rate at which our body functions. The thyroid gland absorbs iodine, so a dose of radioactive iodine (the tracer) is given to the patient. Doctors can then detect the radioactivity of the patient's throat, to see how well the patient's thyroid is working.

DOSIMETRY

Activity

The activity, A, of a radioactive source is the number of decays, N, per second. It is measured in bequerels where 1 Bq = 1 decay per second.

Absorbed dose

The greater the transfer of radiation energy to the body the greater the chance of damage to the body. The absorbed dose, D, is the energy absorbed per unit mass of the absorbing material and is measured in grays, Gy.

$$1 \text{ Gy} = 1 \text{ J/kg}$$

The biological effects of radiation

All ionising radiation can cause damage to the body. There is no minimum amount of radiation which is safe. The risk of biological harm from an exposure to radiation depends on:

- the absorbed dose
- the kind of radiation
- the body organs or tissue exposed.

The body tissue or organs may receive the same absorbed dose from alpha or gamma radiation, but the biological effects will be different. To solve this problem a radiation weighting factor,W_R is used which is simply a number given to each kind of radiation as a measure of its biological effect. Some examples are given below.

W_R	Type of radiation
1	beta particles / gamma rays
10	protons and fast neutrons
20	alpha particles

Dose equivalent

When scientists try to work out the effect on our bodies of a dose of radiation they prefer to talk in terms of dose equivalent. The dose equivalent H is the product of D and W_R.

$$\text{Dose equivalent} = \text{absorbed dose} \times \text{radiation weighting factor}$$

$$\boxed{\mathbf{H = DW_R}}$$

The dose equivalent is measured in sieverts, Sv.

Example
A worker in the nuclear industry receives the following absorbed doses in a year.
30 mGy from gamma radiation, $W_R = 1$
300 mGy from fast neutrons, $W_R = 10$
Calculate the dose equivalent for the year.

$$H = DW_R$$

for gamma $H = 30 \times 10^{-3} \times 1 = 30 \times 10^{-3}$ Sv
for neutrons $H = 300 \times 10^{-6} \times 10 = 3.0 \times 10^{-3}$ Sv

total $H = 30 \times 10^{-3} + 3.0 \times 10^{-3} = 33 \times 10^{-3}$ Sv

Background radiation
Everyone is exposed to background radiation from natural and from man-made radioactive material. Background radiation is always present. Some of the factors affecting background radiation levels are:

- Rocks which contain radioactive material, expose us to ionising particles
- Cosmic rays from the sun and outer space emit lots of protons which cause ionisation in our atmosphere
- Building material contain radioactive particles and radioactive radon gas seeps up from the soil and collects in buildings, mainly due to lack of ventilation.
- The human body contains radioactive potassium and carbon
- In some jobs people are at greater risk. Radiographers exposed to X-rays used in hospitals and nuclear workers from the reactor.

Natural radiation is by far the greatest influence on our exposure to background radiation.

Examples

	Natural source	Annual dose (mSv)		Man made	Annual dose (mSv)
	From Earth	0.4		Medical	0.25
	Cosmic	0.3		Weapons (fall out)	0.01
	Food	0.37		Occupational	0.01
	Buildings (radon)	0.8		Nuclear discharges	0.002
	Total	1.87		Total	0.272

The individual values above do not need to be memorised but notice that the annual dose equivalent per year is about 2 mSv.

HALF-LIFE AND SAFETY

Half-life

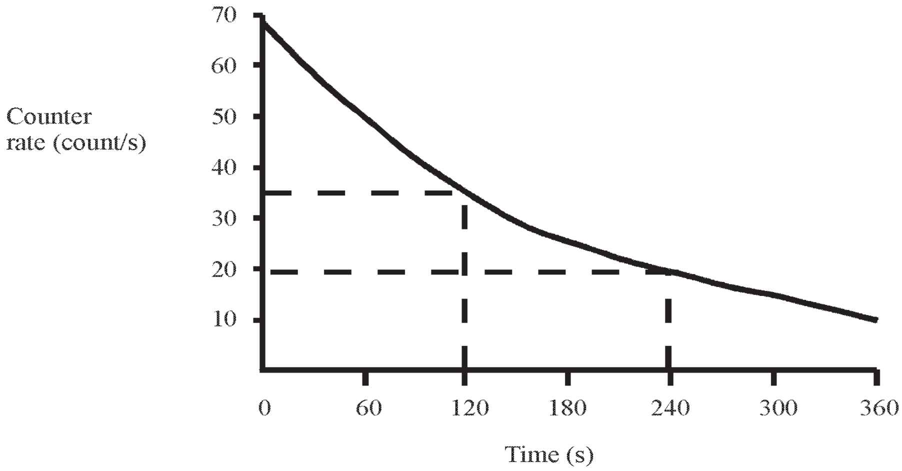
Radioactive decay is a random process. This means that for a radioactive source, it can never be predicted when an atom is about to decay. In any radioactive source, the activity decreases with time because the number of unstable atoms gradually decreases leaving fewer atoms to decay.

The **half-life** of a radioactive source is the time for the activity to fall to half its original value.

Examples

1. *A Geiger-Muller tube and ratemeter were used to measure the half-life of radioactive caesium-140. The activity of the source was noted every 60 s. The results are shown in the table. By plotting a suitable graph, find the half-life of caesium-140.*

Time (s)	*0*	*60*	*120*	*180*	*240*	*300*	*360*
Count Rate (counts/s) (corrected for background)	*70*	*50*	*35*	*25*	*20*	*15*	*10*



From the graph the time taken to fall from 70 counts/s to 35 counts/s = 120 s
35 counts/s to 17.5 counts/s = 120 s

Average half life of caesium-140 = 120 s.

2. *A source falls from 80 MBq to 5 MBq in 8 days. Calculate its half-life.*

80 → 40 → 20 → 10 → 5

This takes 4 half-lifes (count the arrows) = 8 days
One half life = 2 days

Safety with radioactivity

- Always use forceps or a lifting tool to remove a source. Never use bare hands.
- Arrange a source so that its radiation window points away from the body.
- Never bring a source close to your eyes for examination. It should be identified by a colour or number.
- When in use, a source must be attended by an authorised person and it must be returned to a locked and labelled store in its special shielded box immediately after use.
- After any experiment with radioactive materials, wash your hands thoroughly before you eat. (This applies particularly to the handling of radioactive rock samples and all open sources.)
- In the U.K. students under 16 may not handle radioactive sources.

Reducing the dose equivalent

- Use shielding, by keeping all radioactive materials in sealed containers made of thick lead. Wear protective lead aprons to protect the trunk of the body. Any window used for viewing radioactive material should be made of lead glass.
- Keep as far away from the radioactive materials as possible.
- Keep the times for which you are exposed to the material as short and as few as possible (dentists often ask you to hold the X-ray film in place while they keep well behind the screen. This may seem unfair - but the dentist takes lots of X-rays over the year and so is at greater risk.)

Radioactive hazard warning sign

- The sign should be displayed on all doors/corridors leading to where radioactive materials are stored.
- The sign should be displayed on all containers of radioactive materials.

NUCLEAR REACTORS

Advantages of using nuclear power to produce electricity

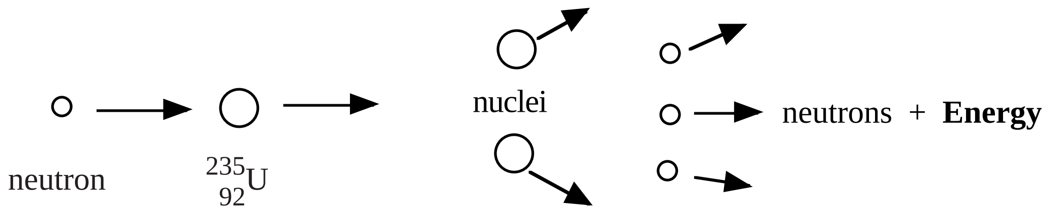
- Fossil fuels are running out, so nuclear power provides a convenient way of producing electricity.
- A nuclear power station needs very little fuel compared with a coal or oil-fired power station. A tonne of uranium gives as much energy as 25000 tonnes of coal.
- Unlike fossil fuels, nuclear fuel does not release large quantities of carbon dioxide and sulphur dioxide into the atmosphere,which are a cause of acid rain.

Disadvantages of using nuclear power to produce electricity

- A serious accident in a nuclear power station is a major disaster. British nuclear reactors cannot blow up like a nuclear bomb but even a conventional explosion can possibly release tonnes of radioactive materials into the atmosphere. (The Chernobyl disaster was an example of a serious accident.)
- Nuclear power stations produce radioactive waste, some of which is very difficult to deal with.
- After a few decades nuclear power stations themselves will have to be disposed of.

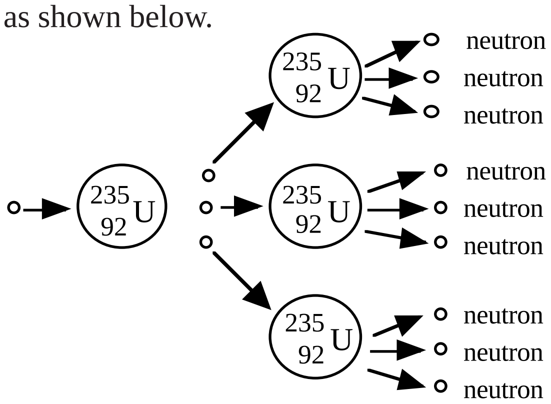
Nuclear fission

An atom of uranium can be split by a neutron. This can produce two new nuclei plus the emission of neutrons and the release of energy.



Chain reaction

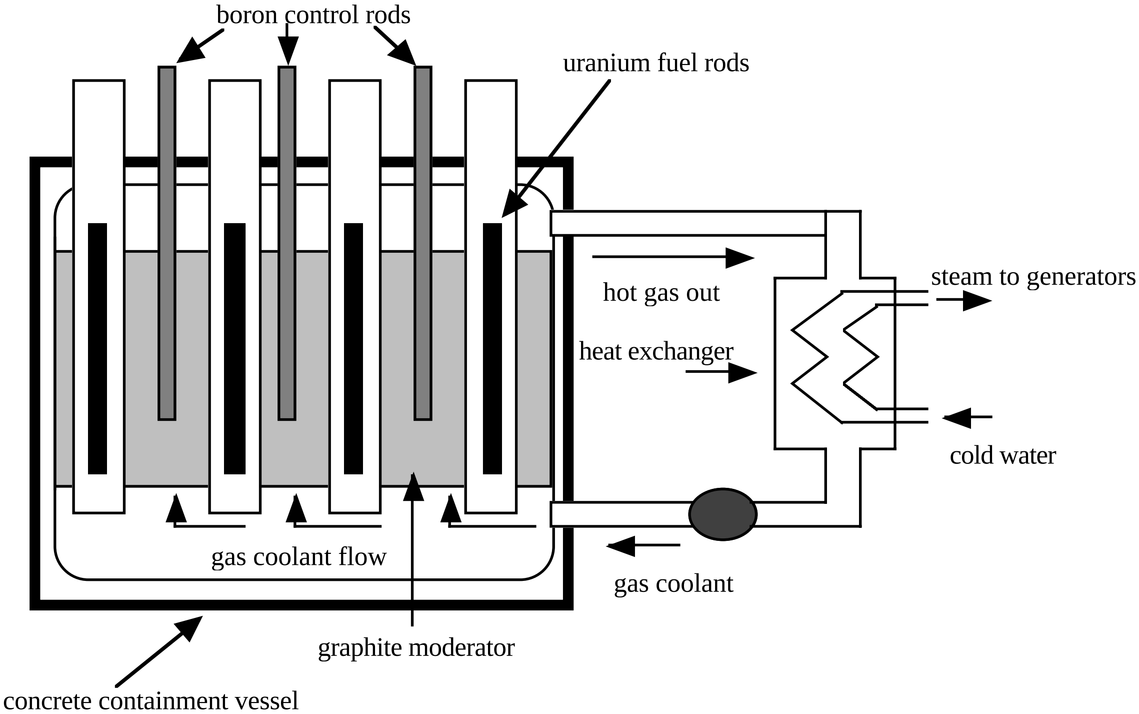
Once a nucleus has divided by fission, the neutrons that are emitted can strike other neighbouring nuclei and cause them to split releasing energy each time. This results in what is called a chain reaction as shown below.



In a controlled chain reaction, on average only one neutron from each fission will strike another nucleus and cause it to divide. This is what happens in a nuclear power station. In an uncontrolled chain reaction all the neutrons from each fission strike other nuclei producing a large surge of energy. This occurs in atomic bombs.

The nuclear reactor

There are five main parts of a reactor as shown in the diagram below:



- The fuel rods are made of uranium-238 enriched with uranium-235 which produce energy by fission.
- The moderator, normally made of graphite, has the fuel rods embedded in it. The purpose of the moderator is to slow down neutrons that are produced in fission, since a nucleus is split more easily by slow moving neutrons.
- The control rods are normally made of boron, and they control the rate of production of energy. The boron rods absorb neutrons so by lowering them into the reactor, the reaction can be slowed down. In the event of an emergency they are pushed right into the core of the reactor and the chain reaction stops completely.
- A cooling system is needed to cool the reactor and to transfer heat to the boilers in order to generate electricity. British gas-cooled reactors use carbon dioxide gas as a coolant.
- The containment vessel is made of thick concrete which acts as a shield to absorb neutrons and other radiations.

Radioactive waste

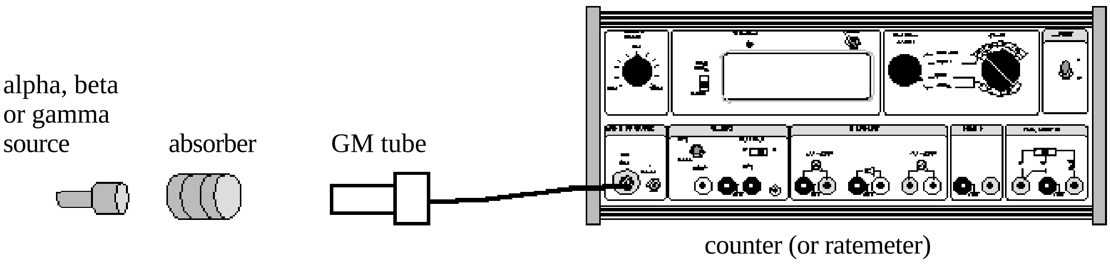
Nuclear power stations produce radioactive waste materials, some of which have half-lives of hundreds of years. These waste products are first set in concrete and steel containers then buried deep under ground or dropped to the bottom of the sea. These types of disposals are very controversial. Some scientists believe the containers will keep the radioactive material safe for along time, other scientists are worried that the containers will not remain intact for such a long time. Most recently the British government has decided to dig up radioactive waste buried in the 1960's near Dounreay in Scotland for fear of radioactive leakage.

ACTIVITY 1 (Teacher Demonstration)

Title: **Absorption of radiation**

Aim: To determine the absorption ability of alpha, beta and gamma radiations.

Apparatus: Geiger-Muller tube, alpha,beta and gamma sources, counter (or ratemeter), paper, thin and thick sheet aluminium, thin and thick sheet lead.



Instructions

- Copy the table of results.
- Watch the teacher demonstration and complete the table.

Absorber / Source	No absorber	Paper	Thin aluminium	Thick aluminium	Thin lead	Thick lead
Alpha Souce						
Beta Souce						
Gamma Souce						

- Write down your conclusions from the results.

ACTIVITY 2

Title: **Radioactive decay by simulation**

Aim: To determine how radioactive decay happens using a simulation of a random process.

Apparatus: 100 penny coins (or cubes marked on one side).

Instructions

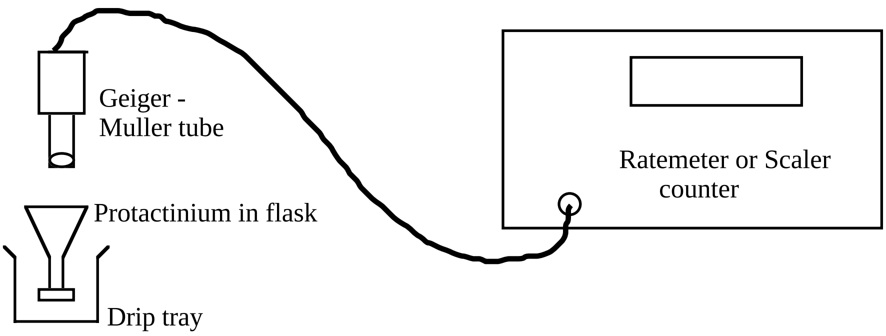
- Toss each coin (or cube) and remove any which land heads up (or cubes with marked side up).
- Copy the table below.
- Plot a graph of number of coins or cubes removed (count rate) against number of throws (time).
- Write a conclusion based the results of the experiment.

Number of throws	Number of coins removed (Number of cubes removed)

ACTIVITY 3 (Teacher Demonstration)

Title: **Measurement of the half-life of protactinium-234** (Outcome 3)

Apparatus: Geiger - Muller tube, counter, radioactive source (protactinium) (or video of experiment).



Instructions

- Measure the background count.
- Record the measurements of count rate and time.
- Use an appropriate format to determine the half-life of the source.

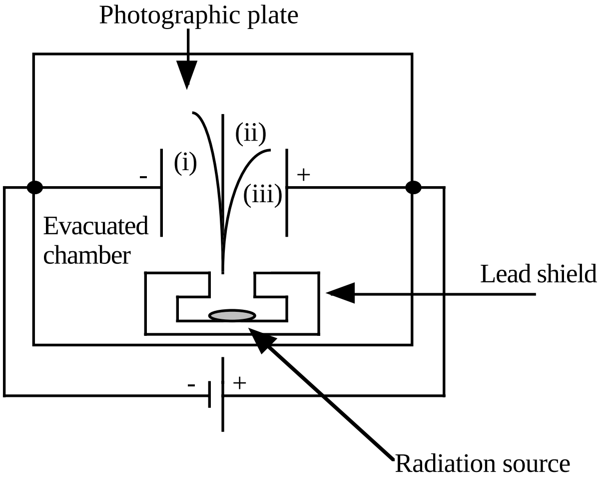
RADIOACTIVITY PROBLEMS

Ionising radiations

1. Using a diagram, describe the simple model of an atom.

2. Describe what is meant by the term ionisation.

3. In an experiment, radiation from a sample of radium is passed through an electric field. It is split into three different components (as shown in the diagram below).



(a) Name the radiations labelled (i), (ii) and (iii).
(b) Which radiation is deflected most by the electrostatic field?
(c) What is the function of the lead shield?
(d) Why is the experiment carried out in an evacuated chamber?
(e) What is the purpose of the photographic film?

3. The brain can suffer from cancer called glioblastoma. This form of cancer is treated by injecting the patient with boron-10 and then irradiating the patient with neutrons. This produces two particles lithium and an alpha particle.
(a) Explain how the alpha particle could help with the glioblastoma.
(b) Why could this process be dangerous for healthy tissue?

4. The table below represents data obtained from an absorption experiment using three separate radioactive sources (background count = 20 counts per minute).

	Count rate (per minute)		
Absorber	Source A	Source B	Source C
air	3125	900	420
paper	3130	880	38
1 mm aluminium	3000	380	20
10 mm lead	1900	20	21

(a) What effect did paper have on each of the three sources?
(b) Use the data in the table to try to identify the type of radiation from each source.

Dosimetry

5. What do we mean by the activity of radioactive material?

6. What does the risk of biological harm from radiation depend on?

7. A worker spends some time in an area where she is exposed to the following radiations:
   thermal neutrons = 8 mGy radiation weighting factor= 3
   fast neutrons = 40 μGy radiation weighting factor= 10
   (a) Calculate the dose equivalent for each type of neutron.
   (b) What is the total dose equivalent for the exposure?

8. What does the radiation weighting factor for each radiation give us an indication of?

9. In the course of his work an industrial worker receives a dose equivalent of 200 μSv. Determine the absorbed dose if he is exposed to alpha particles, with a radiation weighting factor of 20.

10. An unknown radioactive material has an absorbed dose of 500 μGy and gives a dose equivalent of 1 mSv. Calculate the radiation weighting factor of the material.

11. A patient receives a chest X-ray with a dose equivalent of 2.0 mSv. If the quality factor of the X-ray is 1, calculate the absorbed dose of the patient.

12. A lady has a dental X-ray which produces an absorbed dose of 0.3 mGy. Calculate the dose equivalent of this X-ray.

13. A nuclear worker is exposed to a radioactive material producing an absorbed dose of 10 mGy. She finds that the material emits particles with a radiation weighting factor of 3. Calculate the dose equivalent for this exposure.

14. A physics teacher uses a gamma source in an experimental demonstration on absorption The teacher receives an absorbed equivalent of 0.5 μSv. Calculate her absorbed dose if the radiation weighting factor for gamma radiation is 1.

15. (a) Alpha particles produce a dose equivalent of 50 mSv from an absorbed dose of 2.5 mGy. Calculate the radiation weighting factor of the alpha particles.
    (b) Why does exposure to alpha radiation increase the risk of cancer more than X-rays or gamma rays?

16. The unit for absorbed dose is the gray, Gy. Explain this term and give another unit for absorbed dose.

17. What is background radiation and from where does it originate?

Half life and safety

18. Explain what is meant by 'half-life'.

19. The following data was obtained from an experiment to determine the half life of a radioactive source:

Time (minutes)	0	20	40	60	80
Count rate (number of counts per minute)	100	60	45	30	20

(a) Describe how you could carry out this experiment.
(b) Determine the half-life of the radioactive source.

20. A radioactive material has a half life of 5 days. If the original activity is 120 Bq, what will be the activity after 20 days?

21. If a radioactive material has a half life of 600 years, how long will it take for the activity to fall to 10 Bq if the original activity was 80 Bq?

22. A radioactive substance has a half-life of 4 hours. What fraction of the original activity is left after one day?

23. The activity of a source starts at 100 MBq. After 20 days it has fallen to 6.25 MBq. Calculate the half life of the source.

24. What is the half-life of a radioactive source if the activity falls from 4000 kBq to 125 kBq in 40 days?

25. The half life of Cobalt-60 is 5 years. If the source, 25 years ago, had an activity of 500kBq, what would be the activity now?

26. What are the main sources of background radiation.

27. The table of results below show how the count rate for a radioactive source varies with time. The background count was 60 counts per minute.

Time (minutes)	0	5	10	15	20
Count rate (counts/minute)	1660	1100	750	510	350

(a) Plot a graph of corrected count against time.
(b) Determine the half-life of the source.

28. Describe the safety procedures when handling radioactive materials.

29. How can the dose equivalent be reduced for a radioactive source?

30. Write a note on the storage of radioactive material including warning signs and where they should be displayed.

Nuclear reactors

31. Explain what is meant by fission?

32. (a) What is a chain reaction?
    (b) Explain how a chain reaction works in a nuclear reactor and a nuclear bomb.

33. In a nuclear reactor what is the purpose of the following:
    (a) the concrete shield surrounding the reactor
    (b) the carbon dioxide pumped through the reactor
    (c) the graphite moderator?

34. How is the temperature of a nuclear reactor controlled?

35. Write down some advantages and disadvantages of using nuclear fuel to generate electricity.

36. (a) Why does radioactive waste worry many people?
    (b) Describe the problems with the storage and disposal of radioactive waste?

NUMERICAL ANSWERS

7. a) H = 24 mSv for thermal neutrons.
   H = 400 μSv for fast neutrons.
   b) 24.4 mSv

9. 10 mGy

10. 2

11. 2 mGy

12. 0.3 mSv

13. 30 mSv

14. 0.5 mGy

15. 20

20 7.5 Bq.

21. 1800 years
22. 1/64

23. 5 days.

24. 8 days.

25. 15.625 kBq.

27. b) 8 minutes