Radioactivity

Atomic Structure

All atoms have the same basic structure:

- Orbiting electrons (negative charge)
- Nucleus, comprising of:
  - Protons (positive charge)
  - Neutrons (no charge)

In all atoms the number of protons = number of electrons. This makes atoms uncharged, or neutral.

Naming atoms:

Atomic (proton) number \( Z = \) number of protons in the nucleus

Mass (nucleon) number \( A = \) total number of protons plus neutrons in the nucleus

Symbol for the element \( ^{A}_{Z}X \)

What is Radioactivity?

Some elements give out random bursts of radiation. Each individual nucleus can only do this once, and when it has happened, it is said to have decayed. As even a tiny sample of material contains billions of atoms, many bursts of radiation can be emitted before all the nuclei have decayed.

**Ionizing** – it can knock electrons out of other atoms.

The atom left behind is now charged and is called an ion. It does not have equal numbers of protons and electrons.

Elements that behave like this are called radioactive.

We can measure the radioactivity as the number of decays (and, therefore, bursts of radiation emitted) per second.

1 decay per second = 1 Becquerel, Bq

Questions

1. Copy and complete the table.

<table>
<thead>
<tr>
<th></th>
<th>No. of protons</th>
<th>No. of electrons</th>
<th>No. of neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (^{12}_{6}) C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barium (^{13}_{56}) Ba</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead (^{82}_{36}) Pb</td>
<td>82</td>
<td></td>
<td>125</td>
</tr>
<tr>
<td>Iron (^{56}_{26}) Fe</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen (^{1}_{1}) H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium (^{2}_{3}) He</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium (^{3}_{2}) He</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Element X (^{4}_{2}) X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. a. Draw a diagram to show all the protons and neutrons in the nuclei of \(^{35}_{17}\)Cl and \(^{37}_{17}\)Cl.
   b. What word do we use to describe these two nuclei?
   c. Why is there no difference in the way the two types of chlorine atoms behave in chemical reactions?
   d. If naturally occurring chlorine is 75% \(^{35}_{17}\)Cl and 25% \(^{37}_{17}\)Cl explain why on a periodic table it is recorded as \(^{35.4}_{17}\)Cl?

3. What is a Becquerel?

4. If ionizing radiation knocks electrons out of atoms, will the ions left behind be positively or negatively charged?

Why?

5. Explain what you understand by the term ‘radioactive element’.

Electrons are held in orbit around the nucleus by electrostatic attraction.

Elements that behave like this are called radioactive.

We can measure the radioactivity as the number of decays (and, therefore, bursts of radiation emitted) per second.
In 1803, John Dalton noted that chemical compounds always formed from the same ratio of elements, suggesting particles were involved. He called these atoms from the Greek, meaning indivisible.

J.J. Thomson (1897) discovered the electron, a particle that could be knocked out of an atom. He suggested a ‘plum pudding’ model of the atom.

Rutherford, Geiger, and Marsden investigated this in 1910. They decided to probe the nucleus further with alpha particles. These are particles with two positive charges, which they considered to be like little bullets.

1. Detector detects the alpha particles that have travelled through the foil. It can be moved to any angle round the foil so that the number of alpha particles in any direction can be recorded.

2. The majority of alpha particles travelled through the foil with very little change in direction.

3. A very small number were turned through angles greater than 90°.

4. Plum pudding model cannot explain this since as the positive and negative charges were reasonably evenly distributed no alpha particles should get scattered through large angles.

5. Rutherford proposed the nuclear model.

Kinetic energy is transferred to potential energy in the electric field round the nucleus as the alpha particle does work against the repulsive force. This is returned to kinetic energy on leaving the region near the nucleus.

- The larger the charge on the nucleus the greater was the angle of scatter.
- The thicker the foil the greater the probability that an alpha particle passes close to a nucleus.
- Slower alpha particles remain in the field around the nucleus for longer – increases the angle of scattering.

Rarity of large angle of scatter tells us the nucleus is very small.

Bohr further developed the atomic model by suggesting that the electrons were arranged in energy levels around the nucleus.

To move up a level it has to absorb precisely the right amount of energy from an electromagnetic wave.

If an electron moved down a level, it has to get rid of some energy in the form of an electromagnetic wave.

Questions
1. List the main conclusions of the alpha scattering experiment.
2. What evidence did Thomson have for the plum pudding model?
3. Suggest why the alpha scattering apparatus has to be evacuated (have all the air taken out of it).
4. Suggest why the gold foil used in the alpha scattering experiment needs to be very thin.
5. The diameter of an atom is about $10^{-10}$ m and of a gold nucleus $10^{-14}$ m. Show that the probability of directly hitting a nucleus with an alpha particle is about 1 in 108. What assumptions have you made?
Radioactive elements are naturally found in the environment and are continually emitting radiation. This naturally occurring radiation is called **background radiation**, which we are all exposed to throughout our lives.

Background radiation comes from a number of sources. (Note that these are averaged across the population and may differ for different groups, for example depending on any medical treatment you may have, or whether you make many aeroplane flights.)

- **50%** Radioactive radon gas from rocks – see below.
- **12%** Cosmic rays – radiation from outer space that passes through the Earth’s atmosphere.
- **12%** Medical – cancer treatment and diagnosis of diseases.
- **10%** Directly from radioactive elements in rocks, and building materials.
- **14%** Internal from food and drink. Radioactive material from rocks and minerals taken up by plants into the food chain.
- **0.4%** Air travel – being closer to space means less cosmic rays are absorbed by the atmosphere.
- **0.4%** Nuclear weapons testing.
- **0.2%** Occupational, due to certain jobs.
- **<0.1%** Waste from nuclear power.

One of the major sources of background radiation is radon gas. This is produced by minute amounts of uranium, which occurs naturally in rocks, and is present in all parts of the country. It disperses outdoors so is only a problem if trapped inside a building. Exposure to high levels of radon can lead to an increased risk of lung cancer.

Since we all inhale radon throughout our lives it accounts for about half our annual radiation dose in the UK.

Geological conditions in some areas produce higher than average radon concentrations as shown in the map.

**Questions**

1. Make a list of sources of background radiation.
2. Give at least two reasons why the percentages shown above in the sources of background radiation are only averages and will differ for different people.
3. On average what percentage of the total background radiation is man-made?
4. Should we worry about background radiation?
RADIOACTIVITY  Three Types of Nuclear Radiation

There are three types of radiation emitted by radioactive materials. They are all emitted from unstable nuclei:

<table>
<thead>
<tr>
<th>Name</th>
<th>Identity</th>
<th>Mass</th>
<th>Charge</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha (α)</td>
<td>Helium nucleus</td>
<td>4</td>
<td>+2</td>
<td>Massive and highly charged. Therefore, interacts strongly with other matter causing ionization, and loses energy rapidly. Easily stopped and short range</td>
</tr>
<tr>
<td>Beta (β)</td>
<td>Fast moving electron ejected from the nucleus. Note that it is not an atomic orbital electron</td>
<td>(\frac{1}{1870})</td>
<td>-1</td>
<td>Nearly 8000 \times ) less massive than alpha and only half the charge. Therefore, does not interact as strongly with other matter causing less ionization, and loses energy more gradually. Harder to stop and has a longer range</td>
</tr>
<tr>
<td>Gamma (γ)</td>
<td>Electromagnetic wave</td>
<td>0</td>
<td>0</td>
<td>No mass or charge so only weakly interacts with matter. Therefore, very difficult to stop</td>
</tr>
</tbody>
</table>

Questions
1. Describe the differences between alpha, beta, and gamma radiation. What materials will stop each one?
2. Alpha and beta particles are deflected in both electric and magnetic fields but gamma is not. Explain why. Why are alpha and beta deflected in opposite directions?
3. A student has a radioactive source. When the source is placed 1 cm in front of a GM tube connected to a ratemeter it counts 600 counts per minute.
   - Moving the source back to 10 cm the count drops to 300 counts per minute.
   - Replacing the source at 1 cm and inserting 2 mm thickness of aluminium foil gives 300 counts per minute.
   - Moving the source back to 5 cm and inserting 2 cm of lead gives 150 counts per minute.
   Explain how you know what type(s) of radiation the source emits.
4. Many smoke alarms contain a small radioactive source emitting alpha particles. This is inside an aluminium box, and placed high on a ceiling. Use the properties of alpha particles to explain why smoke alarms do not pose any health risk.
Most nuclei never change; they are stable. Radioactive materials contain unstable nuclei. These can break up and emit radiation. When this happens, we say the nucleus has decayed. The result for alpha and beta decay is the nucleus of a different element. For gamma decay, it is the same element but it has less energy.

**Alpha decay**

In alpha decay, the nucleus loses two protons and two neutrons.

Alpha particle is especially stable so is easily lost from a nucleus.

Mass number decreases by 4 (2 protons + 2 neutrons lost). Atomic number decreases by 2 (2 protons lost).

Atomic number

\[ \frac{A}{Z} X \rightarrow \frac{A-4}{Z-2} Y + \frac{4}{2} He \]

Or

\[ \frac{A}{Z} X \rightarrow \frac{A-4}{Z-2} Y + \frac{4}{2} \alpha \]

**Beta decay**

- **Beta-minus**
  
  Neutron becomes a proton and electron.

  Daughter nucleus has one more proton than the parent so the atomic number increases by one.

  Overall number of protons plus neutrons is unchanged so the mass number does not change.

  \[ \frac{A}{Z} X \rightarrow \frac{A}{Z+1} Y + 0^{-1} e^- \]

  Or

  \[ \frac{A}{Z} X \rightarrow \frac{A}{Z+1} Y + 0^{-1} \beta^- \]

- **Beta-plus**

  Proton becomes a neutron and a positron (an anti-electron with all the same properties as an electron but the opposite charge).

  Daughter nucleus has one less proton than the parent so the atomic number decreases by one.

  Overall number of protons plus neutrons is unchanged so the mass number does not change.

  \[ \frac{A}{Z} X \rightarrow \frac{A}{Z-1} Y + 0^{+1} e^+ \]

  Or

  \[ \frac{A}{Z} X \rightarrow \frac{A}{Z-1} Y + 0^{+1} \beta^+ \]

**Gamma decay**

Often after either alpha or beta decay the nucleons have an excess of energy. By rearranging the layout of their protons and neutrons, they reach a lower energy state and the excess energy is emitted in the form of a gamma ray.

\[ \frac{A}{Z} X \rightarrow \frac{A}{Z} X + \gamma \]

**Rules for nuclear equations**

The total mass number must be the same on both sides of the equation.

The total atomic number on both sides of the equation must be the same.

The total charge must be the same on both sides of the equation.

**Questions**

Copy and complete the following nuclear equations:

1. \( ^{212}_{84} \text{Po} \rightarrow ^{212}_{82} \text{Pb} + \text{____} \).
2. \( ^{228}_{90} \text{Th} \rightarrow \text{____} ^{92}_{38} \text{Ra} + \frac{3}{2} \alpha \).
3. \( ^{214}_{82} \text{Pb} \rightarrow ^{214}_{83} \text{Bi} + \text{____} \).
4. \( ^{15}_{8} \text{O} \rightarrow ^{15}_{7} \text{N} + \text{____} \).
5. \( \text{____} \text{Si} \rightarrow ^{27}_{13} \text{Al} + \frac{9}{1}^{-1} \alpha \).
6. \( ^{238}_{90} \text{U} \rightarrow ^{234}_{90} \text{Th} + \frac{3}{2} \alpha \).
7. \( ^{74}_{33} \text{As} \rightarrow \text{____} ^{74}_{34} \text{Se} + \frac{1}{1}^{-} \).
8. \( ^{227}_{89} \text{Ac} \rightarrow ^{87}_{87} \text{Fr} + \text{____} \).
Nuclei have positive charge due to the protons in them. All the protons repel, so why does the nucleus not explode?

There is another force acting called the strong nuclear force. This acts between all nucleons, both protons and neutrons.

For small nuclei, a proton:neutron ratio of 1:1 is sufficient for the strong nuclear force to balance the electrostatic force. For larger nuclei, we need more neutrons to provide extra strong nuclear force, without increasing the electrostatic repulsion, so the ratio rises to 1.6:1.

These isotopes need to gain neutrons and lose protons to move towards the line of stability. They have too much strong nuclear force and not enough electrostatic force so are unstable. N.B. Remember alpha particle is \( ^4_2 \) He.

For elements where \( Z > 80 \) these decay by \( \alpha \) decay.

Alpha particles consist of two protons and two neutrons. Therefore, the atomic number falls by two and the mass number by four:

\[
\frac{A}{Z} X \rightarrow \frac{(A-4)}{(Z-2)} Y + \frac{4}{2} \text{He}
\]

Electrostatic repulsion between all protons.

For elements where \( Z > 80 \) these decay by \( \alpha \) decay. Alpha decay in this region (and also both types of beta decay)

N.B. Remember alpha particle is \( ^4_2 \) He.

These isotopes need to gain protons and lose neutrons to move towards the line of stability. They have too much strong nuclear force and not enough electrostatic force. \( \beta^- \) decay allows this to happen. A neutron turns into a proton and an electron. The equations for this process are:

\[
n \rightarrow p + e^- \\
\text{Overall } \frac{A}{Z} X \rightarrow \frac{A}{(Z+1)} Y + 0^{-^1} \beta^-. 
\]

\( \text{N.B. remember the beta particle is an electron.} \)

E.g.

\[
\begin{align*}
\frac{40}{20} \text{Ca} & \rightarrow \frac{37}{21} \text{Sc} + \frac{3}{2} \beta^- . \\
\frac{165}{66} \text{Dy} & \rightarrow \frac{165}{67} \text{Ho} + \frac{0}{3} \beta^- . \\
\frac{110}{50} \text{Sn} & \rightarrow \frac{110}{49} \text{In} + \frac{0}{1} \beta^+. \\
\frac{18}{10} \text{Ne} & \rightarrow \frac{18}{9} \text{F} + \frac{0}{1} \beta^+. 
\end{align*}
\]

Questions

1. Explain why proportionately more neutrons are needed in larger nuclei?
2. Using the graph above, calculate the ratio \( Z:N \) when \( Z = 6 \) and when \( Z = 80 \). Comment on your answer.
3. Why does the line on the graph curve away from the line \( Z = N \)?
4. What type of decay occurs in isotopes with too much strong nuclear force? How do these changes help the nucleus to become more stable?
5. Repeat question 3 for isotopes with too much electrostatic force.
6. Nuclei do not contain electrons, so where does the electron emitted from a nucleus in beta-minus decay come from?
7. Balance the equation \( \frac{11}{6} \text{C} \rightarrow \frac{11}{1} \text{B} \rightarrow \frac{11}{1} \text{B}^+ \). (Hint: are there too many protons or too many neutrons in the carbon nucleus?) Hence will \( \beta^+ \) or \( \beta^- \) decay occur?
RADIOACTIVITY  Fundamental Particles

A fundamental particle is one that cannot be split into anything simpler.

The word atom means ‘indivisible’ because scientists once thought atoms were fundamental particles.

We now know that they are not fundamental because we know that they are made of electrons, protons, and neutrons.

Scientists now think that quarks, together with electrons and positrons are examples of fundamental particles.

There are actually six types of quark given odd names. They also have fractional charges as shown below.

<table>
<thead>
<tr>
<th></th>
<th>Charge</th>
<th></th>
<th>Charge</th>
<th></th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>$u^+$</td>
<td>Charm</td>
<td>$c^+$</td>
<td>Top</td>
<td>$t^+$</td>
</tr>
<tr>
<td></td>
<td>$\frac{2}{3}$</td>
<td></td>
<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3}$</td>
<td></td>
</tr>
<tr>
<td>Down</td>
<td>$d^-$</td>
<td>Strange</td>
<td>$s^-$</td>
<td>Bottom</td>
<td>$b^-$</td>
</tr>
<tr>
<td></td>
<td>$\frac{1}{3}$</td>
<td></td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
<td></td>
</tr>
</tbody>
</table>

Protons and neutrons are made of just two types of quark, the up and the down. Other particles have to be created in special machines called particle accelerators.

Proton – two up and one down quarks.

Neutron – one up and two down quarks.

Charge = $(+\frac{2}{3}) + (+\frac{2}{3}) + (-\frac{1}{3}) = +1$

Charge = $(+\frac{2}{3}) + (-\frac{1}{3}) + (-\frac{1}{3}) = 0$

Beta decay

In beta decay, one of the up quarks changes to a down quark or vice versa.

An example of antimatter.

All particles have antiparticles; they are identical in mass but opposite in charge. Our Universe is made of matter. Antimatter is made in particle accelerators or as the result of some nuclear processes such as beta-plus decay.

Normally we are not allowed fractional charges, but quarks never occur on their own, only in combinations that add up to a whole charge.

Questions

1. What is meant by the statement ‘an electron is a fundamental particle’?
2. How many different types of quark make up protons and neutrons?
3. What quarks are found in a neutron?
4. Describe the changes in quarks when a proton decays to a neutron by beta-plus decay.
5. What is antimatter?
Most types of nuclei never change; they are stable. However, radioactive materials contain unstable nuclei. The nucleus of an unstable atom can break up (decay) and when this happens, it emits radiation. A nucleus of a different element is left behind.

As time goes by radioactive materials contain fewer and fewer unstable atoms and so become less and less radioactive and emit less and less radiation.

There is no way of predicting when an individual nucleus will decay; it is a completely random process. A nucleus may decay in the next second or not for a million years. This means it is impossible to tell how long it will take for all the nuclei to decay.

Like throwing a die, you cannot predict when a six will be thrown. However, given a very large number of dice you can estimate that a certain proportion, \(\frac{1}{6}\)th, will land as a six.

We define activity as the number of nuclei that decay per second (N.B. 1 decay per second = 1 Bq). The time it takes for the activity of a radioactive material to halve (because half of the unstable nuclei that were originally there have decayed) is called the half-life.

We see the activity falling as there are fewer nuclei available to decay. However, note that the time taken to halve is independent of the number of nuclei, in this case 2 seconds. Half-lives are unique to each individual isotope and range from billions of years to fractions of a second.

The half-life of a radioactive isotope is formally defined as:

\[
\text{The time it takes for half the nuclei of the isotope in a sample to decay, or the time it takes for the count rate from a sample containing the isotope to fall to half its initial level.}
\]

Calculations

1. **Numerically** e.g. a radioisotope has an activity of 6400 Bq and a half-life of 15 mins.

   After 15 mins the activity will be \(\frac{6400 \text{ Bq}}{2} = 3200 \text{ Bq}\).

   After 30 mins the activity will be \(\frac{3200 \text{ Bq}}{2} = 1600 \text{ Bq}\).

   After 45 mins the activity will be \(\frac{1600 \text{ Bq}}{2} = 800 \text{ Bq}\).

   After 1 hour the activity will be \(\frac{800 \text{ Bq}}{2} = 400 \text{ Bq}\).

Alternatively, consider the number of half-lives, e.g. \(1\frac{1}{2}\) hrs = \(6 \times 15\) mins = 6 half-lives.

Therefore, activity = \(\frac{\text{original activity}}{(2 \times 2 \times 2 \times 2 \times 2)}\)

(i.e. divide by 2, six times)

\[= \frac{\text{original activity}}{2^6}\]

In general, activity = \(\frac{\text{original activity}}{2^{\text{no. of half-lives}}}\)

Therefore after 6 half-lives, in this case, activity = \(\frac{6400 \text{ Bq}}{2^6} = 100 \text{ Bq}\).
Questions

1. What is the activity of a radioactive source?

2. Write down a definition of half-life. Suggest why we can measure the half-life of a substance, but not its ‘full life’ (i.e. the time for all the atoms to decay).

3. $^{99m}$Tc (Technetium) has a half-life of 6 hrs. A sample of technetium has an initial count rate of 128 000 Bq
   i. What will the count rate be after: a. 6 hrs? b. 18 hrs?
   ii. How many hours will it take the count rate to fall to: a. 32 000 Bq? b. 8000 Bq? c. 1000 Bq?

4. A student has a sample of $^{137}$Ba (Barium). They record the count rate every 60 s and record the following results:

<table>
<thead>
<tr>
<th>Time in seconds</th>
<th>0</th>
<th>60</th>
<th>120</th>
<th>180</th>
<th>240</th>
<th>300</th>
<th>360</th>
<th>420</th>
<th>480</th>
<th>540</th>
<th>600</th>
<th>660</th>
<th>720</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count rate (decays/s)</td>
<td>30.8</td>
<td>23.8</td>
<td>18.4</td>
<td>14.2</td>
<td>11.1</td>
<td>8.7</td>
<td>6.9</td>
<td>5.4</td>
<td>4.4</td>
<td>3.5</td>
<td>2.9</td>
<td>2.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

   The background count rate, with no source present, was 0.8 counts per second.
   a. Copy the table and include a row for the corrected count rate.
   b. Draw a graph of count rate vs. time and use it to show that the half-life is approximately 156 s.
   c. Do you think this isotope would present significant disposal problems, why or why not?
   d. A student has a sample of radioactive material. In one lesson the activity recorded was 2000 Bq. The next day, at the same time, the count rate was just over 500 Bq. Which of the following isotopes is the sample most likely to be?

5. A student has a sample of radioactive material. In one lesson the activity recorded was 2000 Bq. The next day, at the same time, the count rate was just over 500 Bq. Which of the following isotopes is the sample most likely to be?
   a. $^{131}$I (iodine) half-life = 6.7 hrs.  
   b. $^{87}$Sr (strontium) half-life = 2.9 hrs.  
   c. $^{40}$K (potassium) half-life = 12.5 hrs.  
   d. $^{187}$W (tungsten) half-life = 24 hrs.
All nuclear radiation is ionizing. It can knock electrons out of atoms, or break molecules into bits. If these molecules are part of a living cell, this may kill the cell.

If the molecule is DNA, the damage caused by the radiation may affect the way it replicates. This is called mutation. Sometimes this leads to cancer.

**Alpha particles** are heavy and highly charged, and interact strongly with atoms. They can travel only very short distances and are easily stopped. They cannot penetrate human skin. Alpha emitters are only dangerous when inhaled, ingested, injected, or absorbed through a wound.

**Beta particles** are also charged, but interact less strongly than alpha particles, so travel further and penetrate more: they can penetrate skin. Clothing provides some protection. They can cause radiation burns on prolonged exposure but are hazardous to internal organs only when inhaled, ingested, injected, or absorbed.

**Gamma rays** are uncharged, so do not interact directly with atoms, and travel many metres in air. They easily penetrate the human body, causing organ damage. Their effects can be reduced by concrete or lead shielding.

Many people work with radiation, e.g. radiologists in hospitals, and nuclear power plant workers. Their exposure is carefully recorded. They wear a film badge, which becomes gradually more fogged, depending on how much exposure they have had. If their exposure is too high in a set period, they will usually be given other jobs away from radiation sources, temporarily.

Irradiation occurs when the emitted radiation hits an object. Moving away will reduce the exposure.

Something is contaminated if the radioactive atoms are in contact with it. Moving away will spread the contamination.

Questions:

1. Explain which type of radiation is most harmful:
   a. Outside the body.
   b. Inside the body.
2. Explain the difference between contamination and irradiation. Which would you consider a more serious problem?
3. How does nuclear radiation cause damage to living tissues?
4. What is a Sievert?
5. Explain three precautions you should take if you had to handle a low activity radioactive source.
Nuclear fission is the splitting of an atomic nucleus. A large parent nucleus, such as 235-uranium or 239-plutonium, splits into two smaller daughter nuclei, of approximately equal size. This process also releases energy (heat) which can be used to generate electricity (see p111). Normally, this will happen spontaneously but can be speeded up by inducing fission.

1. Parent nucleus ($^{239}$Pu or $^{235}$U) absorbs a slow moving neutron. The forces in the nucleus are unbalanced and the nucleus splits.

2. This increases the strong nuclear force in the nucleus, but does not increase the electrostatic repulsion (see p72).

3. The daughter nuclei have a lot of kinetic energy, the energy released by the fission process. This causes heating of the material.

If uranium were burned chemically to uranium oxide, it would release about 4500 J/g. The equivalent energy released from nuclear fission is $8.2 \times 10^{10}$ J/g.

The daughter products themselves are radioactive because they still tend to be neutron rich (i.e. lying above the N/Z curve), and decay, releasing more thermal energy and nuclear radiation. They have a wide range of half-lives. These factors need to be taken into account when considering their disposal, (see p112).

Fuel rods of uranium or plutonium.

Control rods made of boron or cadmium.

Lead/concrete shielding.

Nuclear reactors are designed to control the chain reaction and prevent an explosion.

Reactor core gets hot due to heat released in the fuel rods by the nuclear fission reaction.

Core made of graphite or heavy water to slow down the neutrons. This is called the moderator and makes the neutrons more likely to be absorbed by further nuclei.

Control rods absorb neutrons before they can cause further fissions.

Lowering the control rods absorbs more neutrons and slows the reaction, raising the control rods speeds it up.

1. Balance this equation, a fission reaction of uranium producing the daughter nuclei barium and krypton.
   \[ \frac{235}{92}U + \frac{1}{0}n \rightarrow \_\_\_\_\_\_\_\_\_\_\_\_ \frac{56}{2}Ba + \_\_\_\_\_\_\_\_\_\_\_\_ \frac{90}{38}Kr + 2 \frac{1}{0}n.\]

2. In what form is the majority of the energy released by a nuclear reaction?

3. Why do the products of fission reactions need careful handling?

4. How do the control rods in a reactor control the rate of the nuclear reaction?

5. For a stable chain reaction, neither speeding up nor slowing down, suggest how many neutrons from each fission should go on to cause a further fission.

6. Use the data above to show that the energy released from the fission of 1 g of $^{235}$U is about 20 million times as much as when the same gram is burnt in oxygen to form uranium oxide.

Questions

**RADIOACTIVITY Nuclear Fission**
In the nucleus, the **STRONG NUCLEAR FORCE** attracts protons and neutrons together; it is stronger than the **ELECTROSTATIC REPULSION** between the protons but it is a very short-range force.

This means that the gas containing the nuclei has to be very hot, dense, and under high pressure.

The gas is so hot that none of the electrons now orbits the nuclei. This is called plasma.

This is very difficult to do on Earth as this plasma would melt any container. Confining plasma is a major area of research because for the same mass of fuel, fusion of hydrogen to helium releases much more energy than fission and is the reaction occurring in the core of stars. We have a plentiful supply of hydrogen in water on Earth and the products are not polluting.

To fuse two nuclei they must be brought very close together so the strong nuclear force can bind their protons and neutrons together.

To do this you have to overcome the electrostatic repulsion between the nuclei.

Therefore, the nuclei have to travel very fast so they have a lot of kinetic energy to do work against the repulsive force.

When the nuclei join, energy is released as the kinetic energy of the product nucleus.

The nucleus formed has less mass than the total mass of the nuclei that fused to create it. The missing mass (or mass defect) has been converted to energy by Einstein’s famous relationship

\[ \Delta E = \Delta mc^2 \]

\( \Delta E \) = energy released in J  
\( \Delta m \) = mass loss in kg  
\( c \) = speed of light = \( 3 \times 10^8 \) m/s

Scientists still have not achieved the process under control. They can do it where the reaction is explosive, in a hydrogen bomb. Some scientists once claimed they could do fusion at room temperature, but no one has been able to repeat this.

**Key**
- H⁺ proton
- Deuterium nucleus (1n + 1p)
- ⁴²He nucleus
- Positron (β⁺ particle)

**Questions**
1. Explain the differences between nuclear fission and fusion.
2. What are the two forces that must be kept in balance in a stable nucleus?
3. What is plasma?
4. Why does fusion require such high temperatures and what problems may occur as a result?
5. Explain why scientists are working hard to achieve controlled fusion on Earth.
6. A helium-4 nucleus is only 99.3% of the mass of the 4 hydrogen nuclei from which it was formed. The other 0.7% of its mass is converted into energy. Use Einstein’s equation \( \Delta E=\Delta mc^2 \) to show that the energy released from the fusion of 1 kg of hydrogen nuclei, is about \( 6.3 \times 10^{14} \) J (c = speed of light = \( 3 \times 10^8 \) m/s).
Stable nuclei are bombarded with protons. These unstable proton-rich nuclei decay by beta-plus emission with short half-lives. They emit positrons.

Positron emitter made into a drug (designed to collect quickly in the organ of interest) and injected into the patient.

1. Unstable nucleus undergoes beta-plus decay and emits a positron (e+).
2. Positron travels about 1 mm before meeting an electron.
3. The two particles annihilate each other and become two gamma rays.
4. Gamma rays travel off in opposite directions to conserve momentum.
5. Gamma ray pairs are detected by circular detectors, which give a good indication of their origin.

6. The origin of the gamma rays shows where the positron emitting drug has collected.

This can be used to find out how well the drug moves round the body and how well organs of interest are working, or if they contain a tumour.

X-rays are high frequency, short wavelength, electromagnetic waves. They are ionizing so can damage cells. Exposure to them needs to be limited.

The benefits of the use of X-rays to diagnose medical problems often outweigh any cell damage caused.

X-rays expose photographic film and bones show up as a shadow.

Bone contains more heavy atoms, e.g. calcium, which absorbs X-rays strongly.

Flesh contains lighter atoms that do not absorb X-rays strongly.

Progress of the drug can be tracked by a radiation detector outside the body.

Monitoring the flow of the radioisotope over time can tell doctors about how organs are working.

Radioisotope attached to a drug that is absorbed by an organ of interest, e.g. a kidney.

Blockage – radioisotope will not pass and no radiation detected in this area outside body.

Short half-life used so radiation does not stay in the body too long.

Alpha emitters cannot be used as they would not pass through the body and are highly ionizing so would cause a lot of cell damage.

If the radiation dose is small, the cells may be able to repair themselves. Large doses of radiation can kill cells. This can be used to kill cancerous cells.

Ionizing radiation can damage the DNA in cells.

Cancerous cells are those where the DNA has been damaged and grow and divide uncontrollably.

Source of gamma rays

Source rotated around patient centred on the tumour.

Cells around the tumour receive less radiation – they should recover.

Radiotherapy may not be successful if the tumour is very large. In this case radiotherapy may be used to reduce suffering.

This is called *palliative* care.

Questions
1. Which types of radiation, alpha, beta, or gamma can pass through flesh?
2. Why do the radioisotopes injected into patients always have short half-lives?
3. What absorbs X-rays better, flesh or bone?
4. What does PET stand for? Describe how it works, for example to identify the location of a cancerous tumour.
5. The thyroid gland stores iodine. How could injecting a patient with radioactive iodine-123 allow a doctor to find out how well the thyroid gland is working?
6. Ionizing radiation can cause the DNA in cells to mutate and cause cancer. Therefore, why can we also use ionizing radiation as a treatment for cancer?
7. Why is the source of gamma rays in radiotherapy rotated around the patient?
8. All ionizing radiation causes damage to the body. How do doctors justify exposing patients to it?
**RADIOACTIVITY** Other Uses of Radioactivity

**Key considerations**
- **Half-life?**
  - All need long half-lives
  - Small – activity remains fairly constant over a long period.
- **Does it need to cause ionization?**
  - Alpha particles are not very penetrating so do not escape the alarm.
  - Beta particles ionize air between plates.
  - Gamma penetrate right through food.

**Questions**
1. Explain whether an alpha, beta, or gamma source is most useful for the following and why:
   a. Smoke alarms.
   b. Detecting aluminium foil thickness in a factory.
   c. Following the flow of oil along a pipe.
2. Should a radioactive material with a long or short half-life be chosen for the following and why?
   a. Smoke alarm.
   b. Tracer in an oil pipe.
   c. Thickness detection in a factory.
3. Many people are concerned about the effect on their health of radioactive sources. How would you address the following concerns?
   a. ‘I don’t have a smoke alarm as I do not want a radioactive source in my house.’
   b. ‘I am concerned that irradiated food might be radioactive.’
Radioactivity

Carbon Dating

Carbon-14 nuclei are radioactive and decay by giving out a beta particle to form nitrogen nuclei.

\[ ^{14}_{6}C \rightarrow ^{14}_{7}N = \beta^{-} \]

Carbon-14 has a half-life of 5730 years.

Measuring the activity of a sample of ancient materials that were once living and comparing the activity to a living sample can give a fairly accurate indication of when the ancient material was alive.

(It works for plant or animal material because animals eat plants and absorb carbon-14 from them.)

Dating of rocks

Many rocks contain traces of radioactive uranium. This decays to stable lead with a half-life of 4.5 billion years.

Assumption: the concentration of \(^{14}\)CO\(_2\) in the atmosphere has remained constant.

Very small quantities are involved leading to significant uncertainties.

Questions

1. The graph shows the radioactive decay of carbon-14.
   a. Use the graph to calculate the half-life of carbon-14. What does carbon-14 decay into?
   b. A wooden post from an archaeological dig produces 150 counts/min. Wood from an identical species of tree currently alive gives 600 counts/min. How long ago did the wood from the archaeological dig die?
   c. What assumption have you made in the above calculation?
2. Two samples of rock are analysed. The ratio of 238-uranium to 206-lead are as follows:
   Sample A: uranium to lead 5:1
   Sample B: uranium to lead 7:1.
   Which rock is older and how do you know? What assumption have you made?
3. The age of the Earth is thought to be about 4.5 billion years. Why can there be no rock in which the number of lead nuclei formed from the decay of uranium outweighs the number of uranium nuclei remaining?
**RADIOACTIVITY Nuclear Power and Weapons**

See p77 for a description of the nuclear fission process and the nuclear reactor.

Large amounts of radiation is produced by a radioactive core (gamma rays, alpha and beta particles, high-energy neutrons). Extra neutrons absorbed by reactor casing – this makes them neutron rich and radioactive (by beta decay, see p72).

Thick lead and concrete surrounds the reactor to prevent this radiation escaping.

Uranium is the fuel for most commercial nuclear reactors. It is obtained by mining uranium ore.

**The nuclear debate**

FOR
- Uranium contains far more energy per kilogram than fossil fuels. Although it is non-renewable, it will last longer.
- Allows fossil fuels to be used as a raw material to make other useful materials.
- Nuclear reactors do not release any greenhouse gases that contribute to global warming.
- Waste gases do not lead to acid rain.

AGAINST
- Potential risk of an accidental release or theft of radioactive material.
- Mining uranium exposes people to radiation risk.
- Nuclear reactors have very high maintenance costs.
- Cost of waste disposal and decommissioning at the end of a reactor’s life.
- Radiation can cause cancer.

**Questions**

1. Write out a list of energy changes in a nuclear power station starting from nuclear energy stored in uranium fuel and ending with electrical energy in the wires leading from the generator.
2. Where does the fuel for a nuclear power station come from and what has to happen to it before it can be used?
3. The energy released by 1 kg of $^{235}$U is about $8 \times 10^{13}$ J. Show that this could light a 60 W light bulb for about 42 thousand years.
4. Using the diagram of a nuclear power plant above explain:
   a. Why is the reactor surrounded by a thick layer of concrete and lead?
   b. Why is the pressure vessel made of steel?
   c. Why are the pipes in the heat exchangers coiled up?
5. Nuclear weapons cause damage to living things in three ways – what are they?
6. ‘Nuclear power damages the environment and should be banned.’ Give arguments in favour and against this statement.
RADIOACTIVITY Radioactive Waste

Sources: • Nuclear fission power stations (p111).
• Industrial users of radioactivity (p109).
• Hospitals and other medical establishments (p108).
• Laboratories.
• Decommissioned nuclear weapons.

These wastes should be disposed of in a way that does not significantly increase the naturally occurring background level of radiation around the disposal site.

Waste is classified into three levels by considering:

• How long the waste will remain at a hazardous level.
• The concentration of radioactive material in the waste.
• Whether it is heat generating.

Radioactive isotopes, e.g. fission products from a reactor. 95% of total radioactivity but a very small volume.

Requires both shielding and cooling.

Allowed to cool under water for about 3 months.

Some spent fuel still contains unreacted isotopes that are in too low a concentration to be useful. They are extracted, concentrated, and added to new reactor fuel.

Waste is mixed with glass (which is chemically unreactive and insoluble). Helps to prevent waste leaking out.

Eventually the store will be filled with concrete and sealed when the waste has cooled enough and the store is full.

Would allow water potentially carry groundwater.

Air circulated by fans to remove heat produced by the still decaying waste.

Questions
1. What are the three classifications of nuclear waste?
2. What types of materials make up low-level waste?
3. What is the main constituent of intermediate level waste?
4. What constitutes high-level waste and why is this generally hot?
5. What happens to low-level waste?
6. What happens to intermediate level waste?
7. What happens to high-level waste?
8. Why are spent fuel rods left in cooling ponds for 3 months after use?
9. You are responsible for finding a site for a new managed underground radioactive waste store.
   a. What features would you look for in identifying a suitable site?
   b. What concerns might local residents have?
   c. How might you go about addressing these concerns?