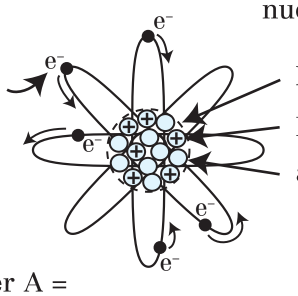
RADIOACTIVITY Atomic Structure

All atoms have the same basic structure:

Orbiting electrons (negative charge)



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

Nucleus, comprising of:

Protons (positive charge) and neutrons (no charge) } Nucleons as they make up the nucleus.

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

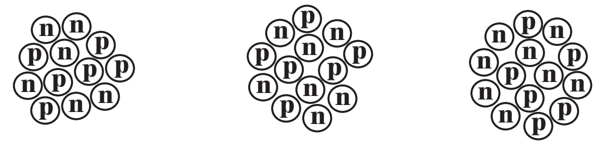
Mass (nucleon) number A = total number of protons plus neutrons in the nucleus

$^{A}_{Z}X$ ← Symbol for the element

Each element has a unique number of protons. Therefore, the atomic number uniquely identifies the element.

Some atoms of the same element have different numbers of neutrons.

$^{12}_{6}C$ $^{13}_{6}C$ $^{14}_{6}C$



E.g. all these atoms are carbon as they all have 6 protons, but they have different numbers of neutrons. They are called isotopes of carbon.

Isotopes are always the same element, i.e. same atomic number but have different numbers of neutrons (and so mass number).

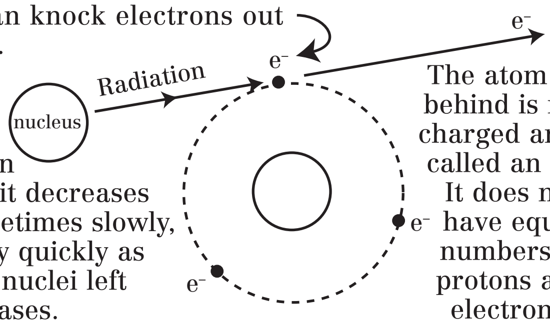
The relative masses of protons, neutrons, and electrons and their relative electric charges are:

	Mass	Charge
Proton	1	+1
Neutron	1	0
Electron	$\frac{1}{1870}$	–1

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.

The emission of this radiation is random but it decreases over time, sometimes slowly, sometimes very quickly as the number of nuclei left to decay decreases.

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.

	No. of protons	No. of electrons	No. of neutrons
Carbon $^{12}_{6}C$			
Barium $^{137}_{56}Ba$			
Lead $^{\_\_}_{\_\_}Pb$		82	125
Iron $^{56}_{\_\_}Fe$	26		
Hydrogen $^{1}_{1}H$			
Helium $^{4}_{2}He$			
Helium $^{3}_{2}He$			
Element X $^{A}_{Z}X$			

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 $^{35.5}_{17}Cl$?
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’.

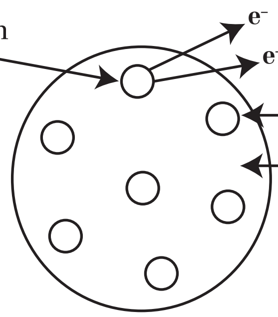
RADIOACTIVITY A History of Our Understanding of the Atom

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.

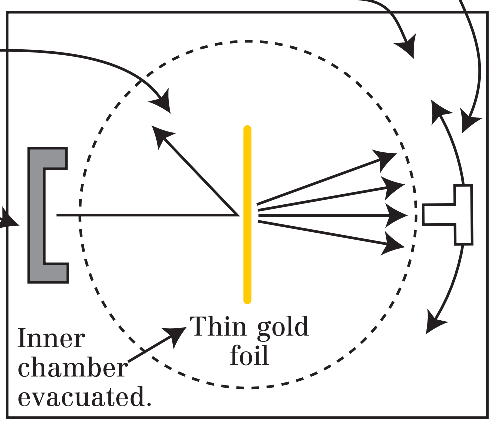
J.J. Thomson (1897) discovered the electron, a particle that could be knocked out of an atom. He suggested a 'plum pudding' model of the atom.

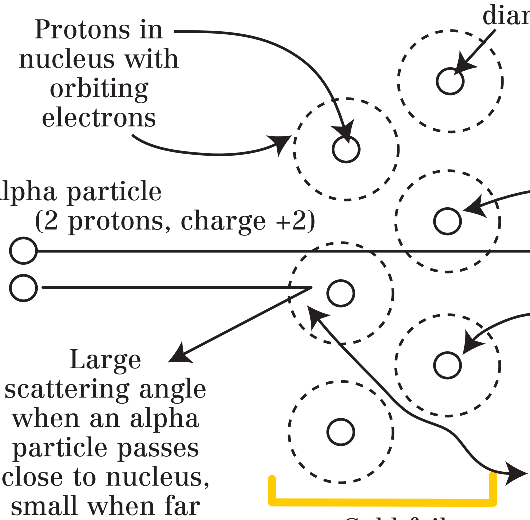
Rutherford, Geiger, and Marsden investigated this in 1910. They decided to probe the nucleus further with alpha particles. These are particles with two positive charges, which they considered to be like little bullets.

The model was so named as the electrons appeared like the fruit in a pudding.



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.





Summary

The alpha scattering experiment proves that:
1. Atoms have massive, positively charged nuclei.
2. The majority of the mass of the atom is the nucleus.
3. Electrons orbit outside of the nucleus. Most of the atom is empty space.

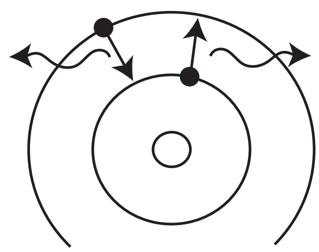
Bohr further developed the atomic model by suggesting that the electrons were arranged in energy levels around the nucleus.

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.

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.



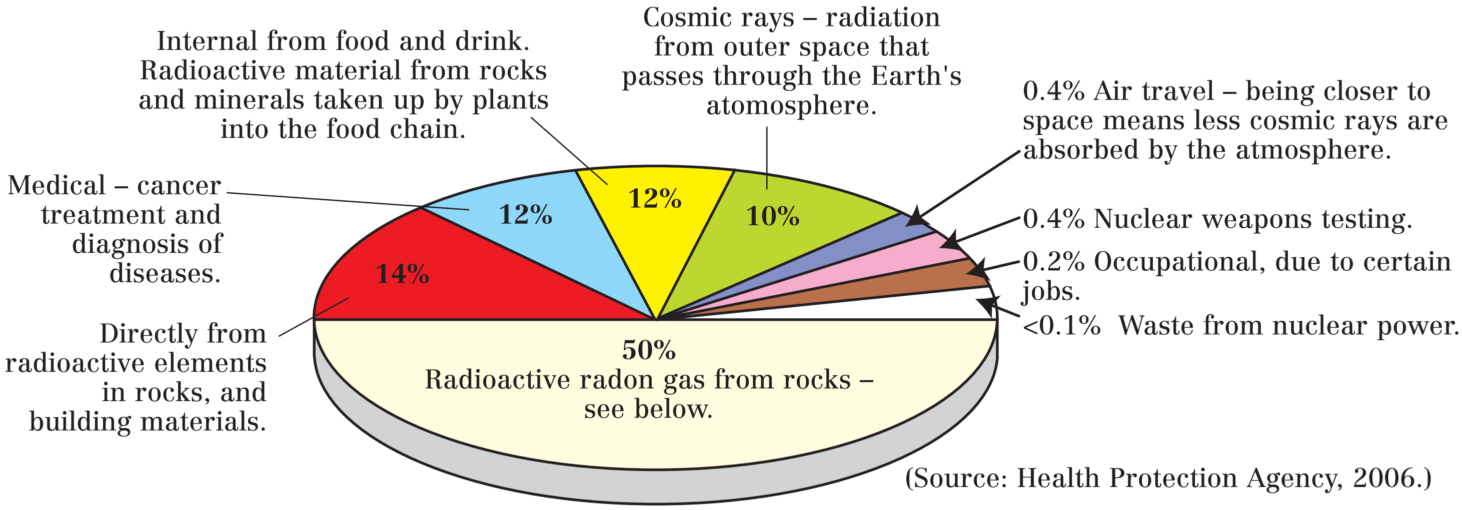
Questions

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?

RADIOACTIVITY Background Radiation

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.

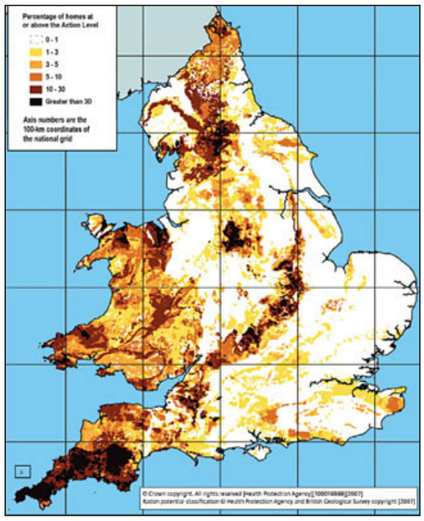
Background radiation comes from a number of sources. (Note that these are averaged across the population and may differ for different groups, for example depending on any medical treatment you may have, or whether you make many aeroplane flights.)

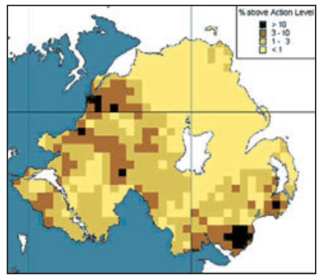


(Source: Health Protection Agency, 2006.)

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.

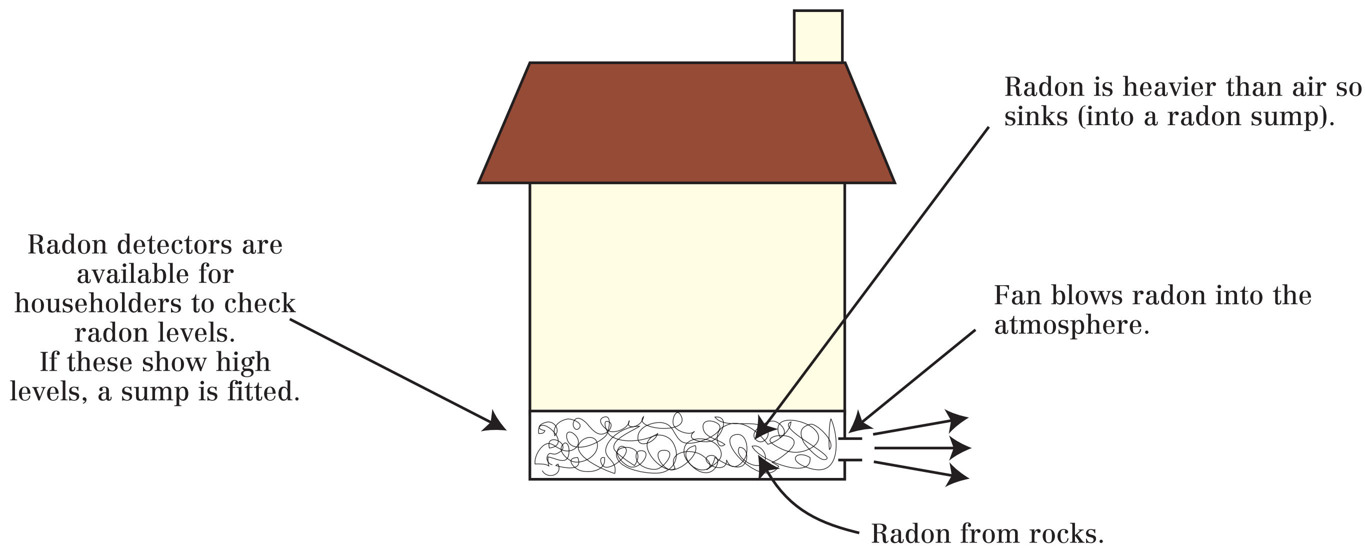




Maps courtesy of the Health Protection Agency and the British Geological Survey

For more information go to: www.ukradon.co.uk

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

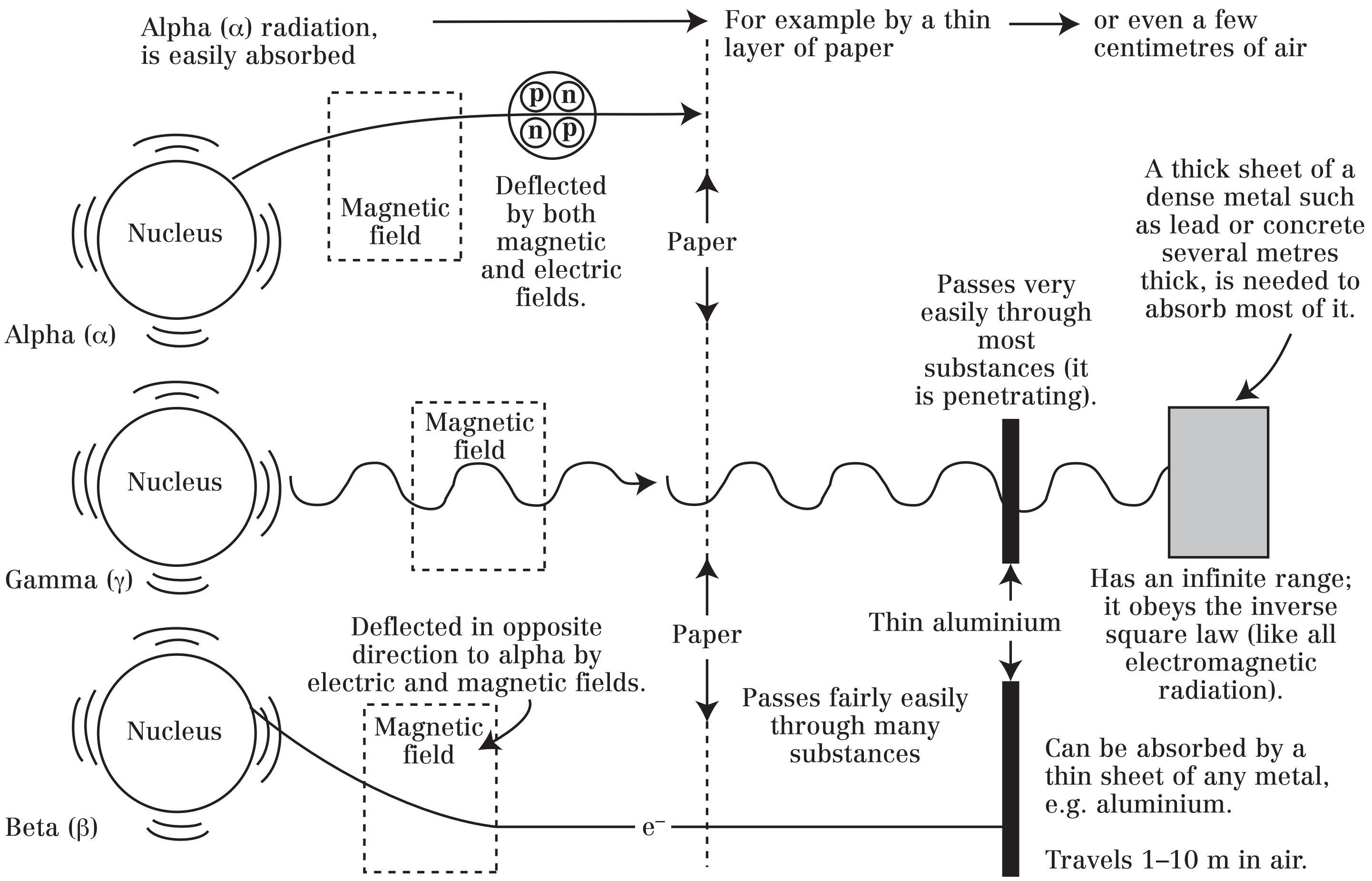


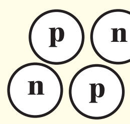
Questions

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*:



Name	Identity		Mass	Charge	
Alpha (α)	Helium *nucleus*	 $^4_2$He	4	+2	Massive and highly charged. Therefore, interacts strongly with other matter causing ionization, and loses energy rapidly. Easily stopped and short range
Beta (β)	Fast moving electron ejected from the *nucleus*. Note that it is not an atomic orbital electron	e^-	$\frac{1}{1870}$	−1	Nearly 8000 × 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
Gamma (γ)	Electromagnetic wave		0	0	No mass or charge so only weakly interacts with matter. Therefore, very difficult to stop

Questions

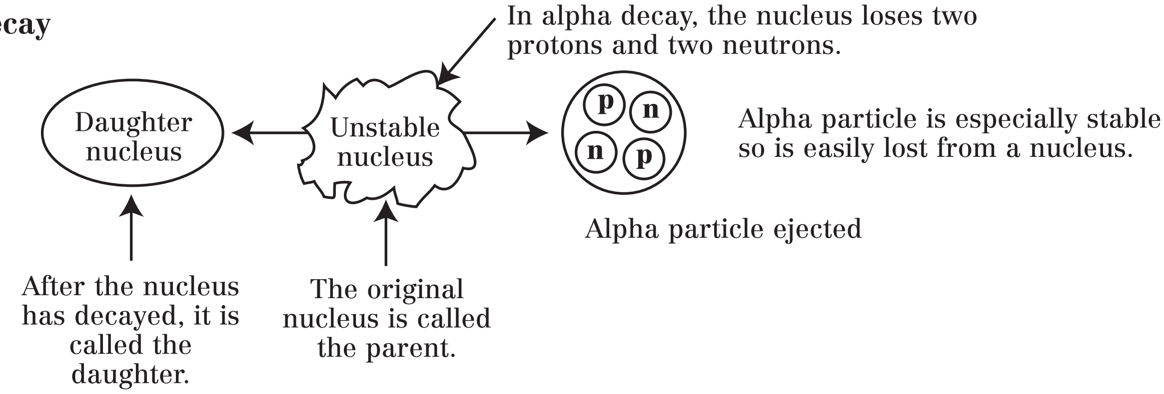
1. Describe the differences between alpha, beta, and gamma radiation. What materials will stop each one?
2. Alpha and beta particles are deflected in both electric and magnetic fields but gamma is not. Explain why. Why are alpha and beta deflected in opposite directions?
3. A student has a radioactive 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.

RADIOACTIVITY Radioactive Decay and Equations

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



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

Atomic number

$$^{A}_{Z}X \rightarrow \, ^{(A-4)}_{(Z-2)}Y + \, ^{4}_{2}He \qquad \text{Or} \qquad ^{A}_{Z}X \rightarrow \, ^{(A-4)}_{(Z-2)}Y + \, ^{4}_{2}\alpha$$

Beta decay

Beta-minus 

Neutron becomes a proton and electron.

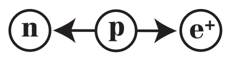
Daughter nucleus has one more proton than the parent so the atomic number increases by one.

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

$$^{A}_{Z}X \rightarrow \, ^{A}_{(Z+1)}Y + \, ^{0}_{-1}e^{-}$$

Or

$$^{A}_{Z}X \rightarrow \, ^{A}_{(Z+1)}Y + \, ^{0}_{-1}\beta^{-}$$

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.

$$^{A}_{Z}X \rightarrow \, ^{A}_{(Z-1)}Y + \, ^{0}_{+1}e^{+}$$

Or

$$^{A}_{Z}X \rightarrow \, ^{A}_{(Z-1)}Y + \, ^{0}_{+1}\beta^{+}$$

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.

$$^{A}_{Z}X \rightarrow \, ^{A}_{Z}X + \gamma$$

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:

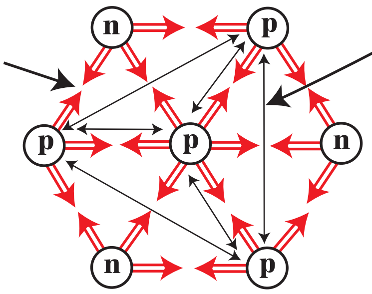
1. $^{215}_{84}Po \rightarrow \, ^{211}_{82}Pb + \underline{\quad}$.
2. $^{228}_{90}Th \rightarrow \underline{\quad} Ra + \, ^{4}_{2}\alpha$.
3. $^{214}_{82}Pb \rightarrow \, ^{214}_{83}Bi + \underline{\quad}$.
4. $^{15}_{8}O \rightarrow \, ^{15}_{7}N + \underline{\quad}$.
5. $\underline{\quad}\, Si \rightarrow \, ^{27}_{13}Al + \, ^{0}_{+1}\underline{\quad}^{+}$.
6. $^{238}_{\underline{\quad}}U \rightarrow \, ^{\underline{\quad}}_{90}Th + \, ^{4}_{2}\alpha$.
7. $^{74}_{33}As \rightarrow \underline{\quad}\, Se + \, ^{0}_{-1}\underline{\quad}^{-}$.
8. $^{227}_{89}Ac \rightarrow \, ^{\underline{\quad}}_{87}Fr + \underline{\quad}$.

RADIOACTIVITY N/Z Curve

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.

Strong nuclear attraction only acts between adjacent nucleons.



Electrostatic repulsion between all protons.

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.

Plotting the number of protons vs. number of neutrons in stable nuclei gives this graph.

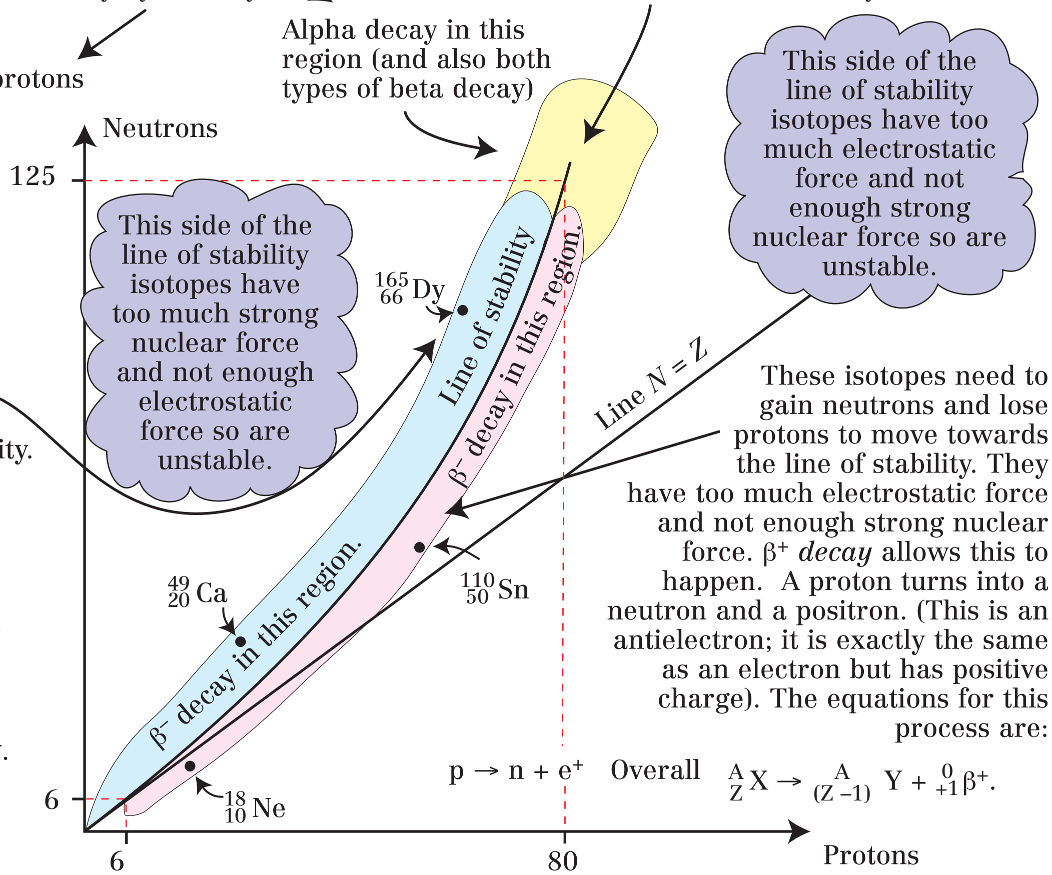
For elements where $Z > 80$ these decay by α decay.

If a nucleus has a proton:neutron mixture close to this line it is stable and does not decay.

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

$${}^{A}_{Z}X \rightarrow {}^{(A-4)}_{(Z-2)}Y + {}^{4}_{2}He$$

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. β^- *decay* allows this to happen.
A neutron turns into a proton and an electron. The equations for this process are:

$n \rightarrow p + e^-$

Overall $\quad {}^{A}_{Z}X \rightarrow {}^{A}_{(Z+1)}Y + {}^{0}_{-1}\beta^-$.

These isotopes need to gain neutrons and lose protons to move towards the line of stability. They have too much electrostatic force and not enough strong nuclear force. β^+ *decay* allows this to happen. A proton turns into a neutron and a positron. (This is an antielectron; it is exactly the same as an electron but has positive charge). The equations for this process are:

$p \rightarrow n + e^+$ Overall $\quad {}^{A}_{Z}X \rightarrow {}^{A}_{(Z-1)}Y + {}^{0}_{+1}\beta^+$.

N.B. remember the beta particle is an electron.

E.g.

${}^{49}_{20}Ca \rightarrow {}^{49}_{21}Sc + {}^{0}_{-1}\beta^-$. $\qquad {}^{165}_{66}Dy \rightarrow {}^{165}_{67}Ho + {}^{0}_{-1}\beta^-$.

Parent $\qquad$ Daughter

E.g.

${}^{110}_{50}Sn \rightarrow {}^{110}_{49}In + {}^{0}_{+1}\beta^+$.

${}^{18}_{10}Ne \rightarrow {}^{18}_{9}F + {}^{0}_{+1}\beta^+$.

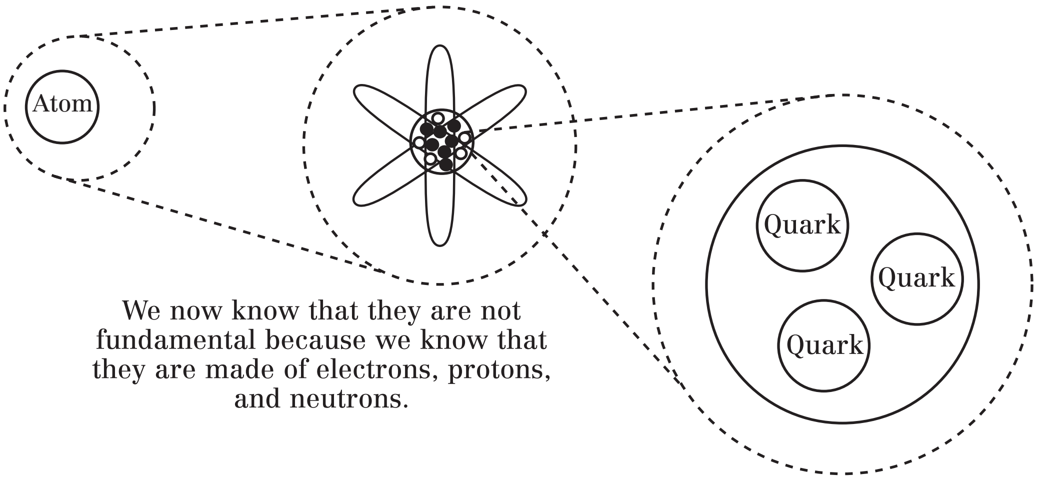
Questions

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. Why does the line on the graph curve away from the line $Z = N$?
3. What type of decay occurs in isotopes with too much strong nuclear force? How do these changes help the nucleus to become more stable?
4. Repeat question 3 for isotopes with too much electrostatic force.
5. Nuclei do not contain electrons, so where does the electron emitted from a nucleus in beta-minus decay come from?
6. Balance the equation ${}^{11}_{6}C \rightarrow {}^{11}_{\_\_}B + \_\_\_\_$. (Hint: are there too many protons or too many neutrons in the carbon nucleus?), hence will β^+ or β^- 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.

Similar experiments to Rutherford's alpha scattering using electrons fired at protons and neutrons reveals that they are made up of smaller particles – *quarks*.

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

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.

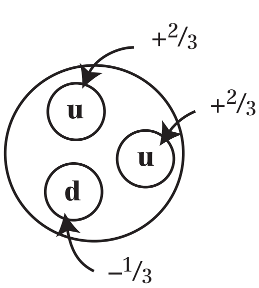
There are actually six types of quark given odd names. They also have fractional charges as shown below.

Up	Charge	Charm	Charge	Top	Charge
u	$+^2/_3$	c	$+^2/_3$	t	$+^2/_3$
Down	Charge	Strange	Charge	Bottom	Charge
d	$-^1/_3$	s	$-^1/_3$	b	$-^1/_3$

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

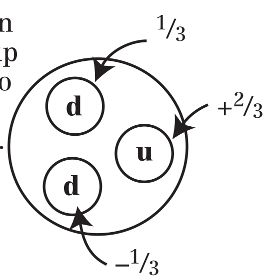
Protons and neutrons are made of just two types of quark, the up and the down. Other particles have to be created in special machines called particle accelerators.

Proton – two up and one down quarks.



Charge = $(+^2/_3) + (+^2/_3) + (-^1/_3) = +1$

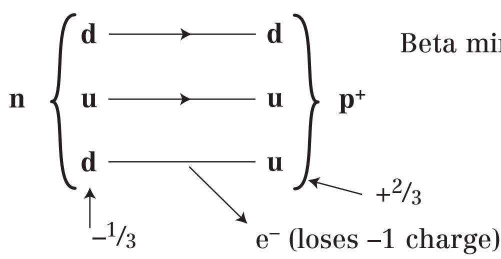
Neutron – one up and two down quarks.

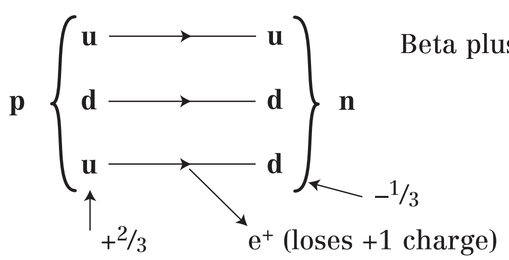


Charge = $(+^2/_3) + (-^1/_3) + (-^1/_3) = 0$

Beta decay

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





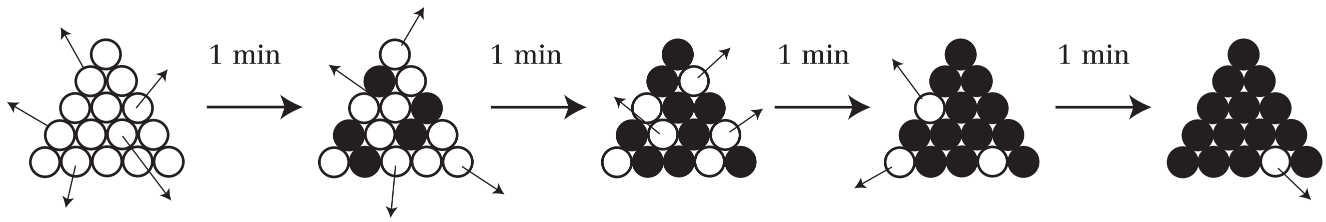
Questions

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?

RADIOACTIVITY Half-Life

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.

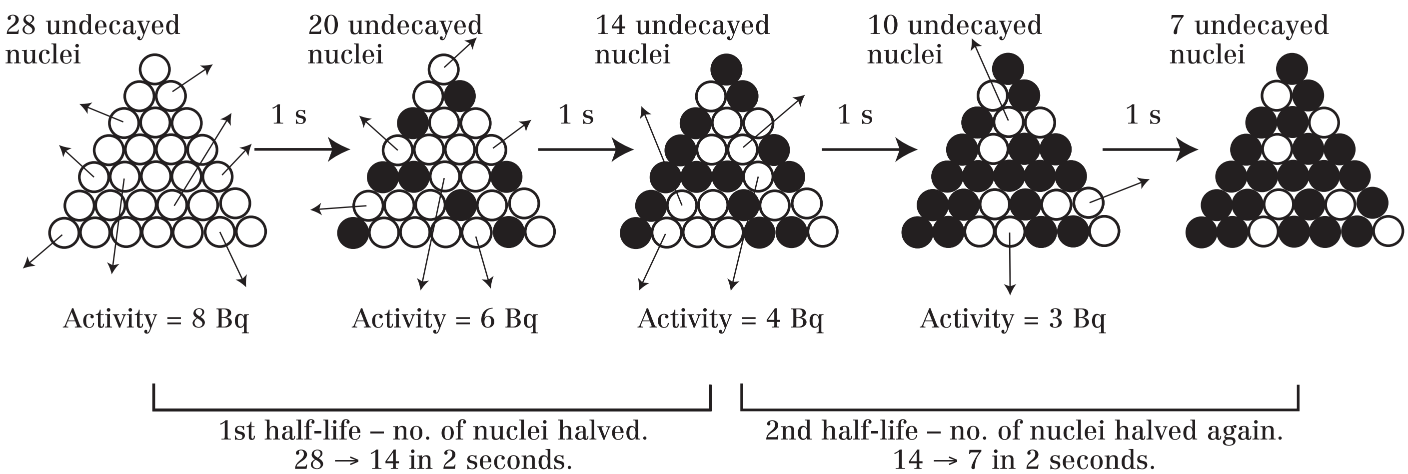


As time goes by radioactive materials contain fewer and fewer unstable atoms and so become less and less radioactive and emit less and less radiation.

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, $^1/_6$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:

> '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 $\dfrac{6400\text{ Bq}}{2} = 3200$ Bq.

After 30 mins the activity will be $\dfrac{3200\text{ Bq}}{2} = 1600$ Bq.

After 45 mins the activity will be $\dfrac{1600\text{ Bq}}{2} = 800$ Bq.

After 1 hour the activity will be $\dfrac{800\text{ Bq}}{2} = 400$ Bq.

Alternatively, consider the number of half-lives, e.g. $1^1/_2$ hrs = 6 × 15 mins = 6 half-lives.

Therefore

activity $= \dfrac{\text{original activity}}{(2 \times 2 \times 2 \times 2 \times 2 \times 2)}$

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

$= \dfrac{\text{original activity}}{2^6}$

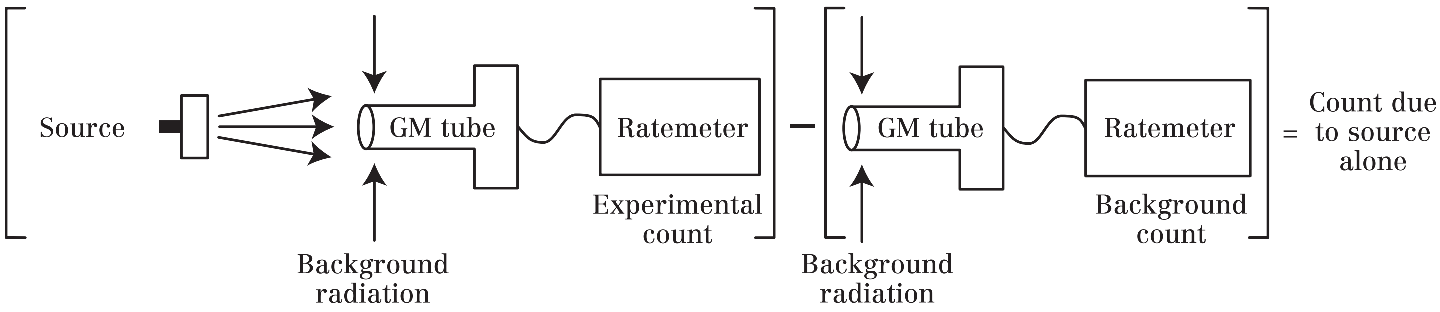
In general,

activity $= \dfrac{\text{original activity}}{2^{\text{no. of half-lives}}}$

Therefore after 6 half-lives, in this case,

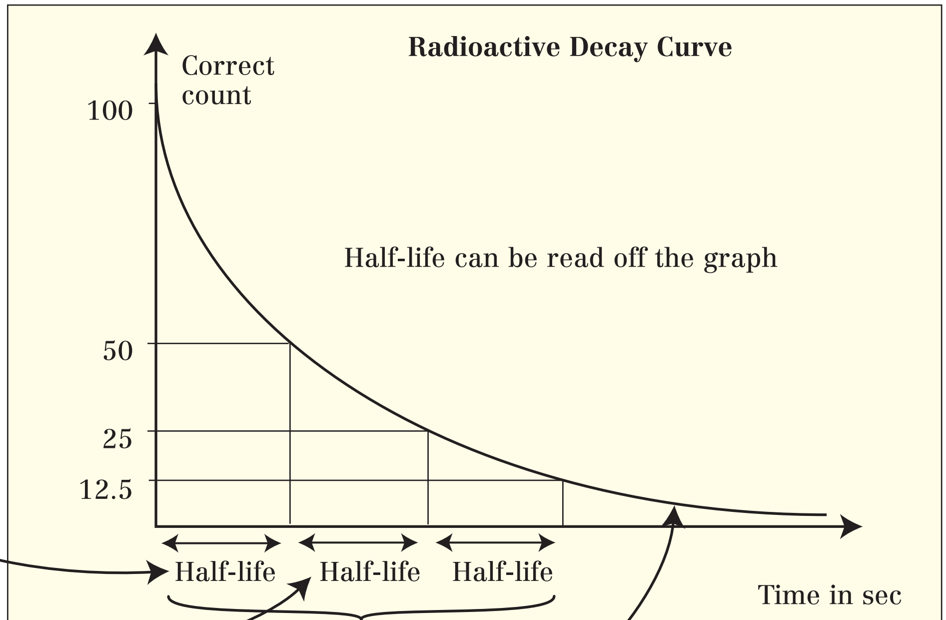
activity $= \dfrac{6400\text{ Bq}}{2^6} = 100$ Bq.

2. Graphically A graph of activity vs. time can be plotted from experimental measurements. We must remember to subtract the background count from the actual count to find the count due to the source alone. We call this the *corrected count rate*.



Results:

As long as the sample is large enough, this curve is smooth, because although the process is random, probability tells us half the atoms will decay in a certain time, but not which.



1st half-life, time taken to drop from 100 to 50 counts.

2nd half-life, time taken to halve again from 50 to 25 counts.

Half-life is constant, irrespective of starting count.

Nuclear radiation never completely dies away, but eventually drops to a negligible level, close to the background. At this point, a source is considered safe. Consideration of half-life therefore, has importance when considering which isotopes to use for various applications and the disposal of radioactive waste – see section on applications of radioactivity.

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. ${}^{99}_{43}$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 ${}^{137}_{56}$Ba (Barium). They record the count rate every 60 s and record the following results:

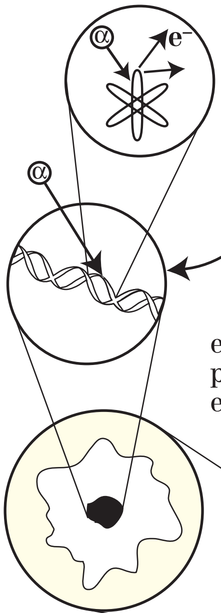
Time in seconds	0	60	120	180	240	300	360	420	480	540	600	660	720
Count rate (decays/s)	30.8	23.8	18.4	14.2	11.1	8.7	6.9	5.4	4.4	3.5	2.9	2.4	2.0

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?
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. ${}^{135}_{53}$I (iodine) half-life = 6.7 hrs.
   b. ${}^{87}_{38}$Sr (strontium) half-life = 2.9 hrs.
   c. ${}^{42}_{19}$K (potassium) half-life = 12.5 hrs.
   d. ${}^{187}_{74}$W (tungsten) half-life = 24 hrs.

RADIOACTIVITY Is Radiation Dangerous?

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.

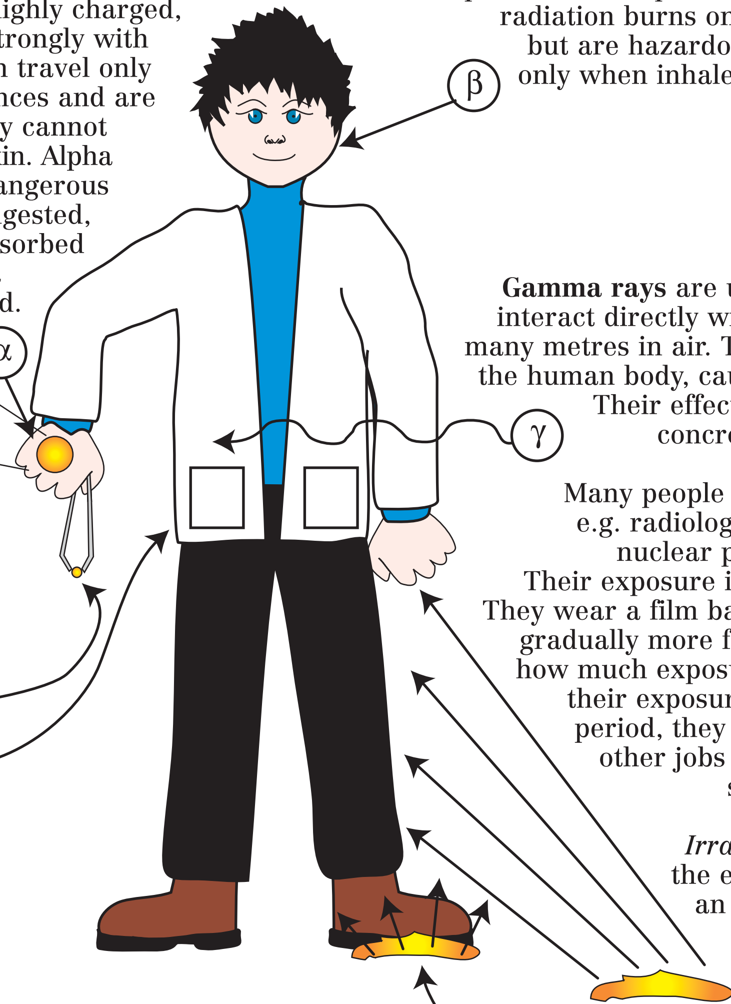
Radiation dose is measured in Sieverts. This unit measures the amount of energy deposited in the tissue by the radiation, and takes account of the type of radiation, because some particles are more effective at damaging cells than others. It is a measure of the possible harm done to your body.



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.

Radioactive materials have to be handled safely. Various precautions to adopt include:

- Keeping source as far from body as possible – usually using tongs.
- Protective clothing – usually only for highly active sources.
- Keeping exposure time as short as possible.
- Keeping the source in appropriate storage, usually shielded, e.g. lead, and labelled.

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.

All exposure to radiation is potentially hazardous, but consider

- Type of radiation
- Activity of source
- Contamination or irradiation
- Length of exposure
- Benefits – e.g. medical treatment

Questions

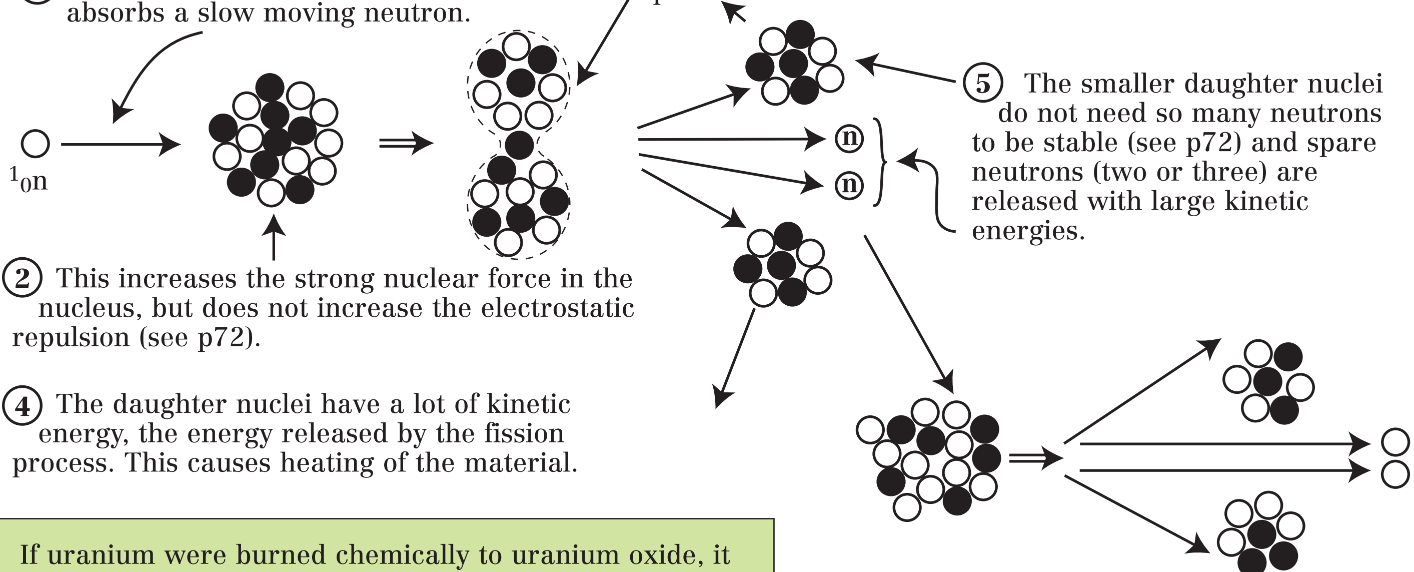
1. Explain which type of radiation is most harmful:
   a. Outside the body.
   b. Inside the body.
2. Explain the difference between contamination and irradiation. Which would you consider a more serious problem?
3. How does nuclear radiation cause damage to living tissues?
4. What is a Sievert?
5. Explain three precautions you should take if you had to handle a low activity radioactive source.

RADIOACTIVITY Nuclear Fission

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.
2. This increases the strong nuclear force in the nucleus, but does not increase the electrostatic repulsion (see p72).
3. The forces in the nucleus are unbalanced and the nucleus splits.
4. The daughter nuclei have a lot of kinetic energy, the energy released by the fission process. This causes heating of the material.
5. The smaller daughter nuclei do not need so many neutrons to be stable (see p72) and spare neutrons (two or three) are released with large kinetic energies.

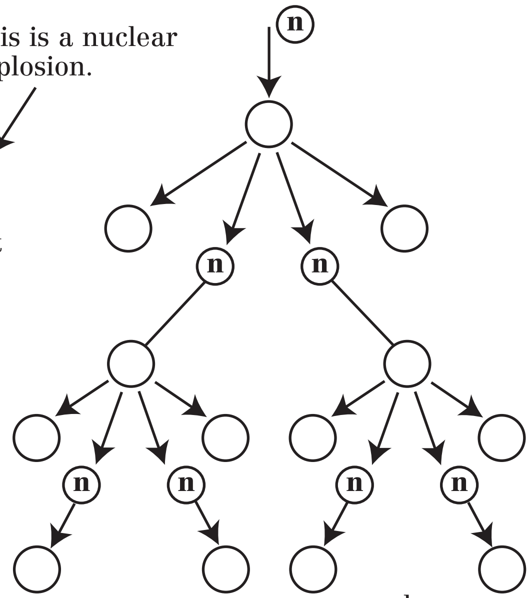


6. These excess neutrons may go on to be absorbed by other ^{239}Pu or ^{235}U nuclei causing them to split.
7. If all the spare neutrons were to go on to cause further fissions, this would rapidly build up into an uncontrolled *chain reaction*.

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

This is a nuclear explosion.



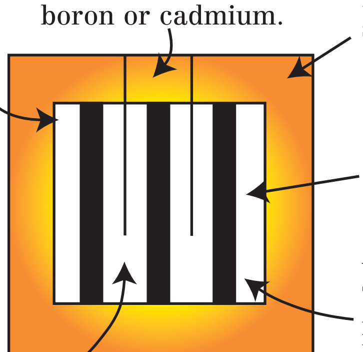
and so on . . .

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

Fuel rods of uranium or plutonium.

Control rods made of boron or cadmium.

Lead/concrete shielding.



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.

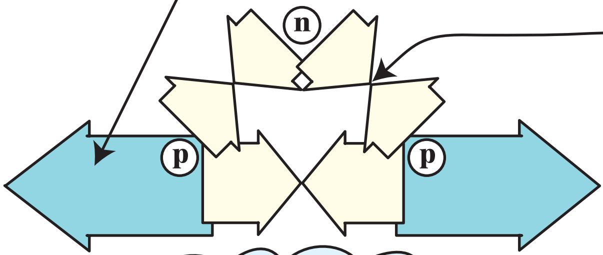
Questions

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

Nuclear Fusion

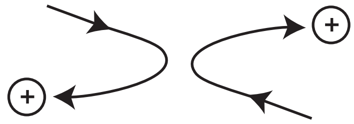
Nuclear fusion is the joining of two light nuclei to form a heavier nucleus. It is the process by which energy is released in stars.

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.

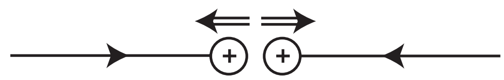


To fuse two nuclei they must be brought very close together so the strong nuclear force can bind their protons and neutrons together.

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

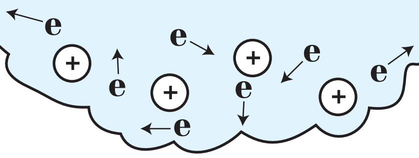


Therefore, the nuclei have to travel very fast so they have a lot of kinetic energy to do work against the repulsive force.



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.



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

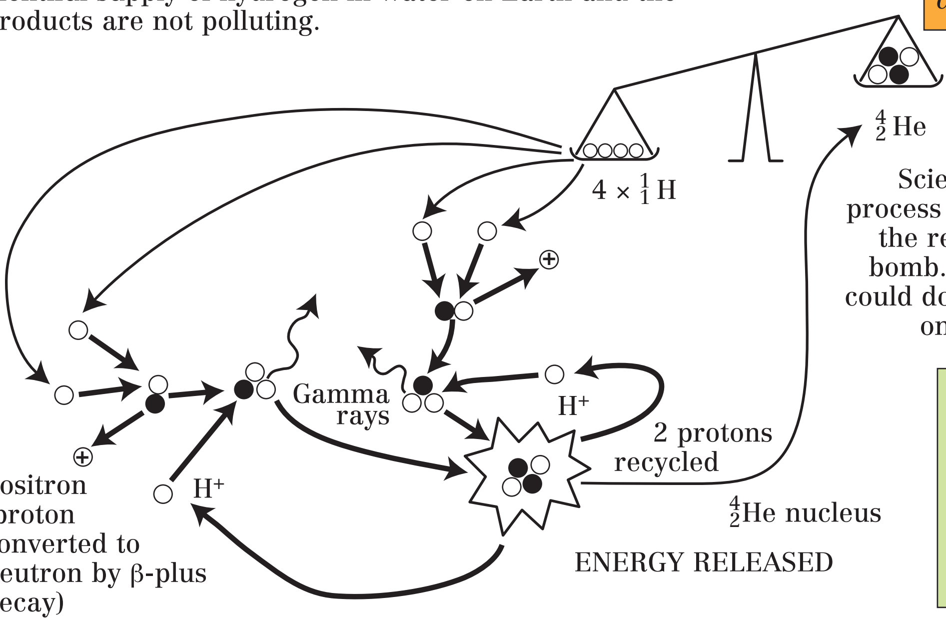
The nucleus formed has less mass than the total mass of the nuclei that fused to create it. The missing mass (or mass defect) has been converted to energy by Einstein's famous relationship

$$\Delta E = \Delta mc^2$$

ΔE = energy released in J
Δm = mass loss in kg
c = speed of light = 3×10^8 m/s

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.

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)
- ●○○ $^3_2$He 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 6.3×10^{14} J (c = speed of light = 3×10^8 m/s).