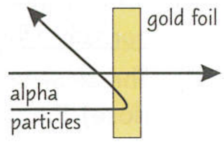
The Model of the Atom

We used to think atoms were tiny solid spheres (like ball-bearings), but they're much more complex than that...

The Theory of Atomic Structure Has Changed Over Time

1) In 1897 J. J. Thomson discovered that electrons could be removed from atoms, so atoms must be made up of smaller bits. He suggested the 'plum-pudding' model — that atoms were spheres of positive charge with tiny negative electrons stuck in them like fruit in a plum pudding.
2) That "plum pudding" theory didn't last very long though. In 1909, Rutherford and Marsden tried firing a beam of alpha particles (see p.51) at thin gold foil. From the plum-pudding model, they expected the particles to pass straight through the gold sheet, or only be slightly deflected.
3) But although most of the particles did go straight through the sheet, some were deflected more than they had expected, and a few were deflected back the way they had come — something the plum-pudding model couldn't explain.



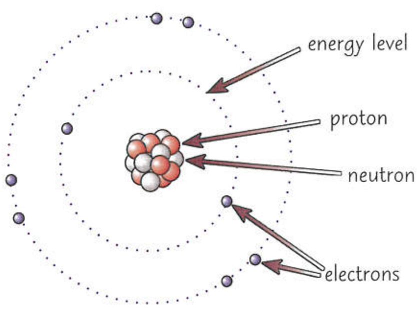
4) Being a pretty clued-up guy, Rutherford realised this meant that most of the mass of the atom was concentrated at the centre in a tiny nucleus.
5) He also realised that most of an atom is just empty space, and that the nucleus must have a positive charge, since it repelled the positive alpha particles.
6) This led to the creation of the nuclear model of the atom.
7) Niels Bohr tweaked Rutherford's idea a few years later by proposing a model where the electrons were in fixed orbits at set distances from the nucleus. These distances were called energy levels (p.50).
8) He suggested that electrons can only exist in these fixed orbits (or shells), and not anywhere inbetween.
9) This model is known as the Bohr model and is pretty close to our currently accepted model of the atom.

The Current Model of the Atom — Protons, Neutrons and Electrons

The quantities to do with atoms are really tiny, so they're written in standard form: $A \times 10^n$ where A is a number between 1 and 10 and n is the number of places the decimal point would move if you wrote the number out in decimal form.

According to our current model of the atom:

1) An atom is a positively-charged nucleus surrounded by negatively-charged electrons.
2) Virtually all the mass of the atom is in the nucleus. The nucleus is tiny — about 10 000 times smaller than the whole atom. It contains protons (which are positively charged) and neutrons (which are neutral). The rest of the atom is mostly empty space.
3) The negative electrons whizz round outside the nucleus in fixed orbits called energy levels or shells. They give the atom its overall size of around 1×10^{-10} m.



4) Atoms are neutral, so the number of protons = the number of electrons. This is because protons and electrons have an equal but opposite relative charge.
5) If an atom loses an electron it becomes a positive ion. If it gains an electron it becomes a negative ion (p.50).
6) Atoms can join together to form molecules — e.g. molecules of oxygen gas are made up of two oxygen atoms bonded together. Small molecules like this have a typical size of 10^{-10} m — the same sort of scale as the size of an atom.

Particle	Relative Mass	Relative Charge
Proton	1	+1
Neutron	1	0
Electron	0.0005	–1

These models don't have anything on my miniature trains...

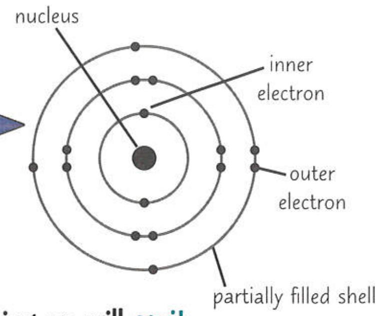
That's a whole lot of history, considering this is a book about physics. It's all good, educational fun though.

Q1 a) Describe the current model of the atom. [4 marks]
b) Describe how the radius of an atom compares to the size of its nucleus. [1 mark]

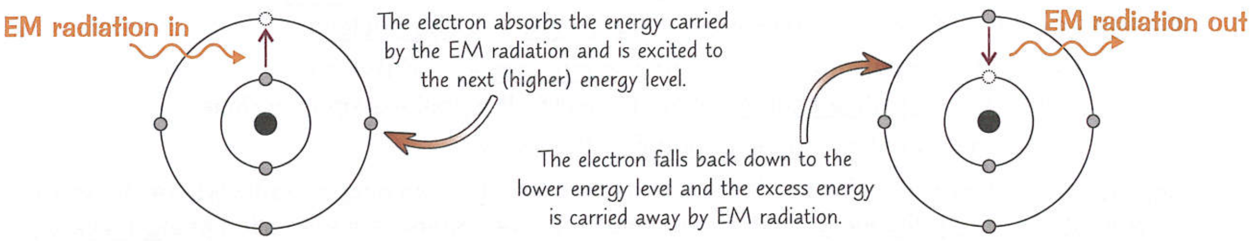
Electron Energy Levels

There's some quirky stuff on this page — and the best part is that you can tell everyone you've been doing a little quantum physics today. Honestly. And if you study physics to a higher level, things get even quirkier.

Electrons Can be Excited to Higher Energy Levels



1) Electrons in an atom sit in different energy levels or shells.
2) Each energy level is a different distance from the nucleus.
3) An inner electron can move up to a higher energy level if it absorbs electromagnetic (EM) radiation with the right amount of energy.
4) When it does move up, it moves to an empty or partially filled shell and is said to be 'excited'.
5) The electron will then quickly fall back to its original energy level, and in doing so will emit (lose) the same amount of energy it absorbed. The energy is carried away by EM radiation.



6) The part of the EM spectrum the radiation emitted from the atom is from depends on its energy. This depends on the energy levels the electron moves between. A higher energy means a higher frequency of EM radiation — p.43. Often, visible light is released when electrons move between energy levels.
7) As you move further out from the nucleus, the energy levels get closer together (so the difference in energy between two levels next to each other gets smaller).
8) This means that an excited electron falling from the third energy level to the second would release less energy than an excited electron falling from the second energy level to the first. So the frequency of the generated radiation decreases as you get further from the nucleus.
9) Changes within the nucleus itself lead to the production of high energy, high frequency gamma rays (p.51).

An Atom is Ionised if it Loses an Electron

1) If an outer electron absorbs radiation with enough energy, it can move so far that it leaves the atom.
2) It is now a free electron and the atom is said to have been ionised.
3) The atom is now a positive ion. It's positive because there are now more protons than electrons.
4) An atom can lose more than one electron. The more electrons it loses, the greater its positive charge.

Nuclear Radiation Ionises Atoms

1) Ionising radiation is any radiation that can knock electrons from atoms.
2) How likely it is that each type of radiation will ionise an atom varies. You can see more about the different types of ionising nuclear radiation on the next page.

Ionising radiation — good for getting creases out of your clothes...

So, an electron absorbs EM radiation and moves up one or more energy levels, then falls back to its original energy level and loses the same amount of energy it absorbed, which is carried away by EM radiation. Simple...

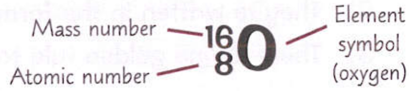
Q1 What is a positive ion and how is one formed? [2 marks]

Isotopes and Nuclear Radiation

Isotopes and ionisation. They sound similar, but they're totally different, so read this page carefully.

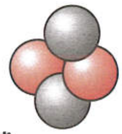
Isotopes are Different Forms of the Same Element

Every oxygen atom has 8 protons.



1) Each element has a set number of protons (so each nucleus has a given positive charge). The number of protons in an atom is called its atomic number or its proton number.
2) The mass (nucleon) number of an atom (the mass of the nucleus) is the number of protons + the number of neutrons in its nucleus.
3) Elements (usually isotopes) can be written as, e.g. carbon-14. This means that the mass number is 14.
4) Isotopes of an element are atoms with the same number of protons (the same atomic number) but a different number of neutrons (a different mass number). E.g. $^{16}_{8}O$ and $^{18}_{8}O$ are two isotopes of oxygen.
5) All elements have different isotopes, but there are usually only one or two stable ones.
6) The other unstable isotopes tend to decay into other elements and give out radiation as they try to become more stable. This process is called radioactive decay.
7) Radioactive substances spit out one or more types of ionising radiation when they decay: alpha, beta, gamma. They can also emit neutrons (n).

Alpha Particles are Helium Nuclei

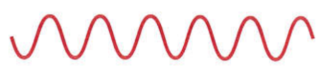


1) Alpha radiation is when an alpha particle (α) is emitted from the nucleus. An α-particle is two neutrons and two protons (like a helium nucleus).
2) They don't penetrate very far into materials and are stopped quickly — they can only travel a few cm in air and are absorbed by a thin sheet of paper.
3) Because of their size they are strongly ionising.

Beta Particles can be Electrons or Positrons

1) A beta-minus particle (β^-) is simply a fast-moving electron released by the nucleus. Beta-minus particles have virtually no mass and a relative charge of −1.
2) A beta-plus particle (β^+) is a fast-moving positron. The positron is the antiparticle of the electron. This just means it has exactly the same mass as the electron, but a positive (+1) charge.
3) They are both moderately ionising. Beta-minus particles have a range in air of a few metres and are absorbed by a sheet of aluminium (around 5 mm thick).
4) Positrons have a smaller range, because when they hit an electron the two destroy each other and produce gamma rays — this is called annihilation and it's used in PET scanning (see p.56).

Gamma Rays are EM Waves with a Short Wavelength



1) After a nucleus has decayed, it often undergoes nuclear rearrangement and releases some energy. Gamma rays (γ) are waves of EM radiation (p.43) released by the nucleus that carry away this energy.
2) They penetrate far into materials without being stopped and will travel a long distance through air.
3) This means they are weakly ionising because they tend to pass through rather than collide with atoms. Eventually they hit something and do damage.
4) They can be absorbed by thick sheets of lead or metres of concrete.

Isotopes of an outfit — same dress, different accessories...

Knowing different kinds of radiation and what can absorb them could bag you a few easy marks in an exam.

Q1 For each of alpha, beta-minus and gamma radiations, give an example of a material that could be used to absorb it. Refer to the material's thickness in your answer. [3 marks]

Nuclear Equations

Nuclear equations show radioactive decay and once you get the hang of them they're dead easy. Get going.

Mass and Atomic Numbers Have to Balance

1) Nuclear equations are a way of showing radioactive decay by using element symbols (p.51).
2) They're written in the form: atom before decay → atom after decay + radiation emitted.
3) There is one golden rule to remember: the total mass and atomic numbers must be equal on both sides.

Alpha Decay Decreases the Charge and Mass of the Nucleus

When a nucleus emits an alpha particle, it loses two protons and two neutrons, so:

- the mass number decreases by 4.
- the atomic number decreases by 2.

$$^{226}_{88}\text{Ra} \rightarrow \, ^{222}_{86}\text{Rn} + \, ^{4}_{2}\alpha$$

mass number:	226	→	222	+	4	(= 226)
atomic number:	88	→	86	+	2	(= 88)

In both alpha and beta emissions, a new element will be formed, as the number of protons (atomic number) changes.

Beta-minus Decay Increases the Charge of the Nucleus

In a beta-minus decay, a neutron changes into a proton and an electron, so:

- the mass number doesn't change — as it has lost a neutron but gained a proton.
- the atomic number increases by 1 — because it has one more proton.

$$^{14}_{6}\text{C} \rightarrow \, ^{14}_{7}\text{N} + \, ^{0}_{-1}\beta$$

mass number:	14	→	14	+	0	(= 14)
atomic number:	6	→	7	+	(–1)	(= 6)

Positron Emission Decreases the Charge of the Nucleus

In beta-plus decay, a proton changes into a neutron and a positron, so:

- the mass number doesn't change — as it has lost a proton but gained a neutron.
- the atomic number decreases by 1 — because it has one less proton.

$$^{18}_{9}\text{F} \rightarrow \, ^{18}_{8}\text{O} + \, ^{0}_{1}\beta$$

mass number:	18	→	18	+	0	(= 18)
atomic number:	9	→	8	+	1	(= 9)

Neutron Emission Decreases the Mass of the Nucleus

When a nucleus emits a neutron:

- the mass number decreases by 1 — as it has lost a neutron.
- the atomic number stays the same.

$$^{13}_{4}\text{Be} \rightarrow \, ^{12}_{4}\text{Be} + \, ^{1}_{0}\text{n}$$

mass number:	13	→	12	+	1	(= 13)
atomic number:	4	→	4	+	0	(= 4)

Gamma Rays Don't Change the Charge or Mass of the Nucleus

1) Gamma rays (γ) are a way of getting rid of excess energy from an atom. The nucleus goes from an excited state to a more stable state by emitting a gamma ray.
2) The mass and atomic numbers stay the same after a gamma ray has been emitted.

Keep balanced during revision and practise nuclear equations...

Nuclear equations are simple, but that doesn't mean you shouldn't practise them. Try these questions on for size.

Q1 What type of radiation is given off in this decay? $^{8}_{3}\text{Li} \rightarrow \, ^{8}_{4}\text{Be}$ + radiation. [1 mark]

Q2 Write the nuclear equation for $^{219}_{86}\text{Rn}$ decaying to polonium (Po) by emitting an alpha particle. [3 marks]

Half-Life

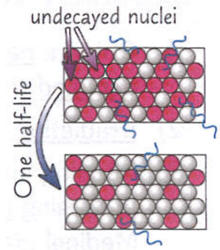
How quickly unstable nuclei decay is measured using activity and half-life — two very important terms.

Radioactivity is a Totally Random Process

1) Radioactive sources contain radioactive isotopes that give out radiation from the nuclei of their atoms.
2) This process is entirely random. This means that if you have 1000 unstable nuclei, you can't say when any one of them is going to decay, or which one will decay next.

3) If there are lots of nuclei though, you can predict how many will have decayed in a given time based on the half-life of the source (see below). The rate at which a source decays is called its ACTIVITY. Activity is measured in becquerels, Bq. 1 Bq is 1 decay per second.
4) Activity can be measured with a Geiger-Müller tube, which clicks each time it detects radiation. The tube can be attached to a counter, which displays the number of clicks per second (the count-rate).
5) You can also detect radiation using photographic film. The more radiation the film's exposed to, the darker it becomes (just like when you expose it to light).

The Radioactivity of a Source Decreases Over Time



1) Each time a radioactive nucleus decays, one more radioactive nucleus disappears. As the unstable nuclei all steadily disappear, the activity as a whole will decrease.
2) For some isotopes it takes just a few hours before nearly all the unstable nuclei have decayed, whilst others last for millions of years.
3) The problem with trying to measure this is that the activity never reaches zero, so we have to use the idea of half-life to measure how quickly the activity drops off.

The half-life is the average time taken for the number of radioactive nuclei in an isotope to halve.

4) A short half-life means the activity falls quickly, because the nuclei are very unstable and rapidly decay. Sources with a short half-life are dangerous because of the high amount of radiation they emit at the start, but they quickly become safe. (Half-life can also be described as the time taken for the activity to halve.)
5) A long half-life means the activity falls more slowly because most of the nuclei don't decay for a long time — the source just sits there, releasing small amounts of radiation for a long time. This can be dangerous because nearby areas are exposed to radiation for (millions of) years.

EXAMPLE: The activity of a radioactive sample is measured as 640 Bq. Two hours later it has fallen to 40 Bq. Find its half-life.

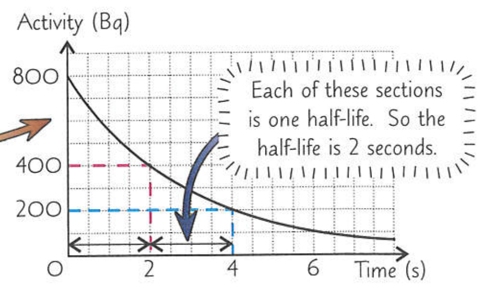
1) Count how many half-lives it took to fall to 40 Bq.

Initial activity:		after 1 half-life:		after 2 half-lives:		after 3 half-lives:		after 4 half-lives:
640	(÷2) →	320	(÷2) →	160	(÷2) →	80	(÷2) →	40

2) Calculate the half-life of the sample. Two hours is four half-lives — so the half-life is 2 hours ÷ 4 = 30 min

You Can Measure Half-Life Using a Graph

1) If you plot a graph of activity against time (taking into account background radiation, p.54), it will always be shaped like the one to the right.
2) The half-life is found from the graph by finding the time interval on the bottom axis corresponding to a halving of the activity on the vertical axis. Easy.



The half-life of a box of chocolates is about five minutes...

Half-life — the average time for the number of radioactive nuclei or the activity to halve. Simple.

Q1 A radioactive source has a half-life of 60 h and an activity of 480 Bq. Find its activity after 240 h. [2 marks]

Background Radiation and Contamination

Forget love — radiation is all around. Don't panic too much though, it's usually a pretty small amount.

Background Radiation Comes From Many Sources

Background radiation is the low-level radiation that's around us all the time. It comes from:

1) Radioactivity of naturally occurring unstable isotopes which are all around us — in the air, in some foods, building materials and some of the rocks under our feet.
2) Radiation from space, which is known as cosmic rays. These come mostly from the Sun. Luckily, the Earth's atmosphere protects us from much of this radiation.
3) Radiation due to human activity, e.g. fallout from nuclear explosions or nuclear waste. But this represents a tiny proportion of the total background radiation.

Coloured bits indicate more radiation from rocks

The amount of radiation you're exposed to (and so the amount of energy your body absorbs) is called the absorbed radiation dose. Your radiation dose varies depending on where you live or if you have a job that involves radiation.

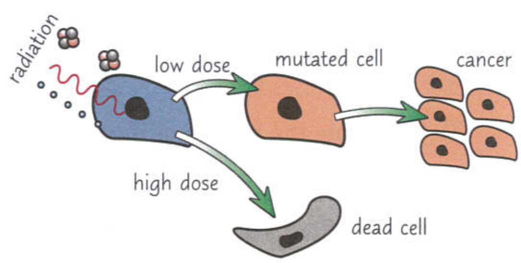
Exposure to Radiation is called Irradiation

1) Objects near a radioactive source are irradiated by it. This simply means they're exposed to it (we're always being irradiated by background radiation sources).
2) Irradiating something does not make it radioactive (and won't turn you into a superhero).
3) Keeping sources in lead-lined boxes, standing behind barriers or being in a different room and using remote-controlled arms are all ways of reducing the effects of irradiation. Medical staff who work with radiation also wear photographic film badges to monitor their exposure.

Contamination is Radioactive Particles Getting onto Objects

1) If unwanted radioactive atoms get onto an object, the object is said to be contaminated. E.g. if you touch a radioactive source without wearing gloves, your hands would be contaminated.
2) These contaminating atoms might then decay, releasing radiation which could cause you harm.
3) Contamination is especially dangerous because radioactive particles could get inside your body.
4) Once a person is contaminated, they are at risk of harm until either the contamination is removed (which isn't always possible) or all the radioactive atoms have decayed.
5) Gloves and tongs should be used when handling sources, to avoid particles getting stuck to your skin or under your nails. Some industrial workers wear protective suits to stop them breathing in particles.

Radiation Damages Cells by Ionisation



1) Radiation can enter living cells and ionise atoms and molecules within them. This can lead to tissue damage.
2) Lower doses tend to cause minor damage without killing the cells. This can give rise to mutant cells which divide uncontrollably. This is cancer.
3) Higher doses tend to kill cells completely, causing radiation sickness (leading to vomiting, tiredness and hair loss) if a lot of cells all get blatted at once.
4) Outside the body, beta and gamma radiation are the most dangerous, because they can penetrate the body and get to the delicate organs. Alpha is less dangerous, because it can't penetrate the skin.
5) Inside the body, alpha sources are the most dangerous. Alpha particles are strongly ionising, so they do all their damage in a very localised area. That means contamination, rather than irradiation, is the major concern when working with alpha sources.

Background radiation — the ugly wallpaper of the Universe...

Make sure you can describe how to prevent irradiation and contamination, and why it's so important that you do.

Q1 Give three sources of background radiation. [3 marks]

Uses of Radiation

Ionising radiation is very dangerous stuff, but used in the right way it can be incredibly useful.

The Hazards Associated with a Radioactive Source Depend on its Half-Life

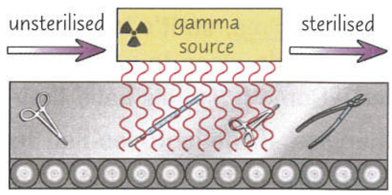
1) The lower the activity (see p.53) of a radioactive source, the safer it is to be around.
2) If two sources that produce the same type of radiation start off with the same activity, the one with the longer half-life will be more dangerous. This is because, after any period of time, the activity of the source with a short half-life will have fallen more than the activity of the source with a long half-life.
3) If the two sources have different initial activities, the danger associated with them changes over time. Even if its initial activity is lower (so it is initially safer), the source with the longer half-life will be more dangerous after a certain period of time because its activity falls more slowly.
4) When choosing a radioactive source for an application, it's important to find a balance between a source that has the right level of activity for the right amount of time, and that isn't too dangerous for too long. Careful planning of storage and disposal of sources is needed, especially for sources with long half-lives.

Household Fire Alarms Use Alpha Radiation

1) A weak source of alpha radiation (p.51) is placed in a smoke detector, close to two electrodes.
2) The source causes ionisation, and a current of charged particles flows.
3) If there is a fire then smoke will absorb the charged particles — the current stops and the alarm sounds.

Food and Equipment can be Sterilised Using Gamma Rays

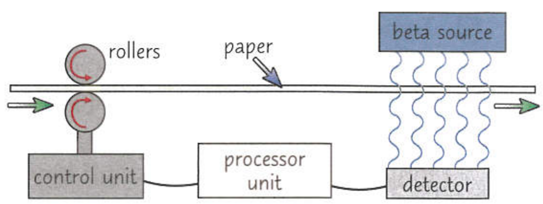
1) Food can be irradiated with (p.54) a high dose of gamma rays which will kill all microbes. This means that the food doesn't go bad as quickly as it would do otherwise.
2) Similarly, medical equipment can be sterilised using gamma rays instead of being boiled.



3) Irradiation is a particularly good method of sterilisation because, unlike boiling, it doesn't involve high temperatures, so fresh fruit or plastic instruments can be totally sterilised without being damaged.
4) The radioactive source used for this needs to be a very strong emitter of gamma rays with a reasonably long half-life (at least several months) so that it doesn't need replacing too often.

Radiation is Used in Tracers and Thickness Gauges

1) Certain radioactive isotopes can be used as tracers. A medical tracer is injected into a patient (or swallowed) and its progress around the body is followed using an external detector. This method can be used to detect and diagnose medical conditions (e.g. cancer).
2) All isotopes which are taken into the body must be BETA or GAMMA emitters (never alpha), so that the radiation passes out of the body without doing too much damage. They should only last a few hours, so that the radioactivity inside the patient quickly disappears (i.e. they should have a short half-life).
3) Gamma emitting tracers are also used in industry to detect leaks in underground pipes.
4) Beta radiation is used in thickness control. You direct radiation through the stuff being made (e.g. paper), and put a detector on the other side, connected to a control unit. When the amount of detected radiation changes, it means the paper is coming out too thick or too thin, so the control unit adjusts the rollers to give the correct thickness.



5) It needs to be a beta source, because then the paper will partly block the radiation (see p.51). If it all goes through (or none of it does), then the reading won't change at all as the thickness changes.

High activity is dangerous? Time for a rest then...

But only a short one — then make sure you can describe why different types of radiation have different uses.

Q1 Explain why radioactive sources that emit alpha radiation are not used as medical tracers. [2 marks]

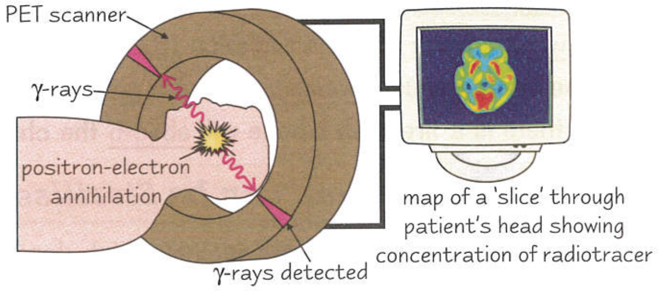
PET Scanning and Radiotherapy

And the uses keep on coming — we use radiation in lots of medical treatments like radiotherapy.

PET Scanning Can Help Diagnose Illnesses

Positron emission tomography or PET scanning is a technique used to show tissue or organ function, and can be used to diagnose medical conditions. For example, it can identify active cancer tumours by showing metabolic activity in tissue. Cancer cells have a much higher metabolism than healthy cells because they're growing like mad. And here's how it all works — put your best brains in, 'cos this is detailed:

1) Inject the patient with a substance used by the body, e.g. glucose, containing a positron-emitting radioactive isotope with a short half-life so it acts as a tracer, e.g. ^{11}C, ^{13}N, ^{15}O or ^{18}F. Over an hour or so the tracer moves through the body to the organs.
2) Positrons emitted by the isotope meet electrons in an organ and annihilate (see page 51), emitting high-energy gamma rays in opposite directions that are detected. Detectors around the body detect each pair of gamma rays — the tumour will lie along the same path as each pair. By detecting at least three pairs, the location of the tumour can be accurately found by triangulation.
3) The distribution of radioactivity matches up with metabolic activity. This is because more of the radioactive glucose (or whatever) injected into the patient is taken up and used by cells that are doing more work (cells with an increased metabolism, in other words).



4) The isotopes used in PET scanning have short half-lives, so it's important that they're made close to where they'll be used. Some hospitals have their own cyclotron to make the isotopes on-site.
5) Otherwise, if the isotopes had to be transported over a large distance, their activity could be too low by the time they arrived at the hospital, making them no longer as useful.

Radiation can be Used Internally or Externally to Treat Tumours

1) With internal radiation therapy, a radioactive material is placed inside the body into or near a tumour. This can be done in many ways, e.g. by injecting or implanting a small amount of radioactive substance.
2) Alpha emitters are usually injected near to the tumour. As alpha particles are strongly ionising, they do lots of damage to the nearby area (the cancerous cells), but the damage to normal tissue surrounding the tumour is limited because they have such a short range.
3) Beta emitters are often used in implants, placed inside or next to a tumour. Beta radiation is able to penetrate the casing of the implant (unlike alpha particles, which would be stopped) before damaging nearby cancerous cells. As they have a longer range than alpha particles, they can damage healthy cells further away from the cancerous cells.
4) The half-lives of the sources used for internal treatments are usually short, to limit the time that a radioactive substance is inside the patient's body.
5) Tumours can be treated externally using gamma rays aimed at the tumour, as these are able to penetrate through the patient's body. The radiation is carefully focused on the tumour, and sometimes shielding is placed on other areas of the patient's body, but some damage is still done to surrounding healthy cells.
6) The sources used in external radiotherapy treatments should have long half-lives, so they don't have to be replaced often.
7) The machines used for radiotherapy are often surrounded by shielding and kept in a designated room to reduce the risk to staff and patients in the hospital.

PET scanning — how they check prices at the pet shop...

That's a lot of stuff to get your head around. Re-read this page, have a quick tea break, then try this question.

Q1 Explain how a PET scan can detect a cancerous tumour in a patient. [4 marks]

Nuclear Fission

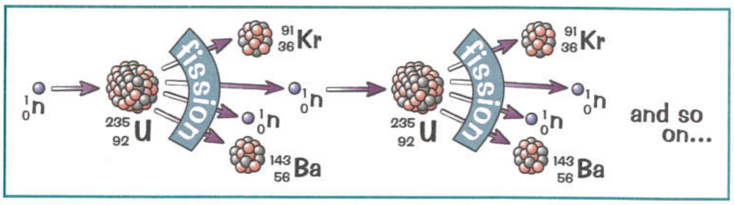
It's amazing how much energy there is trapped in a little atom. This energy is released by nuclear fission.

Nuclear Fission — the Splitting Up of Big Atomic Nuclei

Nuclear fission is a type of nuclear reaction that is used to release energy from uranium (or plutonium) atoms, e.g. in a nuclear reactor. Huge amounts of energy can be released this way by using a chain reaction...

The Chain Reaction:

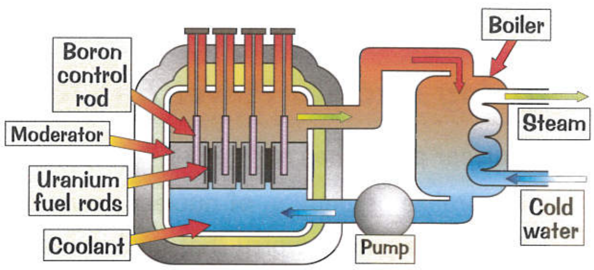
1) A slow-moving neutron is fired at a large, unstable nucleus — often uranium-235. The neutron is absorbed by the nucleus — this makes the atom more unstable and causes it to split.
2) When the U-235 atom splits it forms two new lighter elements ('daughter nuclei') and energy is released.
3) There are lots of different pairs of atoms that uranium can split into, e.g. krypton-91 and barium-143, but all these new nuclei are radioactive.
4) Each time a uranium atom splits up, it also spits out two or three neutrons, which can hit other uranium nuclei, causing them to split also, and so on and so on. This is a chain reaction.



A neutron can be absorbed by the nucleus because it has no charge — i.e. it's not repelled by the positive charge of the nucleus.

Chain Reactions in Reactors Must be Carefully Controlled

1) The neutrons released by fission reactions in a nuclear reactor have a lot of energy.
2) These neutrons will only cause other nuclear fissions (and cause a chain reaction) if they are moving slowly enough to be captured by the uranium nuclei in the fuel rods. These slow-moving neutrons are called thermal neutrons.
3) To do this, the uranium fuel rods are placed in a moderator (for example, graphite) to slow down the fast-moving neutrons.
4) Control rods, often made of boron, limit the rate of fission by absorbing excess neutrons. They are placed inbetween the fuel rods and are raised and lowered into the reactor to control the chain reaction.
5) This creates a steady rate of nuclear fission, where one new neutron produces another fission.
6) If the chain reaction in a nuclear reactor is left to continue unchecked, large amounts of energy are released in a very short time. Many new fissions will follow each fission, causing a runaway reaction which could lead to an explosion.



Nuclear Power Stations are Really Glorified Steam Engines

1) Nuclear power stations are powered by nuclear reactors that create controlled chain reactions.
2) The energy released by fission is transferred to the thermal energy store of the moderator. This is then transferred to the thermal energy store of the coolant, and then to the thermal energy store of the cold water passing through the boiler. This causes the water to boil (p.94) and energy to be transferred to the kinetic energy store of the steam.
3) This energy is then transferred to the kinetic energy store of a turbine and then to the kinetic energy store of a generator. The energy is then transferred away from the generator electrically.

Revise nuclear power — full steam ahead...

Nuclear reactors are carefully-designed to release energy safely, but they still have issues (see next page).

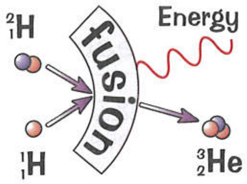
Q1 Draw a diagram showing how fission can lead to a chain reaction. [3 marks]

Nuclear Fusion and Nuclear Power

Loads of energy's released either when you break apart really big nuclei or join together really small nuclei. You can't do much with the ones in the middle, I'm afraid. But at least that's one less thing to learn...

Nuclear Fusion — Joining Small Nuclei

1) Nuclear fusion is the opposite of nuclear fission. In nuclear fusion, two light nuclei collide at high speed and join (fuse) to create a larger, heavier nucleus. For example, hydrogen nuclei can fuse to produce a helium nucleus.

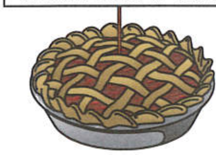


2) This heavier nucleus does not have as much mass as the two separate, light nuclei did. Some of the mass of the lighter nuclei is converted to energy (don't panic, you don't need to know how). This energy is then released as radiation.

Fusion Only Happens at High Temperatures and Pressures

1) The big problem is that fusion only happens at really high pressures and temperatures (about 10 000 000 °C). This is because the positively charged nuclei have to get very close to fuse, so the strong force due to electrostatic repulsion (p.82) has to be overcome.
2) It's really hard to create the right conditions for fusion. No material can withstand that kind of temperature — it would just be vaporised. So fusion reactors are really hard and expensive to try to build.
3) There are a few experimental reactors around at the moment, but none of them are generating electricity yet. It takes more power to get up to temperature than the reactor can produce.

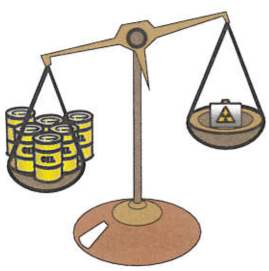
BEWARE: the filling of this fruit pie is hotter than the conditions needed for fusion.



Using Nuclear Power Has Its Pros and Cons

Nuclear power has a lot going for it, but some people are completely against it being used.

1) Public perception of nuclear power can be very negative — it's seen by many to be very dangerous.
2) Some people worry that nuclear waste can never be disposed of safely. The waste products from nuclear fission have very long half-lives, meaning they'll be radioactive for hundreds or thousands (even millions) of years. There is always a danger that they could leak out and pollute land, rivers and oceans.
3) Nuclear power also carries the risk of leaks directly from the power station or a major catastrophe like those at Chernobyl and Fukushima.



4) However, nuclear power is generally a pretty safe way of generating electricity — it's not as risky as some people may think it is.
5) And it's not all doom and gloom. Nuclear power is a very reliable energy resource and reduces the need for fossil fuels (which are already running out — see p.28).
6) Fossil fuels (coal, oil and gas) all release carbon dioxide (CO_2) when they're burnt. This adds to the greenhouse effect and global warming. Burning coal and oil also releases sulfur dioxide that can cause acid rain. Nuclear power doesn't release these gases, so in this way it is a very clean source of energy.
7) Huge amounts of energy can be generated from a relatively small amount of nuclear material. Nuclear fuel (i.e. the uranium) is cheap and readily available.
8) However, the overall cost of nuclear power is high due to the initial cost of the power plant and final decommissioning — dismantling a nuclear plant safely takes decades.

*Pity they can't release energy by confusion...**

Thankfully you don't need to know the complicated processes behind fission and fusion, you just need to have an idea of the steps in them. Remember that fusion is tricky because it needs high temperatures and pressures.

Q1 Explain why fusion only occurs at high temperatures and pressures. [2 marks]

*There'd be plenty of physics books to use as fuel.

The Solar System and Gravity

The Sun is the centre of the Solar System. It's orbited by eight planets, along with a bunch of other objects.

The Solar System has One Star — The Sun

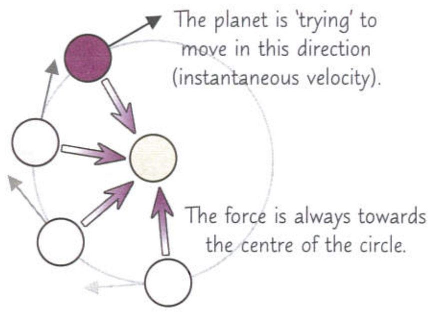
A satellite is an object that orbits a second, more massive object.

The Solar System is all the stuff that orbits our Sun. This includes things like:

1) Planets — these are large objects that orbit a star. The eight planets in our Solar System are, in order (from the Sun outwards): Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune.
2) Dwarf planets, like our pal Pluto. These are planet-like objects that aren't big enough to be planets.
3) Moons — these orbit planets with almost circular orbits. They're a type of natural satellite (i.e. they're not man-made).
4) Artificial satellites (ones humans have built) that usually orbit the Earth in fairly circular orbits.
5) Asteroids — lumps of rock and metals that orbit the Sun. They're usually found in the asteroid belt.
6) Comets — lumps of ice and dust that orbit the Sun. Their orbits are usually highly elliptical (a very stretched out circle) — some travel from near to the Sun to the outskirts of our Solar System.

Gravity Provides the Force That Creates Orbits

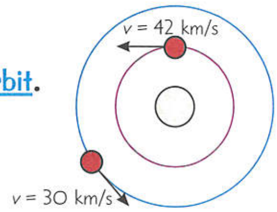
1) The planets move around the Sun in almost circular orbits (same goes for the Earth and the Moon).
2) You saw on p.17 that an object in a circular orbit at a constant speed is constantly accelerating.
3) The force causing this is the centripetal force. It acts towards the centre of the circle.
4) This force would cause the object to just fall towards whatever it was orbiting, but as the object is already moving, it just causes it to change its direction.
5) The object keeps accelerating towards what it's orbiting but the instantaneous velocity (which is at a right angle to the acceleration) keeps it travelling in a circle.
6) The force that makes this happen is provided by the gravitational force (gravity) between the planet and the Sun (or between the planet and its satellites).



The Force due to Gravity Depends on Mass and Distance

1) Back on page 17 you saw that the weight (i.e. the force on an object due to gravity) of any object varies depending on the strength (g) of the gravitational field that it is in.
2) Gravitational field strength depends on the mass of the body creating the field. The larger the mass of the body, the stronger its gravitational field. (The Earth is more massive than the Moon, so an object would weigh more on Earth than it would on the Moon.)
3) Gravitational field strength also varies with distance. The closer you get to a star or planet, the stronger the gravitational force is.
4) The stronger the force, the larger the instantaneous velocity needed to balance it.
5) So the closer to a star or planet you get, the faster you need to go to remain in orbit.
6) For an object in a stable orbit, if the speed of the object changes, the size (radius) of its orbit must do so too. Faster moving objects will move in a stable orbit with a smaller radius than slower moving ones.

The fact that different planets orbit the Sun at different speeds means that the distances between planets vary over time.



Revision's hard work — you've got to plan et...

Make sure you know what orbits what and how to tell a moon from a dwarf planet. Then get your head around all that stuff about orbits — it sounds a bit complicated, but it's really just about balancing forces.

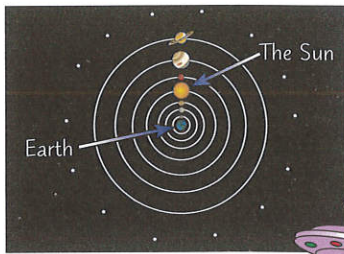
Q1 Describe the orbits of: a) planets b) moons c) comets [3 marks]

Changing Ideas about the Universe

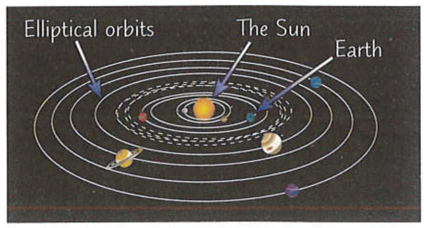
Over time, we've come up with lots of ideas about how the Universe began and how our Solar System looks.

Ancient Greeks Thought the Earth was the Centre of the Solar System

There have been lots of different models of our Solar System:



1) Geocentric model — this theory suggested that the Sun, Moon, planets and stars all orbited the Earth in perfect circles. It arose because people on Earth didn't have telescopes and saw the Sun and Moon travelling across the sky in the same way every day and night. It was the accepted model of the Universe from the time of the ancient Greeks until the 1500s.
2) Next up was the heliocentric model (Sun at the centre of the Solar System). It said that the Earth and all of the planets orbited the Sun in perfect circles.
3) Galileo found one of the best pieces of evidence for this theory — the moons around Jupiter. Whilst looking at Jupiter with a telescope, he noticed some stars in a line near the planet. When he looked again, he saw these 'stars' never moved away from Jupiter and seemed to be carried along with the planet. This showed not everything was in orbit around the Earth — evidence that the geocentric model was wrong.
4) Gradually, evidence for the heliocentric model increased thanks to more technological advances.
5) The current model still says that the planets in our Solar System orbit the Sun — but that these orbits are actually elliptical rather than circular (we treat them as circular to make life easier though) and the Sun isn't really at the centre of the Universe.



Our current view of the Solar System.

Theories for the Creation of the Universe Have Also Changed Over Time

As big as the Universe already is, it looks like it's getting even bigger (it's expanding).
This observation has led to the creation of numerous models that try to explain the creation of the Universe.
These are the two you need to know about:

Steady State — Matter is Always Being Created

1) The 'Steady State' theory says that the Universe has always existed as it is now, and it always will do. It's based on the idea that the Universe appears pretty much the same everywhere.
2) As the Universe expands, new matter is constantly being created.
3) This means that the density (p.93) of the Universe is always roughly the same.
4) In this theory there is no beginning or end to the Universe.

The Big Bang — the Universe Started with an Explosion

1) Initially, all the matter in the Universe occupied a very small space.
2) This tiny space was very dense (p.93) and so was very hot.
3) Then it 'exploded' — space started expanding, and the expansion is still going on.
4) This theory gives a finite age for the Universe (around 13.8 billion years).

Currently, the Big Bang is the accepted theory of how the Universe began.
This is based on evidence shown on the next page.

Forget the Sun, I'm pretty sure everything revolves around me...

Make sure you can describe each theory above and how it compares to our current ideas about the Universe.

Q1 Explain the difference between the geocentric and heliocentric models of the Solar System. [1 mark]

Q2 Give two differences between the Steady State and Big Bang theories. [2 marks]

Red-shift and CMB Radiation

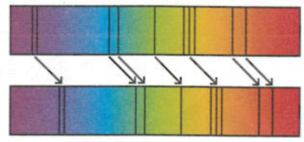
The Big Bang model is the most convincing explanation we've got for how the Universe started.

Red-shift Suggests the Universe is Expanding

Most galaxies seem to be moving away from each other.
There's good evidence for this:

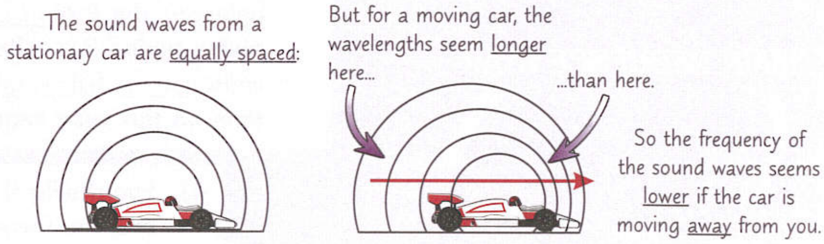
1) Different elements absorb different frequencies (or wavelengths) of light.
2) Each element produces a specific pattern of dark lines at the frequencies that it absorbs in the visible part of the EM spectrum (p.43).
3) When we look at light from distant galaxies we see the same patterns but at slightly lower frequencies than they should be.
4) There's an observed increase in the wavelength of light coming from the galaxies and the patterns have been shifted towards the red end of the spectrum. This is called red-shift.

An absorption spectrum showing dark lines measured on Earth.



The same absorption spectrum measured from light from a distant galaxy. The dark lines in this spectrum are red-shifted.

Red-shift is the same effect as the vrrr-oom from a racing car or the sound of an ambulance as they drive past you. The noise sounds lower-pitched when it's travelling away from you because it drops in frequency (the Doppler effect).



5) Measurements of the red-shift suggest that all the distant galaxies are moving away from us very quickly — and it's the same result whichever direction you look in.
6) More distant galaxies have greater red-shifts than nearer ones — they show a bigger observed increase in wavelength.
7) This means that more distant galaxies are moving away faster than nearer ones. This provides evidence that the whole Universe is expanding.

There's Microwave Radiation from All Directions

1) Scientists have detected low frequency electromagnetic radiation coming from all parts of the Universe.
2) This radiation is mainly in the microwave part of the EM spectrum. It's known as the cosmic microwave background radiation (CMB radiation).

CMB radiation is Strong Evidence for the Big Bang

1) Red-shift can be explained by both the Steady State and Big Bang theories.
2) In both models, objects are moving away from the observer as the Universe expands, so red-shift would be observed for either model.
3) However, CMB radiation only supports the Big Bang model as it shows the Universe had a beginning.
4) This is why the Big Bang theory is currently our accepted model for the start of the Universe.

According to the Big Bang model, the CMB radiation is the leftover energy of the initial explosion.

My brain's shifted towards the tired end of the spectrum...

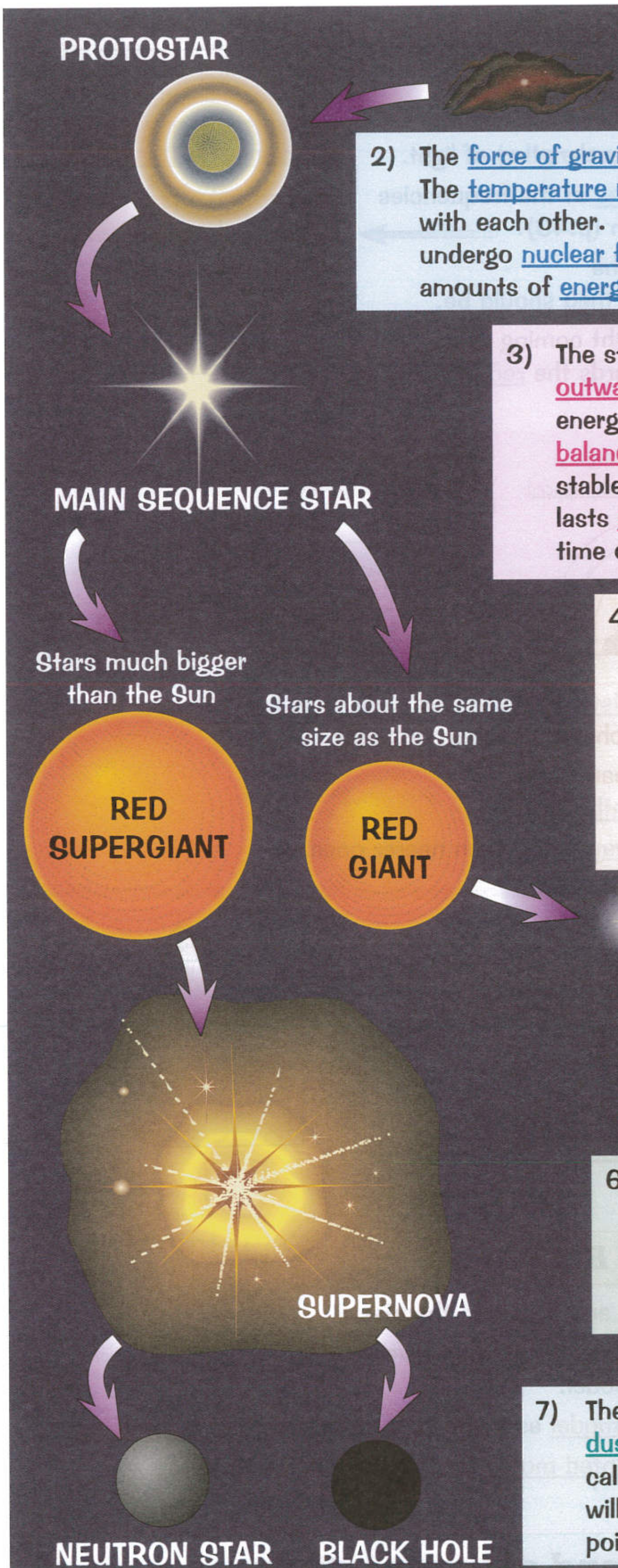
The Big Bang model is the best one we've got to explain how the Universe began, but it may need some tweaking in the future if we find new evidence it can't explain. Scientists, pfft, don't they ever finish anything?

Q1 What is red-shift? [1 mark]

Q2 What theory does CMB radiation support? [1 mark]

The Life Cycle of Stars

Stars go through many traumatic stages in their lives — just like teenagers.



1) Stars initially form from a cloud of dust and gas called a nebula.

2) The force of gravity pulls the dust and gas together to form a protostar. The temperature rises as the star gets denser and more particles collide with each other. When the temperature gets high enough, hydrogen nuclei undergo nuclear fusion (p.58) to form helium nuclei. This gives out huge amounts of energy, which keeps the core of the star hot. A star is born.

3) The star enters a long stable period. During this period, the outward pressure (p.101) caused by thermal expansion (the energy produced by nuclear fusion tries to expand the star) balances the force of gravity pulling everything inwards. In this stable period it's called a main sequence star and it typically lasts several billion years. The heavier the star, the shorter its time on the main sequence. (The Sun is in the middle of this stable period.)

4) Eventually the hydrogen in the core begins to run out and the force due to gravity is larger than the pressure of thermal expansion. The star is compressed, until it is dense and hot enough that the energy (and so pressure) created makes the outer layers of the star expand. The star becomes a red giant (if it is a small star) or a red supergiant (if it is a larger star). It becomes red because the surface cools.

5) A small-to-medium-sized star like the Sun then becomes unstable and ejects its outer layer of dust and gas. This leaves behind a hot, dense solid core — a white dwarf.

6) Big stars, however, start to glow brightly again as they undergo more fusion to make heavier elements. They expand and contract several times, as the balance shifts between gravity and thermal expansion. Eventually, they explode in a supernova.

7) The exploding supernova throws the outer layers of dust and gas into space, leaving a very dense core called a neutron star. If the star is massive enough, it will collapse and become a black hole — a super dense point in space that not even light can escape from.

It's the beginning of the world as we know it...

Pretty neat, seeing how stars like our Sun — which all of us rely on — were made all those years ago.

Q1 Describe the life cycle of a star much larger than our Sun, beginning from a nebula. [6 marks]

Looking Into Space

There are various objects in space, and they emit or reflect different frequencies of EM radiation. And that can be really useful to help us find out what's going on 'out there'.

Telescopes are Used to Observe the Universe

Telescopes help you to see distant objects clearly. There are loads of different kinds (see below) and they all work in different ways. The one you're most likely to have seen is an optical telescope — ones that detect visible light.

Telescopes use refraction (p.34) and reflection (p.38) to allow you to see distant objects. You need to know how to improve the quality of the image you can see using them:

1) Increase the aperture of the telescope. This is the diameter of the objective lens — the big lens at the end of the telescope where light from the distant object enters the telescope.
2) Use a higher quality objective lens.

Space Telescopes Have a Clearer View Than Those on Earth

1) If you're trying to detect light, Earth's atmosphere gets in the way — it absorbs a lot of the light coming from space before it can reach us. To observe the frequencies absorbed, you have to go above the atmosphere.
2) Then there's pollution. Light pollution (light thrown up into the sky from street lamps, etc.) makes it hard to pick out dim objects. And air pollution can reflect and absorb light coming from space.

Night sky in rural area with no light pollution.

Night sky in urban area with light pollution.

3) So to get the best view possible from Earth, a telescope should be on top of a mountain (where there's less atmosphere above it), and in a dark place away from cities (e.g. on Hawaii).
4) To avoid the problem of the atmosphere completely, you can put your telescope in space.

Different Telescopes Detect Different Types of EM Wave

To get as full a picture of the Universe as possible, you need to detect different kinds of EM wave.

1) The earliest telescopes were all optical telescopes. They're used to look at objects close by and in other galaxies. But many objects in the Universe aren't detectable using visible light — so other types of EM telescopes are needed to observe them.
2) From the 1940s onwards, telescopes were developed for all parts of the EM spectrum. These modern telescopes mean we can now 'see' parts of the Universe that we couldn't see before and learn more about the Universe, e.g. its structure.
3) X-ray telescopes are a good way to 'see' violent, high-temperature events in space, like exploding stars.
4) Radio telescopes were responsible for the discovery of the cosmic microwave background radiation (p.61) — this helped scientists to learn more about the origins of the Universe.
5) Telescopes are improving all the time — bigger telescopes give us better resolution (i.e. a lot of detail) and can gather more light, so we can see things we couldn't before as they were too faint. Improved magnification means we can now look further into space — more and more galaxies are being discovered.
6) Modern telescopes often work alongside computers. Computers help create clearer and sharper images and make it easy to capture these pictures so they can be analysed later.
7) Computers make it possible to collect and store huge amounts of data, 24 hours a day, without having to rely on humans. They also make it easier and quicker to analyse all this data.

Now you've got an excuse to stare into space during lessons...

Although you won't see much without a telescope. You need to be able to explain different ways of improving images from telescopes — remember, high up and in a dark place is good, and sticking one in space is even better.

Q1 Give three ways of improving the image you can see through a telescope on Earth. [3 marks]

Revision Questions for Section 3

And that's Section 3 over and done with — time to celebrate with some fun revision questions (woo...).

- Try these questions and tick off each one when you get it right.
- When you've done all the questions for a topic and are completely happy with it, tick off the topic.

Atoms (p.49-50) ☐

1) Briefly explain how the model of the atom has changed over time. ☐
2) True or false? Atoms are neutral. ☐
3) What happens to an electron in an atom if it releases EM radiation? ☐
4) True or false? The frequency of generated radiation increases as the site of generation gets closer to the nucleus. ☐

Radioactivity (p.51-58) ☐

5) What is the atomic number of an atom? ☐
6) What is an isotope? Are they usually stable? ☐
7) Name four things that may be emitted during radioactive decay. ☐
8) For the four types of ionising radiation, give: a) their ionising power, b) their range in air. ☐
9) Explain why alpha radiation could not be used to check the thickness of metal sheets. ☐
10) Describe how the mass and atomic numbers of an atom change if it emits an alpha particle. ☐
11) In what type of nuclear decay does a neutron change into a proton within the nucleus? ☐
12) What type of nuclear decay doesn't change the mass or charge of the nucleus? ☐
13) What is the activity of a radioactive source? What are its units? ☐
14) Define half-life. ☐
15) True or false? A short half-life means a small proportion of the atoms are decaying per second. ☐
16) What is background radiation? ☐
17) Give three uses of radiation. ☐
18) True or false? Radioactive sources used in PET scans have a long half-life. ☐
19) Briefly describe how a fission reaction occurs. ☐
20) True or false? The fission products of uranium-235 are also radioactive. ☐
21) Explain the function of control rods in a fission reactor. ☐
22) State the conditions needed to create a fusion reaction. ☐

Astronomy (p.59-63) ☐

23) Name the eight planets in our Solar System. ☐
24) What do asteroids orbit? ☐
25) Name the force that keeps objects in orbit. ☐
26) Explain how our ideas about our Solar System have changed over time. ☐
27) Compare the Steady State and Big Bang theories. Which is the currently accepted theory? ☐
28) What does CMB radiation stand for? ☐
29) Explain how both the Steady State and Big Bang theories can account for red-shift. ☐
30) List the life cycle stages that a star the size of our Sun goes through. ☐
31) Explain why placing a telescope away from nearby cities improves the images it produces. ☐