Edexcel GCSE Physics

Nuclear Fission & Fusion

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Nuclear Energy

Your notes

Nuclear Energy

- The nucleus of the atom stores a huge amount of energy – roughly one million times greater than the amount of energy involved in chemical reactions
- As a result, nuclear reactions have the potential to transfer large amounts of energy (as seen in nuclear bombs)
- If harnessed in a safe way, nuclear energy could reduce or replace our dependency on fossil fuels, reducing pollution and the emission of greenhouse gases
- This energy can be released nuclear reactions such as:
  - Fusion
  - Fission
  - Radioactive decay
- Fusion is when:

  Two small nuclei join together to produce a larger nucleus
- Nuclear fusion does not happen on Earth naturally, but it does in **Stars**
  - However, fusion reactors can be made artificially
- The fusion of deuterium and tritium (isotopes of hydrogen) fuse to form **helium** with the release of energy
- The amount of energy released during nuclear fusion is huge:
  - The energy from 1 kg of hydrogen that undergoes fusion is equivalent to the energy from burning about 10 million kilograms of coal

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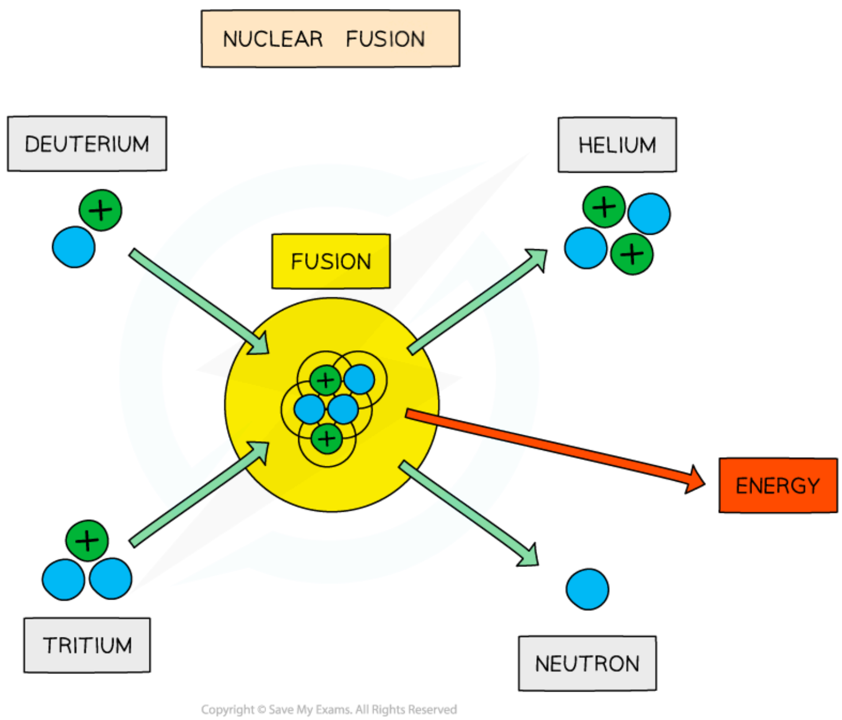

The fusion of deuterium and tritium to form helium with the release of energy

- Fission is when:

  One large nucleus splits into two smaller nuclei

- The large nucleus that splits is often referred to as the **parent** nucleus
  - The smaller nuclei that are split from this are referred to as the **daughter** nuclei
- This is the process behind nuclear power stations

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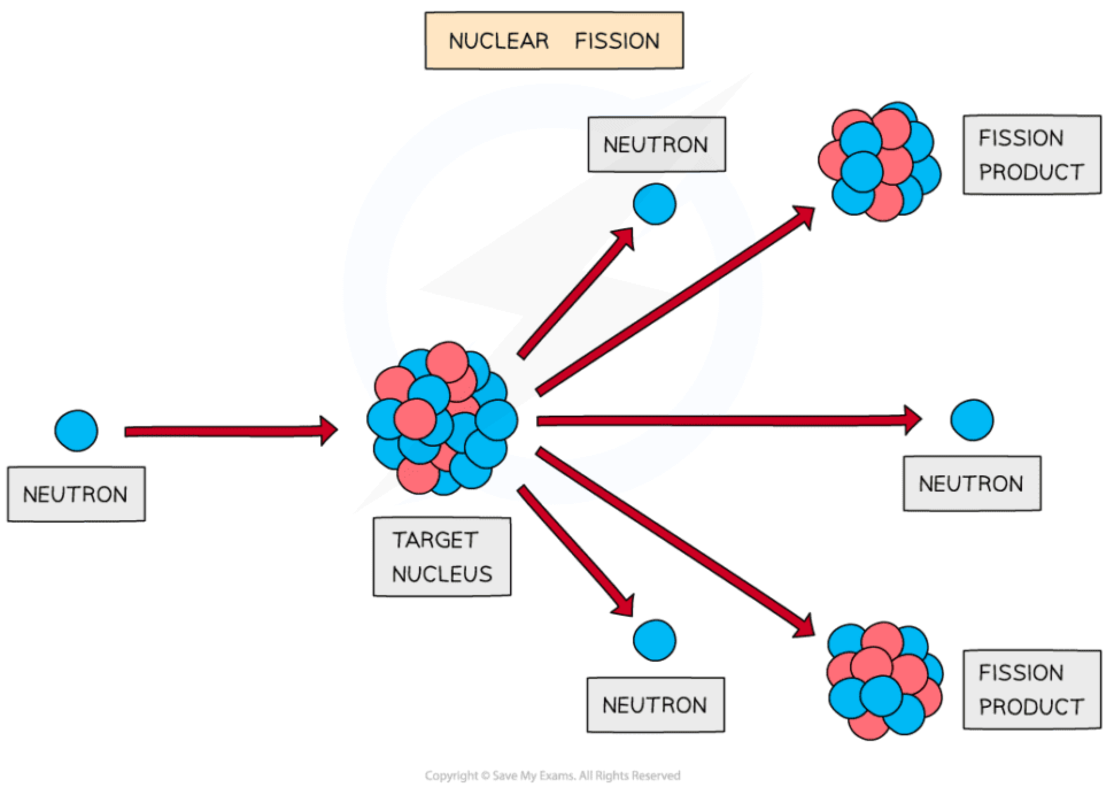

The fission of a nucleus, such as uranium, to produce smaller daughter nuclei with the release of energy

Nuclear Fission

Your notes

Nuclear Fission

- Nuclear fission is defined as:

  The splitting of a large, unstable nucleus into two smaller nuclei

- Isotopes of **uranium** and **plutonium** both undergo fission and are used as fuels in nuclear power stations
- During fission, when a neutron collides with an unstable nucleus (the parent nucleus), the nucleus splits into **two smaller nuclei** (the daughter nuclei) as well as **two or three neutrons**
  - Gamma rays are also emitted

Fission of Uranium-235

- Uranium-235 is commonly used as a fuel in nuclear reactors
- It has a very long half-life of 700 million years
- This means that it would have a low activity and energy would be released very slowly
  - This is unsuitable for producing energy in a nuclear power station
- During induced fission, a **neutron** is absorbed by the uranium-235 nucleus to make uranium-236
- This is very unstable and splits by nuclear fission almost immediately

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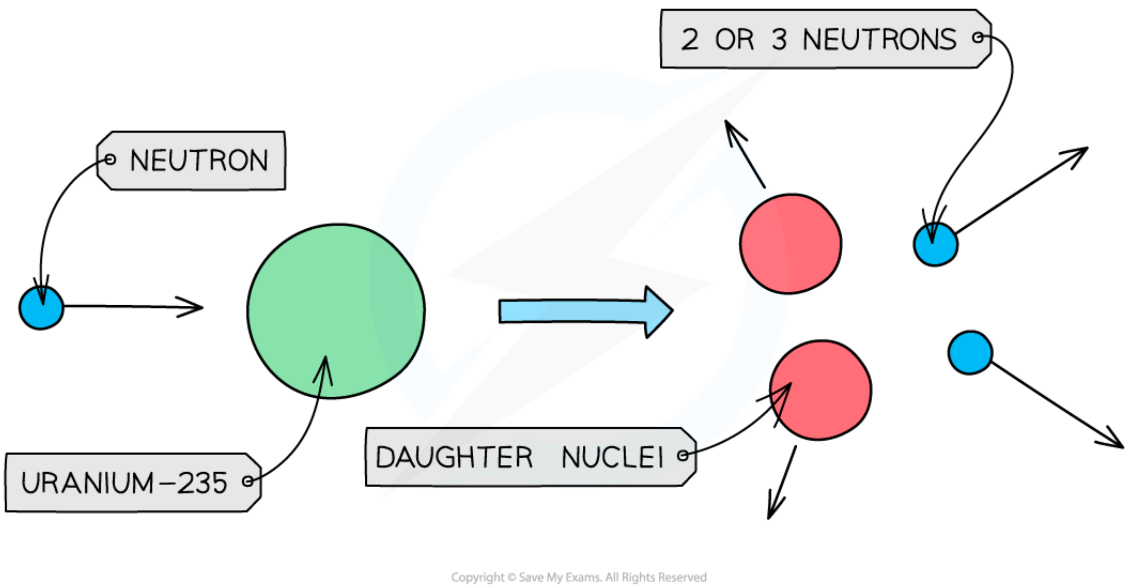


A uranium-235 nucleus is struck by a neutron, breaking it into two smaller daughter nuclei and 2 or 3 neutrons

- These products of the fission reaction move away very **quickly**
  - Energy is transferred from the **nuclear store** to the kinetic store of the products
  - Eventually this energy can be used to heat water to produce steam to generate electricity within the nuclear power station

Worked Example

During a particular spontaneous fission reaction, plutonium-239 splits as shown in the equation below:

$$^{239}_{94}Pu \longrightarrow {}^{112}_{46}Pd + {}^{124}_{48}Cd + \ldots$$

Which answer shows the section missing from this equation?

Your notes

A	$^{3}_{0}n$
B	$^{0}_{0}\gamma$
C	$^{4}_{2}\alpha$
D	$3\,^{1}_{0}n$

Answer: D

Step 1: Identify the different mass and atomic numbers

- Pu (Plutonium) has mass number 239 and atomic number 94
- Pd (Palladium) has mass number 112 and atomic number 46
- Cd (Cadmium) has mass number 124 and atomic number 48

Step 2: Calculate the mass and atomic number of the missing section

- Mass number is equal to the difference between the mass numbers of the reactants and the products

$$239 - (112 + 124) = 3$$

- Atomic number is equal to the difference between the atomic numbers of the reactants and the products

$$94 - (46 + 48) = 0$$

- The answer is therefore not **B** or **C**

Step 3: Determine the correct notation

- Neutrons have a mass number of 1
- The answer is therefore not **A**
- Therefore, this must be three neutrons, which corresponds to **D**

Examiner Tips and Tricks

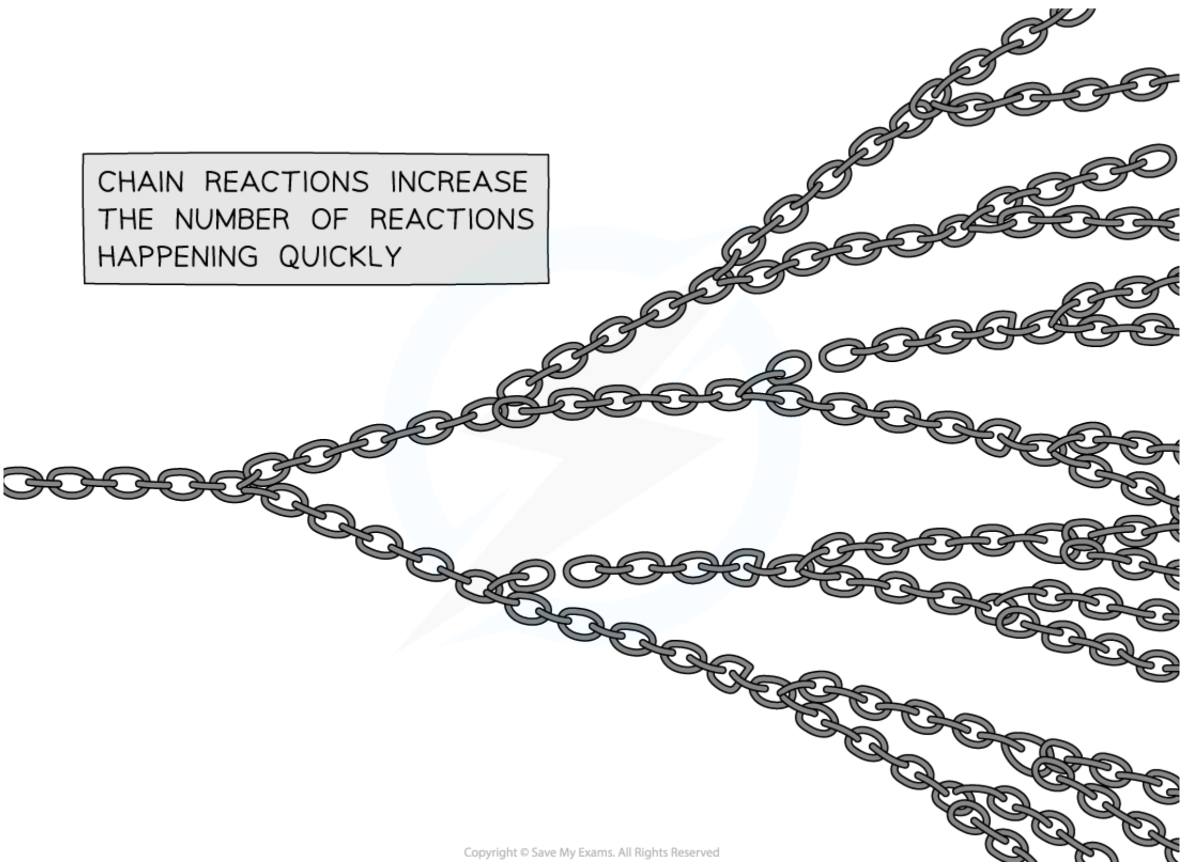
You need to remember that uranium and plutonium are possible elements for fission, but you do not need to know the specific daughter nuclei that are formed.

Nuclear Reactors

Your notes

Chain Reactions

- Only one extra neutron is required to induce a uranium-235 nucleus to split by fission
  - During the fission, it produces **two** or **three** neutrons which move away at high speed
- Each of these new neutrons can start another fission reaction, which again creates further **excess neutrons**
- This process is called a **chain reaction**

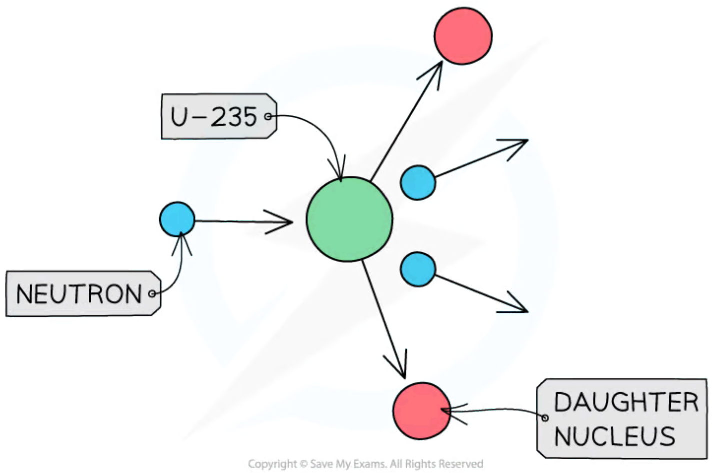


The neutrons released by each fission reaction can go on to create further fissions, like a chain that is linked several times – from each chain comes two more

Your notes

Worked Example

The diagram shows the nuclear fission process for an atom of uranium-235.



Complete the diagram to show how the fission process starts a chain reaction.

Answer:

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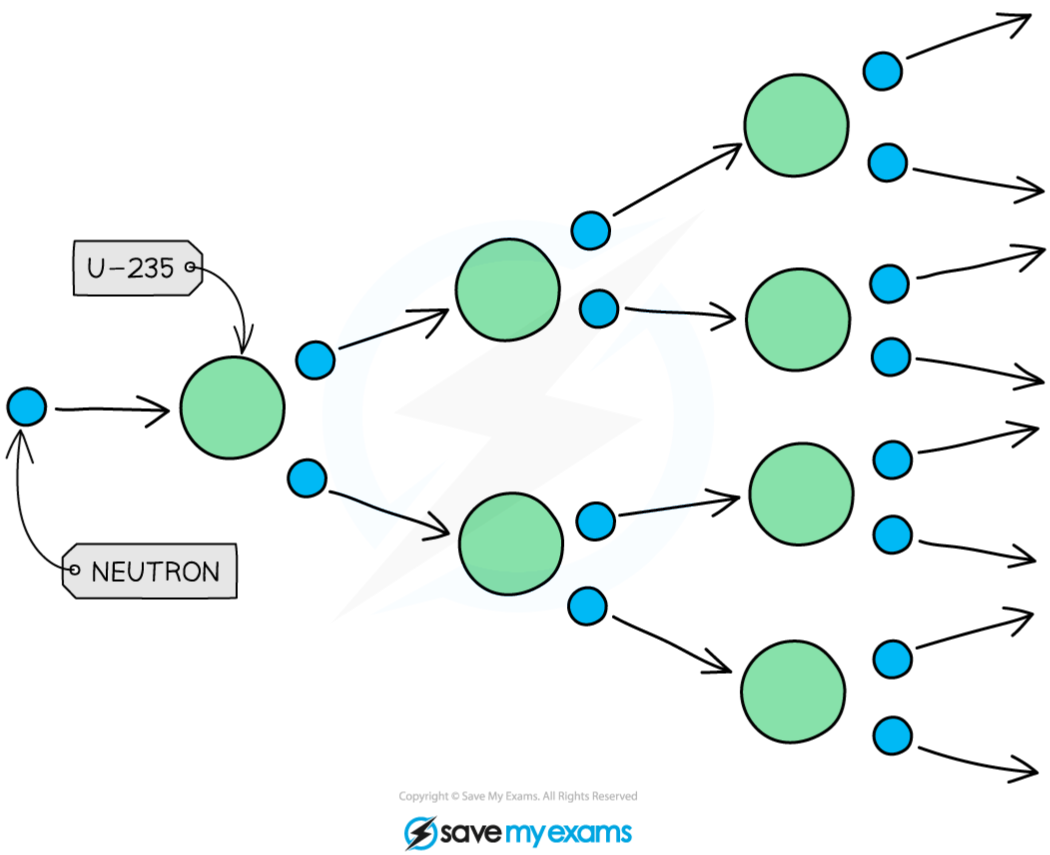

Step 1: Draw the neutrons to show that they hit other U-235 nuclei

- It is the neutrons hitting the uranium-235 nuclei which causes the fission reactions
- The daughter nuclei do not need to be shown, only the neutrons and uranium-235 nuclei

Step 2: Draw the splitting of the U-235 nuclei to show they produce two or more neutrons

- The number of neutrons increases with each fission reaction
- Each reaction requires one neutron but releases two
- More reactions happen as the number of neutrons increases

Examiner Tips and Tricks

You need to be able to draw and interpret different diagrams of nuclear fission and chain reactions. Generally, things move to the right as time goes on in these diagrams, but it is important to read all the information carefully on questions like this. If you have to draw a diagram in an exam remember that the **clarity** of the information is important, not how pretty it looks!

Your notes

Nuclear Reactors

- In a nuclear reactor, a chain reaction is required to keep the reactor running
- When the reactor is producing energy at the correct rate, two factors must be controlled:
  - The number of free neutrons in the reactor
  - The energy of the free neutrons
- To do this, nuclear reactors contain **control rods** and **moderators**

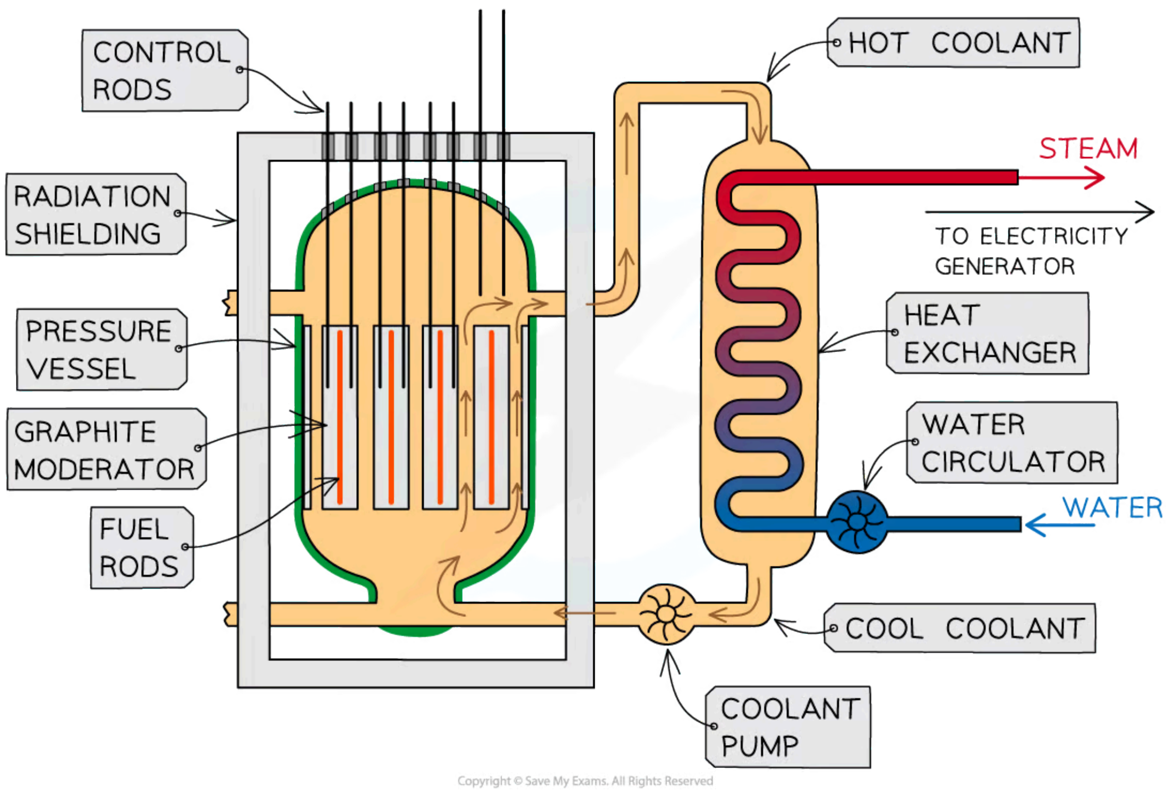

Diagram of a Nuclear Reactor. The overall purpose of the reactor is to collect the heat energy produced from nuclear reactions

Control Rods

Purpose of a control rod: To absorb neutrons

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- Control rods are made of a material which absorb neutrons without becoming dangerously unstable themselves
- The number of neutrons absorbed is controlled by varying the depth of the control rods in the fuel rods
  - Lowering the rods further **decreases** the rate of fission, as more neutrons are absorbed
  - Raising the rods **increases** the rate of fission, as fewer neutrons are absorbed
- This is adjusted automatically so that exactly one fission neutron produced by each fission event goes on to cause another fission
- In the event the nuclear reactor needs to shut down, the control rods can be lowered all the way so no reaction can take place

Moderator

The purpose of a moderator: To slow down neutrons

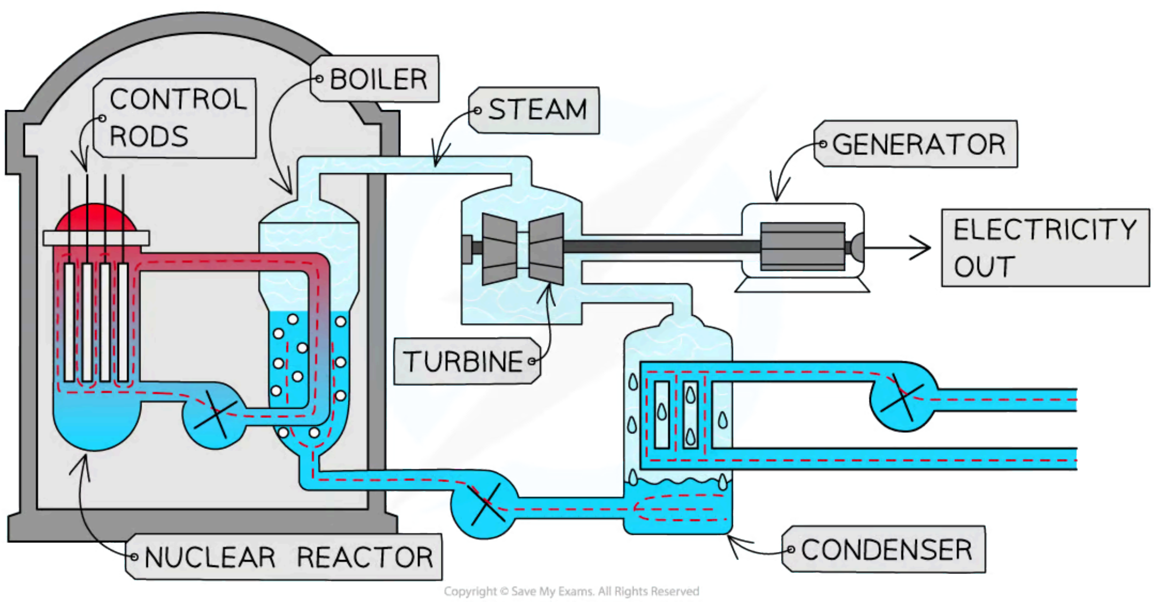
- The moderator is a material that surrounds the fuel rods and control rods inside the reactor core
- The fast-moving neutrons produced by the fission reactions slow down by colliding with the molecules of the moderator, causing them to lose some momentum
- The neutrons are slowed down so that they are in **thermal equilibrium** with the moderator, hence the term 'thermal neutron'
  - This ensures neutrons can react efficiently with the uranium fuel

Your notes

Energy & Waste

Generating Electricity

- The process by which electricity is produced in a nuclear power station is the same as for any other fuel-powered station – the only difference is the process used to produce the heat
- Nuclear fission produces a large quantity of heat which is carried away from the reactor by a coolant (usually pressurised water)
- The **coolant** is then used to heat a separate water source, turning the water into steam
  - A separate source is used in order to reduce the risk of contamination
- The steam is then used to drive **turbines** which then turn **generators**, producing electricity



How electricity is generated from a nuclear reactor

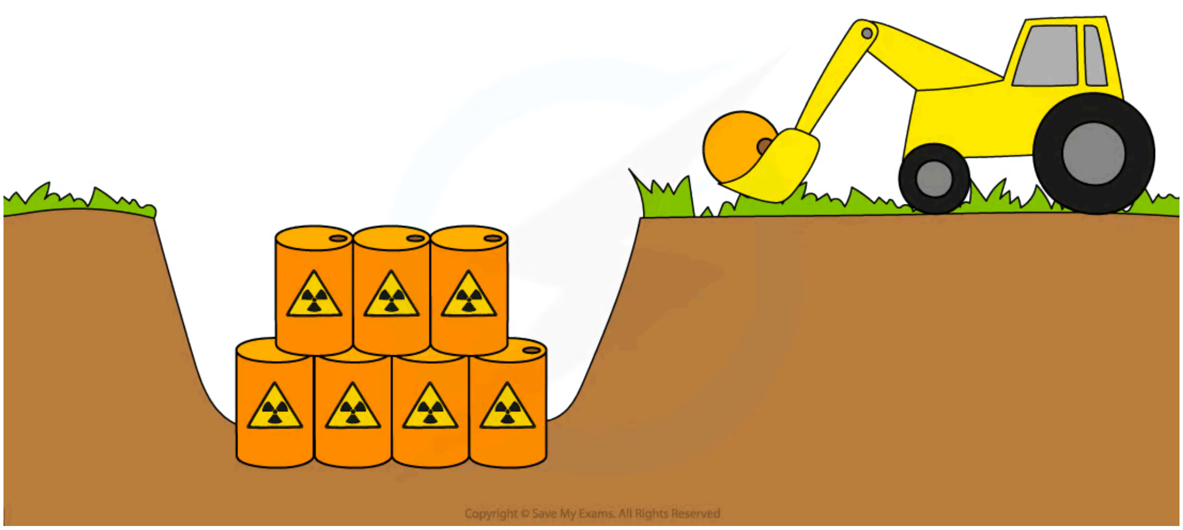
- The **nuclear reactor** is:
  - The part of the power station that provides thermal energy from fission chain reactions
- The **boiler** is:
  - The part of the power station that uses thermal energy to boil water to create steam
- The **turbine** is:

Your notes

  - The part of the power station that uses steam to transfer thermal energy into kinetic energy
- The **generator** is
  - The part of the power station that transfers kinetic energy into electrical energy
- The **condenser** is:
  - The part of the power station that cools the steam back into water

Nuclear Waste

- The biggest problem concerning nuclear power is the waste that it produces
- This waste comprises of the **unusable** fission products from the fission of uranium-235 or from spent fuel rods
  - This is because each fission of a uranium-235 nucleus results in two smaller nuclei being produced
- This is by far the most dangerous type of waste as it will remain radioactive for **thousands of years**
  - These smaller (daughter) nuclei are both highly radioactive – more radioactive, in fact than the original fuel
- As well as being highly radioactive, the spent fuel roads are **extremely hot** and must be handled and stored much more carefully than the other types of waste
- Whilst the amount of waste produced (relative to the amount of energy generated) is fairly small, the waste is extremely dangerous
  - Therefore, it must be stored underground till they are no longer harmful



Nuclear waste is stored underground whilst the fission products are still radioactive

Advantages & Disadvantages of Nuclear Power

Your notes

Advantages & Disadvantages of Nuclear Power

- Nuclear power can scare people if they do not understand it
- It is dangerous if not handled properly, yet it is invisible which can be difficult for some people to comprehend
- However, with increased education on nuclear energy, society can use this knowledge to inform their own decisions and opinions

Advantages	Disadvantages
Nuclear power stations...	**Nuclear power stations...**
Produce no polluting gases, such as carbon dioxide	Produces radioactive waste which is very dangerous and expensive to deal with
Require far less fuel as uranium provides far more energy per kg compared to coal and other fossil fuels	Can have catastrophic consequences on the environment and to the people in the surrounding area in the event of a nuclear meltdown, such as at Chernobyl
Are highly reliable for the production of electricity	Have expensive start up and shut down costs

Nuclear Fusion

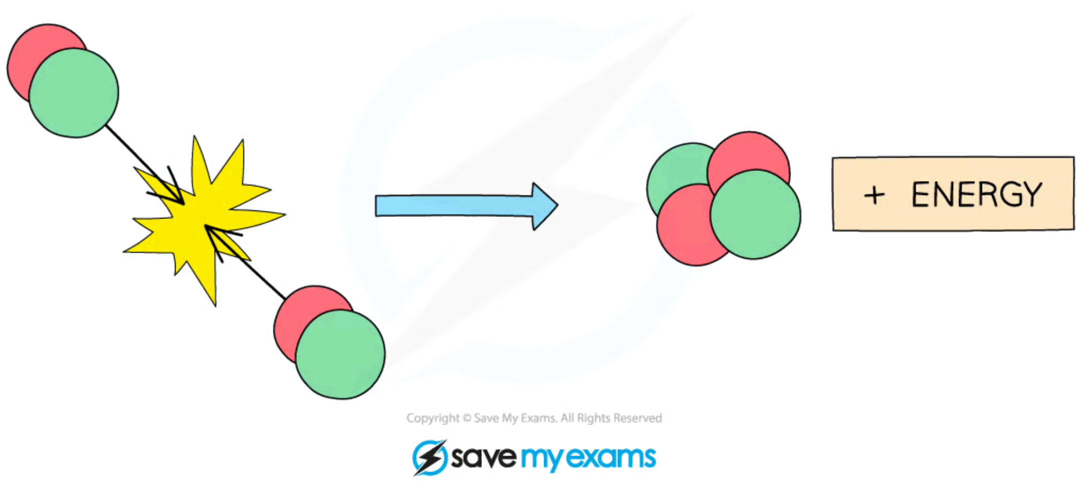
Your notes

Nuclear Fusion

- Small nuclei can react to release energy in a process called **nuclear fusion**
- Nuclear fusion is defined as:

  When two light nuclei join to form a heavier nucleus

- This process requires extremely **high temperatures** to maintain
  - This is why nuclear fusion has proven very hard to reproduce on Earth
- Stars, including the Sun, use nuclear fusion to produce energy
  - Therefore, fusion reactions are very important to life on Earth
- In most stars, hydrogen atoms are fused together to form helium and produce lots of energy



Two hydrogen nuclei are fusing to form a helium nuclei

- The energy produced during nuclear fusion comes from a very small amount of the particle's mass being **converted** into energy
- Albert Einstein described the mass-energy equivalence with his famous equation:

$$E = mc^2$$

- Where:

Your notes

- E = energy released from fusion in Joules (J)
- m = mass converted into energy in kilograms (kg)
- c = the speed of light in metres per second (m/s)
- The amount of energy released during nuclear fusion is huge:
  - The energy from 1 kg of hydrogen that undergoes fusion is equivalent to the energy from burning about 10 million kilograms of coal

Fusion vs Fission

- **Fission** is the process in which large nuclei are split into two smaller nuclei, releasing energy in the process
  - This is the process that produces energy in nuclear power stations, where it is well controlled
  - Fission provides **less** energy per kg of fuel than fusion
  - The products of fission are **radioactive** and hence very dangerous
- **Fusion** is the opposite of that: it involves taking smaller nuclei and bringing them together to form a bigger nucleus
  - The conditions for fusion are very difficult to achieve on Earth, so nuclear fusion is currently only known to occur in the cores of stars
  - Fusion provides **more** energy per kg of fuel than fission
  - The products of fusion are not radioactive and are therefore much **safer** than the products of fission reactions
- The following table summarises some of the key differences between fusion and fission:

Comparison of Nuclear Fusion and Fission Table

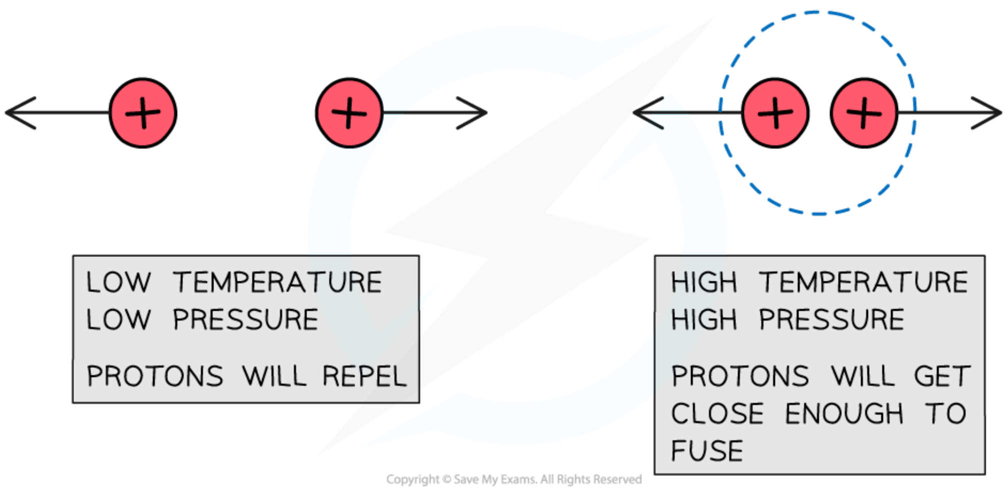
	Fusion	Fission
The process of...	Joining together	Breaking apart
Nuclei are	Small, such as Hydrogen	Large, such as Uranium
Occurs in	Stars	Nuclear Reactors
Produces	Lots of energy, Larger nuclei (commonly not radioactive)	Lots of energy, Daughter nuclei (usually radioactive) 2 or 3 neutrons
Requires	Very high temperatures	High temperatures, Neutron to induce fission

Your notes

The Conditions for Fusion

The Conditions for Fusion

- Since protons have a **positive charge**, they repel each other
  - In order to overcome this repulsion, the protons must have very **high kinetic energy** in order to be travelling towards each other at very **high speeds**



The fusion of two protons is only possible through high temperature and pressure

- In order to make the molecules of a gas travel at such speeds, the gas has to be heated to millions of degrees Celsius – a temperature that is usually only reached at the centre of a star
- In regular conditions, i.e. on Earth, the possibility of collisions between nuclei which result in fusion is very low
  - In order to increase the number of collisions (and hence fusions) that occur between nuclei, high **densities** (and hence **pressures**) are also needed
- The conditions for fusion are:
  - Very **high temperature** of fuel
  - Very **high kinetic energy** / speed of nuclei to overcome repulsion
  - Very **high density** / **pressure** to increase the possibility of suitable collisions

Energy from Fusion

- The main reasons why fusion is not currently used as a source of power on Earth are the difficulties in achieving (and maintaining)
  - High **temperatures**
  - High **pressures**
- Whilst physicists have been able to attain the temperatures and pressure needed, there are difficulties in **containing** them, which inevitably means that only a small amount of fusion can take place
  - Such a small rate of fusion is not useful for current energy needs
- Creating the temperatures needed for fusion requires a great deal of energy
  - Hence, physicists are still a long way from the point where they will produce **more** energy from fusion than the energy needed to start it

Worked Example

An example of a hydrogen fusion reaction which takes place in stars is shown here.

$$^{2}_{1}H + ^{1}_{1}H \longrightarrow ^{3}_{2}He$$

Which of the following is a valid reason as to why hydrogen fusion is not currently possible on Earth?

A. Hydrogen fusion produces dangerous radioactive waste

B. Hydrogen nuclei require very high temperature to fuse together

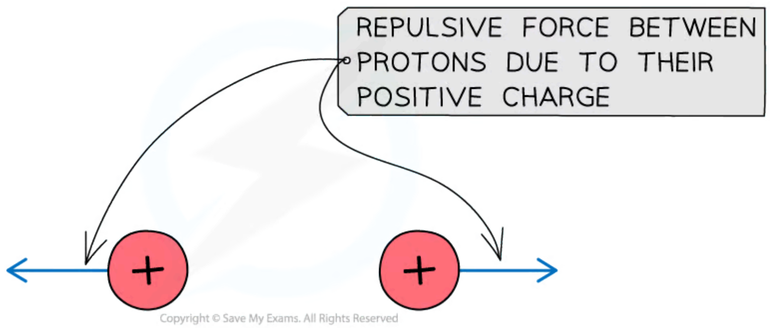
C. Hydrogen is a rare element that would be difficult to get large amounts of

D. Hydrogen fusion does not produce enough energy to be commercially viable

Answer: B

- Hydrogen nuclei have **positive charges**
- So two hydrogen nuclei would have a **repulsive force** between them
- There exists a **repulsive force between protons** that has to be overcome for hydrogen fusion to happen

Your notes



Hydrogen ions are protons, and their positive charge makes them repel one another

- High temperatures are required to give the nuclei enough energy to overcome the repulsive force
- The answer is **not A** because the products of the hydrogen fusion shown in the reaction is helium
  - Helium is an inert gas
- The answer is **not C** because hydrogen is a very abundant element
  - It is the most common element in the universe
- The answer is **not D** because hydrogen fusion would produce a huge amount of energy