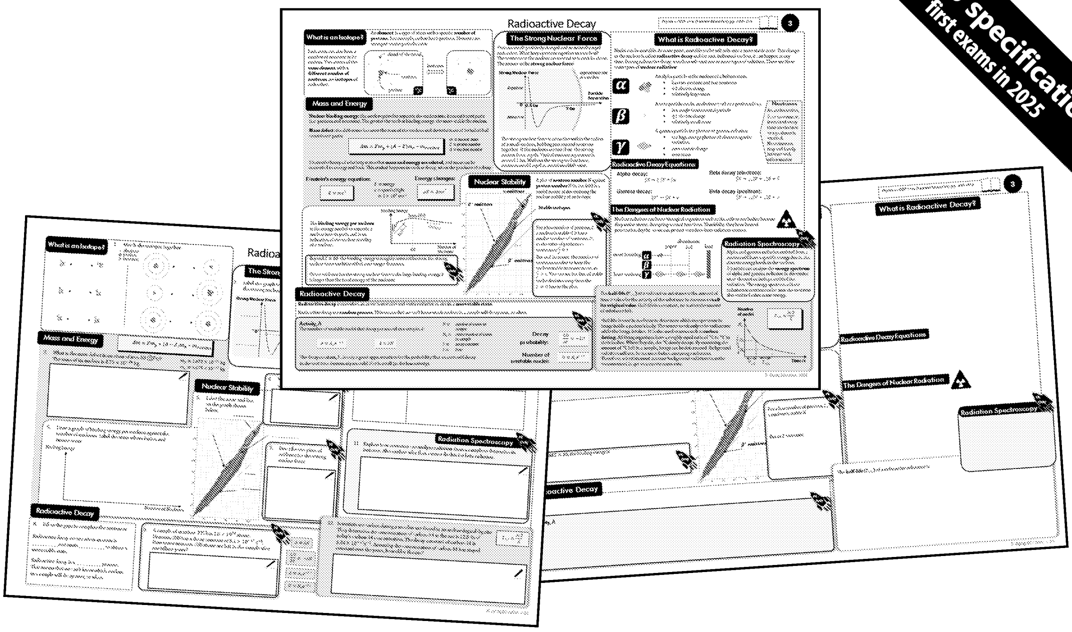
Physics International Baccalaureate Diploma Programme

2023 specification
first exams in 2025



Topic on a Page

for IB Physics:

Theme E: Nuclear and Quantum Physics

zigzageducation.co.uk

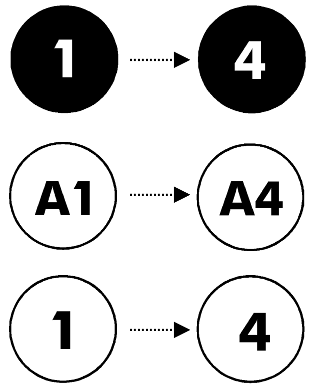
POD 12579

Contents

Teacher's Introduction

This topic-on-a-page resource has been designed to help your students revise the key points of each topic and test their knowledge after you have taught each section of the **IB Physics: Theme E – Nuclear and quantum physics** specification from topics 1 to 5. Each page is closely tied to the IB specification, ensuring all aspects of the course are covered.

There are four sections to this resource, each with its own features:



1. **Summary posters**: these are the main pages which intend to clearly consolidate and recap all the key information from the IB Physics course.
2. **Activity worksheets**: these are identical to the summary posters, but contain a variety of tasks, from filling in missing words to performing calculations. The activity worksheets aim to ensure the student understands all the key knowledge required of them and gives them the opportunity to demonstrate how well they have remembered and understood the content of the course.
3. **Outline-only pages**: these are the summary posters, but with most of the content removed. Students can research the topics, e.g. for homework, and fill in as much information as they can.
4. **Mark scheme**: full answers for the activity worksheets.

The summary posters, activity worksheets and outline-only pages are designed to be A3 size, although they are still useable at A4 with no loss of detail. When photocopying activity worksheets on A3, we suggest photocopying the relevant summary poster on the reverse. If using at A4 size, we suggest photocopying each A3 'worksheet' (for writing answers) as a double-sided A4 page to avoid shrinking the space available for answers.

Each page presents information in a variety of ways, including:

- **Bullet-point processes** – complex processes and lists have been summarised into quick, easy-to-learn points.
- **Illustrative diagrams** – detailed diagrams that visually represent a concept or an event.
- **Method and calculation boxes** – concisely state the equations used in required calculations.
- **Tips and tricks** – extra useful information that can help students when solving problems.

We hope you find these pages useful during your teaching and your students' revision.

September 2024

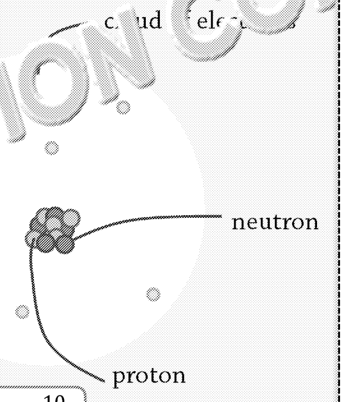
Structure of the Atom

Did you know?
The electrons are described as a 'cloud' because their exact position is not known unless they are measured; only the probability of their position is known before a measurement.

The Atom

The current model of the atom describes a nucleus containing positive protons a… neutral neutrons surrounded by a cloud of electrons.

An atom can have different numbers of protons, neutrons and electrons; however, only stable atoms exist for a long time.



Each atom with a different number of protons is called an **element**.
There are 118 known elements, and they are arranged in the **peri… …**
Each element has a chemical symbol:

$$^{A}_{Z}X$$

Any atom can be described with its element symbol, plus two … The top number, A, is the **mass number**, equal to the number of protons and neutrons in the nucleus. The mass number roughly describes how heavy the atom is. The bottom number, Z, is the **proton number**, equal to the number of protons in the nucleus.

This atom is $^{10}_{5}B$

The Geiger-M…

…he **Geiger-Marsden-Rutherford scatt…** evidence about the structure of the atom. … from J J Thomson's plum pudding model …

The experiment

An alpha source provided a **beam of alpha…** were aimed at a thin piece of **gold foil**. All… (positively charged) were of the **same energ…** experiment was carried out in an **evacuate…** alpha particles were **detected** by a detector… **fixed radial distance** from the point of co… particles and the foil. **Light was emitted…** hit a phosphorescent screen, a process calle… These emissions of light could be seen with…

The c…

Most particles passed through th… making up the foil are likely **mos…** the atom is concentrated in a sm… Some alpha particles were deflect… **must be positively charged** be… particles were repelled as they ap…

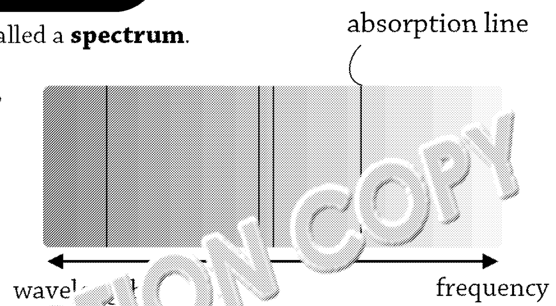
Disco…

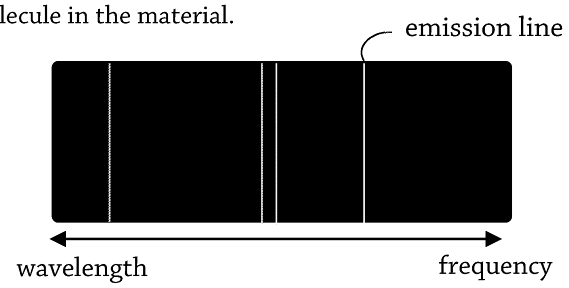
The experiments performed by Geiger and Marsden under Rutherford's instruction showed most of the mass of an atom is at the centre in a nucleus.

Emission and Absorption Spectra

Light from a source will be made from a variety of wavelengths and energies. This variety is called a **spectrum**.

White light is made up from a spectrum of light. When white light passes through a material, some specific energies of light may be absorbed by the material. The atoms in the material have electrons in quantised energy levels. If the energy of a photon of light matches the energy difference between two energy levels, the electron will absorb the photon, becoming excited. These energies of light do not pass through the material, leaving a dark line in the spectrum, called an **absorption line**. Each absorption line relates to a specific element or molecule in the material.





A material such as … with excited electrons. After some time, the exc… back down an energy level, emitting a photon … the difference between the energy levels. The … from this material is therefore mostly dark with **… lines** specific to the atoms or molecules in the material.

These very specific absorption and emission lines show that the energy levels of electrons in atoms are specific, quantised values.

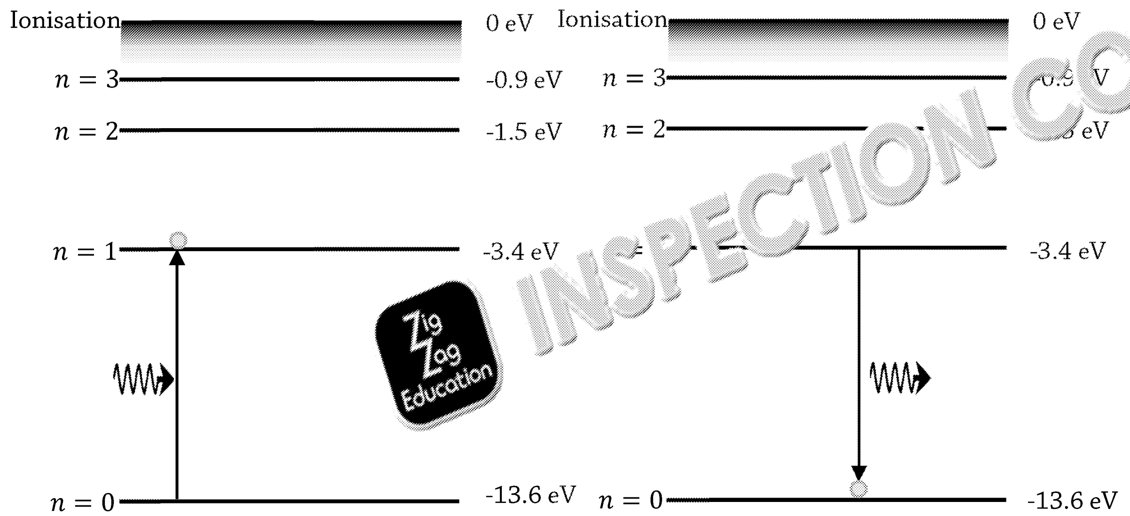
Photon Absorption and Emission

If a photon has the right energy, an electron in an atom will absorb the photon, moving up to a new energy level. The electron becomes excited in this atomic transition.

The energy level diagram to the right shows the energy levels of the electron in a hydrogen atom.

The electron has absorbed a photon, moving from the $n = 0$ to $n = 1$ energy level.

After a short time, the electron will fall back down to its original energy level, emitting a photon in a random direction.



Electrons can move between any energy level if they absorb the right photon, e.g. $n = 2$ to $n = 5$…

The frequency of the photon emitted depends on energy released from the atomic transition.

$$E = hf$$

Th… energy released from an atomic transition i… … to the difference between the energy … For this electron's transition:

$$E = |(-13.6\text{ eV}) - (-3.4\text{ eV})|$$
$$E = 10.2\text{ eV}$$

The quantisation of energy of particles means phot… are absorbed and emitted with specific energies fo… element. Scientists can measure the emission or a… spectrum from an object and work out what eleme… absorbed or emitted those photons. They use this … determine the chemical composition of the object.

Did you know?
In 1868, Pierre J. C. Janssen and Joseph Norma… Lockyer independently observed an unexpected line in the Sun's emission spectrum. They name… new element emitting this wavelength after the… god Helios. This element is now called helium.

Quantum Physics – Additional Higher Level Content

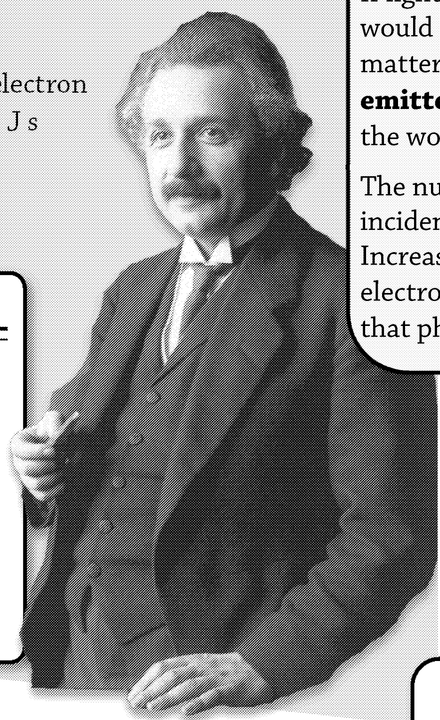
Photoelectric Effect

Photoelectric effect:
A term for the process of electron emission from the surface of a metal due to light incident on its surface. Albert Einstein explained the photoelectric effect in 1905, leading to his Nobel Prize in 1921.

Photoelectric equation:

$$E_{\text{max}} = hf - \phi$$

E_{max} = maximum kinetic energy of electron
h = Planck constant = 6.63×10^{-34} J s
f = frequency of photon
ϕ = work function

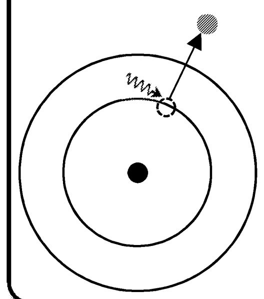


Terms of the photoelectric effect

- **Threshold frequency:** the minimum frequency required to emit electrons from the surface of a metal
- **Work function:** the minimum photon energy (frequency) required to remove an electron
- **Stopping potential:** the potential needed to stop an electron from leaving the atom
- $\boldsymbol{E_{\text{max}}}$**:** the maximum possible kinetic energy of the photoelectrons

The Bohr Model and the Photoelectric Effect

The Bohr model of an atom has the positive nucleus at the centre and the electrons in circular orbits around the nucleus. Each circular orbit represents a different energy level.



In the photoelectric effect, a single photon interacts with an electron, giving the electron enough energy to escape the atom. The removal of an electron from an atom is called ionisation.

Ionisation
An electron absorbs a photon with energy greater than the binding energy of the electron, and the electron is emitted from the atom.

What evidence from the photoelectric effect shows light does not always act like a wave?

If light only behaved as a wave, light incident on a metal surface would eventually transfer enough energy to eject electrons, no matter the power of the light. However, we see **electrons are only emitted when incident light is above a certain energy**, called the work function.

The number of electrons emitted depends only on the number of incident photons (macroscopically, the intensity of light). Increasing the energy of each photon does not lead to more electrons being emitted. This **one-to-one relationship** suggests that photons act like particles, only interacting with one electron.

Wave–Particle Duality

While light is historically considered a wave, and electrons particles, there are several phenomena in which light acts as particles and electrons act as waves.

Demonstrations of wave-like and particle-like behaviour

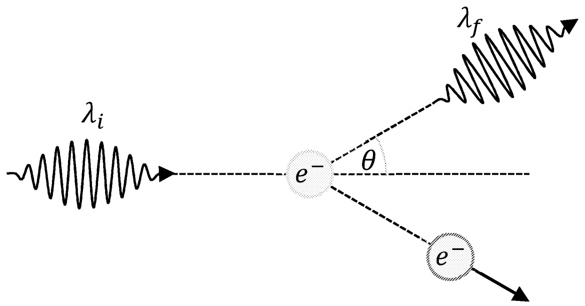
- The process of electron diffraction is evidence of particles displaying wave properties.
- The photoelectric effect is evidence that electromagnetic waves have particle-like properties.
- Compton scattering is also evidence that electromagnetic waves can act like particles.

Compton Scattering

Light can act like a particle, called a **photon**, in certain situations. If a photon with a high frequency interacts with a charged particle, such as an **electron**, the photon can transfer some of its energy to the electron. The photon loses energy, so its frequency decreases and its **wavelength increases**. The electron gains energy in the form of kinetic energy, causing the **electron to recoil** away from the photon.

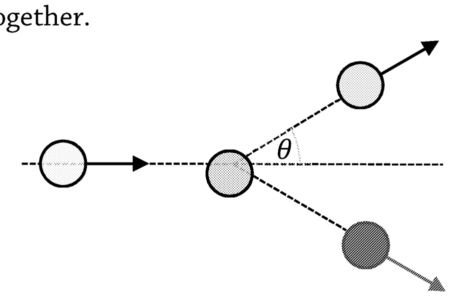
The change in wavelength of the photon can be calculated with the following equation:

$$\lambda_f - \lambda_i = \Delta\lambda = \left(\frac{h}{m_e c}\right)(1 - \cos(\theta))$$



Compton scattering between a photon and a charged particle is like two pool balls colliding together.

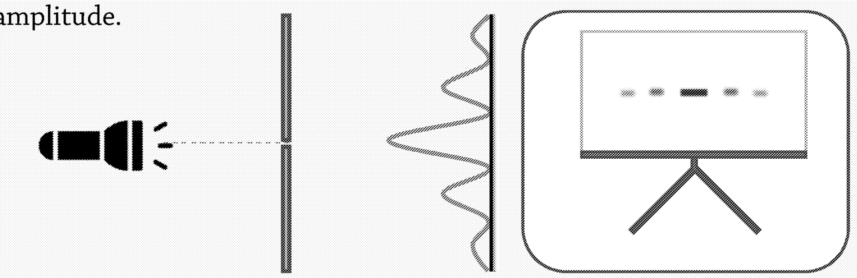
The total momentum and energy of both pool balls is the same before and after the collision.



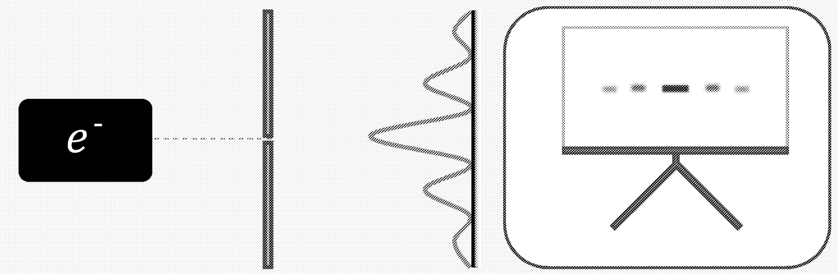
However, when two pool balls collide, they don't change after the collision. But when a photon interacts with a charged particle through Compton scattering, the photon's energy and wavelength changes.

Electron Diffraction

Shining **light** through a slit onto a screen results in a diffraction pattern on the screen. The light wave diffracts as it passes through the slit, spreading out. Parts of the diffracted wave interfere with other parts, causing areas of high and low amplitude.

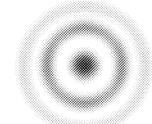


Weirdly, a similar diffraction pattern can be observed when firing **electrons** through a very narrow slit, even though electrons are thought of as particles.



The diffraction of electrons shows they can behave like waves. It's true that all particles can behave like waves in the right conditions. A particle's wavelength is called its de Broglie wavelength.

Did you know?
The horizontal diffraction pattern above forms from a thin rectangular slit. If the slit is circular instead of rectangular, a diffraction pattern called an Airy disc forms.



De Broglie Wavelength

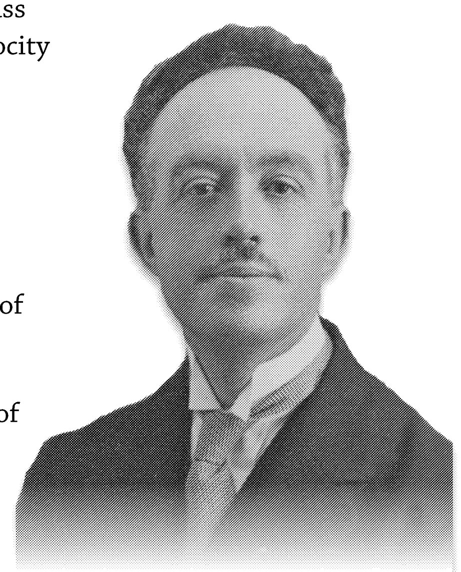
You can also write the de Broglie wavelength in terms of momentum:

$$\lambda = \frac{h}{p}$$

$$\lambda = \frac{h}{mv}$$

λ = wavelength
h = Planck constant = 6.63×10^{-34} J s
m = mass
v = velocity

- The equation can be used to determine the wavelength of an electron undergoing electron diffraction.
- As the momentum increases, the wavelength decreases and the amount of diffraction decreases.
- As the momentum decreases, the wavelength increases and the amount of diffraction increases.

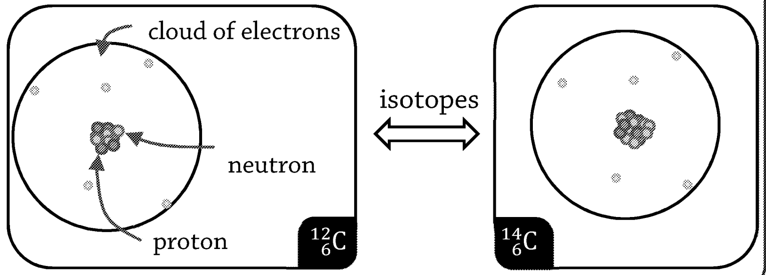


Radioactive Decay

What is an Isotope?

An **element** is a type of atom with a specific **number of protons**. For example, carbon has 6 protons. Elements are arranged on the periodic table.

Each atom can also have a number of neutrons in its nucleus. Two atoms of the **same element** with a **different number of neutrons** are **isotopes** of each other.



Mass and Energy

Nuclear binding energy: the work required to separate the nucleus into its constituent parts (i.e. protons and neutrons). The greater the nuclear binding energy, the more stable the nucleus.

Mass defect: the difference between the mass of the nucleus and the total mass of its individual constituent parts:

$$\Delta m = Zm_p + (A - Z)m_n - m_{nucleus}$$

m = nuclear mass
Z = proton number
A = nucleon number

Einstein's theory of relativity states that **mass and energy are related**, and mass can be converted to energy and back. This is what happens in nuclear decay, when the products of a decay have lower mass than the original nuclei – the **missing mass is converted to energy**.

Einstein's energy equation:

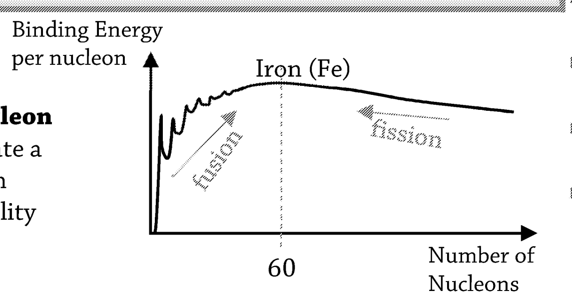
$$E = mc^2$$

E = energy
c = speed of light
$= 3 \times 10^8$ m s^{-1}

Energy changes:

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

The **binding energy per nucleon** is the energy needed to separate a nucleus into its parts and is an indication of the nuclear stability of a nucleus.



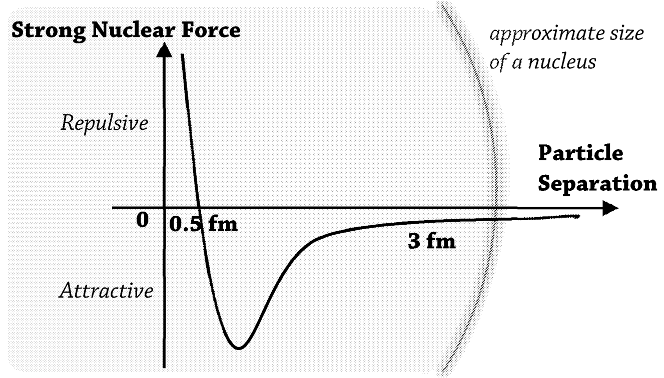
HL Only

Beyond $Z = 60$, the binding energy is roughly constant because the strong nuclear force has little effect over longer distances.

Other evidence for the strong nuclear force is the large binding energy; it is larger than the total energy of the nucleons.

The Strong Nuclear Force

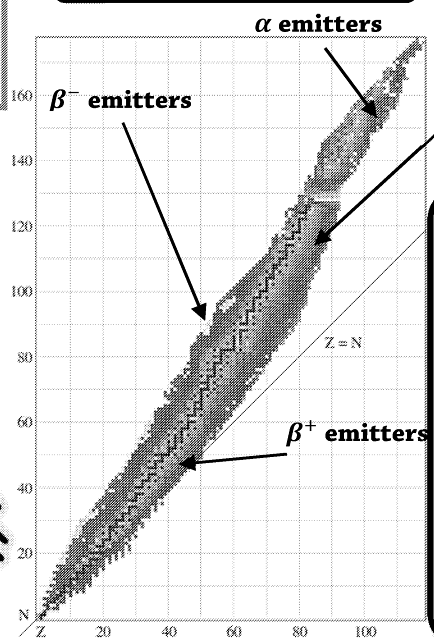
Protons are all positively charged and so naturally repel each other. What keeps protons together in a nucleus? The neutrons in the nucleus are neutral so it can't be those. The answer is the **strong nuclear force**!



The strong nuclear force is attractive within the radius of a small nucleus, holding protons and neutrons together. If the nucleons are too close, the strong nuclear force repels. Typical nucleon separation is around 1 fm. Without the strong nuclear force, nucleons would repel so nuclei wouldn't exist.

Nuclear Stability

A plot of **neutron number** *N* against **proton number** *Z* (to the left) is a useful means of determining the nuclear stability of an isotope.



HL Only

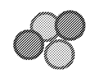
For a low number of protons, Z, a nucleus is stable if it has a similar number of neutrons, N, so the ratio of protons to neutrons is $\frac{N}{Z} \approx 1$.

But as Z increases, the number of neutrons needed to keep the nucleus stable increases more, so $\frac{N}{Z} > 1$. You can see the line of stable nuclei deviates away from the $Z = N$ line in the plot.

What is Radioactive Decay?

Nuclei can be unstable. At some point, unstable nuclei will split into a more stable state. This change in the nucleus is called **radioactive decay** and for each individual nucleus, it can happen at any time. During radioactive decay, a nucleus will emit one or more types of radiation. There are three main types of **nuclear radiation**:

α



An alpha particle is the nucleus of a helium atom.

- has two protons and two neutrons
- +2 electric charge
- relatively large mass

β

A beta particle can be an electron ($-e$) or a positron ($+e$).

- is a single fundamental particle
- ± 1 electric charge
- relatively small mass

γ

A gamma particle is a photon of gamma radiation.

- is a high energy photon of electromagnetic radiation
- zero electric charge
- zero mass

Neutrinos

An antineutrino, $\bar{\nu}$, or neutrino, ν, is emitted every time an electron or a positron is emitted. Neutrinos are tiny and barely interact with other matter.

Radioactive Decay Equations

Alpha decay:

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

Beta decay (electron):

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \bar{\nu}$$

Gamma decay:

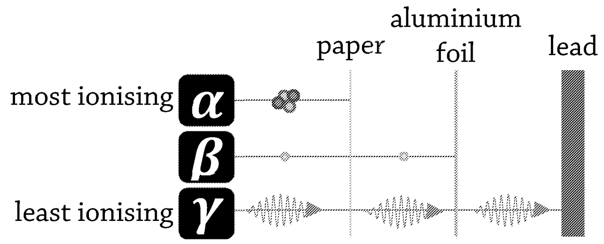
$${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$$

Beta decay (positron):

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{+1}\beta + \nu$$

The Dangers of Nuclear Radiation

Nuclear radiation can harm biological organisms such as the cells in our bodies because they ionise atoms, disrupting normal functions. Thankfully, they have limited penetration depths, so we can protect ourselves from radiation sources.



Radiation Spectroscopy

HL Only

Alpha and gamma radiation emitted from a nucleus will have a specific energy due to the discrete energy levels in the nucleus. Scientists can analyse the **energy spectrum** of alpha and gamma radiation to determine what element or isotope emitted the radiation. The energy spectrum of beta radiation is continuous because the neutrino also emitted takes some energy.

Radioactive Decay

Radioactive decay occurs when an atom is unstable and emits radiation to obtain a **more stable state**.

Radioactive decay is a **random process**. This means that we can't know which nucleus in a sample will decay next, or when.

HL Only

Activity, A

The number of unstable nuclei that decay per second in a sample, A:

$$A = A_0 e^{-\lambda t}$$

$$A = \lambda N$$

N = number of atoms in sample
N_0 = initial number of atoms in sample
λ = decay constant
t = time

Decay probability:

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

Number of unstable nuclei:

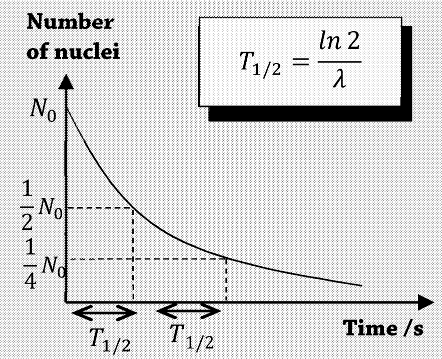
$$N = N_0 e^{-\lambda t}$$

The decay constant, λ, is only a good approximation for the probability that an atom will decay in the unit time (commonly seconds) if λt is small (so for low activity).

The **half-life ($T_{1/2}$)** of a radioactive substance is the amount of time it takes for the activity of the substance to decrease to **half its original value**. Half-life is a constant, no matter the amount of substance left.

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

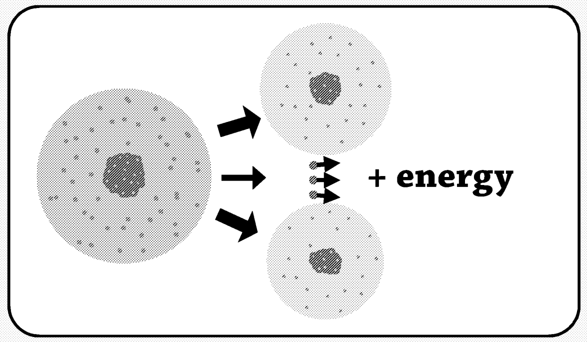
Half-life is used in medicine to determine which isotope to use to image inside a patient's body. The source needs only to be radioactive while the image is taken. It is also used in areas such as **carbon dating**. All living organisms have a roughly equal ratio of ^{12}C to ^{14}C in their bodies. When they die, the ^{14}C slowly decays. By examining the amount of ^{14}C left in a sample, its age can be determined. Background radiation will also be measured when analysing a substance. Therefore, scientists must subtract background radiation from the measurement to get an accurate count rate.



Fission and Fusion

What is Nuclear Fission?

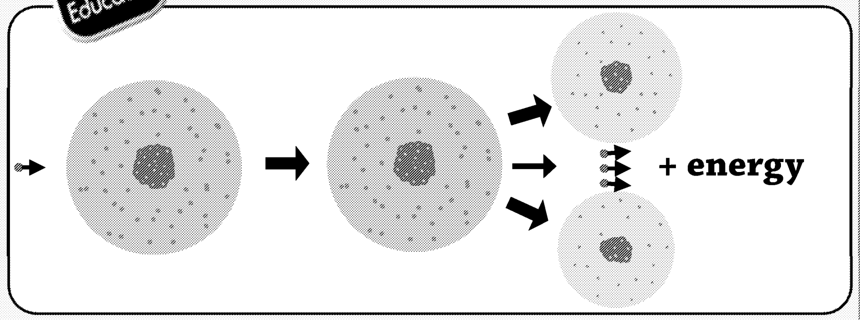
An unstable nucleus can **split into two smaller nuclei**, releasing energy as heat and radiation in the process. This splitting of an atom's nucleu[illegible] nuclear **fission**.



Nuclear fission is different from radioactive de[illegible] roducts are two smaller atoms, and not one large atom wi[illegible] uclear radiation.

The fission process shown o[illegible] **aneous**; the parent nucleus was unstable, so the atom [illegible] on its own.

In the [illegible] ess [illegible] w, the parent nucleus was made unstable by firing a neutro[illegible] ucleus. This is called **neutron-induced** fission.



How much energy is released during fission?

First, you need to **find the change in mass** (aka the mass defect) during the process. Then you can **apply Einstein's famous equation** to convert this change in mass to the **binding energy released**.

$$E = mc^2$$

The equation below shows the neutron-induced fission of uranium-235, a common fuel used in nuclear reactors.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

$^{1}_{0}n$	$^{235}_{92}U$	$^{141}_{56}Ba$	$^{92}_{36}Kr$	$3^{1}_{0}n$
1.008665 u	235.043929 u	140.914411 u	91.926156 u	3.025995 u

These **atomic masses** are equal to the **total mass of the protons and neutrons** inside the nucle[illegible] the **binding energ**[illegible] nucleus toge[illegible] ften be given these [illegible] lem.

$E = ((1.008665\ u + 235.043929\ u) - (140.914411\ u + 91.926156\ u + 3.025995$ [illegible] kg/u) $(2.998 \times 10^8\ m/s)^2$

the change in mass in terms of atomic mass un[illegible]

conversion from u to kg

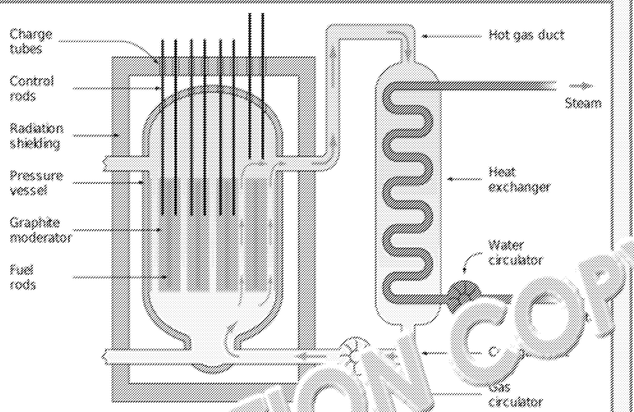
the speed of light, c

$E = 2.777 \times 10^{-11}\ J = \mathbf{173.3\ MeV}$

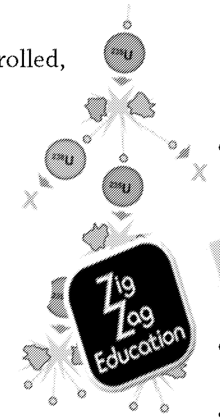
$1\ u = 1.661 \times 10^{-27}\ kg$

Energy Generation from Nuclear Fission

During fission, **energy** and **2–3 neutrons** are released along with the smaller atoms. Energy is released as heat and radiation, which can be used to turn water into steam, driving a turbine, generating electricity.
The **released neutrons** can also be used to **induce fission** in nearby large nuclei, causing more energy and neutrons to be released, and so on.
This **chain reaction** is used to continually generate electricity from fissile material like uranium-235 in **nuclear power plants**.



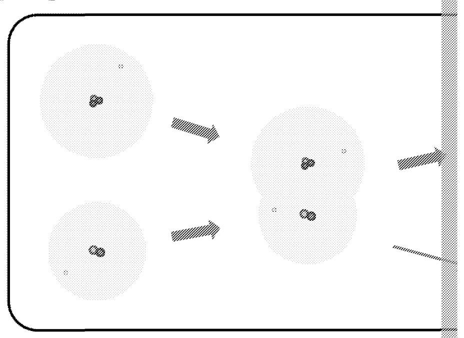
If the number of neutrons inducing fission is not controlled, the number of fission events quickly grows, releasing destructive amounts of energy.



Nuclear reactors produce nuclear waste. This is radioactive material that can remain dangerous for thousands of years. It is important for governments to consider what they will do with the waste from their nuclear reactors, and how they will minimise its effect on the environment and people.

- The **moderato**[illegible] ed of the neutrons as the spe[illegible] to [illegible] pecific value to induce fi[illegible] en graphite or water.
- [illegible] **rol rods** absorb neutrons to ensure that t[illegible] re is only one thermal neutron per fission event. Materials like cadmium or enriched boron are used.
- The **heat exchanger** extracts the heat and allows it to be transferred to produce electricity.
- The **shielding** stops dangerous nuclear radiation from leaving the reactor. Lead is often used.

Nuclear fusion is the joining, or **fusing**, [illegible] **larger atom**. You can think of fusion as



Where do stars get their e

Stars have a lot of mass. Our Sun is 500,[illegible] more massive than Earth! Gravity pulls [illegible] mass together. Through friction and oth[illegible] this mass heats up, creating high tempe[illegible] pressures in the star's centre. When con[illegible] extreme enough, atoms of **hydrogen ca**[illegible] **into helium**, releasing energy. The outw[illegible] pressure from this released energy balan[illegible] so the star keeps its shape and size. This [illegible] star is called a main sequence star.

Just like for fission, to calculate the energ[illegible]

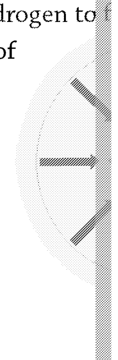
$$4^{1}_{1}H^{+} \rightarrow ^{4}_{2}He^{2+}$$

$4^{1}_{1}H^{+}$	$^{4}_{2}He^{2+}$
1.007277 u	4.002603 u

The L

Stars first fuse hydrogen into helium for [illegible] However, stars have limited hydrogen to [illegible]

In stars like our Sun, as fusion of hydrogen slows down, gravity compresses the core.
The hydrogen around the core fuses, releasing energy that pushes the outer parts of the star out, so they cool. The star swells into a **red giant**.



Hertzsprun

The amount of light a star emits, called it[illegible] **luminosity**, is proportional to its **tempe**[illegible] to the power of 4. Plotting the luminosity [illegible] against their temperatures (H–R diagram[illegible] the regions for different star types. A sta[illegible] **luminosity** is also proportional to its **ra**[illegible] squared. Scientists can measure a star's E[illegible] spectrum and determine its luminosity, temperature and size.

$L \propto T^4$

$L \propto R^2$

$1\ AU = 1.50 \times 10^{15}\ m$

Structure of the Atom

The Atom

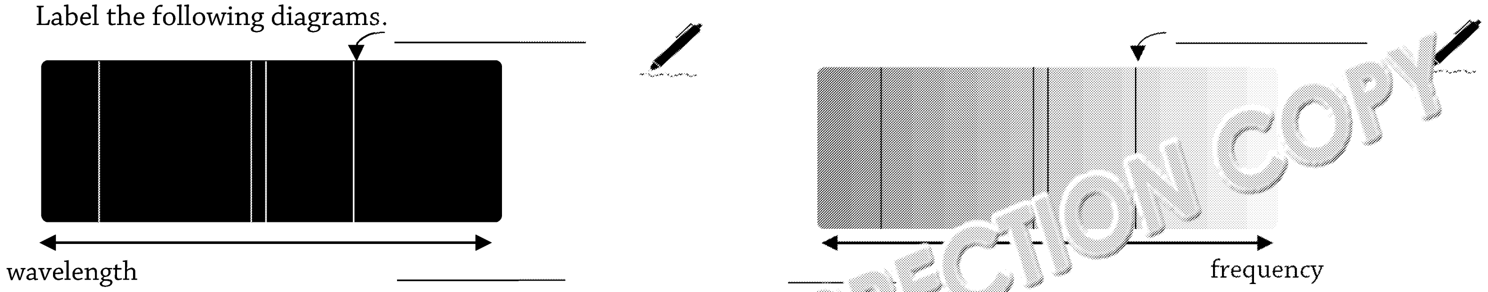
1. Draw a diagram of an atom. Label the three subatomic particles in your atom.

2. Decide whether the following statements are true or f‍‍lse by marking the appropriate column.

Statement	True	False
An atom can have any number of ... ons **and** exist for a long time.		
There are 1... len... s.		
An atom of $^{7}_{3}$... otons and 4 neutrons.		
The mass number is equal to the number of neutrons in the nucleus.		
The symbol used for an element depends on the number of protons in the nucleus.		

Emission and Absorption Spectra

3. Label the following diagrams.

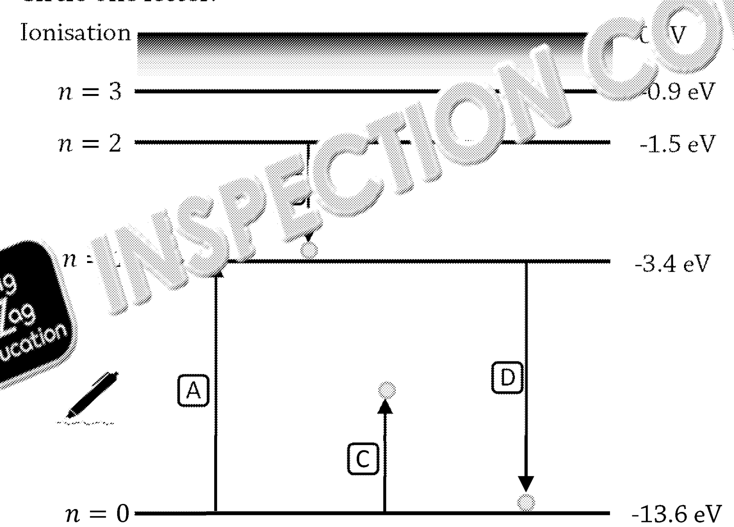


4. Describe how absorption and emission spectra form in th...

Photon Absorption and Emission

5. What happens when a photon passes by an electron in an atom? Write your description in the box below.

6. Which change in energy of an electron shown below is not all...d? Circle one letter.



7. An electron absorbs a photon with a frequen... of 5.2×10^{14} Hz. How much energy doe... the electron gain? Give your answer in joules and then conve... to electronvolts.
$h = 6.63 \times 10^{-34}$ Js

The...

8. In the space below, describ... Marsden. You can use the d...

9. Which conclusions fro...

- ☐ a) The nucleus ...
- ☐ b) Atoms have ...
- ☐ c) Most of the ...
- ☐ d) The nucleus i...
- ☐ e) An atom has...
- ☐ f) The nucleus ...
- ☐ g) An atom can...

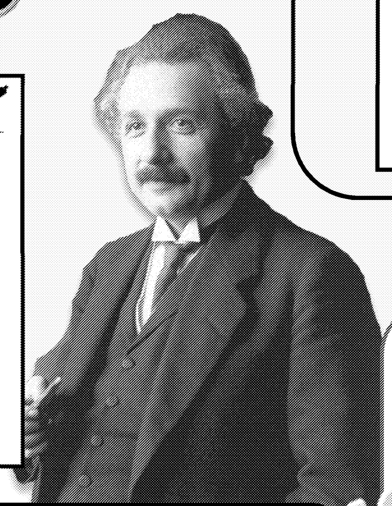
Quantum Physics – Additional Higher Level

Photoelectric Effect

1. What is the photoelectric effect?
   - ☐ a) when a photon is emitted from a metallic surface
   - ☐ b) when multiple photons are emitted from a metallic surface due to incident light
   - ☐ c) when an electron is emitted from a metallic surface due to incident light

2. A photon with a frequency of 3.90×10^{15} Hz interacts with an electron on a zinc surface, causing the electron to be emitted. The work function of zinc is 3.74 eV. What is the maximum kinetic energy of the electron?

$$E_{max} = hf - \phi$$



What evidence from the photoelectric effect shows light does not always act like a wave?

Describe the work function and explain what it means regarding the behaviour of photons.

Wave–Particle Duality

8. Which of the following are true evidence for the wave-like behaviour of particles or particle-like behaviour of photons?
   - ☐ a) Compton scattering is evidence that electromagnetic waves can act like particles.
   - ☐ b) The variation in wavelength of electromagnetic waves is evidence they can act like particles.
   - ☐ c) Electron diffraction is evidence that particles can act like waves.
   - ☐ d) The photoelectric effect is evidence that electromagnetic waves can act like particles.
   - ☐ e) The change in velocity of an electron in an electric field is evidence that particles can act like waves.

The Bohr Model and the Photoelectric Effect

3. Draw the Bohr model of a hydrogen atom (one proton, one electron) with an incident photon ejecting the electron from the atom.

4. What is ionisation?
   - ☐ a) when a nucleus gains negative charge
   - ☐ b) when an atom becomes positively or negatively charged
   - ☐ c) when an atom absorbs an iron atom

Compton Scattering

5. Fill in the gaps to complete the paragraph about Compton scattering.

If a photon with a high frequency interacts with a charged particle, such as an __________, the photon can transfer some of its energy to the electron.

The photon __________ energy, so its frequency __________ and its wavelength increases. The electron gains energy in the form of __________ energy, causing the electron to recoil away from the __________.

6. A photon interacts with an electron, causing the electron to recoil away at 30° from the photon's initial trajectory. What is the change in wavelength of the photon due to the energy lost in this interaction?

$$m_e = 9.11 \times 10^{-31}\ \text{kg}$$

$$\lambda_f - \lambda_i = \Delta\lambda = \left(\frac{h}{m_e c}\right)(1 - \cos(\theta))$$

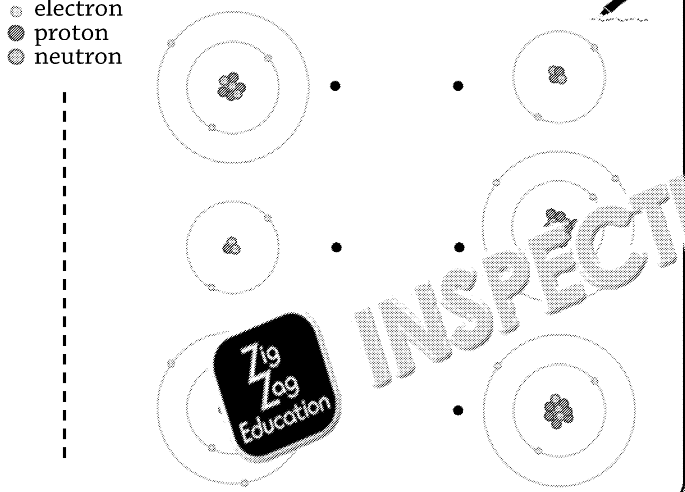
Radioactive Decay

What is an Isotope?

1. Match the isotopes together.

- electron
- proton
- neutron

$^{7}_{4}X$ •	• $^{14}_{6}C$
$^{9}_{3}X$ •	• $^{9}_{4}X$
$^{12}_{6}C$ •	• $^{7}_{3}X$



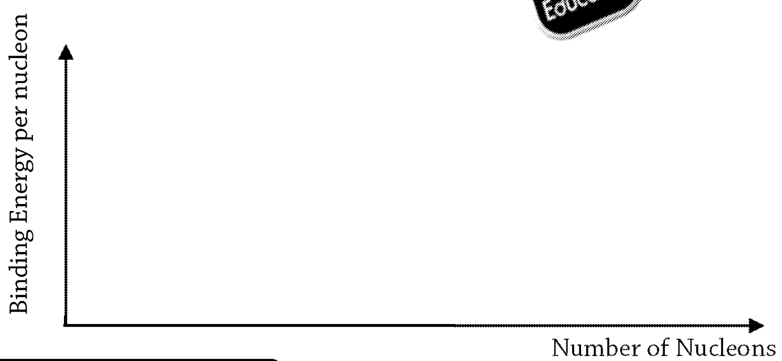
Mass and Energy

$$\Delta m = Zm_p + (A - Z)m_n - m_{nucleus}$$

2. What is the mass defect in an atom of iron-53 ($^{53}_{26}Fe$)? The mass of its nucleus is 8.79×10^{-26} kg.

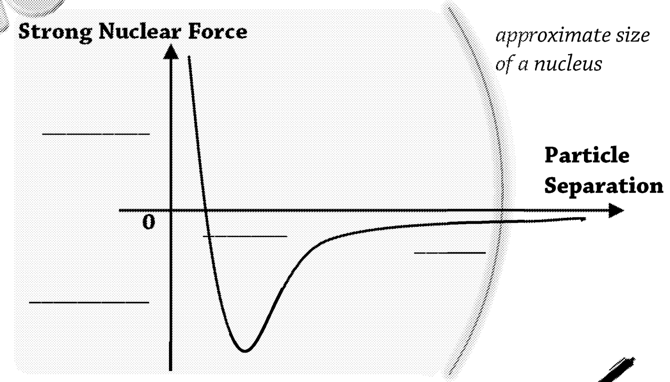
$m_p = 1.673 \times 10^{-27}$ kg
$m_n = 1.675 \times 10^{-27}$ kg

6. Draw a graph of binding energy per nucleon a... th... number of nucleons. Label the areas where ... d fission occur.



The Strong Nuclear Force

3. L... the g..ph below showing the regions where ... strong nuclear force is attractive or repulsive.

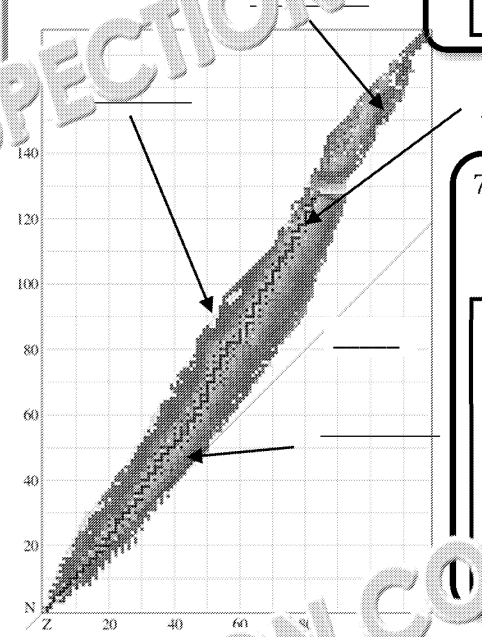


HL Only

4. What is needed to keep an atom stable as Z increases?

Nuclear Stability

5. Label the areas and line on the grap... shown bel...



HL Only

7. Describe one piece of evidence for the strong nuclear force.

Radioactive Decay

8. Fill in the gaps to complete the sentences.

Radioactive decay occurs when an atom is __________ and emits __________ to obtain a more stable state.

Radioactive decay is a __________ process. This means that we can't know which nucleus in a sample will decay next, or when.

HL Only

9. A sample of uraniu... 2..5 ha... 1... $\times 10^{24}$ atoms. Uranium-23... l... ...nstant of 3.1×10^{-17} s^{-1}. How m... ...ium-235 atoms are left in the sample after ...ne ...s?

$A = \lambda N$

$\frac{\Delta N}{\Delta t} = -\lambda N$

$A = A_0 e^{-\lambda t}$

$N = N_0 e^{-\lambda t}$

What...

10. In th... deca... relat...

Ra...

11.

12. Scientists ... They deter... today's car... 3.84×10... constant o...

Fission and Fusion

What is Nuclear Fission?

1. Describe the difference between spontaneous fission and neutron-induced fission.

How much energy is released during fission?

1 u = 1.661×10^{-27} kg

2. A uranium-233 atom undergoes neutron-induced fission, splitting into an atom of antimony, niobium, and 3 neutrons.

$$^{1}_{0}n + ^{233}_{92}U \rightarrow ^{133}_{51}Sb + ^{98}_{41}Nb + 3^{1}_{0}n$$

Given that the atomic mass of uranium-233 is 233.0396 u, of antimony-133 is 132.9153 u, of niobium-98 is 97.9103 u, and the mass of a neutron is 1.0087 u, calculate the energy released from this fission reaction.

Energy Generation from Nuclear Fission

3. Connect the component in a nuclear power generator to its correct description.

Component	Description
Moderator	stops dangerous nuclear radiation from leaving the reactor
Control rods	extracts the heat and allows it to be transferred to produce electricity
Heat exchanger	controls the speed of the neutrons
Shielding	absorb neutrons to ensure that one is one thermal neutron per fission event

4. Fill in the gaps to complete the sentences.

Nuclear reactors produce nuclear __________. This __________ material that can remain dangerous for thousands of years. It is important for governments to consider what they will do with the waste from their nuclear __________, and how they will minimise its effect on the environment and people.

5. List the conditions necessary for ... why these conditions are needed.

Where do stars get their e...

6. Explain how main sequence star...

The Life ...

7. Which of the following sequence... stars use elements as fuel for fus...

- ☐ a) hydrogen → helium →
- ☐ b) hydrogen → helium →
- ☐ c) helium → hydrogen →
- ☐ d) hydrogen → carbon →

Hertzsprung-

9. Two stars known to be equal dist... cosmologists. They measure that... How much higher and larger are... compared to star 2?

$L \propto R^2$ $L \propto T^4$

1 AU $= 1.50 \times 10^{15}$ m

Structure of the Atom

The Atom

The Geiger-M

The experiment

The c

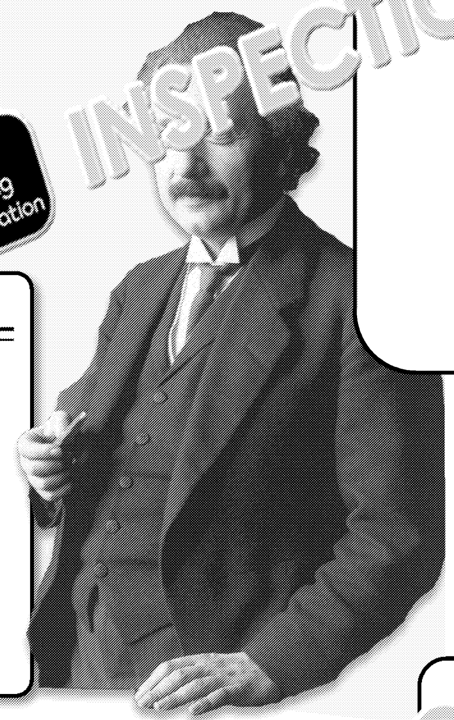
Emission and Absorption Spectra

Disco

Photon Absorption and Emission

Quantum Physics – Additional Higher Level C

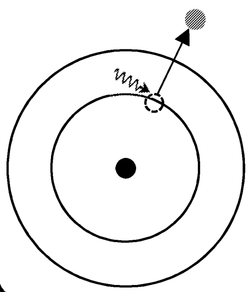
Photoelectric Effect



Terms of the photoelectric effect

What evidence from the photoelectric effect shows light does not always act like a wave?

The Bohr Model and the Photoelectric Effect



Wave–Particle Duality

Demonstration of wave-like and particle-like behaviour

Compton Scattering

Radioactive Decay

What is an Isotope?

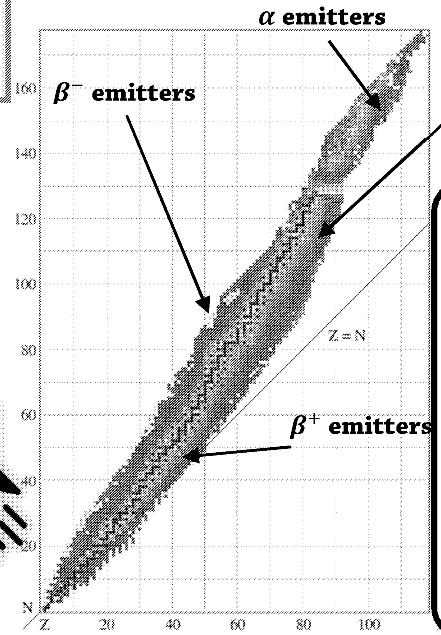
The Strong Nuclear Force

What is Radioactive Decay?

Mass and Energy

Radioactive Decay Equations

Nuclear Stability



HL Only

For a low number of protons, Z, a nucleus is stable if

But as Z increases,

The Dangers of Nuclear Radiation

HL Only

Beyond $Z = 60$, the binding energy is

HL Only

Radiation Spectroscopy

HL Only

Radioactive Decay

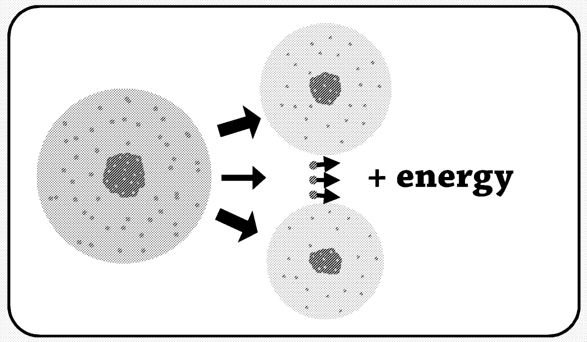
HL Only

Activity, A

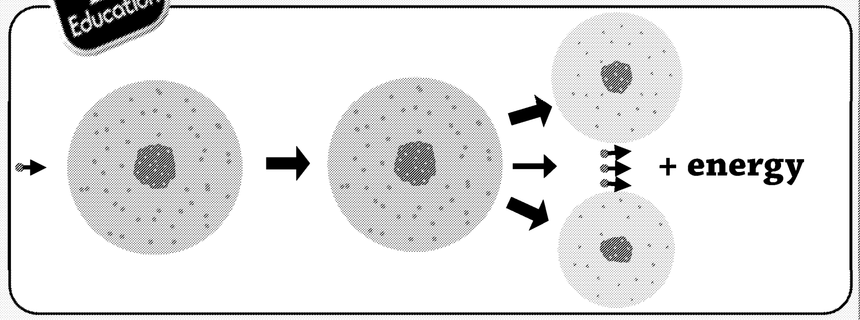
The **half-life** ($T_{1/2}$) of a radioactive substance is

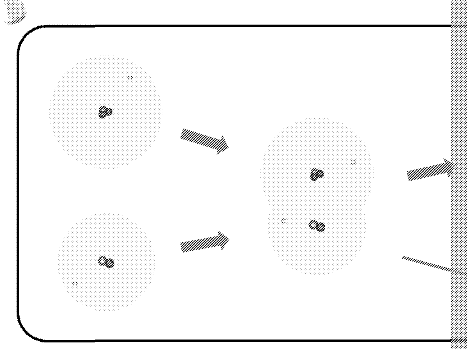
Fission and Fusion

What is Nuclear Fission?



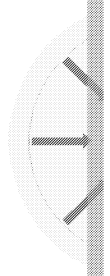
How much energy is released during fission?





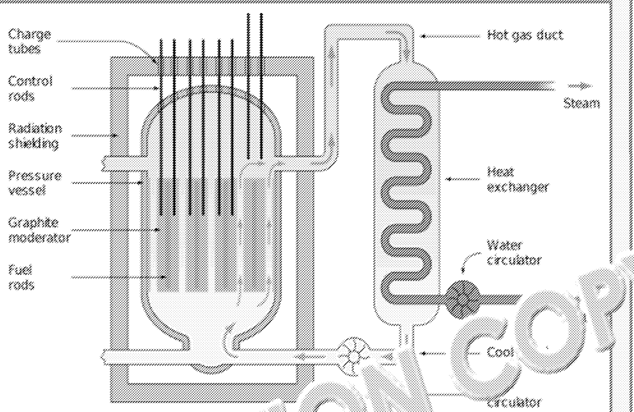
Where do stars get their e

The L



Hertzsprun

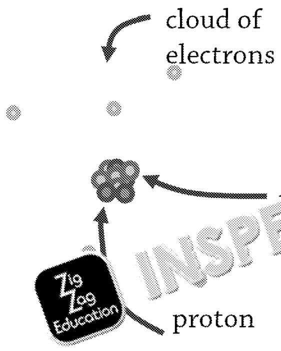
Energy Generation from Nuclear Fission



IB Topic on a Page, Theme E: Mark

E.1 Structure of the Atom

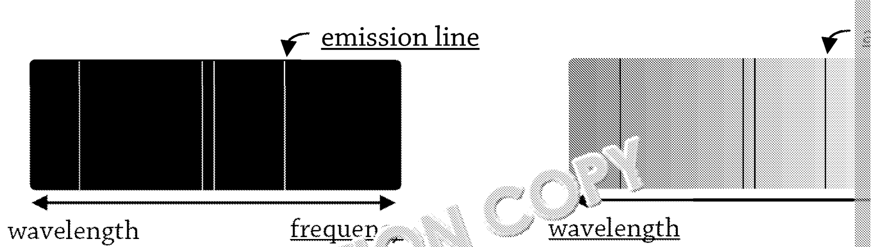
1.



2.

Statement
An atom can have any number of protons or neutrons and exist for
There are 146 known elements.
An atom of $^{7}_{3}$Li has 3 protons and 4 neutrons.
The mass number is equal to the number of neutrons in the nucleu
The symbol used for an element depends on the number of protons i

3.



4. White light that pas... ...rough a material can have some frequencies ... material. Th... ...than lines in the spectrum of the white light. Thi spec... Excited electrons in a material will fall to a lower energy le phot... These photons have specific frequencies, creating an emissi

5. If the photon has the right energy, the electron will absorb the photo level. If the photon does not have the right energy, it will pass by an

6. C

7. $E = hf$

$E = (6.63 \times 10^{-34}\ \text{Js})(5.2 \times 10^{14}\ \text{Hz})$

$E = 3.7 \times 10^{-19}\ \text{J} = 2.3\ \text{eV}$

8. An alpha source provided a **beam of alpha particles** that were aime All alpha particles (positively charged) were of the **same energy** and in an **evacuated chamber**. The alpha particles were **detected** by a det **radial distance** from the point of collision between the particles and t when the particles hit the detector, and these ... ...ions of light could

9. c) and f)

10. *(HL)* $R = R_0 A^{\frac{1}{3}}$

$R = (1.2 \times 10^{-15}$ ...

$R =$ ... 1...

11. *(HL)* ... $\frac{54.4}{n^2}$ eV

$E_2 = -\frac{54.4}{2^2}\ \text{eV} = -13.6\ \text{eV}$

$E_3 = -\frac{54.4}{3^2}\ \text{eV} = -6.0\ \text{eV}$

$\Delta E = 7.6\ \text{eV}$

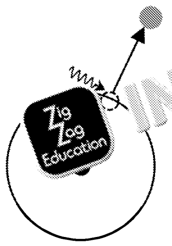
E.2 Quantum Physics

1. c)
2. $KE_{\text{max}} = E_{\text{max}} = hf - \phi$

$$KE_{\text{max}} = \frac{(6.63 \times 10^{-34}\ \text{Js})(3.90 \times 10^{15}\ \text{Hz})}{1.602 \times 10^{-19}\ \text{J/eV}} - (3.74\ \text{eV})$$

$$KE_{\text{max}} = 12.4\ \text{eV}$$

3.

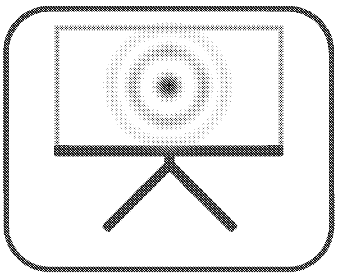


4. b)
5. If a photon with a high frequency interacts with a charged particle, su can transfer some of its energy to the electron. The photon **loses** energ and its wavelength increases. The electron gains energy in the form of electron to recoil away from the **photon**.
6. $\Delta\lambda = \left(\frac{h}{m_e c}\right)(1 - \cos(\theta))$

$$\Delta\lambda = \left(\frac{(6.63 \times 10^{-34}\ \text{Js})}{(9.11 \times 10^{-31}\ \text{kg})(3.0 \times 10^{8}\ \text{ms}^{-1})}\right)(1 - \cos(\ 0°))$$

$$\Delta\lambda = 3.3 \times 10^{-13}\ \text{m}$$

7. The work function is the energy needed by a photon to eject an electro The existence of the work function shows that photons must act like p of ene ... multiple photons cannot eject an electron.
8. a), c) a
9. Firing electrons through a small slit results in a **diffraction** pattern on This diffraction pattern shows that electrons can behave like **waves** in A particle's wavelength is called its **de Broglie** wavelength.
10.



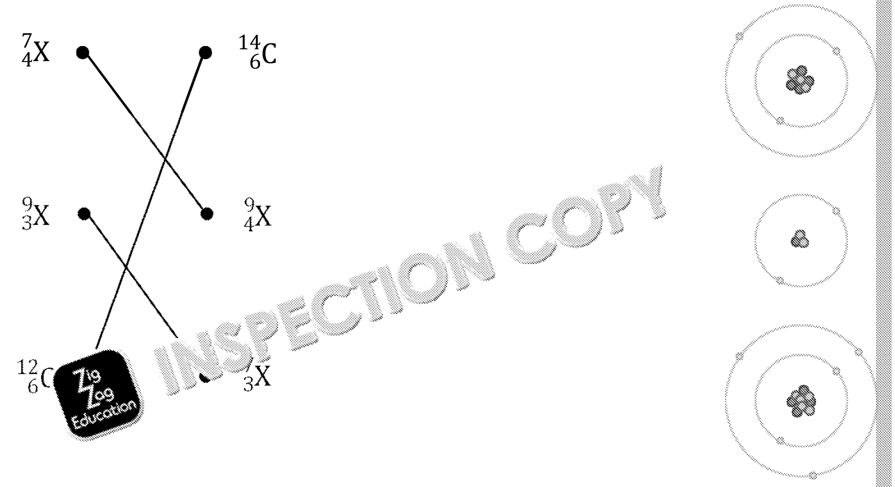
11. $v = \frac{h}{m\lambda}$

$$v = \frac{6.63 \times 10^{\ldots}\ \text{Js}}{(9.1\ldots \times 10^{\ldots}\ \text{kg})(7.15 \times 10^{-6}\ \text{m})}$$

$$v = 1\ldots$$

E.3 Radioactive Decay

1.

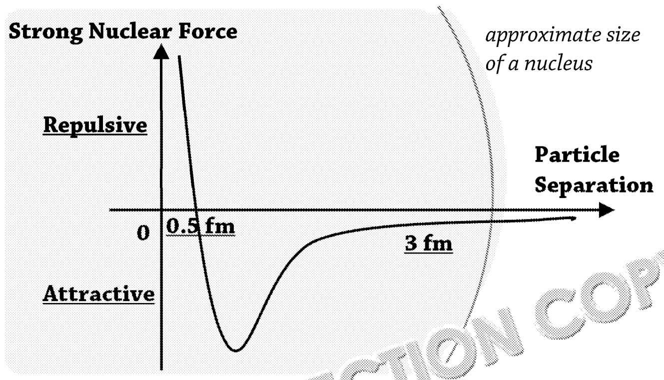


2. $\Delta m = Zm_p + (A - Z)m_n - m_{nucleus}$

$\Delta m = (26)(1.673 \times 10^{-27}\text{kg}) + (53 - 26)(1.675 \times 10^{-27}\text{ kg}) - (8.79 \times$

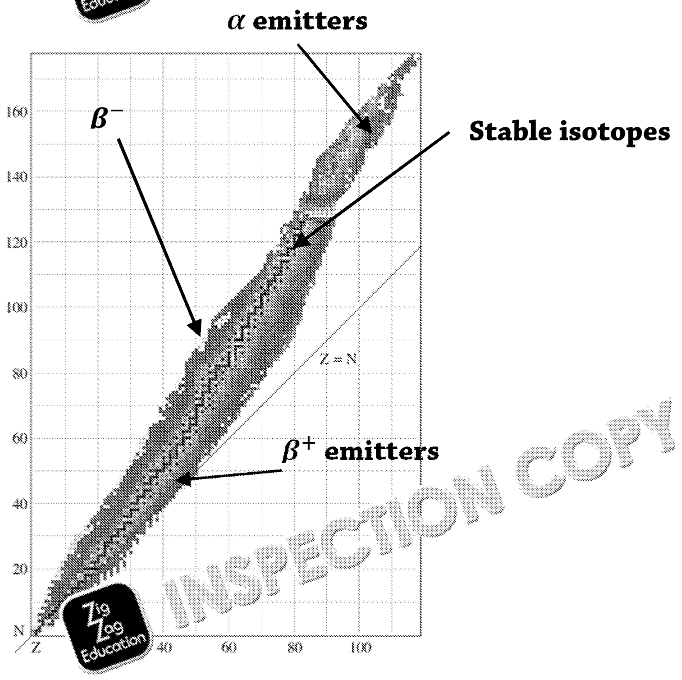
$\Delta m = 8.23 \times 10^{-28}\text{ kg}$

3.

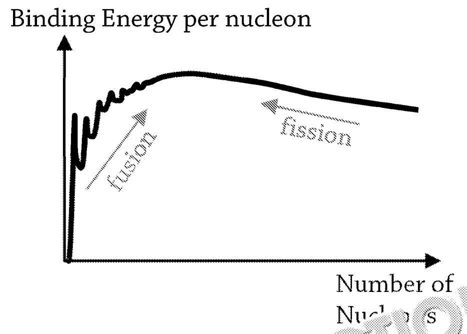


4. *(HL)* As Z, the [illegible] of protons, increases, the number of neutrons, [illegible]
For an[illegible] $Z > 50$, N must be larger than Z.

5.



6.



7. *(HL)* Evidence for th... nuclear force include that fact atoms exis... would otherw... , and the binding energy being much larger tha... consti... significantly contributing to the nucleus's mass.

8. Radioactive decay occurs when an atom is **unstable** and emits **radiati...** state. Radioactive decay is a **random** process. This means that we can't... sample will decay next, or when.

9. *(HL)* $N = N_0 e^{-\lambda t}$

$N = (1.0 \times 10^{24})e^{-(3.1 \times 10^{-17}\ \mathrm{s}^{-1})(60 \times 60 \times 24 \times 365.25 \times 10^{9})}$

$N = 3.8 \times 10^{23}$ atoms

10. *(HL)*

Radiation Name	Radiation Properties
Alpha, α	It is made of two protons and two neutrons (a h... It has a +2 charge and is relatively heavy. Shielded by paper.
Beta, β	It is an electron or a positron. Has a +1 or -1 charge, depending on the type, a... Shielded by aluminium foil.
Gamma, γ	It is a high energy photon (EM radiation). Has no electric charge and no mass. Shielded by thick sheets of lead.

11. **(HL)** Scientists can analyse alpha and gamma radiation emitted from a... isotope since the energy levels are discrete and specific to individual e... can't do this for beta radiation since the neutrino also emitted carries a... energy, hence the energy of the beta radiation is continuous and not sp...

12. First calculate the half-life of carbon-14:

$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$

$T_{\frac{1}{2}} = \frac{\ln 2}{(3.84 \times 10^{-12}\ \mathrm{s}^{-1})}$

$T_{\frac{1}{2}} = 1.81 \times 10^{11}\ \mathrm{s} = 5730$ years

Then determine the number of half-lives passed for carbon-14 to decre...

$12.5\ \% = \frac{125}{1000} = \frac{1}{8} = \left(\frac{1}{2}\right)^3$

Therefore 3 half-lives have passed. Finally, multiply the number o... time of the half-life:

$t = nT_{\frac{1}{2}}$

$t = 3 \times 5730$ years

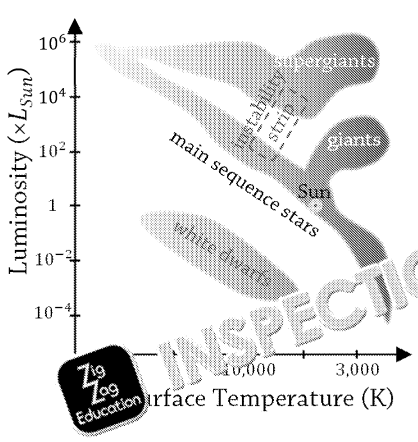
$t = 17\ 200$ years

So, the sample is around 17,000 years old!

E.4/5 Fission and Fusion

1. Spontaneous fission is when an atom randomly splits with no externa[l] ... neutron-induced fission is when an atom splits due to absorbing a neu[tron] ...
2. First calculate the change in mass (aka the mass defect) from the fissio[n] ...
$\Delta m = m_f - m_i$
$\Delta m = (132.9153\ \text{u} + 97.9103\ \text{u} + 3(1.0087\ \text{u})) - ([illegible]3.0396\ \text{u} + 1.0087$ ...
$\Delta m = -0.1966\ \text{u}$
Next, convert this change in mass into energy:
$\Delta E = \Delta mc^2$
Here, Δm should [illegible] grams.
$\Delta E = ([illegible]96\ \text{u})(1.661 \times 10^{-27}\ \text{kg/u})(2.998 \times 10^8\ \text{m/s})^2$
$\Delta E = [illegible] \times 10^{-11}\ \text{J}$
So, 183.2 MeV of energy is released in this fission reaction.
3.
- **Moderator** — controls the speed ...
- **Control rods** — absorb neutrons to ... thermal neutron pe...
- **Heat exchanger** — extracts the heat an[d] ... to produce electricit[y]
- **Shielding** — stops dangerous nu... the reactor

4. Nuclear reactors produce nuclear **waste**. This is **radioactive** material t[h] ... thousands of years. It is important for governments to consider what t[h] ... from their nuclear **reactors**, and how they will minimise its effect on t[h] ...
5. The material whose atoms are to be fused should be at a high tempera[t] ... nuclei of atoms overcome their repulsive forces.
6. The outward pressure from fusion in the star's core balances the inwa[r] ... the star's mass.
7. b)
8. a)
9. The scientists measure that $L_{star\ 1} \approx 2L_{star\ 2}$, so:
$L \propto R^2 \rightarrow (R_{star\ 1})^2 \approx 2(R_{star\ 2})^2$
$R_{star\ 1} \approx \sqrt{2}R_{star\ 2}$
$L \propto T^4 \rightarrow (T_{star\ 1})^4 \approx 2(T_{star\ 2})^4$
$T_{star\ 1} \approx \sqrt[4]{2}T_{star\ 2}$
10.



11. Angle, p is half the change in angular position of the star during the si

$$p = \frac{7''}{2}$$

$$p = 3.5''$$

Convert this into radians and substitute into the equation:

$$p = \frac{(3.5'')}{(3600\ ''/°)} \times \left(\frac{\pi}{180°}\right)$$

$$p = 1.7 \times 10^{-5}\ \text{rad}$$

Now substitute into the given equation:

$$d \approx \frac{2\ \text{AU}}{1.7 \times 10^{-5}\ \text{rad}}$$

$$d \approx 1.2 \times 10^{5}\ \text{AU}$$

Finally, convert this into light years:

$$d = (1.2 \times 10^{5}\ \text{AU})\left(\frac{1.50 \times 10^{15}\ \text{m}}{9.46 \times 10^{15}\ \text{m}}\ \text{ly/AU}\right)$$

$$d = 1.9 \times 10^{4}\ \text{ly}$$

And parsecs:

$$d = (1.2 \times 10^{5}\ \text{AU})\left(\frac{1.50 \times 10^{15}\ \text{m}}{3.09 \times 10^{16}\ \text{m}}\ \text{pc/AU}\right)$$

$$d = 5.8 \times 10^{3}\ \text{pc}$$