

NEW

MASTERING PHYSICS

NSW
FOCUS
AREA **7**

Matter, Energy and the Cosmos

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S

Science Press

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Introduction To Depth Studies

The new physics syllabus contains much the same content as the previous syllabus. While it may be slightly different in terms of the grouping of content areas within the major topics, this author has used personal discretion in linking that content together to present it in a logical, cohesive way.

The major difference in the new syllabus is the inclusion of **mandatory depth studies** – at least one in each of years 11 and 12, each requiring at least **15 hours of independent or collaborative work**, depending on the school preferences and student needs. Student selection of topic, design of work, and presentation of findings, although initial consultation with teachers for guidance is allowed.

Types of depth studies

Practical investigations

- Design and conduct experiments
- Test a claim or hypothesis
- Test or evaluate a device

Secondary sourced investigations

- Literature reviews
- Documentaries or media reports
- Evidence based arguments
- Journal articles or essays (historical or theoretical)
- Environmental management plans
- Analysis of fiction or film for scientific relevance
- Visual presentations
- Investigating emerging technologies

Creative and design projects

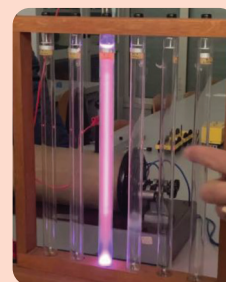
- Design and invent devices or models
- Create portfolios or working models

Field work

- Excursions or engagement with community experts
- Field based data collection and analysis

Data analysis

- Construction and interpretation of graphs and tables
- Analysis of data from various sources
- Longitudinal or resource management data analysis



Purpose of depth studies

Depth studies are designed to:

- Allow students to **explore content in greater detail**
- Develop **scientific thinking and inquiry skills**
- Encourage **creativity, collaboration, and communication**
- Provide opportunities for **authentic, student driven learning**

Assessment of depth studies

The NSW Department of Education requires a minimum 25% of the assessment mark awarded to each student to be derived from their depth study. Many schools in trial programs leading up to implementation of this course are allocating 30% to the depth study.

Examples of depth studies suited to matter, energy and the cosmos

The following gives brief descriptions of possible depth studies for **matter, energy and the cosmos**. These are not mandatory; rather, students are encouraged to select and design their own depth study from an area of study that excites them most. It is also not mandatory to do a depth study on work related to matter, energy and the cosmos. Students can choose from any of the year 12 topics. Whatever topic you choose, especially if it is one of your design, discuss it with your teacher before proceeding to ensure that it is acceptable.

Field work and community engagement

16. Excursion report: Visit to an observatory or planetarium

- Document how atomic and cosmic physics are applied in astronomy.
- Skills: Field work, media report, data analysis.

17. Interview with an astrophysicist or particle physicist

- Explore real-world applications of atomic and cosmic physics.
- Skills: Field work, secondary sourced investigation.

18. Environmental study: Radiation monitoring in urban areas

- Investigate background radiation levels and safety protocols.
- Skills: Environmental management plan, data analysis.

Fiction and pop culture analysis

19. Film analysis: Atomic physics in 'Oppenheimer'

- Evaluate the scientific accuracy and historical context of nuclear development.
- Skills: Analyse fiction/film, evidence based argument.

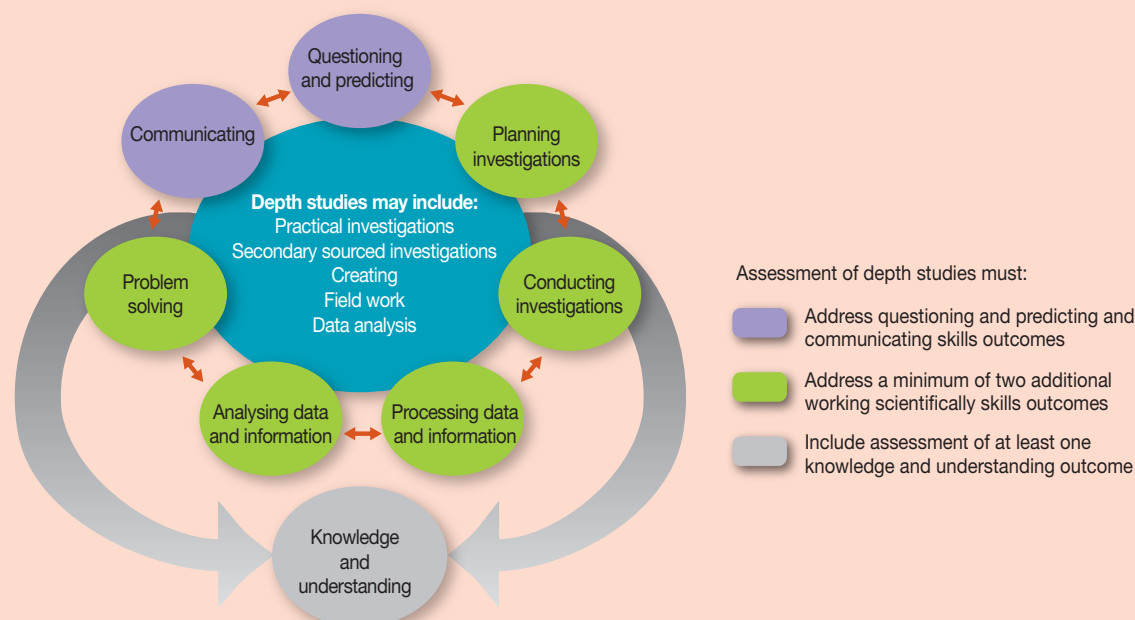
20. Sci-Fi versus reality: Particle accelerators in popular media

- Compare fictional depictions with real-world physics and technology.
- Skills: Media report, theoretical essay, secondary sourced investigation.

Depth study content integration

Each depth study must include:

- **Working scientifically skills**, specifically from **questioning and predicting**, and **communicating**
- **At least two other working scientifically skills outcomes** (e.g. planning investigations, conducting investigations, processing data, analysing data, and problem solving)
- **Further development of at least one knowledge and understanding outcome** (see outcomes in topic areas in the syllabus document)



Words to Watch

account, account for State reasons for, report on, give an account of, narrate a series of events or transactions.

analyse Interpret data to reach conclusions.

annotate Add brief notes to a diagram or graph.

apply Put to use in a particular situation.

assess Make a judgement about the value of something.

calculate Find a numerical answer.

clarify Make clear or plain.

classify Arrange into classes, groups or categories.

comment Give a judgement based on a given statement or result of a calculation.

compare Estimate, measure or note how things are similar or different.

construct Represent or develop in graphical form.

contrast Show how things are different or opposite.

create Originate or bring into existence.

deduce Reach a conclusion from given information.

define Give the precise meaning of a word, phrase or physical quantity.

demonstrate Show by example.

derive Manipulate a mathematical relationship(s) to give a new equation or relationship.

describe Give a detailed account.

design Produce a plan, simulation or model.

determine Find the only possible answer.

discuss Talk or write about a topic, taking into account different issues or ideas.

distinguish Give differences between two or more different items.

draw Represent by means of pencil lines.

estimate Find an approximate value for an unknown quantity.

evaluate Assess the implications and limitations.

examine Inquire into.

explain Make something clear or easy to understand.

extract Choose relevant and/or appropriate details.

extrapolate Infer from what is known.

hypothesise Suggest an explanation for a group of facts or phenomena.

identify Recognise and name.

interpret Draw meaning from.

investigate Plan, inquire into and draw conclusions about.

justify Support an argument or conclusion.

label Add labels to a diagram.

list Give a sequence of names or other brief answers.

measure Find a value for a quantity.

outline Give a brief account or summary.

plan Use strategies to develop a series of steps or processes.

predict Give an expected result.

propose Put forward a plan or suggestion for consideration or action.

recall Present remembered ideas, facts or experiences.

relate Tell or report about happenings, events or circumstances.

represent Use words, images or symbols to convey meaning.

select Choose in preference to another or others.

sequence Arrange in order.

show Give the steps in a calculation or derivation.

sketch Make a quick, rough drawing of something.

solve Work out the answer to a problem.

state Give a specific name, value or other brief answer.

suggest Put forward an idea for consideration.

summarise Give a brief statement of the main points.

synthesise Combine various elements to make a whole.

7.1 Cathode Rays and Discharge Tubes

Account for the origin of cathode rays in a cathode ray tub.

Describe the observations made inside a low pressure tube when a cathode ray interacts with a Maltese cross, a paddle wheel, electric fields, and magnetic fields.

Discovering cathode rays

It is important to realise that when scientists were experimenting with discharge tubes they:

- Did not know about electrons.
- Had no idea about the structure of an atom.
- Did not know what the discharge they observed was.
- Did not know what electricity was.
- Did not know what static electricity was.

So, in exam questions, make sure you do not attribute knowledge to scientists that was not known at their time.

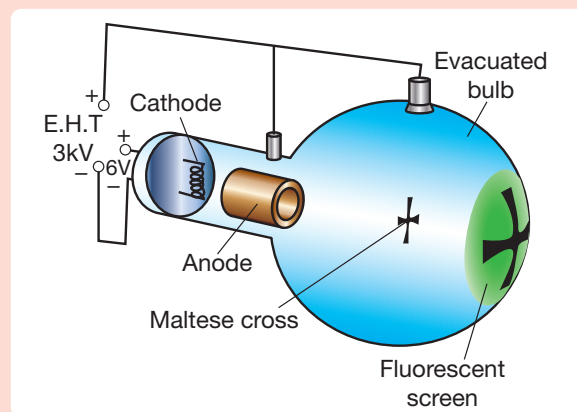
1855 Johann Heinrich Wilhelm Geissler

- Constructed the vacuum pump that was to allow many scientists to research atomic spectra, the structure of atoms and the nature of soon to be discovered cathode rays.

1869 Julius Plücker – The Maltese cross tube

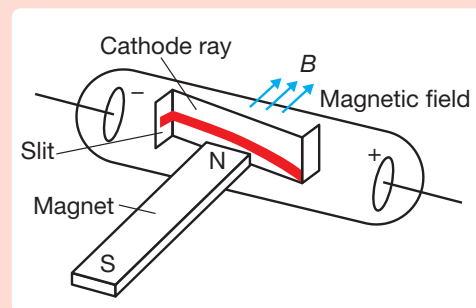
- Cast a sharp cross shaped shadow on the fluorescence, showing that cathode rays:
 - travelled in straight lines
 - are either blocked or absorbed by the metal in the cross
 - could cause fluorescence and
 - therefore had energy and
 - could transfer energy.

These observations, particularly the fluorescence, were used to propose that cathode rays were electromagnetic **waves**, since the only thing known to cause fluorescence at the time was UV light.



The effect of magnetic fields

- If a magnet was brought near a beam of cathode rays, they are deflected by the magnetic field.
- Because magnetic fields only deflect charged particles (**waves cannot be charged**) this deflection indicates two important properties of cathode rays:
 - they are charged and
 - they must therefore be **particles**.
- The direction of the deflection suggested that cathode rays were **negatively charged**.

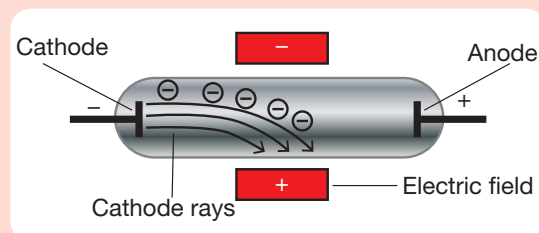


The effect of electric fields

- In the mid 1800s scientists noticed that if an electric field was applied across a beam of cathode rays, they were **not observed to be deflected**.
- This was due to the electric fields they could produce was only quite weak and the pressure of the gas in the discharge tubes was relatively high.
- The fact that they did not **observe** deflection triggered a debate as to whether cathode rays were charged or not and therefore whether they were **waves or particles**.

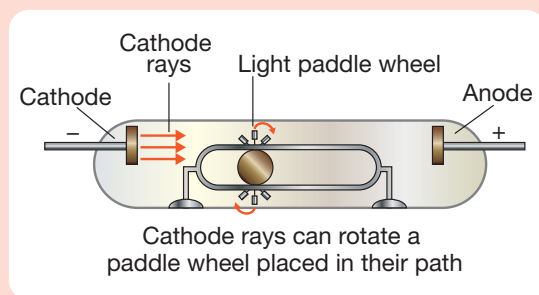
1897 JJ Thomson – Fluorescent display tube

- Solved the problem by (improved technology), observing deflection by both magnetic and electric fields.
- This suggested that cathode rays:
 - are **negatively charged** and
 - therefore must be **particles**.



The paddle wheel tube

- Cathode rays caused the paddle wheel to rotate and roll towards the anode.
- Experiment suggested that cathode rays:
 - had momentum and
 - therefore had mass and
 - were therefore **particles**
 - carried energy and could transfer energy
 - were **negatively charged** and therefore **particles**.



Sample Questions

- In the years leading up to 1897, there was considerable debate about the nature of cathode rays. What was the topic of this debate?
 - What was the problem that gave rise to this debate?
 - How, and when, was the problem solved?
- Copy and complete the following table to summarise the properties of cathode rays that indicate that they could be waves or particle as observed by scientists in 1897.

Property Cathode rays:	Evidence for cathode rays being waves	Evidence for cathode rays being particles	Both a wave and a particle property
Travel in straight lines Are blocked by a metal cross Form sharp shadow of a metal cross Cause fluorescence Carry energy Transfer energy Are deflected by a magnetic field Are deflected by an electric field Are negatively charged Have momentum Have mass			

7.2 Thomson's Experiment 1897

Analyse how observations of cathode rays provide evidence that cathode rays consist of particles with mass and charge.

Explain how the charge to mass ratio of the electron was first determined.

Derive the charge to mass ratio $\frac{q}{m} = \frac{E}{rB^2}$ for an electron in a cathode ray tube with perpendicular electric and magnetic fields.

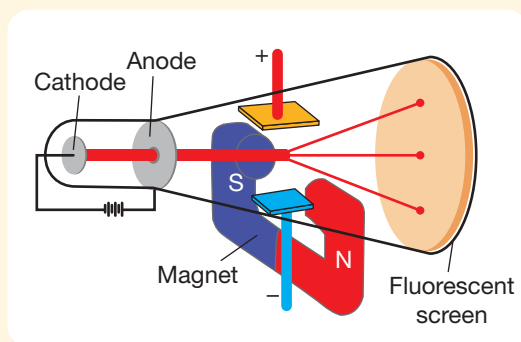
In 1897, little was known about atomic structure – protons, neutrons and electrons were unknown.

The debate about whether cathode rays were particles or waves still raged.

Thomson showed that cathode rays were deflected by electric fields as well as magnetic fields, thus proving their negative charge and particle nature.

No method existed for finding either the charge or the mass of charged particles, so Thomson set out to determine the **ratio of the charge of cathode rays to their mass**.

- He deflected the cathode rays either up or down by the electric field plates, then cancelled this deflection using the electromagnetic field produced by the coils.



- The electric force on the cathode rays:
 $F = Eq = q\frac{V}{d}$ (upwards)

- The magnetic force on the cathode rays:

$$F = Bqv = \frac{mv^2}{r} \text{ (downwards)}$$

- He deflected the cathode rays using the electric field, then cancelled the deflection using the magnetic field.
- In this situation, the magnitude of the two forces would be equal.
- So, from: $F = Eq = Bqv$, from which $v = \frac{E}{B}$
- Thomson then deflected the cathode rays using the magnetic field only, calculating the radius of their deflection whilst in the field using the scale etched on the vacuum tube.
- This gave him $F = Bqv = \frac{mv^2}{r}$
- Which, on rearranging gives $Bq = \frac{mv}{r} = \frac{mE}{Br}$
- Which leads to $\frac{q}{m} = \frac{E}{rB^2}$

Thomson calculated the ratio of the charge to mass of cathode rays to be about to be about 1836 times greater than that of a hydrogen ion. From this he concluded that:

- The charge on cathode rays was 1836 times larger than the charge on a hydrogen ion, or
- The mass of cathode ray particles was 1836 times less than that of a hydrogen ion, or
- Some combination of differences in both the mass and charge which led to this result.

Thomson then went further and assumed:

- That the charge on cathode rays was similar in size to that on a hydrogen ion and
- Then calculated their mass to be 9.11×10^{-31} kg. (Value today is 9.109×10^{-31} kg!)
- They were the same particles predicted by George Stoney in 1894 to be part of an atom and responsible for dynamic electricity. He gave them Stoney's name – electrons.

7.3 The Plum Pudding Model Of the Atom

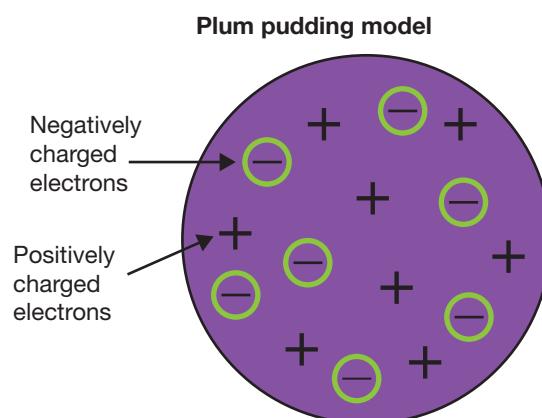
Evaluate the evidence supporting the plum pudding model of the atom.
Analyse how experimental evidence can lead to refinements in scientific models.

The **plum pudding model** of the atom was proposed by JJ Thomson in 1904. This model described the atom as a **sphere of positive charge** with **electrons embedded inside it**, like 'plums' in a pudding. This model wasn't random – it was based on experimental evidence available at the time as summarised below.

Key evidence supporting the plum pudding model

1. Discovery of the electron (cathode ray experiments)

- Thomson discovered the **electron** in 1897 using cathode ray tubes.
- Cathode rays were shown to be **negatively charged particles**, much smaller than atoms.
- This proved atoms were **not indivisible**, contradicting Dalton's model.
- Since atoms are neutral overall, Thomson reasoned that **positive charge must also exist** to balance the electrons.
- This led to the idea of a positively charged mass containing negatively charged electrons.



2. Explaining electrical neutrality

- Atoms have **no net charge**, so the model needed to explain how negative electrons and positive charges coexist.
- Thomson proposed that **positive charge was spread out uniformly** throughout the atom and **neutralised by an appropriate number of electrons**.

3. Behaviour of atoms in electric and magnetic fields

- Experiments showed atoms could be **ionised** (lose electrons) but remained mostly intact.
- This suggested electrons were **loosely bound** inside a larger positive structure – consistent with the plum pudding model.

4. Lack of evidence for a dense nucleus (before 1911)

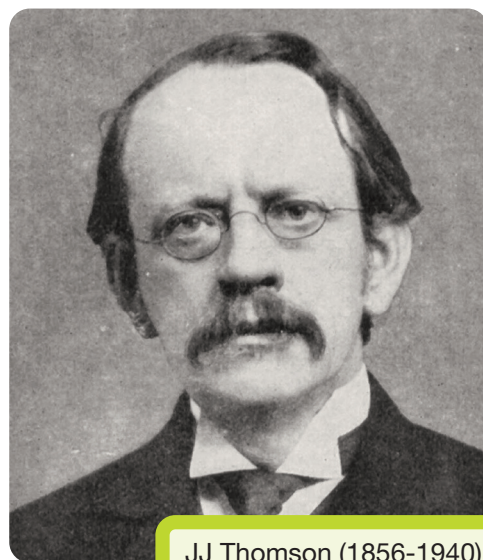
- Before Rutherford's gold foil experiment, there was **no evidence** that atoms had a small, dense centre, so there was no need for the idea of a nucleus.
- All known experiments were consistent with a **diffuse distribution of charge**, supporting Thomson's idea.

5. **Thomson's model was not wrong.** It was the best model available at the time and remained supported until Rutherford's gold foil scattering experiment which could not be explained by this model. A new one had to be developed, following the proper scientific process:

Evidence → Model → New evidence → New model

Sample Questions

1. What key discovery led JJ Thomson to propose the plum pudding model?
(A) The discovery of the electron.
(B) The existence of the nucleus.
(C) The neutron's role in atomic mass.
(D) The quantisation of energy levels.
2. In the plum pudding model, how is positive charge described?
(A) Concentrated in a central nucleus.
(B) Orbiting the electrons.
(C) Spread evenly throughout the atom.
(D) Located only at the atom's surface.
3. What feature of atoms did the plum pudding model successfully explain?
(A) Why atoms emit discrete spectral lines.
(B) Why atoms are electrically neutral.
(C) Why electrons occupy fixed energy levels.
(D) Why atoms have a dense central core.
4. Why did the plum pudding model seem reasonable before 1911?
(A) No experiment had shown evidence of a nucleus.
(B) Protons had already been discovered.
(C) Electrons were known to orbit the nucleus.
(D) Atoms were known to be mostly empty space.
5. Which experiment later disproved the plum pudding model?
(A) Bohr's hydrogen emission spectrum.
(B) Millikan's oil drop experiment.
(C) Rutherford's gold foil experiment.
(D) Chadwick's neutron scattering experiment.
6. What did Thomson's plum pudding model fail to explain?
(A) The results of Rutherford's gold foil experiment.
(B) The mass of the atom.
(C) The neutrality of atoms.
(D) The existence of electrons.
7. Which particle was *not* known at the time of the plum pudding model?
(A) Electron.
(B) Alpha particle.
(C) Proton.
(D) Neutron.
8. What was the main assumption about positive charge in the plum pudding model?
(A) It was located in shells around the electrons.
(B) It was spread uniformly throughout the atom.
(C) It was concentrated in the nucleus.
(D) It orbited the electrons.
9. Why was the plum pudding model eventually replaced?
(A) It didn't include neutrons.
(B) It couldn't explain atomic spectra.
(C) It was too complex to understand.
(D) It was disproven by experimental evidence.
10. Which scientist is credited with disproving the plum pudding model?
(A) Niels Bohr.
(B) Ernest Rutherford.
(C) Robert Millikan.
(D) James Chadwick.

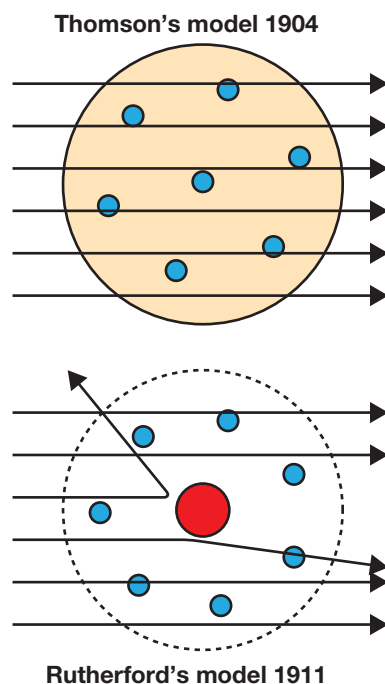
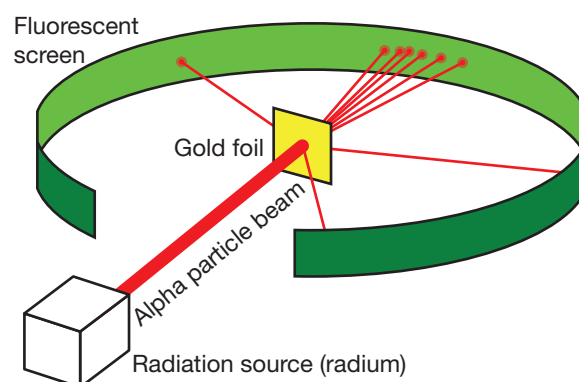


JJ Thomson (1856-1940)

7.4 The Geiger-Marsden Experiment 1909

Explain how the observations of the gold foil experiment led to the proposal of a nuclear model of the atom.

- In 1907 Rutherford worked with Hans Geiger investigating the scattering of alpha particles by a thin gold foil. The alpha particles were produced by the decay of a sample of radioactive radium (Marie Curie, 1898).
- Alpha particles were passed through a vacuum onto a gold foil and scattered. The positions of the scattered particles were seen as small flashes of light on a fluorescent screen.
- The alpha particle scattering was usually only one or two degrees.
- In 1909 Geiger worked with a research student, Ernest Marsden.
- They observed scattering at very large angles.
- This could not be explained by the current model of the structure of matter (Thomson – plum pudding model – 1904).
- For these deflections all the positive charge had to be concentrated in a small mass greater than the mass of the alpha particles.
- Rutherford proposed that the force causing such large deflections had to be large, and that the positively charged alpha particles were repelled by a massive positively charged object.
- The positive charge in an atom of gold was known, but if this charge was collected on a sphere the size of the atom, the repulsion would be far too weak.
- To explain the force experienced by the alpha particle the charge would have to be collected in a much smaller central sphere at the centre of the atom.
- Rutherford proposed the existence of a positively charged nucleus at the centre of atoms and put forward a new model of the structure of an atom based on these ideas in 1911.

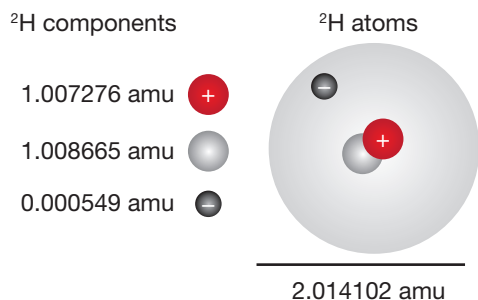


Sample Questions

Note: Atomic masses of nuclides vary according to the resources used, so different values may be given for different stimulus in questions. Always use the given data.

- Define the binding energy of a nucleus.
 - How does the binding energy of a nucleus compare to the binding energy of an atom?
 - How does binding energy relate to mass defect?
- A helium nucleus, mass 4.001505 amu, contains two protons, masses 1.0072766 amu each, and two neutrons, masses 1.008664 amu each. One amu = 1.661×10^{-27} kg and one amu = 931.5 MeV.

 - Find the mass defect for the helium nucleus in kg.
 - Find the mass defect in MeV.
 - Find the binding energy of the helium nucleus in joules.
 - Find the binding energy of the helium nucleus in MeV.
 - Find the binding energy per nucleon in the helium nucleus in joules.
 - Find the binding energy per nucleon in the helium nucleus in MeV.
- Consider the information in the diagram.



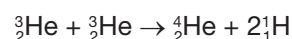
Find:

- The mass defect for the hydrogen atom in kg.
- The mass defect in MeV.
- The binding energy of the hydrogen atom in joules.
- The binding energy of the hydrogen atom in MeV.
- The binding energy per nucleon in the hydrogen atom in joules.
- The binding energy per nucleon in the hydrogen atom in MeV.

Consider the information in the table and use it to answer the next TWO questions.

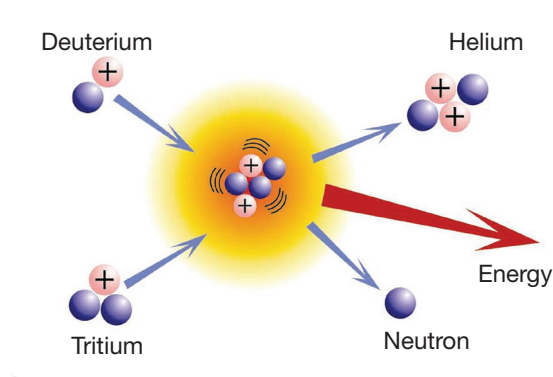
	Mass (amu)		Mass (amu)
^1_1H	1.007825	^1_0n	1.008664
^2_1H	2.014102	^4_2He	4.002603
^3_1H	3.016049	^3_2He	3.016029

- Consider the following nuclear reaction:



- Find the mass defect in amu.
- Find the mass defect in kg.
- Find the mass defect in MeV.
- Find the energy released in joules.
- Find the energy released in MeV.

- Consider the diagram showing deuterium and tritium combining to form helium.



Find:

- The mass defect for the reaction in amu.
 - The mass defect for the reaction in kg.
 - The mass defect in MeV.
 - The energy released in joules.
 - The energy released in MeV.
- The mass defect of a deuterium nucleus is $0.002388 u$. What is its energy equivalent?
 - What, in joules, is the energy equivalent of 1.0 grams of uranium?
 - A nuclear transmutation released 2.50 MeV of energy. Find the mass defect for the reaction.
 - A nuclear transmutation released 6.3×10^{-14} J of energy. Find the mass defect for the reaction.

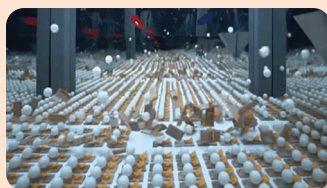
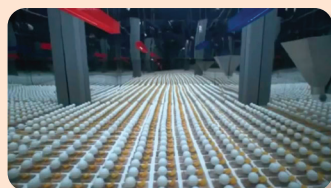
7.36 Controlled and Uncontrolled Reactions

Compare the processes of controlled chain reactions and uncontrolled chain reactions.

Fermi's model of a chain reaction 1942

Fermi's mousetrap experiment 1942

- To try to predict the properties of a nuclear chain reaction, Fermi set up tables of mousetraps and ping pong balls.
- Each mousetrap was set and 'baited' with one or more ping pong balls.
- The 'chain reaction' was started by Fermi dropping another ping pong ball into the middle of one of the tables of traps.
- He analysed the resulting chaos, seeking to find the variables that would result in the 'reaction' continuing to completion.
- Fermi observed from his experiments that whether or not he got a 'chain reaction' depended on how far apart the traps were placed, how many mousetraps were used, and how many ping pong balls were loaded onto each trap.
- From these results, Fermi proposed that each neutron involved in a fission reaction with a nucleus needed, on average, to emit 2.5 neutrons.
- This would provide enough neutrons to make the reaction self-sustaining.
- It also allows for others which would be absorbed by surrounding matter but not cause fission, and
- For those which escaped out of the reaction mixture and for those which had insufficient energy to cause fission despite hitting target nuclei.
- However, sustaining a chain reaction is only the first problem.
- Atoms are much smaller and more numerous than ping pong balls and once an atomic chain reaction starts, it needs to be controlled.
- If it is allowed to escalate out of control and, if sufficient fuel is available, the energy released will cause a nuclear explosion.

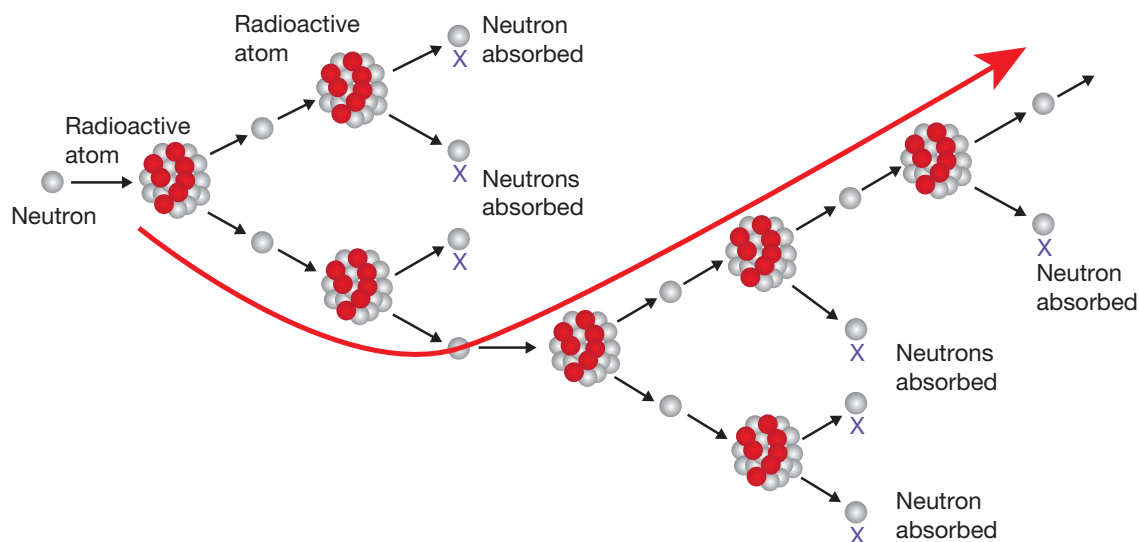


Sample Questions

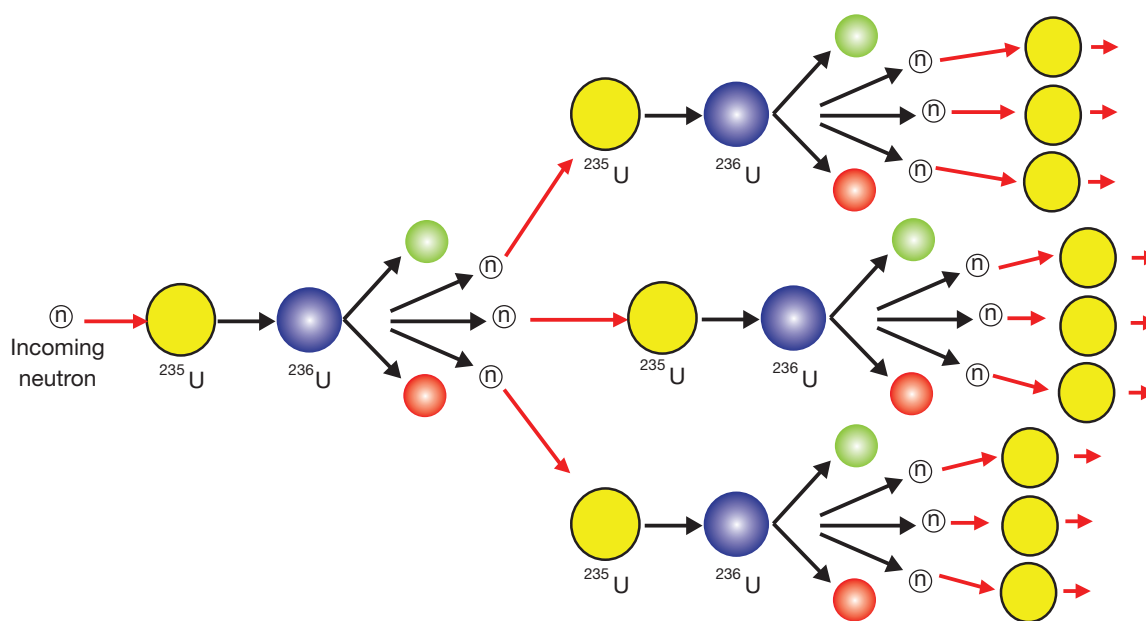
1. Clarify the symbolism in Fermi's model.
2. Predict how Fermi might have set up his mousetrap experiments in order to come to the conclusion that a chain reaction depends on:
 - (a) How far apart the mousetraps are.
 - (b) How many mousetraps are used.
 - (c) How many ping pong balls are used.
3. Interpret the relevance of these results for a real chain reaction.

Controlled and uncontrolled chain reactions

- In a **controlled nuclear reaction** only one fission is allowed to occur for each fission initiated. In other words, the number of fissions occurring remains constant.
- This means that extra neutrons with the energy which makes them able to cause fission must be absorbed by the control rods rather than be allowed to hit fuel atoms.
- Energy is produced at a steady rate.



- In an **uncontrolled reaction**, more than one neutron produced in each fission is able to initiate further fission reactions.
- The number of fissions occurring escalates exponentially and
- Uncontrollable amounts of energy are released.



7.37 Components Of a Fission Reactor

Explain the structure and function of the components of a fission reactor, including fuel, control rods, moderator and coolant.

Fuel

- Most commonly the fuel is uranium-235 or plutonium-239 in the form of small ceramic pellets stacked inside metal fuel rods.
- Enriched uranium has a higher amount of U-235 and sustains a chain reaction better.
- The fuel in the rods undergoes nuclear fission, releasing energy, neutrons, and more fissionable fragments.
- The neutrons drive the chain reaction that powers the reactor and provides the energy.

Control rods

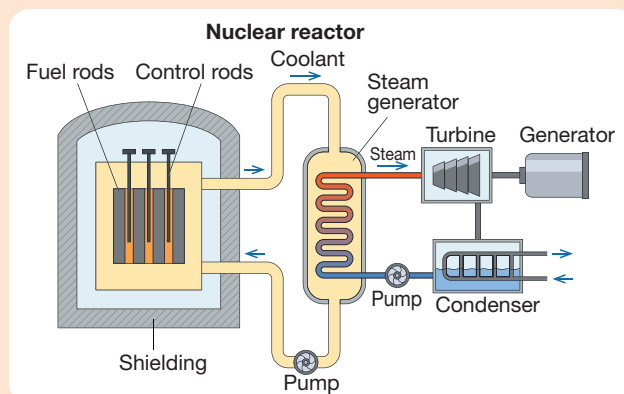
- Control rods made of materials like boron or cadmium to absorb neutrons to regulate the rate of fission.
- Lowering the control rods into the reactor slows the reaction as they then absorb more neutrons.
- Raising them increases reaction rate for the opposite reason. They are fully inserted to shut down the reactor.

Moderator

- Usually water, heavy water, or graphite, the function of the moderator is to **slow down fast neutrons** produced in fission.
- Slower (thermal) neutrons are more likely to cause further fission in U-235. And this ensures the chain reaction remains steady and efficient.

Coolant

- Water, liquid sodium, CO₂ gas, or molten salts to remove heat from the reactor core by transferring it to a steam generator or turbine to produce electricity.
- Prevents overheating and potential meltdown.



Sample Questions

1. Explain why a moderator is needed in a fission reactor.
2. Describe how control rods regulate the rate of fission.
3. What happens inside the fuel when fission occurs?
4. Why is a coolant essential in a nuclear reactor?
5. Explain how the chain reaction is kept stable in a reactor.
6. What would happen if the coolant flow stopped?
7. Describe how the chain reaction in a fission reactor differs from the chain reaction in a nuclear weapon.
8. Explain why enriched uranium is used in many nuclear reactors.
9. How does the coolant help prevent a reactor meltdown?
10. Why is shielding necessary in a nuclear reactor, and what materials are commonly used?

7.38 Energy Released From Fuels

Compare the energy release of nuclear reactions with the energy release of fossil fuels and conventional explosive.

Comparing energy released from fuels

Fossil fuels

For example, coal, petrol, and natural gas.

- Energy comes from **chemical reactions** (breaking and forming chemical bonds).
- Typical energy release is: Petrol: $\sim 44 \text{ MJ kg}^{-1}$
Coal: $\sim 24 \text{ MJ kg}^{-1}$
Natural gas: $\sim 42 \text{ to } 55 \text{ MJ kg}^{-1}$
- Chemical energy densities are relatively low because only **outer electrons** are involved.

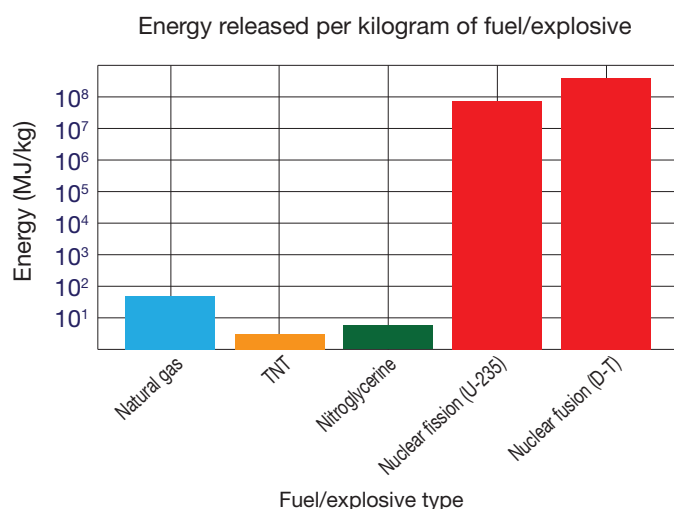
Conventional explosives

For example, TNT and nitroglycerine.

- Also chemical reactions, but designed to release energy **very rapidly**.
- Typical energy release is: TNT $\sim 4.2 \text{ MJ kg}^{-1}$ and nitroglycerine $\sim 6.7 \text{ MJ kg}^{-1}$.
- Lower energy per kg than fossil fuels, but much faster release $\rightarrow$ explosive effect.

Nuclear reactions (fission and fusion)

- Energy comes from changes in the **nucleus**. Mass is converted to energy via $E = mc^2$.
- Typical energy release is: nuclear fission (U-235) $\sim 80\,000\,000 \text{ MJ kg}^{-1}$ and nuclear fusion (deuterium-tritium (D-T)) $\sim 300\,000\,000 \text{ MJ kg}^{-1}$.
- Nuclear reactions release **millions of times more energy per kg** than chemical reactions.



7.39 Timeline Of Nuclear Fission

Outline the contribution of selected scientists to the discovery of nuclear fission.

Nuclear fission discovery and application

As a short research assignment, choose one of the events listed below which relate to the discovery of nuclear fission and its application to energy production, or choose another of your finding, and expand your knowledge of that event.

- 1896** Henri Becquerel discovers radioactivity, showing that atoms can spontaneously emit energy.
- 1898** Marie and Pierre Curie identify new radioactive elements polonium and radium, showing that radioactivity is an intrinsic, not chemical property of atoms.
- 1911-1919** Ernest Rutherford discovers the nucleus in gold foil experiment and performs the first artificial nuclear reaction, then produces a new model of the atom.
- 1932** James Chadwick discovers the neutron.
- 1932** John Cockcroft and Ernest Walton split the atom using a particle accelerator.
- 1934** Enrico Fermi bombards uranium with neutrons; Ida Noddack suggests the nucleus might split.
- 1934** Ida Noddack suggests the nucleus might split – first proposal of nuclear fission.
- 1936** Niels Bohr develops the liquid drop model which proposes nucleus is a tiny droplet of incompressible liquid.
- 1938** Otto Hahn and Fritz Strassmann detect barium after neutron bombardment and provide experimental evidence for nuclear fission.
- 1939** Lise Meitner explains the splitting of the nucleus using Bohr's liquid drop model.
- 1939** Otto Frisch confirms fission experimentally and names it 'fission.'
- 1939** Leo Szilard realises fission can sustain a chain reaction. Warns of huge energy implications.
- 1941** Glenn Seaborg identifies plutonium-239 as a new fissile material. First alternative nuclear fuel.
- 1942** Enrico Fermi demonstrates first controlled chain reaction.
- 1945** Robert Oppenheimer (and others in the Manhattan Project) carry out the first nuclear explosion.
- 1951** First nuclear power plant in Idaho, USA. First breeder plant (produces more fuel than it uses).
- 1954** First commercial nuclear plant, Obninsk, USSR.
- 1957** First large scale civilian nuclear station, Shippingport, Pennsylvania, USA.
- 1960** First pressurised water reactor (PWR) using water at 150 atmospheres pressure in closed circuit as coolant. Boiling temperature of water around 350°C. Most common (70%) modern reactor.



7.40 Why Some Nuclei Decay

Distinguish between the proton-neutron ratio and binding energy in the context of nuclear stability. Analyse graphical representations of nuclear binding energy per nucleon as atomic number increases, and apply this to the iron limit.

Nuclear stability

- Nuclear stability refers to the tendency of a nucleus of an atom to decay.
- Stable atoms have low energy states.
- Unstable atoms will try and become stable by getting to a lower energy state.
- They will typically do this by emitting some form of radioactivity and change in the process.

What makes a nucleus stable?

Science still does not completely understand why certain isotopes are more stable than others but have developed, from observations made, three predictors of stability: neutron to proton ratio, binding energy, and nucleon count.

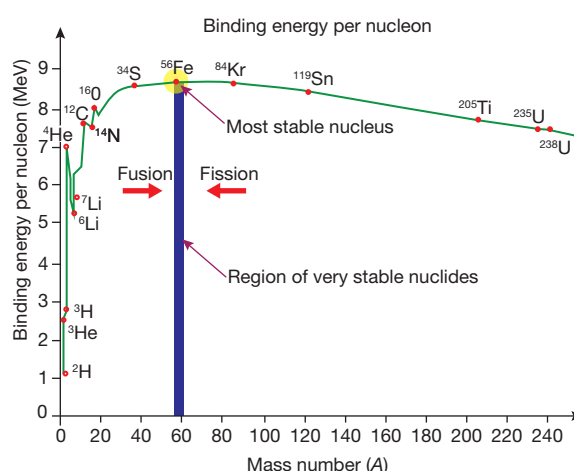
Neutron to proton ratio

- Lighter elements (low atomic and mass numbers) containing almost equal numbers of neutrons and protons are the most stable.
- As the size of the nucleus increases so does instability.
- Up to element 82, lead, the strong nuclear force can hold nuclei together.
- The more protons in a nucleus, the more neutrons needed to diminish proton repulsion.
- But, if there are too many neutrons, the nucleus becomes unstable.
- If an atom has more than 82 protons (= **atomic number of lead**) in the nucleus, there is no arrangement of neutrons that can produce more attractive forces than repulsive forces.
- Therefore, all isotopes of elements beyond lead are radioactive.

Graphical analysis

This concept of nuclear stability is summarised in the stability graph below.

- The binding energy per nucleon increases rapidly from hydrogen to medium mass nuclei, reaches a maximum around iron/nickel, and then gradually decreases for heavier nuclei.
- Fusion of light nuclei (left side) releases energy because the products have higher binding energy per nucleon, moving up the curve towards iron.
- Fission of very heavy nuclei (right side) releases energy because the fission fragments are closer to the iron peak and therefore have higher binding energy per nucleon.
- Because iron sits at the maximum of this curve, neither fusion of heavier elements nor fission of medium mass elements will increase binding energy per nucleon; therefore, iron represents a practical limit for energy-releasing nuclear reactions in stars and reactors.



Sample Questions

1. Explain, using the binding energy per nucleon graph, why fusion of light nuclei releases energy.
2. Explain why fission of very heavy nuclei releases energy.
3. Explain what is meant by the 'iron limit' in nuclear reactions.
4. Why can stars fuse elements only up to iron in their cores?
5. Use the binding energy curve to explain why supernovae are required to form elements heavier than iron.
6. Where on the binding energy per nucleon graph does iron lie?
 - (A) At the maximum.
 - (B) At the minimum for heavy nuclei.
 - (C) At the lowest point.
 - (D) On the far right.
7. Fusion releases energy when the products:
 - (A) Have lower binding energy per nucleon.
 - (B) Are heavier than iron.
 - (C) Move down the binding energy curve.
 - (D) Have higher binding energy per nucleon.
8. Fission of uranium releases energy because the fission fragments:
 - (A) Are lighter than hydrogen.
 - (B) Have higher binding energy per nucleon.
 - (C) Are heavier than uranium.
 - (D) Have lower binding energy per nucleon.
9. Why can't iron undergo energy-producing fusion?
 - (A) It is radioactive.
 - (B) It has too many neutrons.
 - (C) It already has maximum binding energy per nucleon.
 - (D) It cannot absorb neutrons.
10. Which statement best describes the iron limit?
 - (A) Iron cannot undergo nuclear reactions.
 - (B) Iron is the heaviest element in the Universe.
 - (C) No nuclear reaction involving iron can release energy.
 - (D) Iron has the lowest binding energy per nucleon.
11. Using the vertical differences on the graph, compare the energy released by:
 - (a) Fusing hydrogen into helium.
 - (b) Fissioning uranium into two mid mass fragments.
 - (c) Explain which process appears to release more energy per nucleon and why.
12. Choose a heavy nucleus from the right side of the nuclear stability graph (e.g. uranium). Using the graph, explain why splitting this nucleus into two medium mass nuclei results in a net increase in binding energy per nucleon.



Lucas Heights nuclear reactor, New South Wales

7.41 Positron-Electron Annihilation

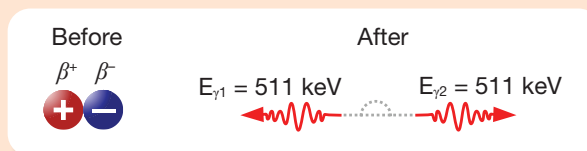
Discuss the process of positron-electron annihilation.

Explain how the law of conservation of mass-energy applies to particle-antiparticle annihilation.

Explain how positron emission tomography (PET) uses positron-electron annihilation to produce a medical scan.

Positron-electron annihilation

- When a **positron** (the antiparticle of the electron) meets an **electron**, they can undergo **annihilation**. A positron has the same mass as an electron but opposite charge.
- When they collide:
 - Their **mass is converted into energy**.
 - The energy is released as **two gamma ray photons**.
 - The photons are emitted in **opposite directions** (180° apart) to **conserve momentum**.



Conservation of mass-energy in annihilation

- The law of **conservation of mass-energy** states that the **total amount of mass and energy before and after a reaction must remain constant**.
- In positron-electron annihilation:
 - **Before the reaction:** There is **mass** (electron + positron). There may also be some **kinetic energy**.
 - **After the reaction:** The **mass disappears**, but it is replaced by **energy carried by gamma photons**.
- So even though the particles vanish, **their mass is fully accounted for as photon energy**. This is a perfect demonstration of **mass-energy equivalence**.

Sample Questions

1. Describe what happens during positron-electron annihilation.
2. Explain why two gamma photons are produced instead of one during annihilation.
3. State how the law of conservation of mass-energy applies to positron-electron annihilation.
4. A positron and electron each have rest mass 9.11×10^{-31} kg. Explain how this mass appears after annihilation.
5. Nuclei which undergo beta-plus decay produce positrons – that is what a beta-plus particle is.
 - (a) Write the general nuclear equation for an atom producing a positron.
 - (b) Write the nuclear equation for a magnesium-23 atom producing a positron.
 - (c) Write the nuclear equation for a fluorine-18 atom producing a positron.

Positrons and PET scans

How PET uses annihilation

- **Positron emission tomography** (PET) is a medical imaging technique that relies directly on positron-electron annihilation. PET works **only because** positron-electron annihilation produces predictable, detectable gamma rays.
- The energy produced by every positron-electron annihilation is identical as their masses are constant and totally converted to energy via $E = mc^2$.

How it works

- **A radioactive tracer is injected** – The tracer contains a **positron-emitting isotope** (e.g. fluorine-18). It accumulates in tissues with high metabolic activity (like active brain regions or cancer cells) where its decay produces positrons that annihilate with electrons generating the gamma rays that produce the image.
- **The isotope emits a positron**, which when a nucleus decays, it releases a **positron**. The positron travels a short distance and meets an electron. They annihilate, producing **two gamma photons**.
- **The photons travel in opposite directions** so that the law of conservation of momentum is conserved. Because they are emitted 180° apart, detectors around the patient can detect them simultaneously.
- **By detecting pairs of photons**, the PET computer calculates the **exact line** where the annihilation occurred. Repeating this millions of times builds a **3-D image** of tracer concentration inside the body.
- **This allows doctors to see** early development of cancer cells which have a high metabolic rate and absorb more of the radioactive tracer, resulting in more annihilation events which produce more energy and a brighter spot on the PET scan.
- **PET scans also monitor** heart function, brain activity, tumour metabolism, blood flow, organ function.



Sample Questions

1. Explain why annihilation photons always have the same energy in PET scanning.
2. Describe how a PET scanner detects the location of annihilation events.
3. Suggest the reason why positrons emitted in PET travel only a short distance before annihilation.
4. Describe the role of the radioactive tracer in PET imaging.
5. Explain why PET scans are useful for detecting cancer.
6. A PET scanner detects two gamma photons 180° apart. Explain what this tells us about the event that produced them.

7.42 Cecilia Payne-Gaposchkin

Describe Payne-Gaposchkin's spectral analysis technique for determining the chemical composition of stars.

Cecilia Payne-Gaposchkin **received, in 1925, the first PhD in astronomy ever awarded by Radcliffe College (Harvard University)**. Her dissertation is widely described as one of the most brilliant in the history of astronomy, and it contained her groundbreaking discovery that stars are made primarily of hydrogen and helium.

Her thesis **rewrote the foundations of astrophysics**. Astronomers had examined spectra of stars for decades, but no one could correctly interpret what the absorption lines meant. Payne-Gaposchkin applied quantum physics and statistical mechanics to show that **line strength depends on temperature**, not just abundance.

This insight unlocked the true meaning of stellar spectra and overturned decades of assumptions.

Before her work, scientists believed stars had the same composition as Earth – mostly heavy elements like iron, silicon, and oxygen. Payne-Gaposchkin demonstrated that stars are **overwhelmingly hydrogen and helium**, with heavy elements making up only a tiny fraction.

This was so different to what the scientific community believed, that senior astronomer Henry Norris Russell told her not to publish the conclusion as fact. Years later, he confirmed she was right.

Payne-Gaposchkin created the modern field of stellar astrophysics and her methods became the blueprint for how astronomers determine stellar composition, temperature, luminosity and spectral classification.

Her discovery that stars are mostly hydrogen and helium, meant that **the Universe is mostly hydrogen and helium**. Understanding stellar composition allowed scientists to model nuclear fusion in the cores of suns. This reshaped cosmology, stellar evolution theory, and nuclear physics.



Sample Questions

1. Research 20 top achievements of Cecilia Payne-Gaposchkin in her field of astrophysics and present this information in a style of your choice.

Data Sheet

Charge on electron, q_e	$-1.602 \times 10^{-19} \text{ C}$
Mass of electron, m_e	$9.109 \times 10^{-31} \text{ kg}$
Mass of neutron, m_n	$1.675 \times 10^{-27} \text{ kg}$
Mass of proton, m_p	$1.673 \times 10^{-27} \text{ kg}$
Speed of sound in air	340 m s^{-1}
Earth's gravitational acceleration, g	9.8 m s^{-2}
Speed of light, c	$3.00 \times 10^8 \text{ m s}^{-1}$
Magnetic permeability constant, μ_0	$4\pi \times 10^{-7} \text{ N A}^{-2}$
Universal gravitational constant, G	$6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$
Mass of Earth, M_E	$6.0 \times 10^{24} \text{ kg}$
Radius of Earth, r_E	$6.371 \times 10^6 \text{ m}$
Planck constant, h	$6.626 \times 10^{-34} \text{ J s}$
Rydberg constant, R (hydrogen)	$1.097 \times 10^7 \text{ m}^{-1}$
Atomic mass unit, u	$1.661 \times 10^{-27} \text{ kg}$ $931.5 \text{ MeV}/c^2$
1 eV	$1.602 \times 10^{-19} \text{ J}$
Density of water, ρ	$1.00 \times 10^3 \text{ kg m}^{-3}$
Wien's displacement constant, b	$2.898 \times 10^{-3} \text{ m K}$

Formula Sheet

Motion, Forces and Gravity

$$s = ut + \frac{1}{2}at^2$$

$$v^2 = u^2 + 2as$$

$$\Delta U = mg\Delta h$$

$$P = \frac{\Delta E}{\Delta t}$$

$$\sum \frac{1}{2}mv_{\text{before}}^2 = \sum \frac{1}{2}mv_{\text{after}}^2$$

$$\Delta \vec{p} = \vec{F}_{\text{net}}\Delta t$$

$$v = \frac{2\pi r}{T}$$

$$U = -\frac{GMm}{r}$$

$$\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$$

$$v = u + at$$

$$\vec{F}_{\text{net}} = m\vec{a}$$

$$W = F_{\parallel}s = Fs\cos\theta$$

$$K = \frac{1}{2}mv^2$$

$$P = F_{\parallel}v = Fv\cos\theta$$

$$\sum m\vec{v}_{\text{before}} = \sum m\vec{v}_{\text{after}}$$

$$a_c = \frac{v^2}{r}$$

$$F_c = \frac{mv^2}{r}$$

$$F = \frac{GMm}{r^2}$$

Electricity and Magnetism

$$E = \frac{V}{d}$$

$$V = \frac{\Delta U}{q}$$

$$W = qV$$

$$W = qEd$$

$$B = \frac{\mu_0 I}{2\pi r}$$

$$B = \frac{\mu_0 NI}{L}$$

$$\Phi = B_{\parallel}A = BA\cos\theta$$

$$\mathcal{E} = -N\frac{\Delta\Phi}{\Delta t}$$

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

$$\vec{F} = q\vec{E}$$

$$F = \frac{1}{4\pi\epsilon_0} \frac{q_1q_2}{r^2}$$

$$I = \frac{q}{t}$$

$$V = IR$$

$$P = VI$$

$$F = qv_{\perp}B = qvB\sin\theta$$

$$F = I\vec{l} \times \vec{B} = I\vec{l}B\sin\theta$$

$$\frac{F}{l} = \frac{\mu_0}{2\pi} \frac{I_1I_2}{r}$$

$$V_pI_p = V_sI_s$$

Waves

$$v = f\lambda$$

$$f = \frac{1}{T}$$

$$d\sin\theta = m\lambda$$

$$n_x = \frac{c}{v_x}$$

$$I = I_{\text{max}}\cos^2\theta$$

$$f_{\text{beat}} = |f_2 - f_1|$$

$$f' = f \frac{(v_{\text{wave}} + v_{\text{observer}})}{(v_{\text{wave}} - v_{\text{source}})}$$

$$n_1\sin\theta_1 = n_2\sin\theta_2$$

$$\sin\theta_c = \frac{n_2}{n_1}$$

$$I_1r_1^2 = I_2r_2^2$$

Quantum, Special Relativity and Nuclear

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

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

$$\lambda_{\text{max}} = \frac{b}{T}$$

$$E = mc^2$$

$$E = hf$$

$$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$l = l_0\sqrt{1 - \frac{v^2}{c^2}}$$

$$P_v = \frac{m_0v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$N_t = N_0e^{-\lambda t}$$