



Volume
One

**ST MARY'S SCIENCE
DEPARTMENT:
PHYSICS**

**A LEVEL PHYSICS YEAR 1
STUDENT INDEPENDENT WORK BOOK
PARTICLES AND RADIATION
3.2.1: PARTICLES**

NAME	
PHYSICS CLASS	
MODULE TEACHER	
ALPS GRADE	



**A-LEVEL PHYSICS
TOPIC 2
INDEPENDENT WORK BOOK**

**THIS MUST
BE BROUGHT
TO ALL
PHYSICS
LESSONS.**



Contents

3.2.1.1 Constituents of the Atom

3.2.1.2 Stable and Unstable Nuclei

3.2.1.3 Particles, Antiparticles and Photons

3.2.1.4 Particle Interactions

3.2.1.5 Classification of particles

3.2.1.6 Quarks and antiquarks

3.2.1.7 Applications of conservation laws

Overview

This section introduces students both to the fundamental properties of matter, and to electromagnetic radiation and quantum phenomena. Through a study of these topics, students become aware of the way ideas develop and evolve in physics. They will appreciate the importance of international collaboration in the development of new experiments and theories in this area of fundamental research.

IMPORTANT NOTE

This book contains all of the activities you can carry out independently in your study periods to enhance your understanding in A-Level Physics.

You may work through the activities in this book and mark this work yourself. Your work will then be reviewed by your teacher in KS5 file checks. This work is in addition to the class work and homework you carry out.

This book may also be used as a revision resource for intervention, internal assessments and external assessments.

Please keep this in your student file.

As part of this course you are expected to **read through this preparatory reading book** and **complete the independent study tasks**.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher.



SECTION 1

INDEPENDENT STUDY TASK

Instructions

Read through the information from the student preparatory book and then produce revision posters on the key points highlighted on the following pages.

These notes should be used as a revision resource for assessments.



INDEPENDENT STUDY TASK 1

Produce an **information sheet** on annihilation and pair production.

This is an independent study task to be carried out outside of lesson.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher



INDEPENDENT STUDY TASK 2

Produce an **information sheet** on particle classification.

This is an independent study task to be carried out outside of lesson.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher



INDEPENDENT STUDY TASK 3

Produce an **information sheet** on particle decay laws.

This is an independent study task to be carried out outside of lesson.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher



INDEPENDENT STUDY TASK 4

Produce an **information sheet** on the Quark Model.

This is an independent study task to be carried out outside of lesson.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher



SECTION 2

KNOWLEDGE CHECKER

Instructions

Read through the information from the student preparatory book and then answer the following questions from the different parts of the topics.

These questions are designed to introduce the different parts of this module.

Use the mark schemes to review your knowledge and understanding.



QUESTIONS

Use the preparatory reading notes to answer these questions.

A1. Describe the nuclear model of the atom.

[1 Mark]

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.....

A2. State the similarities and differences between the properties of two isotopes of the same element.

[1 Mark]

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A3. How do you calculate the specific charge of a particle?

[1 Mark]

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A4. The strong force binds the nucleus together. Explain why the force must be repulsive at very short distances.

[1 Mark]

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A5. The strong force binds the nucleus together. Explain why a nucleus containing two protons is unstable, but one containing two protons and two neutrons is stable.

[1 Mark]

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A6. What equation links the energy of a photon with the frequency of the photon.

[1 Mark]

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Use the preparatory reading notes to answer these questions.



A7. Write down an equation for the reaction between a positron and an electron.
State the name for this type of reaction.

[1 Mark]

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A8. Explain what causes extra particles to be created when two particles collide.

[1 Mark]

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A9. List the four fundamental forces in nature.

[1 Mark]

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A10. Explain what a virtual particle is.

[1 Mark]

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A11. What is a quark?

[1 Mark]

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A12. By how much can the strangeness change in the weak interaction?

[1 Mark]

.....

.....

Use the preparatory reading notes to answer these questions.



A13. Describe how a neutron is made up from quarks.

[1 Mark]

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A14. List the six quantities that are conserved in strong particle interactions.

[1 Mark]

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Use the preparatory reading notes to answer these questions.



ADVANCED SECTION

A15. A photon produces an electron-positron pair, each with 9.48×10^{-14} J of energy. Calculate the frequency of the photon.

[1 Mark]

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A16. Describe how the force of electromagnetic repulsion between two protons is explained by particle exchange.

[1 Mark]

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Use the preparatory reading notes to answer these questions.

A17. Write down the quark composition of the π^- particle.

[1 Mark]

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.....

A18. Explain how the quark composition is changed in the beta minus decay of the neutron.

[1 Mark]

.....
.....



ANSWERS

A1. Describe the nuclear model of the atom.

[1 Mark]

Inside every atom there is a nucleus which contains protons and neutrons. Orbiting this core are electrons.

A2. State the similarities and differences between the properties of two isotopes of the same element.

[1 Mark]

Same chemical properties.
Different stabilities and physical properties.

A3. How do you calculate the specific charge of a particle?

[1 Mark]

Specific Charge = Overall Charge / Mass

A4. The strong force binds the nucleus together. Explain why the force must be repulsive at very short distances.

[1 Mark]

The strong nuclear force must be repulsive at very small nucleon separations to prevent the nucleus being crushed to a point.

A5. The strong force binds the nucleus together. Explain why a nucleus containing two protons is unstable, but one containing two protons and two neutrons is stable.

[1 Mark]

The protons repel each other with an electrostatic force and attract each other with the nuclear strong force. The strong force is not large enough to overcome this repulsion. When two neutrons are added to the nucleus, they attract each other and the protons via the strong force. The strong force is now able to balance out the force of repulsion between the protons.

A6. What equation links the energy of a photon with the frequency of the photon.

[1 Mark]

Energy = Planck's Constant x Frequency

A7. Write down an equation for the reaction between a positron and an electron. State the name for this type of reaction.

[1 Mark]

$e^+ + e^- = \gamma + \gamma$
This is called annihilation.

A8. Explain what causes extra particles to be created when two particles collide.

[1 Mark]

Energy and mass are equivalent. When two particles collide, there is a lot of energy at the point of impact. This energy is converted into mass.



A9. List the four fundamental forces in nature.

[1 Mark]

Strong Nuclear
Weak
Electromagnetic
Gravitational

A10. Explain what a virtual particle is.

[1 Mark]

A virtual particle is a particle which only exists for a short period of time to exchange a force interaction between particles.

A11. What is a quark?

[1 Mark]

A quark is a fundamental particle. Hadrons are comprised of quarks.

A12. By how much can the strangeness change in the weak interaction?

[1 Mark]

Strangeness can change by ± 1 in the weak interaction.

A13. Describe how a neutron is made up from quarks.

[1 Mark]

Up, Up, Down

A14. List the six quantities that are conserved in strong particle interactions.

[1 Mark]

Baryon Number
Lepton Number
Charge
Mass/Energy
Strangeness
Momentum

**ADVANCED SECTION**

A15. A photon produces an electron-positron pair, each with 9.48×10^{-14} J of energy. Calculate the frequency of the photon.

[1 Mark]

$$\text{Total Energy} = 2 \times 9.48 \times 10^{-14} = 1.968 \times 10^{-13}\text{J}$$

$$f = E/h$$

$$f = 1.968 \times 10^{-13} / 6.63 \times 10^{-34} = 2.968 \times 10^{20}$$

$$f = 2.97 \times 10^{20}\text{Hz}$$

A16. Describe how the force of electromagnetic repulsion between two protons is explained by particle exchange.

[1 Mark]

The electrostatic force is due to the exchange of virtual photons that only exist for a very short time. The force is due to the momentum transferred to or gained from the photons as they are emitted or absorbed by a proton.

A17. Write down the quark composition of the Π^- particle.

[1 Mark]

Down, anti-up

A18. Explain how the quark composition is changed in the beta minus decay of the neutron.

[1 Mark]

The weak interaction converts a down quark into an up quark plus an electron and electron-antineutrino.

The neutron becomes a proton.



SECTION 3

QUESTIONS

Instructions

Read through the information from the student preparatory book and then answer the following questions from the different parts of the topics.

Use the mark schemes to review your knowledge and understanding.



TOPIC: 3.2.1.1 Constituents of the Atom

SPEC CHECK

Specification	Completed?
Simple model of the atom, including the proton, neutron and electron. Charge and mass of the proton, neutron and electron in SI units and relative units.	
Specific charge of the proton and the electron, and of nuclei and ions.	
Proton number Z , nucleon number A , nuclide notation.	
Meaning of isotopes and the use of isotopic data.	

QUESTIONS

Q1.1 Define a nucleon.

[1 Mark]

.....

.....

Q1.2 What is the difference between two isotopes of the same element?

[1 Mark]

.....

.....

Which of the particles in Table 1 has:

Q1.3 zero specific charge

[1 Mark]

.....

.....

Q1.4 the largest specific charge?

[1 Mark]

.....

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Q2.1 Explain why the specific charge of an electron is approximately 2000 times that of a hydrogen nucleus.

[4 Marks]

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Q2.2 Which of the two isotopes of uranium, ${}_{92}^{235}\text{U}$ or ${}_{92}^{238}\text{U}$, has the largest specific charge? Explain your answer.

[3 Marks]

.....

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.....

Q3 Show that the specific charge of a nucleus of the isotope ${}_{92}^{238}\text{U}$ is approximately 0.4 times the specific charge of a proton.

[3 Marks]

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Q4. The mass of a copper nucleus is 1.05×10^{-25} kg and its specific charge is 4.41×10^7 C kg⁻¹. Calculate its number of:

Q4.1 Protons

[2 Marks]

.....

.....

.....

.....

Q4.2 nucleons

[1 Mark]

.....

.....



Q4.3 neutrons.

[1 Mark]

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.....

Q4.4 The nucleus of a different isotope of copper has a specific charge of $4.27 \times 10^7 \text{ C kg}^{-1}$. Calculate how many more neutrons are in this nucleus than in the nucleus in **a**.

[4 Marks]

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Q5. An ion of the magnesium isotope ${}_{12}^{23}\text{Mg}$ has a charge of $+2e$.

Q5.1 Calculate the specific charge of this ion.

[2 Marks]

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.....

Q5.2 Show that the specific charge of the nucleus of this ion is 6 times the specific charge of the ion.

[1 Mark]

.....
.....



ANSWERS

Q1.1 A nucleon is a neutron or a proton in a nucleus. (1 mark)

Q1.2 Isotopes of the same element have different numbers of neutrons (and the same number of protons). (1 mark)

Q1.3 Neutron (1 mark)

Q1.4 Electron (1 mark)

Q2.1 Specific charge is charge divided by mass (1 mark).

The magnitude of the charge of an electron and a hydrogen nucleus is the same (1 mark).

The nucleus of a hydrogen atom is a proton, and an electron has a mass which is about 0.0005 times that of a proton (1 mark).

So, the specific charge of an electron is $1 / 0.0005$ or 2000 times that of a hydrogen nucleus (1 mark).

Q2.2 A nucleus of U-235 has the same charge as a nucleus of U-238 as they have the same number of protons (92) (1 mark).

The U-235 nucleus has a smaller mass than the U-238 nucleus as it has fewer neutrons and the same number of protons (1 mark).

The specific charge of a nucleus is its charge divided by its mass. Since the U-235 nucleus has the same charge and less mass than the U-238 nucleus, the specific charge of the U-235 nucleus is less than that of the U-238 nucleus (1 mark).

Q3. The specific charge of a proton = e / m_N , where m_N is the mass of a nucleon (i.e. a proton or neutron) and e is its charge (1 mark).

The charge of a ${}_{92}^{238}\text{U}$ nucleus is $92e$ and its mass is $238m_N$ (1 mark).

Therefore, its specific charge is $92e / 238m_N = (92 / 238) \times (e / m_N) = 0.39 \times (e / m_N)$, which is approximately equal to 0.4 times the specific charge of the proton (1 mark).

Q4.1 The charge of the nucleus = its specific charge \times its mass
 $= (4.41 \times 10^7) \times (1.05 \times 10^{-25}) = 4.63 \times 10^{-18} \text{ C}$ (1 mark)

Therefore, the number of protons in the nucleus = $4.63 \times 10^{-18} / 1.6 \times 10^{-19} = 29$ (1 mark)

Q4.2 The number of nucleons in the nucleus = its mass / the mass of a nucleon
 $= 1.05 \times 10^{-25} / 1.67 \times 10^{-27} = 63$ (1 mark)

Q4.3 The number of neutrons = number of nucleons – number of protons
 $= 63 - 29 = 34$ (1 mark)

Q4.4 The charge of the nucleus is also $4.63 \times 10^{-18} \text{ C}$ as it has the same number of protons. (1 mark)

The mass of the nucleus = its charge / its specific charge
 $= 4.63 \times 10^{-18} / 4.27 \times 10^7 = 1.08 \times 10^{-25} \text{ kg}$ (1 mark)



The number of neutrons in the nucleus = its mass / the mass of a nucleon

$$= 1.08 \times 10^{-25} / 1.67 \times 10^{-27} = 65$$

(1 mark)

Therefore, the nucleus of the isotope in **b** has 31 more neutrons than the nucleus of the isotope in **a**.

(1 mark)

Q5.1 The charge of the ion is $2e$ and its mass is $23m_N$ where m_N is the mass of a nucleon.

(1 mark)

Therefore, the specific charge of the ion = $2e / 23m_N$

$$= (2 \times 1.60 \times 10^{-19}) / (23 \times 1.67 \times 10^{-27}) = 8.33 \times 10^6 \text{ C kg}^{-1}$$

(1 mark)

Q5.2 The specific charge of the nucleus = $12e / 23m_N$ which is 6 times the specific charge of the ion.

(1 mark)



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P	Praise. What were the positive aspects of the work? What did they do well? What skills did they demonstrate?				
I	Improvements. What were the literacy issues in the piece of work?		<i>Write in ink.</i>	<i>Draw in Pencil.</i>	<i>Use a ruler.</i>
	Always use capital letters at the beginning of a sentence.		Learn the spellings identified in your work.		
	Always use capital letters for proper nouns.		Ensure sentences make sense.		
	Make sure you write on the line and not above or below it.		Use correct punctuation.		
	Use scientific vocabulary appropriate to the task.		Vary your sentences to demonstrate your understanding.		
D answer		B answer		A* answer	
The atom is described as a central nucleus containing positive protons and neutral neutrons with negative electrons orbiting. The number of electrons is the same as the number of protons...		...this gives the atom an overall charge of zero/the atoms is hence uncharged... The actual masses or charges are given.		...the nucleus accounts for less than 1% of the entire atom/the nucleus is tiny compared to the atom (owtte). The actual masses and charges are given.	
The notation is described as X being the chemical symbol, Z is the number of protons and A is the number of protons and neutrons...		...in the nucleus. Z is also the number of electrons that orbit the nucleus. The number of neutrons is calculated by $A - Z$A is named as the 'nucleon number'. Examples are given.	
An isotope is described as a different version of the same element. It contains a different number of neutrons but the same number of protons...		...A (the nucleon number) is calculated from the different isotopes that exist for each element...		...and their abundances (owtte). Examples are given.	
An ion is described as an atom with an overall charge due to gaining or losing electrons...		...an atom gaining electrons has an overall negative charge...		...an atom losing electrons has an overall positive charge.	
A photon is described as a 'packet' or 'chunk' of energy given by the equation $E=hf$h is named as the Planck constant and f as the frequency...		...the word 'discrete' is used in the definition.	
Photons are released from annihilation...		...where a particle and its antiparticle touch and * convert in to energy...		* mass is converted into energy. There is a reference to the conservation of mass-energy.	
N	Next Steps. How can they move their work onto the next grade? What didn't they include?			Grade	Effort



TOPIC: 3.2.1.2 Stable and Unstable Nuclei

SPEC CHECK

Specification	Completed?
The strong nuclear force; its role in keeping the nucleus stable; short-range attraction up to approximately 3 fm, very-short range repulsion closer than approximately 0.5 fm.	
Unstable nuclei; alpha and beta decay.	
Equations for alpha decay, β^- decay including the need for the neutrino.	
The existence of the neutrino was hypothesised to account for conservation of energy in beta decay.	
Demonstration of the range of alpha particles using a cloud chamber, spark counter or Geiger counter.	
Use of prefixes for small and large distance measurements.	



TOPIC: 3.2.1.3 Particles, Antiparticles and Photons

SPEC CHECK

Specification	Completed?
For every type of particle, there is a corresponding antiparticle.	
Comparison of particle and antiparticle masses, charge and rest energy in MeV.	
Know that the positron, antiproton, antineutron and antineutrino are the antiparticles of the electron, proton, neutron and neutrino respectively.	
Photon model of electromagnetic radiation, the Planck constant. $E = hf = hc/\lambda$	
Knowledge of annihilation and pair production and the energies involved.	
Detection of gamma radiation	
Determine the frequency and wavelength of the two gamma photons produced when a 'slow' electron and a 'slow' positron annihilate each other.	



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P	Praise. What were the positive aspects of the work? What did they do well? What skills did they demonstrate?				
I	Improvements. What were the literacy issues in the piece of work?		<i>Write in ink.</i>	<i>Draw in Pencil.</i>	<i>Use a ruler.</i>
	Always use capital letters at the beginning of a sentence.		Learn the spellings identified in your work.		
	Always use capital letters for proper nouns.		Ensure sentences make sense.		
	Make sure you write on the line and not above or below it.		Use correct punctuation.		
	Use scientific vocabulary appropriate to the task.		Vary your sentences to demonstrate your understanding.		
D answer		B answer		A* answer	
All particles experience the force of gravity and the e.m. interaction if they are charged...		...hadrons (or baryons and mesons) and leptons may experience the weak interaction...		...but only hadrons (or quarks) experience the strong interaction.	
The exchange particles are named as (virtual) photon, (graviton), W^+ and/or W^- bosons and pions and/or gluons.		The exchange particles are correctly named and matched to the correct force...		...the strong interaction is explained in more detail as gluons exchanged between quarks and pions between hadrons.	
...There is some indication of the order of their strengths (S, EM, W, G)...		...there is some indication of the order of their ranges (W, S, G and EM)...		...with values of $\sim 10^{-18}$, $\sim 10^{-15}$ and infinity (∞) or detailed description eg, within a quark, within a nucleus and no limit to the range.	
The relationship is described as the heavier the exchange particle the shorter the range (of the force) (accept the converse)...		...the mass of a large particle requires large amounts of energy to be borrowed (to create it)...		...meaning it only exists for a short time and hence has a short range.	
Feynman diagrams are explained as showing the particles before and after an interaction.		The lines from the bottom represent the particles before and the lines above (the wiggle) represent the particles after the interaction...		...the 'wiggly' line represents the exchange of a particle (owtte).	
The diagram has straight lines and arrows. One of the decay products is labelled as β^- or e^-the decaying particle is labelled as n and becomes p, the other decay product is labelled as $\bar{\nu}$the decaying particle is labelled as d and becomes u. The exchange particle is labelled as W^- .	
N	Next Steps. How can they move their work onto the next grade? What didn't they include?			Grade	Effort



TOPIC: 3.2.1.5 Classification of Particles

SPEC CHECK

Specification	Completed?
Hadrons are subject to the strong interaction.	
The two classes of hadrons: <ul style="list-style-type: none"> • baryons (proton, neutron) and antibaryons (antiproton and antineutron) • mesons (pion, kaon). 	
Baryon number as a quantum number.	
Conservation of baryon number.	
The proton is the only stable baryon into which other baryons eventually decay.	
The pion as the exchange particle of the strong nuclear force.	
The kaon as a particle that can decay into pions.	
Leptons: electron, muon, neutrino (electron and muon types only) and their antiparticles.	
Lepton number as a quantum number; conservation of lepton number for muon leptons and for electron leptons.	
The muon as a particle that decays into an electron.	
Strange particles as particles that are produced through the strong interaction and decay through the weak interaction (e.g. kaons).	
Strangeness (symbol s) as a quantum number to reflect the fact that strange particles are always created in pairs.	
Conservation of strangeness in strong interactions.	
Strangeness can change by 0, +1 or -1 in weak interactions.	
Appreciation that particle physics relies on the collaborative efforts of large teams of scientists and engineers to validate new knowledge.	
Cosmic ray showers as a source of high energy particles including pions and kaons; observation of stray tracks in a cloud chamber; use of two Geiger counters to detect a cosmic ray shower.	



PRACTICAL SKILLS

Complete the following practical skills-based task to improve your experimental understanding of this part of the course in preparation for **Physics Paper 3**.

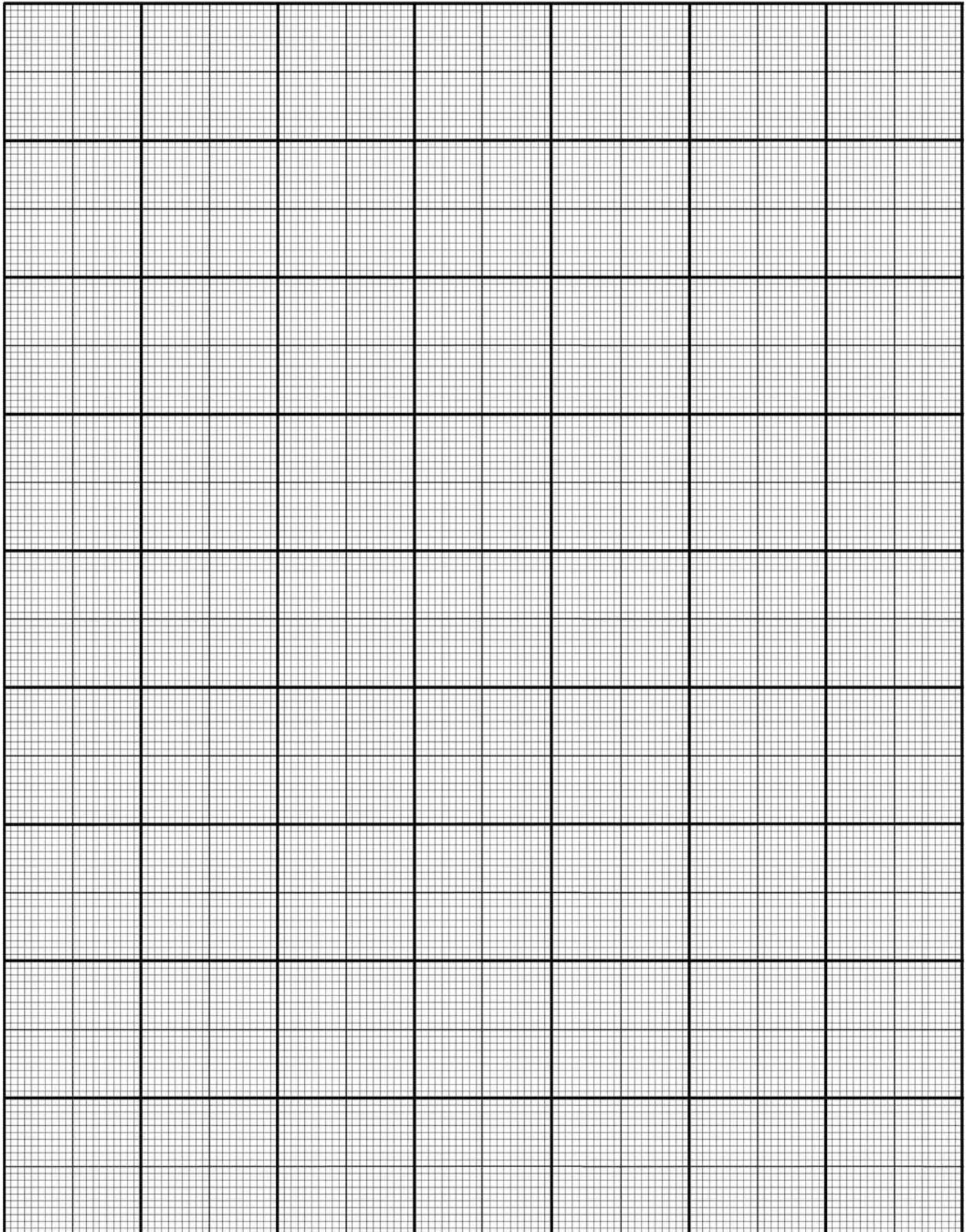
You are going to use data on the fundamental particles to find the theoretical masses of some Hadrons.

Experimental Data

Particle	Mass (MeV)			Mean Mass (MeV)	Uncertainty in Mass	Percentage Uncertainty in Mean
u	4.6	5.1	5.3			
d	7	9	8			
s	172	153	155			
c	1617	1442	1441			
b	4126	4432	4192			
t	195000	174000	171000			
e	0.58	0.45	0.50			
μ	104.9	105.4	106.8			
τ	1823	1854	1654			

Analysis

- A1.** Calculate the mean masses for each of the particles.
- A2.** Calculate the uncertainty in the mass reading for each particle. (This is equal to half the range of the values).
- A3.** What is this as a percentage of the mean? (Divide the uncertainty by the mean value then multiply by 100).
- A4.** Which has the lowest percentage uncertainty in the mean value?
- A5.** How can we describe this value?
- A6.** What is the quark composition of a proton?
- A7.** Use the mean values to calculate the theoretical mass of a proton.
- A8.** What is the percentage uncertainty in this value? (You should add the percentage uncertainties of the quarks used).
- A9.** The actual rest mass of a proton is 938.3 MeV. What is the difference between this and your theoretical value?
- A10.** What is the quark composition of a neutron?
- A11.** Use the mean values to calculate the theoretical mass of a neutron.
- A12.** What is the percentage uncertainty in this value?
- A13.** The actual rest mass of a neutron is 939.6 MeV. What is the difference between this and your theoretical value?
- A14.** What is the quark composition of a neutral pion?
- A15.** Use the mean values to calculate the theoretical mass of a neutral pion.
- A16.** What is the percentage uncertainty in this value?
- A17.** The actual rest mass of a π^0 is 135.0 MeV. What is the difference between this and your theoretical value?





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P	Praise. What were the positive aspects of the work? What did they do well? What skills did they demonstrate?				
I	Improvements. What were the literacy issues in the piece of work?	<i>Write in ink.</i>		<i>Draw in Pencil.</i>	<i>Use a ruler.</i>
	Always use capital letters at the beginning of a sentence.	Learn the spellings identified in your work.			
	Always use capital letters for proper nouns.	Ensure sentences make sense.			
	Make sure you write on the line and not above or below it.	Use correct punctuation.			
	Use scientific vocabulary appropriate to the task.	Vary your sentences to demonstrate your understanding.			
D answer		B answer		A* answer	
An example of a lepton is given, typically electron or muon.		Two or three examples of leptons are given, typically electrons, muons and tauon.		All six leptons are named as electron, muon, tauon and corresponding neutrinos.	
An example of a hadron is given, typically proton or neutron.		At least three examples of hadrons are given, typically proton, neutron and a pion or kaon.		Protons, neutrons, at least one pion and one kaon are given as examples of hadrons.	
Hadrons are made from smaller particles and leptons are not.		Hadrons are made from quarks but leptons are not.		Hadrons are made from quarks but leptons are fundamental (owtte).	
Hadrons and leptons both experience gravity...		...and have (rest) masses...		...both are involved in decay processes.	
The different quarks are named as up (u), down (d) and strange (s)...		...the quark combinations of protons and neutrons are given...		...the quark combinations of at least one pion and one kaon are given.	
Hadrons can be sub-divided into baryons and mesons...		...baryons are made from three quarks and mesons are made from two quarks...		...mesons are made from a quark and an anti-quark.	
Antiparticles are described as having the opposite charge and lepton/baryon number to their corresponding particles...		...an anti-baryon is described as being made from three anti-quarks...		...an anti-meson is described as being made from the opposite quark and anti-quark combination.	
Hadrons and leptons both experience the electromagnetic interaction if they are charged...		...both are affected by the weak interaction...		...only hadrons experience the strong (nuclear) interaction.	
N	Next Steps. How can they move their work onto the next grade? What didn't they include?			Grade	Effort



TOPIC: 3.2.1.6 Quarks and Antiquarks

SPEC CHECK

Specification	Completed?
Properties of quarks and antiquarks: charge, baryon number and strangeness.	
Combinations of quarks and antiquarks required for baryons (proton and neutron only), antibaryons (antiproton and antineutron only) and mesons (pion and kaon only).	
Only knowledge of up (u), down (d) and strange (s) quarks and their antiquarks will be tested.	
The decay of the neutron should be known.	

SUPPORT

Scientists used to think that an atom was the smallest thing that existed. Then Rutherford discovered the **nucleus**, and later in the early 20th century scientists discovered the **proton**, **neutron**, and **electron**. Many more particles have been discovered since, during experiments at CERN in Geneva and at other places around the world. Most recently, the proton, neutron, and various other particles were found to contain **quarks** inside them.

The easiest way to remember the classification of particles is to construct a basic particle 'family tree', as shown in Figure 1.

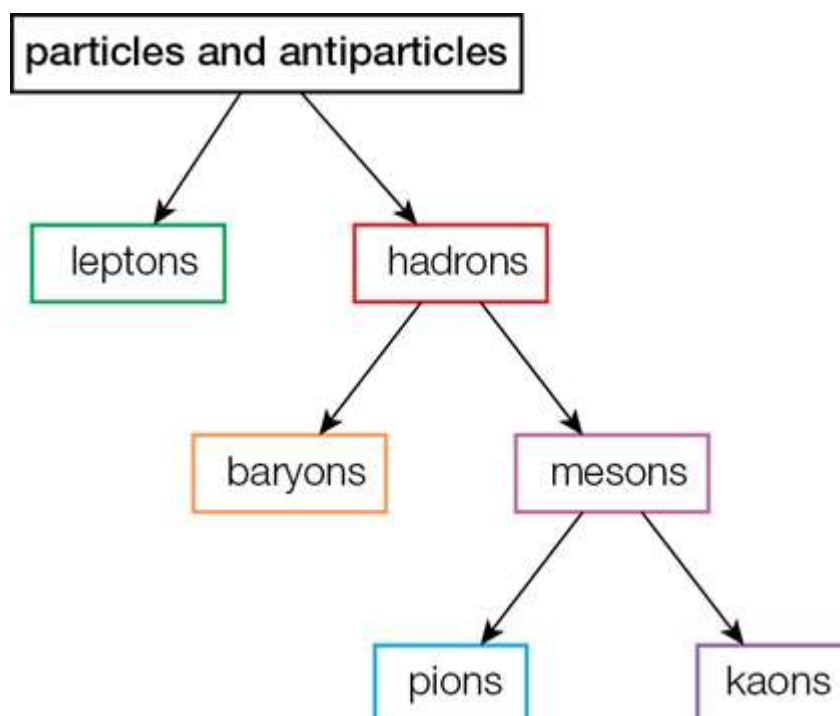


Figure 1 *The particle family tree*

The two main families are the **leptons** and the **hadrons**. Each family contains both **particles** and **antiparticles**.



Leptons

Leptons are **fundamental**; they have no internal structure.

All leptons have a lepton number = ± 1 .

All leptons have baryon number = 0 (as they are **not** baryons).

All leptons have strangeness = 0 (as they do **not** contain strange quarks).

Neutrinos have no charge.

You will need to know the names of the leptons and their symbols, as shown in Figure 2.

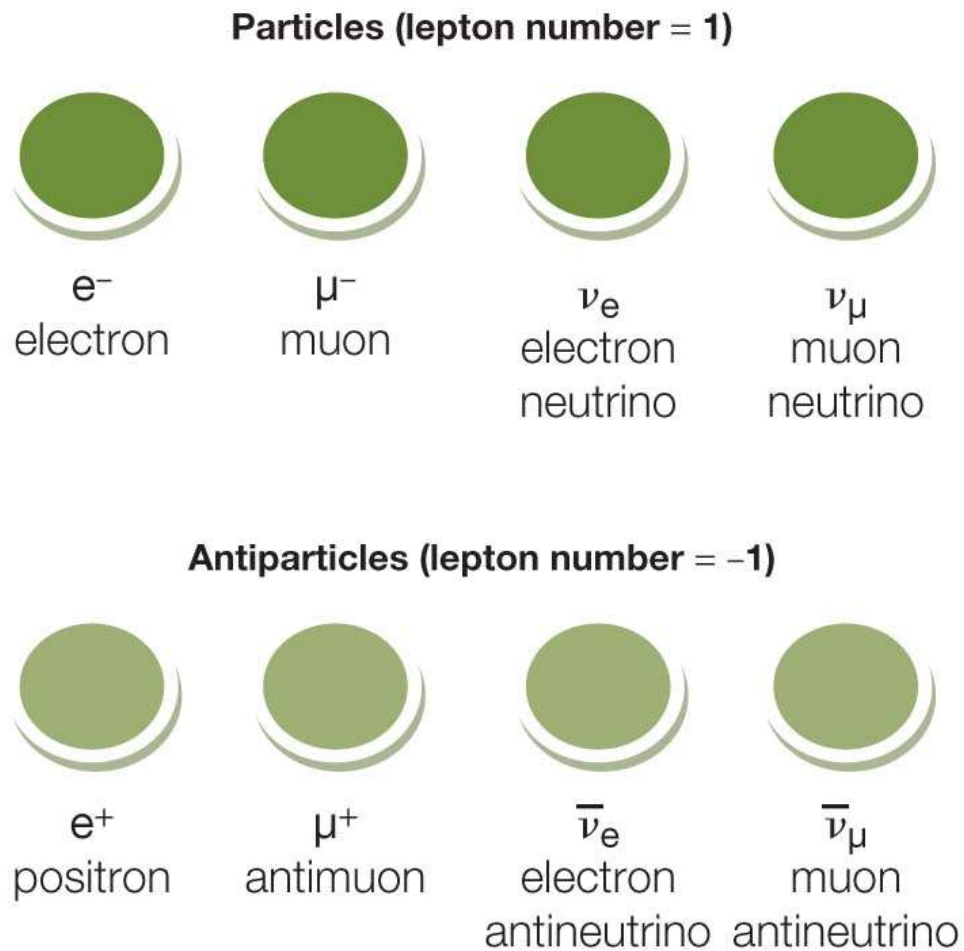


Figure 2 *Leptons and antileptons*



Hadrons

Hadrons are not fundamental as they all contain quarks.

Hadrons consist of two families: **baryons** and **mesons** (see Figure 1).

To show the quark composition of the baryons and mesons you might find it useful to choose a colour to represent each quark.

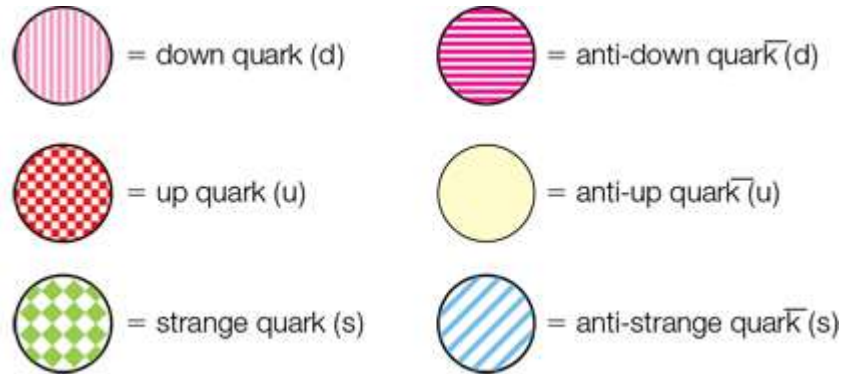


Figure 3 Colour coding the quarks and antiquarks



Baryons

Baryons contain three quarks, and antibaryons contain three antiquarks.

All baryons have baryon number = ± 1 .

All baryons have lepton number = 0 (as they are not leptons).

All baryons have strangeness = 0 (as they do not contain strange quarks).

You will need to know the names of the baryons, their symbols, and their quark composition, as shown in Figure 4.

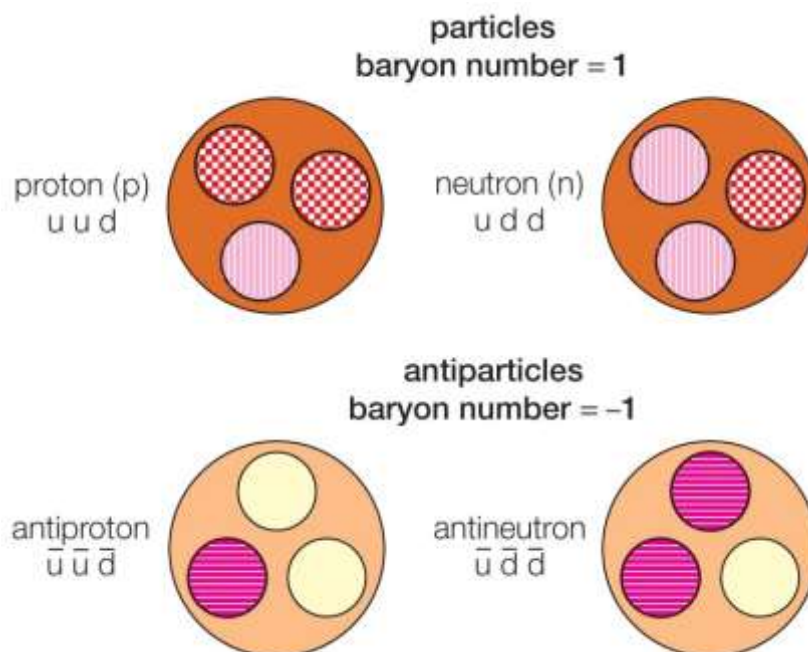


Figure 4 *Quark compositions of the baryons*

Mesons

Mesons contain one quark **and** one antiquark.

All mesons have baryon number = 0 (as they are not baryons).

All mesons have lepton number = 0 (as they are not leptons).

Mesons decay into photons and leptons.

Mesons consist of two more families: **pions** and **kaons**.

You will need to know the names of the mesons, their symbols, and their quark composition – see the information on pions and kaons below.



Pions

Pions contain a quark–antiquark pair; see Figure 5 for the possible quark combinations.

All pions have strangeness = 0.

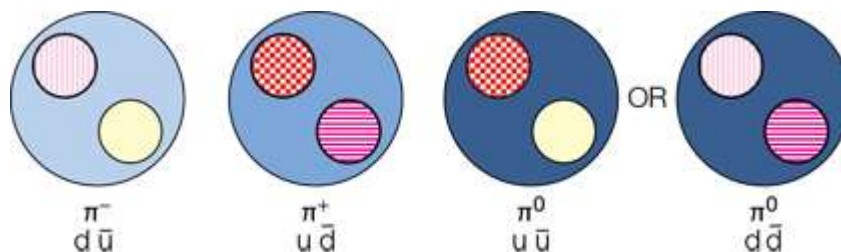


Figure 5 Quark combinations of the pions

Note that the π^0 meson can be any combination of a quark and corresponding antiquark. You may wish to add the information to your family tree.

Kaons

Kaons contain a strange quark or antiquark **and** either an up or down quark or antiquark, in a quark–antiquark pair.

All kaons have strangeness = ± 1 as they contain strange quarks.

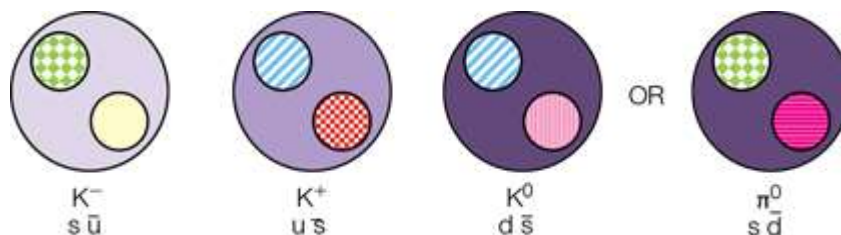


Figure 6 Quark combinations of the kaons

Task

Construct the basic particle family tree including all the particles and other essential facts.

- Make each particle out of a circle of different coloured paper and label the particle with its symbol. (If no coloured paper is available then you could colour in white paper, or use different coloured sticky labels.)
- Stick quarks (smaller circles of coloured paper) on to the hadrons correctly, using one colour for all the up quarks, one for the down quarks, and one for the strange quarks. It would be useful to also label each quark with d, u, and s.
- Group the particles together in families with family titles.
- Make labels for each family, summarising the information given at the beginning of each section about the lepton number, baryon number, and strangeness.
- Add further labels with any facts you discover as you work through the topic.

You should make the particles suitable for a size A3 poster, which you can use to help answer practice questions and can then put up in your bedroom.

By seeing your poster every day, it should help you remember the details of the particle family tree, including the quark composition of all the hadrons.



QUESTIONS

Use your particle family tree to help you answer these questions, and to become familiar with the particle symbols and the quark compositions of the particles.

Q1.1 Identify the hadrons, leptons, baryons, and mesons amongst these particles.

[4 Marks]

p \bar{n} ν_e e^+ μ^- π^0 K^+

.....
.....
.....
.....

Q1.2 State which of the above particles are antiparticles
charged particles.

[2 Marks]

.....
.....
.....
.....

Q2. Quarks may be combined in several ways within the hadron family.

Q2.1 Name the two branches of the hadron family **and** their possible general quark composition, using q for a quark and \bar{q} for an antiquark.

[2 Marks]

.....
.....

Q2.2 State how hadrons differ from all other subatomic particles.

[1 Mark]

.....
.....



Q2.3 Give the quark composition of the following particles:

- neutron
- proton
- π^+
- K^-

[2 Marks]

.....

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Q3.1 Use your family-tree poster to identify which of the following statements about neutrons and antineutrons are **true** and which are **false**.

- An antineutron has a charge of $1.60 \times 10^{-19}C$.
- A neutron is a fundamental particle.
- An antineutron is an unstable particle.
- An antineutron has a rest mass of $1.67 \times 10^{-27}kg$.
- An antineutron is not a fundamental particle.
- A neutron is a stable particle.
- A neutron has a rest mass of $1.67 \times 10^{-27}kg$.
- A neutron has no charge.

[8 Marks]

Q3.2 Which is the only stable baryon?

Add this information as a label to your family tree.

[1 Mark]

.....

.....



Q4. An antimuon may decay in the following way: $\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$.

Q4.1 Exchange each particle for its corresponding antiparticle and each antiparticle for its corresponding particle and complete the equation to show how a muon may decay.

$$\mu^- \rightarrow$$

[1 Mark]

.....

.....

Q4.2 Find one difference and one similarity between a muon and an electron.

Add this information as a label to your family tree.

[2 Marks]

.....

.....



ANSWERS

- Q1.1** Hadrons: proton, antineutron, neutral pion, K^0 (1 mark)
 Leptons: positron, electron neutrino, muon (1 mark)
 Baryons: proton, antineutron (1 mark)
 Mesons: neutral pion, K^0 (1 mark)

Q1.2 positron, antineutron (e^+ , \bar{n}) (1 mark)

Q1.3 proton (p), positron (e^+), muon (μ^-), K^0 (1 mark)

Q2.1 Baryons qqq (**allow** 'three quarks') **or** antibaryons $\bar{q}\bar{q}\bar{q}$ (**allow** '3 antiquarks') (1 mark)

Mesons $q\bar{q}$ (**allow** 'quark-antiquark pair') (1 mark)

Q2.2 Contain quarks **or** feel the strong force. (1 mark)

Q2.3 Neutron udd

Proton uud

π^+ $u\bar{d}$

K^- $\bar{u}s$

Q3.1 Award 1 mark for each correct statement.

- | | |
|---|-------|
| An antineutron has a charge of $1.60 \times 10^{-19}C$. | False |
| A neutron is a fundamental particle. | False |
| An antineutron is an unstable particle. | True |
| An antineutron has a rest mass of $1.67 \times 10^{-27} \text{ kg}$. | True |
| An antineutron is not a fundamental particle. | True |
| A neutron is a stable particle. | False |
| A neutron has a rest mass of $1.67 \times 10^{-27} \text{ kg}$. | True |
| A neutron has no charge. | True |

Q3.2 Proton (1 mark)

Q4.1 $\mu^- \rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu$ (1 mark)

Q4.2 Difference: muons are heavier than electrons. (1 mark)

Similarity: both are negatively charged. (1 mark)



TOPIC: 3.2.1.7 Applications of Conservation Laws

SPEC CHECK

Specification	Completed?
Change of quark character in β^- and in β^+ decay.	
Application of the conservation laws for charge, baryon number, lepton number and strangeness to particle interactions.	
Students should recognise that energy and momentum are conserved in interactions.	



SUPPORT INFORMATION

In order to decide whether a reaction can take place we have to look at the conservation of:

- charge (Q)
- baryon number (B)
- lepton number (L)
- strangeness (S).

Consider the reaction equation and calculate the totals of each on the left-hand side (LHS) and right-hand side (RHS) of the equation.

If they are all conserved, the totals of the LHS and RHS are equal and the reaction can take place.

Strangeness is allowed to vary by ± 1 if the weak interaction is taking place.

Remember that to find the values for charge, baryon number, lepton number, and strangeness you can consult your family tree and its labels.

- Charge of all particles is shown by sign = **or** – **or** 0.
- Only baryons have a baryon number = ± 1 ; other particles have baryon number = 0.
- Only leptons have a lepton number = ± 1 ; other particles have lepton number = 0.
- Only kaons have strangeness; all other particles have strangeness = 0.

Worked example

The decay shown in the equation $p \rightarrow \bar{n} + e^- + \bar{\nu}_e$ cannot occur because it violates two conservation laws.

State the two conservation laws that are violated.

Step 1

Identify Q, B, L, and S for each particle and put it into the equation.

$$Q \quad 1 \rightarrow 0 + 1 + 0$$

$$B \quad 1 \rightarrow -1 + 0 + 0$$

$$L \quad 0 \rightarrow 0 - 1 - 1$$

$$S \quad 0 \rightarrow 0 + 0 + 0$$

Step 2

Decide which equations balance (LHS = RHS) and which equations don't balance (LHS \neq RHS).

$$Q \quad 1 \rightarrow 0 + 1 + 0 \quad \text{yes}$$

$$B \quad 1 \rightarrow -1 + 0 + 0 \quad \text{no}$$

$$L \quad 0 \rightarrow 0 - 1 - 1 \quad \text{no}$$

$$S \quad 0 \rightarrow 0 + 0 + 0 \quad \text{yes}$$

Step 3

B and L don't balance so baryon and lepton number conservation laws are violated.

This is the reason why this decay is not observed in nature.



EXTENSION ACTIVITY QUESTIONS

Feynman diagrams

Feynman diagrams were developed to describe the interactions of charged particles in quantum physics, and they have found a wide use in describing a variety of particle interactions.

They are a type of space–time diagram; the time axis points upwards and the space axis points to the right, as shown in Figure 1. (Particle physicists often reverse this orientation.) Particles are shown as lines with arrows that denote the direction of their travel in time. (Particle physicists show antiparticles moving in the opposite direction.) Note that the lines do not show the actual trajectory of particles in space.

Virtual, or exchange, particles such as the photon or the W boson (W^- or W^+) are shown as wavy lines. W bosons are heavier than a neutron and give rise to the weak force. Since they exist for a very short time they do not violate the law of conservation of energy.

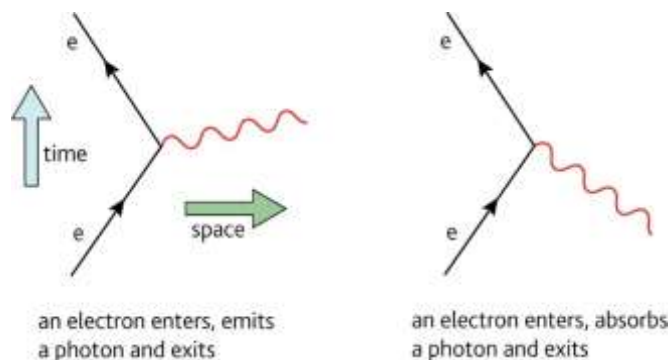


Figure 1

Particle	Symbol	Rest energy / MeV
photon	γ	0
neutrino	ν	0
antineutrino	$\bar{\nu}$	0
neutron	n	939.551
proton	p	938.257
electron	e or β^-	0.511
positron	e^+ or β^+	0.511

Questions

Q1. The Feynman diagram for beta decay is shown in Figure 2.

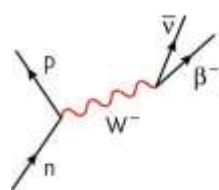


Figure 2

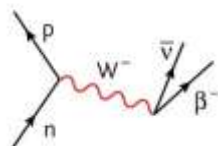


Figure 3

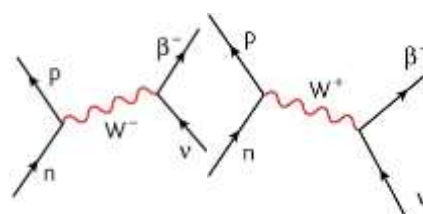


Figure 4

Figure 5



Q1.1 Describe what is happening in **Figure 2**.

[2 Marks]

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Q1.2 State what is wrong with the representation of beta decay as shown in **Figure 3** and explain how it should have been drawn.

[2 Marks]

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Q1.3 State the differences and similarities between **Figure 2** and **Figure 4**?

[2 Marks]

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Q1.4 State the differences and similarities between **Figure 4** and **Figure 5**?

[2 Marks]

.....

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.....



Q2. Draw the Feynman diagram for

Q2.1 pair production of an electron and a positron from a photon,

[1 Mark]

Q2.2 annihilation of an electron and a positron into two photons.

[1 Mark]

Q3. Look at the Feynman diagrams for β^- and β^+ decay in **Figure 6**. Describe, in your own words, the difference between these decays.

[2 Marks]

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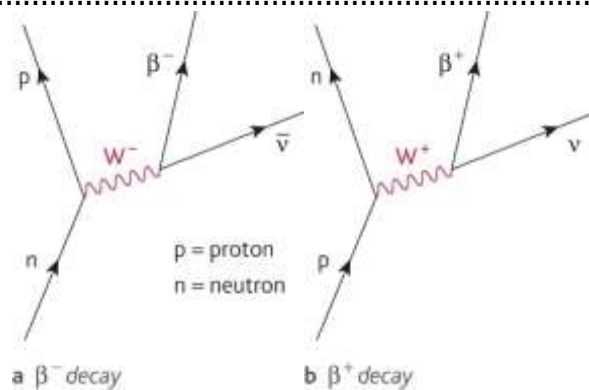


Figure 6



Q4. The rest energies of different particles are given in the data booklet and some of them are given in the article.

Q4.1 Calculate the energy in joules released in the decay $n \rightarrow p + \beta^- + \bar{\nu}$

[4 Marks]

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Q4.2 β^+ decay can be represented as $p \rightarrow n + \beta^+ + \nu$

Look at the rest energies of the particles involved and make a comment on when the decay will occur.

[4 Marks]

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Q4.3 The rest energy of a W boson is 80 GeV. Explain why the W^- boson in **Figure 2** can only exist for a short time.

[1 Mark]

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Q4.3 What are the important differences between a proton and a positron?

[3 Marks]

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Q4.4 Compare and comment on the amount of energy produced when an electron meets a positron in annihilation, and when an electron meets a proton in electron capture.

[2 Marks]

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ANSWERS

Q1.1 A neutron emits a W^- particle and changes to a proton. (1 mark)

The W^- particle, which is the exchange particle, decays into a β^- particle and an antineutrino. (1 mark)

Q1.2 The W^- particle is shown moving backwards in time. It is emitted from the vertex where n, p and W^- meet (1 mark) and should be shown moving forwards in time (that is, up the page) (1 mark).

Q1.3 Differences: in Figure 2 the W^- particle decays into the antineutrino and a beta particle.

In Figure 4 the W^- particle interacts with a neutrino. (1 mark)

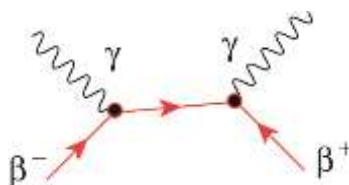
Similarities: both involve the change of a neutron to a proton and a beta particle is emitted. (1 mark)

Q1.4 Differences: in Figure 4 the neutron emits a W^- particle which is absorbed by the neutrino. In Figure 5 the neutrino emits a W^+ particle which is absorbed by the neutron. (1 mark)

Similarities: the same particles enter and exit; the exchange particle is the same mass and type. (1 mark)

Q2.1 The Feynman diagram should show one photon (wavy line) rising to emit an electron and a positron. (1 mark)

Q2.2. The Feynman diagram should show an electron and a positron (lines) rising vertically to meet and emit two photons (wavy lines). (1 mark)



It is also possible that three gamma ray photons are emitted or, if the electron or positron has high kinetic energy, then other particles can be produced such as W^+/W^- and even Z bosons.

Q3. In β^- decay a neutron decays to a proton, a β^- particle and an antineutrino by the weak force. The exchange particle is a W^- particle that exists for a very small time. (1 mark)

In β^+ decay a proton decays to a neutron, a β^+ particle and a neutrino.

The exchange particle is a W^+ particle. (1 mark)

Q4.1 Total energy before decay = rest energy of neutron (1 mark)

Total energy after decay = rest energy of proton + rest energy of electron + energy released

So, energy released = rest energy of neutron – rest energy of proton – rest energy of electron

$$= 939.551 - 938.257 - 0.511 \text{ (MeV)}$$

$$= 0.783 \text{ MeV} \quad (1 \text{ mark})$$

Since $0.783 \text{ MeV} = 783\,000 \text{ eV}$ and $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$, (1 mark)

energy released = $783\,000 \times 1.6 \times 10^{-19} \text{ J} = 1.25 \times 10^{-13} \text{ J}$ (1 mark)

Q4.2 The rest energy of the products (neutron, positron and neutrino) is larger than the proton (1 mark). The reaction does not happen spontaneously with a free proton (1 mark). In a nucleus, when the whole nucleus is considered, there is a decrease in rest mass and so some energy is produced in the reaction (1 mark). Otherwise energy must be given to the proton for the reaction to proceed (1 mark).

Q4.3 If W bosons existed for a long time then energy would not be conserved. (1 mark)



Q4.4 The proton is heavier than the positron.

(1 mark)

The proton is a particle whereas the positron is an antiparticle.

(1 mark)

The positron is a fundamental particle and is not made from any other particle. (The proton is a baryon and made from three quarks, whereas the positron is a lepton.)

(1 mark)

Q4.5 In annihilation, when a positron meets an electron all the rest mass is liberated in the energy of two photons (1 mark).

In electron capture, although the initial particles have greater rest energy, not all the mass is converted to energy as the resulting neutron has mass (1 mark), so there is much less energy available (1 mark).



REVISION CHECKLIST

Specification reference	Checklist questions	
3.2.1.1	Can you represent a simple model of the atom, including the proton, neutron, and electron?	<input type="checkbox"/>
3.2.1.1	Can you describe charge and mass of the proton, neutron, and electron in SI units and relative units?	<input type="checkbox"/>
3.2.1.1	Can you explain the specific charge of the proton and the electron, and of nuclei and ions?	<input type="checkbox"/>
3.2.1.1	Can you define and use 'proton number Z , nucleon number A ' nuclide notation?	<input type="checkbox"/>
3.2.1.1	Can you recognise and use the A_ZX notation?	<input type="checkbox"/>
3.2.1.1	Can you define isotopes and use isotopic data?	<input type="checkbox"/>
3.2.1.2	Can you explain the strong nuclear force and its role in keeping the nucleus stable?	<input type="checkbox"/>
3.2.1.2	Can you describe short-range attraction up to approximately 3 fm and very-short range repulsion closer than approximately 0.5 fm?	<input type="checkbox"/>
3.2.1.2	Can you describe unstable nuclei; alpha and beta decay?	<input type="checkbox"/>
3.2.1.2	Can you use equations for alpha decay and β^- decay, including the need for the neutrino?	<input type="checkbox"/>
3.2.1.2	Can you explain how the existence of the neutrino was hypothesised to account for conservation of energy in beta decay?	<input type="checkbox"/>
3.2.1.3	Can you explain that, for every type of particle, there is a corresponding antiparticle?	<input type="checkbox"/>
3.2.1.3	Can you compare particle and antiparticle mass, charge, and rest energy in MeV?	<input type="checkbox"/>



Specification reference	Checklist questions	
3.2.1.3	Can you explain that the positron, antiproton, antineutron, and antineutrino are the antiparticles of the electron, proton, neutron, and neutrino respectively?	<input type="checkbox"/>
3.2.1.3	Can you use the photon model of electromagnetic radiation and the Planck constant?	<input type="checkbox"/>
3.2.1.3	Can you explain annihilation and pair production, and the energies involved?	<input type="checkbox"/>
3.2.1.4	Can you explain the four fundamental interactions: gravity, electromagnetic, weak nuclear, and strong nuclear?	<input type="checkbox"/>
3.2.1.4	Can you describe the concept of exchange particles to explain forces between elementary particles?	<input type="checkbox"/>
3.2.1.4	Can you explain the electromagnetic force and virtual photons as the exchange particle?	<input type="checkbox"/>
3.2.1.4	Can you describe the weak interaction limited to β^- and β^+ decay, electron capture, and electron–proton collisions?	<input type="checkbox"/>
3.2.1.4	Can you describe W^+ and W^- as exchange particles?	<input type="checkbox"/>
3.2.1.4	Can you draw simple diagrams to represent reactions or interactions in terms of incoming and outgoing particles, and exchange particles?	<input type="checkbox"/>
3.2.1.5	Can you explain that hadrons are subject to the strong interaction?	<input type="checkbox"/>



Specification reference	Checklist questions	
3.2.1.6	Can you describe the properties of quarks and antiquarks in terms of charge, baryon number, and strangeness?	<input type="checkbox"/>
3.2.1.6	Can you explain the combinations of quarks and antiquarks required for baryons (proton and neutron only), antibaryons (antiproton and antineutron only), and mesons (pion and kaon only)?	<input type="checkbox"/>
3.2.1.6	Can you show the decay of the neutron?	<input type="checkbox"/>
3.2.1.7	Can you explain the change of quark character in β^- and β^+ decay?	<input type="checkbox"/>
3.2.1.7	Can you apply the conservation laws for charge, baryon number, lepton number and strangeness to particle interactions, given the necessary data?	<input type="checkbox"/>
3.2.1.7	Can you recognise that energy and momentum are conserved in interactions?	<input type="checkbox"/>



DATASHEET

DATA - FUNDAMENTAL CONSTANTS AND VALUES

Quantity	Symbol	Value	Units
speed of light in vacuo	c	3.00×10^8	m s^{-1}
permeability of free space	μ_0	$4\pi \times 10^{-7}$	H m^{-1}
permittivity of free space	ϵ_0	8.85×10^{-12}	F m^{-1}
magnitude of the charge of electron	e	1.60×10^{-19}	C
the Planck constant	h	6.63×10^{-34}	J s
gravitational constant	G	6.67×10^{-11}	$\text{N m}^2 \text{kg}^{-2}$
the Avogadro constant	N_A	6.02×10^{23}	mol^{-1}
molar gas constant	R	8.31	$\text{J K}^{-1} \text{mol}^{-1}$
the Boltzmann constant	k	1.38×10^{-23}	J K^{-1}
the Stefan constant	σ	5.67×10^{-8}	$\text{W m}^{-2} \text{K}^{-4}$
the Wien constant	α	2.90×10^{-3}	m K
electron rest mass (equivalent to 5.5×10^{-4} u)	m_e	9.11×10^{-31}	kg
electron charge/mass ratio	$\frac{e}{m_e}$	1.76×10^{11}	C kg^{-1}
proton rest mass (equivalent to 1.00728 u)	m_p	$1.67(3) \times 10^{-27}$	kg
proton charge/mass ratio	$\frac{e}{m_p}$	9.58×10^7	C kg^{-1}
neutron rest mass (equivalent to 1.00867 u)	m_n	$1.67(5) \times 10^{-27}$	kg
gravitational field strength	g	9.81	N kg^{-1}
acceleration due to gravity	g	9.81	m s^{-2}
atomic mass unit (1u is equivalent to 931.5 MeV)	u	1.661×10^{-27}	kg

ALGEBRAIC EQUATION

quadratic equation $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

ASTRONOMICAL DATA

Body	Mass/kg	Mean radius/m
Sun	1.99×10^{30}	6.96×10^8
Earth	5.97×10^{24}	6.37×10^6

GEOMETRICAL EQUATIONS

arc length = $r\theta$

circumference of circle = $2\pi r$

area of circle = πr^2

curved surface area of cylinder = $2\pi r h$

area of sphere = $4\pi r^2$

volume of sphere = $\frac{4}{3}\pi r^3$



Particle Physics

Class	Name	Symbol	Rest energy/MeV
photon	photon	γ	0
lepton	neutrino	ν_e	0
		ν_μ	0
	electron	e^\pm	0.510999
	muon	μ^\pm	105.659
mesons	π meson	π^\pm	139.576
		π^0	134.972
	K meson	K^\pm	493.821
		K^0	497.762
baryons	proton	p	938.257
	neutron	n	939.551

Properties of quarks

antiquarks have opposite signs

Type	Charge	Baryon number	Strangeness
u	$+\frac{2}{3}e$	$+\frac{1}{3}$	0
d	$-\frac{1}{3}e$	$+\frac{1}{3}$	0
s	$-\frac{1}{3}e$	$+\frac{1}{3}$	-1

Properties of Leptons

	Lepton number
Particles: $e^-, \nu_e; \mu^-, \nu_\mu$	+1
Antiparticles: $e^+, \bar{\nu}_e, \mu^+, \bar{\nu}_\mu$	-1

Photons and energy levels

photon energy $E = hf = hc / \lambda$
 photoelectricity $hf = \phi + E_{k(\max)}$
 energy levels $hf = E_1 - E_2$
 de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

Waves

wave speed $c = f\lambda$ period $f = \frac{1}{T}$
 first harmonic $f = \frac{1}{2l} \sqrt{\frac{T}{\mu}}$
 fringe spacing $w = \frac{\lambda D}{s}$ diffraction grating $d \sin \theta = n\lambda$
 refractive index of a substance s, $n = \frac{c}{c_s}$
 for two different substances of refractive indices n_1 and n_2 ,
 law of refraction $n_1 \sin \theta_1 = n_2 \sin \theta_2$
 critical angle $\sin \theta_c = \frac{n_2}{n_1}$ for $n_1 > n_2$

Mechanics

moments moment = Fd
 velocity and acceleration $v = \frac{\Delta s}{\Delta t}$ $a = \frac{\Delta v}{\Delta t}$
 equations of motion $v = u + at$ $s = \left(\frac{u+v}{2}\right) t$
 $v^2 = u^2 + 2as$ $s = ut + \frac{at^2}{2}$
 force $F = ma$
 force $F = \frac{\Delta(mv)}{\Delta t}$
 impulse $F \Delta t = \Delta(mv)$
 work, energy and power $W = F s \cos \theta$
 $E_k = \frac{1}{2} m v^2$ $\Delta E_p = mg\Delta h$
 $P = \frac{\Delta W}{\Delta t}, P = Fv$
 efficiency = $\frac{\text{useful output power}}{\text{input power}}$

Materials

density $\rho = \frac{m}{v}$ Hooke's law $F = k \Delta L$
 Young modulus = $\frac{\text{tensile stress}}{\text{tensile strain}}$ tensile stress = $\frac{F}{A}$
 tensile strain = $\frac{\Delta L}{L}$
 energy stored $E = \frac{1}{2} F \Delta L$



Electricity

current and pd $I = \frac{\Delta Q}{\Delta t}$ $V = \frac{W}{Q}$ $R = \frac{V}{I}$

resistivity $\rho = \frac{RA}{L}$

resistors in series $R_T = R_1 + R_2 + R_3 + \dots$

resistors in parallel $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$

power $P = VI = I^2R = \frac{V^2}{R}$

emf $\varepsilon = \frac{E}{Q}$ $\varepsilon = I(R + r)$

Circular motion

magnitude of angular speed $\omega = \frac{v}{r}$

$$\omega = 2\pi f$$

centripetal acceleration $a = \frac{v^2}{r} = \omega^2 r$

centripetal force $F = \frac{mv^2}{r} = m\omega^2 r$

Simple harmonic motion

acceleration $a = -\omega^2 x$

displacement $x = A \cos(\omega t)$

speed $v = \pm \omega \sqrt{(A^2 - x^2)}$

maximum speed $v_{\max} = \omega A$

maximum acceleration $a_{\max} = \omega^2 A$

for a mass-spring system $T = 2\pi \sqrt{\frac{m}{k}}$

for a simple pendulum $T = 2\pi \sqrt{\frac{l}{g}}$

Thermal physics

energy to change temperature $Q = mc\Delta\theta$

energy to change state $Q = ml$

gas law $pV = nRT$
 $pV = NkT$

kinetic theory model $pV = \frac{1}{3} N m (c_{\text{rms}})^2$

kinetic energy of gas molecule $\frac{1}{2} m (c_{\text{rms}})^2 = \frac{3}{2} kT = \frac{3RT}{2N_A}$

Gravitational fields

force between two masses $F = \frac{Gm_1m_2}{r^2}$

gravitational field strength $g = \frac{F}{m}$

magnitude of gravitational field strength in a radial field $g = \frac{GM}{r^2}$

work done $\Delta W = m\Delta V$

gravitational potential $V = -\frac{GM}{r}$
 $g = -\frac{\Delta V}{\Delta r}$

Electric fields and capacitors

force between two point charges $F = \frac{1}{4\pi\epsilon_0} \frac{Q_1Q_2}{r^2}$

force on a charge $F = EQ$

field strength for a uniform field $E = \frac{V}{d}$

work done $\Delta W = Q\Delta V$

field strength for a radial field $E = \frac{1}{4\pi\epsilon_0} \frac{Q}{r^2}$

electric potential $V = \frac{1}{4\pi\epsilon_0} \frac{Q}{r}$

$$E = \frac{\Delta V}{\Delta r}$$

capacitance $C = \frac{Q}{V}$

$$C = \frac{A\epsilon_0\epsilon_r}{d}$$

capacitor energy stored $E = \frac{1}{2} QV = \frac{1}{2} CV^2 = \frac{1}{2} \frac{Q^2}{C}$

capacitor charging $Q = Q_0(1 - e^{-t/RC})$

decay of charge $Q = Q_0 e^{-t/RC}$

time constant RC



Magnetic fields

<i>force on a current</i>	$F = BIl$
<i>force on a moving charge</i>	$F = BQv$
<i>magnetic flux</i>	$\Phi = BA$
<i>magnetic flux linkage</i>	$N\Phi = BAN \cos \theta$
<i>magnitude of induced emf</i>	$\varepsilon = N \frac{\Delta \Phi}{\Delta t}$
	$N\Phi = BAN \cos \theta$
<i>emf induced in a rotating coil</i>	$\varepsilon = BAN\omega \sin \omega t$
<i>alternating current</i>	$I_{\text{rms}} = \frac{I_0}{\sqrt{2}} \quad V_{\text{rms}} = \frac{V_0}{\sqrt{2}}$
<i>transformer equations</i>	$\frac{N_s}{N_p} = \frac{V_s}{V_p}$
	$\text{efficiency} = \frac{I_s V_s}{I_p V_p}$

Nuclear physics

<i>the inverse square law for γ radiation</i>	$I = \frac{k}{x^2}$
<i>radioactive decay</i>	$\frac{\Delta N}{\Delta t} = -\lambda N, N = N_0 e^{-\lambda t}$
<i>activity</i>	$A = \lambda N$
<i>half-life</i>	$T_{1/2} = \frac{\ln 2}{\lambda}$
<i>nuclear radius</i>	$R = R_0 A^{1/3}$
<i>energy-mass equation</i>	$E = mc^2$

OPTIONS

Astrophysics

1 astronomical unit = 1.50×10^{11} m
 1 light year = 9.46×10^{15} m
 1 parsec = 206265 AU = 3.08×10^{16} m
 = 3.26 light year

Hubble constant, $H = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$

$$M = \frac{\text{angle subtended by image at eye}}{\text{angle subtended by object at unaided eye}}$$

in normal adjustment $M = \frac{f_o}{f_e}$

Rayleigh criterion $\theta \approx \frac{\lambda}{D}$

magnitude equation $m - M = 5 \log \frac{d}{10}$

Wien's law $\lambda_{\text{max}} T = 2.9 \times 10^{-3} \text{ m K}$

Stefan's law $P = \sigma AT^4$

Schwarzschild radius $R_s \approx \frac{2GM}{c^2}$

Doppler shift for $v \ll c$ $\frac{\Delta f}{f} = -\frac{\Delta \lambda}{\lambda} = \frac{v}{c}$

red shift $z = -\frac{v}{c}$

Hubble's law $v = Hd$

Medical physics

lens equations $P = \frac{1}{f}$

$$m = \frac{v}{u}$$

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

threshold of hearing $I_0 = 1.0 \times 10^{-12} \text{ W m}^{-2}$

intensity level $\text{intensity level} = 10 \log \frac{I}{I_0}$

absorption $I = I_0 e^{-\mu x}$

$$\mu_m = \frac{\mu}{\rho}$$

ultrasound imaging $Z = p c$

$$\frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

half-lives $\frac{1}{T_B} = \frac{1}{T_B} + \frac{1}{T_P}$



Engineering physics

moment of inertia $I = \Sigma mr^2$

angular kinetic energy $E_k = \frac{1}{2} I \omega^2$

equations of angular motion $\omega_2 = \omega_1 + \alpha t$

$$\omega_2^2 = \omega_1^2 + 2\alpha\theta$$

$$\theta = \omega_1 t + \frac{\alpha t^2}{2}$$

$$\theta = \frac{(\omega_1 + \omega_2) t}{2}$$

torque $T = I \alpha$

$$T = F r$$

angular momentum angular momentum = $I \omega$

angular impulse $T \Delta t = \Delta(I \omega)$

work done $W = T \theta$

power $P = T \omega$

thermodynamics $Q = \Delta U + W$

$$W = p \Delta V$$

adiabatic change $pV^\gamma = \text{constant}$

isothermal change $pV = \text{constant}$

heat engines

$$\text{efficiency} = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H}$$

$$\text{maximum theoretical efficiency} = \frac{T_H - T_C}{T_H}$$

work done per cycle = area of loop

input power = calorific value \times fuel flow rate

$$\text{indicated power} = \frac{\text{area of } p - V \text{ loop}}{\text{number of cycles per second}} \times \text{number of cylinders}$$

output or brake power $P = T \omega$

friction power = indicated power - brake power

heat pumps and refrigerators

refrigerator: $COP_{\text{ref}} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C}$

heat pump: $COP_{\text{hp}} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C}$

Turning points in physics

electrons in fields $F = \frac{eV}{d}$

$$F = Bev$$

$$r = \frac{mv}{Be}$$

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

Millikan's experiment $\frac{QV}{d} = mg$

$$F = 6\pi\eta r v$$

Maxwell's formula $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}}$$

special relativity

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

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

$$E = mc^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Electronics

resonant frequency $f_0 = \frac{1}{2\pi \sqrt{LC}}$

Q-factor $Q = \frac{f_0}{f_B}$

operational amplifiers: open loop $V_{\text{out}} = A_{\text{OL}}(V_+ - V_-)$

inverting amplifier $\frac{V_{\text{out}}}{V_{\text{in}}} = -\frac{R_f}{R_{\text{in}}}$

non-inverting amplifier $\frac{V_{\text{out}}}{V_{\text{in}}} = 1 + \frac{R_f}{R_1}$

summing amplifier $V_{\text{out}} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \dots \right)$

difference amplifier $V_{\text{out}} = (V_+ - V_-) \frac{R_f}{R_1}$

Bandwidth requirement:

for AM bandwidth = $2f_M$

for FM bandwidth = $2(\Delta f + f_M)$



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This document has been produced for educational purposes only.

This document has been produced for the AQA A Level Physics Specification.

Student Voice

If you when using this document, you believe there is an improvement to made, please state this in the space below....

Only constructive and reasoned feedback will be considered.