Please check the examination details below before entering your candidate information

Candidate surname	Other names
StemUp Model Solution	

Centre Number | Candidate Number

Pearson Edexcel Level 3 GCE

Time 1 hour 45 minutes

Paper reference **9PH0/01**

Physics

Advanced

PAPER 1: Advanced Physics I

You must have:
Scientific calculator, ruler, protractor

Total Marks

Instructions

- Use **black** ink or ball-point pen.
- **Fill in the boxes** at the top of this page with your name, centre number and candidate number.
- Answer **all** questions.
- Answer the questions in the spaces provided – *there may be more space than you need.*

Information

- The total mark for this paper is 90.
- The marks for **each** question are shown in brackets – *use this as a guide as to how much time to spend on each question.*
- In the question marked with an **asterisk** (*), marks will be awarded for your ability to structure your answer logically, showing how the points that you make are related or follow on from each other where appropriate.
- The list of data, formulae and relationships is printed at the end of this booklet.

Advice

- Read each question carefully before you start to answer it.
- Try to answer every question.
- Check your answers if you have time at the end.
- You are advised to show your working in calculations including units where appropriate.

Turn over ▶

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Q:1/1/1/1/1/

P 6 9 3 0 6 A 0 1 2 8

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Answer ALL questions.

All multiple choice questions must be answered with a cross in the box ☒ for the correct answer from A to D. If you change your mind about an answer, put a line through the box ☒ and then mark your new answer with a cross ☒.

1 A particle has a mass of 1 u and a charge of -1.6×10^{-19} C.

Which of the following could be the particle?

☒ **A** antiproton

☐ **B** electron

☐ **C** neutron

☐ **D** positron

(Total for Question 1 = 1 mark)

2 The velocity v of a non-relativistic particle can be expressed in terms of combinations of the following quantities: kinetic energy E_k, momentum p and mass m.

Which of the following expressions is correct?

☐ **A** $v = \frac{p^2}{m}$

☒ **B** $v = \sqrt{\frac{2E_k}{m}}$

☐ **C** $v = \frac{E_k}{2p}$

☐ **D** $v = \frac{2E_k}{pm}$

(Total for Question 2 = 1 mark)

3 A ball is thrown with an initial horizontal component of velocity u and an initial vertical component of velocity v. The effects of air resistance are negligible.

Which of the following statements about the motion of the ball is **not** correct?

☐ **A** The magnitude of the acceleration in the vertical plane is g.

☐ **B** The horizontal component of velocity is constant.

☐ **C** The time taken for the ball to reach its maximum height is equal to $\frac{v}{g}$.

☒ **D** The maximum height of the ball depends on the values of u and v.

(Total for Question 3 = 1 mark)

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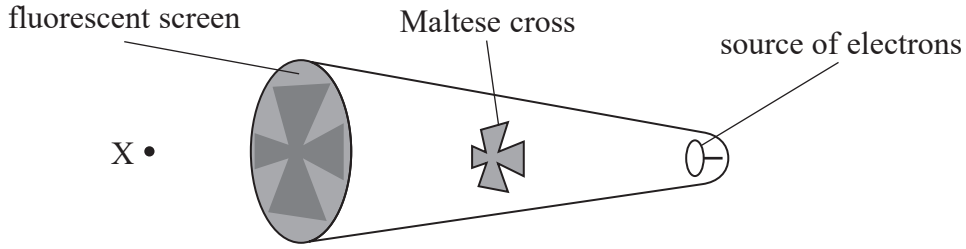
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Questions 4 and 5 refer to the information below.

A demonstration is carried out using a beam of electrons in an evacuated tube.

When electrons hit a fluorescent screen, light is emitted. A piece of metal, in the shape of a Maltese cross, stops electrons and produces a shadow on the screen as shown.



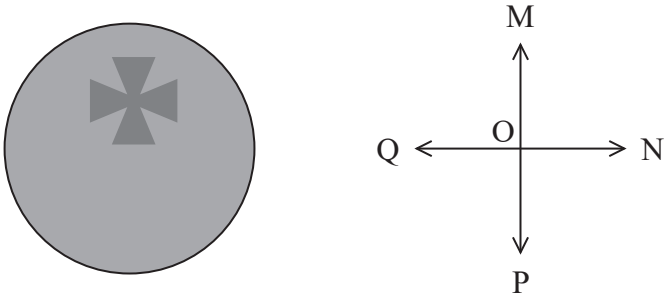
4 The electrons are produced by heating a metal filament.

Which of the following is the name of this process?

- ☒ **A** ionisation
- ☒ **B** scattering
- ☒ **C** the photoelectric effect
- ☒ **D** thermionic emission

(Total for Question 4 = 1 mark)

5 The screen is viewed by an observer at point X in the diagram above. A magnetic field is directed at the beam of electrons. This causes the shadow to move upwards on the screen in the direction OM.



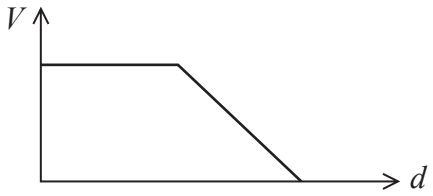
In which of the following directions is the magnetic field acting as seen by this observer?

- ☒ **A** OM
- ☒ **B** ON
- ☒ **C** OP
- ☒ **D** OQ

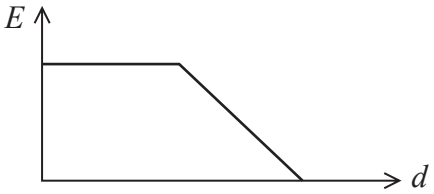
(Total for Question 5 = 1 mark)

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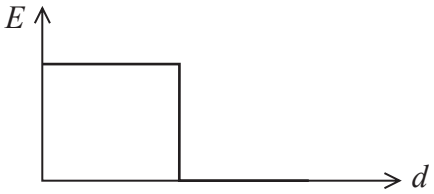
6 The graph shows how the potential V varies with distance d in an electric field.



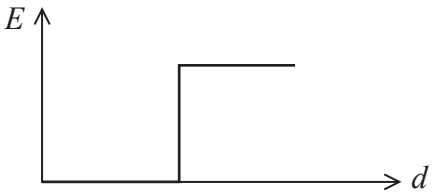
Which of the following shows the corresponding variation in electric field strength E?



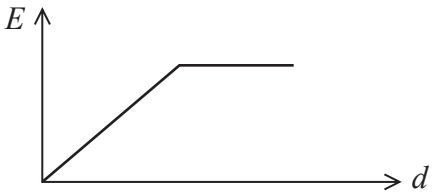
☒ **A**



☒ **B**



☒ **C**



☒ **D**

(Total for Question 6 = 1 mark)

7 Which of the following quantities is a vector?

☒ **A** charge

☒ **B** mass

☒ **C** momentum

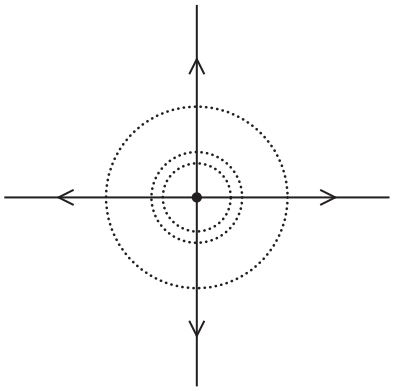
☒ **D** time

(Total for Question 7 = 1 mark)

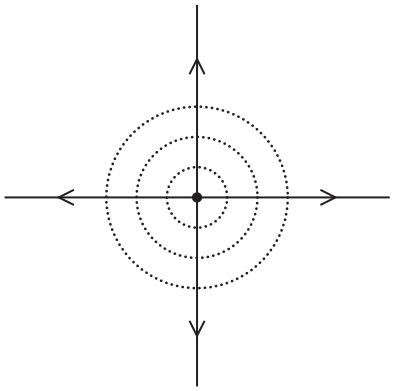
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8 A point object has a charge +Q.

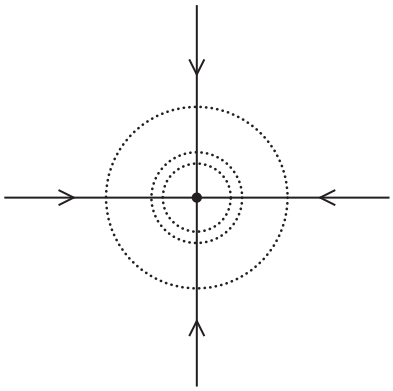
Which of the following diagrams shows equipotential lines differing by a constant potential difference, and electric field lines around the object?



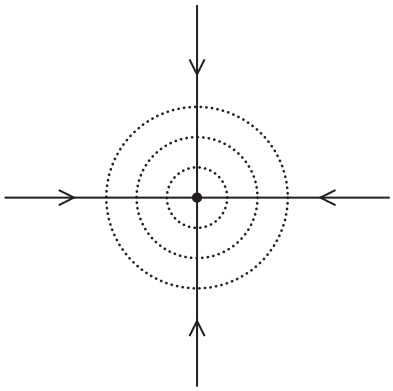
☒ **A**



☐ **B**



☐ **C**



☐ **D**

(Total for Question 8 = 1 mark)

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Questions 9 and 10 refer to the information below.

Alpha particle scattering investigations were first carried out in the early part of the 20th century.

9 An alpha particle with initial kinetic energy 8.8×10^{-13} J approaches a nucleus of a gold $\left({}^{197}_{79}\text{Au}\right)$ atom.

Which of the following is an equation for the closest distance r, in metres, between the alpha particle and the nucleus?

☒ **A** $r = 8.99 \times 10^{9} \left(\dfrac{2 \times 1.6 \times 10^{-19} \times 79 \times 1.6 \times 10^{-19}}{8.8 \times 10^{-13}} \right)$

☒ **B** $r = \dfrac{2 \times 1.6 \times 10^{-19} \times 197 \times 1.6 \times 10^{-19}}{8.99 \times 10^{9} \times 8.8 \times 10^{-13}}$

☒ **C** $r = 8.99 \times 10^{9} \left(\dfrac{8.8 \times 10^{-13}}{4 \times 1.6 \times 10^{-19} \times 79 \times 1.6 \times 10^{-19}} \right)$

☒ **D** $r = 8.99 \times 10^{9} \left(\dfrac{2 \times 79}{8.8 \times 10^{-13}} \right)$

(Total for Question 9 = 1 mark)

10 Which of the following conclusions could **not** be made as a result of these investigations?

☒ **A** The atom is mostly empty space.

☒ **B** The atom is neutral.

☒ **C** The nucleus is charged.

☒ **D** The nucleus is very small compared to the atom.

(Total for Question 10 = 1 mark)

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11 A student drives a go-kart up a slope.

(a) The slope is at an angle of 5.7° to the horizontal. The go-kart moves with a constant velocity of 2.8 m s^{-1}.

Calculate the power of the go-kart.

mass of go-kart and driver = 60 kg
resistive force on the go-kart = 18 N

(4)

Vertical height gained per second = 2.8 m s^{-1} × sin 5.7° = 0.278 m s^{-1}

rate of gain of GPE = mgΔh/t = 60 kg × 9.81 N kg^{-1} × 0.278 m s^{-1} = 163.7 W

work done against resistive force per second = FΔs/t = 18 N × 2.8 m s^{-1} = 50.4 W

P = W/t = 163.7 W + 50.4 W = 214 W

Power = *210 W*

(b) The go-kart is powered by a battery connected to a motor. The rate of thermal energy transfer by the wiring in the motor is 55 W.

Calculate the resistance of the wiring in the motor.

current in motor = 24 A

(2)

$P = I^2R$, so $R = P/I^2$ = 55 W ÷ $(24\ A)^2$

R = 55 W ÷ 576 A^2 = 0.0955 Ω

Resistance of the wiring in the motor = *0.095 Ω*

(Total for Question 11 = 6 marks)

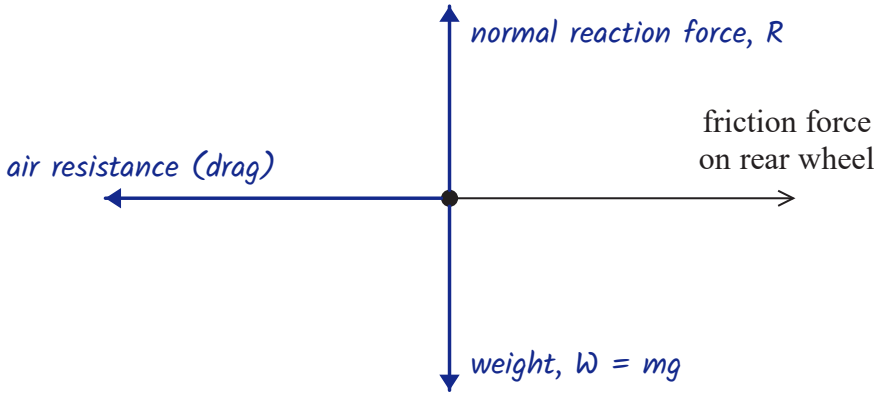
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12 The photograph shows a cyclist cycling at a constant velocity on horizontal ground.



(a) Complete the free-body force diagram to show the four forces acting on the bicycle. Treat the bicycle and cyclist as a single object. One force has been added for you.

(3)

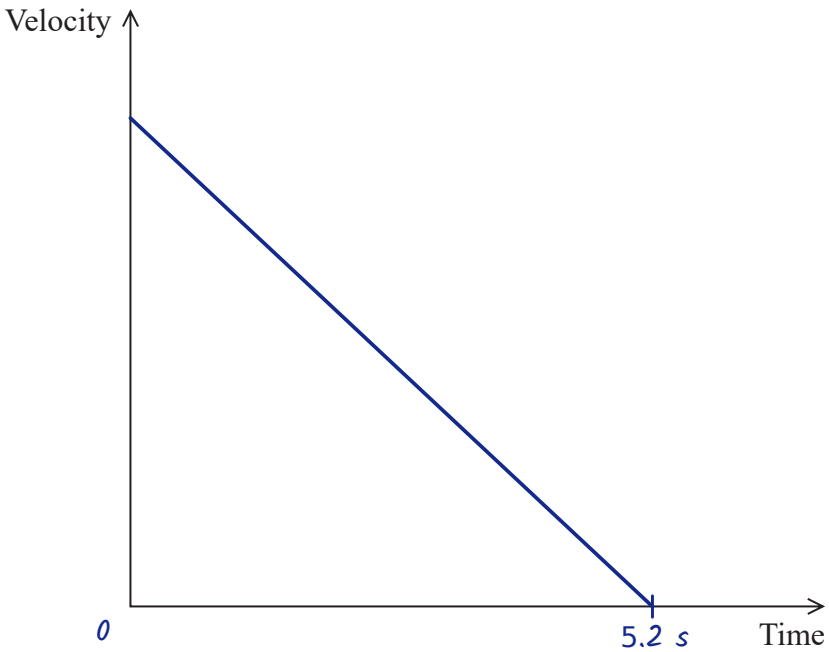


(b) The cyclist stops pedalling and comes to rest in a time of 5.2 s.

(i) Sketch a graph to show how the cyclist's velocity changes during this time.

Assume the deceleration is constant.

(2)



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(ii) The cyclist travels 7.80 m while coming to rest.

Calculate the average resistive force on the cyclist and bicycle.

mass of cyclist and bicycle = 28.0 kg

(4)

$s = (u + v)t/2$ with $v = 0$: $7.80\ m = u \times 5.2\ s \div 2$, so $u = 3.0\ m\ s^{-1}$

$a = (v - u)/t = (0 - 3.0\ m\ s^{-1}) \div 5.2\ s = -0.577\ m\ s^{-2}$

$F = ma = 28.0\ kg \times 0.577\ m\ s^{-2} = 16.2\ N$

Average resistive force = 16 N

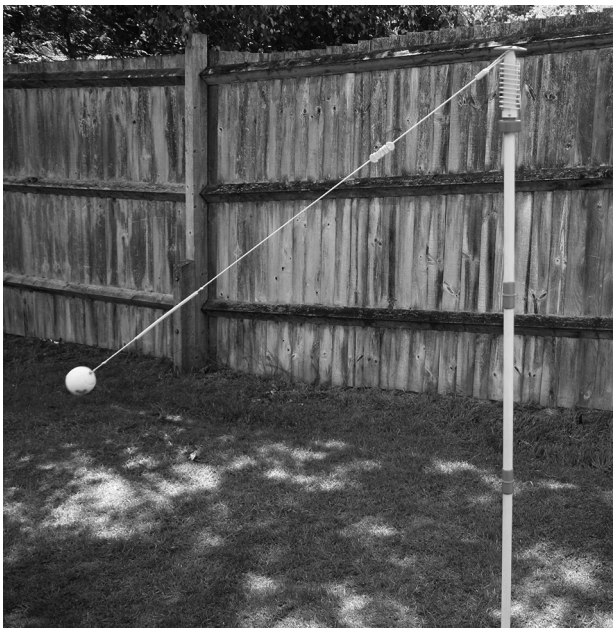
(Total for Question 12 = 9 marks)

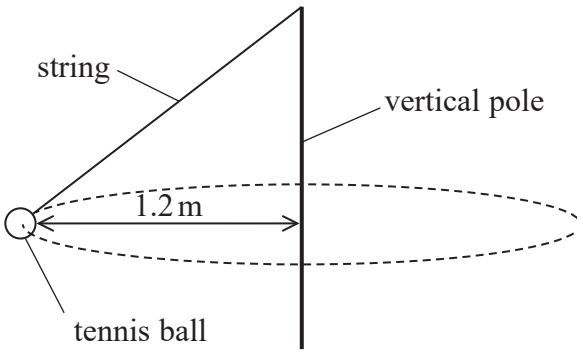
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13 A 'tennis trainer' consists of a tennis ball suspended by a string from the top of a vertical pole. When the ball is hit it travels in a horizontal circle around the pole, as shown in both the photograph and the diagram.





The radius of the path of the ball is 1.2 m and the speed of the ball is 3.8 m s^{-1}.

Deduce whether these values are consistent with the angle between the string and the vertical pole shown in the photograph.

Angle between the string and the pole measured on the photograph = 52°

Horizontally the component of tension provides the centripetal force: $T \sin \theta = mv^2/r$

($F = ma$ with $a = v^2/r$)

Vertically the forces balance: $T \cos \theta = mg$

Dividing: $\tan \theta = v^2/rg = (3.8 \text{ m s}^{-1})^2 \div (1.2 \text{ m} \times 9.81 \text{ m s}^{-2}) = 1.23$

$\theta = 50.8°$ (about 51°), which is within a couple of degrees of the 52° measured, so the values are consistent with the angle in the photograph.

(Total for Question 13 = 5 marks)

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14 Power supplies provide either alternating or direct currents and potential differences.

(a) A power supply produces an alternating potential difference (p.d.). The p.d. has a period of 0.02 s and a peak value of 4.0 V.

(i) Calculate the frequency of the supply.

(1)

$f = 1/T = 1 \div 0.02\ s$

Frequency = 50 Hz

(ii) Calculate the root-mean-square p.d.

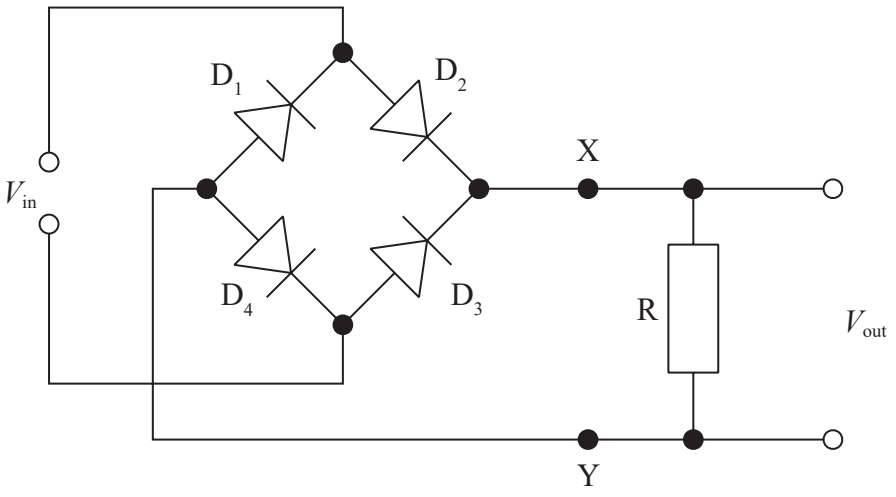
(1)

$V_{rms} = V_0/\sqrt{2} = 4.0\ V \div \sqrt{2} = 2.83\ V$

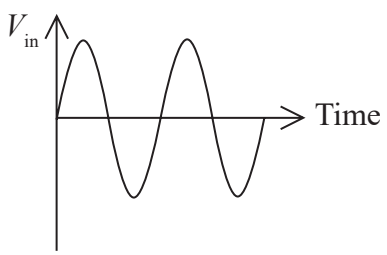
Root-mean-square p.d. = 2.8 V

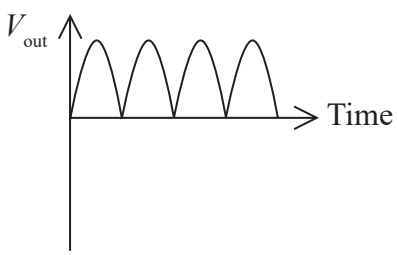
(b) It is possible to convert alternating currents and p.d.s, to direct currents and p.d.s using diodes.

The power supply provides an input V_{in} to the circuit shown. The circuit includes four diodes D_1, D_2, D_3 and D_4 and a resistor R. The circuit produces an output potential difference V_{out}.



A graph of V_{in} against time and a corresponding graph of V_{out} against time are shown below.





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(i) Explain the operation of this circuit. Your answer should refer to D_1, D_2, D_3 and D_4.

(3)

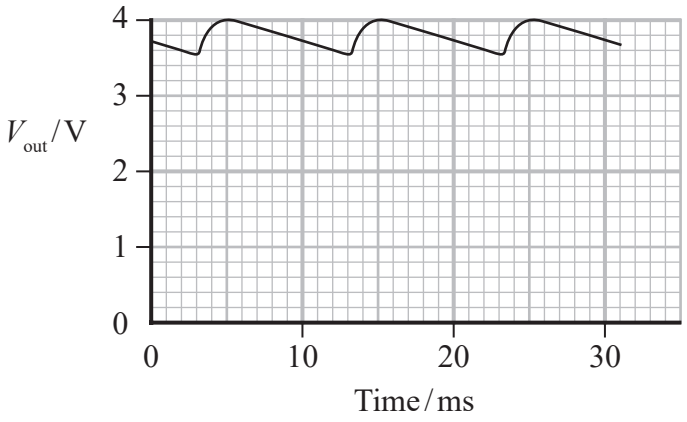
A diode only lets current through in one direction.

In the positive half cycle of the input D2 and D4 conduct (D1 and D3 are reverse biased); in the negative half cycle D1 and D3 conduct (D2 and D4 do not).

In both half cycles the current through R is in the same direction, from X to Y (down through R), so V_{out} is always positive (full-wave rectified).

(ii) A capacitor is added between points X and Y in the circuit.

The new graph of V_{out} against time is shown below.



Determine a value for the capacitance of the capacitor.

resistance of R = 2.2 kΩ

(3)

From the graph the p.d. falls from V_0 = 4.0 V at t = 5 ms to V = 3.55 V at t = 13 ms, so t = 0.008 s

ln V = ln V_0 − t/RC, so RC = t ÷ ln(V_0/V) = 0.008 s ÷ ln(4.0/3.55) = 0.008 s ÷ 0.119 = 0.067 s

C = 0.067 s ÷ 2200 Ω = 3.0×10^{-5} F

Capacitance = 3.0×10^{-5} F

(Total for Question 14 = 8 marks)

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15 A series of experiments was carried out in the 1970s to investigate the structure of protons using the linac at Stanford, USA.

*(a) Explain how an electron is accelerated in a linac.

(6)

A linac consists of a series of metal drift tubes in a line, inside an evacuated chamber. Adjacent tubes are connected to opposite terminals of an alternating power supply, so neighbouring tubes have opposite charge (polarity).

The electrons are accelerated by the electric field (potential difference) between the tubes. Inside a tube there is no field, so the electron moves at constant velocity; the acceleration takes place only in the gaps between the tubes.

The p.d. is alternating so that, as an electron emerges from one tube, the next tube is positive (and the tube it is leaving is negative), so the electron is accelerated across every gap.

The electron must spend the same time in each tube (half the period of the alternating supply). As the electrons travel faster, the tubes must be longer (the distance between the gaps increases along the linac) so that the supply can have a fixed frequency.

(b) The electron leaves the accelerator with a high energy.

Explain why electrons need high energies to investigate the structure of a proton.

(2)

High energy electrons have a large momentum and so a short de Broglie wavelength ($\lambda = h/p$).

The wavelength needs to be comparable to or smaller than the size of the proton (about 10^{-15} m) to resolve its structure.

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(c) An electron leaves the accelerator with a momentum of 20 GeV/c.

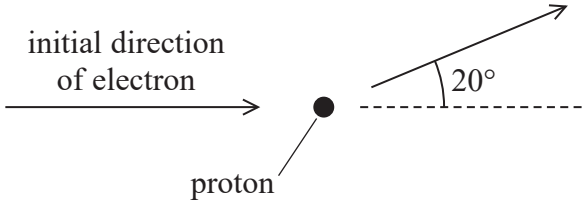
(i) Explain, with reference to base units, why GeV/c can be used as a unit of momentum.

(2)

eV is a unit of energy; energy has base units kg m^2 s^{-2}, and c is a speed with units m s^{-1}

dividing energy by speed: kg m^2 s^{-2} ÷ m s^{-1} = kg m s^{-1}, which are the base units of momentum ($p = mv$), so GeV/c is a unit of momentum.

(ii) An electron with initial momentum 20 GeV/c collides with a stationary proton. After the collision the electron is deflected by an angle of 20° as shown and its momentum is 9.1 GeV/c. The momentum of the proton after the collision is 11.9 GeV/c.



Deduce whether the law of conservation of momentum is obeyed.

(3)

electron after: $p_x = 9.1 \cos 20° = 8.55$ GeV/c, $p_y = 9.1 \sin 20° = 3.11$ GeV/c

conserving momentum: proton $p_x = 20 - 8.55 = 11.45$ GeV/c and $p_y = 3.11$ GeV/c (opposite direction to the electron's)

$p_{proton} = \sqrt{(11.45^2 + 3.11^2)} = 11.86$ GeV/c ≈ 11.9 GeV/c, the value given, so momentum is conserved (the law is obeyed).

(iii) The collisions between electrons and the protons in these experiments are sometimes inelastic.

State what is meant by an inelastic collision.

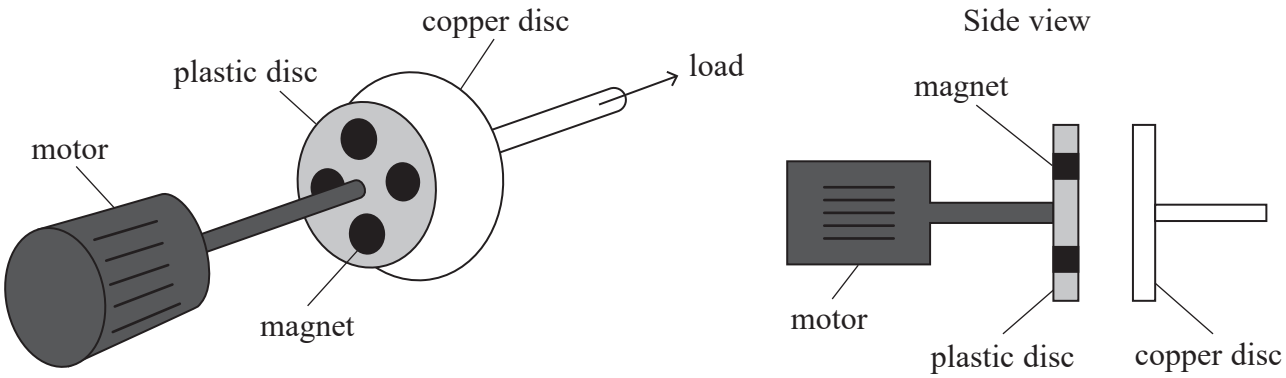
(1)

The total kinetic energy is not conserved.

(Total for Question 15 = 14 marks)

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16 A device called a clutch can be used to connect a motor to a load. The diagram shows a design called an eddy current clutch.



Several magnets are embedded in the plastic disc and it is rotated by the motor.

(a) (i) Explain why a current is induced in the copper disc when the motor is switched on.

(2)

As the plastic disc rotates, the magnets move past the copper disc, so the copper disc experiences a changing magnetic flux (it cuts magnetic flux).

Therefore an e.m.f. is induced in the copper disc (Faraday's law), which drives (eddy) currents in the conducting copper.

(ii) Explain, using Lenz's law, why the copper disc rotates.

(3)

By Lenz's law the induced current flows so as to oppose the change that produces it.

The induced currents produce magnetic fields (there is a force on the current in the magnetic field of the magnets) which pull the copper disc along with the magnets.

So the copper disc rotates in the same direction as the plastic disc, which reduces the rate of change of magnetic flux.

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(b) The motor rotates at 500 revolutions per minute.

Calculate the angular speed ω of the motor.

(2)

$\omega = 2\pi \times 500 \text{ rev} \div 60 \text{ s} = 52.4 \text{ rad s}^{-1}$

$\omega =$ 52 rad s^{-1}

(c) The table shows how the turning effect exerted on a load varies with ω for a particular distance between the copper disc and the plastic disc.

ω / rad s^{-1}	Turning effect / N cm
52.4	1.0
104.7	2.0
157.1	2.8

Explain the trend shown by the data.

(4)

The turning effect is (approximately) proportional to ω: turning effect/ω = 0.019, 0.019 and 0.018 N cm per rad s^{-1}.

As the angular speed increases, the rate of change (cutting) of magnetic flux through the copper disc increases,

so the induced e.m.f. increases and the induced current in the copper disc increases.

A larger current in the magnetic field of the magnets gives a larger force on the copper disc, so a larger turning effect on the load.

(Total for Question 16 = 11 marks)

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17 A cosmic ray, consisting of a fast-moving proton, collides with a proton within the nucleus of an atom in the upper atmosphere. Three particles, a proton, a neutron and a pion result from the collision.

(a) Write a particle equation for this collision.

(2)

$p + p \rightarrow p + n + \pi^+$

(b) The table shows the properties of two quarks.

Quark	Charge / *e*
u	+2/3
d	−1/3

Give the quark structure for each of the particles produced by this collision.

(3)

proton: uud

neutron: udd

pion (π^+): u and anti-d (an up quark and an anti-down quark)

(c) The mass of a pion is 140 MeV/c^2.

Calculate the mass of the pion in kg.

(3)

$E = 140\ MeV = 140 \times 10^6 \times 1.6 \times 10^{-19}\ J = 2.24 \times 10^{-11}\ J$

$m = E/c^2 = 2.24 \times 10^{-11}\ J \div (3.0 \times 10^8\ m\ s^{-1})^2 = 2.49 \times 10^{-28}\ kg$

Mass = 2.5×10^{-28} kg

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(d) The mass of a neutron is about the same as the mass of a proton. A student suggests that the minimum kinetic energy the cosmic ray proton would need to create the pion in this collision is 140 MeV.

Discuss whether this suggestion is correct. Your answer should include reference to the laws of conservation of momentum and conservation of energy.

(4)

There is extra mass after the collision (the neutron has about the same mass as the proton), the extra mass being the mass of the pion. Energy must be conserved, so kinetic energy is needed to create the pion.

According to $\Delta E = c^2 \Delta m$ the extra mass is 140 MeV/c^2, so the energy required for the pion's mass is 140 MeV.

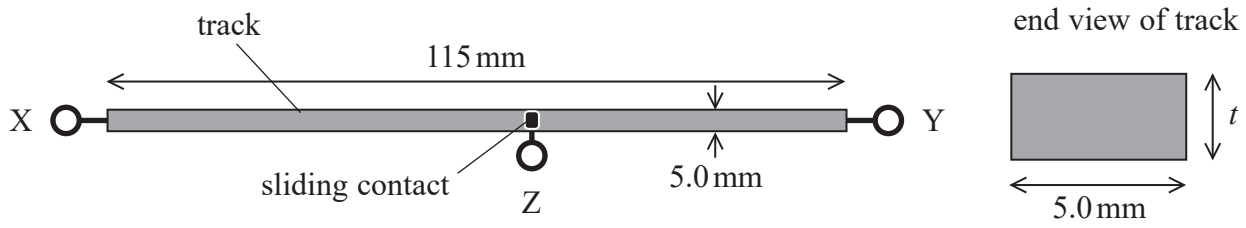
But momentum must also be conserved: the incoming proton has momentum, so the three particles after the collision must have momentum and therefore kinetic energy.

So the incoming proton needs 140 MeV plus the kinetic energy of the product particles: the suggestion is not correct (the minimum is more than 140 MeV).

(Total for Question 17 = 12 marks)

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18 A potential divider circuit may contain a component known as a potentiometer. One type of potentiometer consists of a track with terminals X and Y at either end. There is a sliding contact that can move along the track connected to a terminal Z as shown.



The length of the track is 115 mm and the width is 5.0 mm.

(a) The resistance of the track between terminal X and terminal Y is 12.0 kΩ.

Calculate the thickness t of the track.

resistivity of track material = 0.49 Ω m

(3)

A = width × thickness = 5.0×10^{-3} m × t

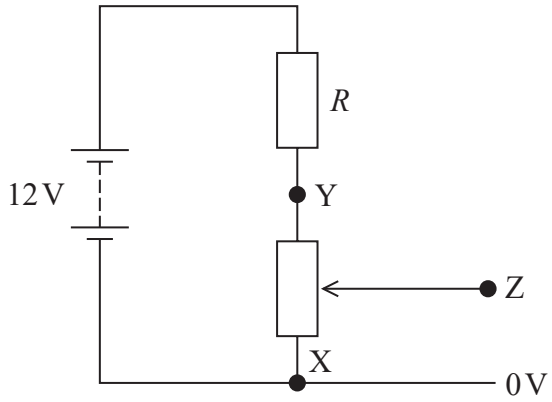
$R = \rho l / A$, so $12.0 \times 10^{3}\ \Omega = (0.49\ \Omega\ m \times 0.115\ m) \div (5.0 \times 10^{-3}\ m \times t)$

$t = 0.0564 \div 60 = 9.4 \times 10^{-4}$ m

$t =$ 9.4×10^{-4} m

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(b) The potentiometer is used to monitor the displacement of a moving tool on a machine in a production line. The tool is attached to the sliding contact. The potentiometer is connected to a resistor of resistance R and a potential difference is applied as shown. The tool moves through a maximum displacement of 60 mm from end X, producing a maximum potential difference of 5.0 V between Z and X.



(i) Show that the potential difference between X and Y is about 10 V.

(2)

The p.d. is proportional to the length of track, so 60 mm of track has 5.0 V across it.

p.d. across XY = (115 mm ÷ 60 mm) × 5.0 V = 9.6 V, which is about 10 V

(ii) Calculate the value of R.

(3)

current in circuit $I = V/R$ = 9.6 V ÷ 12 000 Ω = 8.0×10^{-4} A

p.d. across R = 12 V − 9.6 V = 2.4 V

R = 2.4 V ÷ 8.0×10^{-4} A

R = 3000 Ω

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(iii) When the circuit is assembled, using the correctly calculated resistance value and a battery of e.m.f. 12 V, it is found that the maximum output from the potentiometer is slightly less than 5.0 V.

Explain why the maximum output is slightly less than predicted.

(3)

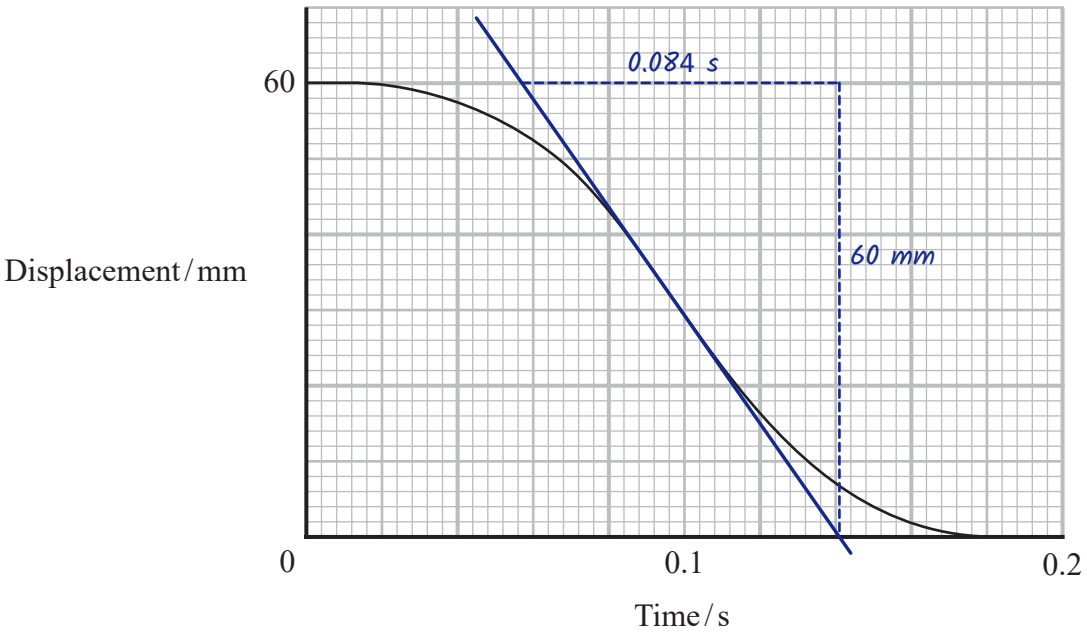
The battery has internal resistance.

There is a p.d. across the internal resistance (lost volts), so the terminal p.d. is less than the e.m.f. of 12 V: V = ε − Ir.

So the p.d. across the potentiometer track is less than 9.6 V and the maximum output is slightly less than 5.0 V.

(iv) The tool on the machine should not travel with a speed any larger than $0.8\,m\,s^{-1}$.

The graph shows how the displacement varies with time for the downward stroke of the moving tool.



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Deduce whether this speed is exceeded by the moving tool.

(4)

Tangent drawn to the curve at the steepest part (maximum speed), see graph.

The tangent passes through 60 mm at t = 0.057 s and 0 mm at t = 0.141 s

speed = gradient = 60 mm ÷ (0.141 s − 0.057 s) = 0.060 m ÷ 0.084 s

maximum speed = 0.71 m s^{-1}

0.71 m s^{-1} is less than 0.8 m s^{-1}, so the speed limit is not exceeded by the moving tool.

(Total for Question 18 = 15 marks)

TOTAL FOR PAPER = 90 MARKS

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List of data, formulae and relationships

Acceleration of free fall	$g = 9.81 \text{ m s}^{-2}$	(close to Earth's surface)
Boltzmann constant	$k = 1.38 \times 10^{-23} \text{ J K}^{-1}$	
Coulomb law constant	$k = \frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^{9} \text{ N m}^2 \text{ C}^{-2}$	
Electron charge	$e = -1.60 \times 10^{-19} \text{ C}$	
Electron mass	$m_e = 9.11 \times 10^{-31} \text{ kg}$	
Electronvolt	$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$	
Gravitational constant	$G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$	
Gravitational field strength	$g = 9.81 \text{ N kg}^{-1}$	(close to Earth's surface)
Permittivity of free space	$\varepsilon_0 = 8.85 \times 10^{-12} \text{ F m}^{-1}$	
Planck constant	$h = 6.63 \times 10^{-34} \text{ J s}$	
Proton mass	$m_p = 1.67 \times 10^{-27} \text{ kg}$	
Speed of light in a vacuum	$c = 3.00 \times 10^{8} \text{ m s}^{-1}$	
Stefan-Boltzmann constant	$\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$	
Unified atomic mass unit	$u = 1.66 \times 10^{-27} \text{ kg}$	

Mechanics

Kinematic equations of motion

$$s = \frac{(u + v)t}{2}$$

$$v = u + at$$

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

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

Forces

$$\Sigma F = ma$$

$$g = \frac{F}{m}$$

$$W = mg$$

moment of force $= Fx$

Momentum

$$p = mv$$

Work, energy and power

$$\Delta W = F\Delta s$$

$$E_k = \tfrac{1}{2}mv^2$$

$$\Delta E_{grav} = mg\Delta h$$

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

$$P = \frac{W}{t}$$

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

$$\text{efficiency} = \frac{\text{useful power output}}{\text{total power input}}$$

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Electric circuits

Potential difference

$$V = \frac{W}{Q}$$

Resistance

$$R = \frac{V}{I}$$

Electrical power and energy

$$P = VI$$

$$P = I^2R$$

$$P = \frac{V^2}{R}$$

$$W = VIt$$

Resistivity

$$R = \frac{\rho l}{A}$$

Current

$$I = \frac{\Delta Q}{\Delta t}$$

$$I = nqvA$$

Materials

Density

$$\rho = \frac{m}{V}$$

Stokes' law

$$F = 6\pi\eta rv$$

Hooke's law

$$\Delta F = k\Delta x$$

Young modulus

$$\text{Stress } \sigma = \frac{F}{A}$$

$$\text{Strain } \varepsilon = \frac{\Delta x}{x}$$

$$E = \frac{\sigma}{\varepsilon}$$

Elastic strain energy

$$\Delta E_{el} = \tfrac{1}{2}F\Delta x$$

Waves and particle nature of light

Wave speed

$$v = f\lambda$$

Speed of a transverse wave on a string

$$v = \sqrt{\frac{T}{\mu}}$$

Intensity of radiation

$$I = \frac{P}{A}$$

Power of a lens

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

$$P = P_1 + P_2 + P_3 + \ldots$$

Thin lens equation

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

Magnification for a lens

$$m = \frac{\text{image height}}{\text{object height}} = \frac{v}{u}$$

Diffraction grating

$$n\lambda = d \sin\theta$$

Refractive index

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

$$n = \frac{c}{v}$$

Critical angle

$$\sin C = \frac{1}{n}$$

Photon model

$$E = hf$$

Einstein's photoelectric equation

$$hf = \phi + \tfrac{1}{2}mv^2_{max}$$

de Broglie wavelength

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

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Further mechanics

Impulse

$$F\Delta t = \Delta p$$

Kinetic energy of a non-relativistic particle

$$E_k = \frac{p^2}{2m}$$

Motion in a circle

$$v = \omega r$$

$$T = \frac{2\pi}{\omega}$$

$$F = ma = \frac{mv^2}{r}$$

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

$$a = r\omega^2$$

$$F = mr\omega^2$$

Fields

Coulomb's law

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$$

Electric field strength

$$E = \frac{F}{Q}$$

$$E = \frac{Q}{4\pi\varepsilon_0 r^2}$$

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

Electric potential

$$V = \frac{Q}{4\pi\varepsilon_0 r}$$

Capacitance

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

Energy stored in a capacitor

$$W = \tfrac{1}{2}QV$$

$$W = \tfrac{1}{2}CV^2$$

$$W = \tfrac{1}{2}\frac{Q^2}{C}$$

Capacitor discharge

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

$$I = I_0 e^{-t/RC}$$

$$V = V_0 e^{-t/RC}$$

$$\ln Q = \ln Q_0 - \frac{t}{RC}$$

$$\ln I = \ln I_0 - \frac{t}{RC}$$

$$\ln V = \ln V_0 - \frac{t}{RC}$$

In a magnetic field

$$F = BIl \sin\theta$$

$$F = Bqv \sin\theta$$

Faraday's and Lenz's laws

$$\mathscr{E} = \frac{-\mathrm{d}(N\phi)}{\mathrm{d}t}$$

Root-mean-square values

$$V_{rms} = \frac{V_0}{\sqrt{2}}$$

$$I_{rms} = \frac{I_0}{\sqrt{2}}$$

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Nuclear and particle physics

In a magnetic field

$$r = \frac{p}{BQ}$$

Thermodynamics

Heating

$$\Delta E = mc\Delta\theta$$

$$\Delta E = L\Delta m$$

Molecular kinetic theory

$$\frac{1}{2}m\langle c^2\rangle = \frac{3}{2}kT$$

$$pV = \frac{1}{3}Nm\langle c^2\rangle$$

Ideal gas equation

$$pV = NkT$$

Stefan-Boltzmann law

$$L = \sigma AT^4$$

$$L = 4\pi r^2\sigma T^4$$

Wien's law

$$\lambda_{max}T = 2.898 \times 10^{-3}\ \text{m K}$$

Space

Intensity

$$I = \frac{L}{4\pi d^2}$$

Redshift of electromagnetic radiation

$$z = \frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$$

Cosmological expansion

$$v = H_0 d$$

Nuclear radiation

Mass-energy

$$\Delta E = c^2\Delta m$$

Radioactive decay

$$A = \lambda N$$

$$\frac{dN}{dt} = -\lambda N$$

$$\lambda = \frac{\ln 2}{t_{½}}$$

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

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

Gravitational fields

Gravitational force

$$F = \frac{Gm_1m_2}{r^2}$$

Gravitational field strength

$$g = \frac{Gm}{r^2}$$

Gravitational potential

$$V_{grav} = \frac{-Gm}{r}$$

Oscillations

Simple harmonic motion

$$F = -kx$$

$$a = -\omega^2 x$$

$$x = A\cos\omega t$$

$$v = -A\omega\sin\omega t$$

$$a = -A\omega^2\cos\omega t$$

$$T = \frac{1}{f} = \frac{2\pi}{\omega}$$

$$\omega = 2\pi f$$

Simple harmonic oscillator

$$T = 2\pi\sqrt{\frac{m}{k}}$$

$$T = 2\pi\sqrt{\frac{l}{g}}$$

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