1.List of data, formulae and relationships

Data

Gravitational constant	$G = 6.67 \times 10^{-11}\ Nm^2kg^{-2}$	
Acceleration of free fall	$g = 9.81\ m\ s^{-2}$	(close to the Earth)
Gravitational field strength	$g - 9.81\ N\ kg^{-1}$	(close to the Earth)
Electronic charge	$e = -1.60 \times 10^{-19}\ C$	
Electronic mass	$m_e = 9.11 \times 10^{-31}\ kg$	
Unified mass unit	$u = 1.66 \times 10^{-27}\ kg$	
Planck constant	$h = 6.63 \times 10^{-34}\ J\ s$	
Speed of light in vacuum	$c = 3.00 \times 10^{8}\ m\ s^{-1}$	
Molar gas constant	$R = 8.31\ J\ K^{-1}\ mol^{-1}$	
Boltzmann constant	$k = 1.38 \times 10^{-23}\ J\ K^{-1}$	
Avogadro constant	$N_a = 6.02 \times 10^{23}\ mol^{-1}$	
Permittivity of free space	$\varepsilon_0 = 8.85 \times 10^{-12}\ Fm^{-1}$	
Permeability of free space	$\mu_0 = 4\pi \times 10^{-7}\ N\ A^{-2}$	

Experimental physics

Percentage uncertainty $= \dfrac{\text{Estimated uncertainty}}{\text{Average value}} \times 100\%$

Mechanics

Force $F = \dfrac{\Delta p}{\Delta t}$

For uniformly accelerated motion:

$v = u + at$

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

$v^2 = + 2ax$

Work done or energy transferred $\Delta W = \Delta E = p\Delta V$ (Presssure p; Volume V)

Power P = Fv

Angular speed $\omega = \dfrac{\Delta\theta}{\Delta t} = \dfrac{v}{r}$ (Radius of circular path r)

Period $T = \dfrac{1}{f} = \dfrac{2\pi}{\omega}$ (Frequency f)

Radial acceleration $a = r\omega^2 = \dfrac{v^2}{r}$

Couple (due to a pair of forces F and $-F$)

= F × (Perpendicular distance from F to $-F$)

Electricity

Electric current	$I = nAQv$(Number of charge carriers per unit volume n)	
Electric power	$P = I^2R$	
Resistors in series	$R = R_1 + R_2 + R_3$	
Resistors in parallel	$R_\theta = R_0(1+\alpha\theta)$	(Temperature coefficient α)
Resistance at temperature θ	$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$	
Capacitance of parallel plates	$C = \frac{\varepsilon_0 \varepsilon_1 A}{d}$	
Capacitors in parallel	$C = C_1 + C_2 + C_3$	
Capacitors in series	$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$	
Energy stored	$W = \frac{1}{2}CV^2$	

Nuclear physics

Mass-energy	$\Delta E = c^2 \Delta m$	
Radioactive decay rate	$\frac{dN}{dt} = -\lambda N$	(Decay constant λ)
	$N = N_0 e^{-\lambda t}$	
Half-life	$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$	
Photon model	$E = hf$	
Energy levels	$hf = E_1 - E_2$	
de Broglie wavelength	$\lambda = \frac{h}{p}$	

Matter and materials

Density	$\rho = \frac{m}{V}$	
Hooke's law	$F = k\Delta x$	
Stress	$\sigma = \frac{F}{A}$	
Strain	$\varepsilon = \frac{\Delta l}{l}$	
Young modules	$E = \frac{Stress}{Strain}$	
Work done in stretching	$\Delta W = ½F\Delta x$	(provided Hooke's law holds)

Oscillations and waves

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

For a mass on a spring $T = 2\pi\sqrt{\frac{m}{k}}$

At distance r from a point source of power P, intensity $I = \frac{P}{4\pi r^2}$

For Young's slits, of slit seperation s, wavelength $\lambda = \frac{xs}{D}$

(Fringe width x; slits to screen distance D)

Refraction $\frac{\sin\theta_1}{\sin\theta_2} = \frac{\lambda_1}{\lambda_2} = \frac{c_1}{c_2} = \frac{n_2}{n_1}$ (Refractive index n)

$\sin\theta_c = \frac{c_1}{c_2}$ (Critical angle θ_c)

$n_1 = \frac{c}{c_1}$

Quantum phenomena

Maximum energy temperature $= hf - \varphi$ (Work function φ)

Thermal physics

Celcius temperature $\theta/°C = T/K - 273.15$

Practical Celsius scale $\theta = \frac{X_\theta - X_0}{X_{100} - X_0} \times 100\,°C$

Thermal energy transfer $\Delta Q = mc\Delta T$ (Specific heat capacity c; temperature change ΔT)

Change of internal energy $\Delta U = \Delta Q + \Delta W$ (Work done on body ΔW)

Thermal energy transferred on change of state $= l\Delta m$

(Specific latent heat or specific enthalpy change l)

Rate of thermal energy transfer by conduction $= kA\dfrac{\Delta T}{\Delta x}$

(Thermal conductivity k; temperature gradient $\dfrac{\Delta T}{\Delta x}$)

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

$T \propto$ *Average kinetic energy of molecules*

Mean kinetic energy of molecules $= 3/2\, kT$ (Boltzmann constant k)

Molar gas constant $R = kN_A$ (Avogadro constant N_A)

Upthrust U = Weight of displaced fluid

Pressure difference in fluid $\Delta p = \rho g \Delta h$

Fields

Electric field strength

uniform field $E = F/Q = V/d$

radial field $E = kQ/r^2$ (Where for free space or air $k = 1/4\pi\varepsilon_0$)

Electric potential

radial field $V = kQ/r$

For an electron in a vacuum tube $e\Delta V = \Delta(1/2\, mv^2)$

Gravitational field strength

radial field $g = GM/r^2$

Gravitational potential

radial field $V = -GM/r$, numerically

Time constant for capacitor charge or discharge = RC

Force on a wire $F = BIl$

Force on a moving charge $F = BQv$

Field inside a long solenoid $= \mu_0 nI$ (Number of turns per metre n)

Field near a long straight wire $= \dfrac{\mu_0 I}{2\pi r}$

E.m.f. induced in a moving conductor $= Blv$

Flux $\Phi = BA$

E.m.f. induced in a coil $= \dfrac{Nd\Phi}{dt}$ (Number of turns N)

For $I = I_0 \sin 2\pi ft$ *and* $V = V_0 \sin 2\pi ft$:

$$I_{\text{rms}} = \frac{I_0}{\sqrt{2}} \text{ and } V_{\text{rms}} = \frac{V_0}{\sqrt{2}}$$

$$\text{Mean power} = I_{\text{rms}} \times V_{\text{rms}} = \frac{I_0 V_0}{2}$$

Mathematics

$\sin (90° - \theta) = \cos \theta$

$\ln (x^n) = n \ln x$

$\ln (e^{kx}) = kx$

Equation of a straight line $y = mx + c$

Surface area cylinder $= 2\pi rh + 2\pi r^2$
sphere $= 4\pi r^2$

Volume cylinder $= \pi r^2 h$
sphere $= {}^4/_3\, \pi r^3$

For small angles: $\sin \theta \approx \tan \theta \approx \theta$ (in radians)
$\cos \theta \approx 1$

2. The list gives some quantities and units. *Underline* those which are base quantities of the International (SI) System of units.

coulomb force length mole newton temperature interval

(2)

Define the volt.

....

....

(2)

Use your definition to express the volt in terms of base units.

....

....

....

(3)

Explain the difference between scalar and vector quantities.

....

....

....

(2)

Is potential difference a scalar or vector quantity?

....

(1)
(Total 10 marks)

3. With the aid of an example, explain the statement "The magnitude of a physical quantity is written as the product of a number and a unit".

....

....

....

....

(2)

Explain why an equation must be homogeneous with respect to the units if it is to be correct.

....

....

....

....

....

(1)

Write down an equation which is homogeneous, but still incorrect.

....

....

(2)

4. For each of the four concepts listed in the left hand column, place a tick by the correct example of that concept in the appropriate box.

A base quantity	mole	☐	length	☐	kilogram	☐
A base unit	coulomb	☐	ampere	☐	volt	☐
A scalar quantity	torque	☐	velocity	☐	kinetic energy	☐
A vector quantity	mass	☐	weight	☐	density	☐

(Total 4 marks)

5. Read the passage and then answer the questions at the end.

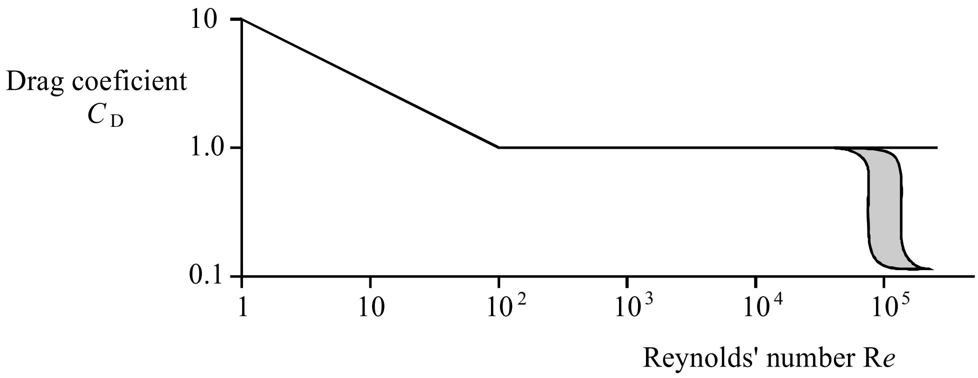
Reynolds' Number

In 1883, Osborne Reynolds studied the way in which different liquids flowed along pipes of various diameters. He observed that when the liquid is moving slowly, it flows smoothly; a streak of dye in the liquid appears as a straight line. Once the speed of the liquid exceeds a certain critical value the streak of dye spreads turbulently over the whole cross section of the pipe. This critical speed depends both on the size of the pipe and the nature of the liquid. Reynolds found that a liquid of density ρ and viscosity μ, flowing along a pipe of diameter d at a steady speed υ, will flow smoothly and not turbulently only if the quantity $\rho\upsilon d/\mu$ is less than about 1300. This dimensionless quantity $\rho\upsilon d/\mu$ is called the Reynolds' Number, *Re.* [Viscosity μ is a measure of how sticky a liquid is: treacle has a high viscosity, water a low viscosity.] The speed of the liquid at which the flow becomes turbulent is also influenced by other factors such as the roughness of the wall of the pipe and the initial quietness of the liquid in the tank from which the liquid is flowing; so the value of 1300 is not strictly a constant.

When a cylinder is immersed in a moving liquid with its axis perpendicular to the liquid flow, it experiences a drag force. This drag force is produced by both the viscous nature of the flowing liquid and its inertia. How smoothly the liquid flows past the cylinder is described in terms of a drag coefficient c_D, which is defined by the equation

$$\frac{F}{l} = 4c_D\rho v^2 r$$

Where *F/l* is the drag force per unit length of the cylinder in the liquid, υ the speed of the liquid flow and *r* the radius of the cylinder. This drag coefficient is not a constant; it value depends on the nature of the liquid flow and hence on the dimensionless quantity $Re = p v d/\mu$, the diameter *d* (= 2*r*) now being that of the cylinder *past* which the liquid flows rather than the diameter of a pipe *along* which it flows.



The graph shows how c_D varies with *Re*. The flat central section is where the drag is largely inertial and the sloping section where it is mostly viscous. The sudden drop at high values of *Re* is where the boundary layer (the liquid immediately in contact with the cylinder) becomes turbulent. The precise position of this transition depends on the roughness of the surface of the cylinder: a rough surface produces a lot of small-scale turbulence which hastens the transition.

(a) Sketch a length of pipe containing a liquid and show how streaks of dye appear when the liquid is flowing smoothly (paragraph 1). Draw a second sketch to show the appearance of the dye when the speed of the liquid exceeds the critical value.

(4)

(b) Explain what is meant by the following as used in the passage:

critical speed (paragraph 1),

initial quietness (paragraph 1),

boundary layer (paragraph 3).

(3)

(c) What are the two situations in the passage where the Reynolds' Number is useful when discussing the flow of a liquid?

In both situations the Reynolds' Number depends on a common feature not given in the formula. What is this common feature?

(3)

(d) The passage states that the quantity $\rho \upsilon d / \mu$ is dimensionless, i.e. has no units. Use this to find the units of viscosity.

Values of viscosity are usually given in N s m^{-2}. Explain whether or not this is consistent with the units you deduced.

(5)

(e) How does the critical speed of a liquid flowing in a given pipe depend upon the density and the viscosity of the liquid?

Discuss whether the critical speed of flow for mercury will be greater or smaller than that for tomato sauce.

(5)

(f) Consider a situation where oil of density 830 kg m^{-3} is moving along a pipe of diameter 0.16 m at an average speed of 0.42 m s^{-1}.

(i) Will the oil flow smoothly or turbulently? Take the viscosity of the oil to be 9.6×10^{-2} N s m^{-2}.

(ii) At one place in the pipe there is a cylindrical rod of radius 1.0 cm with its axis perpendicular to the oil flow.

Sketch this situation and calculate the drag force per unit length on the rod if the drag coefficient is 5.0.

(7)

(g) Consider the graph of drag coefficient against Reynolds' Number for a cylinder.

State the main cause of the drag force for a Reynolds' Number of 10 and for a Reynolds' Number of 1000.

What, approximately, is the value of c_D when Re = 10? Describe the relationship between c_D and Re in the region Re=1 to Re=100.

(5)
(Total 32 marks)

6. Classify each of the terms in the left-hand column by placing a tick in the relevant box.

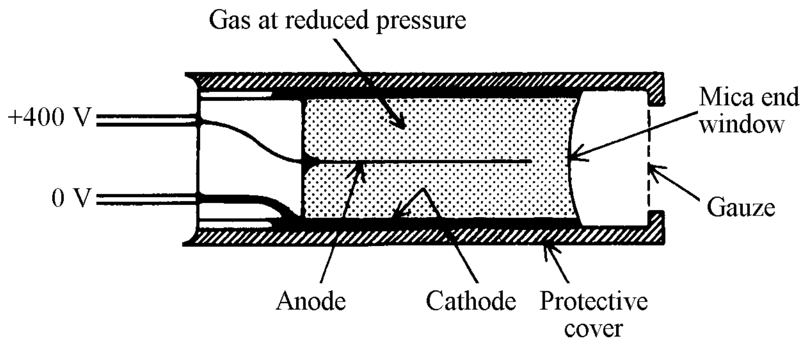
	Base unit	**Derived unit**	**Base quantity**	**Derived quantity**
Length				
Kilogram				
Current				
Power				
Coulomb				
Joule				

(Total 6 marks)

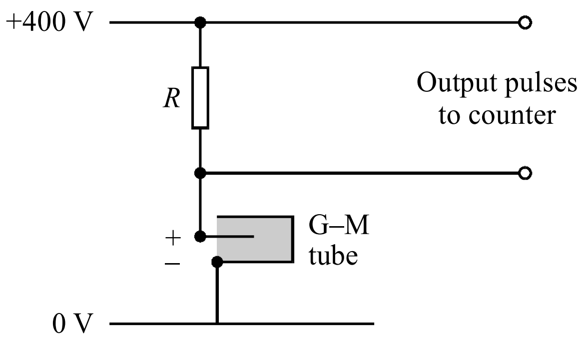
7. Read the passage and then answer the questions at the end.

The Geiger-Müller Tube

This instrument is probably the most versatile and useful of the devices available for detecting radiations from radioactive substances. It is activated by the ionization of the gas it contains and is essentially a form of discharge tube, containing gas at a pressure of about 11 kPa. The voltage at which it operates is just less than that which would produce a continuous discharge in it. Because of the extreme delicacy of the window that must be provided for the particles to enter, it is difficult to design a G–M tube to detect α-particles. A thickness equivalent to a mass per unit area of about 2.0×10^{-2} kg m^{-2} is all that can be allowed. To detect β-particles, a rather thicker window can be used; 30×10^{-2} kg m^{-2} is a common figure.



A typical design is shown in the diagram. The anode consists of a thin wire which runs along the axis of the cylindrical cathode. A large electric field is therefore produced in the immediate vicinity of the anode. In this region any free electrons are sufficiently accelerated to cause further ionization. The process is cumulative, and a small amount of initial ionization can give rise to a considerable "avalanche" of electrons. The electrons, being very light, are collected almost at once by the anode, leaving behind a space-charge formed by the more massive and slow-moving positive ions. In a short time ($\approx 10^{-6}$s) the space-charge becomes sufficiently dense to cancel the electric field round the anode; the ionization process then ceases, and the positive ions are drawn away by the field to the cathode. Thus any ionization of the gas in the tube triggers off an appreciable pulse of current. A single ion pair may be sufficient to initiate a detectable pulse.



The G–M tube is connected in the circuit shown. When an ionizing particle enters the tube, the resulting pulse of current causes a corresponding pulse of p.d. across the resistance *R* in series with it. This is amplified and registered by a suitable device, e.g. a counter.

It is obviously important that only one pulse should be registered for each ionizing particle entering the tube. One method of achieving this is to include a small quantity of a halogen vapour in the tube as a quenching agent. The interval during which these tubes are insensitive to the arrival of further particles is about 10^{-4} a quantity known as the dead time of the counter.

(a) What is meant in the passage by the phrases

(i) *ion pair* (paragraph 2),

(ii) *space-charge* (paragraph 2),

(iii) *dead time* (paragraph 4)?

Explain in your own words what is meant by an "avalanche" of electrons (paragraph 2).

(8)

(b) The mica end window of a G–M tube has a diameter of 24 mm. Calculate the force on the end window when atmospheric pressure is 101 kPa.

Explain why it is difficult to design a G–M tube to detect α-particles.

(6)

(c) (i) The density of mica in the end window of an α-particle detecting G–M tube is 2.8×10^3 kg m^{-3}. The average diameter of a mica molecule is 8.4×10^{-9}m. Calculate the thickness of the end window and hence estimate how many mica molecules make up this thickness.

(ii) Assume that α-particles and β-particles have about the same energy when they are emitted from a nucleus. Suggest why the values of the window thicknesses differ by a factor of 15.

(6)

(d) Sketch the electric field pattern between the anode and the cathode of a G–M tube.

Calculate the acceleration of an electron near to the anode at a place where the electric field strength is 1.2×10^5 V m^{-1}.

(7)

(e) The G–M tube acts as a capacitor of capacitance *C*, typically 10pF, given by

$$C = \frac{2\pi\varepsilon_0 h}{\ln(r_c / r_a)}$$

where r_c and r_a are the radii of the cathode and anode respectively and *h* is the length of the G–M tube.

(i) Show that the expression for *C* is homogeneous with respect to units.

(ii) Calculate a typical time constant for the detecting circuit opposite when $R = 1 \times 10^5 \Omega$.

(5)
(Total 32 marks)

8. Each row in the following table starts with a term in the left hand column. Indicate with a tick which of the three expressions in the same row relates to the first term.

Joule	kg m s^{-2}	☐	kg m s^{-2}	☐	kg $m^2 s^{-3}$	☐
Coulomb	Base Unit	☐	Derived unit	☐	Base quantity	☐
Time	Scalar quantity	☐	Vector quantity	☐	Neither vector nor scalar	☐
Volt	A × W	☐	A × W^{-1}	×	W × A^{-1}	☐

(Total 4 marks)

9. State what is meant by "an equation is homogeneous with respect to its units".

....

....

(1)

Show that the equation $x = ut + 1/2at^2$ is homogeneous with respect to its units.

....

....

....

....

....

(3)

Explain why an equation may be homogeneous with respect to its units but still be incorrect.

....

....

(1)
(Total 5 marks)

10. The joule is the SI unit of energy. Express the joule in the base units of the SI system.

....

....

(1)

A candidate in a physics examination has worked out a formula for the kinetic energy E of a solid sphere spinning about its axis. His formula is

$$E = \tfrac{1}{2}\rho r^5 f^2,$$

where ρ is the density of the sphere, r is its radius and f is the rotation frequency. Show that this formula is homogeneous with respect to base units.

....

....

....

....

....

....

(3)

Why might the formula still be incorrect?

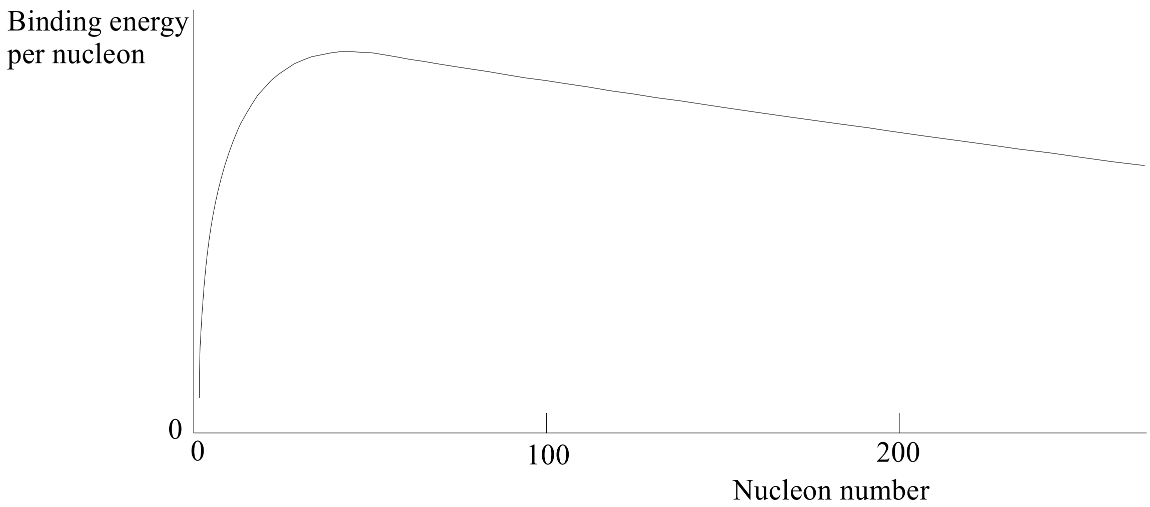
....

....

(1)
(Total 5 marks)

11. A graph of binding energy per nucleon against nucleon (mass) number is shown.

Label the approximate positions of the elements, deuterium D (an isotope of hydrogen), uranium U and iron Fe.



(2)

What is meant by the term *binding energy?*

....

....

....

With reference to the graph, state and explain which of the elements mentioned above would be likely to undergo nuclear fission.

....

....

....

(5)
(Total 7 marks)

12. Calculate the magnitude of the electric field strength at the surface of a nucleus $^{238}_{92}U$. Assume that the radius of this nucleus is 7.4×10^{-15} m.

....

....

....

Magnitude of electric field strength =.......................................

State the direction of this electric field.

....

(4)

State one similarity and one difference between the electric field and the gravitational field produced by the nucleus.

Similarity ....

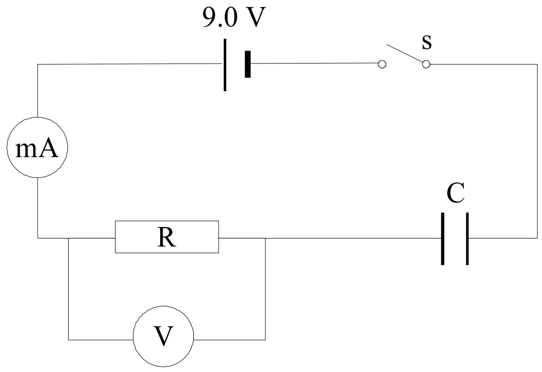
....

Difference ....

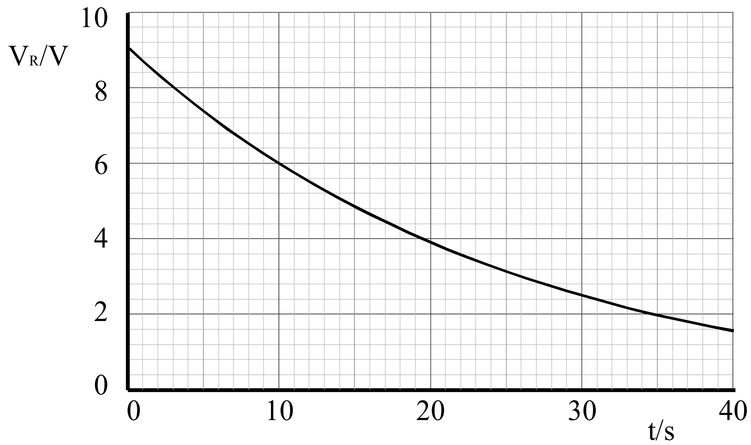
....

(2)
(Total 6 marks)

13. A circuit is set up as shown in the diagram



At $t = 0$ switch S is closed. Readings of the potential difference across the resistor are taken at regular intervals and the graph shown is obtained.



Use the graph to estimate the time constant for this circuit.

....

....

....

....

....

Time constant =...

(2)

The initial current I_0 = 0. 19 mA.

Calculate the resistance of resistor **R** and hence the capacitance of the capacitor **C**.

....

....

Resistance =...

....

....

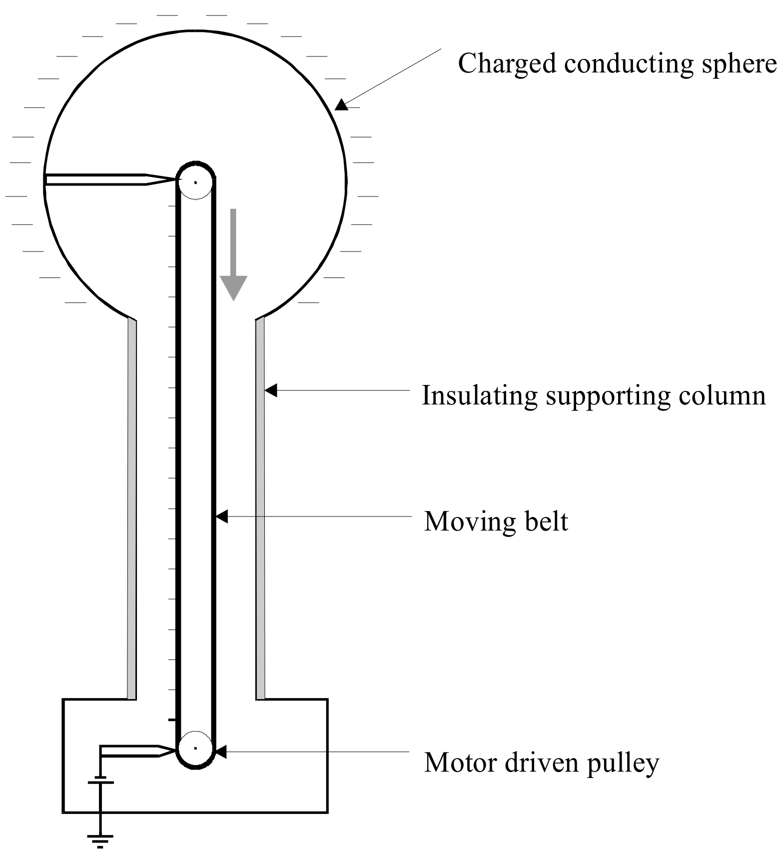
Capacitance =..

(3)

Add to the graph a line showing how the potential difference across the capacitor varies with time over the same period.

(2)
(Total 7 marks)

14. The diagram shows the principle of a Van de Graaff machine for producing high voltages. A spherical hollow conductor is supported by an insulating column. A moving belt collects electrons at the bottom and these are deposited on to the sphere.



(a) Describe how you would use a negatively charged Van de Graaff machine plus other common laboratory materials to show that like charges repel.

(2)

(b) For a belt of width w moving at a speed v, the current I carried to the sphere is given by

$$I = w\upsilon X$$

By considering units, deduce what X represents in this equation.

(3)

(c) (i) Draw a small negatively charged sphere. Add lines showing the electric field in the region around the sphere.

(ii) The electric field close to the surface of a charged sphere of radius 15 cm is found to be 3.6×10^5 N C^{-1}.

Show that the charge on the sphere is a little under 1 μC and calculate the potential of the sphere.

(6)

(d) The sphere of the Van de Graaff is raised to a voltage V and the motor driving the belt is switched off. Charge then leaks through the insulating column reducing the voltage to $V/2$ in 30 s.

(i) How does the motion of the electrons in this leakage current differ from that of the electrons carried by the belt?

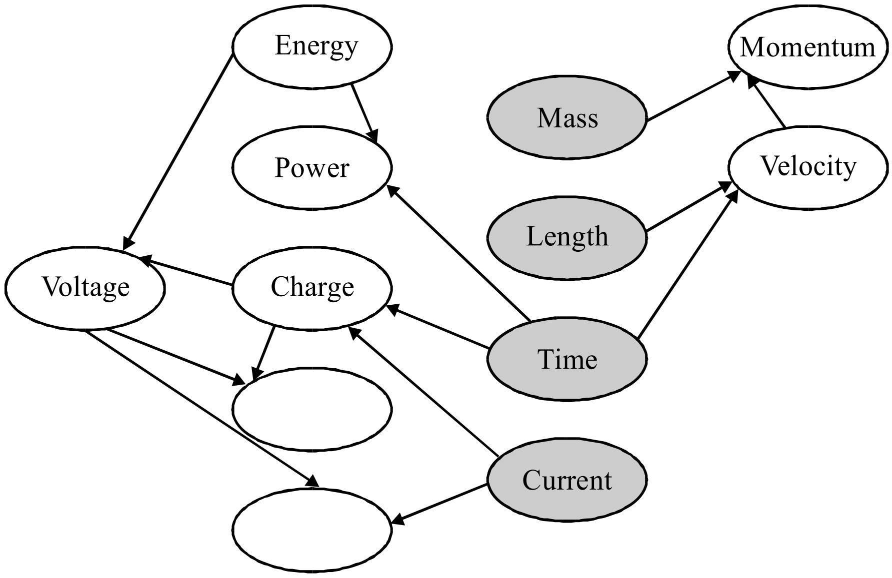
(ii) Sketch a graph showing how the voltage will vary with time for two minutes after the belt ceases to move.

(5)
(Total 16 marks)

15. Many physical quantities are defined from two other physical quantities.

The diagram shows how a number of different quantities are defined by either multiplying or dividing two other quantities.

Write correct quantities in the two blank ellipses below.



(2)

Explain what is special about the physical quantities in the shaded ellipses.

....

....

....

(2)
(Total 4 marks)

16. An example of a nuclear fission reaction is given by the equation below.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{144}_{56}Ba + ^{92}_{36}Kr$$

Data:

Nuclear masses

Uranium –235	= 235.04394u
Barium –144	= 143.92285u
Krypton –92	= 91.92627u
Mass of neutron	= 1.00870u

Use this data to calculate the energy released in joules for each fission.

....

....

....

....

....

....

Energy per fission = ...

(4)

Calculate the power output if 1 mole of uranium–235 undergoes fission by the above reaction and releases its energy in 5.0 s.

....

....

....

....

Power = ...

(3)
(Total 7 marks)

17. Read the passage and then answer the questions at the end.

What is lightning?

Lightning has been a source of wonder to all generations. Its origins, in the processes of the electrification of thunderstorms, are being studied by means of laboratory experiments, together with observational and theoretical studies.

Summer airmass storms and winter-time cold frontal storms can become electrified and produce lightning and thunder. The high currents in the lightning strokes (typically 20 000 A) heat the air sufficiently to cause rapid expansion; the resulting shock wave is heard as thunder. Travelling at the speed of sound, 340 m s^{-1}, the noise arrives after the flash is seen and so the distance to the storm may be estimated. The flash is seen as a result of the effect of the electrical discharge on the gases through which the discharge travels. The lightning may occur completely within the cloud as a cloud stroke, often called sheet lightning, or it may reach the Earth as a ground stroke.

In the production of a ground stroke, the lightning channel first makes its way towards the ground as a weakly luminous negative leader which attracts positive charge from sharp objects on the ground. This leader is a column of negatively charged ions which flow from the charged lower regions of the cloud in a stepwise fashion to form a conducting channel between the cloud and the ground. When a conducting channel is completed the negative charge flows to the ground. The brightest part of the channel appears to move upwards at about 30% of the speed of light. Often there is sufficient charge available to allow several strokes to occur along the same lightning channel within a very short time. The resulting flickering can be observed by the eye and the whole series of strokes is called a flash. The peak electrical power is typically 1×10^8 W per metre of channel, most of which is dissipated in heating the channel to around 30 000ºC.

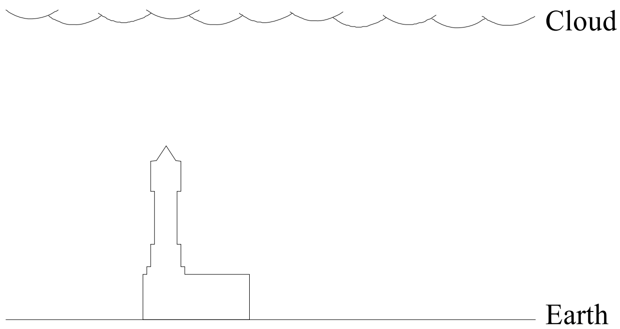
In London the average number of days per year on which thunder is heard is 17, the peak thunderstorm activity being in the late afternoon and evening during summer. When a person is struck by lightning, heart action and breathing stop immediately. Heart action usually starts again spontaneously but breathing may not and, on average, four people are killed by lightning each year in Britain.

(a) (i) Explain how the distance from an observer to a lightning flash may be estimated. Illustrate this for the case where the distance is 1.5 km.

(ii) Explain the meaning of the phrase *sheet lightning* (paragraph 2).

(5)

(b) The diagram represents a storm cloud over a building with a high clock tower.



Copy the diagram. Explain, with the aid of additions to your diagram, what is meant by a *negative leader* (paragraph 3).

(5)

(c) Suppose lightning strikes from a cloud to the Earth along a channel 400 m long. Calculate:

(i) a typical potential difference between cloud and Earth,

(ii) the average electric field strength along such a lightning channel.

(5)

(d) (i) Use the passage to explain how thunder is produced.

(ii) Estimate the pressure of the air within a lightning channel immediately after a lightning flash. Take the atmospheric pressure to be 100 kPa. State any assumptions you make.

(7)

(e) Suggest why those who are killed each year by lightning are usually alone.

(2)

(f) *The flash is seen as a result of the electrical discharge on the gases through which the discharge travels* (paragraph 2).

Rewrite this sentence using the phrases “ionises or excites” and “visible photons”. You may be awarded a mark for the clarity of your answer.

(4)

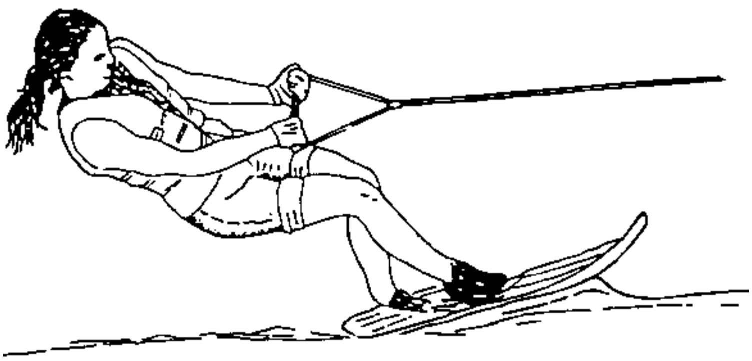
(g) Describe how you would attempt to demonstrate in the laboratory that the electric field strength needed to produce a spark in air is about 3000 V mm^{-1} (3×10^6 V m^{-1}).

Suggest why this value differs from that which you calculated in (c)(ii).

(4)
(Total 32 marks)

[The passage is taken from “Scientific Statement on Lightning”. Dr C P R Saunders, Weather, Vol 49 No 1, the Royal Meteorological Society. Reproduced by permission.]

18. The diagram shows a water skier being pulled at a steady speed in a straight line. Her mass plus the mass of the ski is 65 kg. The pull of the tow-rope on her is 520 N.



(a) (i) What are the horizontal and vertical components *X* and *Y* of the push of the water on the ski? (Ignore air resistance.)

(ii) Her weight and the 520 N towing force exert moments around the point on the ski through which the resultant of *X* and *Y* act.

Explain how she can remain in equilibrium as she is towed along if the size of the towing force varies.

(4)

(b) Later, while still being towed, she moves in a curved path from behind the boat to approach a ramp from which she makes a jump, remaining in the air for over two seconds.

Describe the force which enables her to accelerate centripetally as she moves in a curved path.

Why does she feel “weightless” while in the air during her jump?

(3)

(c) After her jump she again moves with her original velocity, experiencing a towing force of 520 N. Suddenly, she lets go of the tow-rope. Calculate her initial deceleration. Why does her deceleration reduce as she slows down?

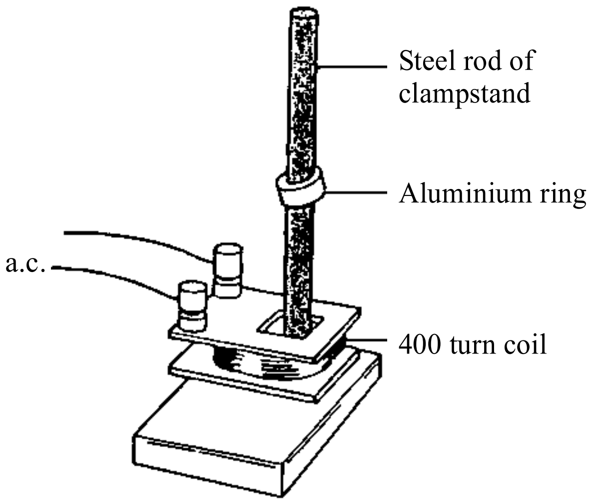
(3)

(d) An observer notices that the waves she produces approaching the shore diffract as they pass through a gap leading to a boatyard. The diffraction of electro-magnetic waves is involved when we collect information about stars and galaxies.

Explain how light diffracted through gratings can yield information about distant stars and galaxies. You may be awarded a mark for the clarity of your answer.

(5)
(Total 15 marks)

19. Apparatus to demonstrate electromagnetic levitation is shown in the diagram.



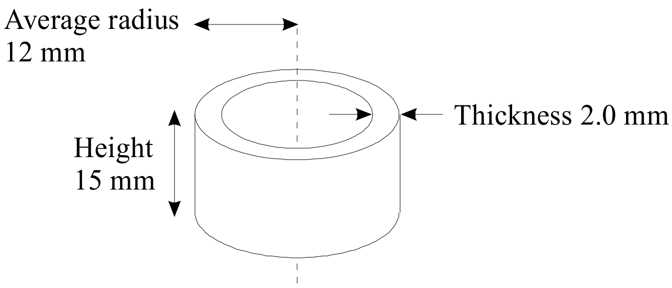
When there is an alternating current in the 400-turn coil, the aluminium ring rises to a few centimetres above the coil. Changes in the size of the alternating current make the ring rise to different heights.

(a) (i) Explain why, when there is a varying current in the coil, there is an induced current in the aluminium ring. Suggest why the ring then experiences an upward force. You may be awarded a mark for the clarity of your answer.

(6)

(ii) In one experiment the power transfer to the aluminium ring is 1.6 W. The induced current is then 140 A. Calculate the resistance of the aluminium ring.

The dimensions of the aluminium ring are given on the diagram below. Use your value for this resistance to find a value for the resistivity of aluminium.



(5)

(b) The aluminium ring becomes hot if the alternating current is left on for a few minutes. In order to try to measure its temperature it is removed from the steel rod and then dropped into a small plastic cup containing cold water.

(i) State what measurements you would take and what physical properties of water and aluminium you would need to look up in order to calculate the initial temperature of the hot aluminium ring.

(3)

(ii) Explain whether experimental errors would make your value for the initial temperature of the aluminium ring too big or too small.

(2)
(Total 16 marks)

20. (a) (i) Particle accelerators are used to increase the energy of charged particles. Circular accelerators can accelerate charged particles to higher energies than can be achieved in linear accelerators. Discuss the principles of physics used in a circular accelerator. You should refer to principles from more than one unit. You may be awarded a mark for the clarity of your answer.

(6)

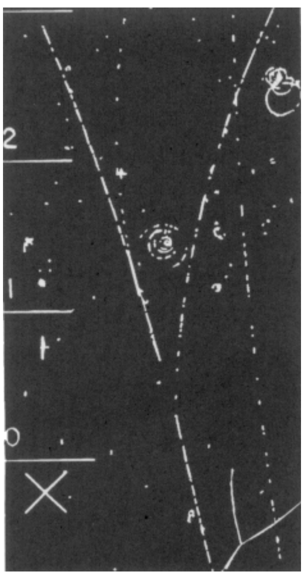
(ii) Show that, if the speed of a charged particle in a circular accelerator is increased, the radius of the circular path increases.

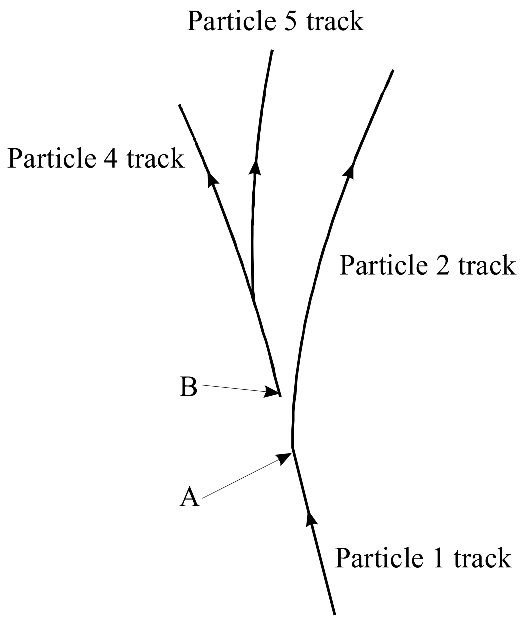
(3)

(b) (i) A bubble chamber contains liquid hydrogen at high pressure. When the high pressure is suddenly released, visible tracks of particles moving through the chamber are produced. Describe the processes which lead to these tracks being made visible.

(3)

(ii) The photograph shows tracks in a hydrogen bubble chamber. The tracks associated with one particular interaction are reproduced as a diagram alongside. There is a magnetic field into the page.





The tracks in the diagram show particle 1 decaying at A into two particles 2 and 3, with particle 3 leaving no track. What can you deduce about particle 2?

Suggest why particle 3 leaves no track.

(3)

(iii) Particle 3 subsequently decays at B into another pair of particles, 4 and 5. The sum of the masses of particles 4 and 5 is less than the mass of particle 3. Explain how this can be the case.

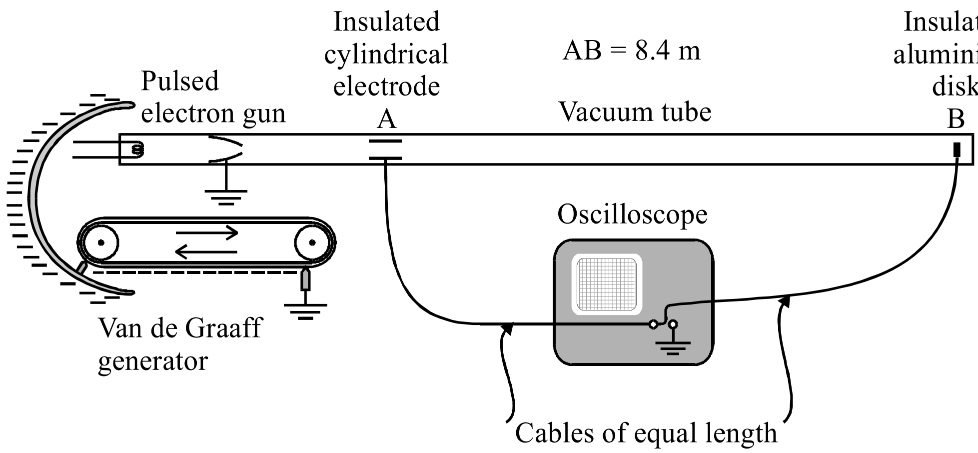
(2)
(Total 17 marks)

21. Read the passage and then answer the questions at the end.

The ultimate speed

According to Newtonian mechanics, there is no upper limit to the speed that may be given to an object. Imagine, for example, that a body is acted on continually by a constant resultant force equal to its weight at the Earth's surface. After six months, starting from rest, its speed would be more than half the speed of light! For an electron, forces very much greater than its weight can be applied, and so it can easily be accelerated to speeds which Newton's laws predict to be greater than the speed of light. As little as 100 V between two electrodes in a vacuum tube would accelerate an electron from rest to about 6×10^6 m s^{-1}. Indeed, if the electrodes were only a few millimetres apart, the electrons' acceleration would be about 10^{15} g. If the acceleration is through millions of volts, the need for a revised non-Newtonian dynamics becomes glaringly obvious.

An experiment was performed in 1962 by W. Bertozzi to measure the speeds of electrons accelerated by a Van de Graaff generator up to measured energies of 1.5 MeV. The experimental arrangement is shown in the diagram.



The idea is to make direct measurements of the time of flight of electrons travelling in a vacuum over a distance AB of 8.4 m. The electrons are released in short bursts of about 3×10^{-9} s duration from the electron gun system. The accelerating voltage is produced by the Van de Graaff generator. A cylindrical electrode at A and an aluminium disk at B pick up signals as a burst passes through A and arrives at B. These signals are carried to an oscilloscope with a calibrated time-base by cables of equal length, giving rise to the following results:

Kinetic energy	T/MeV	0.25	0.50	1.00	1.50
Flight time	$t/10^{-8}$ s	3.85	3.28	3.03	2.92

A direct calorimetric measurement of the kinetic energy of each electron burst is made by monitoring the rate of rise of temperature of the aluminium disk. The number of electrons arriving at B in each burst is found by measuring the rate of rise of the total charge on it. In this way, they were able to confirm that the kinetic energy acquired by an electron accelerated through a potential difference V is eV.

[The passage is adapted from *Special Relativity,* A. P. French, Nelson 1968.]

(a) Calculate the final speed of an object accelerated from rest at 9.81 m s^{-2} for 182.5 days.

(3)

(b) (i) Calculate the electric field strength between two flat electrodes placed 4.0 mm apart when there is a potential difference of 100 V between them.

(ii) What is the force on an electron in this field?

(iii) What is the acceleration of an electron in this field?

(6)

(c) Outline briefly how a Van de Graaff generator can accelerate electrons to very high energies.

(3)

(d) The oscilloscope time-base was set at 10 ns div^{-1}, i.e. 10^{-8} s div^{-1}.

Draw carefully what is seen on the oscilloscope screen when a burst of 1.00 MeV electrons passes down the vacuum tube. Show the time-base scale on the screen.

(4)

(e) When N electrons hit the aluminium disk B, its temperature rises by $\Delta\theta$, where N and $\Delta\theta$ are related by the equation $mc\Delta\theta = NeV$.

(i) What do m and c represent in the product $mc\Delta\theta$?

(ii) Explain what is meant by a potential difference of 1 volt. Hence show that the unit of the product NeV is the joule.

(4)

(f) (i) Calculate the speed υ of the electrons for each value of the flight time given in the table.

(ii) Draw a graph of υ^2 against T, the kinetic energy of the electrons in MeV.

(iii) Does your graph support the prediction of Newtonian mechanics that $\upsilon^2 \propto T$? Justify your answer.

(iv) What would you expect the best fit graph line to do as T rises to 10 MeV and beyond?

(8)

(g) Explain why, in the Bertozzi experiment,

(i) the cables from A and B to the oscilloscope are of equal length,

(ii) a direct calorimetric measurement of the energy of each electron is made.

(3)
(Total 31 marks)

22. (a) The equations $F = kx$ and $V = \dfrac{Q}{C}$ are sometimes referred to as analogous mathematical models for a spring and a capacitor respectively.

(i) State what physical quantities are represented by F, x, V and Q in the equations above.

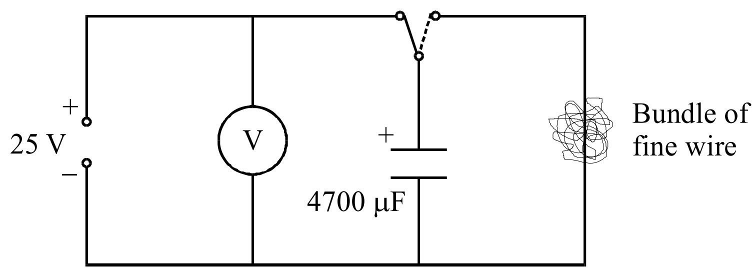
(ii) The energy stored in a capacitor is given by $W_c = \dfrac{1}{2}QV$ and also by $W_c = \dfrac{1}{2}CV^2$.

Write down, by analogy, the two equivalent expressions for the energy W_s stored in a spring.

Show that W_s can also be expressed as $\dfrac{1}{2}kx^2$.

(5)

(b) (i) A 4700 μF capacitor is charged to 25 V and discharged through a tightly wound bundle of fine insulated wire.

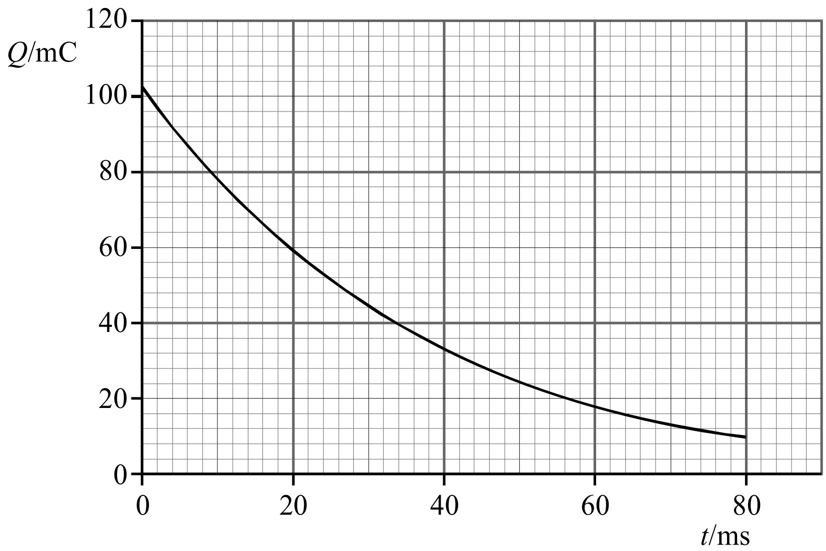


Calculate the energy dissipated in the wire.

Explain why it would be difficult to use this arrangement to demonstrate that $W_c \propto V^2$ for a range of potential differences up to about 50 V. You may be awarded a mark for the clarity of your answer.

(6)

(ii) The graph shows how the charge on the capacitor varies with time as it discharges.

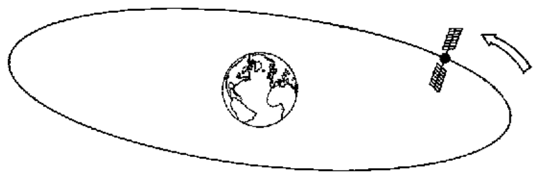


State what name is given to this shape of graph and name another physical phenomenon which gives rise to graphs of this shape.

Showing your working, determine a value for the resistance of the bundle of wire.

(6)
(Total 17 marks)

23. A communications satellite is in geosynchronous orbit around the Earth, i.e. it orbits the Earth once every 24 hours. The radius of the orbit is 4.2×10^4 km.



(a) (i) Show that the acceleration of the satellite is about 0.2 m s^{-2}. In what direction is the acceleration?

(ii) This acceleration is equal to the gravitational field strength g of the Earth at the satellite orbit.

Explain how a knowledge of g at 4.2×10^4 km from the centre of the Earth enables the mass of the Earth to be calculated.

(6)

(b) The satellite's electrical system is powered by an array of 18 000 photovoltaic cells, each of area 12 cm^2.

(i) When fully illuminated in space by sunlight of intensity 1.4 kW m^{-2}, the array produces 4.5 kW of electrical power.

Calculate the efficiency of transfer of solar to electrical energy.

(3)

(ii) In laboratory tests, the internal resistance of a single cell was found to be 40 Ω.

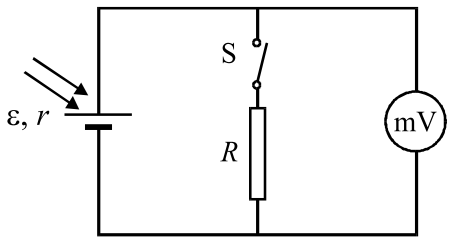
In the satellite the 18 000 cells are arranged in 300 rows of 60 by connecting 60 of them in series and joining 300 such rows in parallel.

Show that the combined resistance of the 18 000 cells in this arrangement is less than 10 Ω.

What e.m.f. will this arrangement produce if the e.m.f. of one cell is $\mathcal{E}$?

(4)

(iii) To measure the internal resistance *r* of one cell, a student uses the circuit shown.

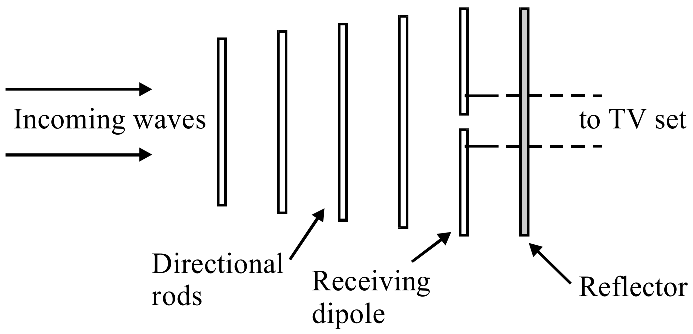


Explain how, by taking readings with the switch S first open and then closed, the student can find the value of *r*.

Suggest a value for the fixed resistor *R* when r is 40 Ω.

(4)
(Total 17 marks)

24. (a) The diagram shows the main features of a rooftop TV aerial. The supporting structure is omitted. The receiving section is the unshaded dipole.



(i) The incoming signal is a plane polarised electromagnetic wave of frequency 1.07 GHz.

Calculate the wavelength of the incoming wave.

Outline how you could demonstrate experimentally, using the aerial and a TV set, that the incoming wave was plane polarised.

(5)

(ii) Two waves, the incoming wave and its reflection from the reflector, are superposed at the receiving dipole.

Explain what is meant by the phrase ‘two waves are superposed’.

Suggest, with a reason, how far the reflector should be placed from the receiving dipole to get the strongest signal for the TV set.

(4)

(b) A plane electromagnetic wave consists of oscillating electric and magnetic fields. The intensity or energy flux I, measured in W m^{-2}, can be expressed as

$$I = \frac{cB_0^2}{2\mu_0}$$

where B_0 is the maximum value of the magnetic flux density and the other symbols have their usual meaning.

(i) Show that the expression for I is homogeneous with respect to units.

(ii) Describe how a coil, together with any other apparatus you require, could be used to detect the presence of a steady magnetic field in the region of a bar magnet.

(6)
(Total 15 marks)

25. Read the passage and then answer the questions at the end.

Light can exert a force

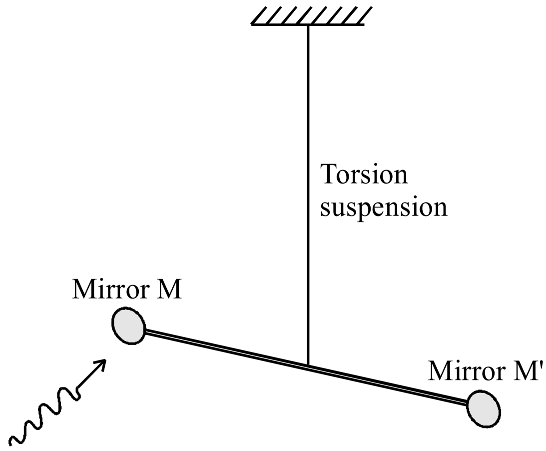
Energy is carried from the Sun to the Earth or from an open fire to a hand by electromagnetic waves. More surprising is the fact that electromagnetic waves also transport linear momentum. This means that it is possible for electromagnetic waves to exert a force, and hence a radiation pressure, on an object, e.g. by shining light on it. Such forces must be small as we do not, after all, get pushed backwards when we raise a window blind and let in the sunlight. Radiation pressure is partly responsible for the way the tails of comets stream away from the Sun. Its use has even been proposed to propel space vehicles, by using reflecting sails that would open when the vehicle is going “down wind”.

When a parallel beam of light, of intensity or energy flux I, falls perpendicularly on an absorbing surface of area A, the energy E incident in a time t is equal to IAt. The momentum p transferred to the surface is given by

$$p = \frac{E}{c} = \frac{IAt}{c}$$

where c is the speed of light. When the light is entirely reflected from the surface the momentum transfer will be twice this amount, just as a perfectly elastic ball transfers twice its initial momentum when it bounces from the Earth.

The first measurement of radiation pressure was made more than a hundred years ago by Nichols and Hull using a torsion balance technique.



They allowed light to fall on mirror M in the diagram, causing the balance arm MM' to turn through a measured angle θ. By switching the beam on and off, they were able to find the resonant frequency f_0 of the torsion balance. A knowledge of θ and f_0, together with details of the suspended mirror system, enabled them to calculate the force, and hence the radiation pressure, exerted by the light. The intensity of their light beam was measured by allowing it to fall on a blackened metal disc and measuring the rise in temperature of the disc. Their experiments measured a radiation pressure of 7.01 μPa compared to the predicted value of 7.06 μPa.

[Adapted from D Halliday and R Resnick: *Phvsics* parts I and 11 Combined, third edition, 1978]

(a) Explain the meaning of the following phrases as used in the passage:

(i) radiation pressure (paragraph 1),

(ii) down wind (paragraph 1),

(iii) perfectly elastic (paragraph 2).

(5)

(b) (i) Show that p = Iat / c is homogeneous with respect to units.

(ii) Light of intensity 12 W cm^{-2} falls for 30 minutes on a mirror of area 460 cm^2 which reflects 80% of the incident light. Calculate the energy reflected from the mirror in this time.

(7)

(c) Consider the following argument:

The momentum transferred to the surface $= IAt / c$ (paragraph 2)
Hence the force exerted on the surface $= IA / c$ (step 1)
Hence the pressure on the surface $= I / c$ (step 2)

(i) State the physical principle used in step 1.

State the physical principle used in step 2.

(ii) In sunlight the force on two sails, each of area 2 km^2, is of the order of 10 N each at a distance from the Sun equal to the Earth's orbital radius.

Discuss the viability of using such sails to propel space vehicles, already in orbit, to reach the outer planets of the solar system.

(5)

(d) Refer to the experiment performed by Nichols and Hull (paragraph 3).

(i) Describe how the balance arm was set into resonant oscillations and sketch a graph of the amplitude of oscillation against the forcing frequency.

(ii) Suggest two ways of modifying the apparatus to increase the angle θ through which the balance arm MM' rotated when M was illuminated.

(5)

(iii) State what data and what measurements, in addition to the rise in temperature of the disc, would be needed in order to establish the intensity of the light beam used.

(iv) The calculated uncertainty in their measured value, 7.01 μPa, of the pressure of light was 1.5%. Discuss briefly whether or not the result of their experiment confirms the theory of radiation pressure.

(5)

(e) (i) Why is the fact that light can transport linear momentum surprising? (paragraph 1).

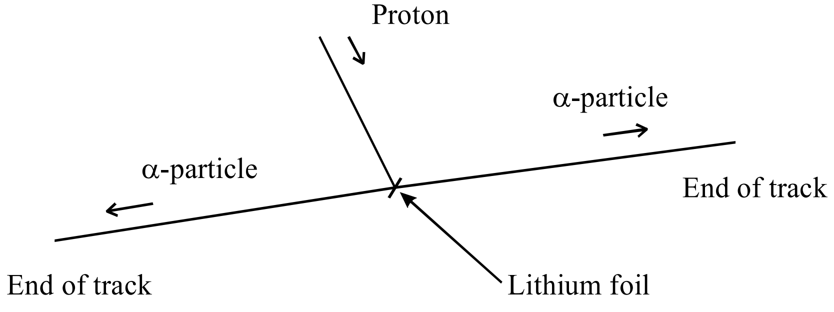
(ii) By considering the equation $p = E/c$, show that the momentum of a single photon of yellow light of energy E, for which $\lambda = 560$ nm, is about 10^{-27} N s.

(4)

(f) Draw a sketch to illustrate "the way the tails of comets stream away from the Sun" (paragraph 1). Your sketch should show the direction in which the comet is moving as well as the direction of the tail.

(2)
(Total 33 marks)

26. In 1932 Cockroft and Walton accelerated protons through a few hundred kilovolts and directed them at a lithium-7 target placed in a cloud chamber. The diagram illustrates the outcome of the experiment.



(a) (i) What evidence is there in the diagram that the two α-particles have the same initial energy?

(ii) Write a nuclear equation for this event.

(4)

(iii) Calculate the kinetic energy of the pair of α-particles in joules, given

mass of proton = 1.007 28 u
mass of lithium nucleus = 7.014 37 u
mass of α-particle = 4.001 50 u

State any assumption you make.

(4)

(b) Describe how the tracks of the protons and α-particles are produced in **either** a cloud chamber **or** a bubble chamber. You may be awarded a mark for the clarity of your answer.

(4)

(c) As the proton approaches the lithium-7 nucleus, it is attracted gravitationally and repelled electrostatically.

Show that the ratio of the electrostatic force between these two particles to the gravitational force between them is independent of their distance *r* apart.

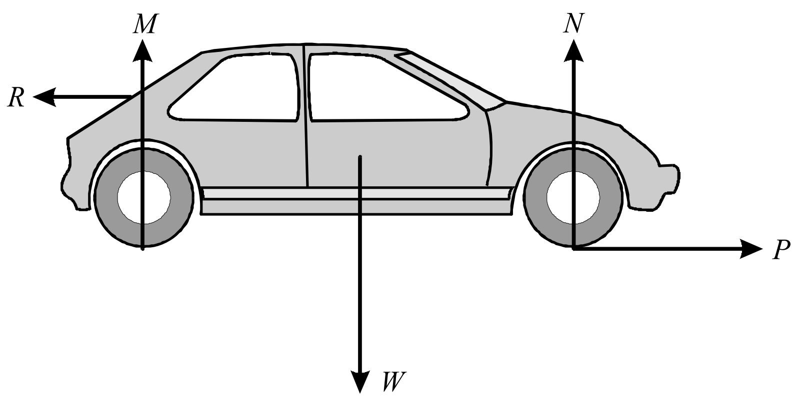
Hence show that this ratio is a very large number. (Refer to the data on the data sheet)

(4)
(Total 16 marks)

27. (a) A car is advertised as being able to accelerate from 0 to 60 miles per hour in 4.5 s.

(i) Given that 1 mile = 1.6 km, calculate the average acceleration of the car. Express this acceleration as a fraction of the acceleration of a freely falling body close to the Earth's surface.

(ii) The diagram shows a free-body force diagram for a front wheel drive car as the car accelerates from rest.



R is the backward push of the air on the car. Describe, in similar terms, each of the forces *P* and *W*.

(5)

(iii) The car's power unit may be considered as a heat engine. Draw a labelled energy flow diagram for this heat engine.

(4)

(b) The car is later travelling at a constant velocity υ of 29 m s^{-1}. A speed trap measures this velocity using microwaves of frequency 1.1×10^{10} Hz.

(i) When the microwaves are reflected from the receding car, a Doppler shift is detected.

What is meant by a **Doppler shift?**

In this case $\frac{\Delta f}{f} = \frac{2\upsilon}{c}$. Calculate the Doppler shift in this case.

(3)

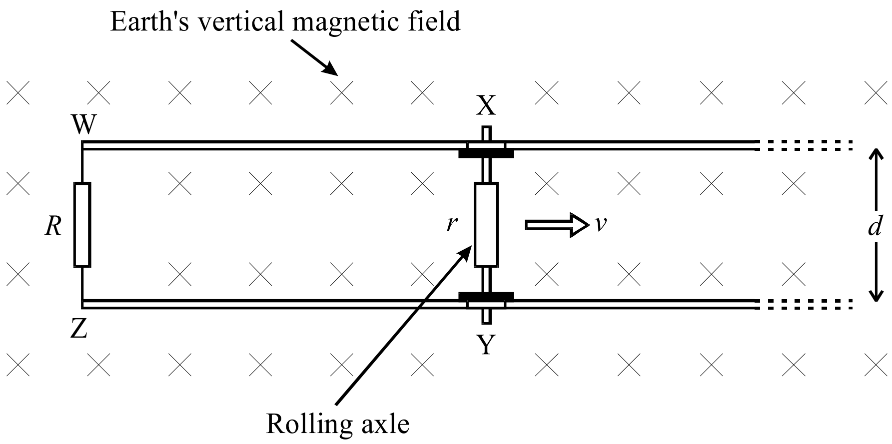
(ii) The wavelength of the microwaves used can be measured in the laboratory. Describe how this could be done.

(4)
(Total 16 marks)

28. The diagram shows a plan view of two horizontal parallel railway rails a distance *d* apart connected at one end by a conducting link WZ of resistance *R*. The rails have negligible electrical resistance.

An engineer rolls an axle XY, of resistance *r*, along the rails at a speed υ.

The vertical component of the Earth's magnetic flux density B_v acts downwards as indicated.



(a) As the axle moves along the rails an e.m.f. $\mathcal{E}$ is induced in the circuit WXYZ.

(i) Explain the origin of this induced e.m.f.

(ii) The size of the e.m.f. is given by $\mathcal{E} = B_v \upsilon d$. Suggest suitable values for *d* and *v* and hence estimate a value for $\mathcal{E}$. Take B_v to be 48 μT.

(5)

(iii) Show that the power *P* transferred to the conducting link of resistance *R* in the circuit WXYZ can be expressed as $P = \mathcal{E}^2 R / (R + r)^2$.

(3)

(b) (i) A small-scale model of this system is set up in a laboratory. State what additional apparatus is needed, how it is used and what readings need to be taken to determine the power transferred to the resistor forming the conducting link in the model.

(4)

(ii) It is suggested that in the laboratory the axle could be driven along the rails by replacing the conducting link WZ with a battery capable of delivering large currents.

Explain how the system would work.

Comment on the practicability of driving a train in this way.

(3)
(Total 15 marks)

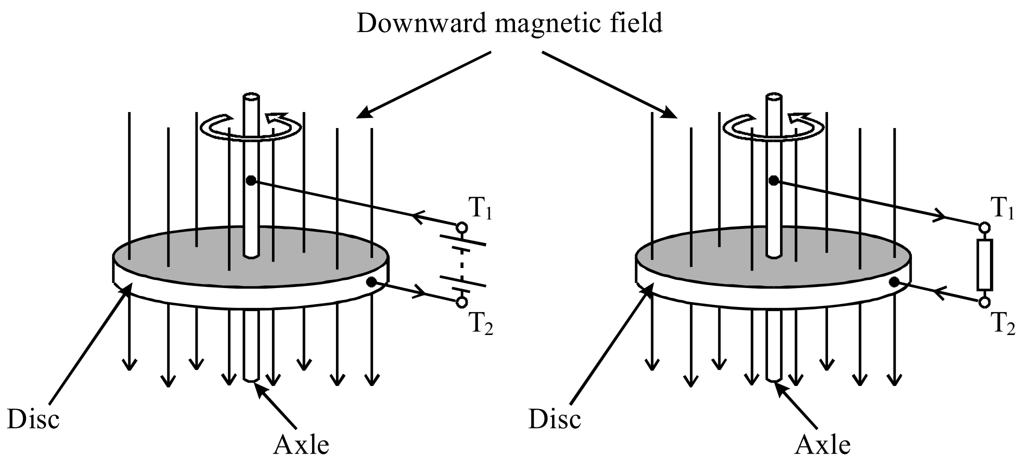
29. Read the passage and then answer the questions at the end.

The homopolar generator

In principle a homopolar generator consists of a conducting disc spinning about an axis in a magnetic field parallel to this axis. When the spinning disc is stopped suddenly, all its kinetic energy can be used to generate large current surges.

In order to spin the disc up to speed, a d.c. power supply is connected as shown in Figure 1. The magnetic force on the current crossing from the axle to the rim of the conducting disc provides the necessary accelerating force. As the conducting disc speeds up, however, there is an increasing voltage generated between the terminals T_1 and T_2. When the power supply is disconnected this voltage can be used to drive a current through a resistor connected between them as shown in Figure 2.

Figure 1 Speeding up disc — **Figure 2 Using generated voltage**



The size of the voltage V generated can be calculated from the relationship

$$V = \pi\left(r_d^2 - r_a^2\right)fB$$

where r_d and r_a are the radii of the disc and axle, f is the frequency of rotation of the disc and B is the magnetic flux density assumed to be uniform over the surface of the disc.

The main purpose of homopolar generators is as research tools to produce huge surges of current when their terminals are suddenly short-circuited. Apart from increasing the magnetic field, higher generated voltages can be obtained by increasing the speed of rotation or the diameter of the disc. The speed cannot be increased indefinitely as the speed of the edge of the disc is limited to a maximum of about 200 m s^{-1} by the mechanical properties of the material, usually steel, from which it is made.

One large homopolar generator in Australia, which is designed to produce huge current surges, measures 3.6 m in diameter, rotates at 15 Hz and is so massive that the kinetic energy it stores at this speed is 580 MJ. When it is short-circuited, the current surges are used to produce short-lived, but extremely high, magnetic fields in order to study the properties of matter under extreme conditions. Such fields, it is proposed, could be used in an electromagnetic gun to project a small mass at speeds of over 7 km s^{-1}. this speed is of the order of the speed of satellites in low orbit and hence the projected masses could be used to study the problems encountered by missiles re-entering the atmosphere.

(a) What is meant by the term 'short-circuited' used in the passage (paragraph 4)?

(2)

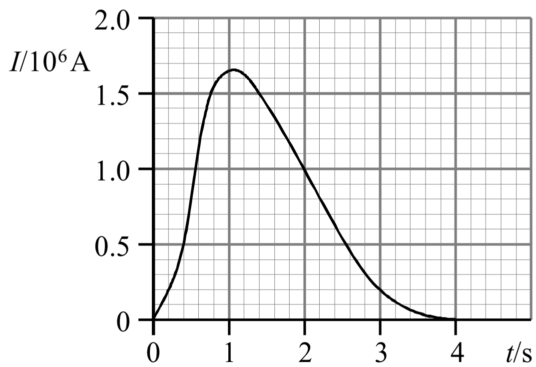
(b) (i) Is the output of a homopolar generator a.c. or d.c.?

(ii) List the quantities on which the voltage generated by a homopolar generator depends.

(iii) Give two uses which are suggested for the huge surges of current produced by a homopolar generator.

(6)

(c) The graph shows a current surge from a short-circuited homopolar generator.



(i) Estimate the charge flowing during this surge. Show each stage of your calculation.

(ii) Calculate the maximum power dissipated when the terminals T_1 and T_2 of the generator, which has an 'internal' resistance 0.12 mΩ (1.2×10^{-4} Ω), are connected together through a negligible external resistance.

(7)

(d) Show that the equation $V = \pi(r_d^2 - r_a^2)fB$ is homogeneous with respect to units.

(4)

(e) Figure 1 shows how the disc of a homopolar generator is spun up to speed.

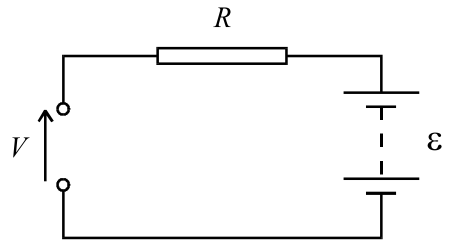
(i) State the main energy change involved.

(ii) What force speeds up the rotation of the disc?

(iii) Show that the speed of the edge of the disc described in the last paragraph is less than the maximum safe speed.

(5)

(f) In the circuit diagram below, the e.m.f of the d.c. power supply used to speed up the disc is $\mathcal{E}$ and the opposing voltage generated by the rotating disc is *V*. The total resistance of the circuit is *R*.



Write down an equation from which the current *I* in the circuit can be calculated and explain why *I* decreases as the speed of the disc increases.

(3)

(g) (i) Show that the speed v of a satellite in a circular orbit at a height *h* above the Earth's surface is given by

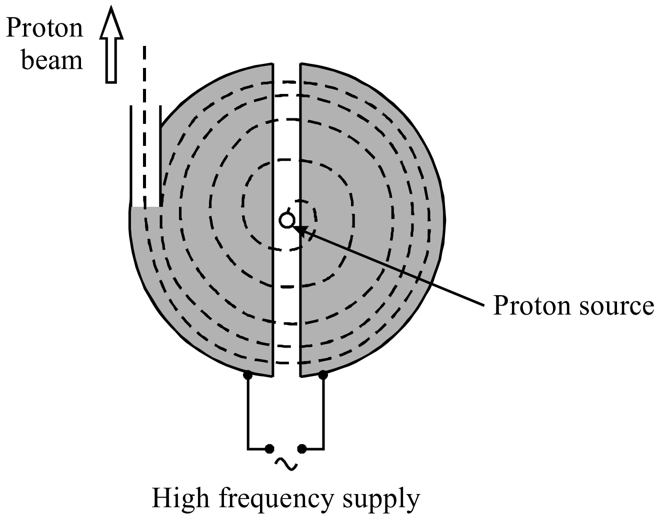
$$v = \sqrt{\frac{Gm_E}{(r_E + h)}}$$

where m_E is the mass of the Earth and r_E is its radius.

(ii) If $m_E = 6.0 \times 10^{24}$ kg and $r_E = 6.4 \times 10^6$ m, for what value of *h* is the orbital speed equal to7 km s^{-1}?

(4)
(Total 31 marks)

30. (a) The simplified diagram shows the ‘dees’ of a cyclotron connected to a high frequency alternating supply. The dashed line shows the path of an accelerated proton. In the shaded region a uniform magnetic field *B* of flux density 0.80 T acts upwards out of the paper.



(i) Explain why the magnetic field must be upwards out of the paper when accelerating protons.

(ii) By considering a proton of mass m and charge e (1.6×10^{-19} C) moving in a circle of radius r in the cyclotron, show that the time t taken to complete one semicircle is given by

$$t = \frac{\pi m}{Be}$$

(5)

(iii) Describe how the energy of the proton is increased in a cyclotron. Give one reason why the energy cannot be increased indefinitely. You may be awarded a mark for the clarity of your answer.

(4)

(iv) Show that the gain in energy of a proton accelerated through a potential difference of 12 kV is about 2×10^{-15} J.

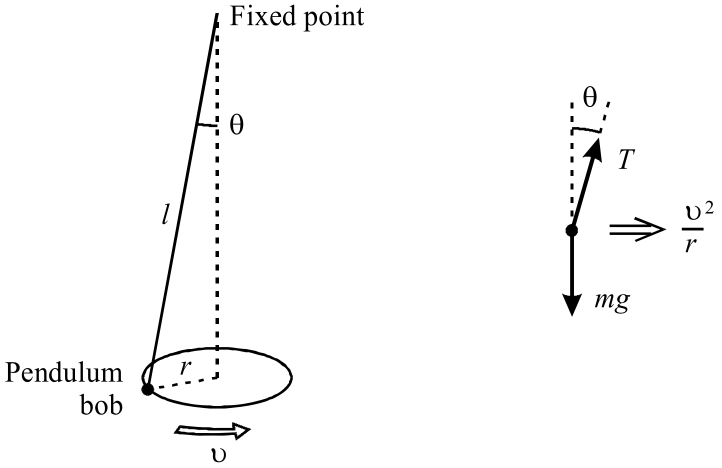
(v) The kinetic energy of a proton circling at a radius *r* can be expressed as

$$\text{k.e.} = \frac{B^2 e^2 r^2}{2m}$$

Calculate the radius of the circle in which a proton will be moving after being accelerated 850 times across a potential difference of 12 kV.

(4)

(b) The diagram shows a pendulum bob of mass *m* which has been set moving in a horizontal circle at a speed υ, together with a free-body force diagram for the bob.



The time *t* taken by the pendulum bob to complete half a circle can be deduced as follows:

$$m\frac{\upsilon^2}{r} = T\sin\theta$$

$$mg = T\cos\theta$$

$$\Rightarrow \frac{v^2}{rg} = \tan\theta$$

$$\text{so } t = \frac{\pi r}{v} = \pi\sqrt{\frac{r}{g\tan\theta}}$$

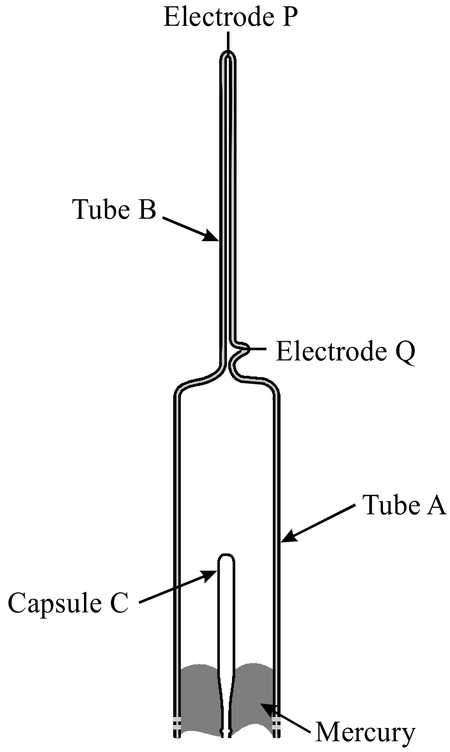
(i) State how Newton's laws of motion are applied in this deduction.

(ii) What assumption is needed in order to show that the expression for *t* deduced above is independent of the radius of the circle in which the pendulum bob is moving?

(iii) Suggest how you might use an arrangement like this as an analogy to demonstrate how protons are accelerated in a cyclotron.

(5)
(Total 18 marks)

31. In 1908 Rutherford and Royds, working at Manchester University, used the apparatus shown to study the nature of α-particles.



Radon gas, $^{222}_{86}\text{Rn}$, which decays by α-emission to an isotope of polonium, Po, is placed at atmospheric pressure in a capsule C made from very thin glass. Any α-particles passing through the glass from C become helium atoms in the evacuated tube A.

(a) (i) Write a nuclear equation for this α decay.

(ii) What must happen to an α-particle in order for it to become a helium atom?

(4)

(b) Even after several days, the helium gas that accumulates in tube A is only at a very low pressure *p*. By raising the level of the mercury, this gas is compressed into the narrow tube B.

(i) Take measurements from the diagram and use them to show that the ratio of the volumes of the tubes A and B is about 150.

(ii) If the pressure of the helium when compressed into tube B is 20 Pa, calculate a value for *p*.

(iii) Explain why the capsule C must have very thin walls.

(6)

(c) When a potential difference is applied across the electrodes P and Q, the helium atoms in tube B are excited and the resulting spectrum for helium can be studied.

(i) Outline how you could study the spectrum of helium in the laboratory. What would you observe in your experiment?

(ii) Explain, in terms of the frequencies of the emitted photons, why the spectrum of a gaseous element is unique to that element.

(iii) Discuss briefly whether the presence of mercury vapour in tube B would have been confusing in this experiment.

(6)
(Total 16 marks)

32. (a) (i) A body can be said to be moving with simple harmonic motion when

$$a = -(2\pi f)^2 x$$

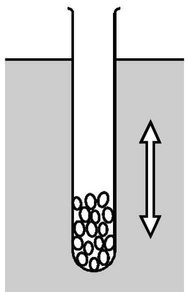
State what a, f and x represent in this equation and explain the significance of the minus sign.

(4)

(ii) Calculate the maximum speed of an electron which is oscillating with simple harmonic motion in a mains wire at 50 Hz with an amplitude of 8.0 μm.

(3)

(b) The diagram shows a weighted test tube of cross-sectional area A and mass m which is oscillating vertically in water.



The frequency f of the oscillations, which can be considered to be independent of their amplitude, is given by

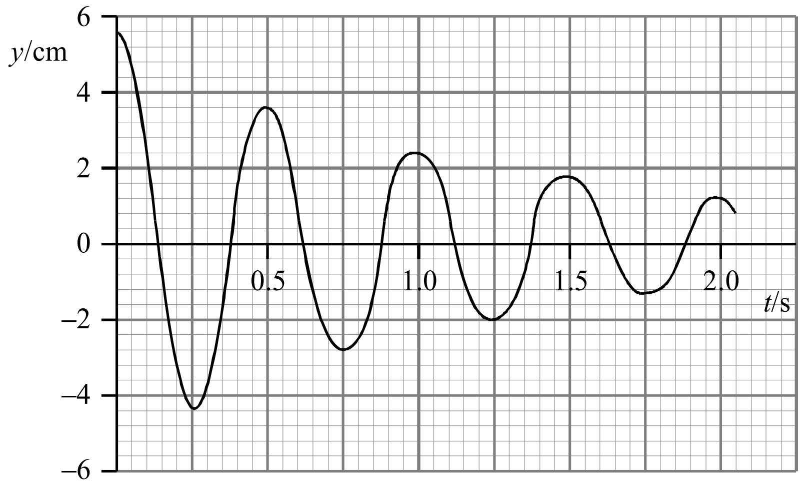
$$2\pi f = \sqrt{\frac{A\rho g}{m}}$$

where ρ is the density of the water and g is the acceleration of free fall.

(i) Show that this equation is homogeneous with respect to units.

(2)

(ii) The graph shows how the vertical displacement y of the test tube varies with time t. This shows that the oscillations of the test tube are damped. The damping is thought to be exponential.



By taking measurements from the graph, discuss whether the damping is exponential in this case.

(3)

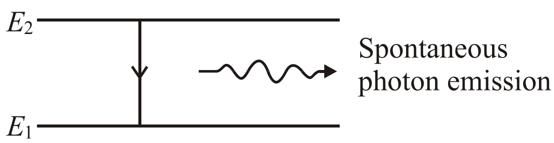
(iii) Sketch a rough graph to show how the kinetic energy of the test tube varies from $t = 0$ to $t = 0.5$ s, i.e. during its first oscillation. Add a scale to the time axis.

(3)
(Total 15 marks)

33. Read the passage and then answer the questions at the end.

Spontaneous and stimulated emission of radiation

An atom in an excited state emits radiation by dropping to a state of lower energy, often the ground state. This is a random process in which each atom has an average lifetime in the excited state. The diagram shows this random process of spontaneous emission.



Einstein proposed that in addition to this process, the transition from an excited state could also be triggered by radiation of the correct frequency. This type of emission is known as stimulated emission. In stimulated emission an incoming photon, which is not absorbed, triggers a transition to the lower energy state, thus producing a second identical photon.

The emitted photons in both spontaneous and stimulated emission have clearly defined frequencies determined by the atom's energy levels. However, other effects, such as Doppler shifts caused by the motion of the atoms, broaden what should be a very sharp line in the emission spectrum into a narrow band.

When a large number of gas atoms are in thermal equilibrium at an absolute temperature T, the number of atoms in each of the energy levels depends only on the temperature. The higher the energy level, the smaller the number of atoms raised to that energy by thermal agitation. If N_1 is the number of atoms at level E_1, the ground state, and N_2 the number of atoms at level E_2, then

$$N_2 = N_1 e^{-\Delta E/kT}$$

where $\Delta E = E_2 - E_1$ and k is a constant. Similar equations relate N_3 to N_2 and N_4 to N_3 etc. An incoming photon may be absorbed and excite an atom in the ground state E_1, a process which subsequently results in spontaneous emission. However, an incoming photon is hardly ever going to interact with an atom already in an excited state such as E_2 to give rise to stimulated emission. This is because $N_2 << N_1$, even at high temperatures, and is why the emission of visible light from excited atoms is usually regarded as a completely random process.

In certain circumstances, however, it is possible to arrange for $N_2 > N_1$, a situation known as population inversion. In this case the gas atoms are not in thermal equilibrium, indeed the 'temperature' of the gas can be thought of as being negative. Each photon now entering the gas is more likely to produce stimulated emission than to be absorbed. In these circumstances the photon flux is increased – a situation described as **l**ight **a**mplification by the **s**timulated **e**mission of radiation or as **laser** action.

[This passage is adapted from *Masers and lasers* by R A Smith in Endeavour, April 1962.]

(a) Explain the meaning of the following phrases as used in the passage:

(i) absolute temperature (paragraph 4),

(ii) Doppler shifts (paragraph 3),

(iii) a random process (paragraphs 1 and 4).

(5)

(b) The diagram above illustrates the spontaneous emission of a photon when an atom has a transition from an excited state E_2 to the ground state E_1.

(i) Calculate the wavelength of the emitted photon when $E_2 - E_1 = 2.0$ eV. To which region of the electromagnetic spectrum does this radiation belong?

(ii) Sketch an energy level diagram showing the ground state and three possible excited states for an atom. Explain, using your diagram, why there can be six possible wavelengths for photons emitted from atoms occupying such a set of excited states.

(7)

(c) (i) Draw a diagram, similar to the diagram above, to illustrate what happens in the stimulated emission of a photon.

(ii) Explain in your own words how light amplification is achieved in a laser.

(4)

(d) State the circumstances under which the 'temperature' of a gas can be thought of as being negative.

(2)

(e) The average kinetic energy of helium atoms of mass 6.7×10^{-27} kg at room temperature is 6.0×10^{-22} J.

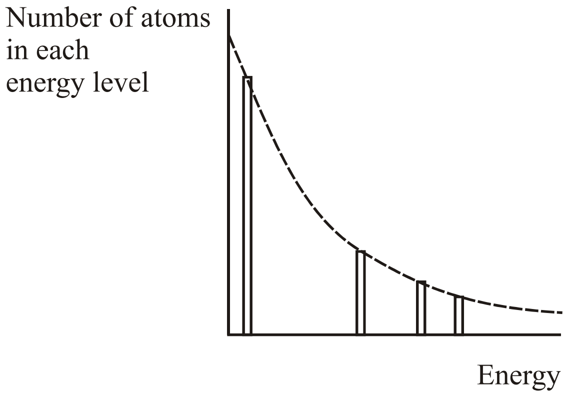
(i) Calculate the average speed of helium atoms at room temperature.

(ii) Show that these helium atoms produce a Doppler shift $\Delta\lambda$ of less than 10^{-12} m for photons of wavelength 600 nm.

(iii) Suggest why the spectral line at 600 nm is found to be broader than 10^{-12} m.

(6)

(f) The diagram shows the number of atoms in some energy levels for a gas in thermal equilibrium at a temperature T.



(i) What determines the number of atoms in each energy level?

(ii) State how atoms are raised to higher energy levels.

(2)

(g) Suppose that a very large number of hydrogen atoms are in thermal equilibrium at a temperature of 1150 K and that two million of these atoms are raised to level E_3, i.e. $E_3 = 2.00 \times 10^6$.

(i) Use $N_4 = N_3 e^{-\Delta E/kT}$ to show that the number of atoms N_4 in level E_4 is just over 2500, given that

$$\Delta E = E_4 - E_3 = 1.06 \times 10^{-19} \text{ J and } k = 1.38 \times 10^{-23} \text{ J K}^{-1}$$

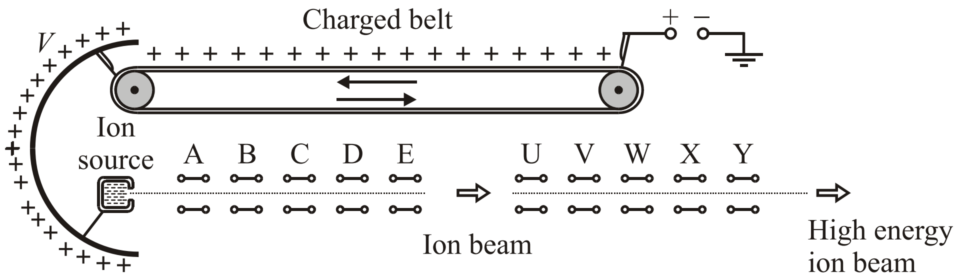
Show all your working.

(ii) Calculate the number of atoms N_5 in level E_5 given that

$$E_5 - E_4 = 0.49 \times 10^{-19} \text{ J}$$

(5)
(Total 31 marks)

34. A Van de Graaff generator can produce a very high voltage V relative to earth using a charged belt.
The diagram shows how this voltage can be used to accelerate positively charged ions to high energies.



(a) The voltage V is used to charge the ion source and a series of cylindrical conducting tubes A to Y. The potential differences between the source and A, A and B, B and C, etc are each 120 kV. Thus the kinetic energy of the singly charged ions emerging from the accelerator is 3.0 MeV.

(i) Show that the mass equivalent of this kinetic energy is about 5×10^{-30} kg and express this as a percentage of the rest mass, 7.0 u, of a lithium atom.

(ii) Calculate the speed with which a singly charged lithium ion, ${}^{7}_{3}\text{Li}^{+}$, emerges from the accelerator.

(7)

(b) The energy of the particles emerging from a Van de Graaff generator can be further increased by injecting them into a linear accelerator (or linac).

(i) Explain the principle of a linac. You may be awarded a mark for the clarity of your answer.

(ii) What fundamental property of matter was first revealed using high energy electrons from such a linac?

(5)

(c) The cylindrical conducting tubes A, B, C... Y in the Van de Graaff generator can be treated as the plates of capacitors connected in series. Thus the first capacitor is formed by tubes A and B between which there is a voltage, the next capacitor by tubes B and C, and so on.

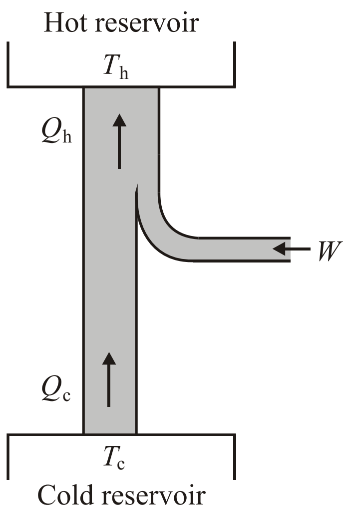
(i) If the capacitance of each capacitor is C, what is the total capacitance of N such capacitors connected in series?

(ii) Draw a diagram to show how such a set of capacitors can be modelled using a number of springs. (Assume each spring obeys Hooke's law.)

If the spring constant of each spring is k, what force is needed in your model to produce a total extension of x?

(4)
(Total 16 marks)

35. The diagram shows the principle of a heat pump as used, for example, in a domestic refrigerator.



(a) (i) List what each of the symbols T_h, Q_h, T_c and Q_c represents for a domestic refrigerator.

(ii) Using symbols from the diagram, write down an equation applying the principle of conservation of energy to this heat pump.

(iii) An electric motor provides the work W for the operation of the heat pump. The motor runs from a 230 V supply and, during a period of operation of 3.5 minutes, uses 42 kJ of energy.

Calculate the current in the motor during this time.

(7)

(b) Draw a diagram, similar to that above, showing the principle of a heat engine.

(3)

(c) A heat pump designed to warm a house in winter uses a small lake as the cold reservoir. When the water in the lake is at 0 °C the effect of using the heat pump is to freeze some of the water, which has a specific latent heat of fusion *l*.

(i) After a day when the heat pump draws 26 MJ of energy from the lake, ice of mass 60 kg is found around the cold reservoir of the heat pump. Calculate a value for *l*.

(ii) Looking up *l* in two data books, a student finds two different values, one of which he assumes is a misprint.

Outline a method that he could use, given normal laboratory apparatus, to decide which value is correct.

(6)
(Total 16 marks)

36. Eros, a stony asteroid, can be considered to be spherical and of radius 7800 m. Its gravitational field is so weak that a stone thrown vertically from its surface at more than 10 m s^{-1} (≈ 22 m.p.h.) will never return.

This speed is called the escape speed v_e from the asteroid.

(a) Sketch the gravitational field of Eros.

(2)

(b) Suggest why any gas molecules diffusing to the surface of Eros from its core do not form an atmosphere.

(2)

(c) The escape speed v_e from a spherical body such as this asteroid is related to the mass m_A and radius r_A of the asteroid by the equation

$$\upsilon_e \sqrt{\frac{2Gm_A}{r_A}}$$

where *G* is the gravitational constant.

(i) Show that this equation is homogeneous with respect to units.

(ii) Show that the mass of Eros is about 6×10^{15} kg and calculate its average density.

(5)

(d) Whether a stone thrown from the surface of Eros escapes or returns can be likened to the indefinite expansion or final contraction of our Universe.

(i) Sketch a graph to show how the size of our Universe varies with time since the Big Bang if it is to expand indefinitely. Label the axes of your graph.

(ii) State what governs whether our Universe will expand indefinitely or come together in a Big Crunch.

(4)

(e) At some future time, an asteroid of mass similar to that of Eros, i.e. of mass 6×10^{15} kg, may be found to be on a course which would result in it colliding with the Earth ten years later. In order to propel it off its course a rocket motor could be attached to the asteroid and fired to produce a force of 2×10^{6} N perpendicular to its path for 7000 s (≈ 2 hours).

(i) Calculate the change in the asteroid's velocity which this rocket firing would produce.

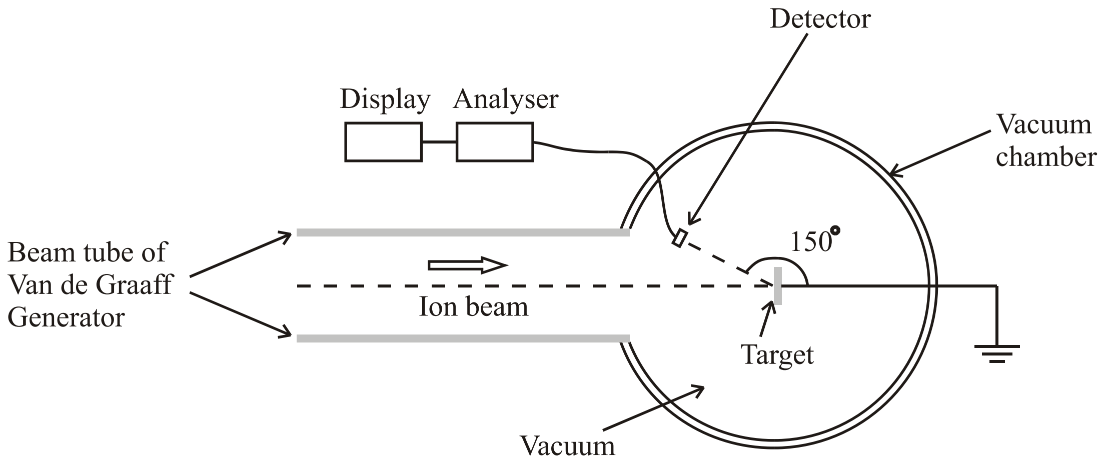
(ii) Suggest with a reason whether such an attempt to alter the asteroid's course would be worthwhile.

(4)
(Total 17 marks)

37. Read the passage and then answer the questions at the end.

Rutherford backscattering

The elastic scattering of energetic ions of elements of low nucleon number from surfaces was first reported by Rutherford and his co-workers. This phenomenon, now known as Rutherford backscattering or RBS, was used during early unmanned lunar exploration to obtain the first factual information on the elemental composition of the Moon's surface. More recently the RBS technique has been used to determine quantitatively the number and nature of trace atoms located in the first few thousand atomic layers of any surface.



The RBS technique is illustrated above. Samples are mounted in a vacuum chamber which is connected to the beam tube of a Van de Graaff generator. This provides a mono-energetic beam of ions which strike the target sample. The particles backscattered through any particular angle, e.g. the 150° shown above, are detected and their energy is analysed. A typical incoming beam energy for helium ions is 2 MeV.

When a flux of high energy ions strikes a material, a very few of the incident particles undergo 'snooker ball' type collisions with the target nuclei. These collisions only occur to those ions which pass close enough to a target nucleus (within about 10^{-5} nm) for wide-angle elastic scattering due to coulombic repulsion to take place. In this type of scattering both energy and momentum are conserved: the ion rebounds with an energy characteristic of the mass of the target nucleus, and the target nucleus recoils.

The kinetic energy T of the scattered ion is always less than its original incoming kinetic energy T_0 and is given by $T = kT_0$, where k depends on the masses m_i and m_t of the ion and the target nucleus and on the angle of scatter. For the extreme case of the ion being scattered through 180°, it can be shown that $k = (m_t - m_i)^2 \div (m_t + m_i)^2$. Measuring k thus enables RBS to distinguish between the different elements in the surface of the target, though it is more difficult to discriminate between heavy elements in the target material than between light ones.

[The passage is adapted from *Rutherford Backscattering* by I. V. Mitchell in IoP Physics Bulletin.]

(a) Explain the meaning of the following phrases used in the passage:

(i) nucleon number (paragraph 1),

(ii) elemental composition (paragraph 1),

(iii) a mono-energetic beam (paragraph 2),

(iv) coulombic repulsion (paragraph 3).

(4)

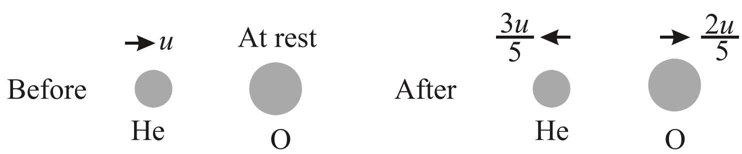
(b) (i) Describe the make-up of a doubly ionised helium-4 ion.

(ii) Show that the speed of such an ion that has an energy of 2 MeV is about 10^7 m s^{-1}. (Unified atomic mass unit u = 1.66×10^{-27} kg)

(iii) Suggest how a beam of such ions from a Van de Graaff generator might differ from a beam of 2 MeV α-particles from a radioactive source.

(5)

(c) The diagram shows the result of a helium ion of mass $4m$ being scattered through 180° after colliding with a stationary oxygen nucleus of mass $16m$, where m is the mass of a proton or a neutron. Velocities are shown above the particles.



(i) Show that momentum is conserved in this collision.

(ii) Use the relationships given in paragraph 4 to calculate k for this collision in two different ways.

(5)

(d) A beam of high energy helium ions, each of mass $4m$, is scattered through 180° from target nuclei of carbon, magnesium, titanium and tin of masses $12m$, $24m$, $48m$ and $120m$ respectively.

(i) Tabulate values for m_t and k for these targets and sketch a graph in your answer book showing how k varies with m_t.

(ii) Use your graph to explain why, when using RBS, it is more difficult to discriminate between trace amounts of heavy elements in the target material than light ones.

(6)

(e) Explain carefully the difference between the elastic scattering that occurs in RBS, and the inelastic scattering that occurs in experiments to probe the structure of protons and neutrons. You may be awarded a mark for the clarity of your answer.

(5)

(f) In a beam of helium ions, each helium ion has a de Broglie wavelength λ associated with it.

(i) Prove that $\lambda = h \div \sqrt{(2mT_0)}$, where m is the mass of a helium ion and T_0 its kinetic energy.

(ii) For 2 MeV helium ions $\lambda = 1.0 \times 10^{-14}$ m. When shorter wavelengths are required it is necessary to use higher energy ion beams. Explain the principle of a linear accelerator (a linac) which can produce higher energy particles. Your answer should include a diagram.

(6)
(Total 31 marks)

38. (a) (i) In the study of the decay of a radioactive source the activity A appears as the subject of the equation $A = \lambda N$.

Explain in words what is meant by activity and state its unit.

(3)

(ii) The discharge of a capacitor through a resistor is analogous to radioactive decay. Write down the equation for capacitor discharge which is analogous to $A = \lambda N$. Explain the analogy between A and the subject of your equation.

(4)

(iii) Outline another analogy in physics and state the similar mathematical relationships which describe the two different phenomena.

(3)

(b) An isolated weather station is fitted with a power source driven by the decay of an isotope of curium, $^{244}_{96}$Cm.

(i) Use the following data to show that about 2×10^{22} atoms of curium-244 are needed to produce an initial power of 20 W.

Half-life of curium-244 = 18 years
Energy per decay of curium-244 = 9.3×10^{-13} J

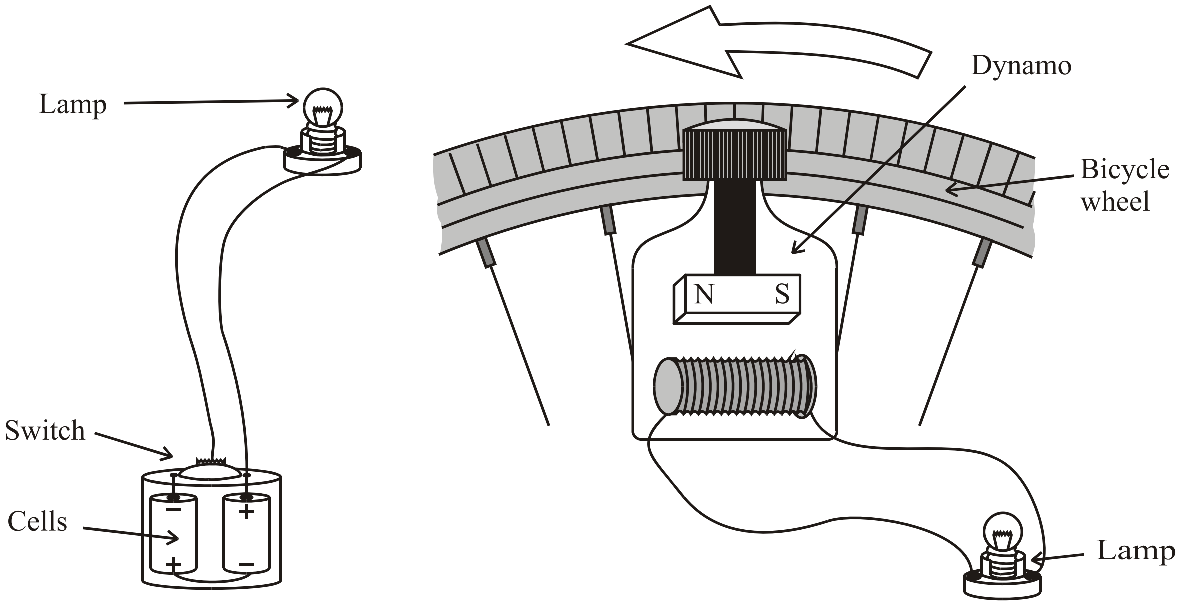
(4)

(ii) After how long will the power of a 20 W source driven by curium-244 fall to 15 W?

(3)
(Total 17 marks)

39. The front lamp of a bicycle can be powered by a battery or by a dynamo (a small electrical generator).

The battery, in System A, consists of two cells plus a sliding switch. The dynamo, in System B, consists of a permanent magnet that is made to rotate close to a fixed coil of wire. The two systems are represented below.



(a) State the energy changes occurring (i) in System A when the lamp is lit, and (ii) in System B when the lamp is lit.

(3)

(b) Discuss the difference in performance of the two lighting systems

(i) during a dark hilly journey of one hour,

(ii) over two years of irregular night use.

(4)

(c) (i) Draw a circuit diagram for the battery system.

(ii) The cells are each of constant e.m.f. 1.2 V and each has a capacity of 0.80 A h, i.e. each can deliver 800 mA for 1 hour or 80 mA for 10 hours, etc.

Calculate the total energy that the battery can supply.

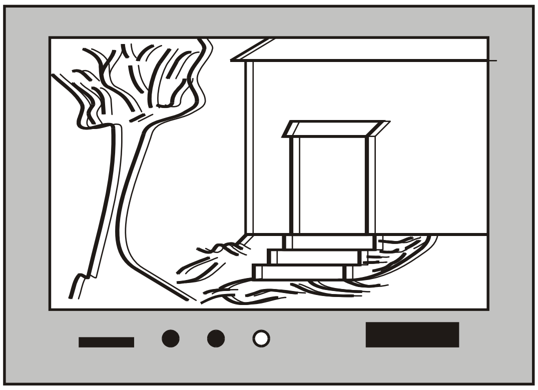
(5)

(d) (i) Explain how the dynamo generates electricity.

(ii) Sketch a graph of current against time for the lamp when the dynamo is operating on a bicycle moving at a constant speed.

(5)
(Total 17 marks)

40. A TV set is connected to its aerial by a long cable. A signal entering the TV set can be reflected back up to the aerial and then reflected again down to the TV set. This can sometimes produce a faint 'shadow' picture to the right of the original picture as shown.



(a) (i) Calculate the delay time between the arrival of the main signal and the reflected signal when the connecting cable is 7.5 m long.

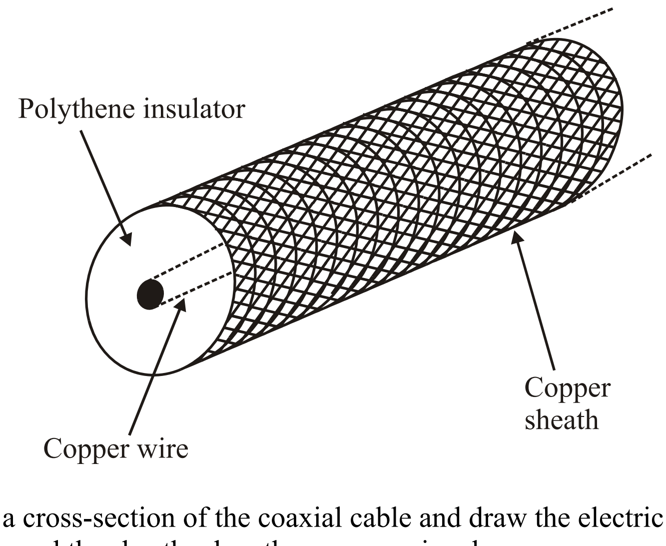
Take the speed of transmission of the signals along the cable to be 1.9×10^8 m s^{-1}.

(ii) The time-base setting in the TV set is 2.0 μs cm^{-1}. Make appropriate calculations to decide whether the 'shadow' picture will be noticeably displaced from the original picture.

(iii) Suggest why any faint shadow appears to the right of the original picture.

(7)

(b) The cable is made up of a central copper wire, and an outer copper sheath wrapped around an insulating material, as shown below. It is called a coaxial cable. The wire and the sheath become oppositely charged when they carry a signal.



(i) Sketch a cross-section of the coaxial cable and draw the electric field produced by the wire and the sheath when they carry a signal.

(ii) Describe the magnetic field both inside and outside the coaxial cable when charges flow in opposite directions along the wire and sheath.

(4)

(c) The inner and outer conductors of a coaxial cable form a capacitor with a capacitance per unit length of 120 pF m^{-1}.

(i) What is the capacitance C of the 7.5 m cable used to connect the TV set to its aerial?

(ii) The property of the cable that is useful in reducing the reflections referred to above is called its impedance Z. For a signal of frequency f, the impedance $Z = \frac{1}{2\pi f C}$.

Show that the unit of Z is the ohm.

(4)
(Total 15 marks)

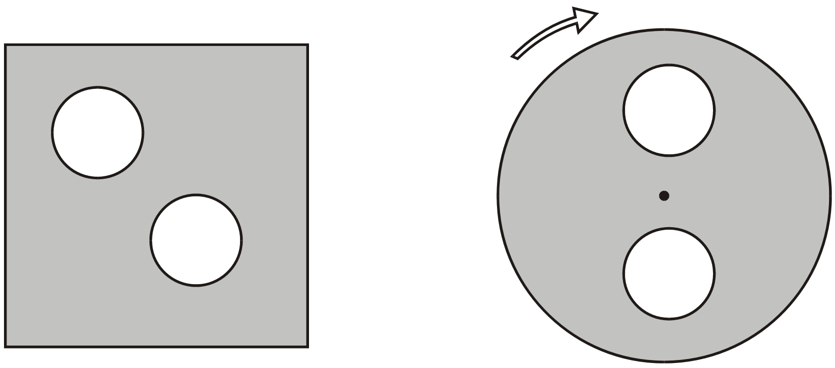
41. Read the passage below and then answer the questions.

An electronic mill

Electrostatic phenomena occur naturally, for example, lightning flashes and the static electricity produced by friction. Early experimenters, such as Benjamin Franklin, showed that there is an electric field around the Earth. This electric field is present because the atmosphere of the Earth acts as a giant capacitor, positive charge collecting in the ionosphere, which lies tens of kilometres above the Earth's surface, and negative charge collecting on the Earth's surface. Two A-level students made a device that used the Earth's electric field to produce a current. This current was directly proportional to the Earth's electric field strength E, so by measuring the current, the students were able to measure E.

The device, called an electrostatic mill, consists of two horizontal plates. One is a fixed aluminium plate with two circular holes cut in it, called the earthed plate. Below and close to this is a circular aluminium disc called the earthed plate. Below and close to this is a circular aluminium disc called the vane plate with two identical holes cut in it. The vane plate is rotated at a constant speed by a motor, and the holes are cut in such a way that the overlap between the two sets of holes varies from zero to a maximum.

Fixed earthed plate



Rotating vane plate

As the vane plate rotates, the Earth's electric field produces an induced charge on the vane plate and, by suitable connections to the plates, a small varying current can be detected. The peak value of this current can be found by passing the current through a resistor and measuring the resulting peak potential difference across the resistor.

At any place where the Earth's electric field strength is E, the charge induced on the vane plate is given by $q = \varepsilon_0 EA$. In this equation A is the area of the vane plate that the Earth's field reaches through the holes in the earthed plate and ε_0 is a constant equal to 9.0×10^{-12} F m^{-1}. This induced charge varies as the vane plate rotates below the earthed plate. When the overlap is a maximum, i.e. when the holes are aligned, A is zero, and the induced charge is then effectively zero.

In terms of applications, an electrostatic could be used to detect the build-up of charge in the atmosphere, such as would occur before a lightning strike, or to check the electric field strength under power lines.

(a) (i) Define electric field strength.

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(ii) Explain the meanings of the following phrases as used in the passage:

- directly proportional (paragraph 1),

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- an induced charge (paragraph 3).

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(4)

(b) Give one example of each of the following:

(i) static electricity produced by friction,

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(ii) a use for an electrostatic mill.

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(2)

(c) An electrostatic mill measures the strength of the Earth's electric field to be 240 N C^{-1}.

(i) Calculate the potential difference between the charged ionosphere and the Earth's surface when they are 60 km apart. State any assumption you make.

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(ii) In these conditions the total charge stored in the 'giant capacitor' formed by the ionosphere and the Earth's surface is 1.1 MC. Calculate the capacitance of this 'giant capacitor'.

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(6)

(d) (i) Why is there an electric field around the Earth?

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(ii) Draw a labelled sketch showing the shape and direction of this field.

(5)

(e) (i) Draw a sketch showing the relative positions of the rotating vane plate and the fixed earthed plate when the induced charge on the vane plate is maximum. (An accurate diagram is not required.)

(2)

(ii) Explain why, in order for the peak current in an electrostatic mill to be proportional to the electric field strength being investigated, the vane plate must be rotated at a constant speed.

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(3)

(iii) Sketch a curve showing how the current in an electrostatic mill varies with time when the frequency of rotation of the vane plate is 50 Hz. Give values on the time axis.

(2)

(f) Show that the equation $q = \varepsilon_0 EA$ is homogeneous with respect to units.

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(3)

(g) The size of the current produced by an electrostatic mill is very small, a few nanoamperes. Explain, with the aid of a circuit diagram, how the peak current from an electrostatic mill is measured (paragraph 3). Give values for any components and ranges for any meters used.

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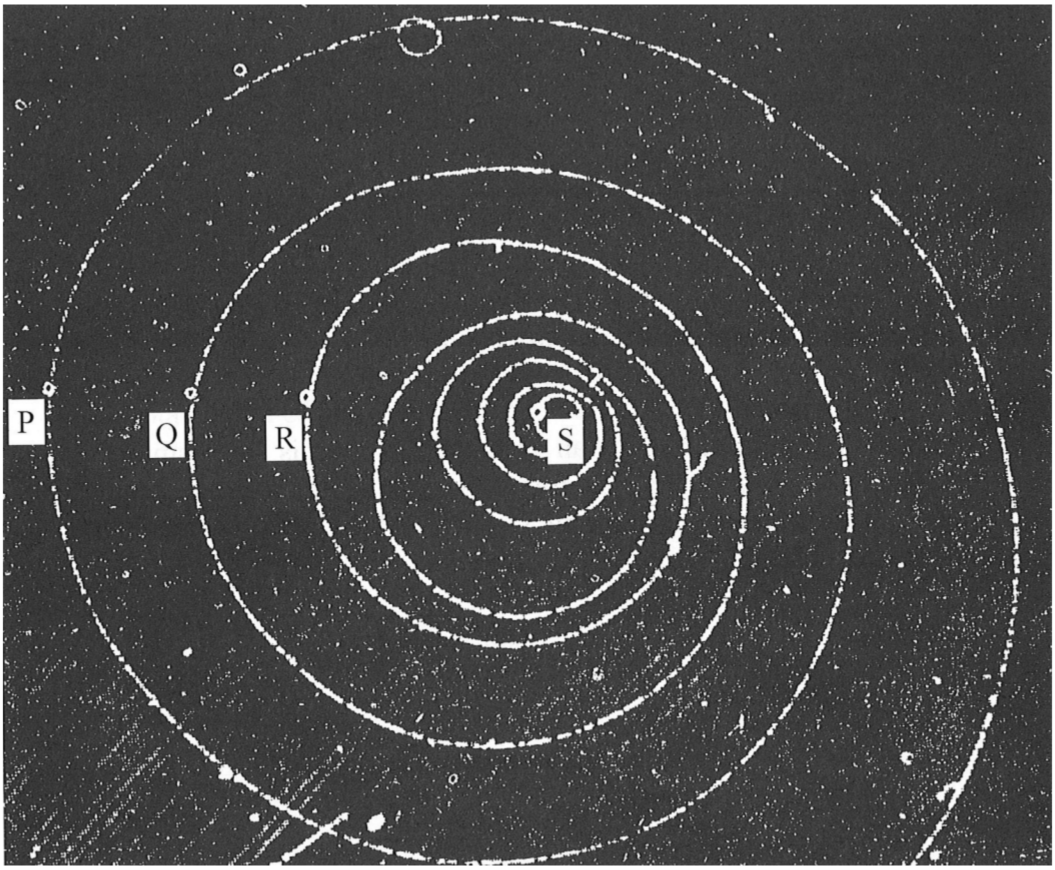
(4)
(Total 31 marks)

42. The photograph shows the path of an electron spiralling inwards anticlockwise in a bubble chamber. **The photograph is full size.**



(a) (i) Explain how the electron produces the white track. You may be awarded a mark for the clarity of your answer.

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(4)

(ii) Explain the origin of the centripetal force that is making the electron spiral in this manner.

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Why does the radius of the circle in which it is moving gradually decrease?

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(4)

(b) Theory shows that the momentum p of the electron at any point on its path is given by $p = Ber$, where B is the magnetic flux density perpendicular to its motion, r is the radius of its path at that point and e has its usual meaning.

(i) The magnetic flux density in the bubble chamber is 1.2 T. By making suitable measurements on the photograph, determine approximate values for the momentum of the electron at P, Q and R. If you are using a transparent ruler, it may help to place a piece of white paper underneath it. (Take the centre of the spiral to be at S.)

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(3)

(ii) The speed v of the electron at all three places P, Q and R on its spiral is 3.0×10^8 m s^{-1} to two significant figures. Deduce the effective mass of the electron at each point and comment on your results.

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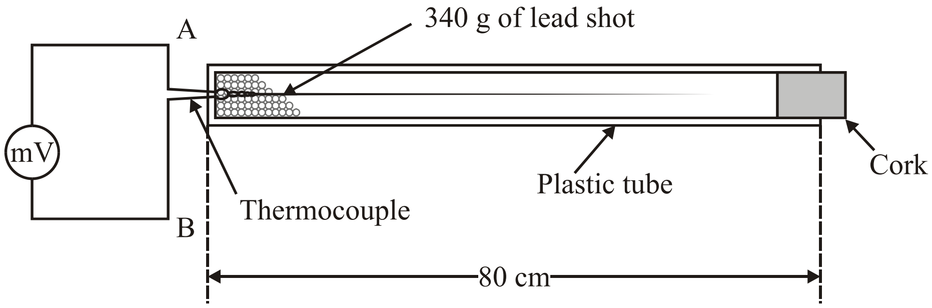
(4)
(Total 15 marks)

43. Some tiny spheres of lead (lead shot) of total mass 340 g are trapped in a long plastic tube. At one end there is an electrical thermometer called a thermocouple. This thermocouple registers changes in temperature as small voltages on a sensitive voltmeter.



(a) The plastic tube is held vertically and then inverted 60 times. All the lead shot is allowed to fall to the bottom of the tube after each inversion.

(i) Explain carefully why the temperature of the lead shot is found to rise.

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(2)

(ii) The specific heat capacity of lead is 130 J kg^{-1} K^{-1}. Estimate the rise in temperature ΔT of the lead shot.

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(3)

(iii) Would you expect the measured value of ΔT to be greater or smaller than your estimated value? Explain your answer.

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(3)

(iv) The specific heat capacity of water is 4200 J kg^{-1} K^{-1}. Discuss the outcome of a similar experiment using a few cm^3 of water in place of the lead shot.

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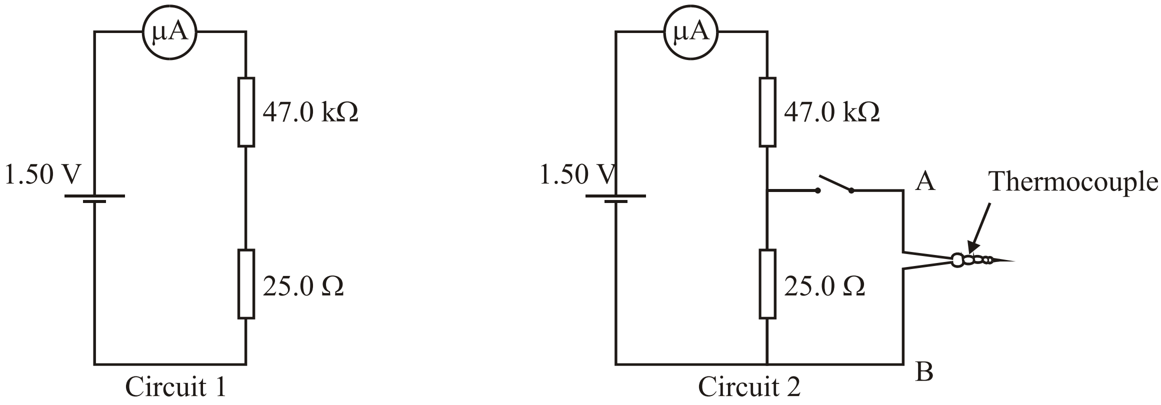
(3)

(b) The thermocouple generates only a fraction of a millivolt in experiments of this kind. In order to check this voltage a potential divider is used.



(i) Calculate, to 3 significant figures, the potential difference across the 25.0 Ω resistor in circuit 1. State any assumption you make.

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(4)

(ii) At the end of the lead shot experiment, when the thermocouple is connected by closing the switch in circuit 2, there is no change in the reading of the microammeter. Suggest what voltage is being generated by the thermocouple.

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(iii) A thermocouple consists of two different metal wires twisted together to form a probe. What advantage does a thermocouple have over a mercury-in-glass thermometer in experiments of this kind, other than its mechanical robustness?

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(2)
(Total 17 marks)

44. (a) (i) What information about a star can be deduced from its spectrum?

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(1)

(ii) In the spectrum of a nearby star, an absorption line is found at 420 nm, which is 20 nm nearer the blue end of the spectrum than its 'laboratory' position. What is the velocity of the star relative to Earth?

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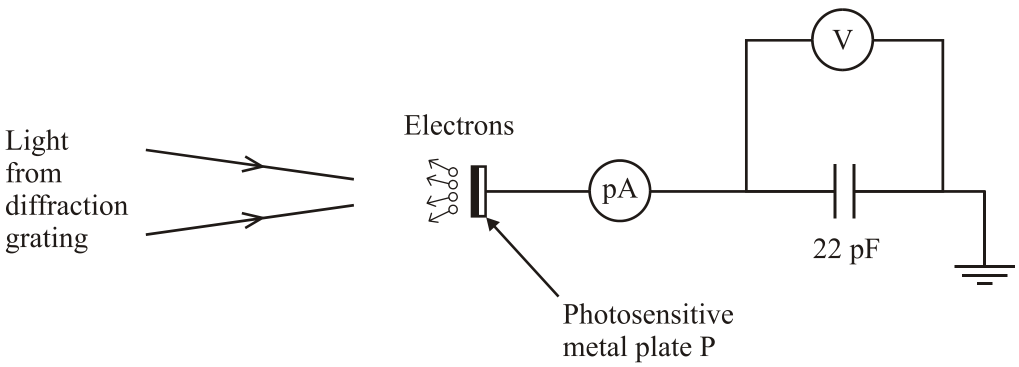
(4)

(b) The diagram shows, in principle, how the light from a star can be analysed. A diffraction grating is used to produce a spectrum of the light and each colour is in turn focused onto a metal plate P. Electrons are emitted from P when the energy of the light photons exceeds the work function of the metal.



The picoammeter registers a current that falls gradually to zero when a certain wavelength of light is focused on P. At the same time the reading on the voltmeter rises from zero to a maximum of 0.58 V.

(i) Explain the origin of this current and state its direction.

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(2)

(ii) Why does the voltmeter reading reach a maximum value?

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(2)

(iii) By calculating the final charge on the capacitor, determine how many electrons are removed from P as the current falls to zero.

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(4)

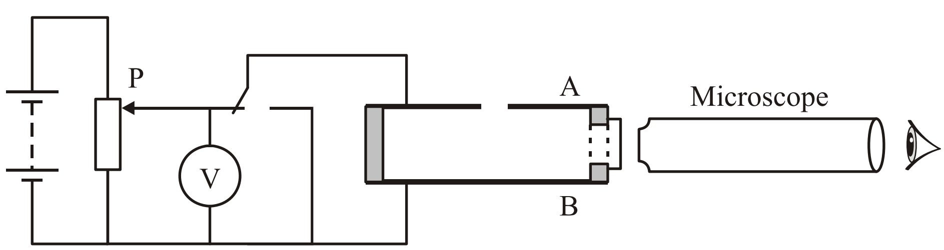
(c) The analysis of light relies here on the photoelectric effect with a photosensitive material – the metal plate. Draw a labelled diagram of the apparatus you would use to measure the work function of a metal in the laboratory. Assume that you have available a monochromatic light source of known frequency.

(4)
(Total 17 marks)

45. Read the passage and then answer the questions.

The Millikan oil-drop experiment

One of the classical experiments of all time was the measurement of the charge of an individual electron by R A Millikan. In the apparatus shown below A and B are two horizontal metal plates. Oil is sprayed in fine drops above the upper plate, and a few of the drops fall through a small hole in this plate. The drops, which are illuminated by a light beam, appear like tiny bright stars when viewed through the microscope, falling slowly under the combined influence of their weight, the buoyant force of the air, and the viscous force opposing their motion.



The action of spraying the oil causes the drops to become electrically charged. If now the plates are charged, the region between the plates becomes a uniform electric field, and by adjusting the potentiometer a drop can be held stationary between the plates. It can be shown that when the field has been adjusted to this value

$$qE = \frac{4}{3}\pi r^3 g(\rho - \rho')$$

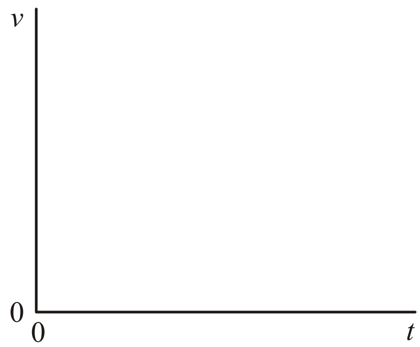
i.e. the upward electric force is equal to weight minus the buoyant force. In this equation q is the charge on the drop, E the electric field strength, g the acceleration due to gravity, r the radius of the drop, ρ the density of the oil and ρ' the density of the air.

The radii of the drops are a few times 10^{-5} cm: much too small to be measured directly. Millikan devised an ingenious method for determining these radii. When the field is switched off, the drop falls slowly and its rate of fall may be measured by timing it as it passes reference cross hairs in the microscope. A body falling in a viscous medium accelerates until a terminal velocity is reached when the net downward force (weight minus buoyant force) equals the viscous force. The viscous force on the drop is equal to $6\pi r\eta v$, where η is called the viscosity of air and v is the terminal velocity of the drop.

During the years 1909–1913, Millikan measured the charges of thousands of different drops. Every drop was found to have a charge equal to some small integral multiple of a basic charge e, i.e. charge is quantised. The best measurements to date give the magnitude of the electronic charge e to be 1.6022×10^{-19} coulomb.

[The passage is adapted from Sears and Zemansky: *College Physics*, 3rd edition, Addison-Wesley 1960.]

(a) (i) On the axes below sketch and label a velocity-time graph for a body released from rest and falling in a viscous medium to illustrate what is meant by terminal velocity (paragraph 3).



(ii) Explain the following phrases used in the passage:

a viscous medium (paragraph 3),

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charge is quantised (paragraph 4).

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(5)

(b) (i) Show that the weight of an oil drop of radius 7.9×10^{-5} cm is about 2×10^{-14} N for oil of density 920 kg m^{-3}.

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(ii) What percentage of its weight is the buoyant force of the air on such a drop? Take the density of air to be 1.2 kg m^{-3}.

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Percentage = ...

(iii) Deduce an algebraic expression for r, the radius of a drop, from the statement

'weight minus buoyant force equals the viscous force'.

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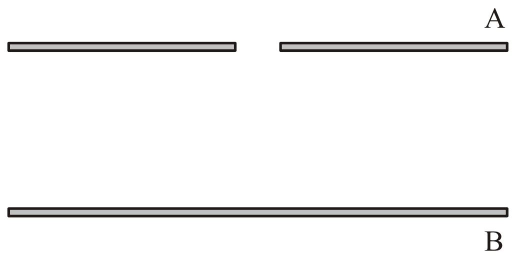
(7)

(c) (i) Draw the electric field pattern between the plates A and B.



(ii) The plates are 12 mm apart. Calculate the potential difference between the plates when the electric field strength is 6.5×10^4 N C^{-1}.

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Potential difference = ...

(iii) If, for this p.d., the potentiometer connection P is set half-way down the resistor, deduce the e.m.f. of the power supply. State any assumption you make.

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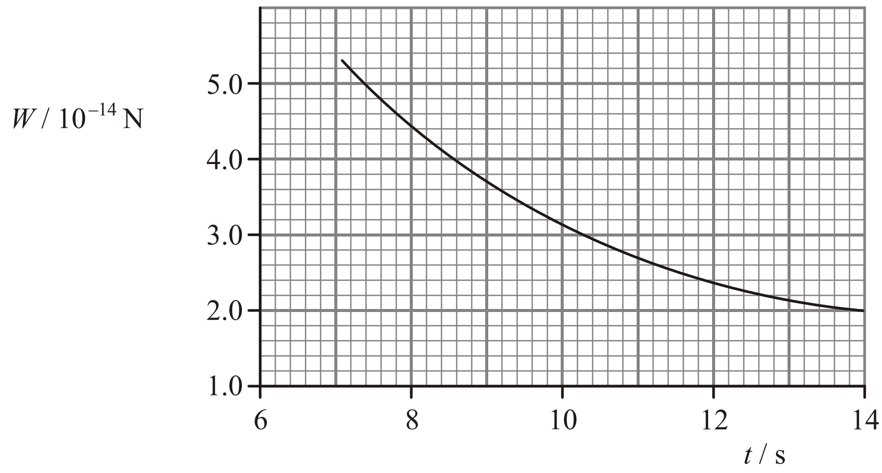
(6)

(d) The graph shows the times t taken for drops of different weights W, each moving at its terminal velocity, to fall a fixed distance when there is no electric field.



By taking suitable readings from the graph, determine whether or not the time t is inversely proportional to the weight W.

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(4)

(e) The passage describes two situations in which an oil drop is in equilibrium:

(i) held stationary (paragraph 2), and (ii) falling at a terminal velocity (paragraph 3).

Draw a free-body force diagram for an oil drop **in each situation**. Label the forces and write an equation giving the relationship between the forces in each case.

(i) (ii)

………………………………………… …………………………………………

(5)

(f) Millikan briefly introduced a radioactive source into the space between the plates A and B in order to change the magnitude of the charge on a drop.

Suggest why he used a source of beta particles rather than an alpha or a gamma source.

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(2)

(g) When a very tiny drop is observed with no electric field, it is seen to jiggle about in a random way as it falls.

Draw a diagram to illustrate the drop's motion, and explain what makes the random jiggling happen.

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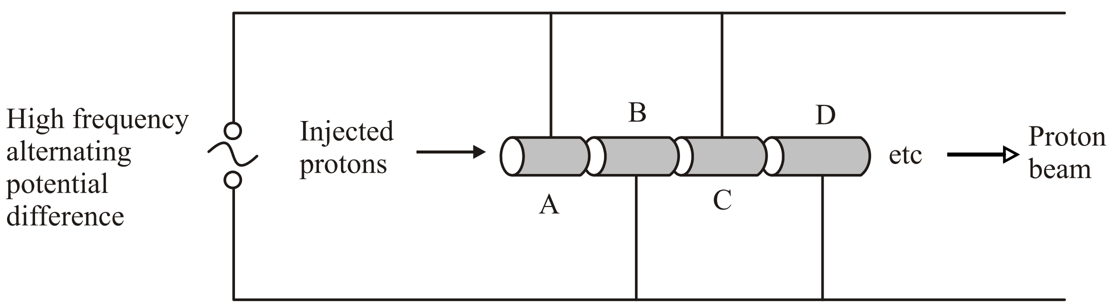
(5)
(Total 34 marks)

46. The diagram shows part of a linear accelerator - a linac. Alternate metal tubes are connected together and to opposite terminals of a high-frequency alternating potential difference of fixed frequency.



(a) Describe how the protons are accelerated as they move along the linac and explain why the tubes get longer towards the right. You may be awarded a mark for the clarity of your answer.

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(5)

(b) A particular linac has 420 metal tubes and the peak voltage of the alternating supply is 800 kV.

(i) Show that the emerging protons have gained a kinetic energy of about 5×10^{-11} J and express the mass equivalent of this energy as a fraction of the mass of a stationary proton. Take the mass of a proton m_p as 1.01 u.

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(6)

(ii) The frequency of the alternating supply is 390 MHz. Calculate how long it takes a proton to travel along the linac.

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Time = ...

(2)

(c) The emerging protons can be made to collide with

(i) a target of fixed protons, e.g. liquid hydrogen, or

(ii) a similar beam of protons travelling in the opposite direction.

State some advantages of either or both experimental arrangement(s).

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(2)
(Total 15 marks)

47. Water molecules oscillate when stimulated by high-frequency electromagnetic waves. A microwave oven heats food that contains water by forcing the water molecules to oscillate at their resonant frequency f_0.

(a) Explain what is meant by resonance and suggest why the microwave frequency is chosen to be about f_0.

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(3)

(b) A microwave oven is used to heat 1.2 kg of meat. The temperature of the meat increases by 75 K in the first 10 minutes.

The power of the microwave source is 800 W.

Calculate the efficiency of the heating process during this time. Take the specific heat capacity of the meat to be 3200 J kg^{-1} K^{-1}.

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Efficiency = ...

Why does the temperature of the meat not continue to rise at this rate for the next 10 minutes?

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(4)

(c) The frequency of the microwaves used is 2500×10^6 Hz.

(i) Show that the wavelength of the microwaves is 12 cm.

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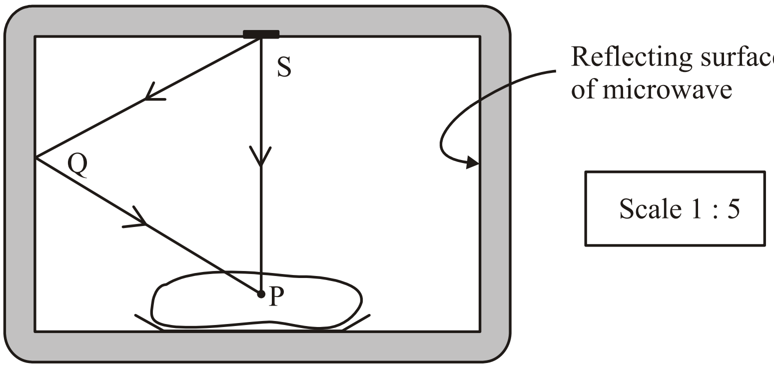
(ii) Microwaves from the source at S reach a point P in the meat both directly and after reflection at Q. The diagram is drawn to one-fifth scale.



Use measurements from the diagram to explain the result of the superposition of these two waves at P.

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(6)

(iii) Superposition causes a stationary wave pattern in the microwave oven.

Explain why this will lead to uneven heating of the meat and suggest how a more even heating can be achieved.

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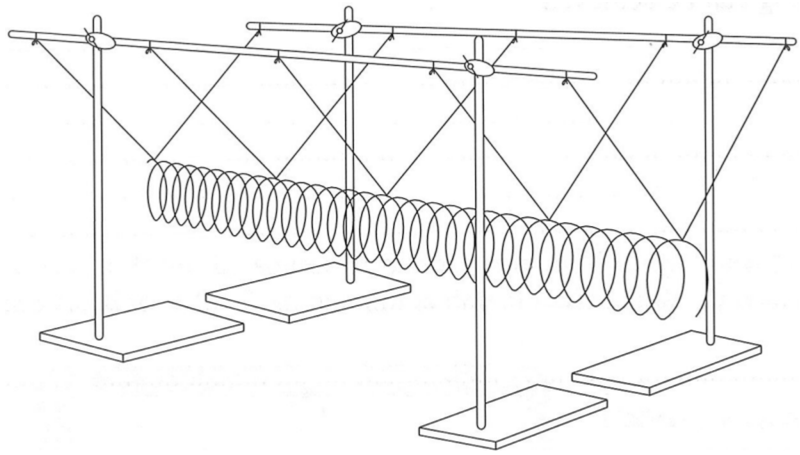
(3)
(Total 16 marks)

48. In order to study the propagation of longitudinal waves on a spring, a metal 'slinky' was suspended as shown.



(a) Describe how you would measure the speed of a short compression pulse along the slinky. How could you improve the reliability of your result?

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(4)

(b) The speed c of the pulse is given by

$$c = \sqrt{\frac{kl^2}{m}}$$

where m and l are the total mass and the suspended length of the slinky, and k is the constant in $F = kx$, i.e. the spring constant of the suspended slinky.

(i) Show that the equation is homogeneous with respect to units.

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(ii) The slinky is cut in half and one half is now suspended in a similar manner. The speed of the pulse on a half slinky with mass $m/2$ and length $l/2$ is found to be the same as that on the whole slinky.

What does this tell you about the value of k for the half slinky?

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(4)

(c) The ends of the suspended metal half slinky are now connected to a d.c. power pack and a current of 5.0 A is passed through it.

(i) A Hall probe, suitably placed inside the slinky, registers a steady magnetic field of 0.34 mT.

Calculate the number of turns per unit length of the slinky.

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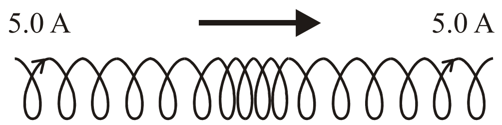
Number of turns per unit length = ...

(3)

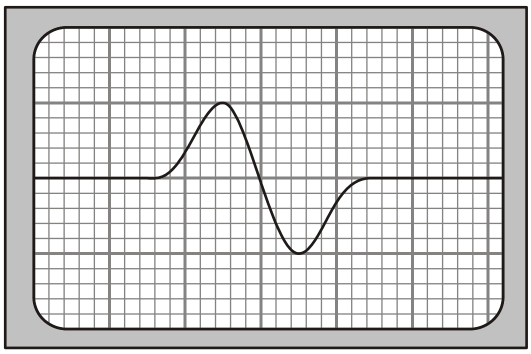
(ii) The Hall probe is then replaced by a short coil, inside the slinky, connected to an oscilloscope. The axis of the coil is parallel to the length of the slinky.

A short compression pulse is sent along the slinky as shown.



Compression pulse

This causes the following trace to appear on the oscilloscope screen as the pulse passes the small coil.



Oscilloscope screen

Explain the shape of the trace as the pulse travels past the coil.

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(4)
(Total 15 marks)