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Winchester College

5th year Easter Revision Papers 2010

Paper 3: Part B Written Paper

Time allowed: **3 hours**

Write your name, candidate number and centre number on all separate pages you hand in. Answer all the questions on separate paper.
All working should be clearly shown. You may lose marks if you do not show your working.
Approximate allocation of marks is shown in brackets.
Graph paper is provided.
You are provided with a sheet of Formulae and Relationships

This paper has **two** sections:
It is recommended that you spend 2 hours on **section A**. This section is worth 120 marks. Answer **all** the questions in this section.

It is recommended that you spend 1 hour on **section B**, not including reading time. This section is worth 50 marks. Answer **three** of the four questions in this section.

Uniformly accelerated motion	$s = ut + \frac{1}{2}at^2$ $v^2 = u^2 + 2as$ $s = \left(\frac{u+v}{2}\right)t$	Magnetic force	$F = BIl \sin \theta$ $F = Qv \sin \theta$
Heating	$\Delta E = mc\Delta\theta$	Electromagnetic induction	$E = - \frac{d(N\phi)}{dt}$
Change of state	$\Delta E = mL$	Hall effect	V - Bvd
Refraction	$n = \frac{\sin\theta_1}{\sin\theta_2}$	Time dilation	$t^1 = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$
Photon energy	$E = hf$	Kinetic theory	$\frac{1}{2m} < c^2 > = \frac{3}{2}kT$
De Broglie wavelength	$\lambda = h/p$	Work done by / on a gas	$W = p\Delta V$
Simple harmonic motion	$x = A \cos \omega t$ $v = -A \omega \sin \omega t$ $a = -A \omega^2 \cos \omega t$ $F = -m \omega^2 x$ $E = \frac{1}{2} mA^2 \omega^2$	Radioactive decay	$\frac{dN}{dt} = - \lambda N$ $N = N_0 e^{-\lambda t}$ $t_{\frac{1}{2}} = \frac{\ln^2}{\lambda}$
		Attenuation loss	$I = I_0 e^{-\mu x}$
Energy stored in a capacitor	$W = \frac{1}{2}QV$	Mass-energy equivalence	$\Delta E = c^2 \Delta m$
Electric force	$W = \frac{Q_1 Q_2}{4\Pi\varepsilon_\theta r^2}$	Hydrogen energy levels	$E_n = - \frac{13.6eV}{n^2}$
Electrostatic potential energy	$W = \frac{Q_1 Q_2}{4\Pi\varepsilon_\theta r}$	Heisenberg uncertainty principle	$\Delta p \Delta x \geq \frac{h}{2\pi}$ $\Delta E \Delta t \geq \frac{h}{2\pi}$
Gravitational force	$F = \frac{-Gm_1 Gm_2}{r^2}$	Wien's law	$\lambda_{max} \propto \frac{1}{T}$
Gravitational potential energy	$E = \frac{-Gm_1 Gm_2}{r}$	Stefans's law	$L = 4\pi\sigma r^2 T^4$
		Electromagnetic radiation from a moving source	$\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$

Data

Gravitational field strength close to the earth's surface	$g = 9.81 \text{N kg}^{-1}$
Elementary charge	$e = 1.60 \times 10^{-19}$ C
Speed of light in vacuum	$c = 3.00 \times 10^{8}$ m s^{-1}
Planck constant	$h = 6.63 \times 10^{-34}$ J s
Permittivity of free space	$\mathcal{E}_0 = 8.85 \times 10^{-12}$ F m^{-1}
Gravitational constant	$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}
Electron mass	$m_e = 9.11 \times 10^{-31}$ kg
Proton mass	$M_p = 1.67 \times 10^{-27}$ kg
Unified atomic mass constant	$u = 1.66 \times 10^{-27}$ kg
Molar gas constant	$R = 8.31$ J K^{-1} mol^{-1}
Avogadro constant	$N_A = 6.02 \times 10^{23}$ mol^{-1}
Boltzmann constant	$k = 1.38 \times 10^{-23}$ J K^{-1}
Stefan-Boltzmann constant	$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

Section A
ANSWER ALL QUESTIONS

3

1 This question is about gravity and some of the effects of gravity which are important in modern astronomy and which lead to the idea of a *Black Hole*.

When a projectile is fired vertically from the surface of the Earth with a small velocity, v, it reaches a height which depends upon v, and then falls back to the surface. Above a certain velocity, called the *escape velocity*, it does not return to the Earth but carries on indefinitely.

The escape velocity is found by equating the projectile's initial kinetic energy to the gravitational potential energy gain in moving the projectile from its starting point to 'infinity'.

(*a*) Show that the escape velocity of a projectile from the surface of a spherical body of mass M and radius R is given by

$$v_{esc} = \sqrt{2GM/R}$$

where G is the universal gravitational constant. [3]

(*b*) Now explain **why** the escape velocity of the projectile can be found by equating its initial kinetic energy to its gravitational potential energy gain in moving from its starting point to 'infinity'. [2]

(*c*) Using data for the Sun given opposite, show that

(i) the mass of the Sun is 2.0×10^{30} kg, and

(ii) the escape velocity from its surface is 6.2×10^5 m s^{-1}. [4]

(*d*) In the later stages of a star's life, when the star has used most of its energy resources, it can shrink to a very much smaller diameter. For example, if the Sun were to shrink until its density were comparable to the density of an atomic nucleus it would have a radius of about 12 km. A star in this state is called a *neutron star.*

Show that the escape velocity from the surface of the Sun, if it were to shrink to this size, would be close to one half of the speed of light. [2]

(*e*) A Black Hole is an object with an escape velocity equal to the speed of light so that nothing, not even light, can ever escape from the surface of the object.

What would the radius of the Sun have to be in order for it to become a Black Hole? [2]

(*f*) Although theory tells us that Black Holes ought to exist it is very difficult to prove that they do since they cannot be observed directly.

Similarly, neutron stars are difficult to see since they are so small and very faint. However, many stars in the sky have close companions and this can be particularly helpful in making observations on neutron stars.

If a neutron star has a companion which is very close and very large, the gravitational field of the smaller star can draw matter from the outer layers of the larger one. The gravitational field at the surface of the neutron star is so intense that the falling matter attains an extremely high velocity, becomes very hot when it reaches the surface and so radiates sufficient electromagnetic energy to be detected by astronomers.

Calculate the kinetic energy attained by one mole (2.0×10^{-3} kg) of hydrogen gas falling onto the surface of the Sun if the Sun had a radius of 12 km. [1]

(*g*) Now use this figure to estimate the temperature reached by the gas if all of that energy were used to heat the gas. [3]

(*h*) A **very rough** idea of the energy of the most energetic photons emitted by a hot gas at a temperature T can be found by equating kT, where k is the Boltzmann constant, to the energy of a photon.

(i) Use this argument to estimate the **smallest** wavelength of a photon emitted by a gas at a temperature of 10^{12} K.

(ii) In what part of the electromagnetic spectrum does this radiation lie? [3]

DATA

Gravitational force constant, G	6.7×10^{-11} N m^2 kg^{-2}
Mass of the Earth	6.0×10^{24} kg
Mean radius of the Earth	6.4×10^{6} m
Radius of the Sun	7.0×10^{8} m
Density of the Sun	1.4×10^{3} kg m^{-3}
Speed of light in vacuo	3.0×10^{8} m s^{-1}
Molar gas constant, R	8.3 J mol^{-1} K^{-1}
Boltzmann constant, k	1.4×10^{23} J K^{-1}
Planck constant, h	6.6×10^{-34} J s

Volume of a sphere $V = \dfrac{4\pi R^3}{3}$

2

For each statement

—*state* the physical principles which are relevant, and

—*show* how they apply to the situation described.

Also:

—*make* calculations and/or give equations wherever possible to show the relationships between the quantities involved.

Spend not more than about *10 minutes* on each statement. It should be unnecessary to write more than about *1 page* on each statement. A suggested approach is given in italics after each statement.

(*a*) A student incorrectly suggests that the storage of energy in a rechargeable pocket torch is by means of capacitors. The bulb of such a torch is marked 2.5 V 0.3 A, but the rest of the torch casing is sealed, and its contents may not be examined.

You could start by estimating the capacitance value needed, or by considering differences between capacitors and batteries. [5]

(*b*) In modern electric showers, the cold water is heated to the desired temperature as it flows through. The heater cannot be connected to a normal 13 A socket, as it draws too much current. A typical shower bath may last 5 minutes, using 10 litres of water, although the optimum flow rate may not be the same in summer as in winter.

Data: Specific heat capacity of water = 4200 J kg^{-1} K^{-1}
Density of water = 1000 kg m^{-3}.

You could start by calculating the flow rate, and hence estimating the electric power required. [5]

(*c*) In one important experiment which led physicists to revise their ideas about the structure of the atom, a beam of alpha particles was directed at a thin metal foil. Some alpha particles were scattered in the metal, and a few were deflected through large angles.

Your discussion might describe briefly the results of the experiment, and outline some of the deductions made from them. A detailed account of the experiment is not required. [5]

2. (d)

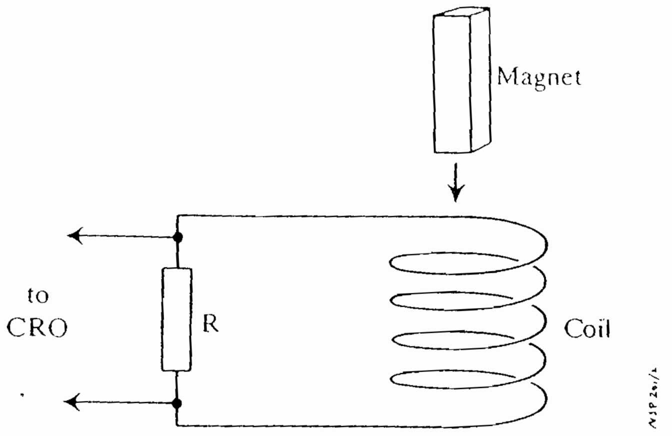


Fig. 1

Fig. 1 shows a coil connected to a resistor R of large value. An oscilloscope is connected across the ends of the resistor. When a bar magnet is allowed to fall freely through the coil, the oscilloscope trace shown in Fig. 2 is observed briefly.

A comparison of the heights of the two peaks on the trace would be one way of starting; the areas enclosed are also interesting.

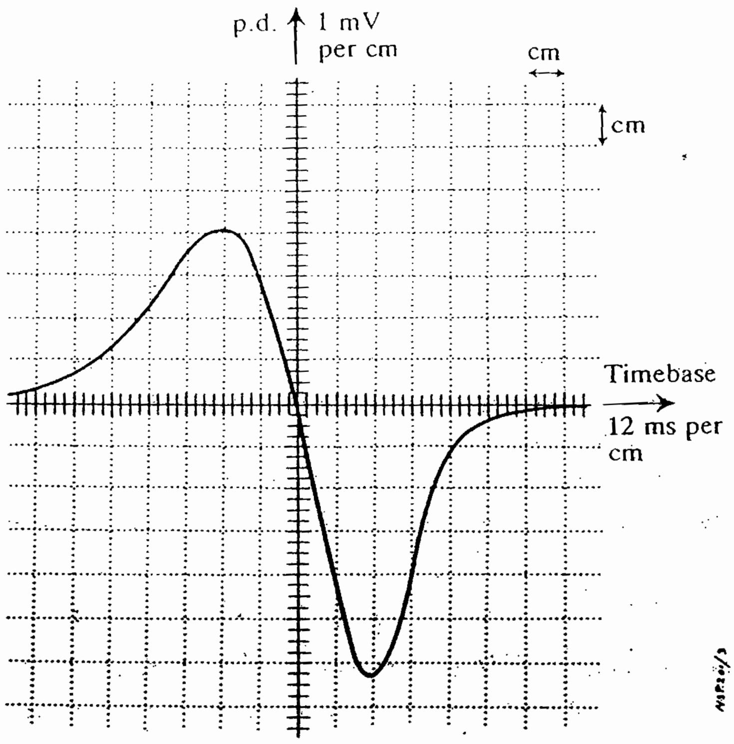


Fig. 2

[5]

3. The suspension of a car is tested by dropping the car from a low height on to a rigid concrete surface. The displacement-time graph for the resulting vertical oscillations of the car is shown in Fig. 1.

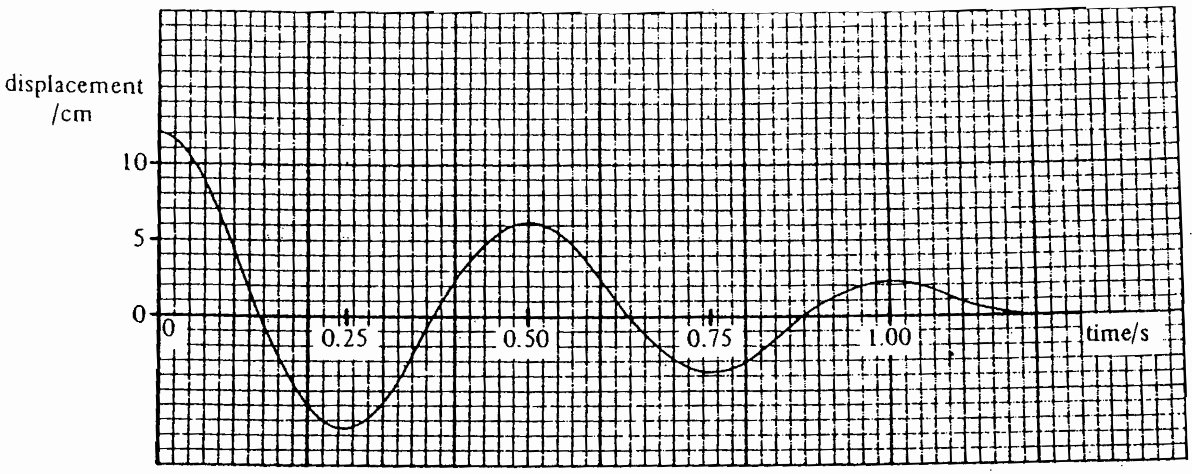


Fig. 1

(a) (i) What is the frequency of the oscillation of the car?

(ii) State how the results show that oscillations are damped.

(b) The effective oscillating mass of the car is 750 kg. The car has an identical spring at each of the four wheels. Determine the spring constant, in N m^{-1}, of each spring.

(c) As a warning for speeding drivers approaching a roundabout it is suggested that the road be made so that it rises and falls as shown in Fig. 2.

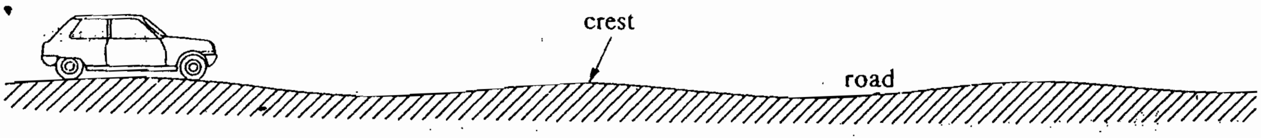


Fig. 2

Resonant oscillations are produced when the speed of the car is 110 km h^{-1}.

(i) State the condition for resonant oscillations to occur.

(ii) Estimate the distance required between the crests to produce resonance.

(iii) Sketch a graph showing how you would expect the amplitude of oscillation of the car to vary with speed of approach to the roundabout.

(9 marks)

4 It is said that electromagnetic radiation exhibits wave-particle duality so that in some ways it behaves as a wave and in others as a particle. The photoelectric effect is a phenomenon which can only be explained if the radiation is considered to be a stream of particles, called photons.

(a) (i) What is the *photoelectric effect*? *(2 marks)*

(ii) Describe an experiment which **demonstrates** the photoelectric effect. Your description should include

—a diagram of the apparatus
—the procedure used
—the observations made

(7 marks)

(b) The apparatus used in (a) may be used to show that there is a *threshold frequency* for photoelectric emission.

(i) What is meant by *threshold frequency*? *(1 mark)*

(ii) How would you use the apparatus to show that there is a threshold frequency? *(2 marks)*

(iii) Explain the effect on the demonstrations you have described in (a) (ii) and (b) (ii) of using a higher intensity source. *(2 marks)*

(c) A monochromatic light source has a power output of 0.50 W and the light has a wavelength of 500 nm. The light is incident on a surface which has a work function of 4.5 eV.

(i) Write down the equation which relates the energy of a photon of radiation to its wavelength, defining all terms in the expression. *(1 mark)*

(ii) Calculate the number of photons emitted by the light source per second. *(4 marks)*

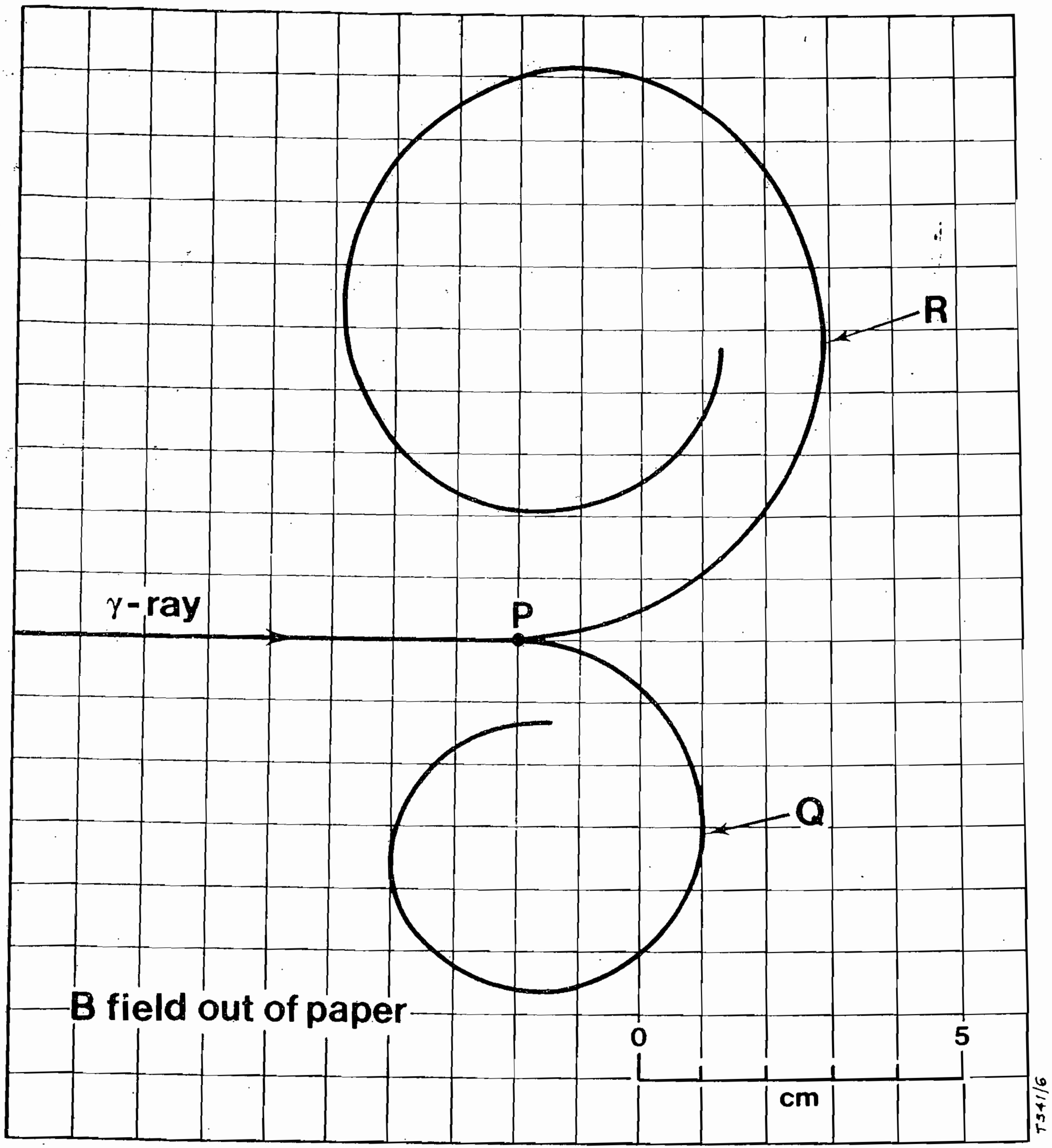
(iii) Determine whether it is possible for the photoelectric effect to occur. *(3 marks)*

Speed of electromagnetic radiation in vacuo $c = 3.0 \times 10^{8}\ \text{m s}^{-1}$
The Planck constant $h = 6.6 \times 10^{-34}\ \text{J s}$
Charge on an electron $e = -1.6 \times 10^{-19}\ \text{C}$

(d) Explain how the existence of line spectra and their explanation in terms of electron transitions in atoms also suggest a particulate nature for light. *(3 marks)*

5. State expressions relating (i) energy to mass; (ii) the energy to the frequency of a quantum of electromagnetic radiation. [2]

Explain how these expressions are used in the interpretation of nuclear reactions and nuclear decay. [5]



The diagram represents a scale tracing from a photograph of an event in a cloud chamber superimposed on a 1 cm grid. A gamma ray passing near a heavy nucleus at P is converted into an electron-positron pair. There is a uniform magnetic field B of 2 mT over the whole volume of the chamber. B is perpendicular to the plane of the photograph and the tracks are in the plane of the photograph.

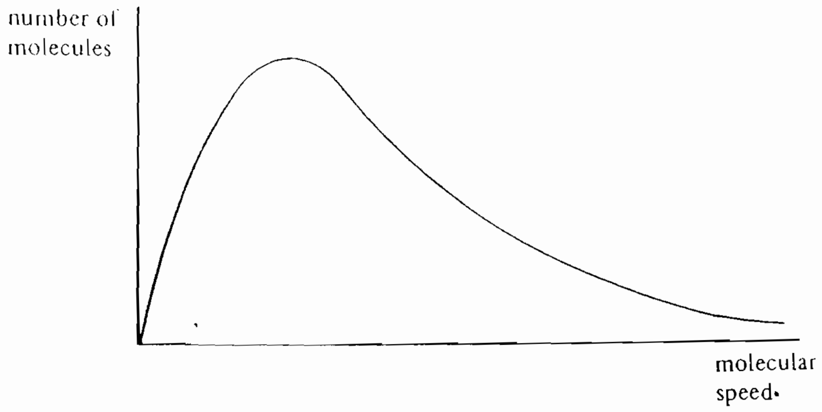
(*a*) Why are the tracks curved and why are they spiral in form? [4]

(*b*) Identify which of Q and R is the electron and which the positron. [1]

(*c*) From measurements of the tracks estimate the initial velocities and kinetic energies of the electron and positron. [5]

(*d*) Assuming that the gamma ray energy equals the sum of the energy equivalents of the masses and the kinetic energies of the electron and positron, calculate the wavelength of the gamma ray. [3]

6. The graph illustrates the distribution of molecular speeds in oxygen at room temperature.



(a) Copy this graph into your answer book and show on it a second curve to show the effect of increasing the temperature of the gas on the distribution of molecular speeds. Label the second curve A.

(b) A sealed vessel has a volume of $1.5 \times 10^{-3}\ \mathrm{m}^3$ and contains oxygen at a pressure of 1.0×10^4 Pa and a temperature of 300 K.

Given that the molar gas constant, $R = 8.3\ \mathrm{J\ mol^{-1}\ K^{-1}}$
the Avogadro constant, $N_A = 6.0 \times 10^{23}\ \mathrm{mol^{-1}}$
and the molar mass of oxygen $= 32 \times 10^{-3}\ \mathrm{kg\ mol^{-1}}$,

determine

(i) the number of moles of oxygen in the vessel

(ii) the number of molecules in the vessel

(iii) the root mean square speed of the molecules in the vessel.

(*10 marks*)

7\. A small rectangular block of mass 37 grams is placed on a turntable at a distance of 6.8 cm from the centre. The motor that drives the turntable is then switched on. The maximum power of the motor is 10 watts. The turntable accelerates from stationary up 45 rpm (revolutions per minute) in 2.1 seconds.

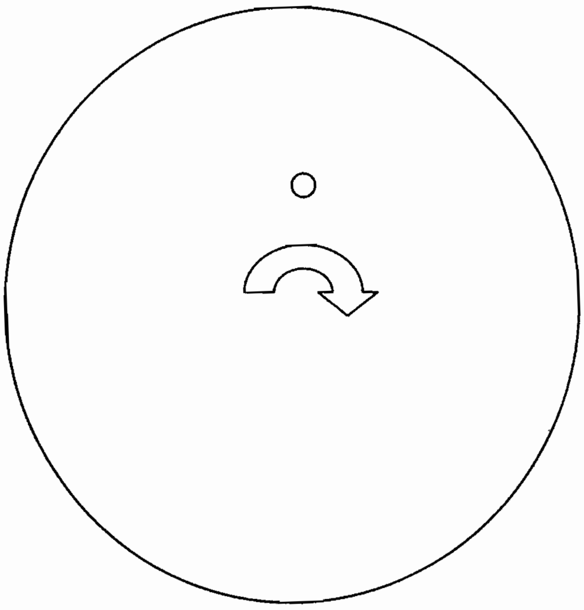
a)

i) Convert 45 rpm into radians per second. [1]

ii) Show that the speed of the rectangular mass once the turntable has reached 45 rpm is over 30 cm/s. [2]

iii) Hence show that the centripetal force required to keep this mass in the same position on the turntable is more than 50 mN. [2]

iv) If the mass, instead of being rectangular, was in fact spherical, it would roll off the turntable. Copy the picture shown below and add the path that the ball would follow as the turntable accelerates from rest in the direction of the arrow. Explain the main features of your prediction. [3]



b) The turntable is made of aluminium 12 mm thick in the shape of a uniform circular disc of diameter 42 cm.

i) Draw a picture of the disc and use it to set up an integral to show that the moment of inertia of the disc (when rotating about its central axis) in terms of its density, diameter and thickness, is given by

$I = 1/32 \; \pi \rho t d^4$

where ρ = density, t = thickness and d = diameter of the disc. [3]

ii) Hence show that the moment of inertia of the disc is nearly 0.1 kg m^2 given that the density of aluminium is 2700 kg / m^3. [1]

7.

iii) If you were hoping to reduce the moment of inertia of the turntable by drilling four small holes in it, where would you drill them? Explain your thinking. [3]

c)

i) The turntable accelerates from rest up to 45 rpm in 2.1 seconds. Calculate the average value of the angular acceleration. Be careful to state the units. [2]

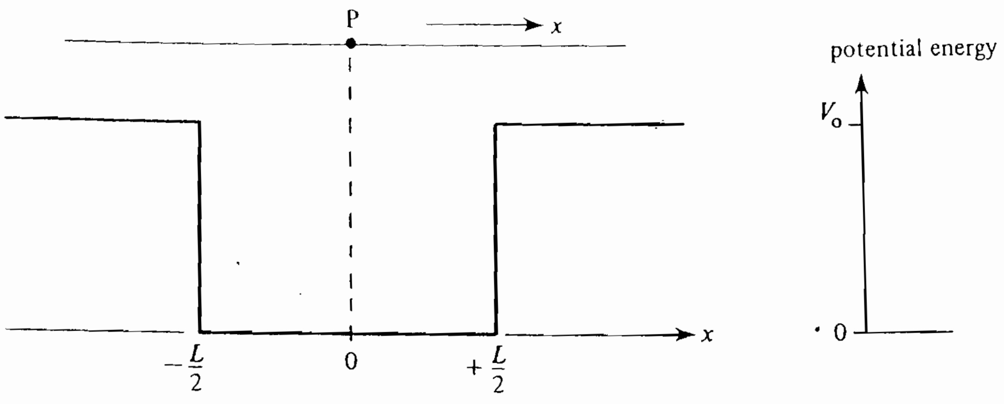
ii) Hence find the average torque required.to achieve this acceleration. You may ignore the effect of the 37 gram mass. [2]

iii) Discuss how much difference the 37 gram mass on top of the turntable would have made if you had allowed for it. Start by finding the moment of inertia of the mass. [3]

Section B.

ANSWER THREE (3) OF THE FOUR (4) QUESTIONS

8. The diagram below shows the variation of V, the potential energy of a particle, with distance x from a fixed point, P.



This is known as a *rectangular potential "well"* of width L and depth V_0. It is a widely used model in atomic and nuclear physics.

(a) Determine the magnitude and direction of the force on a particle in the well when

(i) $-\frac{L}{2} < x < +\frac{L}{2}$

(ii) $x = +\frac{L}{2}$

(iii) $x > \frac{L}{2}$ [4]

(b) (i) A particle moves in the positive direction, starting at the point P with kinetic energy E_K which is greater than V_0. Discuss how the kinetic energy varies as the particle moves away from P.

(ii) Describe the motion of a particle in the well which has an initial kinetic energy less than V_0. [4]

(c) To simplify the analysis, the potential energy of an electron in the hydrogen atom due to the electric field of the nucleus may be represented by a rectangular well.

It is found that the energy, E, of an electron in the well can only have certain values (the energy levels) given by

$$E = \frac{h^2}{8mL^2} n^2$$

where h is the Planck constant $= 6.63 \times 10^{-34}$ J s
m is the mass of the electron $= 9.11 \times 10^{-31}$ kg
and n is an integer which can take values 1, 2, 3, 4, . . . etc.

(i) A photon of electromagnetic radiation of frequency 4.20 × 10^{15} Hz is emitted when an electron moves between the level for which $n = 2$ to that for which $n = 1$. Determine the energy difference between the $n = 2$ and $n = 1$ levels.

(ii) The width of the potential well provides an estimate for the diameter of the hydrogen atom. Calculate this value. [6]

9 This question is about clarifying the idea of wave-particle duality.

Physicists claim *both* that things commonly regarded as particles can behave like waves *and* that things commonly regarded as waves can behave like particles.

(*a*) Outline experimental evidence which supports the claim that particles can behave like waves. [4]

(*b*) Outline experimental evidence which supports the claim that waves can behave like particles. [4]

(*c*) Explain why wave properties of particles may be important for electrons but not for tennis balls, and why particle properties of waves may be important for light waves but not for radio waves. [5]

(*d*) Answer a critic who objects that these ideas are absurd because something cannot be both a wave and a particle at the same time. [2]

10. This question is about some of the implications of Einstein's theory of special relativity.

a) Here are three situations for you to consider:

Situation 1: A horse archer is riding at velocity **u1** and shoots an arrow at a stationary foot soldier. We will assume the arrow travels in an approximately straight line. The soldier observes the arrow travelling at velocity **u2** and catches it on his shield.

Situation 2: A swan flies low over the water at velocity **v1**. It approaches a birdwatcher directly, honking. The speed of sound through air we shall call **v2**.

Situation 3: A star in the Andromeda galaxy emits visible light. The Andromeda galaxy is approaching our own at a certain velocity which we shall label **x**. The speed of light, of course, has the symbol **c**.

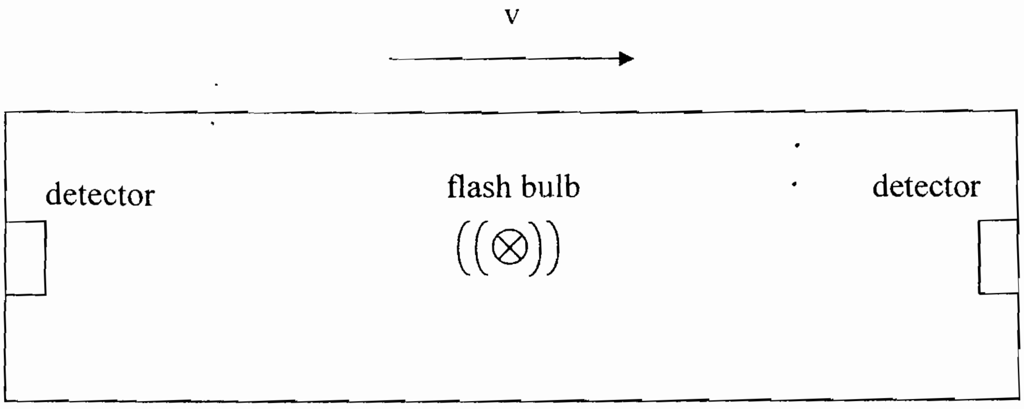
Provide algebraic expressions for each of the following:

The velocity of the arrow relative to the horse archer	
The velocity of the arrow relative to the foot soldier	
The velocity of the honk (in the direction of the birdwatcher) from the swan's frame of reference	
The velocity of the honk from the birdwatcher's frame of reference	
The velocity of the starlight (in the direction of the Earth) from an Andromedan observer's frame of reference	
The velocity of the starlight from an Earth observer's frame of reference	

[3]

b) Compare and contrast these situations. Your answer should include an explanation of why the situation in figure 3 is inconsistent with an aether model of light transmission. It should also explain how it is consistent with Einstein's postulates of special relativity. [5]

10 c) A famous thought experiment involves a spaceship (or railway carriage) with a flashbulb half-way along it (as shown below). The railway carriage travels at a constant velocity relative to an external observer. Compare the time at which the light signal reaches the **back** end of the train and the time at which the light flash reaches the **front** end of the train. Consider this first for the external observer and then for a traveller inside the spaceship and discuss the implications for our concept of time.



[3]

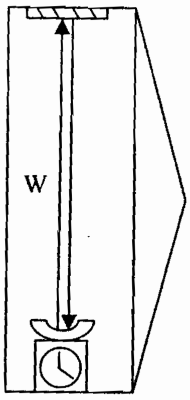
10

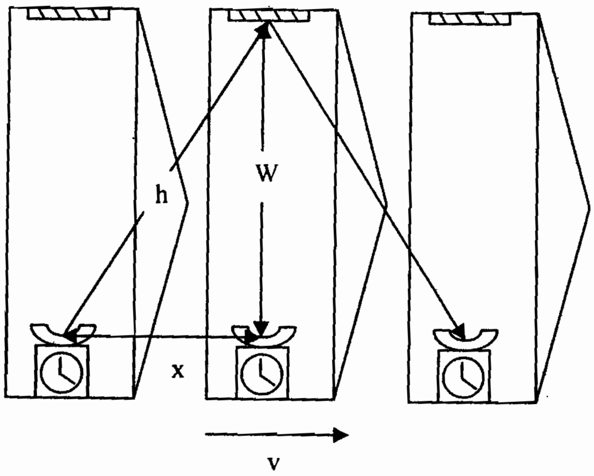
d) The diagram below shows light being emitted, reflected and received by an imaginary clock riding along in a spaceship, which is travelling at a constant velocity v relative to an external observer. The top diagram shows the situation from the rocket's point of view, the lower diagram from the external observer's point of view.

Assuming that the transverse width of the spaceship W remains constant, show how Einstein's postulates lead to his formula for time dilation:

$$t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where t is the time between two ticks of the clock in its own frame of reference and t' is the time between two ticks of the clock in the frame of reference of the external observer.



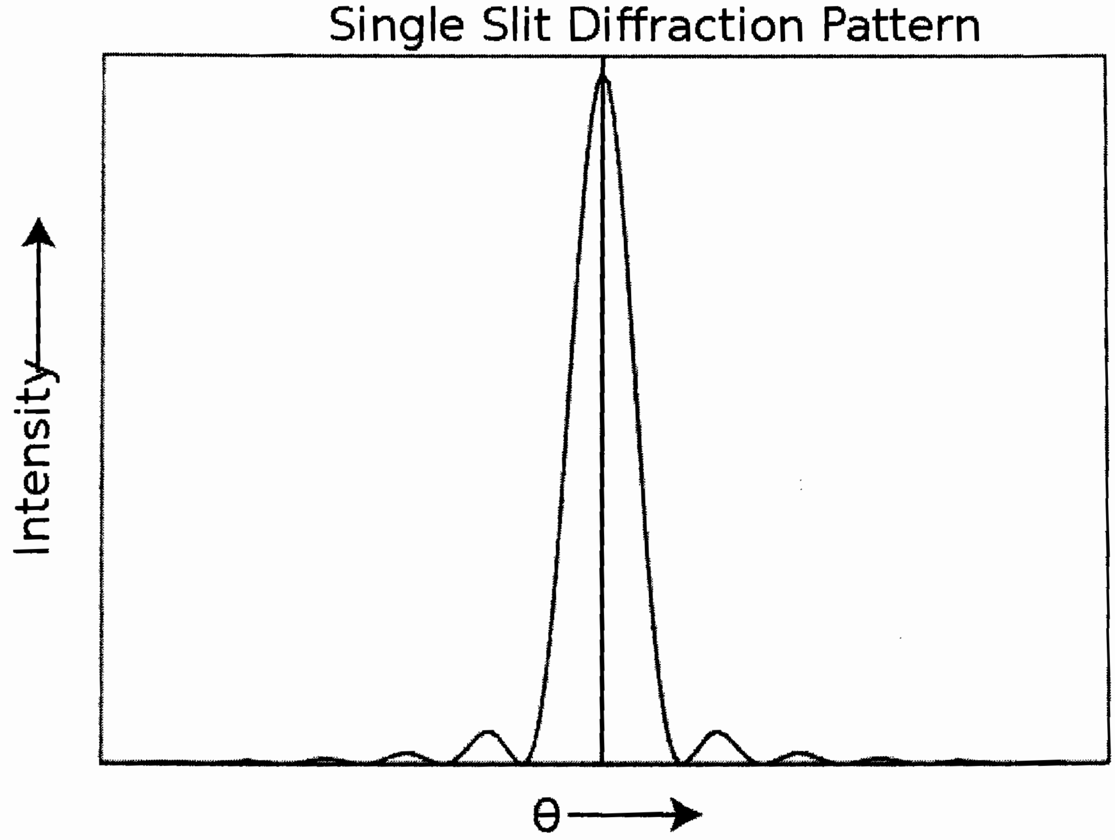


[5]

11\. His question is about the single slit diffraction demonstration and its relationship to the Heisenberg uncertainty principle. Start by reading the text below.

A student has set up some apparatus to examine the diffraction pattern produced by a single slit of variable width when some red laser light is shone on the slit.

The pattern revealed shows a large bright central maximum, with minima on either side of it, with smaller maxima spreading further out to the side (as shown below).



The student is aware that the phenomenon is quite reasonably explained using wave ideas, but worries that since light is made up of photons (that are thought of as particles) then a particle explanation must also be possible. If the demonstration is carried out in very dim light, it can be the case that only one photon passes through the apparatus every 10 seconds or so. In this instance the idea of 'wave superposition and interference' appears to have no meaning.

The single slit demonstration can also be correlated with the Heisenberg uncertainty principle, since if the width of the slit is reduced the position of the particle is better known, but the momentum of the particle becomes less well known.

Heisenberg uncertainty can also be used to explain quantum tunnelling.

a) Explain why a very narrow slit is required to produce a single slit diffraction pattern visible to the naked eye on a screen about 50 cm beyond the slit. (No calculations are required). [2]

11.

b) Explain how the intensity of the light at a given point on the screen may be interpreted in terms of probability. [2]
c) Describe using wave ideas how it is possible for a minimum to be created in the pattern on the screen. [2]
d) If the demonstration were carried out in the very dim light conditions described in the text, then the screen would change in appearance as time went by. Sketch pictures of how the screen might look after 10 seconds, 100 seconds, 1000 seconds, 1 year. (Assume that the screen is covered in some sort of photographic film which records where the photons arrived). [4]
e) Comment on the conceptual problems involved in using what are generally considered to be wave ideas for this dim light demonstration. [1]
f) State the de Broglie formula that relates wavelength to momentum, and use it to explain how the wavelength changes if the momentum increases. [1]
g) If the slit used in the demonstration is made narrower, the lateral location of the particles passing through it becomes better known. By first describing what as a result happens to the diffraction pattern, go on to explain why the lateral momentum of the particle necessarily becomes less well known, as per Heisenberg's uncertainty principle. [3]
h) Quantum tunnelling is the phenomenon whereby a particle with insufficient energy to pass over an energy hill or barrier, can nonetheless appear the other side of it. Use the alternative version of Heisenberg's uncertainty principle (involving energy and time) to explain why this is possible. Start by stating this alternative form. [2]