



Oxford Cambridge and RSA

Thursday 6 June 2024 – Morning

A Level Physics B (Advancing Physics)

H557/02 Scientific literacy in physics

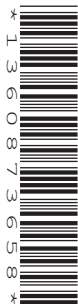
Time allowed: 2 hours 15 minutes

You must have:

- a clean copy of the Advance Notice Article (inside this document)
- the Data, Formulae and Relationships Booklet

You can use:

- a scientific or graphical calculator
- a ruler (cm/mm)



Please write clearly in black ink. **Do not write in the barcodes.**

Centre number

--	--	--	--	--

Candidate number

--	--	--	--

First name(s)

--

Last name

StemUp Model Solution

INSTRUCTIONS

- Use black ink. You can use an HB pencil, but only for graphs and diagrams.
- Write your answer to each question in the space provided. If you need extra space use the lined pages at the end of this booklet. The question numbers must be clearly shown.
- Answer **all** the questions.
- **Use the Insert to answer questions in Section C.**
- Where appropriate, your answer should be supported with working. Marks might be given for using a correct method, even if your answer is wrong.

INFORMATION

- The total mark for this paper is **100**.
- The marks for each question are shown in brackets [].
- Quality of extended response will be assessed in questions marked with an asterisk (*).
- This document has **28** pages.

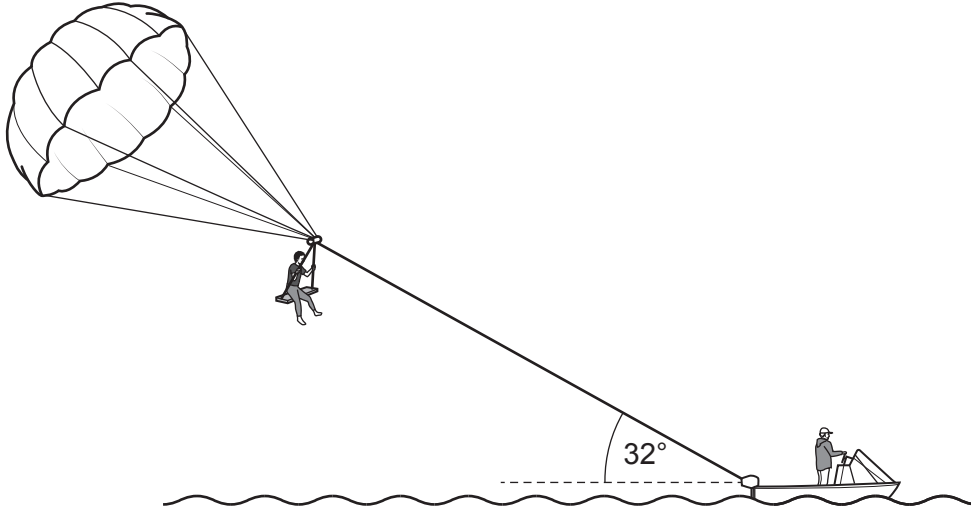
ADVICE

- Read each question carefully before you start your answer.

2
SECTION A

- 1 Parasailing is an adventure sport. The parasailor is pulled behind a motor boat as shown in Fig. 1.

Fig. 1 (not to scale)



The tension in the rope connecting the boat to the parasail is 550 N. The parasailor is moving horizontally at constant velocity.

- (a)
(i) Calculate the vertical component of the tension in the rope.

$$\begin{aligned}\text{vertical component} &= 550 \sin 32^\circ \\ &= 550 \times 0.530 = 291 \text{ N}\end{aligned}$$

$$\text{vertical component} = \dots 291 \dots \text{ N [2]}$$

- (ii) The combined weight of the parasailor and sail is 870 N. Calculate the vertical upwards force on the parasailor and sail.

$$\begin{aligned}\text{upwards force} &= \text{weight} + \text{vertical component of tension} \\ &= 870 + 291\end{aligned}$$

$$\text{vertical upwards force} = \dots 1160 \dots \text{ N [1]}$$

- (iii) Calculate the power required to pull the parasailor and sail through the air at a horizontal velocity of 5.8 m s^{-1} . Explain your reasoning.

$$\text{horizontal force} = 550 \cos 32^\circ = 466 \text{ N}$$

$$P = Fv = 466 \times 5.8 = 2705 \text{ W}$$

power = 2700..... W

Explanation: constant velocity, so no acceleration and no resultant force; the
(magnitude of the) drag equals the (magnitude of the) horizontal component
of the tension, so $P = Fv$. [3]

- (b) Here are some data about the rope that attaches the sail and parasailor to the boat.

diameter = 12.0 mm
 Young modulus = 13.2 GPa
 length = 240 m

Calculate the extension of the rope when the tension in the rope is 550 N.

$$A = \pi r^2 = \pi \times (6.0 \times 10^{-3})^2 = 1.13 \times 10^{-4} \text{ m}^2$$

$$x = FL / AE = 550 \times 240 / (1.13 \times 10^{-4} \times 13.2 \times 10^9)$$

$$= 1.32 \times 10^5 / 1.49 \times 10^6$$

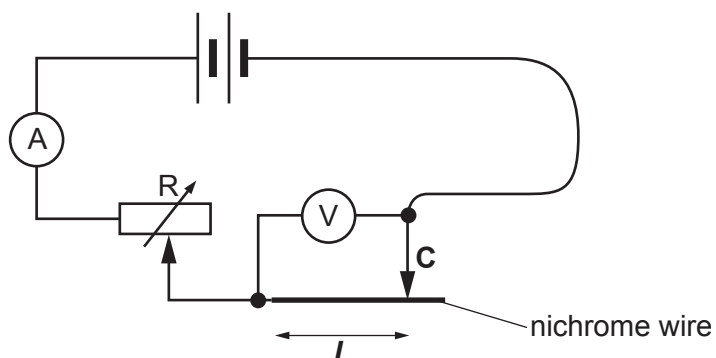
extension = 0.088..... m [2]

- (c) The boat accelerates. State whether the tension in the rope will increase, decrease or remain at 550 N when the parasail is moving at a greater constant horizontal velocity. Explain your answer.

The tension will increase.
At the greater constant velocity the drag (air resistance) on the sail is greater,
so the horizontal component of the tension must be greater to balance it.
 [2]

- 2 The circuit shown in **Fig. 2.1** is used to determine the resistivity of a wire.

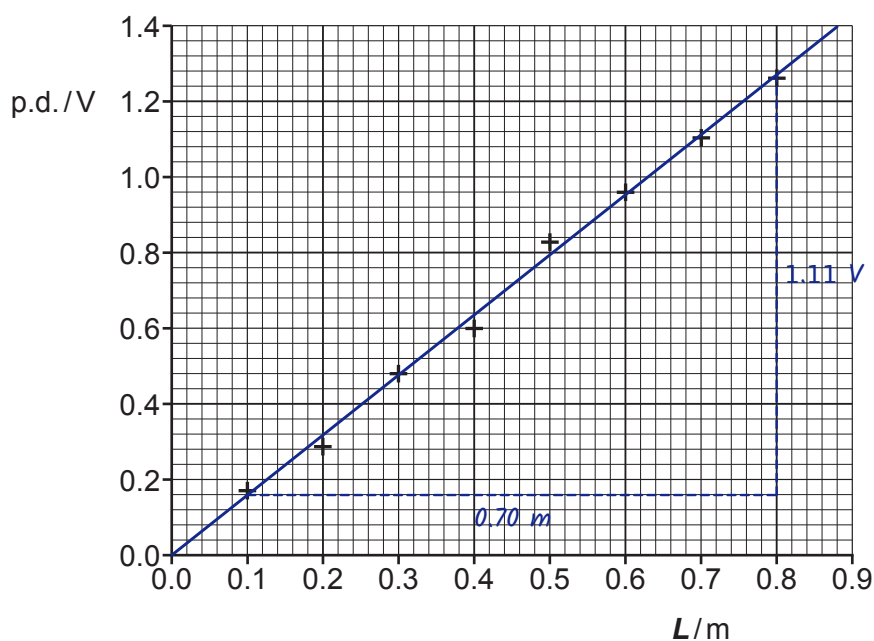
Fig. 2.1



The moving contact **C** changes the length of wire **L** in the circuit. The variable resistor is used to keep the current in the wire constant.

Fig. 2.2 shows the graph of the results obtained.

Fig. 2.2



Here are further data used in the determination of the resistivity:

diameter of the wire = $5.2 \times 10^{-4} \pm 0.1 \times 10^{-4}\text{ m}$

current in the wire in the circuit = $0.29 \pm 0.01\text{ A}$.

- (a) Draw a best-fit line on **Fig. 2.2**. Calculate the gradient of the line.

$$\text{gradient} = (1.27 - 0.16) / (0.80 - 0.10) = 1.11 / 0.70 = 1.59$$

$$\text{gradient} = \dots 1.6 \dots \text{V m}^{-1} \quad [2]$$

- (b) Use the value of the gradient and the further data to determine the resistivity of the material.

Ignore the uncertainties at this stage.

$$\rho = RA / L = (V/L) \times A / I = \text{gradient} \times \pi r^2 / I$$

$$\rho = 1.6 \times \pi \times (2.6 \times 10^{-4})^2 / 0.29$$

$$\text{resistivity} = \dots 1.17 \times 10^{-6} \dots \Omega \text{ m} \quad [2]$$

- (c) Use the uncertainty in the diameter and current values to determine the uncertainty in your value for resistivity calculated above. Ignore any possible uncertainties in the length and p.d. values.

$$\text{largest value: } r = 2.65 \times 10^{-4} \text{ m and } I = 0.28 \text{ A}$$

$$\rho_{\text{max}} = 1.6 \times \pi \times (2.65 \times 10^{-4})^2 / 0.28 = 1.26 \times 10^{-6} \Omega \text{ m}$$

$$\text{uncertainty} = 1.26 \times 10^{-6} - 1.17 \times 10^{-6}$$

$$(\% \text{ check: } 2 \times 1.9\% + 3.4\% = 7.3\%; 0.073 \times 1.17 \times 10^{-6})$$

$$\text{uncertainty in value of resistivity} = \pm \dots 0.09 \times 10^{-6} \dots \Omega \text{ m} \quad [2]$$

- (d) A student repeats the experiment but does not control the current. This leads to higher current values for shorter lengths of wire. Describe and explain the change to the shape of the graph.

..The higher current leads to a temperature increase of the wire (heating).....
 ..This increases the resistance of the wire for a given length (resistivity.....
 ..increases for shorter lengths).....
 ..A greater p.d. will be recorded for the shorter lengths.....
 ..so the graph becomes a curve of (slightly) decreasing gradient, not a straight.....
 ..line.....

[3]

- 3 This question is about simple harmonic motion and resonance.

A 0.25 kg mass is hung from a spring of spring constant 23.0 N m^{-1} .

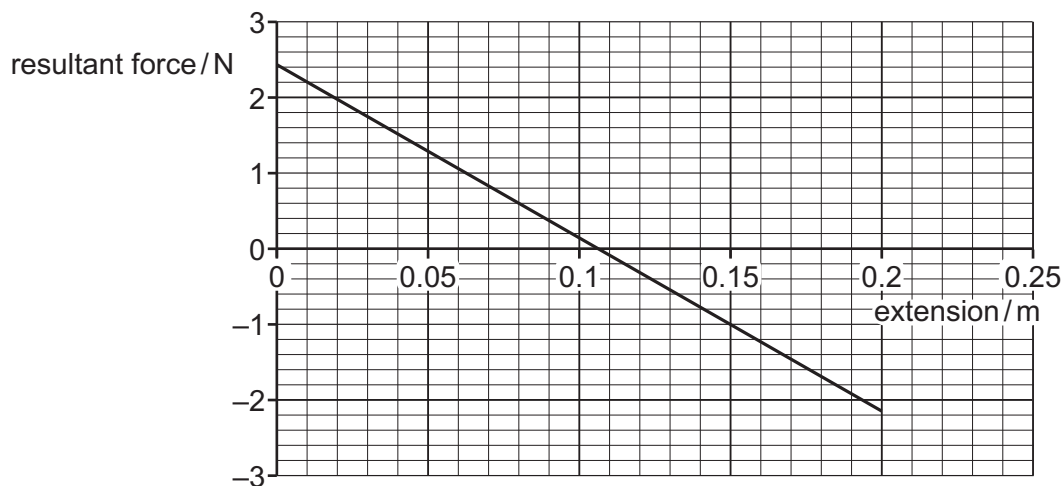
- (a) Show that the extension of the spring is about 0.11 m. This is the equilibrium position.

$$kx = mg, \text{ so } x = mg / k = 0.25 \times 9.81 / 23.0 = 0.107 \text{ m} \approx 0.11 \text{ m}$$

[1]

Fig. 3.1 shows how the resultant force on the mass changes with the extension of the spring. Negative force values show that the resultant force is upwards.

Fig. 3.1



- (b) The spring is extended a further 0.03 m from the equilibrium position and the mass is released.
- (i) Refer to **Fig. 3.1** to explain why the mass will oscillate with simple harmonic motion for oscillations of amplitude less than about 0.11 m.

Fig. 3.1 is a straight line; the resultant force is proportional to the displacement from the equilibrium position (0.11 m) and directed back towards it (a restoring force), for displacements up to 0.11 m either side. Hence $a \propto -x$, which is the condition for SHM.

[2]

- (ii) Explain why the oscillation will **not** be simple harmonic for oscillations with a greater amplitude than 0.11 m.

For greater amplitudes the spring will no longer be extended at the top of the oscillation (it becomes slack or compressed), so the force on the mass will not increase beyond 2.45 N (its weight): the force is no longer proportional to displacement.

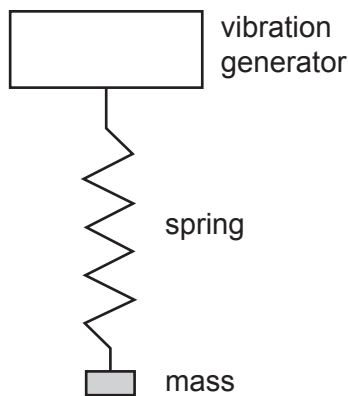
[2]

- (c) The spring and mass are attached to a vibration generator as shown in **Fig. 3.2**. The vibration generator oscillates the spring through a range of frequencies from 0.1 Hz to 3.0 Hz.

Determine the frequency at which the greatest amplitude of oscillations will be observed.

Explain your reasoning.

Fig. 3.2 (not to scale)



$$\begin{aligned}
 f_0 &= (1/2\pi) \sqrt{k/m} \\
 &= (1/2\pi) \times \sqrt{23.0 / 0.25} \\
 &= 9.59 / 2\pi = 1.53 \text{ Hz}
 \end{aligned}$$

frequency = 1.5 Hz

The greatest amplitude occurs at resonance, when the driving frequency of the generator equals the natural frequency of the mass-spring system, 1.5 Hz (within the 0.1 to 3.0 Hz range).

[3]

- (d) The hydrogen chloride molecule (HCl) can be modelled as a light mass (the hydrogen atom) attached to a much heavier mass (the chlorine atom) by an elastic spring. When the hydrogen oscillates at one end of the 'spring' it can be assumed that the chlorine remains stationary.

Explain, using relevant calculations, why the HCl molecule absorbs infrared radiation of wavelength $3.3 \times 10^{-6} \text{ m}$ more strongly than other wavelengths.

spring constant of HCl = 550 N m^{-1}

mass of hydrogen atom = $1.7 \times 10^{-27} \text{ kg}$

$$\text{..natural frequency } f_0 = (1/2\pi) \sqrt{(k/m)} = (1/2\pi) \sqrt{(550 / 1.7 \times 10^{-27})} = 9.1 \times 10^{13} \text{ Hz}$$

$$\text{..frequency of the IR: } f = c/\lambda = 3.0 \times 10^8 / 3.3 \times 10^{-6} = 9.1 \times 10^{13} \text{ Hz}$$

..These are equal, so resonance occurs: energy is transferred readily to the

..oscillating H atom, so this wavelength is absorbed more strongly than others. [3]

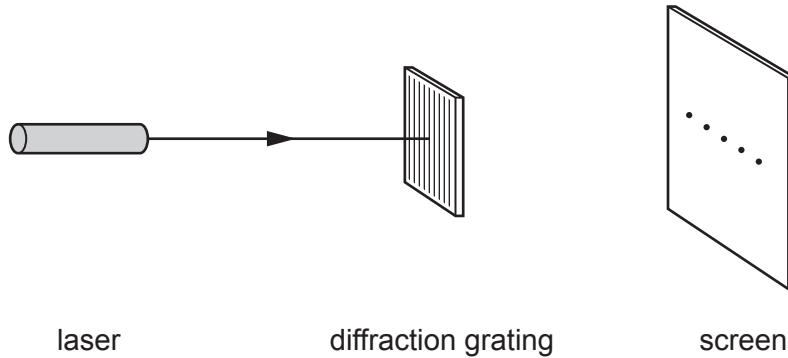
BLANK PAGE

PLEASE DO NOT WRITE ON THIS PAGE

SECTION B

- 4 This question is about different models of light. A laser shines monochromatic light perpendicularly on a diffraction grating as indicated in Fig. 4.1.

Fig. 4.1 (not to scale)



- (a) Explain, using the concepts of path difference and phase, why a series of bright dots is seen across the screen.

Bright dots are seen where the waves from different slits meet (arrive) in phase and superpose constructively (phasors line up). For this the path difference is a whole number of wavelengths, $n\lambda$. [2]

- (b) Ultraviolet light of wavelength 175 nm is incident perpendicularly on a grating of 300 lines mm^{-1} .

- (i) Calculate the angle to the **third** order maximum.

$$d = 1 / 300\,000 = 3.33 \times 10^{-6} \text{ m}$$

$$\sin \theta = n\lambda/d = 3 \times 1.75 \times 10^{-7} \times 300\,000 = 0.158$$

$$\text{angle} = 9.1^\circ \quad [2]$$

- (ii) Calculate the highest order of maximum that is produced using this apparatus.

$$\sin \theta \leq 1, \text{ so } n \leq d/\lambda = 3.33 \times 10^{-6} / 1.75 \times 10^{-7} = 19.05$$

$$\text{highest order of maximum} = 19 \quad [2]$$

- (iii) Ultraviolet light of the same wavelength from a point source is incident on a clean zinc surface. Electrons are ejected from the metal surface.

Use the equation $E_{k(\max)} = hf - \phi$ to calculate the maximum kinetic energy of the electrons ejected.

ϕ , the work function of zinc = 4.3 eV

$$E_k = hc/\lambda - \phi = 6.63 \times 10^{-34} \times 3.0 \times 10^8 / 1.75 \times 10^{-7} - 4.3 \times 1.6 \times 10^{-19} \\ = 1.14 \times 10^{-18} - 6.88 \times 10^{-19}$$

$$E_{k(\max)} = 4.5 \times 10^{-19} \text{ J [2]}$$

- (iv) Although the energy carried by a wave is proportional to the intensity of the source, it is observed that the maximum kinetic energy of the ejected electrons is independent of intensity.

- Explain this observation using the idea of light as photons.
- Suggest and explain the effect of increasing the intensity of light has on the ejection of electrons.

Intensity is a measure of the number of photons striking the surface per second.

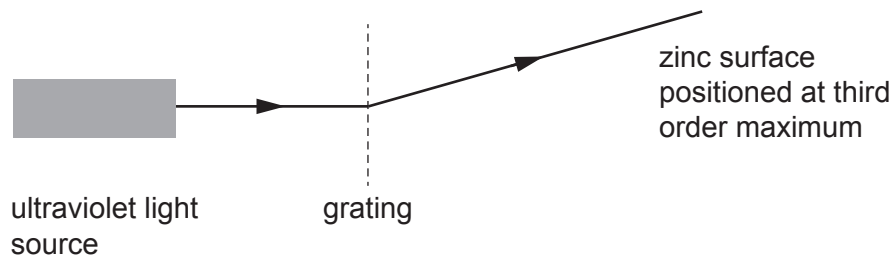
The energy of each individual photon ($E = hf$) depends only on frequency and does not change with intensity.

Each electron is ejected by interaction with a single photon, so the maximum k.e. $hf - \phi$ is the same at any intensity.

Greater intensity means more photons per second, so more electrons are ejected per second (a greater rate of ejection), with the same maximum k.e. [3]

(c) A student suggests the set-up shown in Fig. 4.2.

Fig. 4.2



Electrons are ejected from the zinc surface.

Explain how considering light to be **either** only a particle **or** only a wave **cannot** explain **diffracted** light ejecting electrons from the zinc surface. Suggest how the phasor model of light can explain this observation.

Particle only: (classical) particles travel in straight lines and do not diffract or superpose, so no light would reach the zinc at the third order maximum.

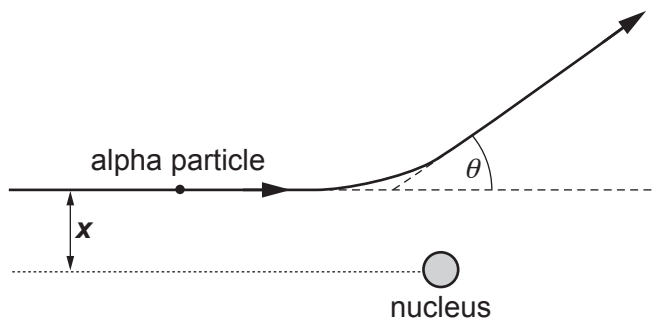
Wave only: wave theory cannot explain the photoelectric effect, because the energy of the light is spread across the metal surface, so low intensity light (as in a diffracted order) should not eject electrons immediately.

Phasor model: the photon 'explores all possible paths' through every slit; phasors for each path rotate at f and are added, which explains the diffraction pattern. The probability of a photon arriving at the zinc is proportional to the (resultant phasor amplitude)², which is large at the maximum, and each photon arriving gives its energy hf to one electron, ejecting it.

[4]

- 5 Fig. 5.1 represents the path of an alpha particle that passes near a positively charged nucleus. θ is the deflection angle.

Fig. 5.1



The distance x is the 'aiming error'.

- (a) Describe and explain how the deflection angle of an alpha particle of the same energy with a smaller aiming error compares to the angle θ shown in Fig. 5.1.

With a smaller aiming error the alpha particle passes closer to the nucleus, so it experiences a greater (repulsive) force and a greater impulse from the nucleus. So it has a greater change of momentum, giving a greater angular deflection (θ larger).

[3]

- (b) If the aiming error x is zero, the alpha particle is deflected through 180° . At the distance of nearest approach to the nucleus the alpha particle is instantaneously stationary.

An alpha particle of energy 4.5 MeV is deflected through 180° by a silver nucleus, $^{107}_{47}\text{Ag}$.

- (i) Calculate the distance of nearest approach of the alpha particle to the silver nucleus.

$$\text{k.e.} = \text{electric p.e. at closest approach: } E = kQq / r$$

$$r = 8.98 \times 10^9 \times 2 \times 47 \times (1.6 \times 10^{-19})^2 / (4.5 \times 1.6 \times 10^{-13})$$

$$\text{distance} = 3.0 \times 10^{-14} \text{ m [2]}$$

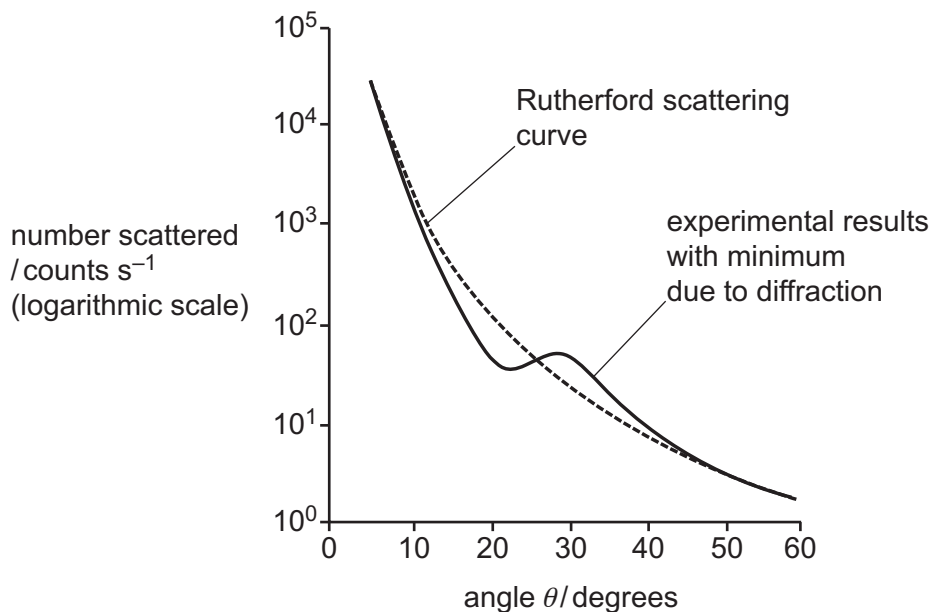
- (ii) State why this value gives a **maximum** radius for the silver nucleus.

A more energetic alpha particle would get closer before stopping, so the radius is no bigger. [1]

- (c)* Electron diffraction can give a better determination of the radius of a nucleus.

Electrons accelerated to 250 MeV are diffracted by nuclei to give a diffraction minimum at angle θ where $\sin \theta = \frac{1.22\lambda}{d}$, where d is the diameter of the nucleus and λ is the de Broglie wavelength of the electron. (Fig. 5.2)

Fig. 5.2



Explain why electrons can get closer to the nucleus than alpha particles.

Calculate the relativistic factor for the accelerated electrons and use this to show that the electrons are moving at nearly the speed of light.

Use the approximation $momentum\ p = \frac{E}{c}$, where E is the energy of the electron, to calculate the de Broglie wavelength and then use information from the graph to calculate a value for the diameter of the nucleus. [6]

rest energy of electron = 0.511 MeV

Electrons are negatively charged (opposite charge to the nucleus), so they are attracted, not repelled, by the nucleus; they can get much closer than alpha particles, which are repelled.

Relativistic factor $\gamma = \text{total energy} / \text{rest energy} = (250 + 0.511) / 0.511 = 490$.

$\gamma = 1/\sqrt{1 - v^2/c^2}$, so $v = c \sqrt{1 - 1/490^2} = 0.999998c = 2.999994 \times 10^8$

m s^{-1} ; the electrons move at nearly the speed of light.

Since $v \approx c$ and $E \gg \text{rest energy}$, $p = E/c = 250 \times 1.6 \times 10^{-13} / 3.0 \times 10^8$

$= 1.33 \times 10^{-19} \text{ kg m s}^{-1}$.

de Broglie wavelength $\lambda = h/p = 6.63 \times 10^{-34} / 1.33 \times 10^{-19} = 5.0 \times 10^{-15}$

m.

From Fig. 5.2 the diffraction minimum is at $\theta \approx 20^\circ$.

$\sin \theta = 1.22\lambda / d$, so $d = 1.22 \times 5.0 \times 10^{-15} / \sin 20^\circ = 6.1 \times 10^{-15} /$

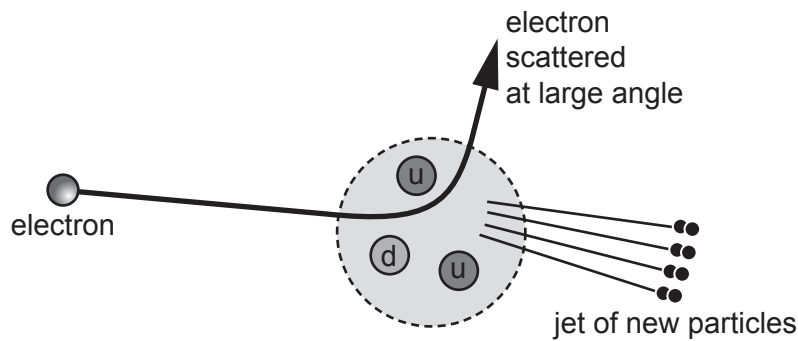
0.342.

$d = 1.8 \times 10^{-14} \text{ m}$, the diameter of the nucleus (radius about $9 \times 10^{-15} \text{ m}$),

smaller than the maximum radius from alpha scattering.

- (d) Electrons accelerated to GeV energies are scattered by particles within individual nucleons. Fig. 5.3 represents such an event.

Fig. 5.3



- (i) State the nucleon that is shown in Fig. 5.3.

proton (u u d) [1]

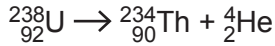
- (ii) Suggest and explain why the kinetic energy of the electron is lower after it has scattered from the nucleon.

*Some of the electron's energy has been transferred to the kinetic energy and
rest energy (mass)
of the new particles produced in the jet, so the electron has less k.e.
afterwards.* [2]

- 6 This question is about isotopes of uranium and their uses.

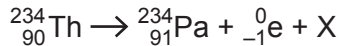
Uranium-238 is the most common isotope of uranium. It decays in a series of steps to the stable isotope, lead-206.

The first step in the decay series is:



(a)

- (i) Thorium-234 decays into protactinium-234. Identify the particle X in the equation below.



.....(electron) antineutrino, $\bar{\nu}_e$ [1]

- (ii) The masses of the two nuclei in part (i) and the beta-minus particle are given below.

Calculate the energy released in the decay.

mass of thorium-234 nucleus: 233.9940 u
 mass of protactinium-234 nucleus: 233.9934 u
 mass of electron: 0.00055 u
 1 atomic mass unit (1 u) = 1.661×10^{-27} kg

$$\text{mass defect} = 233.9940 - 233.9934 - 0.00055 = 5.0 \times 10^{-5} \text{ u}$$

$$= 5.0 \times 10^{-5} \times 1.661 \times 10^{-27} = 8.305 \times 10^{-32} \text{ kg}$$

$$E = mc^2 = 8.305 \times 10^{-32} \times (3.0 \times 10^8)^2 = 7.47 \times 10^{-15} \text{ J}$$

$$\text{energy} = \dots 7.5 \times 10^{-15} \dots \text{ J [2]}$$

- (iii) State why your answer to (a)(ii) is the **maximum** energy of the beta-minus particle.

.....Some energy is transferred to the (anti)neutrino..... [1]

- (b) The age of a sample can be determined by measuring the ratio of uranium-238 to lead-206. It is assumed that all the lead-206 in the sample is produced by the decay series beginning with uranium-238.

The Voyager 1 spacecraft was launched in 1977. It is now moving through space beyond the Solar System. It carries a metal disk giving information about Earth. Included on the disk is a sample of pure uranium-238 with an initial activity of 9.6 Bq.

- (i) Calculate the number of uranium nuclei in the sample when the spacecraft was launched.

$$\text{half-life of uranium-238} = 4.51 \times 10^9 \text{ years}$$

$$\lambda = 0.693 / t_{1/2} = 0.693 / (4.51 \times 10^9 \times 3.16 \times 10^7 \text{ s}) = 4.86 \times 10^{-18} \text{ s}^{-1}$$

$$A = \lambda N, \text{ so } N = 9.6 / 4.86 \times 10^{-18}$$

$$\text{number of nuclei} = \underline{2.0 \times 10^{18}} \dots\dots\dots [2]$$

- (ii) Calculate how many years it will take for one third of the original nuclei in the sample to become stable lead-206.

Assume that the half-life of uranium is the time for half the original nuclei to decay through the series to lead-206.

$$N/N_0 = 2/3 = e^{-\lambda t}, \text{ with } \lambda = 0.693 / 4.51 \times 10^9 = 1.54 \times 10^{-10} \text{ yr}^{-1}$$

$$\ln(2/3) = -0.405 = -1.54 \times 10^{-10} \times t$$

$$t = 0.405 / 1.54 \times 10^{-10}$$

$$\dots\dots\dots \underline{2.6 \times 10^9} \dots\dots\dots \text{years} [3]$$

The isotope uranium-235 is used in nuclear fission reactors.

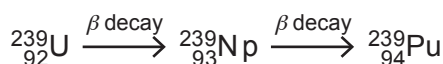
(c)

(i) Explain how the reaction below can lead to a chain reaction.



Each fission releases 3 neutrons; at least one neutron per fission is captured by another U-235 nucleus, causing it to fission and release more neutrons, so the process repeats. [2]

(ii) In a reactor, uranium-238 can capture a neutron to become unstable uranium-239. This decays through two beta decays to plutonium-239 which will fission.



Some designs of reactor can use a mixture of uranium and plutonium isotopes to produce power.

Calculate the minimum mass of neptunium-239 required to produce a steady power of 2.5 MW from the fission of plutonium in a reactor. Explain your reasoning.

Assume that the plutonium is stable and that all the plutonium nuclei are produced by the decay of neptunium-239.

Data:

decay constant of neptunium-239 (${}_{93}^{239}\text{Np}$) = $3.4 \times 10^{-6} \text{ s}^{-1}$

energy released per fission of plutonium-239 = $3.3 \times 10^{-12} \text{ J}$

mass of neptunium-239 atom = $3.97 \times 10^{-25} \text{ kg}$

$$\text{fissions per second} = 2.5 \times 10^6 / 3.3 \times 10^{-12} = 7.58 \times 10^{17} \text{ s}^{-1}$$

$$\text{Np decay rate needed: } \lambda N \geq 7.58 \times 10^{17} \text{ s}^{-1}$$

$$N = 7.58 \times 10^{17} / 3.4 \times 10^{-6} = 2.23 \times 10^{23} \text{ nuclei}$$

$$\text{mass} = 2.23 \times 10^{23} \times 3.97 \times 10^{-25} = 0.0885 \text{ kg}$$

minimum mass required = *0.088* kg

Reasoning: *For steady power, Pu nuclei must be produced at least as fast as they fission, so the number of Pu nuclei fissioned per second $\leq$ the decay rate (activity λN) of the neptunium.* [4]

SECTION C

This section is based on the Advance Notice Article, which is an insert.

7 **Fig. 1** in the article shows how the atmosphere affects the transmission of different wavelengths of electromagnetic radiation.

(a) Suggest why a logarithmic scale is used on the x-axis of the graph and why this choice of scale can make interpreting the data more difficult.

A logarithmic scale allows a great range of wavelengths (10^{-5} to 10^{11} nm) to be shown on one graph. But equal ranges of wavelength do not have equal widths on the scale, so values between gridlines are hard to read and the data need processing. [2]

(b) **Fig. 1** in the article shows that half the gamma rays incident at the top of the atmosphere are absorbed as they pass through the first 120 km of the atmosphere.

Suggest and explain what may affect the proportion of gamma rays absorbed per km as they pass through the atmosphere.

Density of the atmosphere: denser air lower down has more particles per km, so a greater likelihood of a gamma ray interacting per km. Also the energy of the gamma rays (higher energy ones have more energy to transfer by scattering). [2]

- 8 This question is about the resolution of the James Webb Space Telescope (JWST) (lines 19–25 and lines 47–51).

- (a) The diameter of the primary mirror is 6.5 m. Show that the angular resolution limit of the telescope operating at a wavelength of 2000 nm is about $0.4 \mu\text{rad}$.

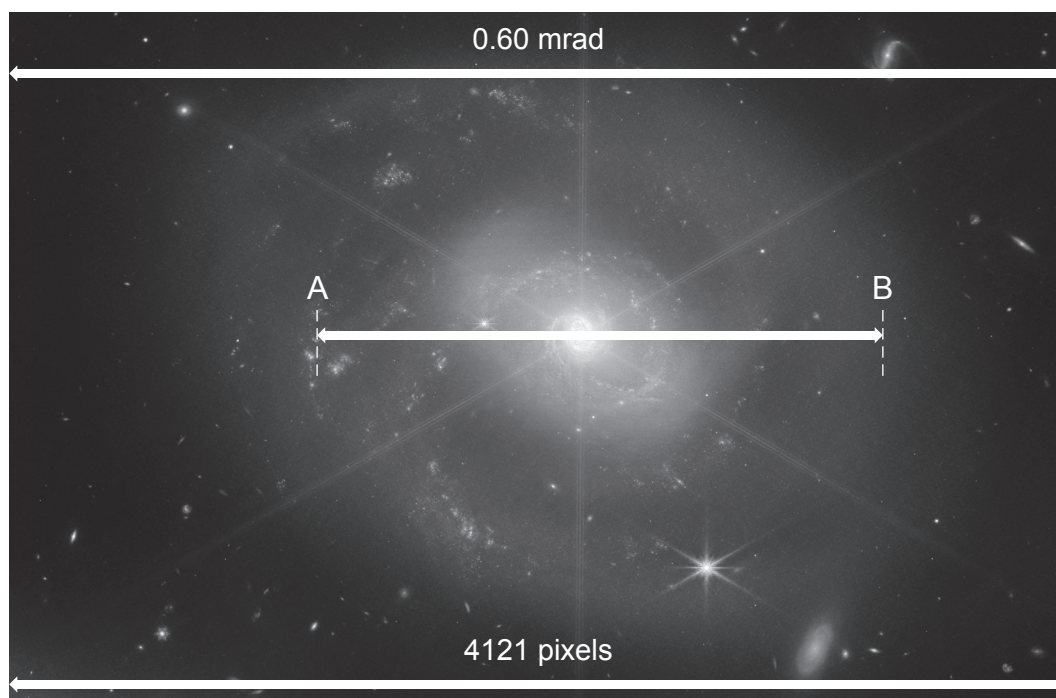
$$\begin{aligned}\text{angular resolution} &= 1.2\lambda/d = 1.2 \times 2000 \times 10^{-9} / 6.5 \\ &= 3.7 \times 10^{-7} \text{ rad} = 0.37 \mu\text{rad} \approx 0.4 \mu\text{rad}\end{aligned}$$

[1]

- (b) Fig. 8 shows an image of a galaxy taken by the JWST.

A and B are points marking the edge of the main section of the galaxy.

Fig. 8



- (i) Calculate the image resolution in rad pixel^{-1} .

Suggest why the camera is designed to resolve to a smaller angle than that calculated in (a).

$$\text{resolution} = 0.60 \times 10^{-3} \text{ rad} / 4121 \text{ pixels} = 1.46 \times 10^{-7}$$

$$\text{image resolution} = \dots 1.5 \times 10^{-7} \dots \text{ rad pixel}^{-1}$$

Suggestion:

...The camera also detects shorter wavelengths (down to 600 nm), which have
...lower (smaller) resolution limits... [2]

- (ii)* Light emitted from the galaxy at wavelength 657 nm is redshifted to a wavelength of 668 nm (lines 53–61).

Calculate the distance to the galaxy in light years and use this value and information from **Fig. 8** to calculate the width, in light years, of the main section of the galaxy between points A and B. Comment on possible causes of error in the value you obtain.

$$\begin{aligned}\text{Hubble constant} &= 73 \text{ km s}^{-1} \text{ Mpc}^{-1} \\ 1 \text{ megaparsec (Mpc)} &= 3.1 \times 10^{22} \text{ m} \\ 1 \text{ light year} &= 9.5 \times 10^{15} \text{ m}\end{aligned}$$

$$v/c = (668 - 657) / 657, \text{ so } v = (11 / 657) \times 3.0 \times 10^8 = 5.0 \times 10^6 \text{ m s}^{-1}$$

$$H_0 = 73 \times 10^3 \text{ m s}^{-1} / 3.1 \times 10^{22} \text{ m} = 2.35 \times 10^{-18} \text{ s}^{-1}$$

$$\text{distance } d = v / H_0 = 5.0 \times 10^6 / 2.35 \times 10^{-18} = 2.13 \times 10^{24} \text{ m}$$

$$d = 2.13 \times 10^{24} / 9.5 \times 10^{15} = 2.24 \times 10^8 \text{ light years (about 223 million)}$$

$$\text{Fig. 8: } AB \text{ is } 0.53 \text{ of the full width, so angle } AB = 0.53 \times 0.60 \text{ mrad} = 0.32 \text{ mrad}$$

$$\text{width} = \text{angle} \times \text{distance} = 0.32 \times 10^{-3} \times 2.24 \times 10^8$$

$$\text{width of main section of galaxy} \approx 7.2 \times 10^4 \text{ light years (72 000 light years)}$$

Comment: *The value of the Hubble constant is uncertain (it has changed over the years and may not be constant over time), so the distance may be wrong. Measuring AB is inaccurate: the edges of the galaxy are not sharp and image resolution limits the measurement.* [6]

- 9 This question is about the Chandra X-ray Observatory (lines 26–32).

The Chandra X-ray Observatory has a highly elliptical orbit. The total energy of the satellite remains constant.

At a distance of 1.5×10^8 m, its furthest point from Earth, the speed of the Chandra is $1.1 \times 10^3 \text{ m s}^{-1}$.

Calculate the speed of the Chandra at a distance of 1.6×10^7 m, its nearest approach to Earth.

Ignore the effect of the Sun and the Moon.

$$\text{Mass of Earth} = 6.0 \times 10^{24} \text{ kg}$$

$$E_{\text{total}} = E_k + E_p \text{ is constant; per kg: } \frac{1}{2}v^2 - GM/r$$

$$\text{at furthest: } \frac{1}{2} \times (1.1 \times 10^3)^2 - 6.67 \times 10^{-11} \times 6.0 \times 10^{24} / 1.5 \times 10^8$$

$$= 6.05 \times 10^5 - 2.668 \times 10^6 = -2.063 \times 10^6 \text{ J kg}^{-1}$$

$$\text{at nearest: } \frac{1}{2}v^2 - 6.67 \times 10^{-11} \times 6.0 \times 10^{24} / 1.6 \times 10^7 = -2.063 \times 10^6$$

$$\frac{1}{2}v^2 = -2.063 \times 10^6 + 2.501 \times 10^7 = 2.295 \times 10^7 \text{ J kg}^{-1}$$

$$v = \sqrt{(2 \times 2.295 \times 10^7)} = 6.78 \times 10^3 \text{ m s}^{-1}$$

$$\text{speed} = \underline{6.8 \times 10^3} \dots \text{ m s}^{-1} \text{ [4]}$$

10 The JWST orbits at the L2 point (lines 41–49).

(a) Calculate the resultant field strength due to the Earth and the Sun at the L2 point.

$$\text{Mass of Sun} = 2.0 \times 10^{30} \text{ kg}$$

$$\text{Mass of Earth} = 6.0 \times 10^{24} \text{ kg}$$

$$g_{\text{Sun}} = GM/r^2 = 6.67 \times 10^{-11} \times 2.0 \times 10^{30} / (1.5 \times 10^{11} + 1.5 \times 10^9)^2$$

$$= 5.81 \times 10^{-3} \text{ N kg}^{-1} \text{ (towards the Sun)}$$

$$g_{\text{Earth}} = 6.67 \times 10^{-11} \times 6.0 \times 10^{24} / (1.5 \times 10^9)^2 = 1.78 \times 10^{-4} \text{ N kg}^{-1}$$

$$\text{both point towards the Sun: } g = -(5.81 \times 10^{-3} + 1.78 \times 10^{-4})$$

$$\text{resultant field strength} = \dots -5.99 \times 10^{-3} \dots \text{ N kg}^{-1} \text{ [3]}$$

(b)

(i) Show that the L2 point will make one revolution of the Sun in about $3.2 \times 10^7 \text{ s}$ (one year).

$$g = v^2/r = 4\pi^2 r / T^2 = 5.99 \times 10^{-3}$$

$$T^2 = 4\pi^2 \times 1.515 \times 10^{11} / 5.99 \times 10^{-3} = 9.98 \times 10^{14} \text{ s}^2$$

$$T = 3.16 \times 10^7 \text{ s} \approx 3.2 \times 10^7 \text{ s (one year)}$$

[2]

- (ii) The mass of the Moon is about 1% that of the Earth. It orbits the Earth at a radius of 3.8×10^8 m.

Suggest and explain the effect of the Moon, if any, on the JWST orbiting around the L2 point.

The Moon has a small (negligible) effect on g at L2: when it is closest to L2, in line with the Sun and Earth, $g_{\text{Moon}} = 6.67 \times 10^{-11} \times 6.0 \times 10^{22} / (1.5 \times 10^9 - 3.8 \times 10^8)^2 = 3.2 \times 10^{-6} \text{ N kg}^{-1}$. This is only about 0.05% of $5.99 \times 10^{-3} \text{ N kg}^{-1}$; the total is still $6.0 \times 10^{-3} \text{ N kg}^{-1}$ to 2 s.f. As the Moon orbits the Earth its distance from L2 varies (1.1×10^9 m to 1.9×10^9 m), so the field strength at L2 varies slightly with a period of a month. This variation in field strength slightly perturbs the orbit of the JWST around L2, so small corrections may be needed. [3]

END OF QUESTION PAPER

[illegible]

Oxford Cambridge and RSA

Copyright Information

OCR is committed to seeking permission to reproduce all third-party content that it uses in its assessment materials. OCR has attempted to identify and contact all copyright holders whose work is used in this paper. To avoid the issue of disclosure of answer-related information to candidates, all copyright acknowledgements are reproduced in the OCR Copyright Acknowledgements Booklet. This is produced for each series of examinations and is freely available to download from our public website (www.ocr.org.uk) after the live examination series.

If OCR has unwittingly failed to correctly acknowledge or clear any third-party content in this assessment material, OCR will be happy to correct its mistake at the earliest possible opportunity.

For queries or further information please contact The OCR Copyright Team, The Triangle Building, Shaftesbury Road, Cambridge CB2 8EA.

OCR is part of Cambridge University Press & Assessment, which is itself a department of the University of Cambridge.