



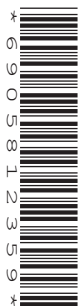
Oxford Cambridge and RSA

A Level Physics B (Advancing physics)

H557/02 Scientific literacy in physics

Friday 8 June 2018 – Morning

Time allowed: 2 hours 15 minutes



You must have:

- the Insert (inserted)
- the Data, Formula and Relationships booklet (sent with general stationery)

You may use:

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



First name

Last name

StemUp Model Solution

Centre
number

Candidate
number

INSTRUCTIONS

- The Insert will be found inside this document.
- Use black ink. You may use an HB pencil for graphs and diagrams.
- Complete the boxes above with your name, centre number and candidate number.
- Answer **all** the questions.
- Write your answer to each question in the space provided. If additional space is required, use the lined page(s) at the end of this booklet. The question number(s) must be clearly shown.
- Do **not** write in the barcodes.

INFORMATION

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

2
SECTION A

Answer **all** the questions.

1 This question is about investigating the polarisation of light.

(a) A student takes two polarising filters as shown in Fig. 1.1.

Unpolarised light is incident on the filter 1.

Filter 2 is initially set up to allow all the light passing through the first filter to be transmitted. The filter 2 is then rotated through 360° .

Describe and explain how the intensity of the transmitted light changes during the rotation of the second filter.

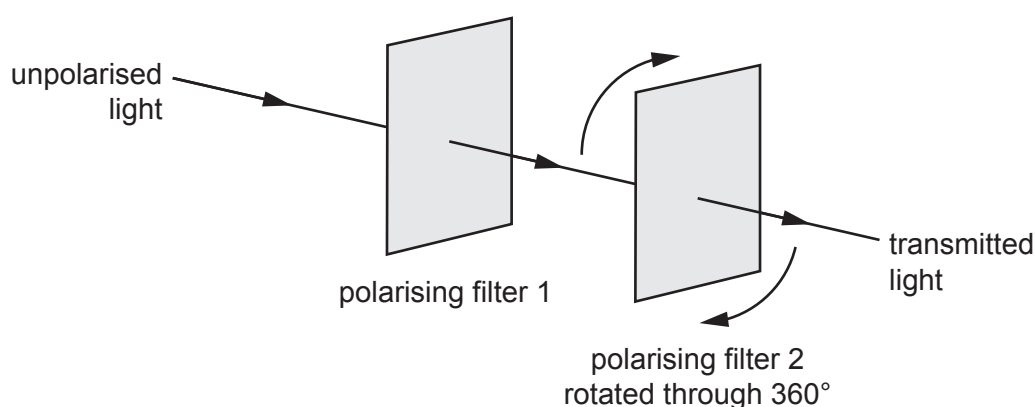


Fig. 1.1

As filter 2 is rotated the transmitted intensity falls to a minimum (zero) after 90° , rises to a maximum at 180° , falls to zero again at 270° and returns to a maximum at 360° .
Unpolarised light oscillates in all planes; filter 1 only transmits light oscillating in one plane, so the light reaching filter 2 is plane polarised. Filter 2 only transmits light oscillating in its own plane: all of it passes when the planes of polarisation are parallel (0° , 180°) and none when they are crossed (90° , 270°). [2]

- (b) The transmitted light strikes an LDR in the circuit shown in Fig. 1.2.

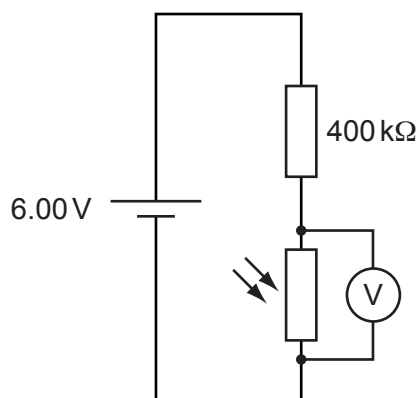


Fig. 1.2

- (i) Describe and explain how the p.d. across the LDR changes as the second filter is rotated through 360° from its original orientation.

You do not need to give values for the p.d. but you should indicate the orientation of the filters which produce maximum and minimum p.d.s.

The LDR and the $400\text{ k}\Omega$ resistor form a potential divider: $V_{\text{LDR}} = 6.00 \times R_{\text{LDR}} / (R_{\text{LDR}} + 400\text{ k}\Omega)$.

The resistance of the LDR falls as the light intensity on it rises.

Minimum p.d. at 0° and 180° (planes of polarisation parallel): intensity is maximum, R_{LDR} is low, a lower proportion of the total resistance.

Maximum p.d. at 90° and 270° (planes crossed): intensity is minimum, R_{LDR} is high, so it takes a higher share of the 6.00 V .

[4]

- (ii) The highest p.d. recorded by the voltmeter is $3.00 \pm 0.01\text{ V}$.

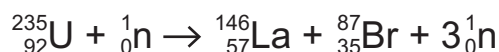
Calculate the **maximum** value of the resistance of the LDR at this point.

Assume that there is no uncertainty in the p.d. of the cell.

$$\begin{aligned} \text{max p.d.} &= 3.00 + 0.01 = 3.01\text{ V, so } 3.01/6.00 = R_{\text{LDR}} / (R_{\text{LDR}} + 400 \times 10^3) \\ 3.01 R_{\text{LDR}} + 3.01 \times 400 \times 10^3 &= 6.00 R_{\text{LDR}} \\ R_{\text{LDR}} &= 3.01 \times 400 \times 10^3 / 2.99 \end{aligned}$$

maximum value of resistance = 4.03×10^5 Ω [2]

- 2 The equation shows a fission reaction.



- (a) Explain how this reaction can become a chain reaction and suggest how the rate of the reaction can be controlled.

Each fission releases 3 neutrons. If on average at least one of these is captured by another U-235 nucleus it causes a further fission, so the reaction becomes self-sustaining.
Control: absorb a proportion of the emitted neutrons (control rods, e.g. boron) so they cannot be captured by U-235 to cause further fissions. [2]

- (b) The graph in Fig. 2.1 shows the binding energies per nucleon of the nuclei involved in the reaction.

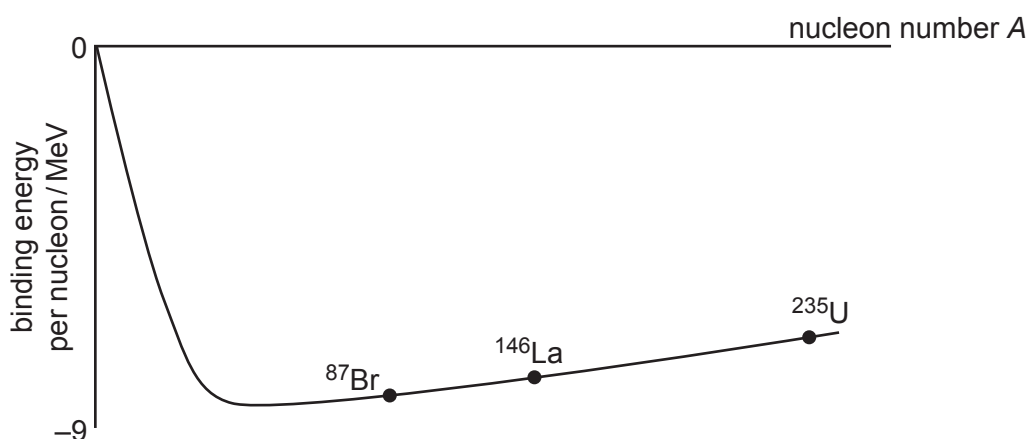


Fig. 2.1

Use the graph to explain why energy is released in the reaction.

The binding energy per nucleon of U-235 is less negative than the (average) binding energy per nucleon of the products La-146 and Br-87. The products are more tightly bound, so their total binding energy is more negative; this difference in energy (mass) is released.

[2]

- (c) Each fission reaction releases about 16 MeV. Calculate the mass change in a single reaction.

$$E = 16 \times 10^6 \text{ eV} \times 1.6 \times 10^{-19} \text{ J eV}^{-1} = 2.56 \times 10^{-12} \text{ J}$$

$$\Delta m = E/c^2 = 2.56 \times 10^{-12} / (3.0 \times 10^8)^2$$

$$\text{mass change} = \dots\dots\dots 2.8 \times 10^{-29} \dots\dots\dots \text{ kg [3]}$$

- (d) Each year, fission reactors around the world produce about $1.4 \times 10^{18} \text{ J}$ of useful energy. Use the data below to calculate an estimate of the time uranium reserves will last at the **current** rate of energy production. Suggest and explain why such an estimate may be inaccurate.

estimated mass of ^{235}U available = $1.6 \times 10^8 \text{ kg}$

mass of ^{235}U atom = $3.9 \times 10^{-25} \text{ kg}$.

efficiency of power stations = 30%

$$\text{number of U-235 atoms} = 1.6 \times 10^8 / 3.9 \times 10^{-25} = 4.1 \times 10^{32}$$

$$\text{useful energy} = 4.1 \times 10^{32} \times 2.56 \times 10^{-12} \text{ J} \times 0.30 = 3.15 \times 10^{20} \text{ J}$$

$$\text{time} = 3.15 \times 10^{20} \text{ J} / 1.4 \times 10^{18} \text{ J per year} = 225 \text{ years}$$

$$\text{time uranium reserves will last} = \dots\dots\dots 225 \dots\dots\dots \text{ years}$$

More uranium reserves may be found in future, as better detection techniques and deeper core samples find new deposits, so the reserves would last longer.

Or there may be fewer than estimated, since it assumes similar rocks yield similar amounts of uranium. Power station efficiency may also increase.

[4]

3 This question is about beta radiation from the decay of potassium-40 ($^{40}_{19}\text{K}$) in bananas.

- (a) An average banana contains about 5×10^{-4} kg of potassium. About 0.012% of this potassium is the beta-emitting isotope, potassium-40.

Show that a single banana will have an activity in the range 10 – 20 Bq.

The mass of one mole of potassium-40 is 0.040 kg.

Potassium-40 decays with half-life 1.3×10^9 years (4.1×10^{16} s).

$$\text{mass of K-40} = (0.012/100) \times 5 \times 10^{-4} \text{ kg} = 6.0 \times 10^{-8} \text{ kg}$$

$$\text{amount of K-40} = 6.0 \times 10^{-8} \text{ kg} / 0.040 \text{ kg mol}^{-1} = 1.5 \times 10^{-6} \text{ mol}$$

$$N = 1.5 \times 10^{-6} \text{ mol} \times 6.0 \times 10^{23} \text{ mol}^{-1} = 9.0 \times 10^{17} \text{ nuclei}$$

$$\lambda = \ln 2 / T_{1/2} = 0.693 / 4.1 \times 10^{16} \text{ s} = 1.69 \times 10^{-17} \text{ s}^{-1}$$

$$\text{activity } A = \lambda N = 1.69 \times 10^{-17} \times 9.0 \times 10^{17} = 15 \text{ Bq}$$

15 Bq lies in the range 10 to 20 Bq

[4]

- (b) The average energy of the beta particles emitted by potassium-40 is 8.3×10^{-14} J.

Show that the equivalent dose received over 20 years by a 70 kg person who eats two bananas every week is about 10 mSv. Assume that all the ingested potassium-40 remained in the body during that time. The quality factor of beta radiation is 1.

$$\text{bananas eaten in 20 years} = 20 \times 52 \times 2 = 2080$$

eaten evenly over 20 years, so on average each has been in the body 10 years

$$\text{decays} = 2080 \times 15 \text{ Bq} \times (10 \times 3.16 \times 10^7 \text{ s}) = 9.86 \times 10^{12}$$

$$\text{energy absorbed} = 9.86 \times 10^{12} \times 8.3 \times 10^{-14} \text{ J} = 0.818 \text{ J}$$

$$\text{absorbed dose} = 0.818 \text{ J} / 70 \text{ kg} = 0.0117 \text{ Gy}$$

$$\text{equivalent dose} = 0.0117 \text{ Gy} \times 1 = 0.0117 \text{ Sv} = 11.7 \text{ mSv} \approx 10 \text{ mSv}$$

[5]

- (c) The risk of contracting cancer is about 5% per sievert. Calculate an estimate of the number of cancers produced in a population of 60 million over a period of twenty years from this equivalent dose.

$$\begin{aligned} \text{number of cancers} &= 60 \times 10^6 \times 0.0117 \text{ Sv} \times 0.05 \text{ Sv}^{-1} \\ &= 35\,000 \text{ (about } 3.5 \times 10^4) \end{aligned}$$

[1]

- (d) The amount of potassium-40 in the body is maintained at a steady level of about 2.0×10^{-5} kg for a 70 kg adult. The excess is excreted.

Suggest and explain one reason why the Government should **not** recommend that people should limit the number of bananas they eat on the basis of radiation risk.

$$\begin{aligned} \text{mass of K-40 in one banana} &= 6.0 \times 10^{-8} \text{ kg (from (a))} \\ \text{steady level in body} &= 2.0 \times 10^{-5} / 6.0 \times 10^{-8} = 330 \text{ bananas' worth} \\ \text{dose over 20 years from this steady level} &\approx 3.8 \text{ mSv} \end{aligned}$$

Eating extra bananas has little effect on the amount of K-40 in the body:
it stays at a steady level and any excess is excreted.
So the assumption that all ingested K-40 stays in the body is incorrect
and the real extra dose is tiny compared with other background sources.

[2]

SECTION B

Answer **all** the questions.

4 This question is about objects falling in a gravitational field.

- (a) In 1589, the Italian physicist Galileo Galilei is said to have dropped different masses from the top of the Leaning Tower of Pisa (Fig. 4.1) to show that all objects accelerate towards the Earth at the same rate.



Fig. 4.1

- (i) The height of the Leaning Tower is 56 m. Calculate the time for a mass to fall to the ground when released from rest at the top of the tower. Ignore the effects of air resistance.

$$s = \frac{1}{2}gt^2 \quad \text{so} \quad t = \sqrt{2s/g}$$

$$t = \sqrt{2 \times 56 / 9.81} = 3.38 \text{ s}$$

time = ...3.4..... s [2]

- (ii) Explain why two objects of different masses dropped from the top of the tower should accelerate at the same rate if air resistance is ignored.

..The gravitational force (weight) on a mass m is $w = mg$

..From $F = ma$, $a = F/m = mg/m = g$, so the mass cancels; every.....

..object has acceleration g , independent of its mass.....

.....

.....

..... [2]

- (b) If Galileo had used two objects with very different masses, he would have observed that they did not both fall with the same acceleration. The air exerts a drag force on falling objects, decreasing their acceleration.

Taking into account the effects of drag, the acceleration a of an object falling through air at velocity v can be modelled using the equation

$$a = 9.81 \text{ ms}^{-2} - Kv^2 \quad \text{where } K \text{ is a constant for the object.}$$

- (i) The motion of a falling object, taking account of drag forces, can be modelled iteratively as shown below:

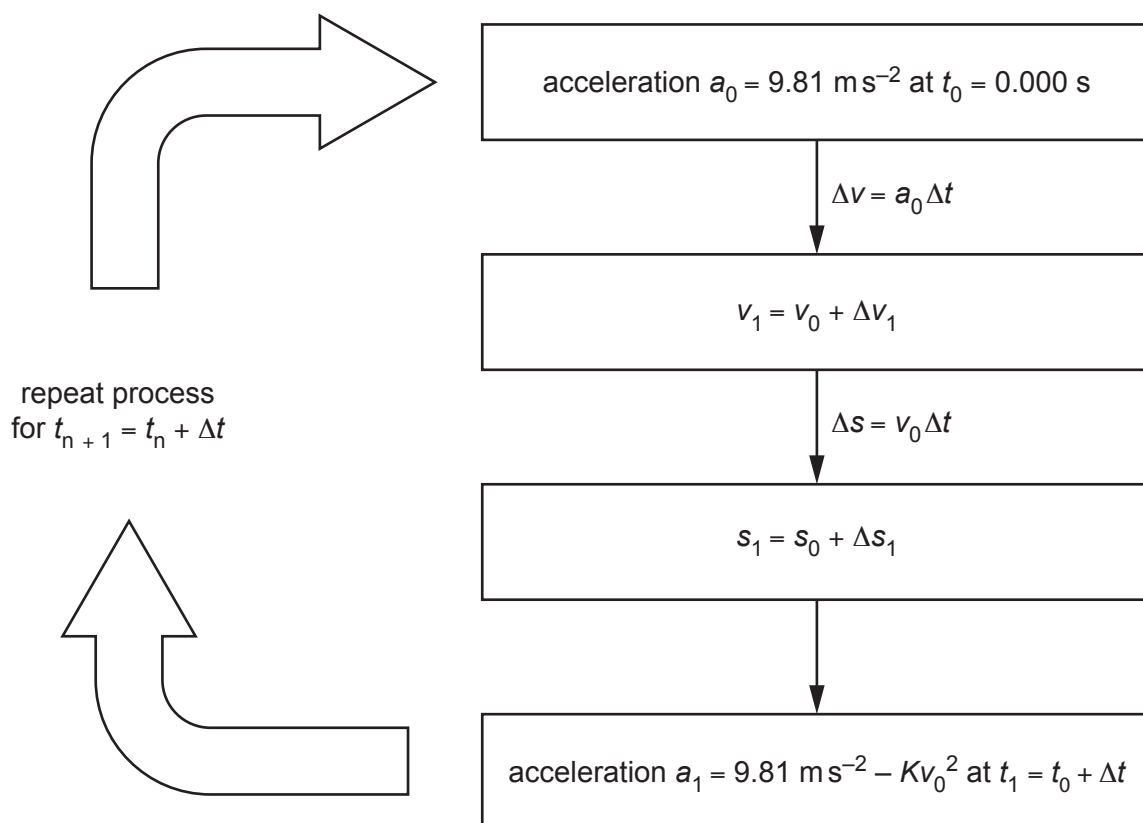


Fig. 4.2

The table below is for a ball with $K = 3.40 \times 10^{-3} \text{ m}^{-1}$, using $\Delta t = 0.200 \text{ s}$. Complete the table.

n	t/s	a/ms^{-2}	$\Delta v/\text{ms}^{-1}$	v/ms^{-1}	$\Delta s/\text{m}$	s/m
0	0.000	9.81	–	0.00	–	0.00
1	0.200	9.81	1.96	1.96	0.00	0.00
2	0.400	9.80	1.96	3.92	0.39	0.39

[3]

(ii)* Further iterations of the calculation produce the graph in Fig. 4.3.

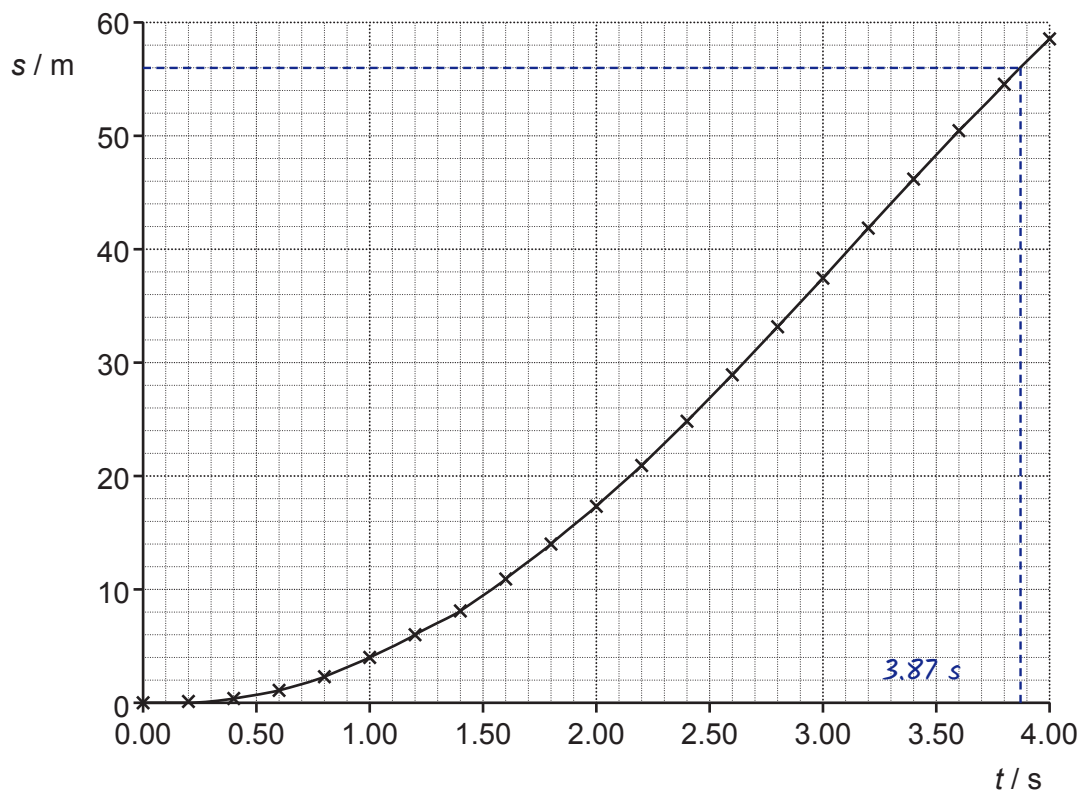


Fig. 4.3

Use data from the graph to estimate the time for this ball to fall from the top of the Leaning Tower to the ground.

Explain why the model may not give an accurate result and how the model could be improved.

Compare your estimate with your value from (a)(i) and use this to suggest and explain whether observers in 1589 would have been able to distinguish between the time of fall of relatively similar masses from the top of the tower. [6]

Reading across from $s = 56$ m to the curve and down to the time axis, the model gives a time of fall of about 3.87 s (3.85 to 3.90 s).
The model is not exact because it holds the acceleration (and velocity) constant over each 0.200 s interval, but in reality the drag increases continuously as v increases, so the acceleration decreases continuously. Holding the acceleration at its value at the start of each interval gives too high an average velocity in each interval, so the model overestimates the distance fallen and underestimates the time of fall.

The model can be improved by reducing the time interval Δt (e.g. 0.01 s on a spreadsheet), so that it gets closer to the continuously varying acceleration and velocity.

Comparison: without drag the time was 3.4 s and with drag about 3.9 s, so drag only adds about 0.5 s, less than one second, even for this ball.

For relatively similar masses the K values would be similar, so the difference in their times of fall would be much smaller than 0.5 s.

A difference of about 0.5 s might just be detected if the two balls were released exactly simultaneously, but a much smaller one could not.

In 1589 observations were by naked eye (and ear), with no accurate clocks or video, reaction times of about 0.2 s, difficulty releasing both at exactly the same moment and a subjective element in judging which landed first.

So observers in 1589 would not have been able to distinguish between the times of fall of relatively similar masses: they would appear to land together.

5 This question is about determining the diameter of the atomic nucleus.

- (a) In 1909, a team led by Ernest Rutherford fired alpha particles at a thin sheet of gold. Most of the alpha particles passed through the sheet with little deflection but about one alpha particle in ten thousand 'bounced back'.

- (i) Explain why such scattering experiments are carried out in a vacuum.

Alpha particles are highly ionising, so in air they would interact with air particles and lose their energy in a short distance (a few cm). Collisions with air particles would also deflect the alpha particles, and these deflections would affect the outcome of the experiment. Evacuating the apparatus reduces interactions over the path length: there are no particles in their way. [3]

- (ii) We can assume that the alpha particles come to rest for an instant at the point where the electrical potential energy of the particle is equal to the kinetic energy of the particle at a large distance from the nucleus.

Calculate the distance of closest approach of a 4.5 MeV alpha particle (${}^4_2\text{He}$) to a gold nucleus (${}^{197}_{79}\text{Au}$) and explain why the use of more energetic alpha particles would result in a different value for the radius of the gold nucleus.

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

$$E_k = 4.5 \times 10^6 \times 1.6 \times 10^{-19} = 7.2 \times 10^{-13} \text{ J}$$

$$r = 9.0 \times 10^9 \times 79 \times 1.6 \times 10^{-19} \times 2 \times 1.6 \times 10^{-19} / 7.2 \times 10^{-13}$$

$$r = 5.06 \times 10^{-14} \text{ m}$$

distance of closest approach = 5.1×10^{-14} m

A more energetic alpha particle would get closer to the nucleus before its electric potential energy equals its initial k.e., so r would be smaller. So the radius found would be smaller: the method only gives an upper limit.

[3]

- (b) Accelerated electrons can also be scattered by atomic nuclei.

The electrons are diffracted by the nuclei giving a minimum at angle θ where $\sin \theta = \frac{1.2\lambda}{d}$ and d is the diameter of the nucleus and λ is the de Broglie wavelength of the electrons.

- (i) Show that the velocity of an electron accelerated through $1.5 \times 10^8 \text{ V}$ is very close to the velocity of light.

rest energy of electron = 0.51 MeV

accelerated through $1.5 \times 10^8 \text{ V}$: kinetic energy = 150 MeV

$\gamma = \text{total energy} / \text{rest energy} = (150 \text{ MeV} + 0.51 \text{ MeV}) / 0.51 \text{ MeV} = 295$

$\gamma = 1/\sqrt{1 - v^2/c^2}$ so $v = c\sqrt{1 - 1/\gamma^2}$

$v = 3.00 \times 10^8 \times \sqrt{1 - 1/295^2}$

$\sqrt{1 - 1/295^2} = 0.999994 \approx 1$

$v = 2.99998 \times 10^8 \text{ m s}^{-1} = 3.00 \times 10^8 \text{ m s}^{-1}$ (3 s.f.), which is

very close to the speed of light c

[4]

- (ii) Calculate the angle of the diffraction minimum for a beam of electrons accelerated through $1.5 \times 10^8 \text{ V}$ scattered from a nucleus of diameter $3.0 \times 10^{-14} \text{ m}$.

For relativistic particles, momentum = $\frac{E}{c}$ where E is the energy of the particle and c is the velocity of light.

$$p = E/c = 1.5 \times 10^8 \times 1.6 \times 10^{-19} \text{ J} / 3.00 \times 10^8 \text{ m s}^{-1} = 8.0 \times 10^{-20} \text{ N s}$$

$$\lambda = h/p = 6.63 \times 10^{-34} / 8.0 \times 10^{-20} = 8.3 \times 10^{-15} \text{ m}$$

$$\sin \theta = 1.2\lambda/d = 1.2 \times 8.3 \times 10^{-15} / 3.0 \times 10^{-14} = 0.33$$

$$\theta = \sin^{-1} 0.33 = 19.4^\circ$$

minimum angle = ...19.....° [4]

- (c) Electron scattering experiments show that the radius r of a nucleus of nucleon number A is proportional to $\sqrt[3]{A}$.

This relationship suggests that the radius of a silver nucleus ($^{107}_{47}\text{Ag}$) is about four-fifths the radius of the gold nucleus. However, calculations similar to those in (a)(ii) suggest that the maximum radius of the silver nucleus is smaller than this.

Use the relationship $r \propto \sqrt[3]{A}$ to calculate the ratio $\frac{\text{radius of a silver atom}}{\text{radius of a gold atom}}$ and show that it is significantly greater than the ratio given by the closest approach method used in (a)(ii).

$$r \propto \sqrt[3]{A}, \text{ so } r_{\text{Ag}}/r_{\text{Au}} = (107/197)^{1/3}$$

$$= (0.543)^{1/3} = 0.82$$

closest approach: $r = kQq/E_k$, so for the same alpha energy $r \propto Q$

$$r_{\text{Ag}}/r_{\text{Au}} = \text{nuclear charge of Ag} / \text{nuclear charge of Au} = 47/79$$

$$= 0.59$$

0.82 is significantly greater than 0.59 (about 40% greater), so the closest approach method gives a much smaller ratio for silver

[4]

6 This question is about conduction in metals and in semiconductors.

- (a) A copper wire of length 1.5 m and radius 2.5×10^{-4} m has a resistance of 0.13Ω at 20°C . Calculate the conductivity of copper at this temperature.

$$\text{conductance } G = 1/R = 1/0.13 \Omega = 7.69 \text{ S}$$

$$A = \pi r^2 = \pi \times (2.5 \times 10^{-4} \text{ m})^2 = 1.96 \times 10^{-7} \text{ m}^2$$

$$G = \sigma A/L \quad \text{so} \quad \sigma = GL/A$$

$$\sigma = 7.69 \text{ S} \times 1.5 \text{ m} / 1.96 \times 10^{-7} \text{ m}^2$$

$$\sigma = 5.88 \times 10^7 \text{ S m}^{-1}$$

$$\text{conductivity at } 20^\circ\text{C} = \dots\dots\dots 5.9 \times 10^7 \dots\dots\dots \text{ S m}^{-1} \text{ [3]}$$

- (b) A simple model of conduction suggests that each copper atom in the wire contributes one or more electrons to a cloud of free electrons that behave rather like particles in a gas. These electrons drift through the wire under the influence of an electric field.

The current I is given by the equation $I = nave$ where:

n is the number of free electrons in the material per m^3

a is the cross-sectional area of the wire

v is the drift velocity of the electrons

e is the electronic charge.

Calculate the drift velocity of the electrons when the copper wire in part (a) carries a current of 2.3 A. The number of free electrons per m^3 in copper = $8.5 \times 10^{28} \text{ m}^{-3}$

$$I = nave \quad \text{so} \quad v = I/(nae)$$

$$v = 2.3 \text{ A} / (8.5 \times 10^{28} \text{ m}^{-3} \times 1.96 \times 10^{-7} \text{ m}^2 \times 1.6 \times 10^{-19} \text{ C})$$

$$v = 8.6 \times 10^{-4} \text{ m s}^{-1}$$

$$\text{drift velocity} = \dots\dots\dots 8.6 \times 10^{-4} \dots\dots\dots \text{ m s}^{-1} \text{ [2]}$$

- (c)* The conductivity σ of semiconductors such as ntc thermistors increases dramatically with temperature T . The relationship is given by the equation

$$\sigma = C e^{-E/kT}$$

where C is a constant, k is the Boltzmann constant and E is the energy required to ionise an atom in the semiconductor.

Use the relationships given in the question to explain the effect of increasing temperature on the conductivity of metals and semiconductors, referring to the microscopic structure of the materials. No calculations are required. [6]

Metals: in a metal such as copper, each atom contributes electrons to a cloud of free electrons (very large n , about 10^{28} m^{-3}) moving through a lattice of positive ions. This number hardly changes with temperature. The electric field accelerates the free electrons between their interactions with the positive ions in the lattice, giving them a drift velocity. Increasing the temperature increases the lattice vibration, so the electrons interact with the ions more often: their mean free path (time between collisions) is reduced. So the increase in drift velocity is lower than the field strength would suggest, and from $I = nAve$ the current for a given p.d. falls: the conductivity of a metal decreases as temperature increases.

Semiconductors: there are far fewer free electrons per m^3 than in a metal, because an energy E is needed to ionise an atom and free an electron to be a charge carrier. Increasing the temperature T increases the energy of the atoms in the semiconductor (typical thermal energy kT), so the fraction E/kT becomes smaller and the Boltzmann factor $e^{-E/kT}$ becomes larger. The Boltzmann factor gives the proportion of atoms with enough energy E to be ionised, so a higher Boltzmann factor means many more atoms are ionised and the number density of charge carriers increases dramatically. This large increase in charge carriers outweighs the extra lattice vibration,

so by $\sigma = Ce^{-E/kT}$ the conductivity of the semiconductor (ntc thermistor) increases dramatically with temperature, whereas the conductivity of the metal decreases.

SECTION C

Answer **all** the questions.

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

- 7 In 1905, Einstein explained the photoelectric effect using the equation

maximum kinetic energy of photoelectrons emitted from a surface = $hf - \phi$

where h is the Planck constant, f is the frequency of light incident on the surface and ϕ is the work function of the surface. Fig. 7.1 shows this relationship for the metal rubidium.

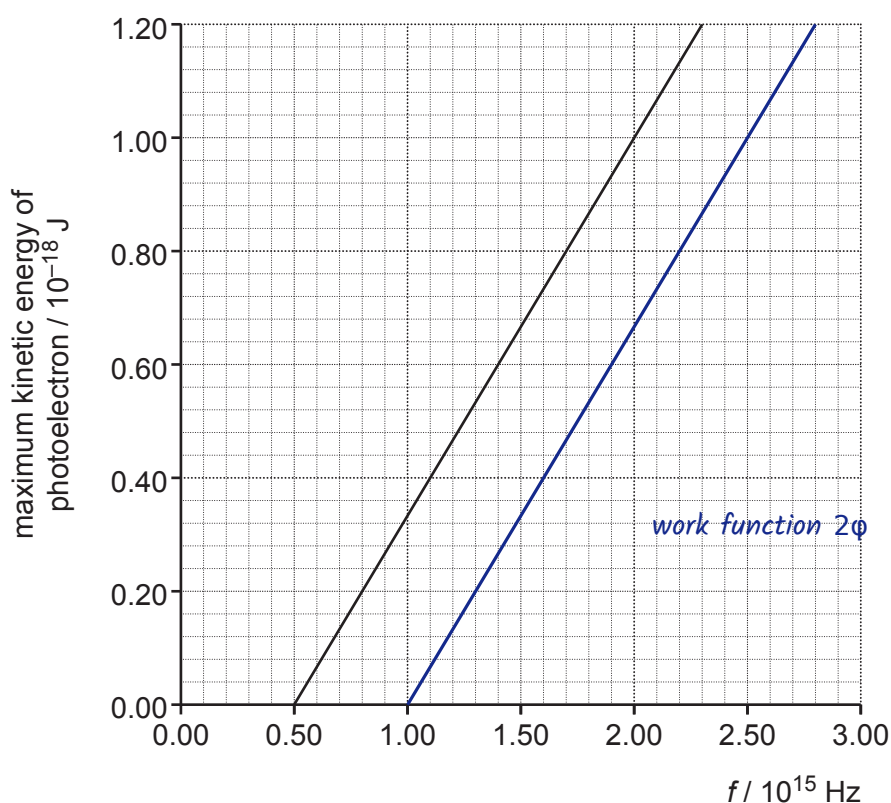


Fig. 7.1

- (a) (i) Use the graph in Fig. 7.1 to find the work function of the metal.

at the threshold frequency $E_k = 0$, so $0 = hf_0 - \phi$, $\phi = hf_0$

from the graph $f_0 = 0.50 \times 10^{15}$ Hz

$\phi = 6.63 \times 10^{-34}$ J s $\times 0.50 \times 10^{15}$ Hz

work function = ... 3.3×10^{-19} J [2]

- (ii) Explain the meaning of the term *work function* and explain why Einstein's equation gives the **maximum** kinetic energy of the electrons emitted for a particular frequency of incident light (lines 14 – 17 in the Article).

Work function: the minimum energy needed for an electron to escape

from the surface.

Not all photons interact with surface electrons; deeper electrons need

more energy to escape, so leave with less than $hf - \phi$. [2]

- (b) Add a second line to the graph of Fig. 7.1 for a metal surface with a work function which is double that of the work function for rubidium. [2]

8* The upper surface of a solar cell is represented in Fig. 8.1.

Use ideas about superposition of waves to explain why a transparent layer of silicon monoxide about 100 nm thick reduces the amount of reflection of light of wavelength 613 nm and increases the efficiency of the solar cell (lines 29 – 30 in the Article). [6]

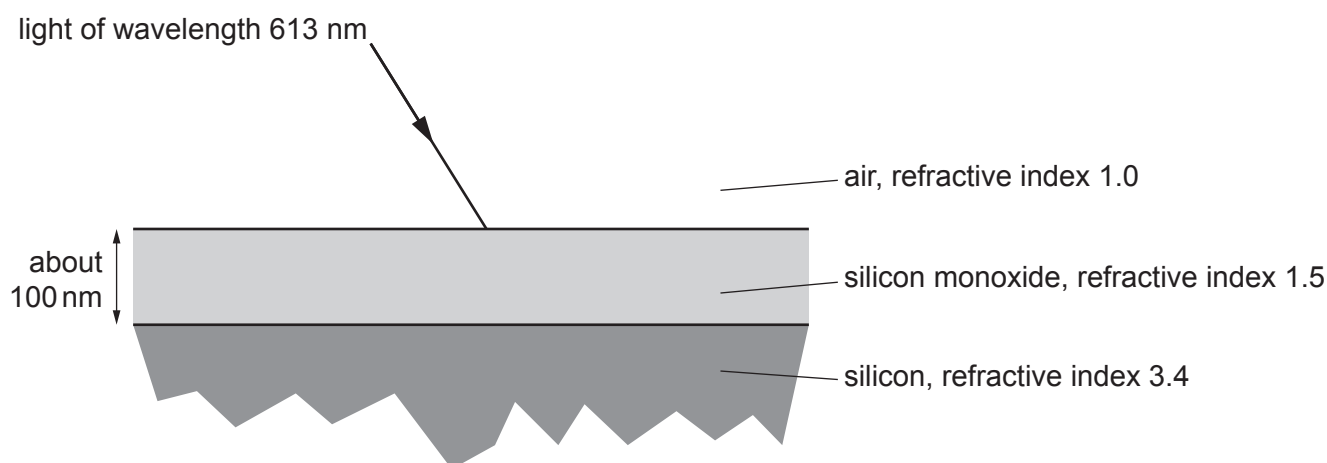


Fig. 8.1

Light is reflected at both boundaries: at the top surface (air to silicon monoxide) and at the lower surface (silicon monoxide to silicon). Reflection at the boundaries introduces a path difference.

The two reflected waves superpose: by the principle of superposition the resultant displacement is the sum of the displacements of the individual waves.

Light reflected from the lower surface travels an extra $2 \times 100 \text{ nm} = 200 \text{ nm}$ through the layer (down and back up), so the path difference is 200 nm.

Light slows down entering a region of higher refractive index: $v = c/n = 3.0 \times 10^8 / 1.5 = 2.0 \times 10^8 \text{ m s}^{-1}$ in the silicon monoxide, so its wavelength is reduced: $\lambda = 613 \text{ nm} / 1.5 = 410 \text{ nm}$.

The path difference of 200 nm is about $\frac{1}{2}\lambda$ ($\frac{1}{2} \times 410 \text{ nm} = 205 \text{ nm}$), so path difference $= (n + \frac{1}{2})\lambda$ with $n = 0$. Both reflections are at a boundary into a higher refractive index, so both have the same phase change.

So the two reflected waves meet in antiphase and cancel (destructive superposition): the intensity of the reflected 613 nm light is greatly reduced.

As less light is reflected, a greater proportion of the incident light is transmitted into the silicon, where more photons interact with electrons in the silicon layer (p-n junction), so the efficiency of the solar cell increases.

- 9 This question is about the effect of the gravitational slingshot on the motion of the Juno space probe (lines 45 – 57 in the Article).

Fig. 9.1 shows a simplified situation in which a space probe of mass m sweeps around a planet of mass M .

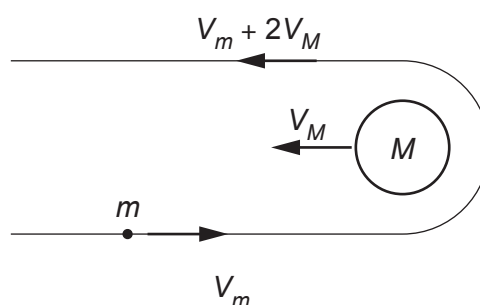


Fig. 9.1

- (a) Show that the change in momentum of the space probe = $2m(V_m + V_M)$.

taking left (direction of V_M) as positive: initial velocity = $-V_m$,
 final velocity = $V_m + 2V_M$; $\Delta v = (V_m + 2V_M) - (-V_m) = 2V_m + 2V_M$
 $\Delta p = m\Delta v = m(2V_m + 2V_M) = 2m(V_m + V_M)$

[2]

- (b) The planet has a much greater mass than the space probe. Use the principle of conservation of momentum to describe the effect that the slingshot will have on the motion of the planet.

Momentum is conserved, so the change of momentum of the planet is equal
 and opposite: $-2m(V_m + V_M)$; the planet is slowed down very slightly.
 As the planet is so much more massive than the probe ($M \gg m$), its
 change in velocity, $2m(V_m + V_M)/M$, is negligible.

[2]

- (c) Use the data below to show that the Juno probe has sufficient energy per kg to move from 1 AU to 5.2 AU after its gravitational slingshot (see lines 58 – 60 in the Article).

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

$$1 \text{ AU} = 1.5 \times 10^{11} \text{ m}$$

$$\text{velocity of Juno after slingshot} = 4.2 \times 10^4 \text{ m s}^{-1}$$

$$5.2 \text{ AU} = 5.2 \times 1.5 \times 10^{11} \text{ m} = 7.8 \times 10^{11} \text{ m}$$

$$\text{energy per kg needed} = \Delta V_{\text{grav}} = -GM/r_2 - (-GM/r_1) = GM(1/r_1 - 1/r_2)$$

$$= 6.67 \times 10^{-11} \times 2.0 \times 10^{30} \times (1/1.5 \times 10^{11} - 1/7.8 \times 10^{11})$$

$$= 7.2 \times 10^8 \text{ J kg}^{-1}$$

$$\text{k.e. per kg after slingshot} = \frac{1}{2}v^2 = \frac{1}{2} \times (4.2 \times 10^4 \text{ m s}^{-1})^2$$

$$= 8.82 \times 10^8 \text{ J kg}^{-1}$$

$$8.82 \times 10^8 \text{ J kg}^{-1} > 7.2 \times 10^8 \text{ J kg}^{-1}, \text{ so Juno has sufficient}$$

$$\text{energy per kg to move from 1 AU to 5.2 AU}$$

[4]

- 10 Solar Impulse 2 recharges its batteries during the day as it climbs from 1500m to 8500m. The solar cells produce an output power of 62.1 kW.

Use data from page 3 of the Article to show that the energy produced by the solar cells over eight hours of daylight is sufficient to lift the plane from 1500m to 8500m and fully recharge the batteries.

Make your reasoning clear.

$$\text{energy from solar cells in 8 hours} = 62\,100\text{ W} \times (8 \times 3600\text{ s}) = 1.79 \times 10^9\text{ J}$$

$$\begin{aligned}\text{energy to lift plane} &= mg\Delta h = 2300\text{ kg} \times 9.81\text{ N kg}^{-1} \times (8500 - 1500)\text{ m} \\ &= 1.58 \times 10^8\text{ J}\end{aligned}$$

$$\text{energy to recharge batteries} = 9.4 \times 10^5\text{ J kg}^{-1} \times 630\text{ kg} = 5.92 \times 10^8\text{ J}$$

$$\text{total energy needed} = 1.58 \times 10^8\text{ J} + 5.92 \times 10^8\text{ J} = 7.5 \times 10^8\text{ J}$$

$$7.5 \times 10^8\text{ J} < 1.79 \times 10^9\text{ J}, \text{ so the energy produced over eight hours}$$

is sufficient to lift the plane and fully recharge the batteries

[4]

- 11 The intensity of solar radiation at 1AU from the Sun is 1.4 kW m^{-2} . At a distance of 5.2AU from the Sun, the solar cells on the Juno probe produce a power of 500 W. Use data from page 4 of the Article to calculate an estimate of the efficiency of the solar cells.

inverse square law: intensity at 5.2 AU = $1.4 \text{ kW m}^{-2} / 5.2^2 = 0.052 \text{ kW m}^{-2}$

power incident on 60 m^2 of cells = $0.052 \text{ kW m}^{-2} \times 60 \text{ m}^2 = 3.1 \text{ kW}$

efficiency = useful output / input = $(500 \text{ W} / 3100 \text{ W}) \times 100\%$

efficiency = ...16..... % [3]

END OF QUESTION PAPER

[illegible]

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