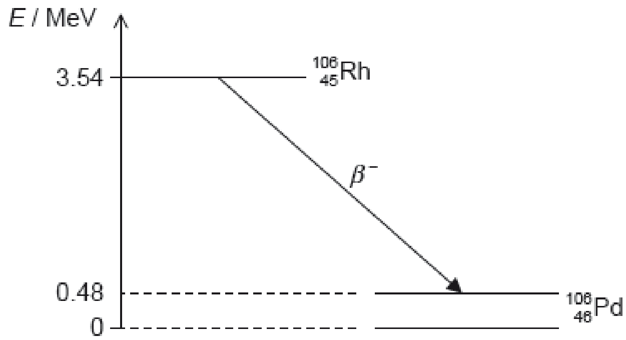
HL Paper 2

Rhodium-106 ($^{106}_{45}\mathrm{Rh}$) decays into palladium-106 ($^{106}_{46}\mathrm{Pd}$) by beta minus (β^-) decay. The diagram shows some of the nuclear energy levels of rhodium-106 and palladium-106. The arrow represents the β^- decay.



b. Bohr modified the Rutherford model by introducing the condition $mvr = n\frac{h}{2\pi}$. Outline the reason for this modification. [3]

c.i. Show that the speed v of an electron in the hydrogen atom is related to the radius r of the orbit by the expression [1]

$$v = \sqrt{\frac{ke^2}{m_e r}}$$

where k is the Coulomb constant.

c.ii. Using the answer in (b) and (c)(i), deduce that the radius r of the electron's orbit in the ground state of hydrogen is given by the following expression. [2]

$$r = \frac{h^2}{4\pi^2 k m_e e^2}$$

c.iii Calculate the electron's orbital radius in (c)(ii). [1]

d.i. Explain what may be deduced about the energy of the electron in the β^- decay. [3]

d.ii. Suggest why the β^- decay is followed by the emission of a gamma ray photon. [1]

d.iii Calculate the wavelength of the gamma ray photon in (d)(ii). [2]

Markscheme

b. the electrons accelerate and so radiate energy

they would therefore spiral into the nucleus/atoms would be unstable

electrons have discrete/only certain energy levels

the only orbits where electrons do not radiate are those that satisfy the Bohr condition «$mvr = n\frac{h}{2\pi}$»

[3 marks]

c.i. $\frac{m_e v^2}{r} = \frac{ke^2}{r^2}$

OR

KE = $\frac{1}{2}$PE hence $\frac{1}{2}m_e v^2 = \frac{1}{2}\frac{ke^2}{r}$

«solving for *v* to get answer»

Answer given – look for correct working

[1 mark]

c.ii. combining $v = \sqrt{\frac{ke^2}{m_e r}}$ with $m_e vr = \frac{h}{2\pi}$ using correct substitution

«*eg* $m_e{}^2 \frac{ke^2}{m_e r} r^2 = \frac{h^2}{4\pi^2}$»

correct algebraic manipulation to gain the answer

Answer given – look for correct working

Do not allow a bald statement of the answer for MP2. Some further working eg cancellation of m or r must be shown

[2 marks]

c.iii. « $r = \frac{(6.63\times10^{-34})^2}{4\pi^2\times8.99\times10^9\times9.11\times10^{-31}\times(1.6\times10^{-19})^2}$ »

$r = 5.3 \times 10^{-11}$ «m»

[1 mark]

d.i. the energy released is 3.54 – 0.48 = 3.06 «MeV»

this is shared by the electron and the antineutrino

so the electron's energy varies from 0 to 3.06 «MeV»

[3 marks]

d.ii. the palladium nucleus emits the photon when it decays into the ground state «from the excited state»

[1 mark]

d.iii. Photon energy

$E = 0.48 \times 10^6 \times 1.6 \times 10^{-19}$ = «7.68×10^{-14} *J*»

λ = «$\frac{hc}{E} = \frac{6.63\times10^{-34}\times3\times10^8}{7.68\times10^{-14}}$ =» 2.6×10^{-12} «m»

*Award **[2]** for a bald correct answer*

Allow ECF from incorrect energy

[2 marks]

Examiners report

b. [N/A]
c.i. [N/A]
c.ii. [N/A]
c.iii. [N/A]
d.i. [N/A]
d.ii. [N/A]

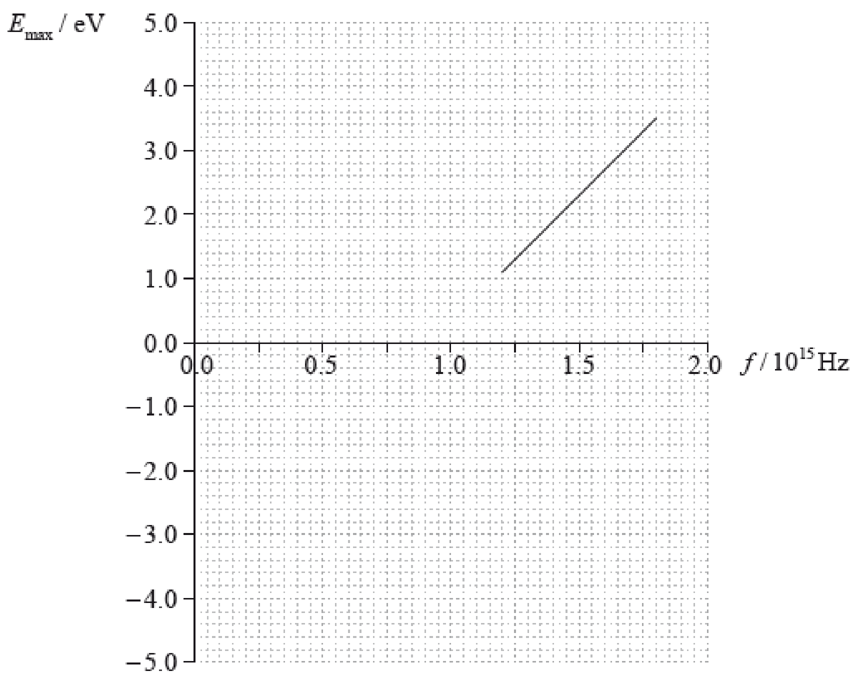
d.iii.[N/A]

This question is in **two** parts. **Part 1** is about the oscillation of a mass. **Part 2** is about the photoelectric effect.

Part 2 Photoelectric effect

A student carries out a photoelectric experiment in which radiation is incident on a metal surface in a vacuum.

A graph of the results of the experiment show how the maximum kinetic energy $E_{\max}$ of the emitted photoelectrons varies with the frequency f of the incident radiation.



Use the graph to

d. Explain why photoelectrons are not emitted from the metal surface unless the frequency of incident light exceeds a minimum value. [2]

e.i. identify the minimum value of the frequency f_0 for photoelectrons to be emitted. [1]

e.ii. determine the Planck constant. [3]

e.iii. calculate the work function, in eV, for the metal surface. [2]

f. The student repeats the experiment with a different metal surface that has a smaller value for the work function. On the graph in (e), draw a line to show how $E_{\max}$ varies with f. [2]

Markscheme

d. light consists of photons with energy $E = hf$;

there is a minimum energy/work function required for electron to leave a particular metal;

hf must be larger than this value;

e.i. (value of intercept on f-axis =) 9.3×10^{14} Hz;

Allow answers in the range of 9.0 to 9.5, but with correct power of ten.

e.ii. attempted use of gradient $\left(\frac{h}{e}\right)$ to evaluate h;

eg $\frac{2.4}{6\times10^{14}} = 4 \times 10^{-15}$ eVs; *(allow answers in the range of 3.9 to* 4.2×10^{-15}*)*

6.4×10^{-34} Js; *(allow ECF, eg answers in the range of 6.2 to* 6.7×10^{-34}*)*

Do not allow a bald answer of 6.6×10^{-34} *as value is known.*

or

use of *y*-intercept $= \frac{-hf_0}{e}$;

$h = \frac{3.77\times1.6\times10^{-19}}{0.93\times10^{15}}$; *(allow intercept between –3.6 and –3.8 eV)*

6.4×10^{-34} Js; *(allow ECF, eg answers in the range of 6.0 to* 6.8×10^{-34}*)*

Do not allow a bald answer of 6.6×10^{-34} *as value is known.*

e.iii. $E = 6.62 \times 10^{-34} \times 9.3 \times 10^{14}$ $(= 6.2 \times 10^{-19}$ J$)$;

an answer in the range of 3.4 to 4.0 eV; *(allow ECF from (e)(i) and (e)(ii))*

or

identifies *y* intercept as work function;

an answer in the range of 3.6 to 3.8 eV;

f. straight line of any length parallel to original data;

to left of original data, intercept on f-axis would be positive;

Examiners report

d. A number of candidates effectively repeated the question by stating that light had to exceed a threshold frequency to cause photoemission. To gain both marks they were expected to refer to the need for photon energy (hf) to be greater than the work function energy for the metal surface.

e.i. To determine the threshold frequency most candidates correctly extended the graph to find the intercept on the *f* axis. Quite large numbers of candidates misread the scale.

e.ii. Various methods were used to determine h. Commonly the gradient was measured, but as always candidates seemed to be unaware that they should choose points on their line as far apart as possible. The gradient in eVs was usually correctly converted to Js.

e.iii. The work function was also determined in a number of different ways. The easiest method was to use the *y* intercept. Most candidates did well on this question.

f. Almost all candidates correctly drew a line parallel and to the left of the original line.

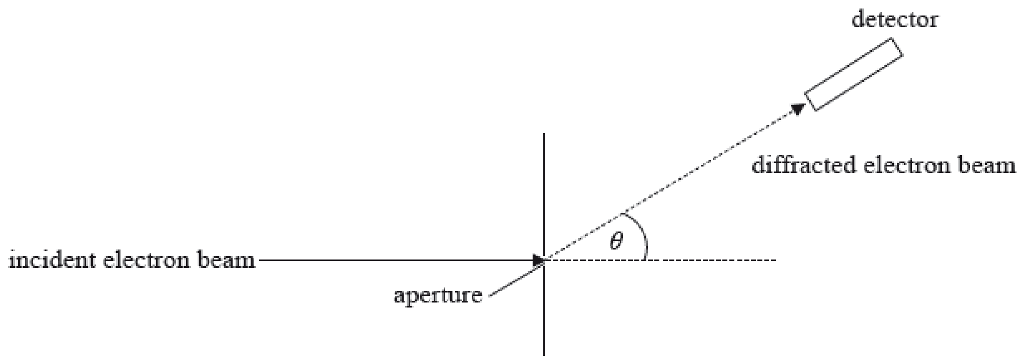
This question is in **two** parts. **Part 1** is about the simple pendulum. **Part 2** is about the de Broglie hypothesis.

Part 2 de Broglie hypothesis

Part 2 b. A beam of electrons is accelerated from rest through a potential difference of 85 V. [3]

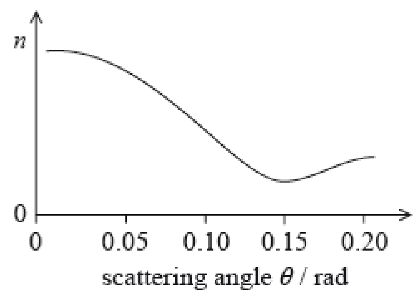
Show that the de Broglie wavelength associated with the electrons in the beam is 0.13 nm.

Part 2 c. Electrons with the same kinetic energy as those in (b) are incident on a circular aperture of diameter 1.1 nm. [4]



The electrons are detected beyond the aperture.

The graph shows the variation with angle θ of the number *n* of electrons detected per second after diffraction by the aperture.



Use your answer to (b) opposite to explain how data from the graph support the de Broglie hypothesis.

Markscheme

Part 2 b. $\text{KE of electron} = 1.4 \times 10^{-17}\ \text{J}$;

combine $\lambda = \frac{h}{p}$ and $E_\text{k} = \frac{p^2}{2m}$ to get $\lambda^2 = \frac{h^2}{2mE_k}$;

$\lambda^2 = \frac{\left[6.6\times10^{-34}\right]^2}{2\times9.1\times10^{-31}\times1.4\times10^{-17}}$;

$\lambda = 1.3 \times 10^{-10}\ \text{m}$

or

$v = \sqrt{\frac{2eV}{m}}$;

$p = \sqrt{2meV}$;

$\lambda = \left(\frac{h}{\sqrt{2meV}} =\right) \frac{6.6\times10^{-34}}{\sqrt{2\times9.1\times10^{-31}\times1.6\times10^{-19}\times85}}$;

$\lambda = 1.3 \times 10^{-10}\ \text{m}$

Part 2 c. minimum read-off at 0.15 rad; *(allow answers in the range of 0.14 rad to 0.16 rad)*

$\lambda = \frac{b\theta_\text{min}}{1.22}$;

$= 1.4 \times 10^{-10}\ \text{m}$;

same/similar wavelength to (b) (so de Broglie hypothesis supported);

*Allow **[3 max]** if 1.22 missing – answer is then 0.162 nm.*

Examiners report

Part 2 b. Candidates answered this well and had been well schooled in the demands of this calculation. However a significant number wrote solutions that were completely unintelligible to the examiners.

Part 2 a. Candidates were required to use the graph of electron beam intensity against scattering angle to show that the scattering aperture diameter was commensurate with the electron wavelength. About half the candidates could achieve this, but some lost marks through omitting the 1.22 factor in the circular aperture equation.

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a. An alpha particle with initial kinetic energy 32 MeV is directed head-on at a nucleus of gold-197 $\left({}^{197}_{79}\mathrm{Au}\right)$. [5]

(i) Show that the distance of closest approach of the alpha particle from the centre of the nucleus is about 7×10^{-15}m.

(ii) Estimate the density of a nucleus of ${}^{197}_{79}\mathrm{Au}$ using the answer to (a)(i) as an estimate of the nuclear radius.

b. The nucleus of ${}^{197}_{79}\mathrm{Au}$ is replaced by a nucleus of the isotope ${}^{195}_{79}\mathrm{Au}$. Suggest the change, if any, to your answers to (a)(i) and (a)(ii). [2]

Distance of closest approach:

Estimate of nuclear density:

c. An alpha particle is confined within a nucleus of gold. Using the uncertainty principle, estimate the kinetic energy, in MeV, of the alpha particle. [3]

Markscheme

a. (i)

32 MeV converted using $32\times10^{6}\times1.6\times10^{-19}$«$=5.12\times10^{-12}$J»

$$d = \ll \frac{kQq}{E} = \frac{8.99\times10^{9}\times2\times79\times\left(1.6\times10^{-19}\right)^{2}}{32\times10^{6}\times1.6\times10^{-19}} = \gg \frac{8.99\times10^{9}\times2\times79\times1.6\times10^{-19}}{32\times10^{6}}$$

OR 7.102×10^{-15}m

«$d\approx7\times10^{-15}$m»

Must see final answer to 2+ SF unless substitution is completely correct with value for k explicit.
Do not allow an approach via $r = R_0 A^{\frac{1}{3}}$.

(ii)
$m\approx197\times1.661\times10^{-27}$
OR
3.27×10^{-25}kg

$V = \frac{4\pi}{3} \times \left(7 \times 10^{-15}\right)^{3}$

OR

1.44×10^{-42}m^{-3}
$\rho = \ll \frac{m}{V} = \frac{3.2722\times10^{-25}}{1.4368\times10^{-42}} = \gg 2.28 \times 10^{17} \approx 2 \times 10^{17}\mathrm{kgm}^{-3}$

Allow working in MeV: 1.28×10^{47}MeVc^{-2}m^{-3}.
Allow ECF from incorrect answers to MP1 or MP2.

b. Distance of closest approach: charge ***or*** number of protons ***or*** force of repulsion is the same so distance is the same

Estimate of nuclear density: «$\rho \propto \frac{A}{\left(A^{\frac{1}{3}}\right)^{3}}$ so» density the same

c. $\Delta x \approx 7 \times 10^{-15}$ m

$$\Delta p \approx \frac{6.63\times10^{-34}}{4\pi\times7\times10^{-15}} \ll= 7.54 \times 10^{-21}\text{Ns} \gg$$

$$E \approx \ll \frac{\Delta p^2}{2m} = \frac{\left(7.54\times10^{-21}\right)^2}{2\times6.6\times10^{-27}} = 4.3 \times 10^{-15}\text{J} = 26897\text{eV} \gg \approx 0.027\text{MeV}$$

Accept $\Delta x \approx 3.5\times10^{-15}$m or $\Delta x \approx 1.4\times10^{-14}$m leading to E≈0.11MeV or 0.0067MeV.
Answer must be in MeV.

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

This question is in **two** parts. **Part 1** is about electric cells. **Part 2** is about atoms.

Part 1 Electric cells

Cells used to power small electrical devices contain both conductors and insulators.

Cells also have the property of internal resistance.

Part 2 Atoms

Photoelectric emission occurs when ultraviolet radiation is incident on the surface of mercury but not when visible light is incident on the metal.

Photoelectric emission occurs when visible light of all wavelengths is incident on caesium.

a. (i) Distinguish between an insulator and a conductor. [4]

(ii) Outline what is meant by the internal resistance of a cell.

c. State what is meant by the photoelectric effect. [1]

d. (i) Suggest why the work function for caesium is smaller than that of mercury. [4]

(ii) Ultraviolet radiation of wavelength 210 nm is incident on the surface of mercury. The work function for mercury is 4.5 eV. Determine the maximum kinetic energy of the photoelectrons emitted.

f. An exact determination of the location of the electron in a hydrogen atom is not possible. Outline how this statement is consistent with the Schrödinger model of the hydrogen atom. [3]

Markscheme

a. (i) conductor has free electrons/charges that are free to move within/through it / insulator does not have free electrons/charges that are free to move within/ through it;

electrons act as charge carriers;

when a pd acts across a conductor a current exists when charge (carriers) move;

Do not allow "good/bad conductor/resistor" or reference to conductivity/ resistivity.

(ii) some of the power/energy delivered by a cell is used/dissipated in driving current through the cell;

power loss can be equated to I^2r where *r* represents the (internal) resistance of the cell; } *(symbols must be defined)*

resistance of contents of cell; *(do not allow "resistance of cell")*

c. the emission of electrons from a (metal) surface by photons/light/electromagnetic radiation (incident on the surface);

d. (i) caesium electrons are less firmly bound / mercury requires more energy to release electron; } *(allow reverse argument)*

If answer is in terms of threshold frequency, frequency must be linked to energy via $E = hf$.

(ii) energy of photon $= \frac{6.63\times10^{-34}\times3\times10^{8}}{2.1\times10^{-7}}$ $\left(= 9.5 \times 10^{-19}\ (\text{J})\right)$;

convert photon energy to eV, 5.9 (eV) / convert work function to joules $7.2 \times 10^{-19}\ (\text{J})$;

so kinetic energy of electron = (photon energy − work function =) 1.4 (eV) ***or*** $2.3 \times 10^{-19}\ (\text{J})$;

*Award **[3]** for a bald correct answer.*

f. (Schrödinger model suggests) electron is described by wavefunction;

that gives probability of finding electron at a particular place / probability of finding electrons is proportional to square of (wavefunction) amplitude;

so position of electron is uncertain;

Examiners report

a. (i) Superficial answers were common. Candidates continue to ignore the mark allocations for questions and therefore misunderstand the number of independent points they should mention in an answer. Here, most said that conductors contain free electrons (or the reverse for insulators) but did not go on to discuss the role of the free electrons in carrying charge or to relate the current to the existence of an electric field across the conductor. Far too many gave answers of the "conductors conduct well" variety that do not score marks.

(ii) Too often candidates were content to suggest that the internal resistance of a cell is the resistance of the cell contents without discussing the physical implications of this. It was rare to see a consideration of the energy dissipation in the cell or an explanation of the way the power loss is related to a "resistance".

c. Many candidates were able to give a complete description of the photoelectric effect.

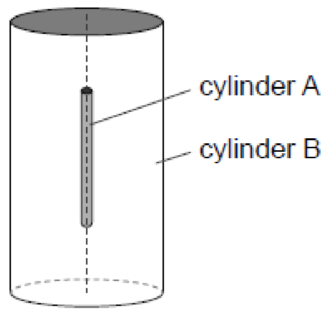
d. (i) Although the majority were able to relate work function to the physics of the electrons in the metal, some could only respond in terms of the minimum frequency required to produce a photocurrent. This did not generally score marks without some supporting remarks.

(ii) Generally, candidates were able to score at least two marks. Work was marred by power of ten errors and by inabilities to convert between the electrovolt and the joule. A major reason for errors was that candidates often did not begin with a clear statement of the photoelectric equation followed by substitution in an organised way.

f. Significant numbers scored two out of three marks. There were some good attempts to link the wavefunction idea to the probability ideas of the theory.

The first scientists to identify alpha particles by a direct method were Rutherford and Royds. They knew that radium-226 ($^{226}_{86}\mathrm{Ra}$) decays by alpha emission to form a nuclide known as radon (Rn).

At the start of the experiment, Rutherford and Royds put 6.2 x 10^{-4} mol of pure radium-226 in a small closed cylinder A. Cylinder A is fixed in the centre of a larger closed cylinder B.



The experiment lasted for 6 days. The decay constant of radium-226 is 1.4 x 10^{-11} s^{-1}.

At the start of the experiment, all the air was removed from cylinder B. The alpha particles combined with electrons as they moved through the wall of cylinder A to form helium gas in cylinder B.

a. Write down the nuclear equation for this decay. [2]

b.i. Deduce that the activity of the radium-226 is almost constant during the experiment. [2]

b.ii. Show that about 3 x 10^{15} alpha particles are emitted by the radium-226 in 6 days. [3]

c.i. The wall of cylinder A is made from glass. Outline why this glass wall had to be very thin. [1]

c.ii. The experiment was carried out at a temperature of 18 °C. The volume of cylinder B was 1.3 x 10^{-5} m^3 and the volume of cylinder A was negligible. Calculate the pressure of the helium gas that was collected in cylinder B over the 6 day period. Helium is a monatomic gas. [3]

Markscheme

a. $^{4}_{2}\alpha$

OR

$^{4}_{2}\mathrm{He}$

$^{222}_{86}\mathrm{Rn}$

*These **must** be seen on the right-hand side of the equation.*

b.i. ***ALTERNATIVE 1***

6 days is 5.18 x 10^5 s

activity after 6 days is $A_0 e^{-1.4\times10^{-11}\times5.8\times10^5} \approx A_0$

OR

A = 0.9999927 A_0 ***or*** 0.9999927 λN_0

OR

states that index of e is so small that $\frac{A}{A_0}$ is ≈ 1

OR

$A - A_0 \approx 10^{-15}$ «s^{-1}»

ALTERNATIVE 2
shows half-life of the order of 10^{11} s or 5.0 x 10^{10} s

converts this to year «1600 y» or days and states half-life much longer than experiment compared to experiment

*Award **[1 max]** if calculations/substitutions have numerical slips but would lead to correct deduction.*

eg: failure to convert 6 days to seconds but correct substitution into equation will give MP2.

Allow working in days, but for MP1 must see conversion of λ or half-life to day^{-1}.

b.ii ***ALTERNATIVE 1***

use of $A = \lambda N_0$

conversion to number of molecules = nN_A = 3.7 x 10^{20}

OR

initial activity = 5.2 x 10^9 «s^{-1}»

number emitted = (6 x 24 x 3600) x 1.4 x 10^{-11} x 3.7 x 10^{20} ***or*** 2.7 x 10^{15} alpha particles

ALTERNATIVE 2
use of $N = N_0 e^{-\lambda t}$

$N_0 = n \times N_A$ = 3.7 x 10^{20}

alpha particles emitted «= number of atoms disintegrated = $N - N_0$ =» $N_0\left(1 - e^{-\lambda\times6\times24\times3600}\right)$ ***or*** 2.7 x 10^{15} alpha particles

Must see correct substitution or answer to 2+ sf for MP3

c.i. alpha particles highly ionizing

OR

alpha particles have a low penetration power

OR

thin glass increases probability of alpha crossing glass

OR

decreases probability of alpha striking atom/nucleus/molecule

Do not allow reference to tunnelling.

c.ii.conversion of temperature to 291 K

p = 4.5 x 10^{-9} x 8.31 x «$\frac{291}{1.3\times10^{-5}}$»

OR

p = 2.7 x 10^{15} x 1.3 x 10^{-23} x «$\frac{291}{1.3\times10^{-5}}$»

0.83 ***or*** 0.84 «Pa»

Allow ECF for 2.7 x 10^{15} from (b)(ii).

Examiners report

a. [N/A]
b.i. [N/A]
b.ii. [N/A]
c.i. [N/A]
c.ii. [N/A]

Part 3 Atomic energy levels

b. Outline how atomic emission spectra provide evidence for the quantization of energy in atoms. [2]

c. Consider an electron confined in a one-dimensional “box” of length *L*. The de Broglie waves associated with the electron are standing waves with wavelengths given by $\frac{2L}{n}$, where *n*=1, 2, 3, … [3]

Show that the energy E_n of the electron is given by

$$En = \frac{n^2h^2}{8m_eL^2}$$

where *h* is Planck’s constant and m_e is the mass of the electron.

d. An electron is confined in a “box” of length $L=1.0\times10^{-10}$m in the *n*=1 energy level. Its position as measured from one end of the box is $(0.5\pm0.5)\times10^{-10}$m. Determine [4]

(i) the momentum of the electron.

(ii) the uncertainty in the momentum.

Markscheme

b. all particles have an associated wavelength / *OWTTE;*

wavelength is given by $\lambda = \frac{h}{p}$, where *h* is Planck’s constant and *p* is momentum;

c. from de Broglie hypothesis, $p_n = \frac{h}{\lambda_n} = \frac{nh}{2L}$;

kinetic energy given by $E_K = \frac{p^2}{2m_e}$;

combined and manipulated to obtain result;

d. (i) $\lambda = \frac{2L}{n} = \frac{2\times1.0\times10^{-10}}{1} = 2.0 \times 10^{-10}$;

$p = \frac{h}{\lambda} = \frac{6.6\times10^{-34}}{2.0\times10^{-10}} = 3.3 \times 10^{-24}\mathrm{kgms}^{-1}$;

*Award **[2]** for alternative methods, e.g. calculating energy then momentum.*

(ii) use of $\Delta x \Delta p \geq \frac{h}{4\pi}$;
to get $\Delta p \geq \frac{6.6\times10^{-34}}{4\pi\times0.5\times10^{-10}} = 1.1 \times 10^{-24}\mathrm{kgms}^{-1}$;

Examiners report

b. [N/A]
c. [N/A]
d. [N/A]

Part 2 Electrons

a. Monochromatic light is incident on a metal surface and electrons are emitted instantaneously from the surface. [4]

Explain why

(i) the emission of the electrons is instantaneous.

(ii) the energy of the emitted electrons does not depend on the intensity of the incident light.

b. The wavelength of the incident light in (a) is 420 nm and the work function of the metal is 3.4×10^{-19}J. [6]

(i) Determine, in joules, the maximum kinetic energy of an emitted electron.

(ii) The metal surface has dimensions of 1.5 mm×2.0 mm. The intensity of the light incident on the surface is 4.5×10^{-6} W m^{-2}. On average, one electron is emitted for every 300 photons that are incident on the surface. Determine the initial electric current leaving the metal surface.

Markscheme

a. (i) mention of photons;

of quantized energy / energy is *hf*;

one to one correspondence with electrons and photons / *OWTTE*;

(so arrival of light causes emission straightaway)

(ii) intensity is a measure of the number of photons not the individual photon energy;

b. (i) $E = \frac{hc}{4.2\times10^{-7}}$;

4.7×10^{-19}J;

so maximum energy (4.7×10^{-19}-3.4×10^{-19}=)1.3×10^{-19}J;

(ii) energy arriving per second=$3\times10^{-6}\times4.5\times10^{-6}$(=$1.35\times10^{-11}$W);
so arrival rate of photons $= \frac{1.35\times10^{-11}}{4.7\times10^{-19}}$ } *(allow ECF from (b)(i))*
(=2.9×10^{7} photons s^{-1});
and a current of $\left(\frac{2.9\times10^{7}\times1.6\times10^{-19}}{300} =\right) 1.5 \times 10^{-14}\mathrm{A}$;

Examiners report

a. [N/A]
b. [N/A]

This question is about nuclear processes.

a. Describe what is meant by [4]

(i) radioactive decay.

(ii) nuclear fusion.

b. Tritium is a radioactive nuclide with a half-life of 4500 days. It decays to an isotope of helium. [3]

Determine the time taken for 90% of a sample of tritium to decay.

c. A nuclide of deuterium $\left({}_1^2\mathrm{H}\right)$ and a nuclide of tritium $\left({}_1^3\mathrm{H}\right)$ undergo nuclear fusion. The reaction equation for this process is [1]

$$ {}_1^2\mathrm{H}+{}_1^3\mathrm{H} \rightarrow {}_2^4\mathrm{He}+\mathrm{X} $$

Identify X.

Markscheme

a. (i) refers to unstable nucleus/isotope / refers to spontaneous/random process;

which emits named radiation (from nucleus) / forms different nucleus/isotope;

(ii) combination of two nuclei / *OWTTE*; *(do not allow “particles” or “atoms”)*
to form new nuclide with greater mass/larger nucleus/greater number of nucleons;

b. $\lambda=\frac{\ln 2}{4500}\left(=1.54\times 10^{-4}\right)$;

$0.1N_0=N_0\mathrm{e}^{-1.54\times 10^{-4}t}$;

1.5×10^4(d) ***or*** 1.3×10^9(s);

*Award **[2 max]** if answer is time to lose 10% (680 d).*

Allow answer to be expressed in any time units.

*Award **[3]** for a bald correct answer.*

or

$\ln 0.1=\frac{-0.69t}{t_{\frac{1}{2}}}$;
t=3.3×4500;
1.5×10^4(d);
*Award **[2 max]** if answer is time to lose 10% (680 d).*
Allow answer to be expressed in any time units.
*Award **[3]** for a bald correct answer.*

c. ${}_0^1n$/neutron;

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

This question is about the photoelectric effect.

Monochromatic light of wavelength 420 nm is incident on a clean metal surface. The work function of the metal is 2.6×10^{-19} J.

a. Outline why the wave model of light cannot account for the photoelectric effect. [3]

b.i. Calculate, in eV, the maximum kinetic energy of the photoelectrons emitted. [3]

b.ii. The intensity of the light is $5.1\ \mu\mathrm{W\,m^{-2}}$. Determine the number of photoelectrons emitted per second for each mm^2 of the metal surface. Each photon has a 1 in 800 chance of ejecting an electron. [3]

Markscheme

a. electrons require energy for release;

electrons (are observed) to appear instantaneously;

wave model requires time delay (to build up enough energy);

or

the kinetic energy of the (emitted) electrons depends on frequency (of incident light);

with no electron emission below a threshold frequency;

a wave model suggests emission at all frequencies;

or

*Award **[2 max]** only for this approach.*

a maximum electron energy is observed (for a particular wavelength);

a wave model would permit any value so no maximum;

Only allow one route, candidate cannot pick facts from the three alternatives.

b.i. (photon) energy $\frac{hc}{\lambda} = \frac{6.63\times10^{-34}\times3.00\times10^{8}}{420\times10^{-9}}$ $(= 4.74 \times 10^{-19}\ \mathrm{J})$;

$E_{\max} = (hf - \phi =)\ 4.74 \times 10^{-19} - 2.60 \times 10^{-19}$;

1.33 ***or*** 1.34 (eV); } *(this mark is for correct conversion to eV; allow ECF from incorrect MP1 and MP2)*

*Award **[3]** for a bald correct answer.*

*If no unit given, assume eV and mark accordingly – eg: award **[2 max]** for a non-conversion.*

b.ii. $5.1\ \mu\mathrm{W\,m^{-2}} = 5.1 \times 10^{-12}\ (\mathrm{Js^{-1}mm^{-2}})$;

(number of incident photons per mm^2 per second) = $\frac{5.1\times10^{-12}}{4.74\times10^{-19}}$ $(= 1.08 \times 10^{7})$;

(number of photoelectrons per mm^2 per second) = $\frac{1.08\times10^{7}}{800}$ $(= 1.3 \times 10^{4})$;

Accept 1.4 $\times$ 10^4 using rounded energy in (b)(i).

For alternative approaches look for the following in any order:

correct transformation from power/m^2 to energy/s/mm^2;

correct use of incoming photon energy; *(must see "photon")*

Allow ECF from (b)(i) if identifiable correct insertion of 800 factor and final calculation.

Award **[3]** *for a bald correct answer.*

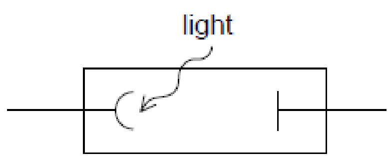
Examiners report

a. A number of alternative arguments can be used in this question. The most frequent one was the approach via the instantaneous appearance of the electron when radiation of even the lowest intensities is incident. Too many candidates simply quoted some random observations supposing that the examiner would be happy to join up the thinking. However, one route was allowed with arguments that linked the observation quoted with the predictions that would follow from a consideration of the wave model.

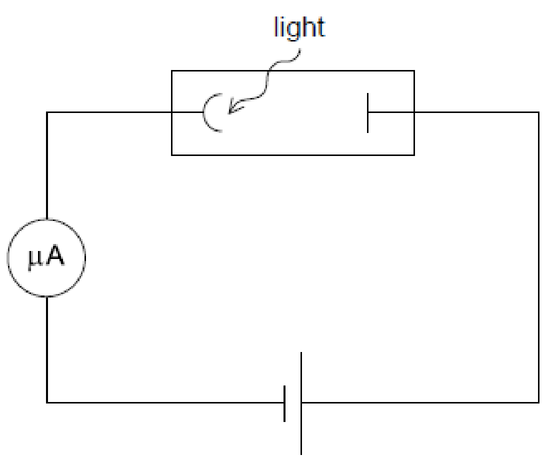
b.i. Many candidates can now carry out this and similar calculations fluently and confidently.

b.ii Again, a large number of correct solutions were seen with many more deficient in one or two aspects of the solution.

Yellow light of photon energy 3.5 x 10^{-19} J is incident on the surface of a particular photocell.



The photocell is connected to a cell as shown. The photoelectric current is at its maximum value (the saturation current).



Radiation with a greater photon energy than that in (b) is now incident on the photocell. The intensity of this radiation is the same as that in (b).

a.i. Calculate the wavelength of the light. [1]

a.ii. Electrons emitted from the surface of the photocell have almost no kinetic energy. Explain why this does not contradict the law of conservation of energy. [2]

b. Radiation of photon energy 5.2 x 10^{-19} J is now incident on the photocell. Calculate the maximum velocity of the emitted electrons. [2]

c.i. Describe the change in the number of photons per second incident on the surface of the photocell. [1]

c.ii. State and explain the effect on the maximum photoelectric current as a result of increasing the photon energy in this way. [3]

Markscheme

a.i. wavelength = «$\frac{hc}{E} = \frac{1.99 \times 10^{-25}}{3.5 \times 10^{-19}} =$» 5.7 x 10^{-7} «m»

If no unit assume m.

a.ii. «potential» energy is required to leave surface

Do not allow reference to "binding energy".
Ignore statements of conservation of energy.

all/most energy given to potential «so none left for kinetic energy»

b. energy surplus = 1.7 x 10^{-19} J

$v_{max} = \sqrt{\frac{2 \times 1.7 \times 10^{-19}}{9.1 \times 10^{-31}}} = 6.1 \times 10^{5}$ «m s^{-1}»

*Award **[1 max]** if surplus of 5.2 x 10^{-19}J used (answer: 1.1 x 10^{6} m s^{-1})*

c.i. «same intensity of radiation so same total energy delivered per square metre per second»

light has higher photon energy so fewer photons incident per second

Reason is required

c.ii. 1:1 correspondence between photon and electron

so fewer electrons per second

current smaller

Allow ECF from (c)(i)
Allow ECF from MP2 to MP3.

Examiners report

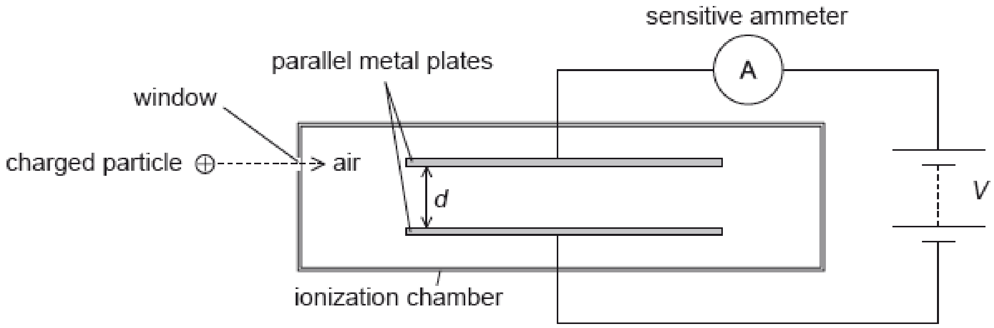
a.i. [N/A]
a.ii. [N/A]
b. [N/A]
c.i. [N/A]
[N/A]

c.ii.

This question is in **two** parts. **Part 1** is about electric fields and radioactive decay. **Part 2** is about waves.

Part 1 Electric fields and radioactive decay

An ionization chamber is a device which can be used to detect charged particles.



The charged particles enter the chamber through a thin window. They then ionize the air between the parallel metal plates. A high potential difference across the plates creates an electric field that causes the ions to move towards the plates. Charge now flows around the circuit and a current is detected by the sensitive ammeter.

The separation of the plates *d* is 12 mm and the potential difference V between the plates is 5.2 kV. An ionized air molecule M with charge $+2e$ is produced when a charged particle collides with an air molecule.

Radium-226 $\left({}^{226}_{88}\mathrm{Ra}\right)$ decays into an isotope of radon (Rn) by the emission of an alpha particle and a gamma-ray photon. The alpha particle may be detected using the ionization chamber but the gamma-ray photon is unlikely to be detected.

a. On the diagram, draw the shape of the electric field between the plates. [2]

b.i. Calculate the electric field strength between the plates. [1]

b.ii. Calculate the force on M. [2]

b.iii. Determine the change in the electric potential energy of M as it moves from the positive to the negative plate. [3]

c.ii. Construct the nuclear equation for the decay of radium-226. [2]

$${}^{226}_{88}\mathrm{Ra} \rightarrow {}^{\cdots\cdots}_{\cdots\cdots}\mathrm{Rn} + {}^{\cdots\cdots}_{\cdots\cdots}\mathrm{He} + {}^{0}_{0}\gamma$$

c.iii. Radium-226 has a half-life of 1600 years. Determine the time, in years, it takes for the activity of radium-226 to fall to 5% of its original activity. [3]

Markscheme

a. minimum of three lines equally spaced and distributed, perpendicular to the plates and downwards; edge effect shown; } *(condone lines that do not touch plates)*

b.i. $4.3 \times 10^{5}\ (\mathrm{NC}^{-1})$

b.ii. $(F = Eq =)\ 4.3 \times 10^{5} \times 2 \times 1.6 \times 10^{-19}$; *(allow ECF from (b)(i))*

1.4×10^{-13} (N);

*Award **[2]** for a bald correct answer.*

b.iii. $\Delta E_{\mathrm{P}} = q\Delta V$ ***or*** $3.2 \times 10^{-19} \times 5.2 \times 10^{3}$;

1.7×10^{-15} (J);

negative/loss;

c.ii. $\left({}^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He} + {}^{0}_{0}\gamma\right)$

${}^{222}_{86}\mathrm{Rn}$ ***or*** ${}^{4}_{2}\mathrm{He}$;

numbers balance top and bottom on right-hand side;

c.iii. $\lambda = \frac{\ln 2}{1600} = 4.33 \times 10^{-4}$ (yr^{-1});

$0.05 = \mathrm{e}^{-\lambda t}$;

6900 (years);

*Award **[3]** for a bald correct answer.*

*Award **[2 max]** for 2.18×10^{11} (s).*

*Award **[1 max]** to a candidate who identifies time as about 4.3 half-lives but cannot get further or gives an approximate reasoned answer.*

*However award **[3]** if number n of half-lives is calculated from $0.05 = 2^{-n}$ (= 4.32 usually from use of $\log_2$ working) and time shown.*

Examiners report

a. Field patterns were often negligently drawn. Lines did not meet both plates, edge effects were ignored, and the (vital) equality of spacing between drawn lines was not considered. Candidates continue to show their inadequacy in responding to questions that demand a careful and accurate diagram.

b.i. This sequence of calculations was often undertaken well with appropriate figures carried through from part to part.

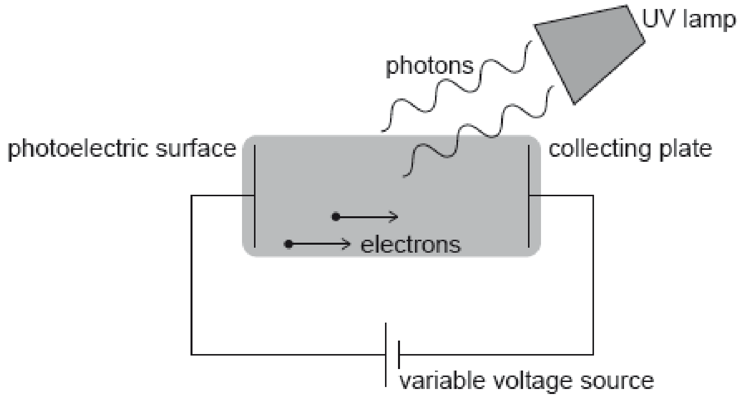
b.ii. This sequence of calculations was often undertaken well with appropriate figures carried through from part to part.

b.iii. This sequence of calculations was often undertaken well with appropriate figures carried through from part to part. The only common error was the omission of a consideration of the gain or loss of the energy change in part (iii).

c.ii. As one of the easiest questions on the paper this was predictably well done.

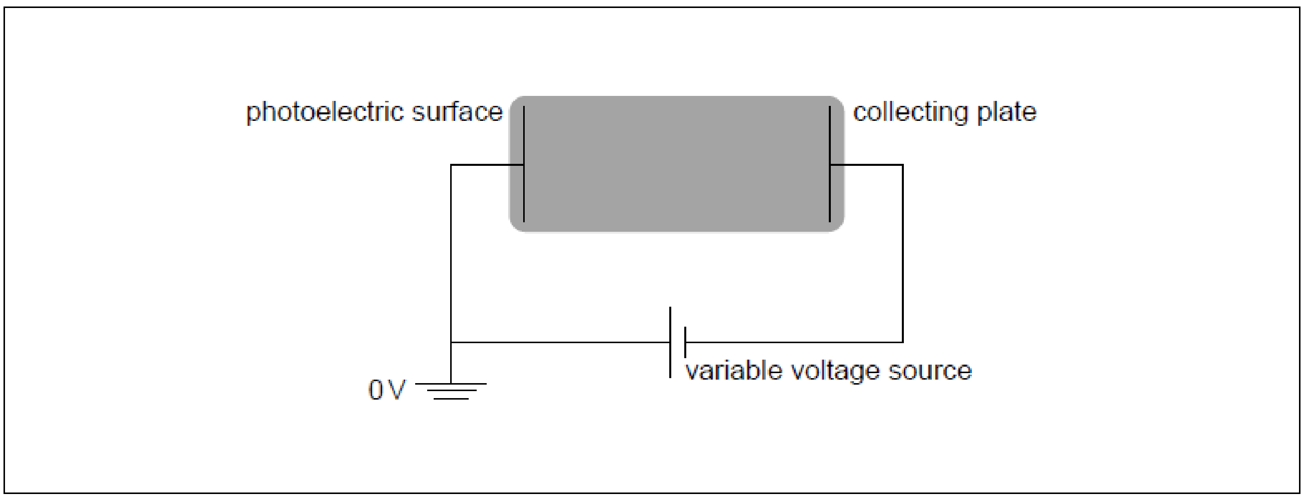
c.iii. In the past candidates have found calculation involving exponential change difficult. On this occasion, however examiners saw a large number of correct and well explained solutions from candidates.

Hydrogen atoms in an ultraviolet (UV) lamp make transitions from the first excited state to the ground state. Photons are emitted and are incident on a photoelectric surface as shown.



The photons cause the emission of electrons from the photoelectric surface. The work function of the photoelectric surface is 5.1 eV.

The electric potential of the photoelectric surface is 0 V. The variable voltage is adjusted so that the collecting plate is at –1.2 V.



a. Show that the energy of photons from the UV lamp is about 10 eV. [2]

b.i. Calculate, in J, the maximum kinetic energy of the emitted electrons. [2]

b.ii. Suggest, with reference to conservation of energy, how the variable voltage source can be used to stop all emitted electrons from reaching the collecting plate. [2]

b.iii. The variable voltage can be adjusted so that no electrons reach the collecting plate. Write down the minimum value of the voltage for which no electrons reach the collecting plate. [1]

c.i. On the diagram, draw and label the equipotential lines at –0.4 V and –0.8 V. [2]

c.ii. An electron is emitted from the photoelectric surface with kinetic energy 2.1 eV. Calculate the speed of the electron at the collecting plate. [2]

Markscheme

a. E_1 = –13.6 «eV» $E_2 = -\frac{13.6}{4}$ = –3.4 «eV»

energy of photon is difference $E_2 - E_1$ = 10.2 «≈ 10 eV»

Must see at least 10.2 eV.

[2 marks]

b.i. 10 – 5.1 = 4.9 «eV»

$4.9 \times 1.6 \times 10^{-19} = 7.8 \times 10^{-19}$ «J»

Allow 5.1 *if* 10.2 *is used to give* 8.2×10^{-19} «J».

b.ii. EPE produced by battery

exceeds maximum KE of electrons / electrons don't have enough KE

For first mark, accept explanation in terms of electric potential energy difference of electrons between surface and plate.

[2 marks]

b.iii. 4.9 «V»

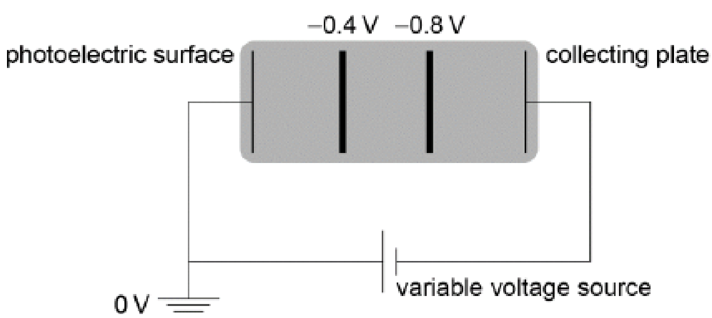
Allow 5.1 if 10.2 is used in (b)(i).

Ignore sign on answer.

[1 mark]

c.i. two equally spaced vertical lines (judge by eye) at approximately 1/3 and 2/3

labelled correctly



[2 marks]

c.ii. kinetic energy at collecting plate = 0.9 «eV»

speed = «$\sqrt{\frac{2\times0.9\times1.6\times10^{-19}}{9.11\times10^{-31}}}$» = 5.6×10^5 «ms^{-1}»

Allow ECF from MP1

[2 marks]

Examiners report

a. [N/A]
b.i. [N/A]
b.ii. [N/A]
b.iii. [N/A]
c.i. [N/A]
c.ii. [N/A]

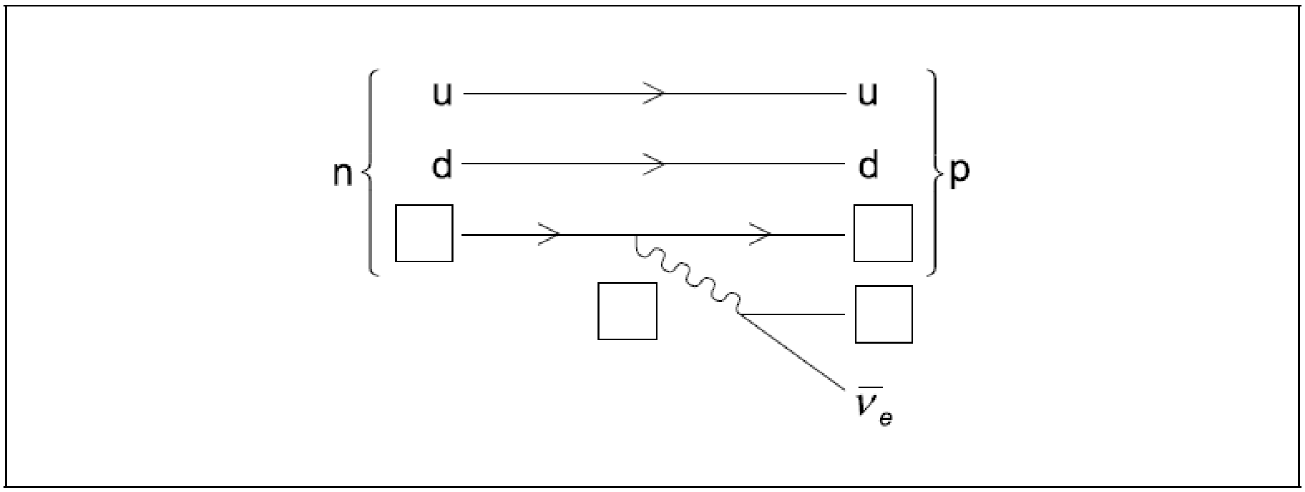
a. A particular K meson has a quark structure $\bar{u}s$. State the charge, strangeness and baryon number for this meson. [2]

Charge: . . . .

Strangeness: . . . .

Baryon number: . . . .

b. The Feynman diagram shows the changes that occur during beta minus (β^-) decay. [3]



Label the diagram by inserting the **four** missing particle symbols **and** the direction of the arrows for the decay particles.

d. C-14 decay is used to estimate the age of an old dead tree. The activity of C-14 in the dead tree is determined to have **fallen to** 21% of its original value. C-14 has a half-life of 5700 years. [4]

(i) Explain why the activity of C-14 in the dead tree decreases with time.

(ii) Calculate, in years, the age of the dead tree. Give your answer to an appropriate number of significant figures.

Markscheme

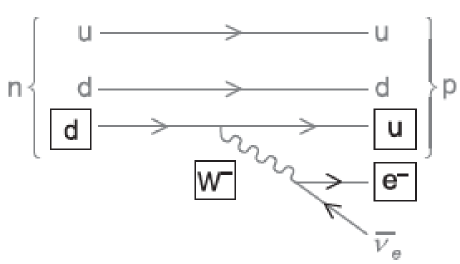
a. *charge:* –1«e» ***or*** negative ***or*** *K*$^-$

strangeness: –1

baryon number: 0

Negative signs required.
Award **[2]** for three correct answers, **[1 max]** for two correct answer and **[0]** for one correct answer.

b.



correct symbols for both missing quarks

exchange particle and electron labelled W ***or*** W$^-$ and e ***or*** e$^-$

*Do not allow W^+ **or** e^+ **or** β^+. Allow β **or** β^-.*

arrows for both electron and anti-neutrino correct

Allow ECF from previous marking point.

d. i

number of C-14 atoms/nuclei are decreasing

OR

decreasing activity proportional to number of C-14 atoms/nuclei

OR

$A = A_0 e^{-\lambda t}$ so A decreases as t increases

Do not allow "particles"

Must see reference to atoms or nuclei or an equation, just "C-14 is decreasing" is not enough.

ii
$0.21 = (0.5)^n$
OR
$$0.21 = e^{-\left(\frac{\ln 2 \times t}{5700}\right)}$$

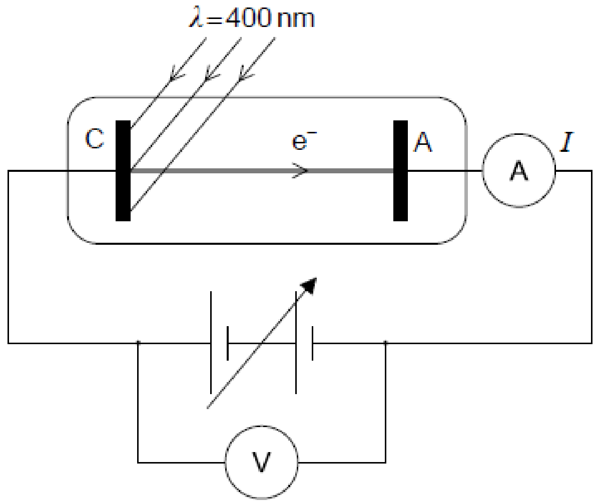
n = 2.252 half-lives or t =1 2834 «y»
Early rounding to 2.25 gives 12825 y

13000 y rounded correctly to two significant figures:
Both needed; answer must be in year for MP3.
Allow ECF from MP2.
*Award **[3]** for a bald correct answer.*

Examiners report

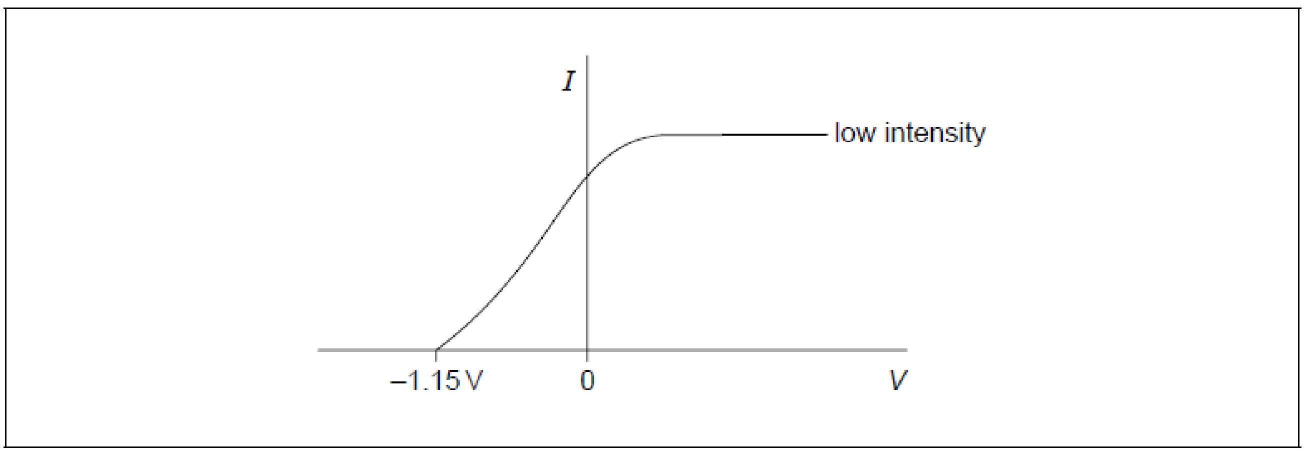
a. [N/A]
b. [N/A]
d. [N/A]

An apparatus is used to investigate the photoelectric effect. A caesium cathode C is illuminated by a variable light source. A variable power supply is connected between C and the collecting anode A. The photoelectric current I is measured using an ammeter.



a. A current is observed on the ammeter when violet light illuminates C. With V held constant the current becomes zero when the violet light is replaced by red light of the same intensity. Explain this observation. [3]

b. The graph shows the variation of photoelectric current *I* with potential difference *V* between C and A when violet light of a particular intensity is used. [6]



The intensity of the light source is increased without changing its wavelength.

(i) Draw, on the axes, a graph to show the variation of *I* with *V* for the increased intensity.

(ii) The wavelength of the violet light is 400 nm. Determine, in eV, the work function of caesium.

(iii) *V* is adjusted to +2.50V. Calculate the maximum kinetic energy of the photoelectrons just before they reach A.

Markscheme

a. reference to photon

OR

energy = hf ***or*** $= \frac{hc}{\lambda}$

violet photons have greater energy than red photons

when $hf > \Phi$ ***or*** photon energy> work function then electrons are ejected

frequency of red light < threshold frequency «so no emission»
OR
energy of red light/photon < work function «so no emission»

b. i

line with same negative intercept «–1.15V»

otherwise above existing line everywhere and of similar shape with clear plateau

Award this marking point even if intercept is wrong.

ii
$\frac{hc}{\lambda e} = «\frac{6.63\times10^{-34}\times3\times10^{8}}{40\times10^{-9}\times1.6\times10^{-19}} =»$ 3.11 «eV»

Intermediate answer is 4.97×10^{-19} *J.*

Accept approach using f *rather than c/λ*

«3.10 – 1.15 =» 1.96 «eV»
*Award **[2]** for a bald correct answer in eV.*
*Award **[1 max]** if correct answer is given in J* (3.12×10^{-19} J).

iii

«KE = *qVs* =» 1.15 «eV»

OR

1.84×10^{-19} «J»

Allow ECF from MP1 to MP2.

adds 2.50 eV = 3.65 eV

OR

5.84×10^{-19} J

Must see units in this question to identify energy unit used.
*Award **[2]** for a bald correct answer that includes units.*
*Award **[1 max]** for correct answer without units.*

Examiners report

a. [N/A]
b. [N/A]

This question is about electrical generation using nuclear power.

Exposure to radiation is a safety risk both to miners of uranium ore and to workers in nuclear power plants.

b. Outline why uranium ore needs to be enriched before it can be used successfully in a nuclear reactor. [3]

c. (i) One possible waste product of a nuclear reactor is the nuclide caesium-137 $\left({}^{137}_{55}\mathrm{Cs}\right)$ which decays by the emission of a beta-minus (β^-) particle to form a nuclide of barium (Ba). [6]

State the nuclear reaction for this decay.

$$^{137}_{55}\mathrm{Cs} \rightarrow \,^{\cdots\cdots}_{\cdots\cdots}\mathrm{Ba} + \,^{\cdots\cdots}_{\cdots\cdots}\beta^{-} + \cdots\cdots$$

(ii) The half-life of caesium-137 is 30 years. Determine the fraction of caesium-137 remaining in the waste after 100 years.

d. Some waste products in nuclear reactors are good absorbers of neutrons. Suggest why the formation of such waste products requires the removal of the uranium fuel rods well before the uranium is completely used up. [2]

Markscheme

b. U-238 is much more common than U-235 in ore;

U-235 is more likely to undergo fission / critical amount of U-235 required to ensure fission / *OWTTE*;

U-238 absorbs neutrons;

U-238 reduces reaction rate in reactor;

c. (i) $^{137}_{56}\mathrm{Ba}$;

$^{0}_{-1}\beta^{-}$;

anti-neutrino / $\bar{v}$;

(ii) $\lambda = \left(\frac{\ln 2}{30} =\right) 0.0231\mathrm{year}^{-1}$;
$(N = N_0)\,\mathrm{e}^{-0.0231\times100}$;
0.099 ***or*** 9.9%;

d. proportion of waste builds up in fuel rod as uranium is consumed;

increasing numbers of neutrons will be absorbed;

this reduces the number available to sustain the chain reaction;

build up of waste deforms fuel rod (which can then be difficult to remove);

Examiners report

b. [N/A]
c. [N/A]
d. [N/A]

This question is in **two** parts. **Part 1** is about simple harmonic motion (SHM) and waves. **Part 2** is about atomic and nuclear energy levels.

Part 1 Simple harmonic motion (SHM) and waves

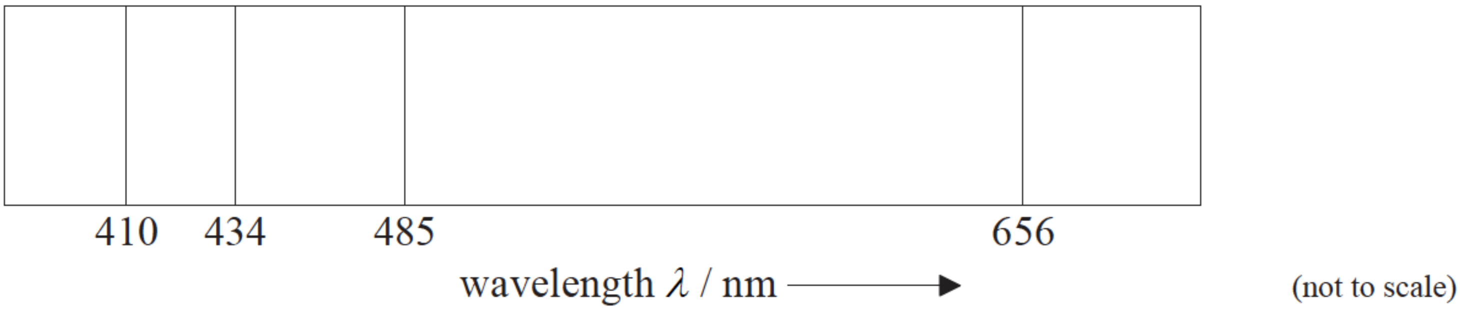
Part 2 Atomic and nuclear energy levels

a. A particle P moves with simple harmonic motion. [3]

(i) State, with reference to the motion of P, what is meant by simple harmonic motion.

(ii) State the phase difference between the displacement and the velocity of P.

d. The diagram shows four spectral lines in the visible line emission spectrum of atomic hydrogen. [6]



(i) Outline how such a spectrum may be obtained in the laboratory.

(ii) Explain how such spectra give evidence for the existence of discrete atomic energy levels.

e. The energies of the principal energy levels in atomic hydrogen measured in eV are given by the expression [4]

$E_n = -\frac{13.6}{n^2}$ where n=1, 2, 3 ....

The visible lines in the spectrum correspond to electron transitions that end at n=2.

(i) Calculate the energy of the level corresponding to n=2.

(ii) Show that the spectral line of wavelength λ=485nm is the result of an electron transition from n=4.

f. The alpha particles and gamma rays produced in radioactive decay have discrete energy spectra. This suggests that nuclei also possess discrete energy levels. However, beta particles produced in radioactive decay have continuous energy spectra. Describe how the existence of the antineutrino accounts for the continuous nature of beta spectra. [2]

Markscheme

a. (i) the acceleration (of a particle/P) is (directly) proportional to displacement;

and is directed towards equilibrium/in the opposite direction to displacement;

Do not accept "directed towards the centre".

(ii) $\frac{\pi}{2}$/90°/quarter of a period;

d. (i) light from a hydrogen discharge tube/hot hydrogen gas/ hydrogen tube with potential difference across it;

is passed onto a prism/diffraction grating;

and then is observed on a screen/through a telescope;

Accept good labelled diagram for explanation of any marking point.

(ii) each wavelength corresponds to the energy of the photon emitted;
when an electron makes a transition from a higher to lower energy level;
since only discrete wavelengths/finite number of wavelengths are present, then only discrete energy levels are present / *OWTTE*;

e. (i) −3.40 eV;

*Award **[0]** for omitted negative sign.*

(ii) energy difference between levels$= \frac{hc}{\lambda e} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{4.85 \times 10^{-7} \times 1.6 \times 10^{-19}}$;
=2.55eV;
$[3.40 - 2.55] = 0.85 = \frac{13.6}{n^2}$ to give n^2=16;
n=4;
*Award **[3]** for reversed argument.*

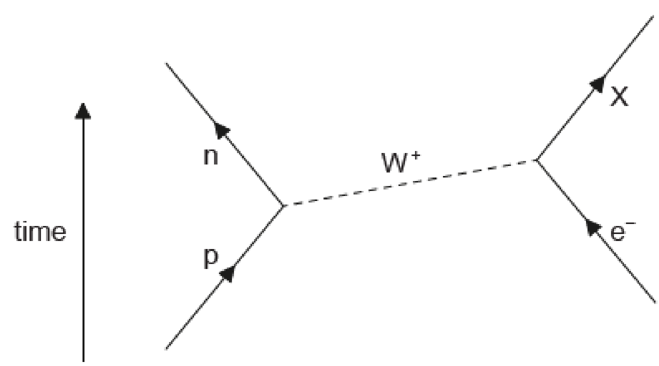
f. the total emitted energy is shared between the electron and the antineutrino;

the energy/velocity can be shared/distributed in an infinite number of ways / *OWTTE*;

Examiners report

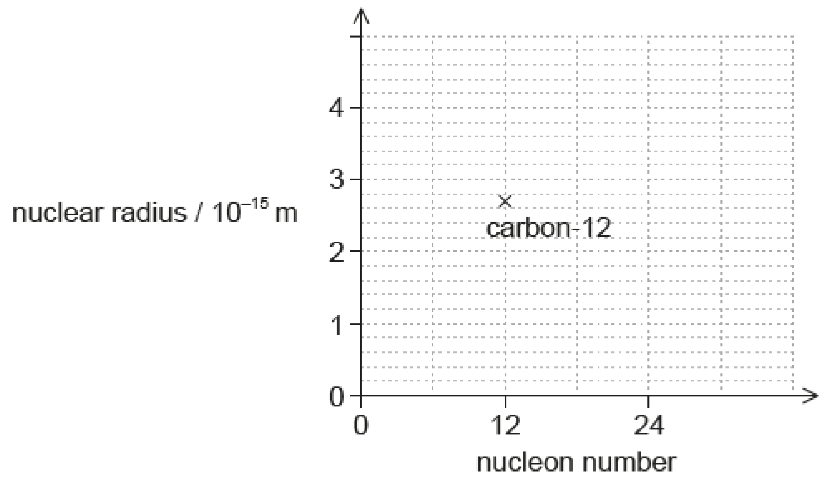
a. [N/A]
d. [N/A]
e. [N/A]
f. [N/A]

The Feynman diagram shows electron capture.



Particles can be used in scattering experiments to estimate nuclear sizes.

Electron diffraction experiments indicate that the nuclear radius of carbon-12 is 2.7 x 10^{-15} m. The graph shows the variation of nuclear radius with nucleon number. The nuclear radius of the carbon-12 is shown on the graph.



a.i. State and explain the nature of the particle labelled X. [3]

b.i. Outline how these experiments are carried out. [2]

b.ii. Outline why the particles must be accelerated to high energies in scattering experiments. [3]

c. State and explain **one** example of a scientific analogy. [2]

d.i. Determine the radius of the magnesium-24 nucleus. [2]

d.ii. Plot the position of magnesium-24 on the graph. [1]

d.iii. Draw a line on the graph, to show the variation of nuclear radius with nucleon number. [2]

Markscheme

a.i. «electron» neutrino

it has a lepton number of 1 «as lepton number is conserved»

it has a charge of zero/is neutral «as charge is conserved»
OR
it has a baryon number of 0 «as baryon number is conserved»

Do not allow antineutrino

Do not credit answers referring to energy

b.i. «high energy particles incident on» thin sample

detect angle/position of deflected particles

reference to interference/diffraction/minimum/maximum/numbers of particles

Allow "foil" instead of thin

b.ii. $\lambda \propto \frac{1}{\sqrt{E}}$ ***OR*** $\lambda \propto \frac{1}{E}$

so high energy gives small λ

to match the small nuclear size

Alternative 2

$E = hf$/energy is proportional to frequency

frequency is inversely proportional to wavelength/$c = f\lambda$

to match the small nuclear size

Alternative 3

higher energy means closer approach to nucleus

to overcome the repulsive force from the nucleus

so greater precision in measurement of the size of the nucleus

Accept inversely proportional

Only allow marks awarded from ***one*** *alternative*

c. two analogous situations stated

one element of the analogy equated to an element of physics

eg: moving away from Earth is like climbing a hill where the contours correspond to the equipotentials

Atoms in an ideal gas behave like pool balls

The forces between them only act during collisions

d.i. $R = 2.7 \times 10^{-15} \times 2^{\frac{1}{3}}$

$3.4 - 3.5 \times 10^{-15}$ «m»

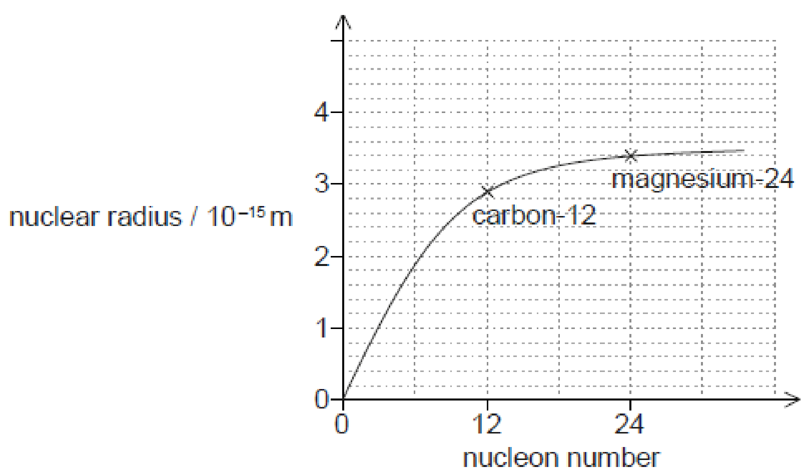
Allow use of the Fermi radius from the data booklet

d.ii. correctly plotted

Allow ECF from (d)(i)

d.iii. single smooth curve passing through both points with decreasing gradient

through origin



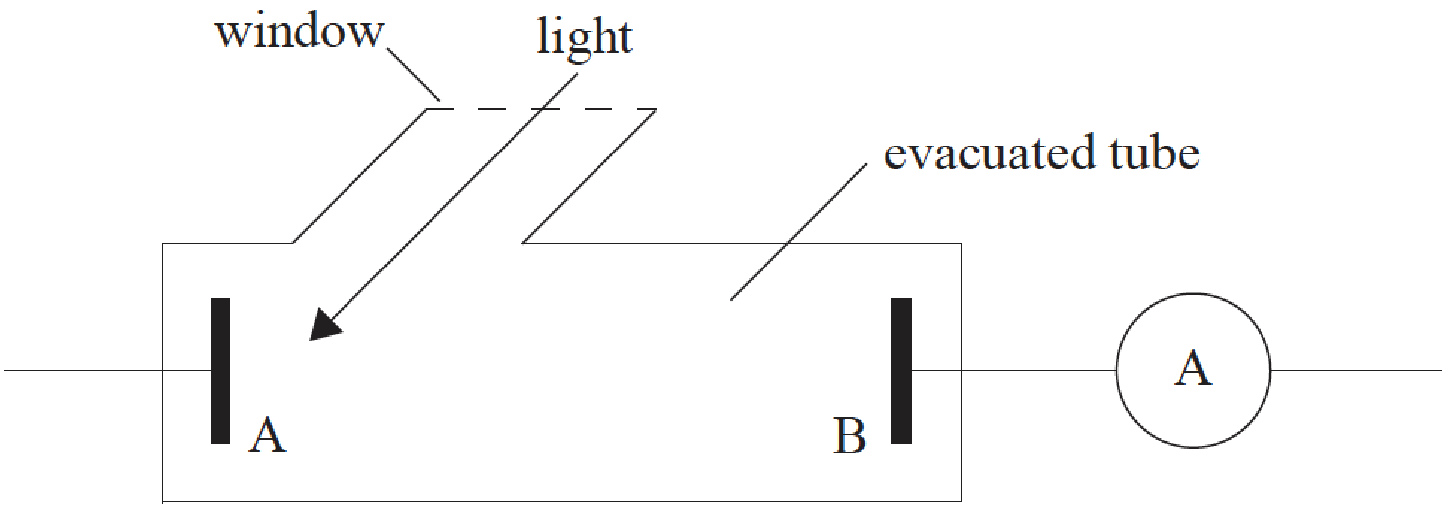
Examiners report

a.i. [N/A]
b.i. [N/A]
b.ii. [N/A]
c. [N/A]
d.i. [N/A]
d.ii. [N/A]
[N/A]

d.iii.

Part 3 The photoelectric effect and the Heisenberg uncertainty principle

f. Light is incident on a metal surface A. A potential difference is applied between A and an electrode B. Photoelectrons arrive at B and the resulting current is measured by a sensitive ammeter. (Note: the complete electrical circuit is not shown.) [6]



(i) The frequency of the light is reduced until the current measured by the ammeter falls to zero. Explain how Einstein's photoelectric theory accounts for this observation.

(ii) A different metal surface is used so that a current is again measured. Outline the effect on the photoelectric current when the intensity of the light is doubled and the frequency remains constant.

g. A photon of energy 6.6×10^{-19}J is incident upon a clean sodium surface. The work function of sodium is 3.7×10^{-19}J. The photon causes an electron to be emitted from the surface with the maximum possible kinetic energy. The position of this electron is measured with an uncertainty of 5.0×10^{-9}m. [5]

Calculate the

(i) momentum of the electron.

(ii) uncertainty in the momentum of the electron.

Markscheme

f. (i) light consists of photons/quanta/packets of energy;

(each) photon has energy *E=hf* / photon energy depends on frequency;

a single photon interacts with a single electron giving up all its energy;

a certain amount of energy is required to eject an electron from the metal;

if photon energy is less than this energy/work function/frequency <u>below threshold</u>, no electrons are emitted;

(ii) increasing the intensity increases the photoelectric current;
photocurrent will change as a different metal has a different work function/threshold frequency;

g. (i) $E_K = [6.6 - 3.7] \times 10^{-19} = 2.9 \times 10^{-19}\,(\mathrm{J})$;

$E_K = \frac{p2}{2m} \Rightarrow p = \sqrt{2mE_K} = \sqrt{2 \times 9.1\,(1) \times 10^{-31} \times 2.9 \times 10^{-19}}$;

$p=7.2\times10^{-25}$(kg ms^{-1}); *(allow answers in the range of 7.2 to 7.3×10^{-25})*

*Award **[3]** for a bald correct answer.*

(ii) $\Delta p = \frac{\frac{h}{4\pi}}{\Delta x} = \frac{\frac{6.6(3)\times10^{-34}}{4\pi}}{5.0\times10^{-9}}$;
$=1.1\times10^{-26}$(kg ms^{-1});
*Award **[2]** for a bald correct answer.*

Examiners report

f. fi) Many wrote essentially the same point, about threshold frequency, in a number of different ways in their answers. Examiners were surprised at how few mentioned photons.

fii) It was common to score one mark here for discussing an increase in the photocurrent but a significant number scored two marks.

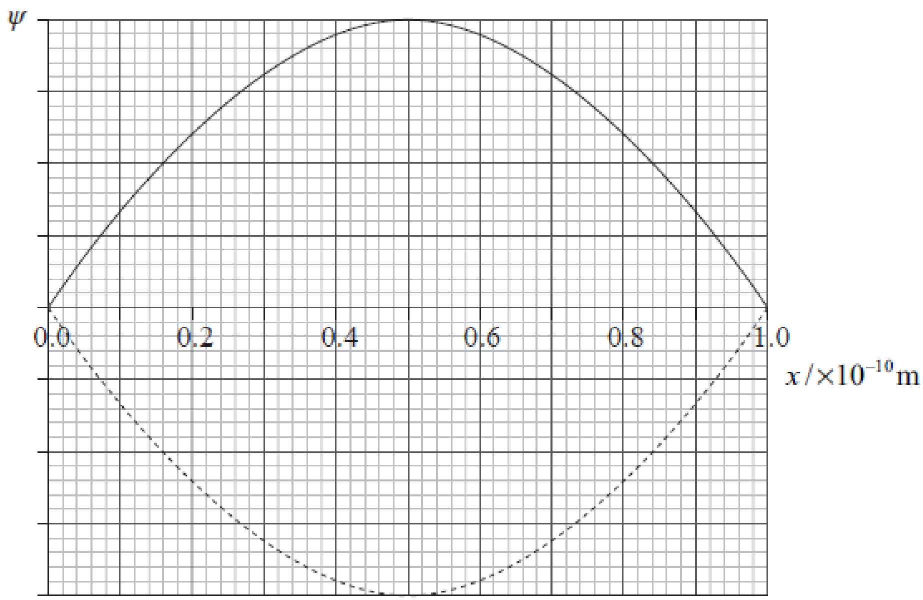
g. gi) This was answered well and of those that couldn't finish the calculation, most were able to calculate the kinetic energy for the first mark.

gii) The calculation in this question was tackled well by most.

This question is in **two** parts. **Part 1** is about quantum aspects of the electron. **Part 2** is about electric circuits.

Part 1 Quantum aspects of the electron

The wavefunction ψ for an electron confined to move within a "box" of linear size L =1.0×10^{-10}m, is a standing wave as shown.



a. State what is meant by a wavefunction. [1]

b. State the position near which this electron is most likely to be found. [1]

c. Calculate the momentum of the electron. [2]

d. The energy, in joules, of the electron in a hydrogen atom, is given by $E = \frac{2.18\times10^{-18}}{n^2}$ where *n* is a positive integer. Calculate the wavelength of the photon emitted in a transition from the first excited state of hydrogen to the ground state. [3]

e. The electron stays in the first excited state of hydrogen for a time of approximately Δt=1.0×10^{-10}s. [4]

(i) Determine the uncertainty in the energy of the electron in the first excited state.

(ii) Suggest, with reference to your answer to (e)(i), why the photons emitted in transitions from the first excited state of hydrogen to the ground state will, in fact, have a small range of wavelengths.

Markscheme

a. a function whose (absolute squared) value may be used to calculate the probability of finding a particle near a given position / quantity related to the probability of finding an electron near a given position/at a given position;

b. middle of the box / (near) 0.5×10^{-10}m;

c. the de Broglie wavelength is 2.0×10^{-10}m;

$p = \frac{h}{\lambda} = \frac{6.63\times10^{-34}}{2.0\times10^{-10}} = 3.3 \times 10^{-24}\text{Ns};$

d. difference in energy is

$\Delta E\left(= -\frac{2.18\times10^{-18}}{2^2} + \frac{2.18\times10^{-18}}{1^2}\right) = 1.635 \times 10^{-18}\text{J};$

$\lambda = \frac{hc}{\Delta E};$

$\lambda = \left(\frac{6.63\times10^{-34}\times3.0\times10^{8}}{1.635\times10^{-18}}\right) = 1.22 \times 10^{-7}\text{m};$

e. (i) attempt at using the energy – time uncertainty relation;

$\Delta E\left(= \frac{h}{4\pi\Delta t} = \frac{6.63\times10^{-34}}{4\pi\times1.0\times10^{-10}}\right) = 5.3 \times 10^{-25}\text{J};$

(ii) the wavelength of the photons is determined by the difference in energy between the two levels;
and that energy difference is not well defined/definite/not always the same (because of the uncertainty principle);

Examiners report

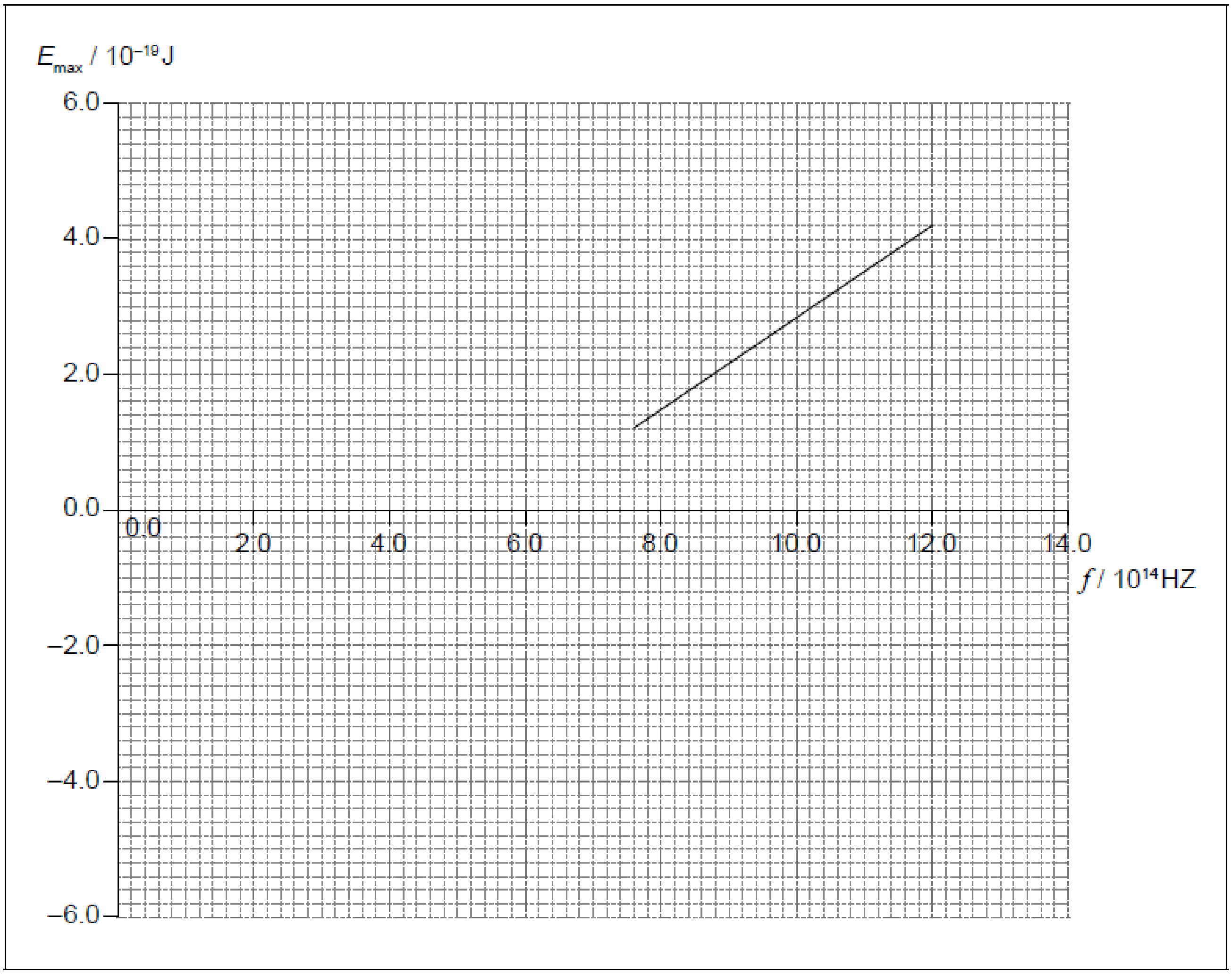
a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]
e. [N/A]

Two observations about the photoelectric effect are

Observation 1: For light below the threshold frequency no electrons are emitted from the metal surface.

Observation 2: For light above the threshold frequency, the emission of electrons is almost instantaneous.

The graph shows how the maximum kinetic energy E_{max} of electrons emitted from a surface of barium metal varies with the frequency *f* of the incident radiation.



a. Explain how each observation provides support for the particle theory but not the wave theory of light. [4]

Observation 1: . . . .

. . . .

. . . .

. . . .

. . . .

Observation 2: . . . .

. . . .

. . . .

. . . .

. . . .

b.i. Determine a value for Planck's constant. [2]

b.ii. State what is meant by the work function of a metal. [1]

b.iii. Calculate the work function of barium in eV. [2]

c. The experiment is repeated with a metal surface of cadmium, which has a greater work function. Draw a second line on the graph to represent the results of this experiment. [2]

Markscheme

a. *Observation 1:*

particle – photon energy is below the work function

OR

E = *hf* and energy is too small «to emit electrons»

wave – the energy of an *em* wave is independent of frequency

Observation 2:
particle – a single electron absorbs the energy of a single photon «in an almost instantaneous interaction»
wave – it would take time for the energy to build up to eject the electron

b.i. attempt to calculate gradient of graph = «$\frac{4.2\times10^{-19}}{6.2\times10^{14}}$»

$= 6.8 - 6.9 \times 10^{-34}$ «Js»

Do not allow a bald answer of 6.63 x 10^{-34} Js or 6.6 x 10^{-34} Js.

b.ii ***ALTERNATIVE 1***

minimum energy required to remove an electron «from the metal surface»

ALTERNATIVE 2
energy required to remove the least tightly bound electron «from the metal surface»

b.iii ***ALTERNATIVE 1***

reading of *y* intercept from graph in range 3.8 – 4.2 × 10^{-19} «J»

conversion to eV = 2.4 – 2.6 «eV»

ALTERNATIVE 2
reading of x intercept from graph «5.8 – 6.0 × 10^{14} Hz» and using hf_0 to get 3.8 – 4.2 × 10^{-19} «J»
conversion to eV = 2.4 – 2.6 «eV»

c. line parallel to existing line

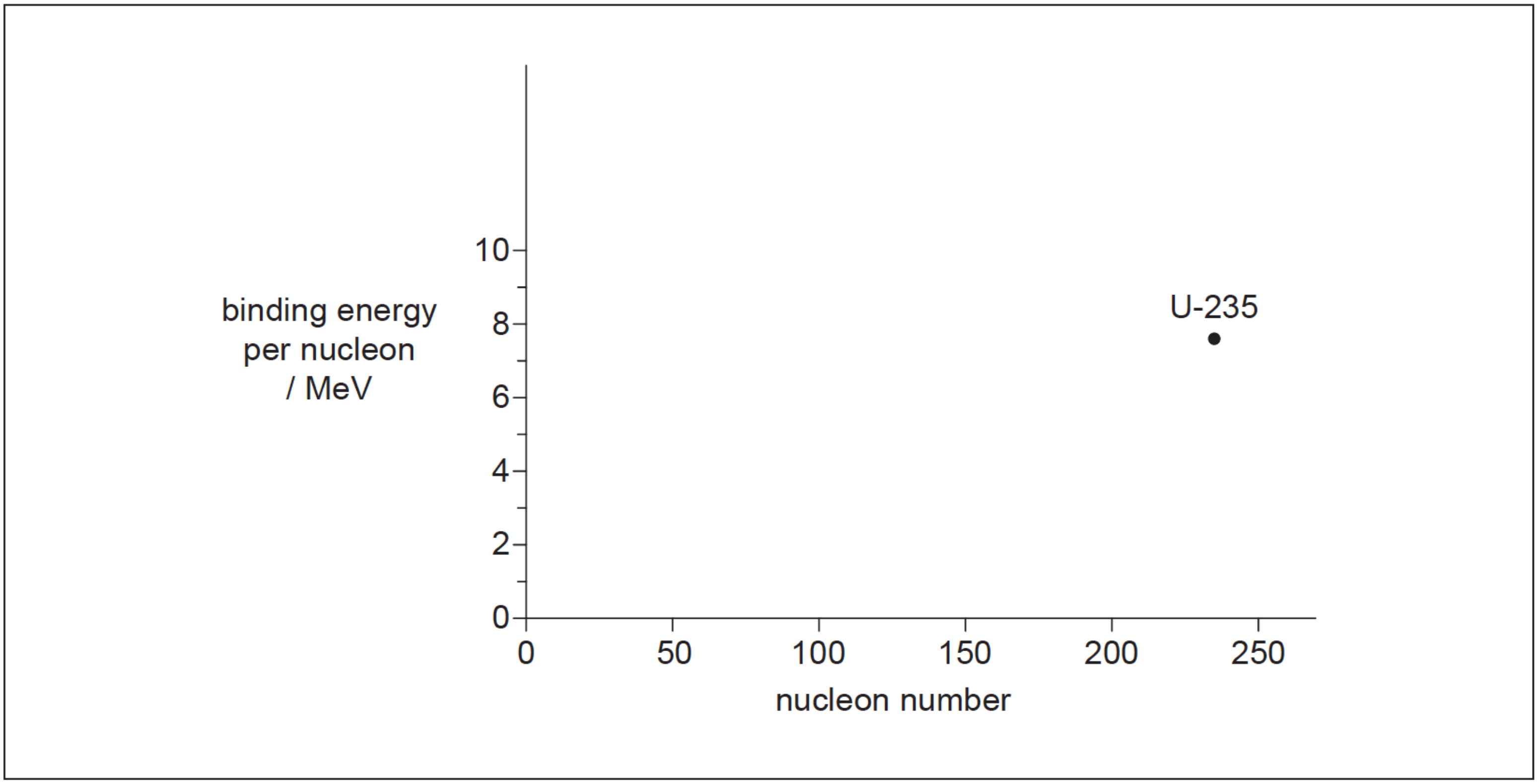
to the right of the existing line

Examiners report

a. [N/A]
b.i. [N/A]
b.ii. [N/A]
b.iii. [N/A]
c. [N/A]

Part 2 Nuclear energy and radioactivity

The graph shows the variation of binding energy per nucleon with nucleon number. The position for uranium-235 (U-235) is shown.



U-235 $\left({}^{235}_{92}\mathrm{U}\right)$ can undergo alpha decay to form an isotope of thorium (Th).

(i) State the nuclear equation for this decay.

(ii) A sample of rock contains a mass of 5.6 mg of U-235 at the present day. The half-life of U-235 is 7.0×10^{8} years. Determine the initial mass of the U-235 if the rock sample was formed 3.9×10^{9} years ago.

Markscheme

(i) ${}^{235}_{92}\mathrm{U} \rightarrow {}^{231}_{90}\mathrm{Th} + {}^{4}_{2}\alpha$; *(allow He for α; treat charge indications as neutral)*

(ii) $\lambda = \frac{\ln 2}{7.0\times10^{8}} \left(= 9.9 \times 10^{-10}\mathrm{year}^{-1}\right)$;

$m_0 = 5.6\mathrm{e}^{3.9\times10^{9}\times9.9\times10^{-10}}\ (\mathrm{mg})$

266 mg; } *(unit must match eg: allow 266 mg or 0.226 g but not 266 g or 0.266 kg)*

or

number of half-lives $= \left(\frac{3.9\times10^{9}}{7\times10^{8}} =\right) 5.57$

initial mass = $5.6\times2^{5.57}$;

266 mg; } *(unit must match eg: allow 266 mg or 0.226 g but not 266 g or 0.266 kg)*

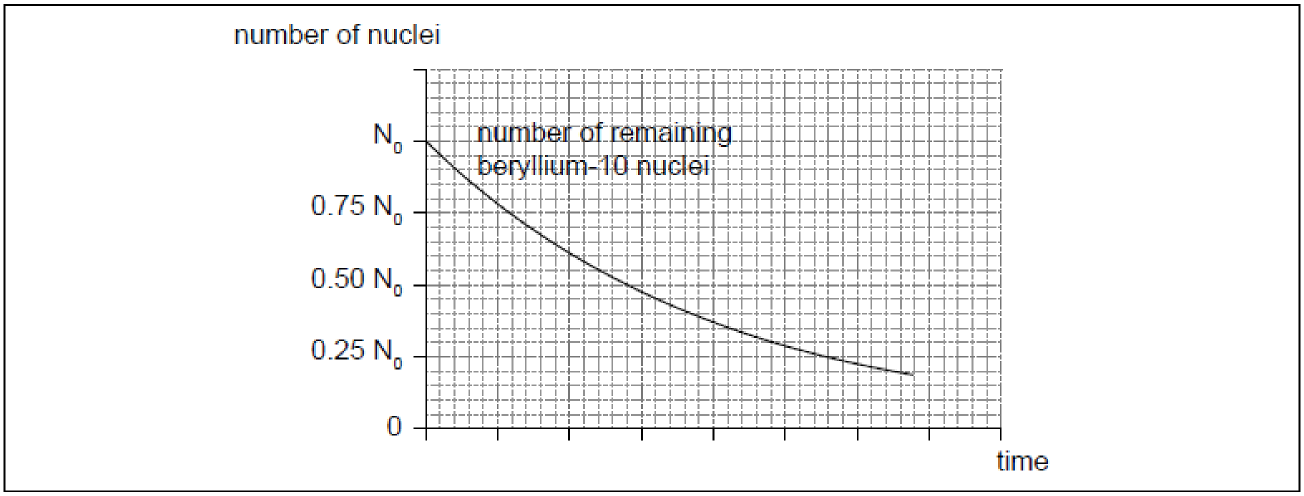
*Award **[3]** for a bald correct answer.*

Examiners report

[N/A]

The radioactive nuclide beryllium-10 (Be-10) undergoes beta minus (β–) decay to form a stable boron (B) nuclide.

The initial number of nuclei in a pure sample of beryllium-10 is N_0. The graph shows how the number of remaining **beryllium** nuclei in the sample varies with time.



An ice sample is moved to a laboratory for analysis. The temperature of the sample is –20 °C.

a. Identify the missing information for this decay. [2]

$$ {}^{10}_{\square}\mathrm{Be} \rightarrow {}^{\square}_{5}\mathrm{B} + {}^{\square}_{\square}\mathrm{e} + {}^{0}_{0}\square $$

b.iii Beryllium-10 is used to investigate ice samples from Antarctica. A sample of ice initially contains 7.6×10^{11} atoms of beryllium-10. The present activity of the sample is 8.0×10^{-3} Bq. [3]

Determine, in years, the age of the sample.

c.iv The temperature in the laboratory is higher than the temperature of the ice sample. Describe **one** other energy transfer that occurs between the ice sample and the laboratory. [2]

Markscheme

a. ${}^{10}_{4}\mathrm{Be} \rightarrow {}^{10}_{5}\mathrm{B} + {}^{0}_{-1}\mathrm{e} + \overline{\mathrm{V}}_{\mathrm{e}}$

antineutrino ***AND*** charge ***AND*** mass number of electron ${}^{0}_{-1}\mathrm{e}, \overline{\mathrm{V}}$

conservation of mass number ***AND*** charge ${}^{10}_{5}\mathrm{B}, {}^{10}_{4}\mathrm{Be}$

Do not accept V.

Accept $\bar{V}$ without subscript e.

[2 marks]

b.iii. λ «$= \frac{\ln 2}{1.4 \times 10^6}$» $= 4.95 \times 10^{-7}$ «y^{-1}»

rearranging of $A = \lambda N_0 e^{-\lambda t}$ to give $-\lambda t = \ln \frac{8.0 \times 10^{-3} \times 365 \times 24 \times 60 \times 60}{4.95 \times 10^{-7} \times 7.6 \times 10^{11}}$ «$= -0.400$»

$t = \frac{-0.400}{-4.95 \times 10^{-7}} = 8.1 \times 10^5$ «y»

Allow ECF from MP1

[3 marks]

c.iv. from the laboratory to the sample

conduction – contact between ice and lab surface.

OR

convection – movement of air currents

Must clearly see direction of energy transfer for MP1.

Must see more than just words "conduction" or "convection" for MP2.

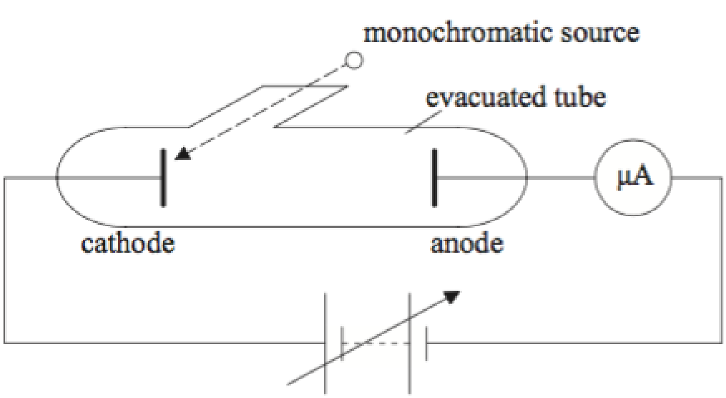
[2 marks]

Examiners report

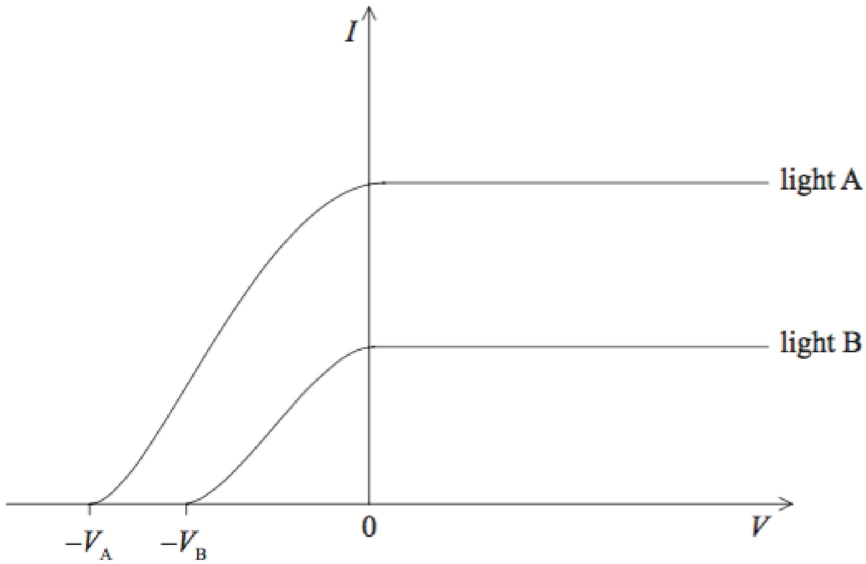
a. [N/A]
b.iii. [N/A]
c.iv. [N/A]

Photoelectric effect and de Broglie wavelength

The diagram is a representation of apparatus used to study the photoelectric effect.



Light from the monochromatic source is incident on a cathode placed in an evacuated tube. A variable voltage supply is connected between anode and cathode and the photoelectric current is registered by the microammeter. The sketch graph shows how the photoelectric current I varies with the potential difference V between anode and cathode for two sources of light, A and B, of different frequencies and intensities.



a. Explain with reference to the Einstein model, which graph, A or B, corresponds to the light with the greater frequency. [4]

b. The frequency of the light that produces graph A is 8.8×10^{14}Hz. The magnitude of V_A is 1.6V. [3]

(i) State the value of the maximum energy, in eV, of the electrons emitted from the cathode.

(ii) Determine the work function, in eV, of the surface of the cathode.

c. The frequency of the incident light is increased but the intensity remains constant. Explain why this increase in frequency results in a change to the maximum photoelectric current (saturation current). [3]

d. The electrons emitted from the photo-cathode have an associated de Broglie wavelength. Describe what is meant by the de Broglie wavelength. [2]

Markscheme

a. *Look for these main points.*

light consists of photons whose energy depends on the frequency/*hf*;

hence the energy available to the (photo)electrons will depend on f;

the potentials V_A and V_B correspond to/are a measure of the maximum kinetic of the emitted electrons;

the work function (of metal)/energy to emit electron is same for both light sources;

as electrons in A have more kinetic energy available, this frequency must be higher;
(so A)

b. (i) 1.6 eV ; *(answer must be expressed in eV)*

(ii) energy of photons = $\left(\frac{6.6\times10^{-34}\times8.8\times10^{14}}{1.6\times10^{-19}}=\right)3.6\,(\mathrm{eV})$;

work function=(3.6–1.6=) 2.0eV;

Allow answer in J if (b)(i) expressed in joule (ECF), otherwise award ***[1 max].***

c. photon energy increases (because frequency increases);

so for same intensity fewer photons per second;

so current reduced / fewer electrons emitted per second;

d. all particles/electrons exhibit wave properties/have an associated wavelength (called the de Broglie wavelength);

the wavelength is equal to the Planck constant divided by the momentum of the particle/electron/ $\lambda = \frac{h}{p}$ with terms defined; { *(terms **must** be defined for mark)*

Examiners report

a. Marks were very poor here. It was a rare candidate who explained the answer “with reference to the Einstein model” as requested. There was only a spasmodic mention of the role of the photon or its energy. Many candidates demonstrated misunderstandings about the effect itself. Some thought that electrons arrive and photons are emitted; this was a disturbingly common misapprehension. Consequently it was difficult to award marks.

b. i) This was commonly correct but often expressed in joule rather than eV as demanded by the question.

(ii) Again, units were often inappropriate but credit was given if the earlier unit in (b)(i) was incorrect. Many were able to manipulate Einstein’s equation with ease.

c. Almost all candidates suggested that, in the photoelectric effect, when the frequency of incident light increases but the intensity remains constant, then the maximum emitted current increases. They neglected the dependence of the energy of the photon on its frequency. This is further evidence of the lack of understanding by candidates with this area of the syllabus.

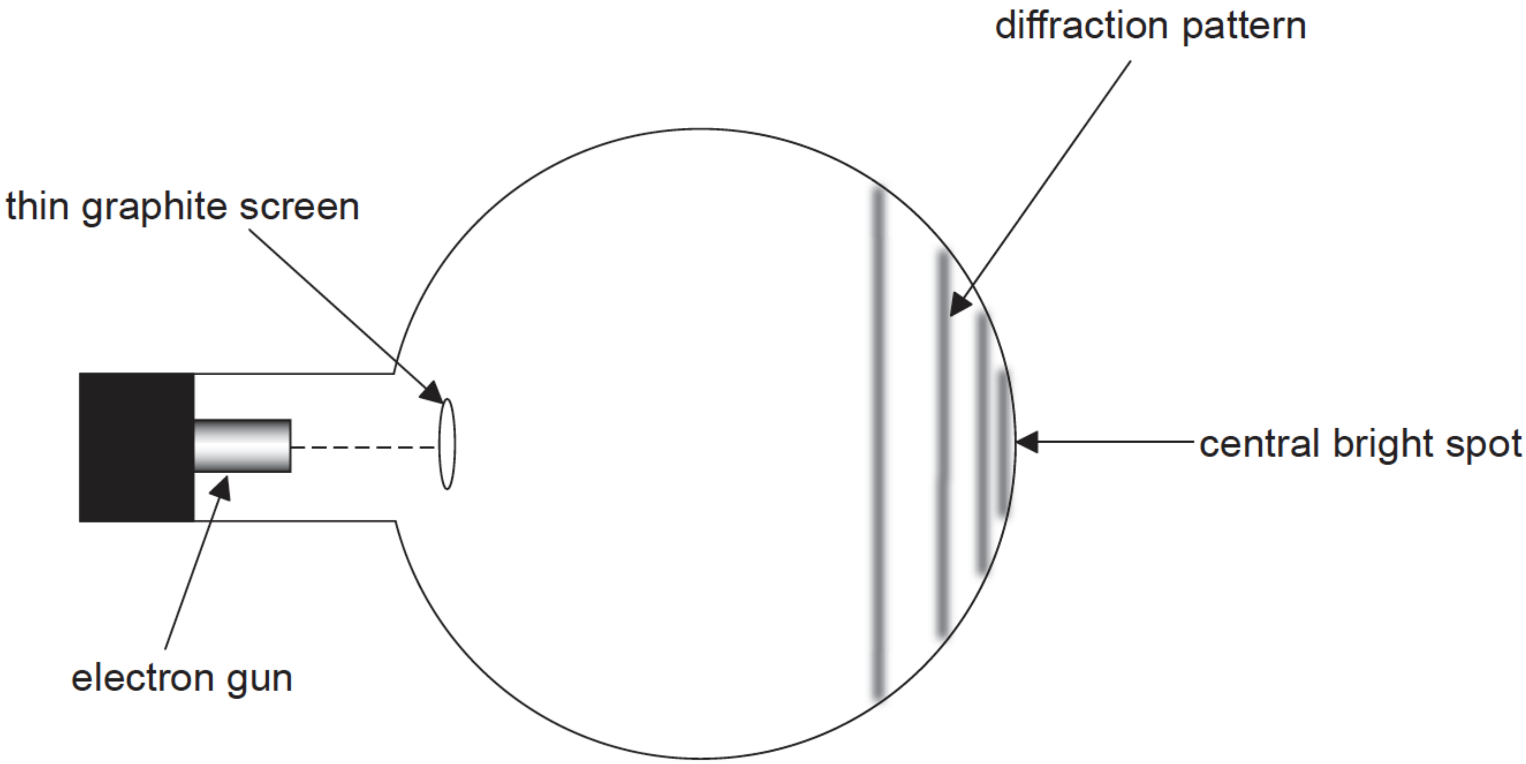
d. Candidates often described what the de Broglie wavelength is, or gave an equation for it, but rarely both (as the markscheme and the mark allocation required).

This question is in two parts. **Part 1** is about thermal properties of matter. **Part 2** is about quantum physics.

Part 1 Thermal properties of matter

Part 2 Quantum physics

The diagram shows the end of an electron diffraction tube.



A pattern forms when diffracted electrons are incident on a fluorescent layer at the end of the tube.

b. Three ice cubes at a temperature of 0ºC are dropped into a container of water at a temperature of 22ºC. The mass of each ice cube is 25 g and the mass of the water is 330 g. The ice melts, so that the temperature of the water decreases. The thermal capacity of the container is negligible. [8]

(i) The following data are available.

Specific latent heat of fusion of ice = 3.3×10^5 J kg^{-1}
Specific heat capacity of water = 4.2×10^3 J kg^{-1} K^{-1}

Calculate the final temperature of the water when all of the ice has melted. Assume that no thermal energy is exchanged between the water and the surroundings.

(ii) Explain how the first law of thermodynamics applies to the water when the ice cubes are dropped into it.

c. Explain how the pattern demonstrates that electrons have wave properties. [3]

d. Electrons are accelerated to a speed of 3.6×10^7 ms^{-1} by the electric field. [5]

(i) Calculate the de Broglie wavelength of the electrons.

(ii) The cathode and anode are 22 mm apart and the field is uniform.
The potential difference between the cathode and the anode is 3.7 kV.
Show that the acceleration of the electrons is approximately 3×10^{16}ms^{-2}.

e. State what can be deduced about an electron from the amplitude of its associated wavefunction. [2]

f. An electron reaching the central bright spot on the fluorescent screen has a small uncertainty in its position. Outline what the Heisenberg uncertainty principle is able to predict about another property of this electron. [2]

Markscheme

b. (i) use of $M \times 4.2 \times 10^3 \times \Delta\theta$;

$ml = 75 \times 10^{-3} \times 3.3 \times 10^5$ / 24750 J;

recognition that melted ice warms and water cools to common final temperature;

3.4°C;

(ii) work done on water by dropping cubes / negligible work done;
W negative or unchanged;
water gives thermal energy to ice;
Q negative;
water cools to a lower temperature;
ΔU negative / *U* decreases;

c. bright and dark rings/circles / circular fringes;

maximum and minimum / constructive and destructive;

mention of interference / mention of superposition;

link to interference being characteristic of waves;

d. (i) ($p=m_e v=$) 3.28×10^{-23} Ns;

$$\lambda = \left(\frac{\mathrm{h}}{\mathrm{p}} = \frac{6.63 \times 10^{-34}}{3.28 \times 10^{-23}} = \right) 2.02 \times 10^{-11} \mathrm{m};$$

(ii) $E = \left(\frac{\Delta V}{\Delta x}\right) = \frac{3.7 \times 10^3}{22 \times 10^{-3}} \left(= 1.68 \times 10^5\right) \mathrm{Vm}^{-1}$;
$F = (Eq) = 1.68 \times 10^5 \times 1.6 \times 10^{-19} = \left(2.69 \times 10^{-14}\right) \mathrm{N}$;
$a = \frac{F}{m} = \left(\frac{2.69 \times 10^{-14}}{9.11 \times 10^{-31}}\right) = 2.95 \times 10^{16} \mathrm{ms}^{-2}$;

or

use of appropriate equation, eg $v^2 = u^2 + 2as$;

correct substitution (ignoring powers of ten);

$a = 2.95 \times 10^{16}$ ms^{-2}

e. square of amplitude (of wavefunction);

(proportional to) probability of finding an electron (at a particular point);

f. relates position to momentum (or velocity);

large uncertainty in momentum / most information on momentum is lost;

Examiners report

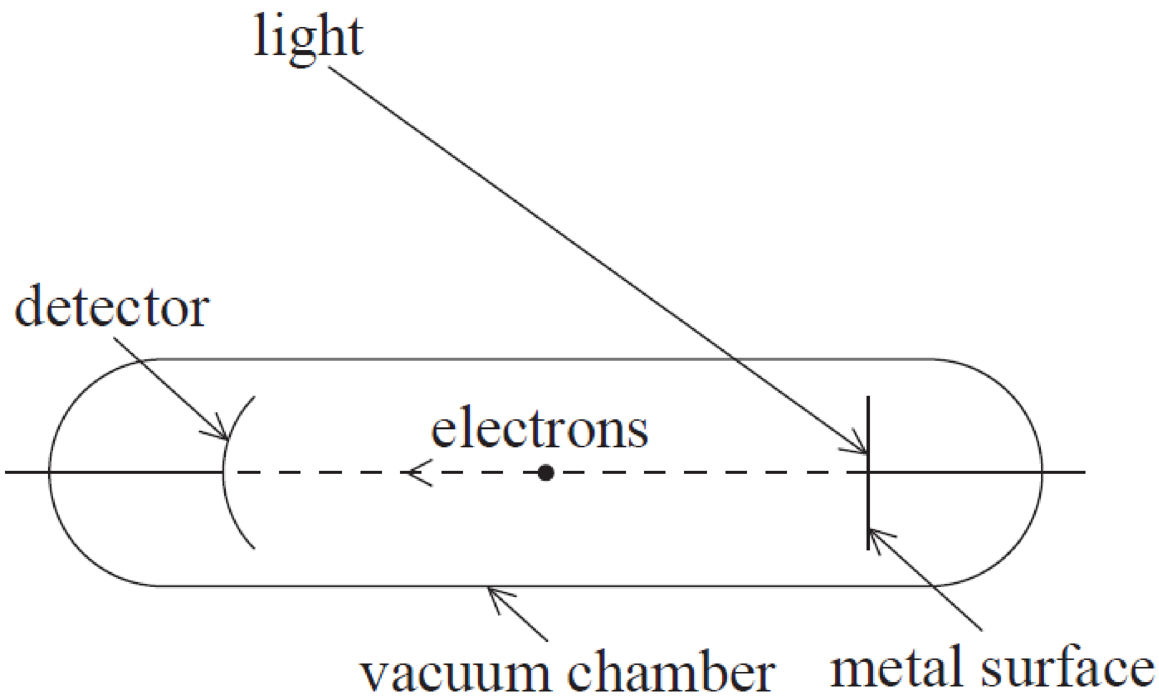
b. [N/A]
c. [N/A]
d. [N/A]
e. [N/A]
f. [N/A]

This question is in **two** parts. **Part 1** is about photoelectricity. **Part 2** is about electrical and magnetic force fields.

Part 1 Photoelectricity

a. State what is meant by work function. [1]

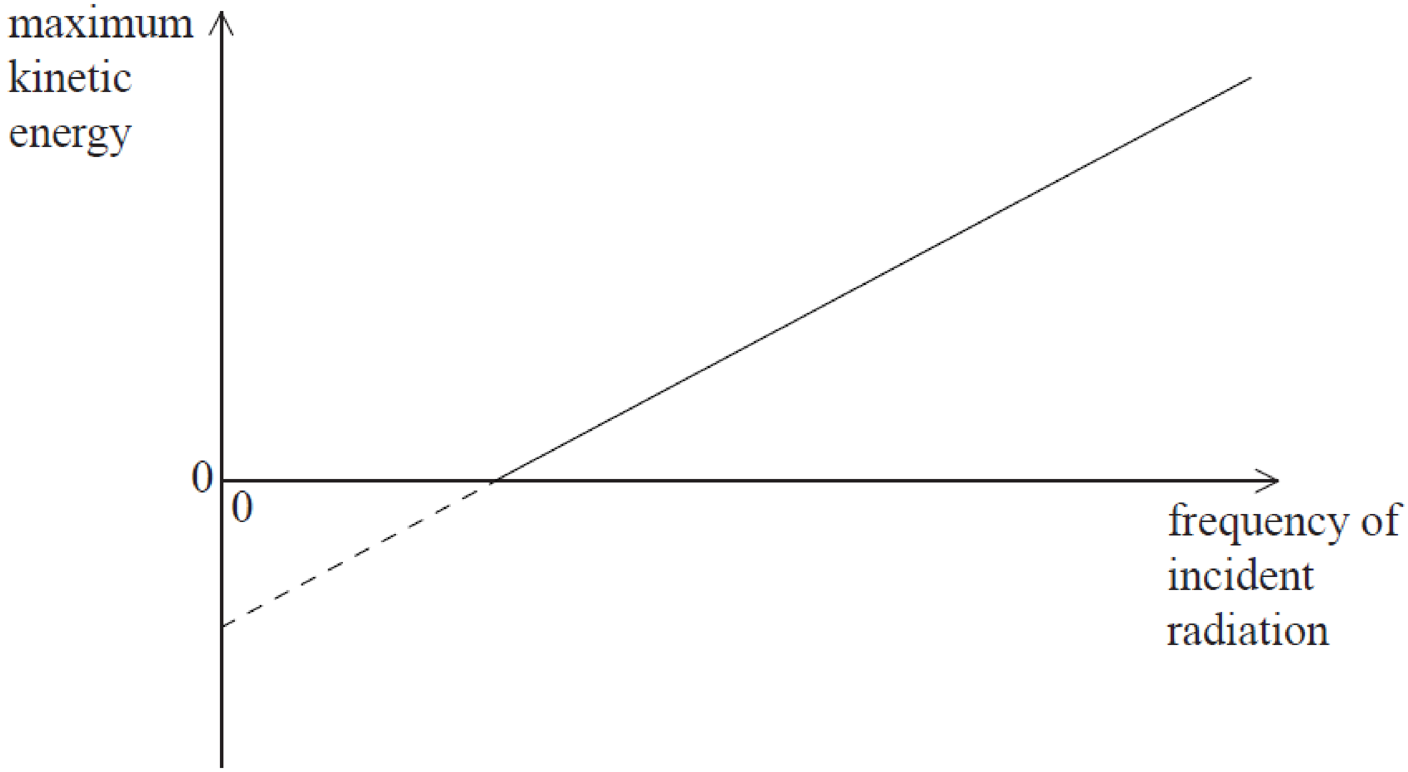
b. The diagram shows part of an experimental arrangement used to investigate the photoelectric effect. [4]



(i) Explain how the maximum kinetic energy of the emitted electrons is determined experimentally.

(ii) On the diagram, draw the power supply and other necessary components needed in order to carry out the experiment in (b)(i).

c. Using results obtained with the apparatus in (b), the following graph was drawn. The graph shows how the maximum kinetic energy of the photoelectrons varies with the frequency of the incident radiation. [3]



State how the graph can be used to determine

(i) a value for the Planck constant.

(ii) the work function of the material.

(iii) the threshold wavelength of the material.

d. In an experiment, light at a particular frequency is incident on a surface and electrons are emitted. Explain what happens to the number of electrons emitted per second when the intensity of this light is increased. [2]

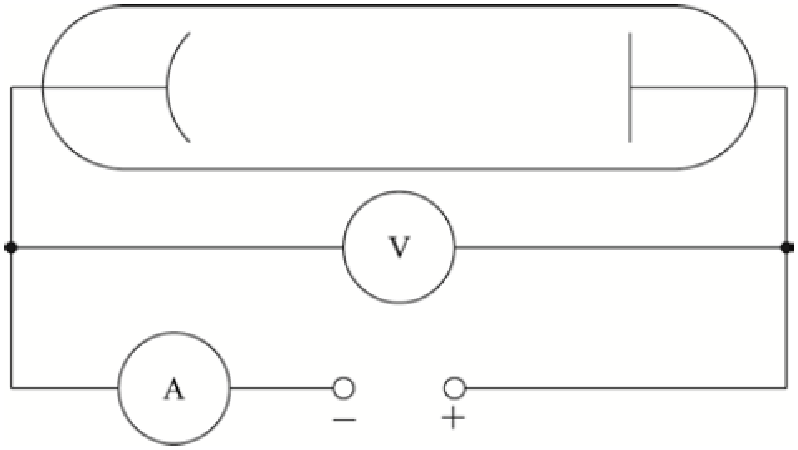
Markscheme

a. minimum (photon) energy needed to eject electrons (from a surface);

b. (i) apply stopping potential / *OWTTE;*

maximum kinetic energy =*eV;*

(ii)



power supply negative connected to detector;
ammeter and voltmeter correctly connected;
Allow voltmeter connected directly across power supply.

c. (i) Planck constant = gradient;

(ii) work function = (–) intercept on maximum kinetic energy (*allow 'y'*) axis;

(iii) $\lambda_0 = \frac{c}{\text{frequencyintercept}}$ **or** $\frac{hc}{\text{maxkeintercept}}$;

d. more intense light means more photons per second;

so more electrons are ejected (per second);

Examiners report

a. Most candidates choosing this option were able to answer this well although a minority forgot to mention that this was the **minimum** energy needed for a photon to eject an electron from a metal surface.

b. (i) The technique for measuring the maximum kinetic energy of the emitted electrons was poorly known. Centres would be well advised to use a simulation if they do not have the opportunity to actually perform this experiment with a photocell.

(ii) Given that is such a simple circuit this was very badly answered with many 'circuits' not being circuits at all – in essence, ignoring the polarity needed for the cell, this is a simple resistance measuring circuit. Few realised that the detector must have a negative voltage to prevent the electrons from reaching it.

c. (i) In recognising that the gradient gives a value for the Planck constant, most candidates answered this correctly.

(ii) Again, this was well answered although few candidates mentioned that the work function was the negative of the value of the maximum kinetic energy intercept.

(iii) This was more involved and less well answered. Although many realised that the threshold frequency was the intercept on the frequency axis, few went on to say that the threshold wavelength was the speed of light divided by this value.

d. Only those candidates approaching this by relating the intensity of light to the number of incident photons per second tended to be successful here. By stating this it was a simple matter or recognising that there is a one to one correspondence between photons and electrons so more intense light inevitably meant more electrons emitted per second. Many wasted time in explaining why emission of electrons meant that the incident light had a frequency higher than the threshold frequency.

Part 2 Radioactivity

Radium-224 $\left({}^{224}_{88}\mathrm{RA}\right)$ is a radioactive nuclide that decays to form radon-220. Radon-220 is itself radioactive and undergoes a further decay. The table shows the series of radioactive nuclides that are formed as the decays proceed. The series ends with a stable isotope of lead.

Parent nuclide	Emitter	Half-life	Daughter nuclide(s)
radium-224	alpha	3.64 days	radon-220 (Rn)
radon-220	alpha	55 seconds	polonium-216 (Po)
polonium-216	alpha	0.15 seconds	lead-212 (Pb)
lead-212	beta	10.6 hours	bismuth-212 (Bi)
bismuth-212	beta alpha	60.6 minutes	polonium-212 thallium (Tl)
polonium-212	alpha	3.0×10^{-7} seconds	lead-208 (stable)
thallium	beta	3.1 minutes	lead-208 (stable)

f. For the final thallium nuclide, identify the [2]

(i) nucleon number.

(ii) proton number.

g. Radon-220 is a radioactive gas. It is released by rocks such as granite. In some parts of the world, houses are built from materials containing granite. Explain why it is unlikely that radon-220 will build up in sufficient quantity to be harmful in these houses. [2]

h. (i) Calculate, in hour^{-1}, the decay constant of lead-212. [6]

(ii) In a pure sample of lead-212 at one instant, 8.0×10^{-3} kg of the lead-212 is present. Calculate the mass of lead-212 that remains after a period of 35 hours.

(iii) A sample of pure radium begins to decay by the series shown in the table. At one instant, a mass of 8.0×10^{-3} kg of lead-212 is present in the sample. Suggest why, after 35 hours, there will be a greater mass of lead-212 present in the sample than the value you calculated in (h)(ii).

Markscheme

f. (i) 208;

(ii) 81;

g. because the half-life is (only) 55 s;

radon is produced slowly but decays quickly (so cannot build up);

h. (i) $\left(\lambda = \frac{\ln 2}{T_{\frac{1}{2}}} = \frac{0.693}{10.6} = \right) 6.5 \times 10^{-2} \text{hour}^{-1}$

(ii) use of λ from (h)(i);

correct substitution into $N = N_0 e^{-\lambda t}$;

8.0 to 8.3 × 10^{-4} kg;

(iii) the rate of decay/activity of polonium/radium;
is greater than the rate of decay/activity of lead;

Examiners report

f. [N/A]
g. [N/A]
h. [N/A]

This question is in two parts. **Part 1** is about current electricity. **Part 2** is about atoms.

Part 1 Current electricity

Part 2 Atoms

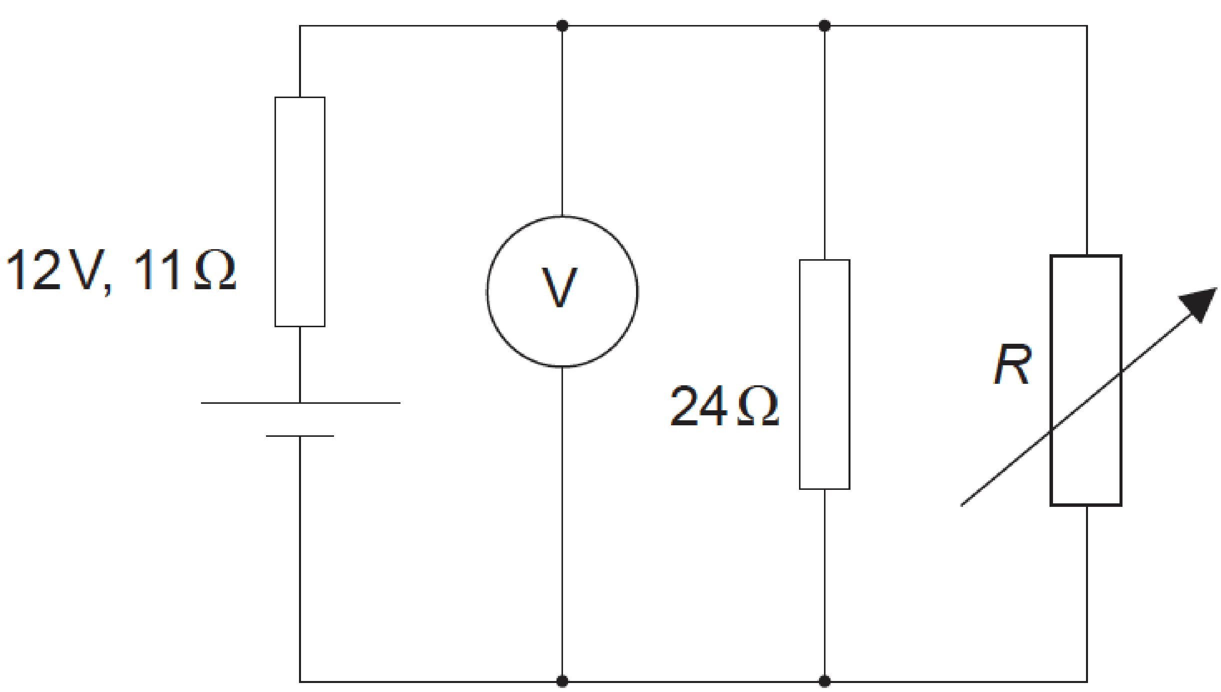
a. A 24Ω resistor is made from a conducting wire. [8]

(i) The diameter of the wire is 0.30 mm and the wire has a resistivity of 1.7 × 10^{-8} Ω m. Calculate the length of the wire.

(ii) A potential difference of 12V is applied between the ends of the wire. Calculate the acceleration of a free electron in the wire.

(iii) Suggest why the average speed of the free electron does not keep increasing even though it is being accelerated.

b. An electric circuit consists of a supply connected to a 24Ω resistor in parallel with a variable resistor of resistance R. The supply has an emf of 12V and an internal resistance of 11Ω. [7]



Power supplies deliver maximum power to an external circuit when the resistance of the external circuit equals the internal resistance of the power supply.

(i) Determine the value of R for this circuit at which maximum power is delivered to the external circuit.

(ii) Calculate the reading on the voltmeter for the value of R you determined in (b)(i).

(iii) Calculate the power dissipated in the 24Ω resistor when the maximum power is being delivered to the external circuit.

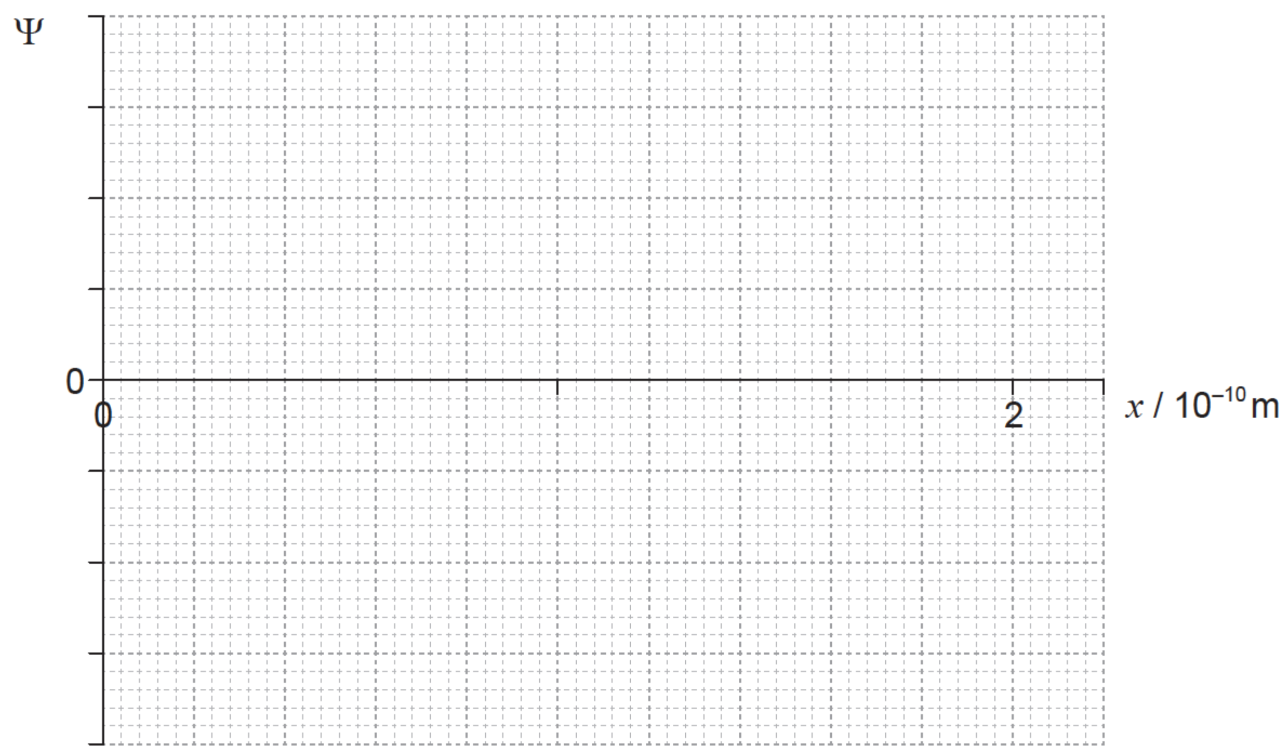
c. State what is meant by the wavefunction of an electron. [1]

d. An electron is confined in a length of 2.0×10^{-10} m. [9]

(i) Determine the uncertainty in the momentum of the electron.

(ii) The electron has a momentum of 2.0×10^{-23}Ns. Determine the de Broglie wavelength of the electron.

(iii) On the axes, sketch the variation of the wavefunction Ψ of the electron in (d)(ii) with distance x. You may assume that $\Psi = 0$ when $x = 0$.



(iv) Identify the feature of your graph in (d)(iii) that gives the probability of finding the electron at a particular position and at a particular time.

Markscheme

a. (i) $l = \frac{\pi d^2 R}{4\rho}$ seen / correct substitution

into equation: $24 = \frac{l \times 1.7 \times 10^{-8}}{\pi \times (0.15 \times 10^{-3})^2}$; } *(condone use of r for $\frac{d}{2}$ in first alternative)*

99.7 (m);

*Award **[2]** for bald correct answer.*

*Award **[1 max]** if area is incorrectly calculated, answer is 399 m if conversion to radius ignored, ie: allow ECF for second marking point if area is incorrect provided working clear.*

(ii) electric field= $\left(\frac{12}{99.7}=\right) 0.120\ (\mathrm{Vm}^{-1})$; *(allow ECF from (a)(i))*

electric force=($e \times E$=0.120×1.6×10^{-19}=)1.92×10^{-20}(N);

acceleration= $\left(\frac{F}{m}=\frac{1.92\times10^{-20}}{9.1\times10^{-31}}=\right) 2.11\times10^{10}(ms^{-2})$; } *(5.27×10^{9} if radius used in (a)(i) allow as ECF)*

or

work done on electron = (Vq =)12×1.6×10^{-19};

energy gained by electron = $m_e \times a \times$distance travelled = 9.11 × 10^{-31} × a × 99.8;

2.11×10^{10} (ms^{-2});

*Award **[3]** for a bald correct answer.*

(iii) free electrons collide with ions and other electrons;
speed decreases during collisions / transfer their kinetic during collisions;
kinetic energy transferred to heat / wires have resistance;
and speed increases/acceleration until next collision;

b. (i) use of total resistance = 11Ω; *(can be seen in second marking point)*

$\frac{1}{11}=\frac{1}{R}+\frac{1}{24}$;

20.3(Ω);

(ii) as current is same in resistor network and cell and resistance is same, half of emf must appear across resistor network;
6.0 (V);

or

$I=\frac{12}{(11+11)}=0.545\ (\mathrm{A})$;
V=(0.545×11=) 6.0(V);

Other calculations are acceptable.

*Award **[2]** for a bald correct answer.*

(iii) pd across 2Ω=6.0V; *(allow ECF from(b)(ii))*
$\left(\frac{V^2}{R}=\frac{36}{24}=\right) 1.5\ (\mathrm{W})$;
*Award **[2]** for a bald correct answer.*

c. measure of the probability of finding an electron (at a particular place and time);

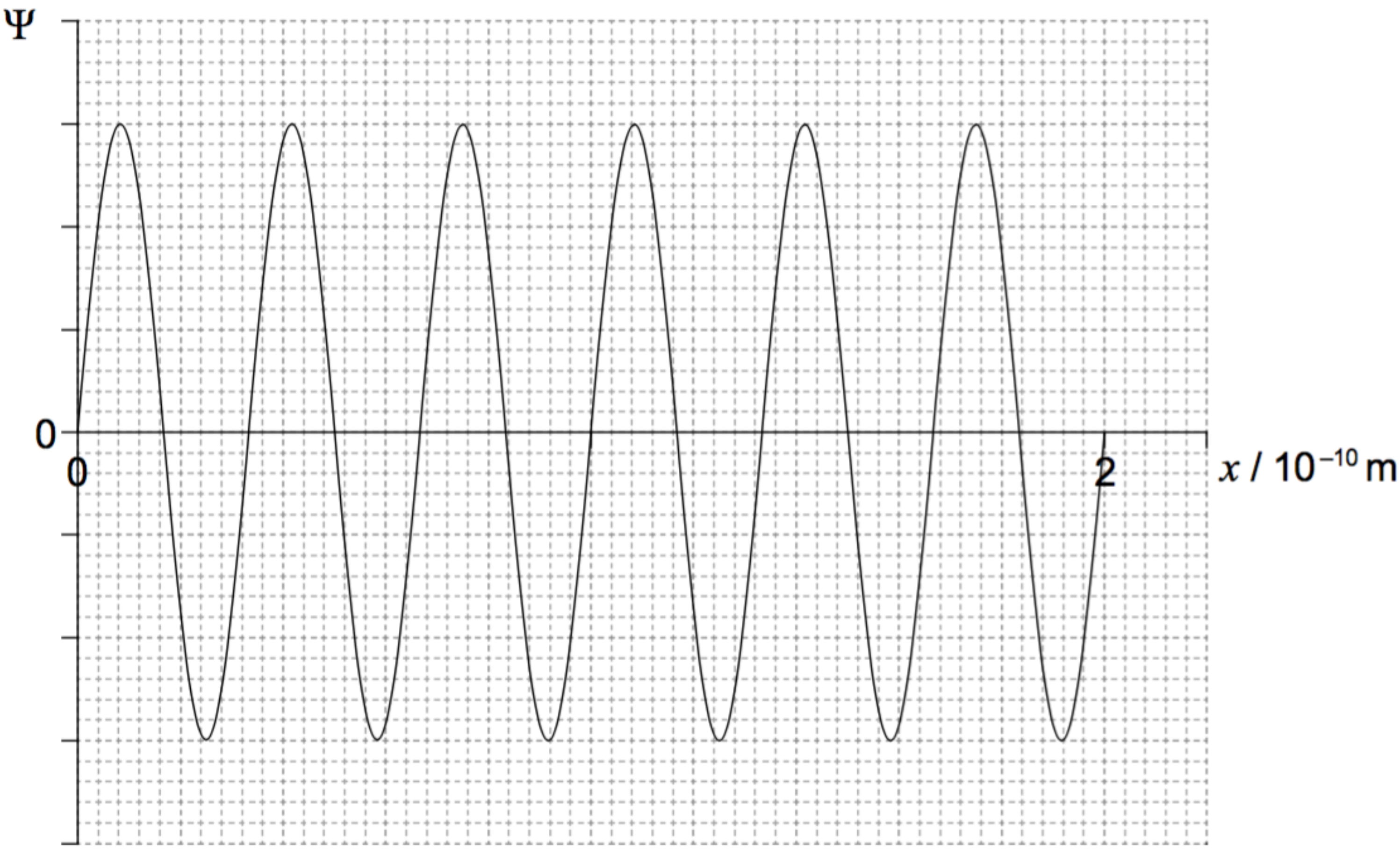
d. (i) $\Delta p=\frac{h}{4\pi\Delta x}$ and Δx=2.0×10^{-10}; *(both needed)*

2.64×10^{-25}(Ns); *(also accept 5.28×10^{-25}(Ns))*

*Award **[2]** for a bald correct answer.*

(ii) $\lambda=\frac{h}{p}\left(=\frac{6.63\times10^{-34}}{2\times10^{-23}}\right)$;
3.3×10^{-11} (m);
*Award **[2]** for a bald correct answer.*

(iii)



periodic behaviour shown anywhere between 0 nm and 0.2 nm;
6 loops/repetitions shown anywhere between 0 nm and 0.2nm; } *(allow ECF for division of 2×10^{-10} by answer to d(ii))*
wavefunction completely fills from 0 nm to 0.2 nm and does not go beyond;

(iv) amplitude of Ψ/graph;
squared;

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]