SL Paper 3

This question is about radioactive decay.

The half-life of Au-189 is 8.84 minutes. A freshly prepared sample of the isotope has an activity of 124Bq.

a. A nucleus of a radioactive isotope of gold (Au-189) emits a neutrino in the decay to a nucleus of an isotope of platinum (Pt). [2]

In the nuclear reaction equation below, state the name of the particle X and identify the nucleon number A and proton number Z of the nucleus of the isotope of platinum.

$$ {}^{189}_{79}Au \rightarrow {}^{A}_{Z}Pt + X + v $$

X:

A:

Z:

b. (i) Calculate the decay constant of Au-189. [3]

(ii) Determine the activity of the sample after 12.0 min.

Markscheme

a. *X*: positron ***or*** β^+;

A: 189 and *Z*: 78; *(both responses needed)*

b. (i) $0.0784\ \mathrm{min}^{-1}$;

(ii) recognize to use $A = A_0 e^{-\lambda t}$;

$A = 48.4\ \mathrm{Bq}$;

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

Examiners report

a. A surprisingly large number of candidates were unable to correctly identify the products of beta plus decay.

b. Unit errors were often made in (i) and in (ii) there was often some very strange arithmetic to be seen.

This question is about radioactive decay.

In a particular nuclear medical imaging technique, carbon-11 $\left({}^{11}_{6}\mathrm{C}\right)$ is used. It is radioactive and decays through β^+ decay to boron (B).

The half-life of carbon-11 is 20.3 minutes.

a.i. Identify the numbers and the particle to complete the decay equation. [2]

$$^{11}_{6}\mathrm{C} \rightarrow {}^{\cdots\cdots}_{5}\mathrm{B} + {}^{\cdots\cdots}_{\cdots\cdots}\beta^{+} + \ldots\ldots\ldots\ldots$$

a.ii. State the nature of the β^{+} particle. [1]

b.i. Outline a method for measuring the half-life of an isotope, such as the half-life of carbon-11. [3]

b.ii. State the law of radioactive decay. [1]

b.iii. Derive the relationship between the half-life $T_{\frac{1}{2}}$ and the decay constant λ , using the law of radioactive decay. [2]

b.iv. Calculate the number of nuclei of carbon-11 that will produce an activity of 4.2×10^{20} Bq. [2]

Markscheme

a.i. $\left({}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{+1}\beta^{+} + v \text{ (or neutrino)}\right)$

${}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{+1}\beta^{+}$;

v (or neutrino);

*Award **[1]** for all the correct numbers and **[1]** for the neutrino.*

a.ii. positron / antielectron / lepton;

b.i. measure activity as a function of time;

create a graph of activity with time, and estimate half-life from the graph;

make at least three estimates of half-life from the graph and take mean;

or

measure activity as a function of time;

create a graph of ln(A) with time, find the decay constant λ from the gradient;

estimate the half-life using $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$;

b.ii. the rate of decay is proportional to the amount of (radioactive) material remaining;

the number of undecayed nuclei at time t is given by $N = N_0 e^{-\lambda t}$, where N_0 is the number of undecayed nuclei at time $t = 0$ and λ is the decay constant;

b.iii. $\frac{N_0}{2} = N_0 e^{-T_{\frac{1}{2}}}$;

$\ln\left(\frac{1}{2}\right) = -\lambda T_{\frac{1}{2}}$ so $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$;

b.iv. $\lambda = \frac{\ln 2}{60 \times 20.3}$ $(= 5.69 \times 10^{-4} s^{-1})$;

$\frac{A}{\lambda} = \frac{4.2 \times 10^{20}}{5.69 \times 10^{-4}} = 7.4 \times 10^{23}$;

Examiners report

a.i. (a)(i) was well answered.

a.ii. (a)(ii) was well answered.

b.i. (b)(i) was poorly answered, with many referring to measurement of the loss of mass of the sample.

b.ii. (b)(ii) was very poorly answered.

b.iii. Most did not use the law of radioactive decay, as required in (b)(iii).

b.iv. (b)(iv) was either very well answered or very poorly answered.

This question is about wave–particle duality.

A particle of mass 6.4×10^{-27} kg and charge 3.2×10^{-19} C is accelerated from rest through a potential difference of 25 kV.

a. Describe what is meant by the de Broglie hypothesis. [2]

b. (i) Calculate the kinetic energy of the particle. [4]

(ii) Determine the de Broglie wavelength of the particle.

Markscheme

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

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

b. (i) $E_{\mathrm{K}}(= 3.2 \times 10^{-19} \times 25 \times 10^{3}) = 8.0 \times 10^{-15}$ (J) ***or*** 50 (keV);

(ii) use of $E_{\mathrm{K}} = \frac{p^2}{2m}$ and $p = \frac{h}{\lambda}$ ***or*** use of $E_{\mathrm{K}} = \frac{1}{2}mv^2$ and $p = mv = \frac{h}{\lambda}$;

$p = 1.0 \times 10^{-20}$ (Ns);

$\lambda = \left(\frac{h}{p} =\right)$ 6.6×10^{-14} (m) ***or*** 6.5×10^{-14} (m);

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

Examiners report

a. The de Broglie hypothesis was sometimes stated poorly and symbols sometimes not defined.

b. In (i) the kintetic energy was usually correct, but in (ii) far fewer correct answers were seen due to both algebraic and arithmetic errors. A common mistake was to treat the de Broglie wavelength as electromagnetic.

This question is about nuclear physics and radioactive decay.

a. Define *decay constant.* [1]

b. A sample of 1.6 mol of the radioactive nuclide radon-210 $\left({}^{210}_{86}\mathrm{Rn}\right)$ decays into polonium-206 $\left({}^{206}_{84}\mathrm{Po}\right)$ with the production of one other particle. [5]

$${}^{210}_{86}\mathrm{Rn} \rightarrow {}^{206}_{84}\mathrm{Po} + \mathrm{X}$$

(i) Identify particle X.
(ii) The radioactive decay constant of radon-210 is $8.0\times10^{-5}\,\mathrm{s}^{-1}$. Determine the time required to produce 1.1 mol of polonium-206.

c. Particle X has an initial kinetic energy of 6.2MeV after the decay in (b). In a scattering experiment, particle X is aimed head-on at a stationary gold-197 $\left({}^{197}_{76}\mathrm{Au}\right)$ nucleus. [3]

Determine the distance of closest approach of particle X to the Au nucleus.

Markscheme

a. the probability of decay of a nucleus per unit time;

b. (i) alpha particle / helium nucleus;

(ii) number of Po nuclei produced=number of Rn nuclei decayed *(seen or implied)*;
$0.5 = 1.6e^{-\lambda t}$;
$t = \left(-\frac{\ln\frac{0.5}{1.6}}{\lambda} =\right)\frac{1.163}{8.0\times10^{-5}}$;
1.5×10^{4}(s);

c. initial kinetic energy=electric potential energy at closest distance;

kinetic energy $E = \left(6.2\times10^{6}\times1.6\times10^{-19} =\right) 9.9\times10^{-13}\,(\mathrm{J})$;

$d = k\frac{q_1q_2}{E} = 8.99\times10^{9}\frac{2\times79\times\left[1.6\times10^{-19}\right]^2}{9.9\times10^{-13}}\,(\mathrm{m})$ ***or*** $= 3.7\times10^{-14}\,(\mathrm{m})$;

Examiners report

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

This question is about radioactive decay.

A nucleus of magnesium-23 decays forming a nucleus of sodium-23 with the emission of an electron neutrino and a β^+ particle.

a. Outline why the existence of neutrinos was hypothesized to account for the energy spectrum of beta decay. [3]

b. The decay constant for magnesium-23 is $0.061\ \mathrm{s}^{-1}$. Calculate the time taken for the number of magnesium-23 nuclei to fall to 12.5% of its initial value. [2]

Markscheme

a. spectrum of beta decay is continuous;

with a maximum value of energy;

the resulting energy difference between energy of any $\beta^{(+)}$ and maximum $\beta^{(+)}$ energy is accounted for by the energy of the neutrino / reference to energy difference between parent energy level and excited energy level of daughter;

b. $T_{\frac{1}{2}} = \frac{\text{In}2}{0.061} = 11.4\,(\text{s})$;

$\left(N = \frac{1}{8}N_0 \text{ so}\right) t = \left(3T_{\frac{1}{2}} =\right) 34\,(\text{s})$

or

$t = -\frac{\text{In}0.125}{0.061}$;

t=34(s);

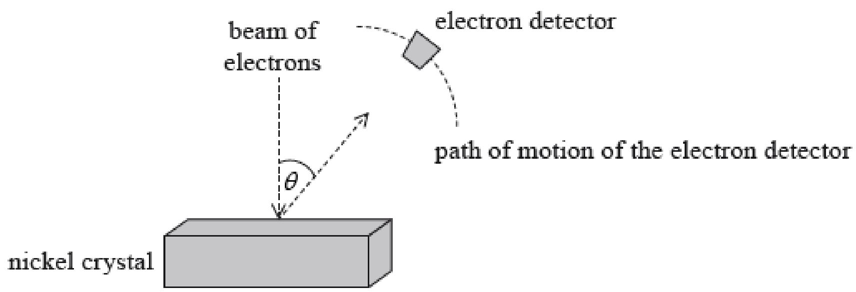
Examiners report

a. [N/A]

b. [N/A]

This question is about the wave nature of matter.

In 1927 Davisson and Germer tested the de Broglie hypothesis. They directed a beam of electrons onto a nickel crystal as shown in the diagram. The experiment was carried out in a vacuum.



a. Describe wave-particle duality in relation to the de Broglie hypothesis. [2]

b.i. The electrons were accelerated through a potential difference of 54 V. Show that the associated de Broglie wavelength for the electrons is about 2×10^{-10} m. [2]

b.ii. The electron detector recorded a large number of electrons at a particular scattering angle θ. Explain why a maximum in the number of scattered electrons is observed at a particular angle. [2]

Markscheme

a. a particle with momentum has a wavelength ;

where $\lambda = \frac{h}{p}$ and wavelength is λ, momentum is p and Planck's constant is h;

b.i. $p = \sqrt{2m_e \times eV} = \sqrt{2 \times 9.11 \times 10^{-31} \times 1.60 \times 10^{-19} \times 54}\ (= 3.97 \times 10^{-24}\ \mathrm{kg\,m\,s^{-1}})$;

$\lambda = \left(\frac{h}{\sqrt{2m_e \times eV}} = \frac{6.63 \times 10^{-34}}{3.97 \times 10^{-24}} =\right)\ 1.7 \times 10^{-10}\ \mathrm{m}; \}$

(must see 2+ significant figures to award this mark)

b.ii. electrons scatter off the periodic structure of the nickel lattice;

separation of ions/atoms is such that diffraction occurs (leading to a maximum in the intensity of scattered electrons);

Examiners report

a. (a) was usually well answered.

b.i. (b)(i) was either well answered or incorrect.

b.ii. (b)(ii) was very poorly answered.

This question is about the photoelectric effect.

In a photoelectric experiment, light of wavelength 450 nm is incident on a sodium surface. The work function for sodium is 2.4 eV.

a. (i) Calculate, in eV, the maximum kinetic energy of the emitted electrons. [5]

(ii) The number of electrons leaving the sodium surface per second is 2×10^{15}. Calculate the current leaving the sodium surface.

b. The wavelength of the light incident on the sodium surface is decreased without changing its intensity. Explain why the number of electrons emitted from the sodium will decrease. [4]

Markscheme

a. (i) photon energy $= \left(\frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{450 \times 10^{-9}} =\right) 4.4 \times 10^{-19}\ (\mathrm{J})$;

=2.76(eV) ;

2.76 - 2.4 = 0.36 (eV) ;

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

*Award **[1 max]** if the energy of the photon is not converted from Joules to eV (giving E_K =-2.4 eV).*

(ii) $2 \times 10^{15} \times 1.6 \times 10^{-19}$;

3×10^{-4} (A);

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

b. light consists of photons;

frequency of photons increases so energy of photons increases;

same intensity of radiation means fewer photons;

fewer photons means fewer (photo)electrons;

(the emitted number of electrons falls)

Examiners report

a. In part (a)(i) many correct answers were seen, however there were quite a few mistakes in converting the photon energy to eV. Part (a)(ii) was easy, but some candidates thought that the KE of the electrons needed to be used.

b. Candidates found (b) difficult as the answer is slightly counter-intuitive. Very few candidates seemed to know that equal intensity of light means equal total photon energy per second. Many assumed it meant equal number of photons per second. The answers were mostly disorganised and did not reflect a logical scientific argument that would be expected at this level.

This question is about quantum physics.

a. Describe the de Broglie hypothesis. [2]

b. An electron is accelerated from rest through a potential difference of 5.0 kV. [6]

(i) Calculate the momentum of the electron after acceleration.
(ii) Calculate the wavelength of the electron.
(iii) Determine the energy of a photon that has the same wavelength as the electron in (b)(ii).

c. The momentum of the electron is known precisely. Deduce that all the information on its position is lost. [2]

d. With reference to Schrödinger's model, state the meaning of the amplitude of the wavefunction for the electron. [1]

Markscheme

a. all particles have an associated wavelength/behave like waves;

with $\lambda = \frac{h}{p}$ and symbols defined/described using terms;

b. (i) $p = \left(\sqrt{2mE} = \sqrt{2meV} =\right) \sqrt{2 \times 9.11 \times 10^{-31} \times 1.6 \times 10^{-19} \times 5.0 \times 10^{3}}$;

$= 3.8 \times 10^{-23}\,(\mathrm{Ns})$;

or

$v = \left(\sqrt{\frac{2eV}{m}} =\right) \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 5.0 \times 10^{3}}{9.11 \times 10^{-31}}}$;

$p = (mv =) 3.8 \times 10^{-23} (Ns)$;

(ii) $\lambda = \left(\frac{h}{p} =\right) \frac{6.63\times10^{-34}}{3.8\times10^{-23}}$;
$=1.7\times10^{-11}$m;
This is a question testing units for this option. Do not award second marking point for an incorrect or missing unit.

(iii) $E = \left(hf = \frac{hc}{\lambda} =\right) \frac{6.63\times10^{-34}\times3.0\times10^{8}}{1.7\times10^{-11}}$;
$E=1.2\times10^{-14}$(J);

or

$E = (cp =)3.0 \times 10^8 \times 3.8 \times 10^{-23}$;

$E = 1.2 \times 10^{-14}(J)$;
Allow ECF from (b)(ii).

c. reference to the Heisenberg uncertainty principle / $\Delta x \Delta p \geq \frac{h}{4\pi}$;

Δp = 0 implies Δx is large /$\Delta x=\infty$;

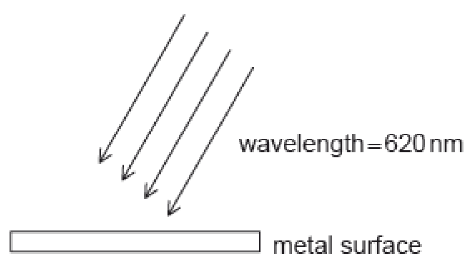
d. the (square of the) amplitude gives the probability of finding the electron at a given point in space;

Examiners report

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

This question is about the photoelectric effect.

When light is incident on a clean metal surface, electrons can be emitted through the photoelectric effect.



a. Outline how the Einstein model is used to explain the photoelectric effect. [2]

b. State why, although the incident light is monochromatic, the energies of the emitted electrons vary. [1]

c. Explain why no electrons are emitted if the frequency of the incident light is less than a certain value, no matter how intense the light. [2]

d. For monochromatic light of wavelength 620 nm a stopping potential of 1.75 V is required. Determine the minimum energy required to emit an electron from the metal surface. [2]

Markscheme

a. light made of photons of energy $E = hf$;

electrons are released immediately from the metal;

if electron gains sufficient energy (from a photon);

b. different electrons may be bound by a different amount of energy to the metal;

c. insufficient photon energy to eject surface electrons;

greater intensity means more photons but still none with enough energy;

d. $E_{\max} = (1.75 \times 1.60 \times 10^{-19} =)\ 2.80 \times 10^{-19}$ (J);

$\phi = \left(hf - E_{\max} = 6.63 \times 10^{-34} \times \frac{3.00\times10^{8}}{620\times10^{-9}} - 2.80 \times 10^{-19} =\right)\ 4.1 \times 10^{-20}$ (J);

Examiners report

a. The general idea of the photon explanation of the photoelectric effect was well known, but only a few clearly referred to photon energy transfer. Very few could explain why monochromatic light gives varied electron energies, most referring to various frequencies of light as the reason. The common mistake was the electron gaining different amounts of energy from different frequencies (despite monochromatic being stated in the question). While threshold frequency was well understood the effect of intensity was usually overlooked. The calculation was usually well attempted.

b. The general idea of the photon explanation of the photoelectric effect was well known, but only a few clearly referred to photon energy transfer. Very few could explain why monochromatic light gives varied electron energies, most referring to various frequencies of light as the reason. The common mistake was the electron gaining different amounts of energy from different frequencies (despite monochromatic being stated in the question). While threshold frequency was well understood the effect of intensity was usually overlooked. The calculation was usually well attempted.

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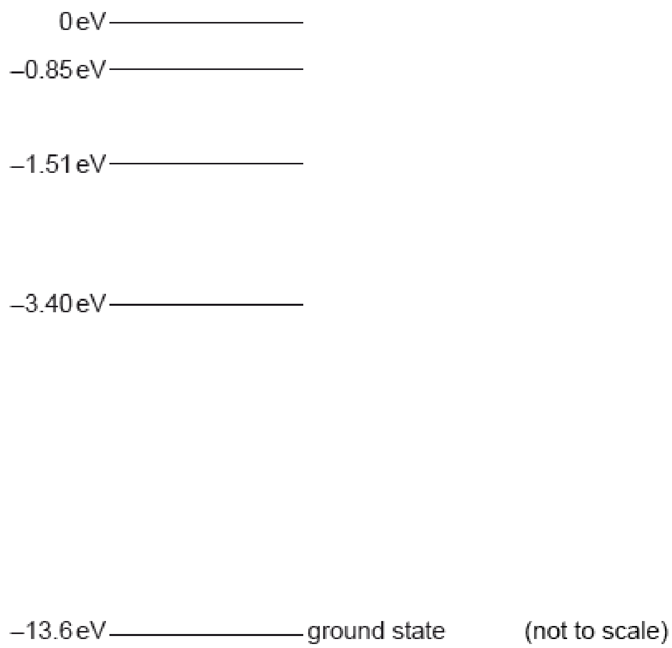
This question is about energy level transitions.

Some of the electron energy levels for a hydrogen atom are shown.



A hydrogen atom is excited to the $-1.51\ \mathrm{eV}$ level.

Monochromatic radiation is incident on gaseous hydrogen. All the hydrogen atoms are in the ground state. Describe what could happen to the radiation and to the hydrogen atoms if the incident photon energy is equal to

a.i. On the diagram, label using arrows all the possible transitions that might occur as the hydrogen atom returns to the ground state. [1]

a.ii. State the energy in eV of the maximum wavelength photon emitted as the hydrogen atom returns to the ground state. [1]

b.i. 10.2 eV. [2]

b.ii. 9.0 eV. [1]

Markscheme

a.i. only the three correct arrows on diagram;

(–1.51 to –3.40, –1.15 to –13.6 and –3.40 to –13.6)

a.ii. 1.89 eV; *(allow ECF from diagram)*

b.i. photon is absorbed;

electron (in a hydrogen atom) raised to higher/–3.40 eV/excited state;

b.ii. no absorption / photon pass through;

Examiners report

a.i. The hydrogen atom energy diagram was generally well-answered. The energy of the maximum wavelength was usually confused with the maximum frequency. The description of the photons of different energies were usually answered incompletely, not referring to both the radiation and the hydrogen atoms. A number of candidates referred to hydrogen atoms jumping energy levels, rather than electrons.

a.ii. The hydrogen atom energy diagram was generally well-answered. The energy of the maximum wavelength was usually confused with the maximum frequency. The description of the photons of different energies were usually answered incompletely, not referring to both the radiation and the hydrogen atoms. A number of candidates referred to hydrogen atoms jumping energy levels, rather than electrons.

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This question is about radioactive decay.

a. Define the *decay constant* of a radioactive isotope. [1]

b. Show that the decay constant λ is related to the half-life $T_{\frac{1}{2}}$ by the expression [2]

$$\lambda T_{\frac{1}{2}} = \ln 2.$$

c. Strontium-90 is a radioactive isotope with a half-life of 28 years. Calculate the time taken for 65% of the strontium-90 nuclei in a sample of the isotope to decay. [3]

Markscheme

a. probability of decay (of a nucleus) per unit time;

Accept $\frac{A}{N}$ with symbols defined.

b. $N = N_0 \mathrm{e}^{-\lambda t}$ and $N = \frac{N_0}{2}$ when $t = T_{\frac{1}{2}}$ ***or*** $\frac{N_0}{2} = N_0 \mathrm{e}^{-\lambda T_{\frac{1}{2}}}$;

$\frac{1}{2} = \mathrm{e}^{-\lambda T_{\frac{1}{2}}}$ ***or*** $2 = \mathrm{e}^{\lambda T_{\frac{1}{2}}}$;

$\left(\text{so } \ln 2 = \lambda T_{\frac{1}{2}}\right)$

Answer given, award marks for correct working only.

c. $\lambda = \frac{\ln 2}{28}$ ***or*** $0.025\ (\mathrm{y}^{-1})$;

$0.35 = \mathrm{e}^{-0.025t}$;

$t = 42$ (years);

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

*Award **[2 max]** for an answer of 17 years (using 0.65 instead of 0.35).*

or

$0.35 = \left[\frac{1}{2}\right]^x$ where $x = \frac{t}{T_{\frac{1}{2}}}$;

$\frac{t}{T_{\frac{1}{2}}} = 1.5$;

$t = 42\ (\text{years})$;

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

*Award **[2 max]** for an answer of 17 years (using 0.65 instead of 0.35).*

Examiners report

a. (a) was an easy mark.

b. In (b) about half of the candidates could derive the relationship between half-life and decay constant, but many were completely lost.

c. The half-life calculation in (c) was generally well done, but a common mistake was to use 0.65 as the fraction remaining.

This question is about wave–particle duality.

In the photoelectric effect, electrons are not emitted from the surface of a metal if the frequency of the incident light is below a certain value called the threshold frequency.

Light of frequency $1.0 \times 10^{15}\ \text{Hz}$ is incident on the surface of a metal. The work function of the metal is $3.2 \times 10^{-19}\ \text{J}$.

a. (i) Explain, with reference to the Einstein model of the photoelectric effect, the existence of the threshold frequency. [5]

(ii) State, with reference to your answer in (a)(i), the reason why the threshold frequency is different for different metals.

b. (i) Show that the maximum kinetic energy of the emitted electrons is $3.4 \times 10^{-19}\ \text{J}$. [5]

(ii) Determine the de Broglie wavelength of the electrons in (b)(i).

Markscheme

a. (i) light consists of photons/quanta;

a certain minimum amount of energy (the work function) is required to remove an electron from the metal;

if the photon energy is below this energy/work function no electrons will be emitted;

the energy of the photons is proportional to the frequency / $E = hf$ (with terms defined);

*If work function is mentioned it must be defined to award **[4]**.*

(ii) different metals need a different amount of minimum energy for electrons to be removed;

Accept answers in terms of work function if defined either here or in (a)(i).

b. (i) $KE_{\max} = hf - \phi$;

$= 6.6 \times 10^{-34} \times 1.0 \times 10^{15} - 3.2 \times 10^{-19}$;

$= 3.4 \times 10^{-19}\ \mathrm{J}$

(ii) use of $E = \frac{p^2}{2m}$ and $p = \frac{h}{\lambda}$ ***or*** use of $v = \sqrt{\frac{2E}{m}}$ and $p = mv = \frac{h}{\lambda}$;

to give $\lambda = \frac{h}{\sqrt{2mE}}$;

$\lambda = 8.4 \times 10^{-10}\ \mathrm{m}$;

Examiners report

a. In (a) (i) many candidates showed clearly that they understood the concept of the Einstein model and the existence of a threshold frequency. However, a significant minority of candidates had very little understanding of the topic. Those who answered (i) well had no problem in answering part (ii) correctly.

b. The problem on maximum kinetic energy was often done well but the standard calculation of the de Broglie wavelength was often done poorly with many candidates unable to make a start.

This question is about nuclear energy levels and nuclear decay.

a. The isotope bismuth-212 undergoes α-decay to an isotope of thallium. In this decay a gamma-ray photon is also produced. The isotope potassium-40 undergoes β^+ decay to an isotope of argon. [5]

Outline how the

(i) α particle spectrum and the gamma spectrum of the decay of bismuth-212 give evidence for the existence of discrete nuclear energy levels.

(ii) β^+ spectrum of the decay of potassium-40 led to the existence of the neutrino being postulated.

b. The isotope potassium-40 occurs naturally in many rock formations. In a particular sample of rock it is found that, out of the total number of argon plus potassium-40 atoms, 23% are potassium-40 atoms. [3]

Determine the age of the rock sample. The decay constant for potassium-40 is $5.3 \times 10^{-10}\mathrm{yr}^{-1}$.

Markscheme

a. (i) the α particles produced have discrete energies;

the gamma rays produced have discrete energies;

since the energies of the α particles and of the photons are determined by the difference in nuclear energy levels this implies that nuclear energy levels are also discrete;

(ii) the β^+ spectrum is continuous;
the neutrino was postulated to account for those β^+ with less energy than the maximum;

b. recognize that $\frac{N}{N_0}$=0.23;

$0.23 = e^{-5.3\times10^{-10}t}$;

t=2.8×10[9] yr;

Examiners report

a.

b.

This question is about plutonium as a power source.

Plutonium ($^{238}_{94}\text{Pu}$) decays by alpha emission. The energy of the alpha particle emitted is 8.8×10^{-13}J. The decay constant of plutonium-238 is $8.1\times10^{-3}\text{yr}^{-1}$.

a. Define *decay constant*. [1]

b. Plutonium-238 is to be used as a power source in a space probe. [6]

(i) Determine the initial activity of plutonium such that the power released by plutonium is 6.0 W.

(ii) The power source becomes useless when the power released decreases to 4.0 W. Determine the time, in years, for which the power source can be used in the space probe.

Markscheme

a. the probability of decay per unit time / constant of proportionality in the equation relating activity to number of nuclei;

b. (i) power $P = A_0 \times E \Rightarrow A_0 = \frac{P}{E}$;

$A_0 = \left(\frac{6.0}{8.8\times10^{-13}} =\right) 6.8 \times 10^{12}\text{Bq}$;

(ii) realization that power is proportional to activity / $P = P_0\text{e}^{-\lambda t}$;

$4.0 = 6.0\text{e}^{-8.1\times10^{-3}t}$;

taking logs to get $\ln\frac{4}{6} = -8.1 \times 10^{-3}t$;

$t = \left(\frac{\ln\frac{4}{6}}{-8.1\times10^{-3}} =\right) 50\text{yr}$;

First marking point may be implicit in second.
*Award **[2 max]** for using half-life (86 years) and linear fit to give 57 years.*
*Award **[4]** for correct answer by other methods.*

Examiners report

a. [N/A]

b. [N/A]

This question is about radioactive decay.

a. A nuclide of the isotope potassium-40 $\left({}^{40}_{19}\mathrm{K}\right)$ decays into a stable nuclide of the isotope argon-40 $\left({}^{40}_{18}\mathrm{Ar}\right)$. Identify the particles X and Y in the nuclear equation below. [2]

$${}^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{18}\mathrm{Ar} + \mathrm{X} + \mathrm{Y}$$

b. The half-life of potassium-40 is 1.3×10^{9}yr. In a particular rock sample it is found that 85 % of the original potassium-40 nuclei have decayed. [3]

Determine the age of the rock.

c. State the quantities that need to be measured in order to determine the half-life of a long-lived isotope such as potassium-40. [2]

Markscheme

a. neutrino/v;

positron / e^{+} / ${}^{0}_{+1}\mathrm{e}$ / β^{+};

*Award **[1 max]** for wrongly stating electron and antineutrino. Both needed for the ECF.*

Order of answers is not important.

b. $\lambda = \left(\frac{\ln 2}{1.3\times10^{9}} =\right) 5.31 \times 10^{-10}\mathrm{yr}^{-1}$;

$0.15 = \mathrm{e}^{\left[-5.31\times10^{-10}\times t\right]}$;

t=3.6×10^{9}yr;

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

or

$(0.5)^{n}$=0.15;

$n = \frac{\log(0.15)}{\log(0.5)} = 2.74\mathrm{half}-\mathrm{lives}$;

$2.74\times1.3\times10^{9}=3.6\times10^{9}$yr;

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

c. the count rate/activity of a sample;

the mass/number of atoms in the sample;

Examiners report

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

This question is about radioactive decay.

Sodium-22 undergoes β^{+} decay.

a. Identify the missing entries in the following nuclear reaction. [3]

$$^{22}_{11}\text{Na} \rightarrow {}^{22}_{\dots}\text{Ne} + {}^{0}_{\dots}e + {}^{0}_{0}\dots$$

b. Define *half-life*. [1]

c. Sodium-22 has a decay constant of 0.27 yr^{-1}. [4]

(i) Calculate, in years, the half-life of sodium-22.

(ii) A sample of sodium-22 has initially 5.0 × 10^{23} atoms. Calculate the number of sodium-22 atoms remaining in the sample after 5.0 years.

Markscheme

a. $^{22}_{11}\text{Na} \rightarrow {}^{22}_{10}\text{Ne} + {}^{0}_{+1}e + {}^{0}_{0}v$

$^{22}_{10}\text{Ne}$;

$^{0}_{+1}e$ (*accept* $^{0}_{+}e$)

$^{0}_{0}v$; (*award **[0]** for* $^{0}_{0}\overline{v}$)

b. time taken for half/50% of the nuclei to decay / activity to drop by half/50%;

c. (i) $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$;

$\frac{0.693}{0.27\text{yr}^{-1}}$=2.6 (years);

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

(ii) *N*=5.0 x 10^{23} x $e^{-0.27\times5.0}$;
N=1.3 x 10^{23};
*Award **[2]** for a bald correct answer.*

Examiners report

a. This question was well done in general.

b. Many candidates referred to mass halving rather than activity.

c.

This question is about the photoelectric effect.

a. Describe the concept of a photon. [2]

b. In the photoelectric effect there exists a threshold frequency below which no emission of photoelectrons takes place. [4]

Outline how the

(i) wave theory of light is unable to account for this observation.

(ii) concepts of the photon and work function are able to account for this observation.

c. Light of wavelength 420 nm is incident on a clean metal surface. The work function of the metal is 2.0 eV. [6]

Determine the

(i) threshold frequency for this metal.

(ii) maximum kinetic energy in eV of the emitted electrons.

Markscheme

a. light consists of discrete packets/quanta/bundles of energy/particle;

each photon has an energy of *hf* (where *h* is the Planck constant and *f* is the frequency of light);

b. (i) the energy of a (em) wave depends on amplitude (not frequency);

so increasing the intensity should have resulted in electrons being emitted (at any frequency) / *OWTTE*;

(ii) the work function is the minimum energy required to eject an electron from a metal surface;
if the photon energy (*hf*) is less than the work function then no emission will take place;

c. (i) recognizes that work function = h×threshold frequency;

$$f_0 = \left(\frac{2.0\times1.6\times10^{-19}}{6.6\times10^{-34}} =\right) 4.8\times10^{14}\mathrm{Hz};$$

(ii) recognize that maximum KE=hf-hf_0 ***or*** hf-Φ;

$$f_0 = \left(\frac{c}{\lambda} = \frac{3.0\times10^{8}}{4.2\times10^{-7}} =\right) 7.14\times10^{14}\mathrm{Hz};$$
$$hf\,(\mathrm{eV}) = \left(\frac{6.6\times10^{-34}\times7.14\times10^{14}}{1.6\times10^{-19}} =\right) 2.96\mathrm{eV};$$

max KE=(2.96–2.0=)0.96eV;

Examiners report

a.

b.

c.

This question is about the photoelectric effect and the de Broglie hypothesis.

When photons are incident on a lithium surface photoelectrons are emitted. The work function ϕ of lithium is 2.9 eV.

a. Define *work function.* [1]

b. Determine the maximum wavelength of the photons that can cause photoemission. [2]

c. Calculate the momentum of an electron that has the same de Broglie wavelength as the wavelength of the photons in (b). [2]

Markscheme

a. minimum energy/work required to remove an electron (from the surface of the substance);

b. $f_{\text{min}} = \frac{2.9\times1.6\times10^{-19}}{6.63\times10^{-34}} = \left(7.0\times10^{14}\right)\text{(Hz)};$

$\lambda_{\text{max}} = \left(\frac{3.00\times10^{8}}{7.0\times10^{14}}\right) = 4.3\times10^{-7}\text{ (m)};$

c. $p = \left(\frac{h}{\lambda_{\text{max}}} =\right)\frac{6.63\times10^{-34}}{4.3\times10^{-7}};$

$=1.5\times10^{-27}$ (kg ms^{-1});

Allow ECF from (b).

or

$p = \left(\frac{\phi}{c} =\right)\frac{2.9\times1.6\times10^{-19}}{3.00\times10^{8}}$

$=1.5\times10^{-27}$ (kg ms^{-1});

Allow ECF from (b).

Examiners report

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

This question is about radioactive decay.

Nitrogen-13 $\left({}^{13}_{7}\text{N}\right)$ is an isotope that is used in medical diagnosis. The decay constant of nitrogen-13 is $1.2\times10^{-3}s^{-1}$.

a. (i) Define *decay constant*. [3]

(ii) A sample of nitrogen-13 has an initial activity of 800 Bq. The sample cannot be used for diagnostic purposes if its activity becomes less than 150 Bq. Determine the time it takes for the activity of the sample to fall to 150 Bq.

b. (i) Calculate the half-life of nitrogen-13. [4]

(ii) Outline how the half-life of a sample of nitrogen-13 can be measured in a laboratory.

c. Nitrogen-13 undergoes β+ decay. Outline the experimental evidence that suggests another particle, the neutrino, is also emitted in the decay. [2]

Markscheme

a. (i) probability that a nucleus decays in unit time;

(ii) $150 = 800e^{-1.2\times10^{-3}t}$;
1400s;

b. (i) 580 s;

(ii) activity/count rate measured at regular time intervals/for at least three half-lives;
plot graph activity/count rate versus time;
detail of determination of half-life from graph;

c. beta energy spectrum is continuous and associated gamma spectrum is discrete;

difference in energies accounted for by existence of another particle;

or

if another particle not present;
then momentum not conserved in beta decay;

Examiners report

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

This question is about radioactive decay.

Meteorites contain a small proportion of radioactive aluminium-26 $\left({}^{26}_{13}\mathrm{Al}\right)$ in the rock.

The amount of ${}^{26}_{13}\mathrm{Al}$ is constant while the meteorite is in space due to bombardment with cosmic rays.

After reaching Earth, the number of radioactive decays per unit time in a meteorite sample begins to diminish with time. The half-life of aluminium-26 is 7.2×10^{5} years.

a. Aluminium-26 decays into an isotope of magnesium (Mg) by β^{+} decay. [2]

$$ {}^{26}_{13}\mathrm{Al} \rightarrow {}^{\mathrm{X}}_{\mathrm{Y}}\,\mathrm{Mg} + \beta^{+} + \mathrm{Z} $$

Identify X, Y and Z in this nuclear decay process.

X:

Y:

Z:

b. Explain why the beta particles emitted from the aluminium-26 have a continuous range of energies. [2]

c.i. State what is meant by half-life. [1]

c.ii. A meteorite which has just fallen to Earth has an activity of 36.8 Bq. A second meteorite of the same mass, which arrived some time ago, has an activity of 11.2 Bq. Determine, in years, the time since the second meteorite arrived on Earth. [3]

Markscheme

a. *X*: 26 and *Y*: 12; *(both needed for **[1]**)*

Z: *v*/neutrino;

Do not allow the antineutrino.

b. total energy released is fixed;

neutrino carries some of this energy;

(leaving the beta particle with a range of energies)

c.i. the time taken for half the radioactive nuclides to decay / the time taken for the activity to decrease to half its initial value;

Do not allow reference to change in weight.

c.ii. $\lambda = \left(\frac{\ln 2}{7.2 \times 10^5} =\right)\ 9.63 \times 10^{-7}$;

$11.2 = 36.8 e^{-(9.63 \times 10^{-7})t}$;

$t = 1.24 \times 10^6\ (\mathrm{yr})$;

Examiners report

a. This was generally well answered, although a significant minority insisted that nuclear half-life is defined by a loss of mass.

b. This was generally well answered, although a significant minority insisted that nuclear half-life is defined by a loss of mass.

c.i. This was generally well answered, although a significant minority insisted that nuclear half-life is defined by a loss of mass.

c.ii. This was generally well answered, although a significant minority insisted that nuclear half-life is defined by a loss of mass.

This question is about the de Broglie hypothesis.

a. State the de Broglie hypothesis. [2]

b. Determine the de Broglie wavelength of a proton that has been accelerated from rest through a potential difference of 1.2 kV. [2]

c. Explain why a precise knowledge of the de Broglie wavelength of the proton implies that its position cannot be observed. [2]

Markscheme

a. particles have an associated wavelength;

wavelength=$\frac{h}{mv}$ or $\frac{h}{p}$; *(symbols must be defined)*

b. $\lambda = \frac{h}{\sqrt{2\mathrm{meV}}}$;

8.3×10^{-13}m;

c. (Heisenberg suggests that) Δ*p*Δ*x* is a constant ***or*** $\geq \frac{h}{4\pi}$;

if λ is known then Δ*p* is zero therefore uncertainty in position Δ*x* is infinite/very large;

*Award **[1 max]** if Δp and Δx not defined.*

or

(the Uncertainty Principle states that) it is impossible to know the position and momentum of a particle at the same time;
if λ is precise then momentum is precise so position is not known;

Examiners report

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

This question is about the photoelectric effect.

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

b. Light of frequency 8.7×10^{14}Hz is incident on the surface of a metal in a photocell. The surface area of the metal is 9.0×10^{-6}m^2 and the intensity of the light is 1.1×10^{-3}Wm^{-2}. [4]

(i) Deduce that the maximum possible photoelectric current in the photocell is 2.7 nA.

(ii) The maximum kinetic energy of photoelectrons released from the metal surface is 1.2 eV. Calculate the value of the work function of the metal.

Markscheme

a. ejection of electron from metal surface following absorption of em radiation/photon;

b. (i) energy of one photon = $6.67\times10^{-34}\times8.7\times10^{14}$(=$5.8\times10^{-19}$J);

number of electrons released from surface per second $= \frac{9.0\times10^{-6}\times1.1\times10^{-3}}{5.8\times10^{-19}}$;
=1.7×10^{10};
current=$1.7\times10^{10}\times1.6\times10^{-19}$;
= 2.7nA

(ii) 2.4eV ***or*** 3.9×10^{-19}J;

Examiners report

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

This question is about neutrinos.

The spectrum of electron energies emitted in a typical β-decay is continuous. Describe how this observation led physicists to propose the existence of the particles now called neutrinos.

Markscheme

Look for these points:

idea that total energy released in the decay is fixed;

beta particle energies are less than this value/continuous;

the neutrino is postulated to account for this “missing” energy;

Examiners report

[N/A]

This question is about radioactive decay.

Nuclide X has a half-life that is estimated to be in the thousands of years.

a. Outline how the half-life of X can be determined experimentally. [4]

b. A pure sample of X has a mass of 1.8 kg. The half-life of X is 9000 years. Determine the mass of X remaining after 25000 years. [3]

Markscheme

a. measurement of mass of sample / determination of molar mass;

determination of number of nuclei N;

measurement of activity A;

determination of decay constant from $\lambda = \frac{A}{N}$;

half-life from $T_{\frac{1}{2}} = \frac{1n2}{\lambda}$;

b. $\lambda = \left(\frac{ln2}{T_{\frac{1}{2}}} = \frac{ln2}{9000} =\right) 7.70 \times 10^{-5} \mathrm{yr}^{-1}$;

$m = \left(m_0 e^{-\lambda t} =\right) 1.8 \times e^{-7.70 \times 10^{-5} \times 25000}$;

m=0.26 (kg);

or

$\frac{25000}{9000} = 2.77$ half-lives;

fractional mass left = $\left(\frac{1}{2}\right)^{2.77} = 0.15$;

mass left=1.8×0.15=0.26 (kg);

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

Examiners report

a. Most candidates were very uncertain about determining a very long half-life. Part marks were often obtained for stating how half-life was obtained from the decay constant, but determination of activity and number of sample atoms was not usually mentioned. Most candidates described how the half-life of a nuclide with a short half-life can be found.

b. In (b) surprisingly few candidates know the easy way to calculate fraction remaining. Find the number of half-lives passed (n). Fraction remaining = 0.5^n. This works even when n is non-integer. Most obtained at least 1 mark for finding the decay constant or the number of half-lives. Quite a few candidates assumed a proportional relationship for the non-integer part of n.

This question is about radioactive decay.

a. Potassium-40 (K-40) is a radioactive isotope that occurs naturally in many different types of rock. A very small percentage of the isotope undergoes β^+ decay to form an isotope of argon (Ar). Construct and complete the nuclear reaction equation for this decay. [2]

b. Overall about 10% of a sample of K-40 will decay to argon. In a particular rock sample it is found that there are 1.6×10^{22} atoms of K-40 and 8.4×10^{21} atoms of argon. The half-life of K-40 is 1.2×10^{9} yr. Estimate the time elapsed since the rock sample was formed. [4]

Markscheme

a. $\left({}^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{18}\mathrm{Ar} + {}^{0}_{1}\beta^{+} + v\right)$

${}^{40}_{18}\mathrm{Ar}$;

v; (do not accept $\bar{v}$)

b. original number of K-40 atoms=(1.6×10^{22}+[$8.4\times10^{21}\times10$]=)1.0×10^{23};

decay constant=$\frac{\ln 2}{1.2\times10^{9}}$ ***or*** 5.8×10^{-10}(yr^{-1});

$1.6\times10^{22} = 1.0\times10^{23}\mathrm{e}^{-5.8\times10^{-10}t}$;

to give t=3.2×10^{9} (yr);

Accept any alternative method that leads to the correct answer.

*Award **[3 max]** ECF after incorrect value for N_0 (eg. use of 2.44×10^{22} to give 7.3×10^{22} yr).*

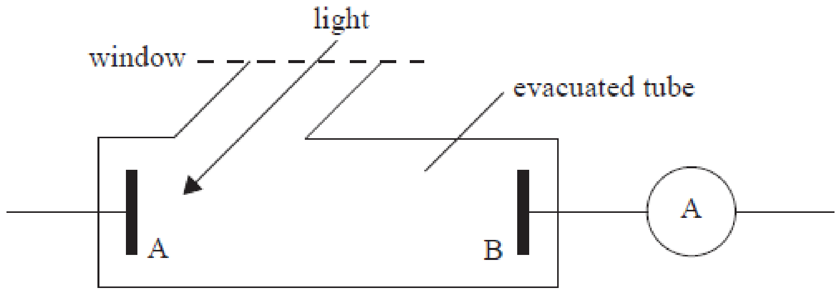
*Award **[2 max]** for approximate answers (eg. 3.0×10^{9} yr based on an estimate of between two and three half-lives.)*

Examiners report

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

This question is about the photoelectric effect.

In an experiment to investigate the photoelectric effect, light of frequency f is incident on the metal surface A, shown in the diagram below. A potential difference is applied between A and B. The photoelectric current is measured by a sensitive ammeter. (Note: the complete electrical circuit is not shown.)



When the frequency of the light is reduced to a certain value, the current measured by the ammeter becomes zero. Explain how Einstein's photoelectric theory accounts for this observation.

Markscheme

light consists of photons/quanta/packets of energy;

each photon has energy $E=hf$ / photon energy depends on frequency;

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

if photon energy is less than this energy, no electrons are emitted;

Examiners report

[N/A]

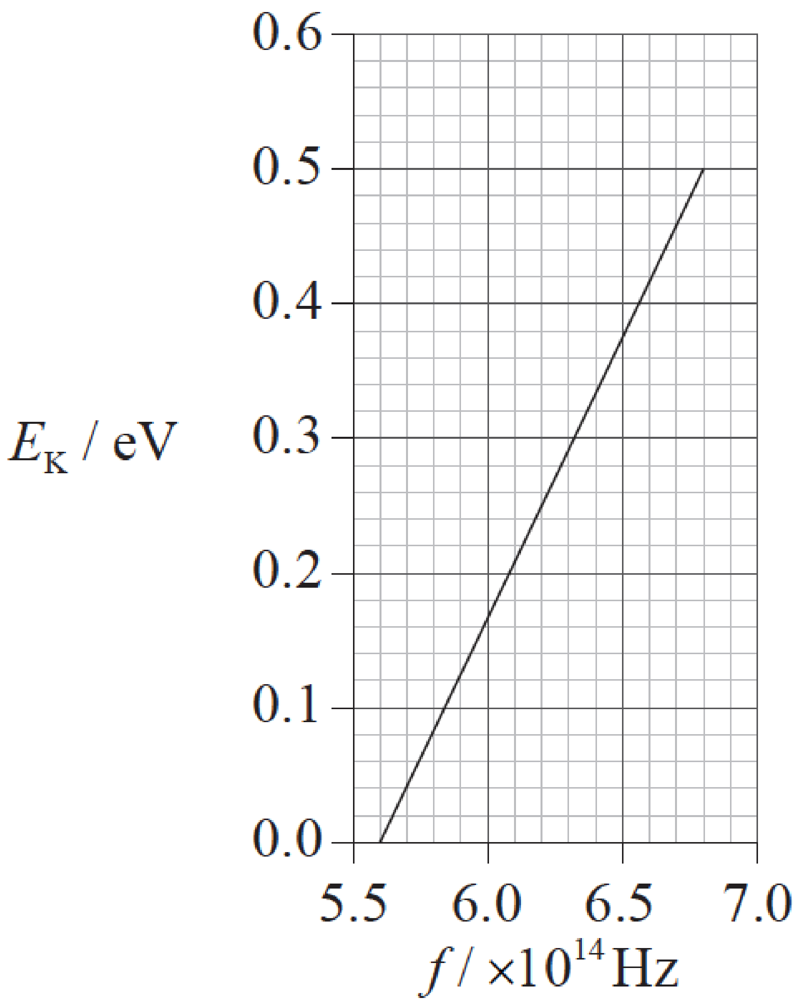
This question is about the photoelectric effect.

a. Monochromatic light of different frequencies is incident on a metal surface placed in a vacuum. As the frequency is increased a value is reached at which electrons are emitted from the surface. Below this frequency, no matter how intense the light, no electrons are emitted. Outline how the [6]

(i) wave theory of light is unable to account for these observations.

(ii) Einstein model of the photoelectric effect is able to account for these observations.

b. The graph shows how the maximum kinetic energy E_K of the ejected electrons in (a) varies with the frequency f of the incident light. [5]



Use the graph to determine the

(i) Planck constant.

(ii) work function of the metal.

c. Show that electrons of energy 0.50 eV have a de Broglie wavelength of about 1.7×10^{-9}m. [3]

Markscheme

a. (i) electrons in the metal require a minimum amount of energy to be ejected from the metal;

(according to wave theory) the energy of a wave is dependent on intensity and not frequency;

so given enough time to absorb energy electron emission should take place at any frequency no matter what the intensity / *OWTTE*;

(ii) photons have energy *hf*/proportional to frequency (of the light);
an electron may be ejected if this energy is equal to or greater than a threshold value/work function;
the intensity determines the rate of release of photoelectrons, but not their energy;

b. (i) recognize that slope of graph$=\frac{h}{e}$ ***or*** *h* (in eV s);

evidence of finding slope eg. $\frac{0.5}{[6.8-5.6]\times10^{14}}=4.17\times10^{-15}$; } (accept values in the range of 4.0 to 4.2×10^{-15})

$h=1.6\times10^{-19}\times4.17\times10^{-15}=6.7\times10^{-34}\,(\mathrm{Js})$; } (accept values in the range of 6.4 and 6.7×10^{-34}(Js))

*Award **[0]** for an unsupported correct answer.*

(ii) threshold frequency=5.6×10^{14}(Hz);
work function (hf_0)=$6.63\times10^{-34}\times5.6\times10^{-14}=3.7\times10^{-19}$(J) ***or*** 2.3(eV);
*If necessary award **[2]** for use of ECF value of h from (b)(i).*
*Award **[2]** for use of any data point and W=hf-Ek giving an answer of $3.7(\pm0.1)\times10^{-19}$(J).*
*Award **[2]** for a bald correct answer.*

c. use $p=\frac{h}{\lambda}$ and $E_{\rm K}=\frac{p^2}{2m}$ to show that $\lambda=\frac{h}{\sqrt{2mE_{\rm K}}}$; *(allow equivalent working)*

electron kinetic energy=$0.5\times1.6\times10^{-19}$(J) ***or*** 8.0×10^{-20}(J);

$\lambda=\left(\frac{6.63\times10^{-34}}{\sqrt{2\times9.11\times10^{-31}\times8.0\times10^{-20}}}=\right)1.74\times10^{-9}\,(\mathrm{m})$; } *(must see to three significant figures or better)*

($\approx1.7\times10^{-9}$m)

Award marks for evidence of valid working, as the answer is given in the question.

Examiners report

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

This question is about quarks and interactions.

a. Outline how interactions in particle physics are understood in terms of exchange particles. [2]

c. Determine whether or not strangeness is conserved in this decay. [2]

d. The total energy of the particle represented by the dotted line is 1.2 GeV more than what is allowed by energy conservation. Determine the time interval from the emission of the particle from the s quark to its conversion into the d $\bar{\mathrm{d}}$ pair. [2]

e. The pion is unstable and decays through the weak interaction into a neutrino and an anti-muon. [2]

Draw a Feynman diagram for the decay of the pion, labelling all particles in the diagram.

Markscheme

a. exchange particles are virtual particles/bosons;

that mediate/carry/transmit the weak/strong/em force between interacting particles / *OWTTE*;

Award first marking point for named bosons also, e.g. photons, W, Z, gluons.

c. strangeness in initial state is –1 and zero in the final;

hence it is not conserved;

*Award **[0]** for unsupported second marking point.*

d. $\Delta t\approx\frac{h}{4\pi\Delta E}=\frac{6.63\times10^{-34}}{4\pi\times1.2\times10^{9}\times1.6\times10^{-19}}$;

$\Delta t\approx3\times10^{-25}\mathrm{s}$;

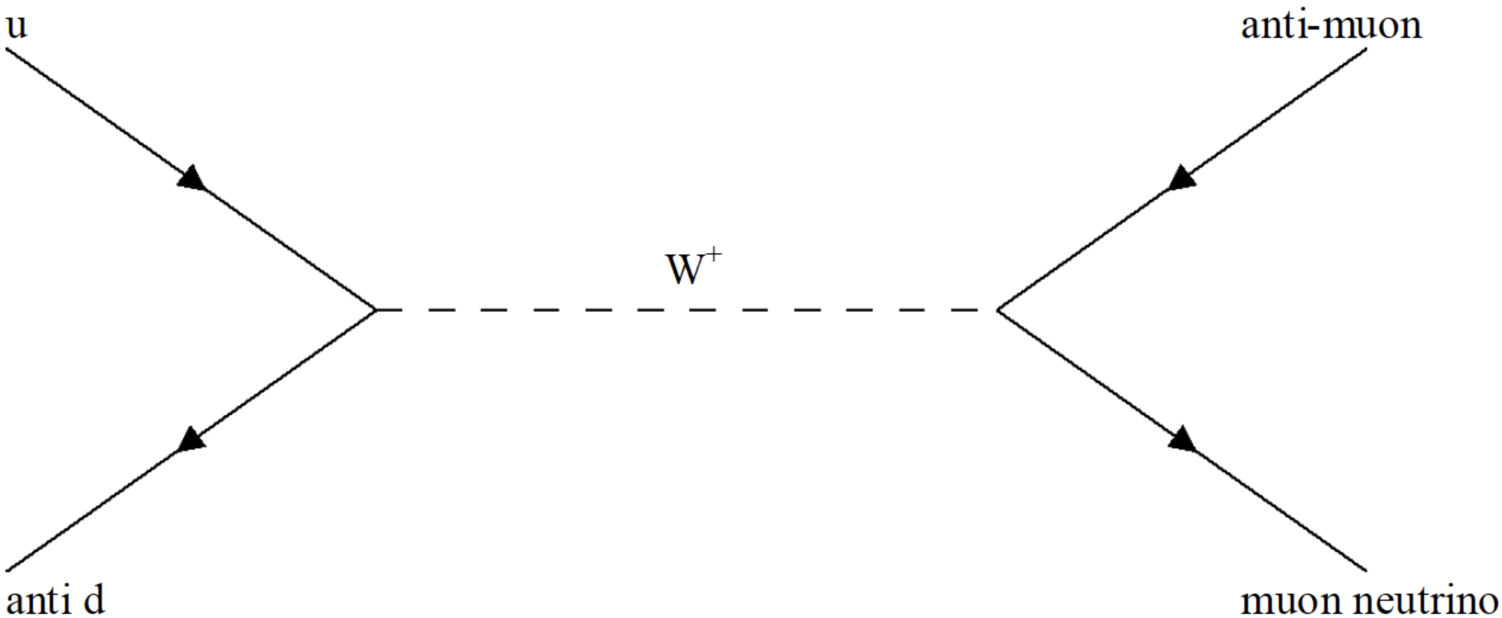
e. 

diagram as above;
correctly labelled W^+;

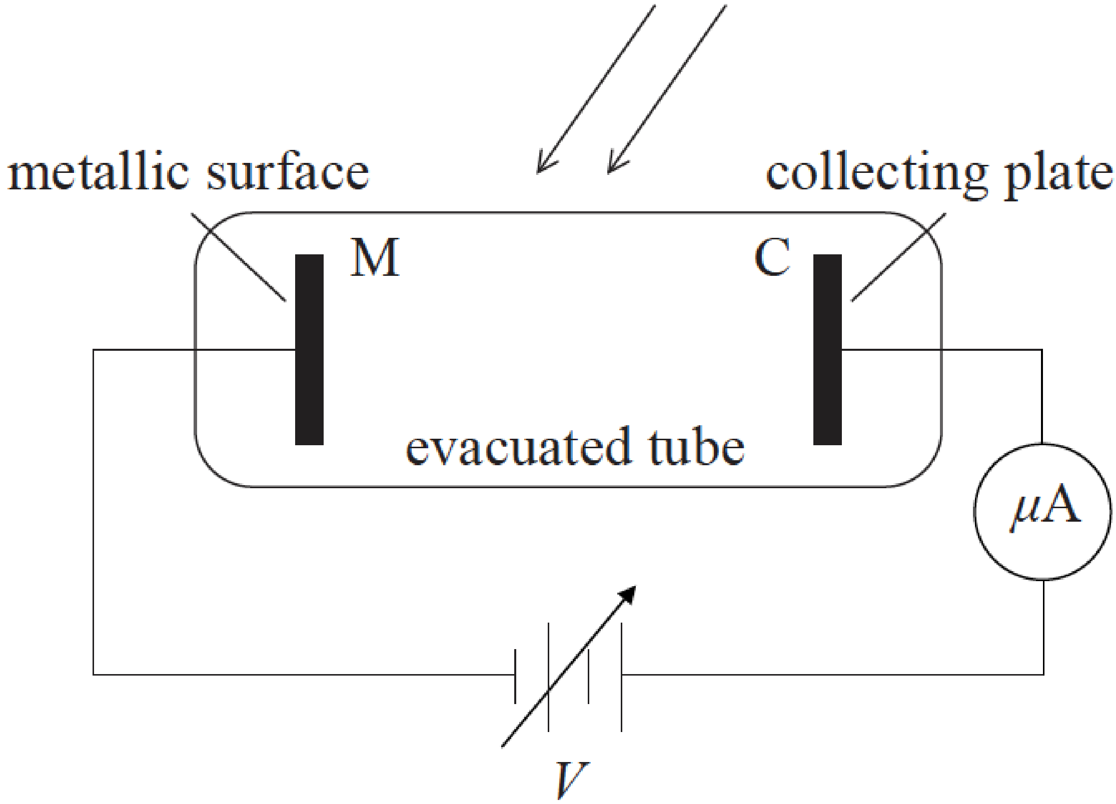
Allow time to run vertically. Allow particle symbols. Ignore missing or wrong arrow directions.

Examiners report

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

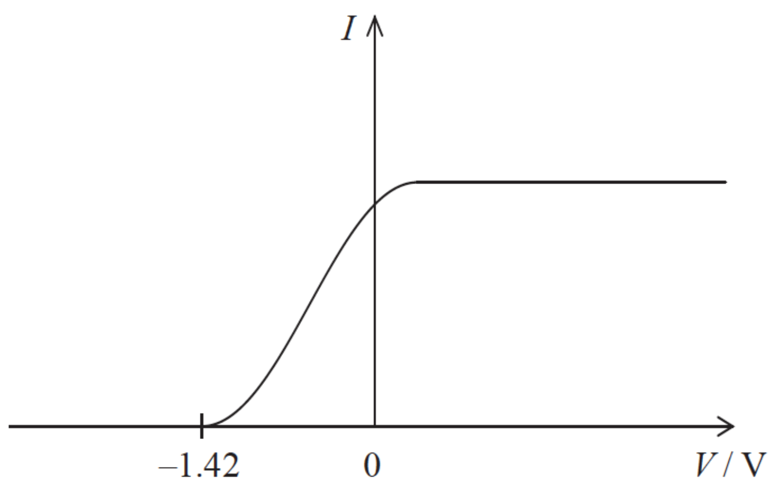
This question is about the photoelectric effect.

The diagram shows apparatus used to investigate the photoelectric effect.



a. When red light is incident on the metallic surface M the microammeter registers a current. Explain how a current is established in this circuit even though nothing joins M to C inside the tube. [2]

b. The graph shows the variation with voltage *V* of the current *I* in the circuit. [5]



The work function of the metallic surface M is 0.48 eV.

(i) Define *work function*.

(ii) State the maximum kinetic energy of an electron immediately after it has been emitted from M.

(iii) Calculate the energy of a photon incident on M.

(iv) The red light incident on M is now replaced by blue light. The number of photons incident on M per second is the same as in (b).

On the axes opposite, sketch a graph to show the variation with *V* of the current *I*.

Markscheme

a. the light causes emission of (photo)electrons;

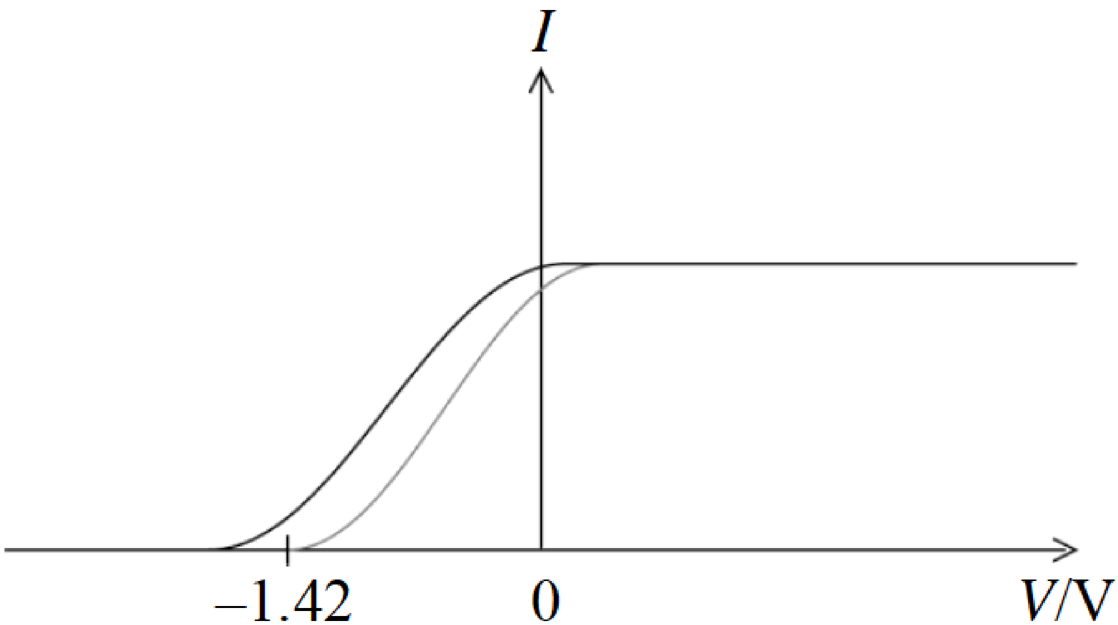
which move (from M) to C;

b. (i) the (minimum) energy required to eject an electron from the metal;

(ii) 1.42 eV;
Allow answer in Joules.

(iii) (1.42+0.48)=1.90 eV;
Allow answer in Joules.

(iv) line starting to the left of where red curve starts;
and saturates at the same value as red;

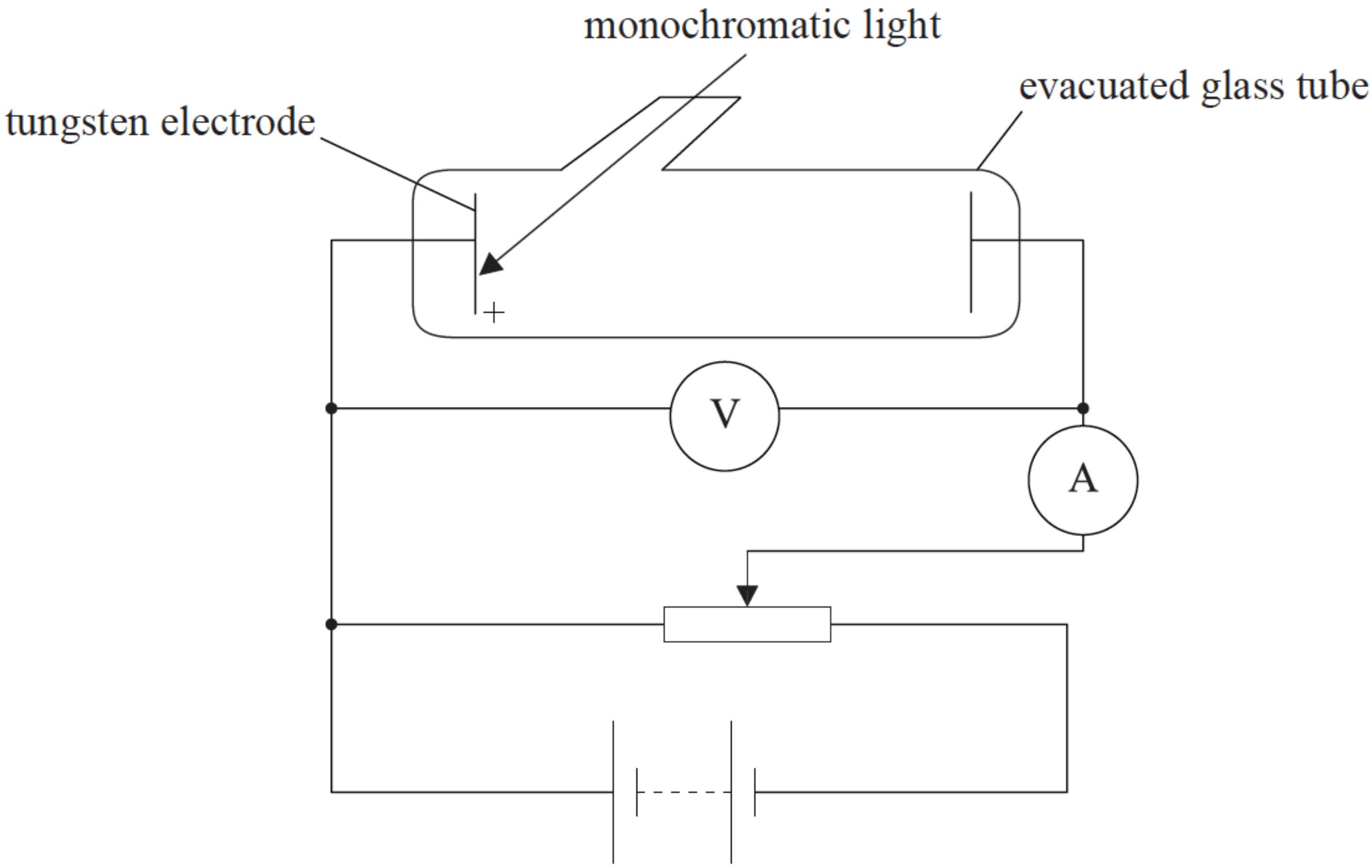


Examiners report

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

This question is about the photoelectric effect.

a. The diagram shows the set up of an experiment designed to verify the Einstein model of the photoelectric effect. [3]

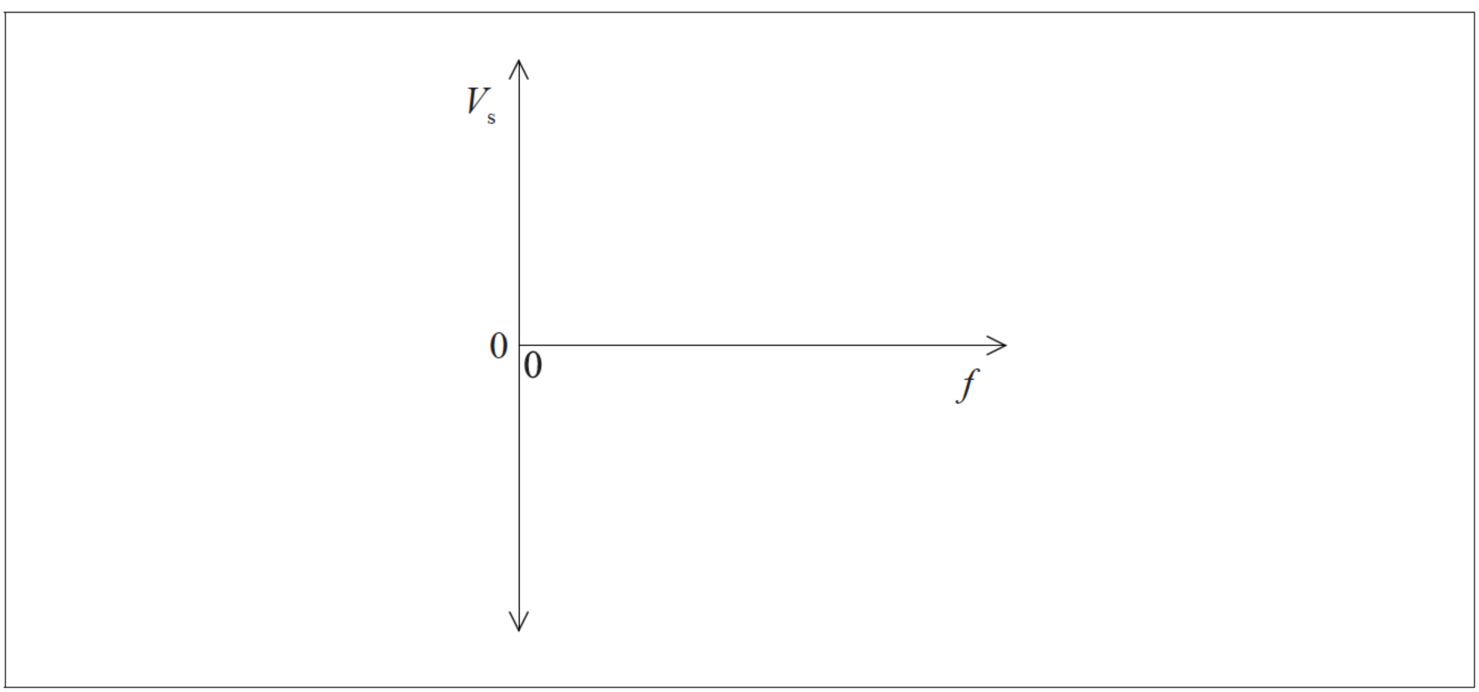


The tungsten electrode is positive.

Explain how the maximum kinetic energy of electrons ejected from the positive electrode is determined.

b. Light of frequency f is shone onto the tungsten electrode in (a). The potential V_s for which the photoelectric current is zero is recorded for different values of f. [7]

(i) Using the axes below, sketch a graph of how you might expect V_s to vary with f.



(ii) State the Einstein photoelectric equation in a form that relates V_s and f. Define, other than the electron charge, any other symbols that you might use.

(iii) Outline how a graph of V_s against f can be used to find the Planck constant and work function of tungsten.

c. The work function of tungsten is 4.5eV. Show that the de Broglie wavelength of an electron that has this energy is about 0.6nm. [3]

Markscheme

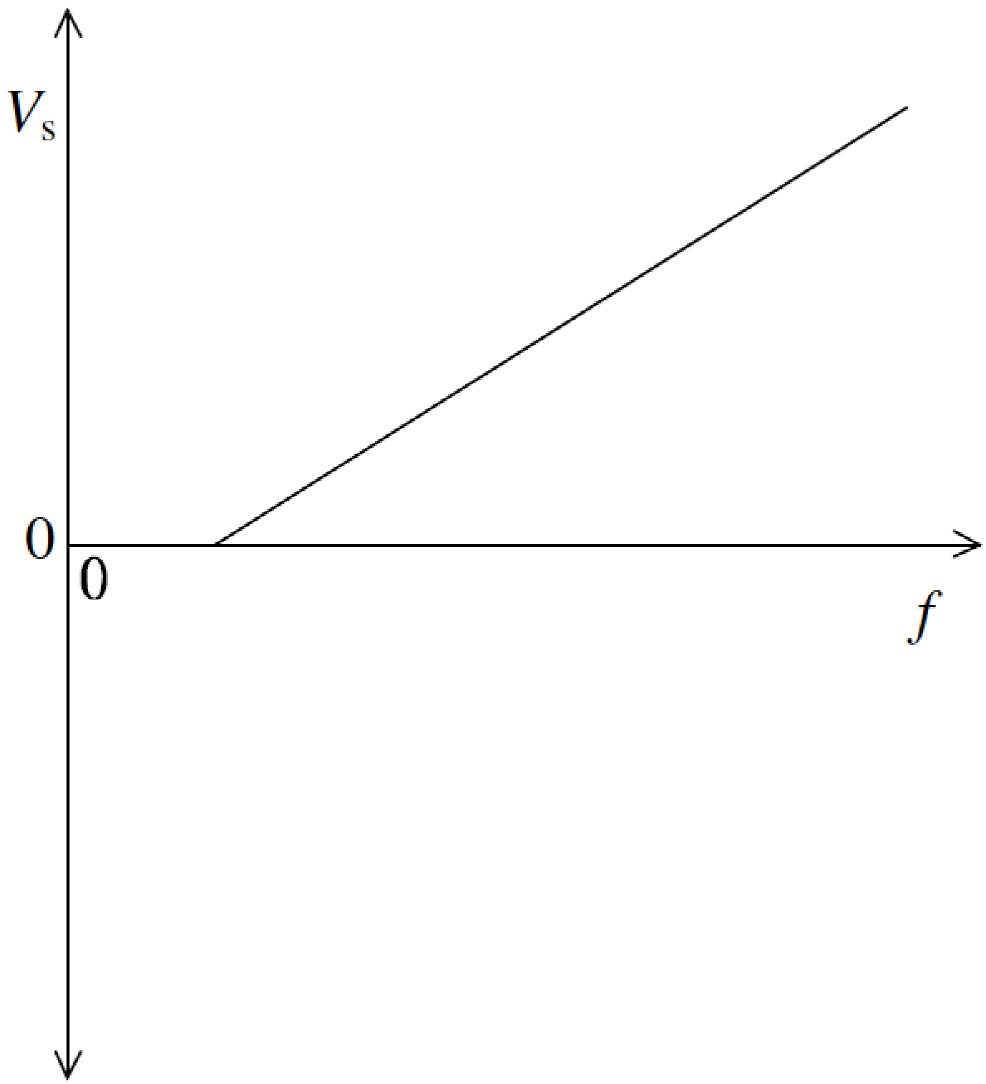
a. the potential difference is varied (using the potential divider);

until the current registered by the ammeter is zero;

the maximum kinetic energy of the (ejected) electrons is this potential times the electron charge;

b.

(i)



straight line;
with non-zero intercept on f axis;

(ii) $V_s e = hf - hf_0$ ***or*** $V_s e = hf - \phi$;
f_0→the frequency below which no electron emission takes place;
h→the Planck constant;
ϕ→the minimum energy required to eject an electron from tungsten;
*Award **[2 max]** if the equation is not given.*

(iii) *Planck constant:* slope/gradient of graph×e;
work function: extrapolation to intercept on V_s axis and $\phi = V_s$-intercept×e / when $V_s=0$, $\phi = hf$ so intercept gives f when $V_s=0$ and $\phi = h$ (f-intercept);

c. use of $p=\frac{h}{\lambda}$ and $E_k=\frac{p^2}{2m}$;

$\lambda=\frac{h}{\sqrt{2E_k m}}$;

$=\frac{6.6\times10^{-34}}{2\times4.5\times1.6\times10^{-19}\times9.1\times10^{-31}}=5.765\times10^{-10}\text{m};$

≈0.6nm

Examiners report

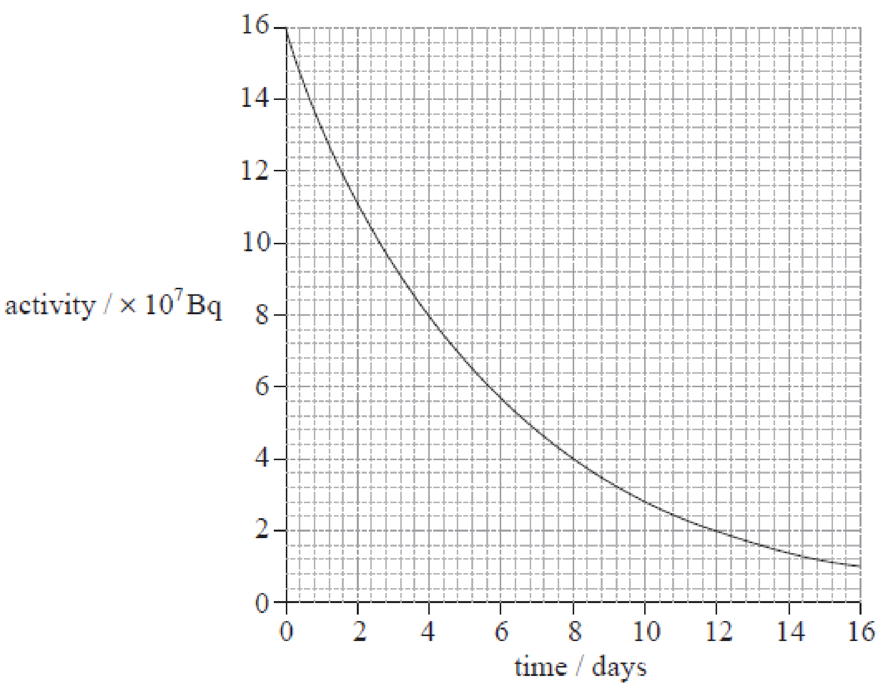
a. [N/A]
b. [N/A]
c. [N/A]

This question is about radioactive decay.

Iodine-124 (I-124) is an unstable radioisotope with proton number 53. It undergoes beta plus decay to form an isotope of tellurium (Te).

a. State the reaction for the decay of the I-124 nuclide. [2]

b. The graph below shows how the activity of a sample of iodine-124 changes with time. [6]



(i) State the half-life of iodine-124.

(ii) Calculate the activity of the sample at 21 days.

(iii) A sample of an unknown radioisotope has a half-life twice that of iodine-124 and the same initial activity as the sample of iodine-124. On the axes opposite, draw a graph to show how the activity of the sample would change with time. Label this graph X.

(iv) A second sample of iodine-124 has half the initial activity as the original sample of iodine-124. On the axes opposite, draw a graph to show how the activity of this sample would change with time. Label this graph Y.

Markscheme

a. ${}^{124}_{53}\mathrm{I} \rightarrow {}^{124}_{52}\mathrm{Te} + {}^{0}_{1}\beta^{+}$;

${}^{0}_{0}v/v$;

Do not allow an antineutrino.

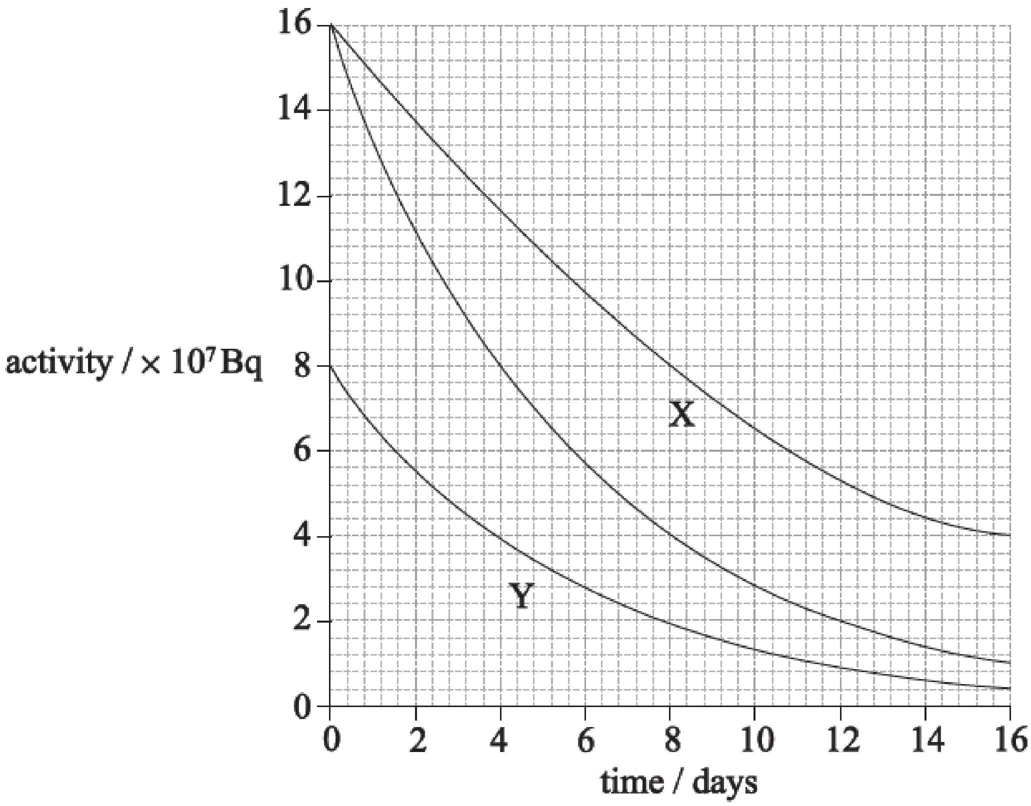
*Award **[1 max]** for* ${}^{124}_{53}\mathrm{I} \rightarrow {}^{124}_{54}\mathrm{Te} + {}^{0}_{1}\beta^{-} + \bar{v}$.

b. (i) 4 days;

(ii) $\lambda = \frac{\ln 2}{T_{\frac{1}{2}}} = \frac{\ln 2}{4} = \left(0.173\text{day}^{-1}\right)$;
$A = A_0 e^{-\lambda t} = 16 \times 10^7 \times e^{-0.173 \times 21}\ (\text{Bq})$;
$A = 4.2 \times 10^6$ Bq;
*Award **[2 max]** for bald answer in range* $4.2–4.5 \times 10^6$ Bq*, or linear interpolation between half lives giving* 4.4×10^6 Bq.

(iii) graph passing through or near (0,16), (8,8) and (16,4) – see below;

(iv) graph passing through or near (0,8), (4,4) and (8,2) – see below;
Do not penalize if graph does not pass through (12,1) and (16,0.5).



Examiners report

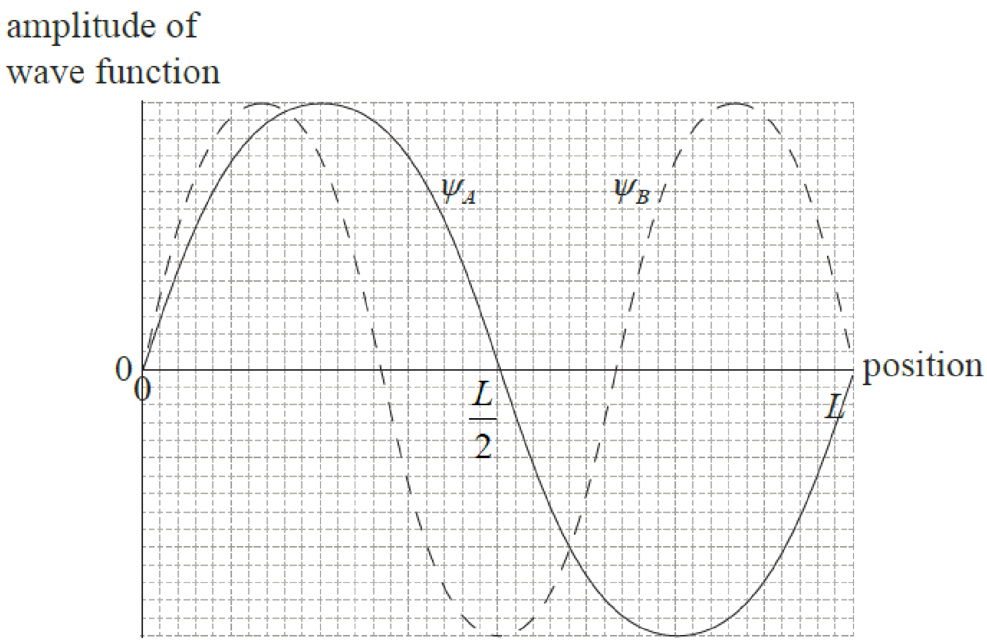
a. [N/A]
b. [N/A]

This question is about atomic energy levels.

a. Explain how atomic spectra provide evidence for the quantization of energy in atoms. [3]

b. Outline how the de Broglie hypothesis explains the existence of a **discrete** set of wavefunctions for electrons confined in a box of length *L*. [3]

c. The diagram below shows the shape of two allowed wavefunctions ψ_A and ψ_B for an electron confined in a one-dimensional box of length L. [6]



(i) With reference to the de Broglie hypothesis, suggest which wavefunction corresponds to the larger electron energy.

(ii) Predict and explain which wavefunction indicates a larger probability of finding the electron near the position $\frac{L}{2}$ in the box.

(iii) On the graph in (c) on page 7, sketch a possible wavefunction for the **lowest** energy state of the electron.

Markscheme

a. atomic spectra have discrete line structures / only discrete frequencies/wavelengths;

photon energy is related to frequency/wavelength;

photons have discrete energies;

photons arise from electron transitions between energy levels;

which must have discrete values of energy;

b. de Broglie suggests that electrons/all particles have an associated wavelength; this wave will be a stationary wave which meets the boundary conditions of the box; the stationary wave has wavelength $\frac{2L}{n}$ (where L is the length of the box and where n is an integer);

c. (i) wavelength of ψ_A larger than ψ_B;

therefore momentum of ψ_B larger than ψ_A (from de Broglie hypothesis); therefore ψ_B has larger energy;

*Award **[1 max]** for a bald correct answer.*

or

ψ_B has n=3, ψ_A has n=2;
$E_K \propto n^2$;
so ψ_B corresponds to the larger energy;

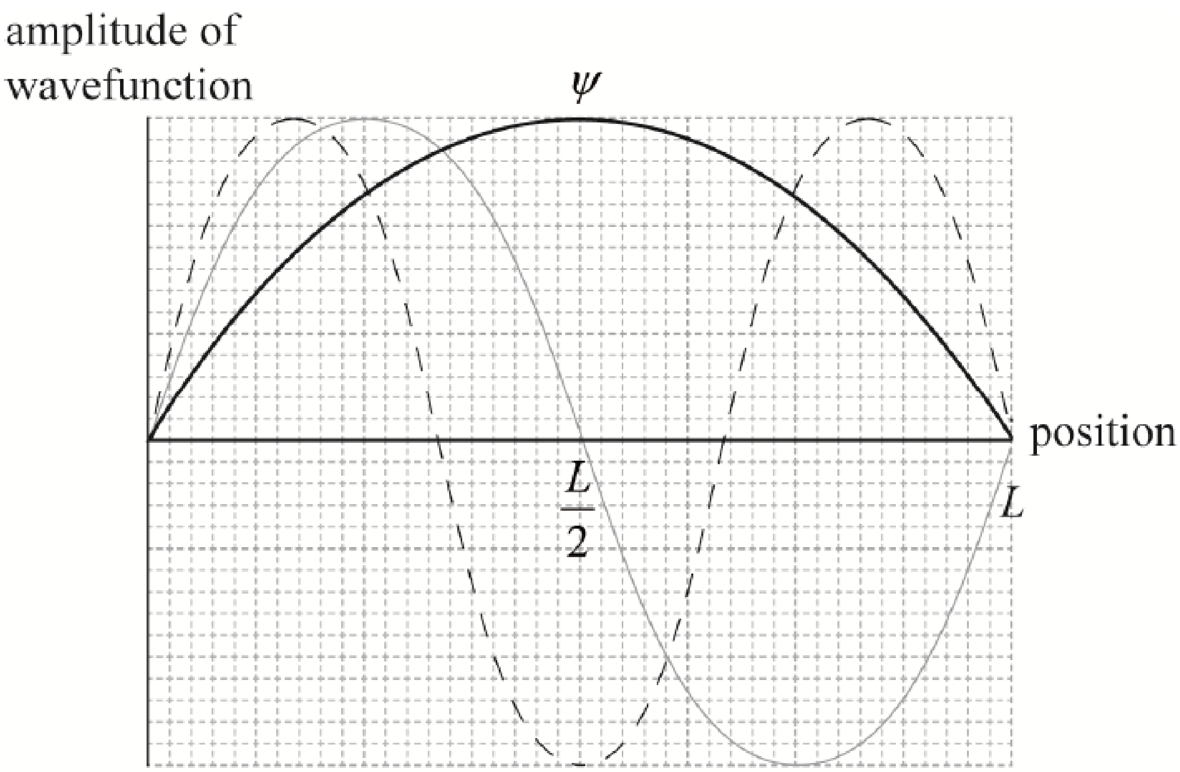
(ii) ψ_A=0, ψ_B≠0 in the middle of the box/at $\frac{L}{2}$;
so ψ_B corresponds to the larger probability since probability $\propto |\psi|^2$;
Accept $\propto \psi^2$.

or

the probability (of finding the electron) is related to the amplitude;
amplitude of ψ_B is greater than amplitude of ψ_A so ψ_B is more likely to be found;

*Award **[1 max]** for a bald correct answer.*

(iii)



correct sketch; (accept -ψ)
Accept wavefunction with any amplitude.

Examiners report

a. (a) Candidates struggled with this question. Although they demonstrated some familiarity with the idea, they could not clearly describe the connection between atomic structure and the emission spectra, usually discussing electrons without photons. The arguments leading from atomic spectra to energy levels were not logically organised.

b. There were very few correct answers to (b).

c. (i) was reasonably well done by many, although many did not refer to the de Broglie hypothesis explicitly and thus relate wavelength to momentum and so to energy.

(ii) was poorly answered. Not many candidates understood the relation between amplitude and probability of locating the particle.

(iii) was well done by most.