Mark scheme – Quantum Physics

Question			Answer/Indicative content	Marks	Guidance
1			A	1	
			Total	**1**	
2			B	1	
			Total	**1**	
3			**D**	1	
			Total	**1**	
4			B	1	
			Total	**1**	
5			C	1	
			Total	**1**	
6			**D**	**1**	
			Total	**1**	
7			B	1	
			Total	**1**	
8			A	1	
			Total	**1**	
9			D	1	
			Total	**1**	
10			D	1	**Examiner's Comments** All of the questions showed a positive discrimination, and the less able candidates could access the easier questions. The questions in Section A do require careful reading and scrutiny. Candidates are advised to reflect carefully before recording their response in the box. Candidates must endeavour to use a variety of quick techniques when answering multiple choice questions. The candidates to demonstrate their knowledge and understanding of physics.
			Total	**1**	
11			A	1	
			Total	**1**	

1 2			A	1	**Examiner's Comments** All of the questions showed a positive discrimination, and the less able candidates could access the easier questions. The questions in Section A do require careful reading and scrutiny. Candidates are advised to reflect carefully before recording their response in the box. Candidates must endeavour to use a variety of quick techniques when answering multiple choice questions.
			Total	**1**	
1 3			D	1	
			Total	**1**	
1 4			The emission of electrons from the surface of a metal when electromagnetic waves (of frequency greater than the threshold frequency) are incident on the metal.	B1	
			Total	**1**	
1 5			Diffraction (of electrons by matter)	B1	**Examiner's Comments** The majority of the candidates scored a mark for recalling that electron diffraction provided the key evidence for the wave-like behaviour of electrons. Two of the most frequent incorrect responses were *refraction* and the *photoelectric effect*.
			Total	**1**	
1 6			The minimum frequency of the EM waves / light / uv / photon for the removal of (surface) electron(s)	**B1**	**Allow** 'minimum / smallest frequency of EM wave to cause photoelectron emission' Not **wave** **Examiner's Comments** To gain the one mark for the threshold frequency candidates had to mention *electromagnetic waves* or *photon* and *minimum frequency* for the removal of electrons. Less than a third of the candidates gave an adequate definition. Poorer answers confused *threshold frequency* with *work function* of the metal.
			Total	**1**	
1 7			**C**	**1**	
			Total	**1**	
1 8			**D**	**1**	
			Total	**1**	
1 9			D	1	

			Total	**1**	
20			A	1	
			Total	**1**	
21			**C**	1	
			Total	**1**	
22			**D**	1	**<u>Examiner's Comments</u>** Slightly more than half of the candidates got the correct answer **D** in this question on the photoelectric equation. No detailed calculations were necessary here. The maximum kinetic energy of a photoelectron had to be 2.0 eV (difference between photon energy of 5.0 eV and the work function of the metal 3.0 eV), which made the value of 3.0 eV impossible. The most popular distractor was **A**.
			Total	**1**	
23			**D**	1	
			Total	**1**	
24			D	1	
			Total	**1**	
25			**C**	1	
			Total	**1**	
26			**B**	**1**	
			Total	**1**	
27			A	1	
			Total	**1**	
28			The <u>minimum</u> energy needed to remove an electron (from the surface of a metal)	B1	**Allow** work done for energy **Allow** photoelectron for electron **<u>Examiner's Comments</u>** This is a standard definition which candidates should be able to state. Candidates should remember that the work function is a <u>minimum</u> energy. There is occasionally a misconception regarding ionisation, and also some careless use of language for the removal of the electron. Words such as escape and eject are

					acceptable, but terms such as dislocation are not clear enough. The definition does not require the statement that it is from the surface of the metal this time, but that does not mean that it will not be required in the future.
			Total	**1**	
29			A	1	
			Total	**1**	
30			B	1	
			Total	**1**	
31			**D**	**1**	
			Total	**1**	
32	a		$\lambda\left(=\frac{h}{mv}\right)=\frac{6.63\times10^{-34}}{9.11\times10^{-31}\times5.5\times10^{5}}$ $= 1.3(2) \times 10^{-9}$ (m)	**C1** **A1**	**<u>Examiner's Comments</u>** The final question was either answered very well or candidates chose an incorrect equation, often $E = \frac{hc}{\lambda}$.
	b	i	Energy of a <u>photon</u>	**B1**	**Ignore** h is Planck constant and f is frequency **<u>Examiner's Comments</u>** Many candidates simply defined the symbols as opposed to the term. It was expected that candidates would state that hf was the energy of a *photon*.
		ii	<u>Minimum</u> energy required to remove/emit (a single) <u>electron</u> from the metal surface	**B1**	**Ignore** 'it is work function' **Ignore** photoelectric effect **<u>Examiner's Comments</u>** Again, a common answer was to state that ϕ represented the work function rather than defining what is meant by work function. Good candidates stated that the work function was the minimum energy needed to remove an electron from a metal surface.
			Total	**4**	
33			The rate of photons incident on **M** is doubled.	B1	
			The rate of emission of photoelectrons / current is doubled.	B1	
			Total	**2**	
34			$h \rightarrow$ J s / $h \rightarrow \frac{\text{N m}}{\text{s}}$ / J $\rightarrow$ kg m^2 s^{-2}	C1 A1	

			base unit = kg m^2 s^{-1}		
			Total	**2**	
35	a		(kinetic energy =) 1.6 × 10^{-19} × 300	C1	
			$eV = \frac{1}{2}mv^2$	C1	
			$v = \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 300}{9.11 \times 10^{-31}}}$	C1	**Note** 1.05 × 10^{14} scores 2 marks; omitted square rooting
			speed = 1.03 × 10^7 (m s^{-1})	A0	**Examiner's Comments** Good candidates clearly showed the steps to determine the velocity. Weaker candidates found this question difficult. Clear substitution of numbers is required for these marks to be awarded.
	b		$\lambda = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 1.0 \times 10^7}$	C1	**Allow** ECF from the previous question part
			λ = 7.3 × 10^{-11} (m)	B1	**Allow** 2 marks for 7.1 × 10^{-11}, v = 1.03 × 10^7 used **Examiner's Comments** This part was generally well answered although some candidates confused terms in the equation or could not deal with the powers of ten. Some candidates were confused and used $E=hc/\lambda$.
	c		Momentum / (kinetic) energy / speed (of electrons) increases / (de Broglie) wavelength decreases	B1	
			Radius / diameter of rings decreases / pattern becomes 'smaller' (AW) or the rings are now brighter	B1	**Examiner's Comments** This was another question where candidates were expected to explain their answers. In this case a step by step approach was helpful. Some candidates stated that the energy and the wavelength would increase. Others thought that the pattern would become larger because of the increase in energy. Candidates should be encouraged to write clear, logical explanations.
			Total	**7**	
36	a		electrons emitted / s = 1.0 × 10^{-9} / 1.6 × 10^{-19} = 6.25 × 10^9	C1	
			photons arriving = 6.25 × 10^9 × 20 = 1.25 10^{11}	C1	
			ε = 1.25 10^{11} × 4.0 × 10^{-19} = 5.0 × 10^{-8} (J s^{-1})	A1	**Allow ecf**: 1 out of 3 for correct answer from any quoted number of electrons emitted / s
	b		ε = hc / λ	C1	
			3.5 × 10^{-19} = 6.6 × 10^{-34} × 3.0 × 10^8/ λ	M1	
			λ= 5.66 × 10^{-7} (m)	A1	
			Total	**6**	

3 7			Use of E = hf or E = hc/λ **EITHER** (λ) number = $(500 \times 10^{-9})/(2.5 \times 10^{-11})$ number = 2.0×10^{4} **OR** (E) number = $(7.96 \times 10^{-15})/(3.98 \times 10^{-19})$ number = 2.0×10^{4} **OR** (f) number = $(1.2 \times 10^{19}) / (6 \times 10^{14})$ number = 2.0×10^{4}	C1 C1 A1 C1 A1 C1 A1	**Allow** ECF from **(b)** **Allow** ECF from **(b)**
			Total	**3**	
3 8			energy of <u>two</u> photons = $2 \times mc^2$ or $2 \times \frac{hc}{\lambda} = 2 \times$ $\lambda = \frac{h}{mc} = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 3.0 \times 10^{8}}$	C1	
				C1	Correct use of $\frac{hc}{\lambda} = mc^2$
			wavelength = 2.4×10^{-12} (m)	A1	
			Total	**3**	
3 9			$\frac{hc}{\lambda} = \phi + KE_{max}$ and $\phi = 2.3 \times 1.6 \times 10^{-19}$	C1	
			$\frac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{5.1 \times 10^{-7}} = 2.3 \times 1.6 \times 10^{-19} + KE_{m}$	C1	
			$KE_{max} = 2.2 \times 10^{-20}$ (J)	A1	**Allow** 3 marks for an answer of 2.0×10^{-20} J; value of *h* to 2 s.f. is used.
			Total	**3**	
4 0		i	Less energy used from power stations, which in turn produce less carbon dioxide emissions and hence less environmental damage **or** Infrequent need for disposal of LED lamps has less impact on landfill sites or use of natural resources.	B1	
		ii	The energy of a photon depends on the wavelength **or** frequency.	B1	
		ii	Energy does not depend on intensity therefore energy of the photon is the same.	B1	
			Total	**3**	

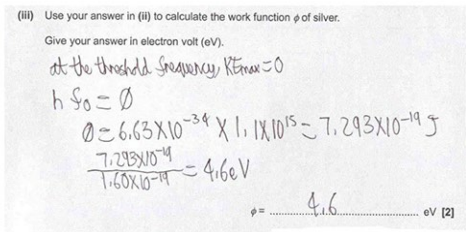
41			Photon mentioned / one-to-one interaction (between electron and photon) (Maximum KE of electrons decreases as wavelength increases because) $KE_{(max)} = \frac{hc}{\lambda} - \phi$ (Any subject) or threshold frequenc (When $\lambda < \lambda_0$) energy (of photon) > work function / f > threshold frequency **and** electrons emitted / $KE_{(max)} \neq 0$ **or** (When $\lambda = \lambda_0$) energy (of photon) = work function / f = threshold frequency **and** electrons just emitted / not emitted / $KE_{(max)} = 0$ **or** (When $\lambda > \lambda_0$) energy (of photon) < work function / f < threshold frequency **and** electrons not emitted / $KE_{(max)} = 0$	B1 B1 B1	**Not** $KE_{(max)} = hf - \varphi$ by itself, but **allow** with $c = f\lambda$ **Allow** $\frac{hc}{\lambda}$ **or** hf for 'energy of photon' and φ for 'work function' for this **B1** mark **Not** f_0 for threshold frequency **Allow** λ_0 / threshold wavelength is the maximum wavelength for electrons to be emitted **Allow** threshold frequency is the minimum frequency for electron(s) to be emitted **Allow** work function is the minimum energy for electron(s) to be emitted
			Total	**3**	
42			$\frac{hc}{\lambda} = 2 \times 9.11 \times 10^{-31} \times (3.0 \times 10^8)^2$	C1	
			$\lambda = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^8}{2 \times 9.11 \times 10^{-31} \times (3.0 \times 10^8)^2}$	C1	
			$\lambda = 1.2 \times 10^{-12}$ (m)	A1	**Allow** 2 marks for 2.4×10^{-12} (m); factor of 2 omitted in the first line.
			Total	**3**	
43			$3.2 \times 1.6 \times 10^{-19}$ or $6.63 \times 10^{-34} \times 960 \times 10^{12}$	C1	
			$E_{k\,max} = 6.63 \times 10^{-34} \times 960 \times 10^{12} - 5.12 \times 10^{-19}$	C1	
			$E_{k\,max} = 1.2 \times 10^{-19}$ (J)	A1	**Note** answer to 3 SF is 1.24×10^{-19} (J) **Examiner's Comments** This part was generally well answered. Some weaker candidates were not able to rearrange Einstein's equation. Other candidates were unable to change electron volt to joule.
			Total	**3**	
44	a		Photon(s) mentioned One-to-one interaction between photons and electrons Energy of photon is independent of intensity / intensity is to do with rate (of	**B1** **B1** **B1**	**Allow** 'photon absorbed by an electron' **Allow:** collide etc. for interaction **Allow** $E = hf$ or $E = hc/\lambda$

			photons / photoelectric emission) / photon energy depends on frequency / energy of photon depends on wavelength / photon energy ∝ frequency / photon energy ∝ 1/λ energy of uv photon(s) > work function (of zinc) / frequency of uv > threshold frequency	B1	**Allow** energy of light photon(s) < work function (of zinc) / frequency of light > threshold frequency **Allow** ≥ instead of > here **Not** $f > f_0$ **Examiner's Comment** Many candidates wrote enthusiastically about photoelectric effect and understood the significance of work function energy (or threshold frequency) and the one-to-one interaction between photon and an electron. Some candidates did not mention 'photons' and this limited the marks they could acquire. The role of intensity was less understood. Many candidates thought it was linked to 'the *number of photons'* or *'the amount of electrons emitted.* The important term **rate** of the missing ingredient. Top-end candidates gave eloquent answers, typified by the response: *'intensity of visible light only affects the rate of photons incident on the plate but not the energy of each photon'.* Two common misconceptions were: • Photons were emitted from the negative plate. • Confusing threshold frequency and work function energy.
	b		$\phi = \frac{6.63\times10^{-34}\times3.0\times10^{8}}{2.9\times10^{-7}}$ or 6.86×10^{-19} (J) $E = 5.1\times1.60\times10^{-19}$ or 8.16×10^{-19} (J) max kinetic energy = $(8.16 - 6.86)\times10^{-19}$ max kinetic energy = 1.3×10^{-19} (J)	C1 C1 A 1	**Note:** Using 5.1 and not 8.16×10^{-19} cannot score this mark or the next mark **Allow** 2 marks for 0.81 eV **Examiner's Comment** This was a notable success for most of the candidates. Examiners were pleased to see a range of techniques being used to get the correct answer of 1.3×10^{-19} J. Many answers showed excellent structure, effortless conversion of energy from electronvolt to joule and excellent use of the calculator when dealing with powers of ten. Most candidates scored three marks. A small number of candidates left the final answer as 0.81 eV; the only thing missing was the conversion to J.
	c		Any <u>three</u> from: The electrons are repelled by **C** / electrons travel against the electric field (AW) The electrons are emitted with a 'range' of speed / velocity / kinetic energy (AW) As V increases the slow(er) electrons do not reach **C and** hence *I* decreases maximum KE in the range 2.1 <u>eV</u> to 2.2 <u>eV</u> or 3.36×10^{-19} <u>J</u> to 3.52×10^{-19} <u>J</u>	B1×3	**Note** 'range' can be implied by 'highest' or 'lowest' **Allow** 'find p.d. when current is (just) zero, and then KE = $e\times V$ **Examiner's Comment** The electrons emitted from the metal plate have a **range** of kinetic energy. The emitted electrons are repelled by the negative electrode **C.** Fewer electrons reach **C** as the p.d. is increased.

					When the p.d. is about 2.2 V, and the current zero, the most energetic electron are stopped from reaching **C.** This makes the maximum kinetic energy of the electrons equal to 2.2 eV or 3.4×10^{-19} J. The question baffled most candidates. Some top-end candidates commented on *'the electrons repelled by* ***C****'* and the maximum kinetic energy of the emitted electrons being 2.2 eV. Such answers were rare. Too many candidates made guesses with answers such as *'the current drops because resistance increases'* and *'temperature increases and hence the current decreases'.*
			Total	**10**	
45			$E = (hc/\lambda =)\ 6.63 \times 10^{-34} \times 3.0 \times 10^{8}/450 \times 10^{-9}$	C1	
			$E = 4.42 \times 10^{-19}$ (J)	C1	
			energy = 2.76 (eV)	A1	**N.B.** the answer here must be 2 SF or more
			Total	**3**	
46			$E = \frac{6.63\times10^{-34}\times3.0\times10^{8}}{480\times10^{-9}}$ or $E = 4.1(4) \times$	C1	
			$N = \frac{1.2\times10^{-3}}{4.1(4)\times10^{-19}}$	C1	
			$N = 2.9 \times 10^{15}$ (s^{-1})	A1	**Examiner's Comments** The term 'photon' and the 480 nm wavelength should have prompted most candidates to calculate the energy of a single photon. The most common answer was to divide the 1.2 mW by 480 nm. Once again, it was the top-end candidates who correctly arrived at the answer of 2.9×10^{15} photons per second. About 1 in every five candidates omitted this question.
			Total	**3**	
47			$(E =)\ 1.8 \times 1.6 \times 10^{-19}$ **or** 2.88×10^{-19} (J)	C1	
			$1.8 \times 1.6 \times 10^{-19} = \frac{6.63\times10^{-34}\times3.0\times10^{8}}{\lambda}$	C1	
			$\lambda = 6.9 \times 10^{-7}$ (m)	A1	
			Total	**3**	
48	a		The wave model cannot explain why there is a threshold frequency for metals.	B1	
			The new model / photon model proposed one-to-one interaction between photons and electrons and this successfully explained why threshold frequency exists.	B1	

			Any further one from: Energy of photon (hf) must be greater than or equal to work function of metal. The kinetic energy of emitted electrons was independent of the incident intensity. Correct reference to hf = Φ + KEmax	B1	
	b	i	$E = \frac{6.63\times10^{-34}\times3.0\times10^{8}}{380\times10^{-9}}$ or $\phi = 1.1\times1.6$	C1	
		i	$\frac{6.63\times10^{-34}\times3.0\times10^{8}}{380\times10^{-9}} = 1.1\times1.6\times10^{-19} + \frac{1}{2}\times9.11\times10^{-31}v^2$	C1	This is substituting values into $\frac{hc}{\lambda} = \phi + \frac{1}{2}mv^2$
		i	speed = 8.7 × 10^5 (m s^{-1})	A1	
		ii	The energy of a photon depends only on wavelength or frequency, so intensity does not change the maximum speed of the photoelectrons.	B1	
			Total	**7**	
49	a		$^{238}_{92}U \rightarrow {}^{234}_{90}Th$ + ... $^{4}_{2}He$ or $^{4}_{2}\alpha$	**B1** **B1**	**allow** proton and / or nucleon number to the right of symbol **allow** γ-photon; zero for any other extra particle **Examiner's Comments** Most candidates made a good start to the paper writing a correct equation for the nuclear decay.
	b		mv = (4.00 − 0.0665) × 10^{-25} × 2.40 × 10^5 = 9.44 × 10^{-20} v = 9.44 × 10^{-20}/ 6.65 × 10^{-27} = 1.42 × 10^7 k.e. = ½ × 6.65 × 10^{-27} × (1.42 × 10^7)^2 = 6.70 × 10^{-13} (J) 6.70 × 10^{-13} / 1.60 × 10^{-13} = 4.19 (MeV)	**C1** **C1** **A1** **B1**	**allow** 0.07 × 10^{-25} for α-particle mass **max** 3 if use 4.00 instead of 3.93 in momentum eq'n **allow** ratio of masses 234 and 4 **or** calculations using 234u and 4u **allow** p^2/2m calculation for k.e. **accept** 4.0 to 4.2; **ecf** (calculated value of k.e. in J)/e **N.B.** the correct answer automatically gains all 4 marks **Examiner's Comments** One mark in this question was reserved for converting units from joule into mega electronvolt. This was the only mark awarded to half of the candidates. Few recognised this to be an isolated system, applying the conservation of momentum to solve the problem. Few appeared to realise that the mass of an alpha particle is given in the Data, Formulae, and Relationships Booklet, calculating it instead by summing the masses of neutrons and protons. The most common incorrect approach was to use the formula $E = mc^2$ or to equate the kinetic energies of the thorium nucleus and alpha particle.
	c		ΔA = 32 = $4n_\alpha$ so n_α = 8 ΔZ = 10 = $2n_\alpha - n_\beta$ so n_β = 6 argument / reasoning given for both n_α and n_β	**B1** **B1** **B1**	**allow** 8 (decays), i.e no mention of α particles **allow** 10 − 16 = −6; **NOT** 14 − 8 = 6; **must state** β(−) particles e.g. change in mass number caused by α decay,change in proton number combination of α and β **Examiner's Comments**

					A significant number had no idea where to start and left the page blank. Of the rest most managed to decide on 8 alpha particles. A minority worked initially with the proton number rather than the nucleon number incorrectly choosing 5. The explanations about the choice of 6 beta particles were often just restricted to equating the numbers correctly rather than giving any description of the transformation of neutrons into protons.
			Total	**9**	
50	a		Any four from: • electrons may be diffracted by graphite/carbon/atoms/crystal lattice • to produce rings / circular interference fringes • diffraction of electrons occurs when the wavelength is comparable / similar to the gap size • changes in the electron's speed/energy change the size of the ring / interference fringe spacing • electrons have a (de Broglie) wavelength given by $\lambda=h/p$ • reason for the rings as opposed to linear pattern, e.g. graphite atoms are irregularly arranged.	B1 x 4	**Examiner's Comments** The final question gave candidates the opportunity to describe the electron diffraction experiment. Answers were often vague, lacking necessary detail. Most candidates were able to describe electrons being diffracted by a graphite crystal lattice. Additional marks could have been gained by discussing the observations, the idea that electrons have a de Broglie wavelength and how the wavelength may be changed and the effect on the observations of a change in wavelength. Some candidates described why a circular pattern may be produced.
	b	i	Threshold frequency is the minimum frequency (of the incident EM waves/photon) to detach / emit / remove / release an electron (from the surface of the silver)	B1	**Allow** electrons **Allow** photoelectron / photoelectrons **Examiner's Comments** The majority of the candidates gained a mark for this question. When the mark was not scored, it was often due to candidates not realising it was the "minimum" frequency or answering the question in terms of energy.
		ii	$1.1(0) \times 10^{15}$ (Hz)	B1	**Examiner's Comments** Most candidates were able to read the threshold frequency from the graph. Where errors were made it was for either mis-reading the scale as 1.2 or omitting the 10^{15} Hz. **AfL** When reading data from a graph, read the scale and the units from each axis.

		ii i	$6.63 \times 10^{-34} \times 1.1 \times 10^{15}$ or 7.293×10^{-19} 4.6 (eV)	C1 A1	**Allow** substitution of point from graph into Einstein's equation **Allow** use of gradient as the Planck constant **Note** 4.558... eV **<u>Examiner's Comments</u>** The majority of the candidates scored two marks on this question. Again, clear working assists candidates with appropriate units being included in intermediate stages of the calculation. Most candidates calculated the work function from the threshold frequency, their answer to the previous part. Some candidates correctly took a data point from the graph and substituted it into Einstein's photoelectric equation which also gained credit. **Exemplar 8**  The candidate states the condition for the threshold frequency, indicates clearly the calculation of the work function in joule, before clearly demonstrating the conversion to electron volt so gained both marks.
			Total	**8**	
5 1		i	$E = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{490 \times 10^{-9}}$ energy = 4.1×10^{-19} (J)	C1 A1	**Note** answer to 3 SF is 4.06×10^{-19}
		ii	(number of photons =) $\frac{0.230}{4.06 \times 10^{-19}}$ number of photons = 5.7×10^{17}	C1 A1	Possible ECF from **(b)(i)** **Note** answer is 5.6×10^{17} when 4.1×10^{-19} is used
			Total	**4**	
5 2			One photon interacts with one electron energy of photon = (maximum) KE (of electron) + work function (of the metal)	B1 B1	**Ignore** references to frequencies and threshold frequency **Allow** photoelectron instead of electron throughout **Note** an equation is required **Allow** $hf = KE_{(max)} + \varphi$, with *$hf$ = energy of photon, $KE_{(max)}$ = (maximum) KE (of electron) and φ = work function ***Not** hf = Planck constant × frequency (since there is no reference to 'energy of photon') **Allow** energy of photon**<u>s</u>** = ...as BOD **Allow** φ instead of work function for this mark

			Work function is the **minimum energy** (required) to remove **electron** (from the surface of a metal) Electron removed / photoelectric effect when energy of photon is greater than / equal to work function (of the metal)	B1 B1	**Allow** 'work done' instead of 'energy' **Allow** ...electron**s** ....as BOD **Allow** electron removed / photoelectric effect when $hf > \varphi$ or electron removed / photoelectric effect when $hf = \varphi$ or electron not removed / no photoelectric effect when $hf < \varphi$ **Allow** electrons and photons as BOD **Examiner's Comments** This question on the photoelectric effect provided excellent discrimination with most candidates demonstrating good knowledge of the photoelectric effect. The work function was well defined and the key idea of the one-to-one interaction between a photon and an electron was communicated well. Some candidates took work function and threshold frequency to be synonymous, and the Einstein's photoelectric equation was quoted without much interpretation. Candidates are once again reminded that in descriptions it is important to define any terms used. Rather than just writing $hf = \varphi + KEmax$ (which appears on the Data, Formulae and Relationship booklet), it would have would have been better to write energy of photon = work function of the metal + maximum kinetic energy of the electron as an alternative to annotating the formula with "where h is , f is , φ is, $KEmax$ is " Overall, the terms highlighted in the question helped candidates to provide focused responses. Many candidates continue to show knowledge of the quantum physics.
			Total	**4**	
5 3		i	2.76 − 2.3 = 0.46 eV (so only 0.5% of energy/AW)	B1	**allow** 2.8 − 2.3 = 0.5 eV and 3.0 − 2.3 = 0.7 eV possible **ecf** from **(b)**
		ii	n = 2000 × 4^9 (= 5.24 × 10^8) Q = ne = 8.4 × 10^{-11} (C) I = 8.4 × 10^{-11} / 2.5 × 10^{-9} average current = 0.034 (A)	C1 C1 A1	**allow ecf** for wrong n **allow** 34 m(A); answer is 1.7 × 10^{-5} A if 2000 omitted (2/3) **Examiner's Comments** Almost all of the candidates attempted this last section of the paper with some success. In part (i) most candidates showed that they understood the theory behind the question and subtracted the appropriate two numbers from part (b) to gain the mark. Part (ii) was done well with a significant number obtaining the correct answer. Another large group forgot that 2000 electrons were released and performed the calculation for only a single electron being multiplied up and so forfeited the final mark.
			Total	**4**	
5 4	a	i	At point P: path difference between slits and screen is a whole / integer number of wavelengths (for constructive	**B1**	**Allow** nλ or λ **Not** phase difference

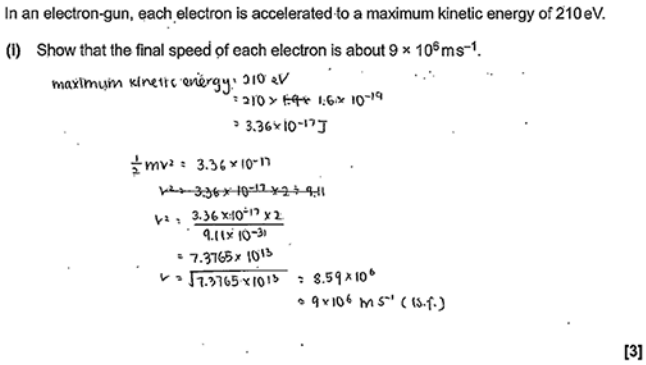
			interference) At point Q: path difference between slits and screen is an <u>odd number of half wavelengths</u> (for destructive interference)	B1	**Allow** $(n + \frac{1}{2})\lambda$ **Not** $\lambda/2$ **Examiner's Comments** It was expected that candidates would describe the path difference in terms of the wavelength. Candidates often realised that the bright line would have a path difference of an integer number of wavelengths, this was often written as nλ. To explain the dark line many candidates struggled with the appropriate relationship in terms of λ or did not state an odd number of half wavelengths.
		ii	**1** x = 4.22 mm $\lambda = \frac{4.22 \times 10^{-3} \times 0.56 \times 10^{-3}}{4.50}$ 5.25 × 10^{-7} m **2** $\frac{0.02}{4.5}$ or $\frac{0.02}{0.56}$ or $\frac{0.2}{42.2}$ $\left(\frac{0.02}{4.5} + \frac{0.02}{0.56} + \frac{0.2}{42.2}\right) \times 100 = 4.48\ \%$ Alternative max / min method: $\lambda_{max} = \frac{4.24 \times 10^{-3} \times 0.58 \times 10^{-3}}{4.48} = 5.49 \times$ and/or $\lambda_{min} = \frac{4.20 \times 10^{-3} \times 0.54 \times 10^{-3}}{4.52} = 5.02 \times 1$ $\frac{\Delta\lambda}{\lambda} \times 100 = 4.4\%\ or\ 4.6\%$	C1 C1 A1 C1 A1 B1 B1	**Note x** = 42.2 mm or 4.2 × 10^{-2} m scores zero **Note x** = 3.84, 4.77 × 10^{-7} m may score max 2 **Allow** 4% or 5% with evidence of working **Ignore** significant figures **Examiner's Comments** Although candidates correctly identified the correct equation, a large number of candidates did not determine the fringe spacing correctly. Some candidates used 42.2 cm, others divided 42.2 cm by 11, 15 or 20. Furthermore, some candidates did not convert the slit separation from millimetres to metres. Candidates were able to identify the equation from the Data, Formulae and Relationships Booklet. Most candidates were able to determine at least one percentage uncertainty for the individual quantities correctly. Mistakes were made either on determining the other quantities or adding the percentage uncertainties. Some candidates attempted a maximum / minimum method – the common error with this method was not dividing maximum by minimum or minimum by maximum.
	b	i	$\frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{5.25 \text{ x } 10^{-7}} = \frac{1.989 \times 10^{-25}}{\mathbf{5\ b\ ii\ 1}} = 3.79$ $n = \frac{50 \times 10^{-3}}{3.79 \times 10^{-19}} = 2.5 \times 10^{23} \times \mathbf{5\ b\ ii\ 1} = 1.3 \times$	C1 A1	**Allow** ecf from **bii** **Examiner's Comments** Candidates found this question difficult. Many could not determine the energy of a photon correctly – an error carried forward was allowed from **5(b)(ii)1.** The question also required candidates to realise that 50.0 mW is equivalent to 50.0 mJ s^{-1}. A common error was to divide the power by the charge on an electron.
		ii	2.6 eV = 2.6 × 1.6 × 10^{-19}= 4.16 × 10^{-19} J ORA	M1	**Allow** photon has 2.37 eV of energy

			Energy of photon is less than work function so photoelectrons will not be emitted	A1	**Allow** conclusion based **5 c i** **Examiner's Comments** To explain whether photoelectrons will be emitted, candidates needed to convert the work function measured in electron volt to joule. A clear conclusion was needed.
			Total	**11**	
5 5		i	Kinetic energy (of proton) changes to potential (energy) **or** Potential energy increases as the kinetic energy (of the proton) decreases **or** Potential energy increases as work is done against the field / against repulsion / positive charge	B1	**Allow** 'it' / PE for (electric) potential energy **Allow** KE / E_k
		ii	energy = 0.52 × 10^6 × 1.60 × 10^{-19} **or** 8.3(2) × 10^{-14} (J) $\frac{1.60 \times 10^{-19} \times 27 \times 1.60 \times 10^{-19}}{4\pi\varepsilon_0 R} = 8.32 \times 10^{-1}$ R = 7.5 × 10^{-14} (m)	C1 C1 A1	**Allow** 2 mark for 1.6 × 10^{-13} (m); Z = 59 used **Allow** 2 mark for 8.9 × 10^{-14} (m); Z = 32 used **Allow** 1 mark for 2.8 × 10^{-15} (m); Z = 1 used **Allow** 1 mark for 1.2 × 10^{-32} (m); energy = 5.2 × 10^5 used **Examiner's Comments** The above question on electric potential energy provided excellent discrimination with middle and upper quartile candidates showing how to produce immaculate answers – identify the physics, write down the correct physical equation, do any necessary conversions (e.g. MeV to J), rearrange the equation, substitute correctly and then write the final answer in standard form to the correct number of significant figures. About a third of the candidates scored full marks. ? Some of the missed opportunities or errors were: • Using an incorrect equation with the distance squared • Not correctly converting the kinetic energy 0.52 MeV into joule (J) • Using the equation $r = r_0A^{1/3}$ for the mean radius of a nucleus to determine the minimum distance

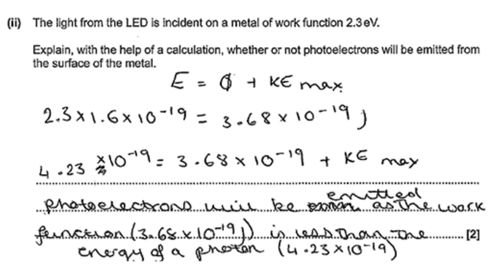
			Total	**4**	
56			Any **<u>one</u>** from: Energy of visible light photon < work function (of zinc) (frequency of) visible (light/photon) < threshold frequency Any **<u>one</u>** from: Energy of UV photon > work function (of zinc) (frequency of) UV (radiation/photon) > threshold frequency Any **<u>two</u>** from: • Collapse of leaf linked to removal of electrons • One-to-one interaction of photon and (surface) electron • Photon energy is independent of intensity / Intensity linked to rate of photons (incident on the zinc plate)	**B1** **B1** **B1 × 2**	**Allow** f for frequency, λ for wavelength and ϕ for work function throughout **Allow** 'overcome' / 'met' / 'reached' when describing > or < **Allow** photon**<u>s</u>** **Not** f_0 for threshold frequency **Allow** equivalent statement with wavelength **Allow** = instead of > or < throughout for UV **Allow** equivalent statement with wavelength **Ignore** stem / plate / leaf / electroscope becoming positive **<u>Examiner's Comments</u>** This question on the photoelectric effect was enthusiastically answered by candidates. Good discrimination enabled many of the top-end candidates to score full marks. The question was scrutinised well with many candidates explaining why the leaf fell with the ultraviolet radiation. The one-to-one interaction between UV photons and surface electrons was nicely embedded in the descriptions. Some of the candidates would have benefitted by writing their answers in bullet points. There were a few missed opportunities and misconceptions, these are outlined below: • Photons were emitted from the zinc plate (rather than electrons) • Threshold frequency and work function were properties of the photons or electrons (and not zinc) • Threshold frequency and work function were synonymous • Intensity was linked to number of photons (rather than to the **rate** of photons) • Referring to '*not enough energy*' instead of work function of the metal in the description
			Total	**4**	

5 7			5.0 eV = 8.0 × 10^{-19} (J) and 2.0 eV = 3.2 × 10^{-19} (J)	B1	**Allow** correct answers in terms of threshold frequency / wavelength for the metals and the frequency / wavelength of the photon
			photon energy = $\frac{6.63\times10^{-34}\times3.0\times10^{8}}{300\times10^{-9}} = 6.6(3)\times10^{-19}$ (J)	B1	**Allow** first two B1 marks for photon energy quoted as 6.6 × 10^{-19} J and 4.1 eV
			energy of photon > work function of **X** Or energy of photon < work function of **Y**	B1	
			Hence electrons emitted from **X** with speed / KE from zero to a maximum value and no electrons are emitted from **Y**	B1	
			Total	**4**	
5 8		i	total nucleon number after fusion = 3 + 3 − 4 = 2	M1	**Allow** other correct methods
		i	total proton number after fusion = 1 +1 − 2 = 0	M1	
		i	(Hence it must be 2 neutrons ${}^{1}_{0}n$ after the fusion reaction)	A0	
		ii	(BE of neutron(s) = 0 and BE of ${}^{4}_{2}He$ = 28.4 MeV) BE of ${}^{3}_{1}H$ nucleus = ½ × (28.4 − 11) = 8.7 (MeV)	C1	
		ii	BE per nucleon = 8.7/3 = 2.9 (MeV) BE per nucleon = 2.9 × 10^{6} × 1.60 × 10^{-19}	C1	
		ii	BE per nucleon = 4.6 × 10^{-13} (J)	A1	
			Total	**5**	
5 9		i	<u>electron</u> bound to nucleus / represents energy <u>electron</u> must gain to leave the atom / total energy of <u>electron</u> in atom is less than that of a free electron	**B1**	**Allow** ionisation level defined as zero as AW for 'represents electron must gain energy to leave atom / move up energy level' **Allow** potentials for attractive forces are negative. **Examiner's Comments** This item provided good discrimination between the candidates. Many responses referred incompletely to the negative charge of the electron being the only factor, whereas the correct explanation is much more to do with the electron requiring energy to leave the atom and the ionization level being defined as the zero point. Some candidates were on the right path when they referred to the equivalent statement for gravitational potential energies.
		ii	**1** energy = 2.55 (eV) **2** energy = 2.55 × 1.60 × 10^{-19} (J) $\lambda = \frac{6.63\times10^{-34}\times3.0\times10^{8}}{2.55\times1.60\times10^{-19}}$ (Allow any subject) wavelength = 4.9 × 10^{-7} (m) wavelength = 490 (nm)	**B1** **C1** **C1**	Ignore sign Possible ECF from **(ii)1**

				A1	**Note:** wavelength = 488 (nm) to 3 sf **Examiner's Comments** Virtually all candidates correctly evaluated the energy difference to be 2.55 eV. Negative values were condoned but are unlikely to be accepted in future series. Many candidates correctly calculated the wavelength of emitted light, although a minority did not convert the energy into joules or performed the required conversion to nanometres incorrectly.
			Total	**5**	
60		i	Fission reactors produce radioactive by-products which affect future generations and the environment in terms of possible contamination / exposure to humans and animals.	B1	
		ii	No of particles in 1000 g U = 1000/235 × 6.02 × 10^{23} = 2.56 × 10^{24} No of reactions for U = 2.56 × 10^{24}	B1	Appreciate that the key to the answer is the difference in numbers of atoms / nuclei **or** equal number of nucleons involved scores one mark if nothing else achieved.
		ii	Energy from U = 2.56 × 10^{24} × 200 = 5.12 × 10^{26} MeV	B1	
		ii	No of particles in 1000g H = 6.02 × 10^{26} No of reactions = 6.02 × 10^{26}/4 Energy from H = 6.02 × 10^{26}/4 × 28 = 42.14 × 10^{26} MeV	B1	
		ii	Hence energy 42/5 = 8.2 times higher	B1	
		ii	*second method* 235 g of U and 4 g of H / He contain 1 mole of atoms	or B1	
		ii	there are 4.26 moles of U and 250 moles of He	B1	
		ii	so at least 58 times as many energy releases in fusion ratio of energies is only 7 fold in favour of U	B1	
		ii	therefore 58/7 times as much energy released by 1 kg of H	B1	
		ii	*similar alternative argument,* e.g. For U each nucleon 'provides' 0.85 MeV	B1	
		ii	For H each nucleon 'provides' 7 MeV	B1	
		ii	(Approx) same number of nucleons per kg of U or H	B1	
		ii	so 8.2 times as much energy from H	B1	
			Total	**5**	
61		i	(KE =) 210 × 1.60 × 10^{-19} (J) **or** 3.36 × 10^{-17} (J)	C1	**Note** using KE = 210 (J) is wrong physics XP

			$\frac{1}{2} \times 9.11 \times 10^{-31} \times v^2 = 3.36 \times 10^{-17}$ $v = 8.6 \times 10^6$ (ms^{-1})	C1 A1	**Note** the answer must be to more than 1 SF **<u>Examiner's Comments</u>** This was not a straight forward question but most candidates demonstrated excellent knowledge and application of physics here. The conversion of 210 eV was often done correctly. The K.E. equation was used successfully to show the final speed of the electrons to be about 8.6×10^6 m s^{-1}. The exemplar 11 below shows a model response from a top-end candidate. **Exemplar 11**  In an electron-gun, each electron is accelerated to a maximum kinetic energy of 210 eV. (i) Show that the final speed of each electron is about 9×10^6 ms^{-1}. maximum kinetic energy: 210 eV $= 210 \times \cancel{1.9} 1.6 \times 10^{-19}$ $= 3.36 \times 10^{-17}$ J $\frac{1}{2}mv^2 = 3.36 \times 10^{-17}$ $\cancel{v^2 = 3.36 \times 10^{-17} \times 2 \div 9.11}$ $v^2 = \frac{3.36 \times 10^{-17} \times 2}{9.11 \times 10^{-31}}$ $= 7.3765 \times 10^{13}$ $v = \sqrt{7.3765 \times 10^{13}} = 8.59 \times 10^6$ $\approx 9 \times 10^6$ ms^{-1} (1s.f.) [3] This exemplar shows a typical response produced by most of the candidates. The conversion from eV to J is very clear. The correct mass of the electron has been used to get the response of 8.6×10^6 ms^{-1}. It is good to report that very few candidates used 210 J to get the impossible response of 2.1×10^{16} ms^{-1}.
		ii	$\lambda = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 8.6 \times 10^6}$ $\lambda = 8.5 \times 10^{-11}$ (m)	C1 A1	Possible ECF from **(i)** **Allow** 2 marks for 8.1×10^{-11} (m); $v = 9 \times 10^6$ ms^{-1} used **<u>Examiner's Comments</u>** The majority of the candidates effortlessly used the de Broglie equation and their answer from **(b)(i)**, or 9×10^6 m s^{-1}, to calculate the wavelength λ of the electron. **Misconception** The two common mistakes being made here were: • Using 3.0×10^8 m s^{-1} for the speed instead of 8.6×10^6 m s^{-1}. • Using the energy of the photon equation $E = \frac{hc}{\lambda}$ instead of $\lambda = \frac{h}{mv}$.

			Total	**5**	
6 2		i	(surface area =) 4π × (1.4 × $10^9)^2$ **or** 2.46 × 10^{19} (m^2) (intensity = $\frac{P}{4\pi r^2}$) intensity = $\frac{2.7\times10^{27}}{4\pi\times(1.4\times10^9)^2}$ intensity = 1.1 × 10^8 (W m^{-2})	**C1** **C1** **A0**	**Allow** 2.5 × 10^{19} (m^2) **Note**: Using π × (1.4 × $10^9)^2$ is wrong physics; hence no marks in this show question **<u>Examiner's Comments</u>** This was a demanding question designed for middle and top-end candidates. The radiant intensity is equal to the power transmitted per unit cross–sectional area. The area being that of a sphere of radius 1.4 × 10^9 m. The equation 4πR^2 was appropriate here. The common errors, mainly from the low–scoring candidates, were using πR^2 and $\frac{4}{3}\pi R^3$. All the key steps in the calculations had to be structured well for
		ii	$E = \frac{3.00\times10^8\times6.63\times10^{-34}}{5.0\times10^{-7}}$ E = 4.0 × 10^{-19} (J)	**C1** **A1**	**Note**: Answer to 3 SF is 3.98 × 10^{-19} (J) **Allow** 4 × 10^{-19} (J) without any SF penalty **<u>Examiner's Comments</u>** Most candidates were familiar with the equation for the energy of the photon. Answers were generally well–structured and calculations were undertaken without much error in either rearranging the equation or powers of ten. The answer to two significant figures was 4.0 × 10^{-19} J, as in the general rule with such answers, 4 × 10^{-19} J was acceptable without any significant figure penalty.
		iii	(number per second = $\frac{2.7\times10^{27}}{4.0\times10^{-19}}$) number per second = 6.8 × 10^{45} (s^{-1})	**B1**	Possible ECF from **(b)(ii)** **<u>Examiner's Comments</u>** This was a successful end for the top–end candidates, who correctly divided the total output power of Procyon of 2.7 × 10^{27} W by the energy of each photon from **(b)(ii)**. The two common errors were dividing the intensity by the photon energy and changing the photon energy from joule (J) to electron–volt (eV).
			Total	**5**	
6 3		i	(P =) 0.01 × 2.5 **or** 0.01^2 × 250 **or** 2.5^2/250 **or** 0.025 (W) (E_{photon} =) $\frac{6.63\times10^{-34}\times3.0\times10^8}{4.7\times10^{-7}}$ **or** 4.23 × 10^{-19} (J) (number per second = $\frac{0.025}{4.23\times10^{-19}}$)	C1 C1	 **Allow** 4.0 × 10^{-19} (J); which is 2.5 eV

			number per second = 5.9 × 10^{16} (s^{-1})	A1	**Note** using 4.0 × 10^{-19} (J) gives 6.25 × 10^{16} (s^{-1}) **Examiner's Comments** This question required knowledge of both power and energy of photons. It discriminated well with many of the top end candidates getting the correct of 5.9 × 10^{16} s^{-1}. A significant number of candidates scored 1 mark for the energy of the photons. Using the power of 0.025 W in the final step of the calculation proved to be the main obstacle in this calculation. Alternative answers using the energy of a photon as 2.5 eV were allowed. This gave the rate of photons emission to be 4.0 × 10^{16} s^{-1}. **Misconception** The most common mistake was to calculate the energy of the photon in joule, but to write the frequency 6.4 × 10^{14} on the answer line. This wayward answer can perhaps be explained by frequency and the rate of photon emissions having the same units – s^{-1}.
		ii	(E_{photon} =) 2.64 (eV) **or** (φ =) 3.68 × 10^{-19} (J) **or** (f_0 =) 5.55 × 10^{14} (Hz) **or** ($\lambda 0$ =) 5.40 × 10^{-7} (m) Photoelectrons are emitted and 2.6(4) > 2.3 **or** 4.23 × 10^{-19} > 3.68 × 10^{-19} **or** 6.38 × 10^{14} (Hz) > 5.55 × 10^{14} (Hz) **or** 4.7 × 10^{-7} (m) < 5.40 × 10^{-7} (m)	M1 A1	Possible ECF from **(i)** **Allow** 2.6 (eV) **or** 3.7 × 10^{-19} (J) **Allow** 2.5 (eV) as the energy of the photon **Note** the conclusion must be consistent with **(i)** **Allow** $hf > \varphi$ **Note** this can be implied by calculating the KE of the emitted electron **Examiner's Comments** Most candidates showed excellent knowledge and understanding of electronvolts and the photoelectric equation. A variety of answers were accepted. The most common approach was to calculate the energy of the photon in eV, and then either show that this was greater than the work function of the metal or to calculate the kinetic energy of the emitted photoelectron. A lot of confidence in the topic of quantum physics was evident in the answers from the candidates. This is illustrated by exemplar 8 below from a middle-grade candidate. **Exemplar 8**  (ii) The light from the LED is incident on a metal of work function 2.3 eV. Explain, with the help of a calculation, whether or not photoelectrons will be emitted from the surface of the metal. $E = \phi + KE_{max}$ $2.3 \times 1.6 \times 10^{-19} = 3.68 \times 10^{-19}$ J $4.23 \times 10^{-19} = 3.68 \times 10^{-19} + KE_{max}$ Photoelectrons will be ~~seen~~ emitted as the work function (3.68×10⁻¹⁹) is less than the energy of a photon (4.23×10⁻¹⁹) [2] This exemplar shows the right blend of calculations and scientific

					text to support the response. Good command of quantum physics earned this candidate full marks. OCR support Being aware of the contents of the data, formulae and relationship booklet and its layout will support candidates, alleviating the need to recall numerical values of constants and allowing retrieval of correct formulae, or giving assurance that the student has recalled correctly.
			Total	**5**	
6 4		i	The direction of the electric field due to the negative charge is to the left and right for the positive charge.	B1	
		i	The magnitude of the electric field strength due to the positive charge is smaller than that for the negative charge (because of greater distance). (Hence the resultant electric field strength is to the left.)	B1	
		ii	energy = $\frac{Qq}{4\pi\varepsilon_0 r} = \frac{(1.60\times10^{-19})^2}{4\pi\varepsilon_0\times3.0\times10^{-10}}$	C1	
		ii	energy = $7.67(2) \times 10^{-19}$ (J)	C1	
		ii	energy = 4.8 (eV)	A1	
			Total	**5**	
6 5		i	4.1 eV = 6.56×10^{-19} (J) $\frac{6.63\times10^{-34}\times3.00\times10^{8}}{98\times10^{-9}}$ *or* 2.03×10^{-18} 1.4×10^{-18} (J)	C1 C1 A1	**Allow** 1.96×10^{-18} for use of 6.4×10^{-34} (J s) **Allow** 1.3×10^{-18} (J) for use of 6.4×10^{-34} (J s)
		ii	KE is independent of intensity (for constant wavelength) / intensity only affects the number of photons No change in KE_{max}	M1 A1	**Allow** decreasing intensity, decreases the number of photons / energy of a photon only depends on frequency or wavelength
			Total	**5**	
6 6		i	$\varepsilon = eV = 12 \times 1.6 \times 10^{-19} = 1.92 \times 10^{-18}$ (J)	B1	
		i	$½mv^2 = 1.92 \times 10^{-18}$	C1	**Allow** ecf for energy value
		i	$v^2 = 2 \times 1.92 \times 10^{-18} / 9.1 \times 10^{-31} = 4.22 \times 10^{12}$	C1	

		i	$v = 2.05 \times 10^6$ (m s^{-1})	A1	
		ii	accelerates from 0 to v so use v / 2	C1	**ecf (i)**
		ii	$t = 5 \times 10^{-3}/1 \times 10^6 = 5 \times 10^{-9}$ (s)	A1	**Allow** 1 mark for 2.5×10^{-9}s
			Total	**6**	
67		i	$hf = \phi + KE_{(max)}$ and kinetic energy = 0 (at f_0) (therefore $\phi = hf_0$)	**B1**	**Examiner's Comments** About a third of the candidates showed how Einstein's photoelectric equation led to the expression $\phi = hf_0$. The key in securing a mark was stating that the kinetic energy of the electrons is zero at the threshold frequency. Some candidates lost the mark for careless work such as writing $hf_0 = \phi + KE_{max}$.
		ii	Data point (to with ½ small square) and a reasonable straight (best-fit) line drawn with a straight edge / ruler	**B1**	**Not** freehand / wobbly line **Examiner's Comments** Most candidates picked up the mark for plotting the data point and drawing a best fit line. Examiners were a lenient with the marking of the line of best fit. Candidates must use rulers and ensure an equal spread of data plots about their best fit lines.
		iii	Correct conversion from eV to J using 1.6×10^{-19} (gradient = *h*) gradient determined **and** $h = (6.4 \text{ to } 7.4) \times 10^{-34}$ (J s)	**B1** **B1**	**Note** this can be a single value of ϕ or $\Delta\phi$ **Allow** value of h must be given to 2 or 3 SF **Examiner's Comments** The determination of Planck constant h from the gradient of the best fit line was impeccably undertaken by the top-end candidates. A large triangle was used to determine the gradient of the best fit line. More than half of the candidates correctly converted the eV to J. The most common errors here were: • Using **1.0** × 10^{-19}, rather than **1.6** × 10^{-19} to convert eV to J. • Calculating the gradient using eV values. • Omitting the 10^{14} factor for the frequency.
		iv	Draw a worst-fit line (and determine gradient / *h*) (AW) % uncertainty = (*h* from **biii** - *h* from worst line) × 100 ÷ *h* from **biii** **or** Calculate the average *h* using f_0 and ϕ (values)	**B1** **B1** **B1**	**Allow** (line of) maximum / minimum gradient **Ignore** sign **Allow** gradient instead of h

			% uncertainty = (½ range ÷ average h) × 100	**B1**	**Examiner's Comments** About one in ten candidates omitted this question. Many candidates realised that a worst-fit line had to be draw, with or without error bars, and then its gradient used to determine the percentage uncertainty in the experimental value for h. A significant number of candidates gave answers in terms of percentage **difference** between their experimental value and the accepted value for Planck constant.
			Total	**6**	
68		i	$E = hc/\lambda$; $\Delta\varepsilon = E1 - E_2 = hc\Delta\lambda/\lambda^2$	C1	**allow** calculation of $E = hc/\lambda$ twice and difference taken
		i	$\Delta\varepsilon = 6.63 \times 10^{-34} \times 3 \times 10^8 \times 0.6 \times 10^{-9}/ 5.9^2 \times 10^{-14}$	C1	
		i	$\Delta\varepsilon = 3.4 \times 10^{-22}$ (J)	A1	
		ii	$\sin\theta = n\lambda/d$; $1/d = 3 \times 10^5$ (m^{-1})	C1	
		ii	$\theta_1 - \theta_2 = \sin^{-1}(2 \times 589.6 \times 3 \times 10^{-4}) - \sin^{-1}(2 \times 589 \times 3 \times 10^{-4})$	M1	**or** similar
		ii	$\theta_1 - \theta_2 = 20.717 - 20.695 = 0.022^0$	A1	**allow** 20.72 − 20.70
			Total	**6**	
69		i	4.1 eV = = $4.1 \times 1.6 \times 10^{-19}$ or 6.56×10^{-19} J OR $E_k = 6.63 \times 10^{-34} \times 1.2 \times 10^{15} - \phi$ $E_k = 6.63 \times 10^{-34} \times 1.2 \times 1015 - 6.56 \times 10^{-19}$ $E_k = 1.39 \times 10^{-19}$ J $v = \sqrt{\frac{2 \times 1.39 \times 10^{-19}}{9.11 \times 10^{-31}}} = \sqrt{3.06 \times 10^{11}}$ 5.536×10^5 m s^{-1}	**C1** **C1** **C1** **C1** **A0**	**Allow** $f_0 = 9.9 \times 10^{14}$ Hz **Allow** $E_k = 6.63 \times 10^{-34} \times (1.2 \times 10^{15} - 9.9 \times 10^{14})$ **Allow** 1.4×10^{-19} J 3.06×10^{11} scores three marks **Examiner's Comments** Good candidates clearly showed the individual steps in this calculation, e.g. the conversion of electron-volt to joule for the work function, the energy of the photon calculated. It was important that candidates demonstrated that they had substituted the mass of the electron from the data booklet and correctly evaluated the square root term. Examiners expected to see 5.536×10^5 (m s^{-1}) for full credit so that it was clear that candidates had correctly calculated the powers of ten.

					Exemplar 9 is 5.5 × 10⁵ ms⁻¹. $hf = 6.63\times10^{-34} \times 1.2\times10^{15} = 7.956\times10^{-19}$ cm J $4.1\text{ eV} = 6.56\times10^{-19}\text{ J}$ $hf - \phi = KE_{max} = 7.95\times10^{-19} - 6.56\times10^{-19} = 1.39\times$ $\frac{1}{2}mv^2 = 1.39\times10^{-19} = KE$ $\sqrt{\frac{2KE}{m}} = v = \sqrt{\frac{2\times1.39\times10^{-19}}{9.1\times10^{-31}}} = 5.527...\times10^5$ $\approx 5.5\times10^5$ (2sf) In line 3 of the candidate's working, there is a rearrangement of the equation given at the beginning of the question. There is then clear substitution of the energy of a photon which was calculated in line 1 and the work function which had been converted from electron volt to joule in line 2 to give a value for the maximum kinetic energy of the electrons. This scores three marks. In the final part the candidate correctly shows the rearrangement of the kinetic energy equation to give v as the subject and then correctly substitutes in the values including the mass of the electron from the data and formulae sheet. The final answer is given as 5.527 × 10*5* which is then shown to be approximately equal to 5.5 × 10*5* (ms⁻¹). This last part is essential in these show type questions.
		ii	Maximum energy is independent of intensity/(number of photons has increased but) energy of photon is the same/energy of a photon is <u>only</u> dependent on frequency/intensity affects the number of photons/electrons released <u>only</u>/frequency of photon has not changed No change in maximum speed	**M1** **A1**	**Not** "Does not increase" **<u>Examiner's Comments</u>** For this type of question, a clear explanation is needed before the mark for stating the change, if any. Candidates' descriptions were often vague, and few stated that the maximum energy was independent of intensity.
			Total	**6**	
70		i	Electrons behave **or** travel as waves.	B1	

		i	The rings demonstrate that the electrons are diffracted by individual carbon atoms / spacing between carbon atoms.	B1	
		i	The (de Broglie) wavelength of the electrons is comparable to the 'size' of the carbon atoms or the spacing between carbon atoms.	B1	
		ii	$v^2 = \dfrac{1.6 \times 10^{-19} \times 1200}{0.5 \times 9.11 \times 10^{-31}}$ or $v = 2.053.. \times 10^7$ (m	C1	Correct use of ½ $mv^2 = eV$
		ii	$\lambda = \dfrac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 2.053 \times 10^7}$	C1	
		ii	wavelength = 3.5×10^{-11} (m)		
		iii	Results published to allow peer review Procedure shared with other scientists to allow replication	B1	
			Total	**6**	
7	1		***Level 3 (5–6 marks)** at least E3,4 and 2 or 5 at least P1,2 and 5 *There is a well-developed line of reasoning which is clear and logically structured. The information presented is relevant and substantiated.* **Level 2 (3–4 marks)** expect 3 points from E and 2 points from P or 2 points from E and 3 points from P *There is a line of reasoning presented with some structure. The information presented is in the most-part relevant and supported by some evidence.* **Level 1 (1–2 marks)** at least 2 points from E and 1 point from P or vice versa. *The information is basic and communicated in an unstructured way. The information is supported by limited evidence and the relationship to the evidence may not be clear.* **0 marks** No response or no response worthy of credit.	B1	**Experiment (E)** 1. Adjust the potential divider to low or zero voltage 2. connect flying lead to one LED 3. increase voltage until LED just lights or strikes 4. repeat several times and average to find V_{min} 5. repeat for each LED 6. shield LED inside opaque tube to judge strike more accurately. **Processing (P)** 1. a graph of V_{min} against $1/\lambda$ will be a straight line 2. through the origin 3. so need to calculate values of $1/\lambda$ 4. then draw line of best fit through origin 5. gradient G = V_{min} $\boldsymbol{\lambda}$ = hc/e 6. hence h = eG/c
			Total	**6**	

7 2			**Level 3 (5–6 marks)** Description and explanation of pattern changes **and** quantitatively explains link between de Broglie wavelength and potential difference. *There is a well-developed line of reasoning which is clear and logically structured. The information presented is relevant and substantiated.* **Level 2 (3–4 marks)** Clear description of how pattern changes and explanation of pattern changes and qualitatively explains link between de Broglie wavelength and potential difference **or** limited description of how pattern changes and quantitatively explains link between de Broglie wavelength and potential difference. *There is a line of reasoning presented with some structure.* *The information presented is in the most-part relevant and supported by some evidence.* **Level 1 (1–2 marks)** Limited description of how pattern changes and limited attempts to explain qualitatively the link between de Broglie wavelength and potential difference **or** qualitatively explains link between de Broglie wavelength and potential difference. *The information is basic and communicated in an unstructured way. The information is supported by limited evidence and the relationship to the evidence may not be clear.* **0 marks** No response or no response worthy of credit.	B1 ×6	***Indicative scientific points may include:*** ***Description of pattern changes*** • Rings become closer (not just smaller) • Rings become brighter ***Qualititative explanation of pattern changes in terms of de Broglie wavelength and potential difference*** • Electrons gain greater energy • Electrons have a greater speed • Electrons have a greater momentum • Implies smaller wavelength • Smaller wavelength means less diffraction • Shorter wavelength gives shorter path differences between areas of constructive and destructive interference ***Quantitative explanation of pattern changes in terms of de Broglie wavelength and potential difference*** • $eV = \frac{1}{2}mv^2$ • $p = m$v • v^2 α V or p^2 α V • $\lambda = \frac{h}{p}$ or λ α $\frac{1}{v}$ • $\lambda = \frac{h}{\sqrt{2meV}}$ or $\lambda \propto \frac{1}{\sqrt{V}}$ **<u>Examiner's Comments</u>** This question tested an understanding of electron diffraction. Many candidates gave a good qualitative explanation of how the pattern would change. High achieving candidates clearly demonstrated how the de Broglie wavelength λ was related to the potential difference V by equating the energy eV to kinetic energy, then using the definition of momentum and the de Broglie wavelength. Some candidates confused speed v with potential difference V. Many candidates gave a good qualitative explanation. Many candidates did not state that the rings would become brighter. **AfL** Candidates should be able to describe how to use light gates. In particular, candidates should be able to indicate the measurements that are needed to determine speed and acceleration. Candidates should state that the light gates should be connected to a timer or data-logger. **AfL**

					When analysing experimental data, candidates should be able to determine appropriate graphs to plot which will give a straight line (if the given relationship is true). Candidates should also be able to describe how unknown quantities may be determined using the gradient and / or y-intercept. **Misconception** There is some confusion between the equations to use for photoelectric effect and the equations to use when considering the de Broglie wavelength. For the de Broglie wavelength, a common misconception is to relate the energy to wavelength by the equation for the energy of a photon, $E = \frac{hc}{\lambda}$
			Total	**6**	
7 3			**Level 3 (5–6 marks)** Clear explanation of observations **and** clear evidence of particulate nature of electromagnetic waves *There is a well-developed line of reasoning which is clear and logically structured. The information presented is relevant and substantiated.* **Level 2 (3–4 marks)** Clear explanation of observations **or** clear evidence of particulate nature of electromagnetic waves **or** has limited explanation of observations and limited evidence of particulate nature of EM radiation *There is a line of reasoning presented with some structure. The information presented is in the most-part relevant and supported by some evidence.* **Level 1 (1–2 marks)** Has limited explanation of observations **or** limited evidence of particulate nature of EM radiation *The information is basic and communicated in an unstructured way. The information is supported by limited evidence and the relationship to the evidence may not be clear.* **0 marks** No response or no response worthy of credit.	B1	**Indicative scientific points may include:** **Explanation of Observations** • Discharge due to the emission of electrons / negative charge • Intensity depends on distance • <u>Rate</u> of incident photons is more at smaller distances • Greater intensity / rate of uv photons linked to quicker fall • uv causes instantaneous discharge • No effect with light • Intensity of light has no effect on the discharge • Natural discharge over a long period of time **Evidence of particulate nature of em** • Wave theory suggests leaf would fall with light • Photon as packet of energy • One to one interaction • uv <u>photon</u> greater energy than work function / greater frequency than threshold frequency • Light <u>photons</u> have less energy than the work function • $E = hf$ / photon energy depends on frequency • Energy of photon independent of intensity • Energy conserved in interaction • Einstein's equation (words or symbol) **Examiner's Comments** This was the second LoR question. It gave candidates the opportunity to discuss the photoelectric effect. Good answers were structured well and explained the observations with relevant theory. A surprising number of candidates did not appreciate that the white light did not release photoelectrons. Good answers

					clearly explained the differences between the white light and the ultra violet light, the effect of increasing the intensity was related to the rate at which photons were absorbed by the plate and gave appropriate equations.
			Total	**6**	
7 4			***Level 3 (5–6 marks)** Clear explanation and discussion *There is a well-developed line of reasoning which is clear and logically structured. The information presented is relevant and substantiated.* **Level 2 (3–4 marks)** Some explanation and some discussion *There is a line of reasoning presented with some structure. The information presented is in the most-part relevant and supported by some evidence.* **Level 1 (1–2 marks)** Limited explanation **or** limited discussion *The information is basic and communicated in an unstructured way. The information is supported by limited evidence and the relationship to the evidence may not be clear.* **0 marks** No response or no response worthy of credit.	B1 × 6	**Indicative scientific points may include:** **Explanation** • $hf = \Phi + KE_{max}$ (any subject) • A graph of KE_{max} against f is a straight line graph with gradient = h (and intercept = $-\Phi$) • Draw a straight best-fit line through points and determine the gradient using a 'large triangle' **Discussion of accuracy and precision** • % uncertainties are 4.8% for **A** and 9.1% for **B** • Data points widely spread out for **B**. (ORA) • For **B** the value of h is accurate because its closer to the real / actual value (but the results are not precise) • For **A** the value of h is precise because of the smaller % uncertainty (but the result is not accurate)
			Total	**6**	
7 5			**Level 3 (5–6 marks)** Clear description and clear calculations of energy per kg *There is a well-developed line of reasoning which is clear and logically structured. The information presented is relevant and substantiated.* **Level 2 (3–4 marks)** Clear description **OR** Clear calculations of energy per kg **OR** Some description **and** some calculations *There is a line of reasoning presented with some structure. The information presented is in the most-part relevant and supported by*	B1× 6	**Indicative scientific points may include:** **Description** • Energy is produced in both reactions • More energy produced (per reaction) in fission • The (total) binding energy of 'products' is greater • In fusion, nuclei repel (each other) • Fusion requires high temperatures / high KE • Fission reactions are triggered by (slow-)neutrons • Chain reaction possible in fission **Calculations** • 1 kg of uranium has 4.26 mols / 2.56×10^{24} nuclei • 1 kg of deuterium has 500 mol / 3.01×10^{26} nuclei / 1.50×10^{26} 'reactions'

			some evidence. **Level 1 (1–2 marks)** Limited description **OR** Limited calculations *There is an attempt at a logical structure with a line of reasoning. The information is in the most part relevant.* **0 marks** No response or no response worthy of credit		• 200 MeV = 3.2×10^{-11} J • 4 MeV = 6.4×10^{-13} J • Uranium: ~ 10^{14} (J kg^{-1}) (actual value 8.2×10^{13}) • Deuterium: ~ 10^{14} (J kg^{-1}) (actual value 9.6×10^{13}) • The energy per kg is roughly the same **Examiner's Comments** This is the second LoR question. This is designed to assess knowledge of the two nuclear energy reactions and to calculate energy release using some given data. The differences between the fission and fusion reactions were generally well answered although many candidates explained differences in design, operation and waste more than the reactions. The similarities were often not as clear however several candidates gave excellent responses in terms of binding energies and mass differences. Candidates were also expected to complete a calculation to show which produces more energy output per kilogram. This is challenging calculation to follow through fully, but most candidates were able to make some attempt, even if it was only converting MeV to J. Only better candidates realised 2 nuclei of deuterium were used for one fusion reaction. While a small number of candidates did correctly calculate the energy per kilogram, they tended to state that fusion produced more energy rather than a feeling that they are basically equivalent. As usual with LoR questions, a holistic approach is taken to the marking and candidates can access higher levels without necessarily reaching all the marking points. Even so, relatively few candidates were able to access Level 3, generally due to poor calculations and/or descriptions.
			Total	**6**	
76		i	Proton is repelled (by nucleus) (High-speed) proton can get close to (oxygen) nucleus	**B1** **B1**	**Allow** 'proton can experience the strong (nuclear) force' **Not** 'collide / hit nucleus'
		ii	$E = [0.25 - (2.24 - 2.20)] \times 10^{-11}$ (J) **or** 0.21×10^{-11} (J) $\lambda = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{0.21 \times 10^{-11}}$ (Any subject) $\lambda = 9.5 \times 10^{-14}$ (m)	**C1** **C1** **A1**	**Allow** 2 marks for 6.9×10^{-14}; $E = 0.29 \times 10^{-11}$ used **Allow** 1 mark for a value correctly calculated based on any other incorrect value for E (e.g. $8(.0) \times 10^{-14}$ for $E = 0.25 \times 10^{-11}$ and $5(.0) \times 10^{-13}$ for $E = 0.04 \times 10^{-11}$)
		iii	Used in PET (scans)	**M1**	Enter text here.

			Any **one** from: Used to diagnose function of organ / brain / body Detection of cancer / tumour Non-invasive / no surgery / no infection 3D (image)	**A1**	
			Total	**7**	
7 7		i	The wave-model cannot explain the cut-off frequency / threshold frequency	B1	Allow reverse argument in terms of photons, e.g. the photon-model can explain the threshold frequency
		i	Nor why the KE of the electrons is dependent on frequency	B1	and why the KE of the electrons is dependent on frequency.
		ii	h = 32 × 10^{-20}/5 × 10^{-14}	C1	sensible attempt at gradient gains 1 mark
		ii	= 6.4 × 10^{-34} (J s)	A1	
		iii	8.75 ± 0.25 × 10^{14} (Hz)	B1	tolerance is to within grid square
		iv	φ = 6.4 × 10^{-34} × 8.75 × 10^{14}	C1	**ecf (b)(i)(ii)**
		iv	= 5.6 × 10^{-19} (J)	A1	
			Total	**7**	
7 8		i	points from the graph read to the nearest half square size of triangle is greater than half the length of the drawn line <u>and</u> Δ*y* / Δ*x* with correct power of ten shown	B1 B1	**Allow** Δy and Δx to less than half a small square **Ignore** POT **Note** triangle may be determined from read-offs Δx must be greater than 0.3 × 10^6
		ii	$h = \frac{1.2\times10^{-6}\times1.60\times10^{-19}}{3.00\ \times 10^{8}}$ or **(a)(i)** × 5.333 6.4 × 10^{-34} (J s) given to 2 significant figures	C1 A1	
		iii	steepest or shallowest line that passes through all the error bars	B1	**Note** steepest line passes inside the lowest error bar (1.76) since it just cuts the bottom of second error bar.
		iv	gradient determined: 1.0 × 10^{-6} Vm or 1.4 × 10^{-6} V m Δgradient=0.2 × 10^{-6} V m $\frac{\Delta\text{gradient}}{\text{gradient}} \times 100$ = 15%	M1 C1 A1	**Allow** ecf from **(iii)** **Allow** Δh = 1.06 or 1.067 **Allow** 16.7%
			Total	**8**	
7 9		i	energy of blue light / photon of blue light > 2.3 eV / work function or energy of red light / photon of red light < 2.3 eV / work function Energy of photon is independent of	B1 B1 B1	**Not** blue light has frequency > threshold frequency Or red light has frequency < threshold frequency **Allow** intensity linked to <u>rate</u> of photons / <u>rate</u> of electrons emitted per second

			intensity (energy of photon given by equation) $E = hf$ / $E = hc/\lambda$ One photon interacts with one electron	B1	**Allow** E proportional f / E proportional to $1/\lambda$ **<u>Examiner's Comments</u>** The question is clear that the response needs to be given in terms of photons and energies. Many candidates discussed threshold frequencies, and although often correct, does not answer the question. The link between photon energy and frequency needs to be clear and not just a simple dependency – the simple solution for this is to state the equation. The final marking point requires the candidate to appreciate that only one photon can be absorbed by one electron. Standalone statements such as "there is a 1:1 relation" is meaningless in this context unless qualified. Many good candidates were able to score at least 3 marks on this question and it was clear that this is a well understood aspect. There is sufficient space for a fully clear answer and candidates are always to be reminded of the need for conciseness in such a response. **Misconception** Some candidates missed opportunities for marks by describing the effect wholly in terms of frequency, rather than energy.
		ii	(ϕ =) $2.3 \times 1.6 \times 10^{-19}$ **or** (E =) $\frac{6.63\times10^{-34}\times3.0\times10^{8}}{320\times10^{-9}}$ (KE_{max} =) $\frac{6.63\times10^{-34}\times3.0\times10^{8}}{320\times10^{-9}} - 2.3 \times 1.6\times10^{-19}$ (v =) $\sqrt{\frac{2\times2.5356\times10^{-19}}{9.11\times10^{-31}}}$ (wavelength =) $\frac{6.63\times10^{-34}}{9.11\times10^{-31}\times7.46\times10^{5}}$ wavelength = 9.8×10^{-10} (m)	C1 C1 C1 A1	$\phi = 3.68 \times 10^{-19}$ (J); E = 6.2156×10^{-19} (J) $KE_{max} = 2.5356 \times 10^{-19}$ (J) $v = 7.46 \times 10^{5}$ (m s^{-1}) **<u>Examiner's Comments</u>** This is a novel development on what is a common calculation of kinetic energy and as such created some challenge for some candidates. Many were able to score the first marking point, either by converting from eV to joules, or by the calculation of the photon energy. Few candidates scored 2 or 3 marks, as generally an error such as using the speed of light for the electrons occurred. However, a good number of stronger candidates were able to achieve all 4 marks and set out their solutions clearly. It should be noted that the first 3 marks are for setting up the calculations and not the evaluations. This is to not penalise candidates too early for calculational errors and as always highlights the clear need for setting out working as well as possible.
			Total	**8**	