1)

(a)	(i)	**below a certain** frequency (called the threshold frequency) no electrons emitted ✓ **or** minimum frequency for electrons to overcome work function	**1**
(a)	(ii)	(light travels as photons) energy of a photon depends on frequency ✓ below threshold frequency (photon) does not have enough **energy** to liberate an electron ✓ **or** reference to work function eg a photon does not have enough **energy** (to allow the electron) to overcome the work function	**2**
(b)	(i)	(use of $E = hc/\lambda$) $E = 6.63 \times 10^{-34} \times 3.00 \times 10^{8}/5.40 \times 10^{-7}$ ✓ $E = 3.68 \times 10^{-19}$ (J) ✓	**2**
(b)	(ii)	(use of $hf = E_k + \phi$) $3.68 \times 10^{-19} = E_k + 1.40 \times 10^{-19}$ ✓ $E_k = 2.28 \times 10^{-19}$ (J) ✓	**2**

(b) (iii) Calculate the maximum speed of the emitted electron.

$\frac{1}{2}mv^2 = E_k$

$v = \sqrt{\frac{2E_k}{m}}$

answer = 707 ..... m s^{-1}

(2 marks)

(b) (iv) Calculate the de Broglie wavelength of the fastest electrons.

answer = 1.03×10^{-9} ..... m

(2 marks)

2)

ai	the minimum energy required by an electron✓ to escape from a (metal)surface✓	if refer to atom/ionisation zero marks	2	
aii	the (minimum) energy to remove an electron(from an atom)✓ from the ground state✓		2	
b	(use of $hf=eV$) $6.63 \times 10^{-34} \times f = 5.15 \times 1.60 \times 10^{-19}$✓ $f = \frac{5.15 \times 1.60 \times 10^{-19}}{6.63 \times 10^{-34}}$ ✓ $= 1.24 \times 10^{15}$(Hz)	if no working and 1.24×10^{15}(Hz) 1 mark	2	
c	(use of $hf = E_k + \Phi$) $\Phi = 2.28 \times 1.60 \times 10^{-19} = 3.648 \times 10^{-19}$ (J) ✓ $E_k = 5.15 \times 1.60 \times 10^{-19} - 3.648 \times 10^{-19} = 4.59 \times 10^{-19}$ J ✓✓	3 sig figs if clearly used 1.2×10^{15} then final answer must be to 2 sig. figs. for last mark to be awarded accept 4.57 in place of 4.59	3	
d	(use of $c=f\lambda$)	first mark minimum working - determination of wavelength	3	

$\lambda = \frac{3.0 \times 10^{8}}{1.24 \times 10^{15}} = 2.42 \times 10^{-7}$✓ $v = h/m\lambda = 6.63 \times 10^{-34}/(9.11 \times 10^{-31} \times 2.42 \times 10^{-7}$ $v = 3010$ m s^{-1}✓✓	bald answer gets 2 marks range to 3 sig figs 2900 – 3030

3)

(a)	(i)	the (maximum) kinetic energy/speed/velocity/momentum of released electrons increases ✓ this is because increasing the frequency of the photons increases their energy **or** correct application of photoelectric equation ✓	**4**
	(ii)	the number of electrons emitted (per second) increases ✓ because there are now more photons striking the metal surface (per second) ✓	
(b)		experiment/observation needs to be performed (to test a theory) ✓ the results of (the experiment) need to be proved/repeatable/replicated/ confirmed ✓ [**or** threshold frequency ✓ could not be explained by the wave model ✓]	**2**
(c)	(i)	(use of $\phi = hf_0$) $\phi = 6.63 \times 10^{-34} \times 5.5 \times 10^{14}$ ✓ $\phi = 3.65 \times 10^{-19}$ ✓ J ✓	**6**
	(ii)	$E_k = 6.63 \times 10^{-34} \times 6.2 \times 10^{14}$ ✓ $- 3.65 \times 10^{-19}$ ✓ $E_k = 4.6 \times 10^{-20}$ J (accept 5.1×10^{-20} J) ✓	
		Total	**12**

4)

(a)	(i)	*hf* is energy available/received **or** same energy from photons ✓ energy required to remove the electron varies (hence kinetic energy of electrons will vary) ✓	**2**
(a)	(ii)	(work function is the) minimum energy needed to release an electron ✓ (or not enough energy to release electron) below a certain frequency energy of **photon** is less than work function **or** energy of **photon** correctly related to *f* ✓	**2**
(a)	(iii)	joule ✓ (accept eV)	**1**
(b)	(i)	(use of $E = hf$) energy = $6.63 \times 10^{-34} \times 1.5 \times 10^{15}$ ✓ energy = 9.9×10^{-19} (J) ✓	**2**
(b)	(ii)	number of photons per second = $3.0 \times 10^{-10}/9.9 \times 10^{-19}$ ✓ number of photons per second = 3.0×10^{8} ✓	**2**
(c)	(i)	(time taken = $6.8 \times 10^{-19}/3 \times 10^{-22}$) time taken = 2.3×10^{3} s ✓	**1**
(c)	(ii)	light travels as particles/ photons ✓ (or has a particle(like) nature) (which transfer) energy in discrete packets ✓ **or** 1 to 1 interaction **or** theory rejected/modified (in light of validated evidence)	**2**
		Total	**12**

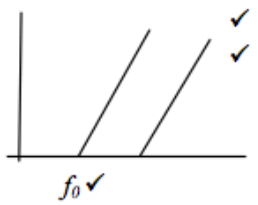
5)

a	ii	photons have energy dependent on frequency OR energy of photons constant ✓ one to one interaction between photon and electron✓ Max KE = photon energy – work function in words or symbols✓ more energy required to remove deeper electrons✓	4

a	iii	(*use of* $hf=\phi+E_{k(max)}$) $6.63 \times 10^{-34} \times f = 4.07 \times 1.60 \times 10^{-19}$ ✓ + 3.51×10^{-20} ✓ $f = 1.04 \times 10^{15}$ (Hz) OR 1.03×10^{15} (Hz) ✓✓ (3 sig figs)	4

b		theory makes predictions tested✓ by repeatable/checked by other scientists/peer reviewed (experiments) OR new evidence that is repeatable/checked by other scientists/peer reviewed✓	2

6)

(b)	(i)	 	**4**
	(ii)	parallel line, higher threshold frequency ✓✓	
	(iii)	Planck's constant ✓	
(c)		(use of $hf_0 = \phi$) $hf = 6.63 \times 10^{-34} \times 2 \times 5.6 \times 10^{14}$ ✓ $\phi = 3.7(1) \times 10^{-19}$ J ✓ $E_k = 2 \times 3.7 \times 10^{-19} - 3.7 \times 10^{-19} = 3.7 \times 10^{-19}$ J ✓	**3**
		Total	**13**

(a)

QWC	descriptor	mark range
good - excellent	The candidate provides a comprehensive and logical explanation which recognises that light consists of photons of energy hf and that an electron at or near the metal surface can only gain the energy of a single photon when it interacts with a photon. In addition, the candidate should recognise the significance of the work function (of the metal) in this context in relation to the maximum kinetic energy that an emitted electron can have. The candidate should also provide some indication of why the kinetic energy of an emitted electron may be less than the maximum kinetic energy. Although the term 'work function' might not be defined or used, the candidate's explanation should clearly state that each electron needs a minimum amount of energy to escape from the metal.	**5 - 6**
modest - adequate	The candidate provides a logical and coherent explanation which includes the key ideas including recognition that light consists of photons of energy hf and that an electron at or near the metal surface can only gain the energy of a single photon when it interacts with a photon. In addition, the candidate should be aware that each electron needs a minimum amount of energy to escape from the metal. They should appreciate that the kinetic energy of an emitted electron is equal to the difference between the energy it gains from a photon and the energy it needs (or uses) to escape from the metal. However, the explanation may lack a key element such as why the kinetic energy of the emitted electrons varies.	**3 - 4**
poor - limited	The candidate provides some correct ideas including recognition that light consists of photons of energy hf and that electrons in the metal (or at its surface) absorb photons and thereby gain energy. Their ideas lack coherence and they fail to recognise or use in their explanation the key idea that one photon is absorbed by one electron.	**1 – 2**
	The explanations expected in a good answer should include most of the following physics ideas	
	energy is needed to remove an electron from the surface	
	work function φ (of the metal) is the minimum energy needed by an electron to escape from the surface	
	light consists of photons , each of energy $E = hf$	
	one photon is absorbed by one electron	
	an electron can escape (from the surface) if $hf > \varphi$	
	kinetic energy of an emitted electron cannot be greater than $hf - \varphi$	
	an electron below the surface needs to do work/uses energy to reach the surface	
	kinetic energy of such an electron will be less than $hf - \varphi$	

7)

(a)	**The candidate's writing should be legible and the spelling, punctuation and grammar should be sufficiently accurate for the meaning to be clear.** The candidate's answer will be assessed holistically. The answer will be assigned to one of the three levels according to the following criteria. **High Level (good to excellent) 5 or 6 marks** The information conveyed by the answer is clearly organised, logical and coherent, using appropriate specialist vocabulary correctly. The form and style of writing is appropriate to answer the question. The candidate provides a comprehensive and coherent description which includes a clear explanation of threshold frequency and why this cannot be explained by the wave theory. The description should include a clear explanation of the photon model of light and this should be linked to the observations such as threshold frequency, the lack of time delay or mentions 1 to 1 interaction, the could not be explained by the wave model. **Intermediate Level (modest to adequate) 3 or 4 marks** The information conveyed by the answer may be less well organised and not fully coherent. There is less use of specialist vocabulary, or specialist vocabulary may be used incorrectly. The form and style of writing is less appropriate. The candidate provides an explanation of threshold frequency and work function. The candidate explains the photon model of light and how this can provide an explanation of threshold frequency, eg relates energy of photon to frequency or talks about packets of energy. **Low Level (poor to limited) 1 or 2 marks** The information conveyed by the answer is poorly organised and may not be relevant or coherent. There is little correct use of specialist vocabulary. The form and style of writing may only be partly appropriate. States what is meant by photoelectric effect. Knowledge of photons/packets of energy. **The explanation expected in a competent answer should include a coherent account of the significance of threshold frequency and how this supports the particle nature of electromagnetic waves.** • threshold frequency minimum frequency for emission of electrons • if frequency below the threshold frequency, no emission even if intensity increased • because the energy of the photon is less than the work function • wave theory can not explain this as energy of wave increases with intensity • light travels as photons • photons have energy that depends on frequency • if frequency is above threshold photon have enough energy • mention of lack of time delay	**max 6**

(b)	(i)	use of $E_k = \frac{1}{2}mv^2$ ½ × 6.6 × 10^{-27} ✓ × v^2 = 9.6 × 10^{-13} ✓ v^2 = 2.91 × 10^{-14} (or v = √2.91 × 10^{-14}) ✓ (v = 1.7 × 10^7 m s^{-1})	**3**
(b)	(ii)	(use of $p = mv$) p = 6.6 × 10^{-27} × 1.7 × 10^7 ✓ p = 1.1 × 10^{-19} ✓ kg m s^{-1}/N s ✓	**3**
(b)	(iii)	(use of $\lambda = \frac{h}{mv}$) λ = 6.63 × 10^{-34}/1.1 × 10^{-19} ✓ λ = 5.9 × 10^{-15} m ✓ (6.03 × 10^{-15} m)	**2**
		Total	**14**

8)

(a)		energy of photon is constant/fixed OR energy given to electron is fixed✓ energy required for electron to leave/escape/emit from the surface/metal OR electron has to overcome work function✓ maximum kinetic energy is the energy of photon minus the work function✓ deeper electrons require energy to get to the surface OR have less E_k than surface electrons✓	3_{max}	mention of energy levels means can only score first mark photoelectric equation alternative for third mark if ϕ and hf defined
(b)	(i)	(*use of E = hf*) energy of photon = 6.63 × 10^{-34} × 3.0 × 10^{15} ✓ = 1.989 × 10^{-18} (J) work function = $hf - E_k$ = 1.989 × 10^{-18} – 1.7 × 10^{-18} = 2.89 × 10^{-19} ✓ work function = 2.89 × 10^{-19}/1.6 × 10^{-19}✓= (1.8 eV)	3	hf gets first mark even if in wrong equation
b	(ii)	work function = hf_0 f_0 = 1.8 × 1.6 ×10^{-19}/6.63×10^{-34} ✓= 4.3 × 10^{14} ✓(Hz)✓(2 sig figs)	3	2 sig . fig stand alone mark Accept 4.4 × 10^{14}
(c)	(i)	decrease the energy of(incident) photons✓ decrease the maximum kinetic energy of electrons✓ OR decrease the energy of(incident) photons✓ hence fewer deeper electrons escape✓ OR below threshold frequency✓ no electrons emitted✓ OR as energy of each photon decreases but intensity is constant (there are more photons/sec)✓ number of emitted electrons(/sec) must increase✓	2	for last two alternatives must get first mark before can qualify for second mark
(c)	(ii)	increase in photons cause increase in (emitted) electrons✓ double number of electrons/photons OR reference to rate/per second✓	2	if refer to energy levels/atoms can only award first mark