Q1.

7	(a)	$\lambda = h/p$ or $\lambda = h/mv$	M1	
		with λ, h and (or mv) p identified	A1	[2]
	(b)	$E = \frac{1}{2} mv^2$	C1	
		$= p^2/2m$ or $v = \sqrt{(2E/m)}$, <u>hence</u>	M1	
		$\lambda = h/\sqrt{(2mE)}$	A0	[2]
	(c)	$E = qV$	C1	
		$(0.4 \times 10^{-9})^2 \times 2 \times 9.11 \times 10^{-31} \times 1.6 \times 10^{-19} \times V = (6.63 \times 10^{-34})^2$	C1	
		$V = 9.4$ V *(2 s.f. scores 2/3)*	A1	[3]
		Total		**[7]**

Q2.

7	(a)	'uniform' distribution	B1	[1]
	(b)	concentric rings	B1	[1]
	(c)	higher speed, more momentum	M1	
		$\lambda = h / p$	M1	
		so λ decreases and ring diameter decreases	A1	[3]

Q3.

5	(a)	(i)	packet/discrete quantity/quantum (of energy) of e.m. radiation	B1	[1]
		(ii)	either $E = (6.63 \times 10^{-34} \times 3 \times 10^8)/(350 \times 10^{-9})$		
			or $E = (6.63 \times 10^{-34} \times 8.57 \times 10^{14})$	M1	
			$E = 5.68 \times 10^{-19}$ J	A0	[1]
		(iii)	0.5	B1	[1]
	(b)	(i)	energy of photon	M1	
			to cause emission of electron <u>from surface</u>		
			either with zero k.e *or* photon energy is minimum	A1	[2]
		(ii)	correct conversion eV $\rightarrow$ J or J $\rightarrow$ eV seen once	B1	
			photon energy must be greater than work function	C1	
			350 nm wavelength and potassium metal	A1	[3]

Q4.

7 (a) charge is quantised / discrete quantities — B1 [1]

(b) (i) parallel so that the electric field is uniform / constant — B1

horizontal so that *either* oil drop will not drift sideways

or field is vertical

or electric force is equal to weight — B1 [2]

(ii) $qE = mg$ — C1

$q \times 850 / (5.4 \times 10^{-3}) = 7.7 \times 10^{-15} \times 9.8$ — C1

$q = 4.8 \times 10^{-19}$ C <u>and is negative</u> — A1 [3]

(c) charge changes by 1.6×10^{-19} C between droplets / integral multiples — M1

so charge on electron is 1.6×10^{-19} C — A0 [1]

Q5.

8 (a) wave theory predicts any frequency would give rise to emission of electron — M1

if exposure time is sufficiently long — A1

photon has (specific value of) energy dependent on frequency — M1

emission if energy greater than threshold / work function / energy to remove electron from surface — A1 [4]

(b) photon is packet/quantum of energy — M1

of electromagnetic radiation — A1

(photon) energy = $h \times$ frequency — B1 [3]

every <u>particle</u> has an (associated) wavelength — B1

wavelength = h / p — M1

where p is the momentum (of the particle) — A1 [3]

Q6.

7 (a) for a wave, electron can 'collect' energy continuously — B1

for a wave, electron will always be emitted / electron will be emitted at all frequencies….. — M1

after a sufficiently long delay — A1 [3]

(b) (i) *either* wavelength is longer than threshold wavelength

or frequency is below the threshold frequency

or photon energy is less than work function — B1 [1]

(ii) $hc / \lambda = \phi + E_{MAX}$ — C1

$(6.63 \times 10^{-34} \times 3.0 \times 10^{8}) / (240 \times 10^{-9}) = \phi + 4.44 \times 10^{-19}$ — C1

$\phi = 3.8 \times 10^{-19}$ J (*allow* 3.9×10^{-19} J) — A1 [3]

(c) (i) photon energy larger — M1

so (maximum) kinetic energy is larger — A1 [2]

(ii) fewer photons (per unit time) — M1

so (maximum) current is smaller — A1 [2]

Q7.

7 **(a)** wavelength of wave associated with a particle		M1	
that is moving		A1	[2]
(b) **(i)** energy of electron $= 850 \times 1.6 \times 10^{-19}$		M1	
$= 1.36 \times 10^{-16}$ J			
energy $= p^2 / 2m$ *or* $p = mv$ <u>and</u> $E_K = ½mv^2$			
momentum $= \sqrt{(1.36 \times 10^{-16} \times 2 \times 9.11 \times 10^{-31})}$		M1	
$= 1.6 \times 10^{-23}$ N s		A0	[2]
(ii) $\lambda = h / p$		C1	
wavelength $= (6.63 \times 10^{-34}) / (1.6 \times 10^{-23})$			
$= 4.1 \times 10^{-11}$ m		A1	[2]
(c) diagram or description showing:			
electron beam in a vacuum		B1	
incident on <u>thin</u> metal target / carbon <u>film</u>		B1	
fluorescent screen		B1	
pattern of concentric rings observed		M1	
pattern similar to diffraction pattern observed with visible light		A1	[5]

Q8.

8 **(a)** packet/quantum/discrete amount of energy		M1	
of electromagnetic radiation		A1	
(allow 1 mark for 'packet of electromagnetic radiation')			
energy = Planck constant × frequency *(seen here or in **b**)*		B1	[3]
(b) each (coloured) line corresponds to one wavelength/frequency		B1	
energy = Planck constant × frequency			
implies specific energy change between energy levels		B1	
so discrete levels		A0	[2]

Q9.

6 **(a)** oil drop charged by friction/beta source		B1	
between parallel <u>metal</u> plates		B1	
plates are horizontal	(1)		
adjustable potential difference/field between plates		B1	
until oil drop is stationary		B1	
$mg = q \times V/d$		B1	
symbols explained	(1)		
oil drop viewed through microscope	(1)		
m determined from terminal speed of drop (when p.d. is zero)	(1)		
(*any two extras, 1 each*)		B2	[7]
(b) 3.2×10^{-19} C		A1	[1]

Q10.

7 (a)	minimum energy to remove an electron from the metal/surface	B1	[1]
(b)	gradient = 4.17×10^{-15} *(allow 4.1 → 4.3)*	C1	
	$h = 4.15 \times 10^{-15} \times 1.6 \times 10^{-19}$ *or* $h = 4.1$ to 4.3×10^{-15} <u>eV s</u>	A1	
	$= 6.6 \times 10^{-34}$ J s	A0	[2]
(c)	graph: straight line parallel to given line		
	with intercept at any higher frequency	B1	
	intercept at between 6.9×10^{14} Hz and 7.1×10^{14} Hz	B1	[3]

Q11.

7 (a) (i)	lowest frequency of e.m. radiation	M1	
	giving rise to emission of electrons (from the surface)	A1	[2]
(ii)	$E = hf$	C1	
	threshold frequency $= (9.0 \times 10^{-19}) / (6.63 \times 10^{-34})$		
	$= 1.4 \times 10^{15}$ Hz	A1	[2]
(b)	*either* 300 nm ≡ 10×10^{15} Hz (and 600 nm ≡ 5.0×10^{14} Hz)		
	or 300 nm ≡ 6.6×10^{-19} J (and 600 nm ≡ 3.3×10^{-19} J)		
	or zinc λ_0 = 340 nm, platinum λ_0 = 220 nm (and sodium λ_0 = 520 nm)	M1	
	emission from sodium <u>and</u> zinc	A1	[2]
(c)	each photon has larger energy	M1	
	fewer photons per unit time	M1	
	fewer electrons emitted per unit time	A1	[3]

Q12.

7 **(a)** each wavelength is associated with a discrete <u>change</u> in energy	M1	
discrete energy <u>change</u> / difference implies discrete levels	A1	[2]
(b) **(i)** **1.** arrow from –0.54 eV to –0.85 eV, labelled L	B1	[1]
2. arrow from –0.54 eV to –3.4 eV, labelled S	B1	[1]
(two correct arrows, but only one label – allow 2 marks)		
(two correct arrows, but no labels – allow 1 mark)		
(ii) $E = hc / \lambda$	C1	
$(3.4 - 0.54) \times 1.6 \times 10^{-19} = (6.63 \times 10^{-34} \times 3.0 \times 10^{8}) / \lambda$	C1	
$\lambda = 4.35 \times 10^{-7}$ m	A1	[3]
(c) $-1.50 \rightarrow -3.4 = 1.9$ eV		
$-0.85 \rightarrow -3.4 = 2.55$ eV (allow 2.6 eV)		
$-0.54 \rightarrow -3.4 = 2.86$ eV (allow 2.9 eV)		
3 correct, 2 marks with –1 mark for each additional energy		
2 correct, 1 mark but no marks if any additional energy differences	B2	[2]

Q13.

2 (a) $E = hc / \lambda = (6.63 \times 10^{-34} \times 3.0 \times 10^{8}) / (486 \times 10^{-9})$ C1

$= 4.09 \times 10^{-19}$ J ...(allow 2 sf)....................................... A1 [2]

(b) energy level drawn at 4.09×10^{-19} J B1

transition 4.09×10^{-19} to zero clear B1

transition 4.09×10^{-19} to 3.03×10^{-19} clear .... B1 [3]

(-1 for reversed arrows, -1 for extra level at 1.06)

Q14.

6 (a) packet/quantum of energy...M1

energy = *hf*...A1 [2]

(b) e.g. threshold frequency outlined

max. k.e. independent of intensity

max. k.e. dependent on frequency (n.b. NOT proportional)

photoelectric current depends on intensity

instantaneous emission .... (*1 each, max 3*)........................ B3 [3]

(c) (i) photons have same energy so E_{max} unchanged

intensity *OR* number of photons per unit time is halved,

so ½*n OR n* reduced B1

(allow 1 mark for statement that E_{max} unchanged and *n* reduced)

(ii) photons have higher energy so E_{max} increases............................ B1

but fewer photons per unit time so *n* decreases .... B1 [4]

(allow 1 mark for statement that E_{max} increases and n reduced)

(allow any argument based on increased efficiency)

Q15.

7 (a)	(i)	quantum/packet/discrete amount of energy electromagnetic mentioned	M1 A1	[2]
	(ii)	max. k.e. corresponds to electron emitted from surface energy is required to bring electron to surface	B1 B1	[2]
(b)		at higher frequency, fewer photons (per second) for same intensity so rate of emission decreases (allow argument based on photoelectric efficiency)	M1 A1	[2]

Q16.

7 (a)		e.g. 'instantaneous' emission (of electrons) threshold frequency below which no emission (max) <u>electron</u> energy dependent on frequency (max) <u>electron</u> energy not dependent on intensity rate of emission (of electrons) depends on intensity (*any three sensible suggestions, 1 each*)	B3	[3]
(b)	(i)	'packet' / quantum of energy of electromagnetic energy / radiation	M1 A1	[2]
	(ii)	discrete wavelengths mean photons have particular energies energy of photon determined by energy change of (orbital) electron so discrete energy levels	M1 M1 A0	[2]
(c)	(i)	three energy changes shown correctly arrows 'pointing' in correct direction wavelengths correctly identified	B1 B1 B1	[3]
	(ii)	chooses λ = 486 nm $\Delta E = hc / \lambda$ $= (6.63 \times 10^{-34} \times 3.0 \times 10^{8}) / (4.86 \times 10^{-9})$ $= 4.09 \times 10^{-19}$ J (*allow 2 s.f.*)	C1 C1 A1	[3]

Q17.

7 (a)		each line corresponds to a (specific) photon energy .... photon emitted when electron changes its energy level .... discrete energy changes so discrete levels	B1 B1 B1	[3]
(b)	(i)	$E = hc / \lambda$ …(*allow ratio ideas*) .... $= (6.63 \times 10^{-34} \times 3.0 \times 10^{8}) / (486 \times 10^{-9})$ $= 4.09 \times 10^{-19}$ J	C1 A1	[2]
	(ii)	four transitions to/from -5.45×10^{-19} J level .... all transitions shown from higher to lower energy (level)	B1 B1	[2]

[Total: 7]

Q18.

7	(a)	(i)	e.g. electron / particle diffraction	B1	[1]
		(ii)	e.g. photoelectric effect	B1	[1]
	(b)	(i)	6	A1	[1]
		(ii)	change in energy = 4.57×10^{-19} J		
			$\lambda = hc / E$	C1	
			$= (6.63 \times 10^{-34} \times 3.0 \times 10^{8}) / (4.57 \times 10^{-19})$		
			$= 4.4 \times 10^{-7}$ m	A1	[2]

Q19.

8	(a)	minimum frequency for electron to be emitted (from surface)	M1	
		of electromagnetic radiation / light / photons	A1	[2]
	(b)	$E = hc / \lambda$ *or* $E = hf$ <u>and</u> $c = f\lambda$	C1	
		either threshold wavelength $= (6.63 \times 10^{-34} \times 3.0 \times 10^{8}) / (5.8 \times 10^{-19})$		
		= 340 nm		
		or energy of 340 nm photon = 4.4×10^{-19} J		
		or threshold frequency = 8.7×10^{14} Hz		
		or 450 nm → 6.7×10^{14} Hz	A1	
		appropriate comment comparing wavelengths / energies / frequencies	B1	
		so no effect on photo-electric current	B1	[4]

Q20.

7	(a)		each line represents photon of specific energy	M1	
			photon emitted as a result of energy change of electron	M1	
			specific energy changes so discrete levels	A1	[3]
	(b)	(i)	arrow from –0.85 eV level to –1.5 eV level	B1	[1]
		(ii)	$\Delta E = hc / \lambda$	C1	
			$= (1.5 - 0.85) \times 1.6 \times 10^{-19}$	C1	
			$= 1.04 \times 10^{-19}$ J		
			$\lambda = (6.63 \times 10^{-34} \times 3.0 \times 10^{8})/(1.04 \times 10^{-19})$		
			$= 1.9 \times 10^{-6}$ m	A1	[3]
	(c)		spectrum appears as continuous spectrum crossed by dark lines	B1	
			two dark lines	B1	
			electrons in gas absorb photons with energies equal to the excitation energies	M1	
			light photons re-emitted in all directions	A1	[4]

Q21.

7	(a)	(i)	packet/quantum of energy of electromagnetic radiation	M1 A1	 [2]
		(ii)	<u>minimum</u> energy to cause emission of an electron (from surface)	B1	[1]
	(b)	(i)	$hc/\lambda = \Phi + E_{max}$ *c* and *h* explained	M1 A1	 [2]
		(ii)	1. *either* when $1/\lambda = 0$, $\Phi = -E_{max}$ or evidence of use of *x*-axis intercept from graph or chooses point close to the line and substitutes values of $1/\lambda$ and E_{max} into $hc/\lambda = \Phi + E_{max}$ $\Phi = 4.0 \times 10^{-19}$ J (allow $\pm 0.2 \times 10^{-19}$ J)	 C1 A1	 [2]
			2. *either* gradient of graph is $1/hc$ gradient = $4.80 \times 10^{24} \rightarrow 5.06 \times 10^{24}$ h = 1/(gradient × 3.0×10^{8}) = 6.6×10^{-34} J s → 6.9×10^{-34} J s	C1 M1 A1	
			or chooses point close to the line and substitutes values of $1/\lambda$ and E_{max} into $hc/\lambda = \Phi + E_{max}$ values of $1/\lambda$ and E_{max} are correct within half a square $h = 6.6 \times 10^{-34}$ J s → 6.9×10^{-34} J s	(C1) (M1) (A1)	 [3]
			(Allow full credit for the correct use of any appropriate method) *(Do not allow 'circular' calculations in **part 2** that lead to the same value of Planck constant that was substituted in **part 1**)*		

Q22.

8	(a)	discrete quantity / packet / quantum of energy of electromagnetic radiation energy of photon = Planck constant × frequency		B1 B1	 [2]
	(b)	threshold frequency rate of emission is proportional to intensity max. kinetic energy of electron dependent on frequency max. kinetic energy independent of intensity (*any three, 1 each, max 3*)	(1) (1) (1) (1)	 B3	 [3]
	(c)	*either* $E = hc/\lambda$ λ = 450 nm to give energy = 4.4×10^{-19} or 2.8 eV 2.8 eV < 3.5 eV so no emission	*or* $hc/\lambda = eV$ work function of *3.5 eV* to give λ = 355 nm 355 nm < 450 nm so no	C1 M1 A1	 [3]
		or work function = 3.5 eV threshold frequency = 8.45×10^{14} Hz 450 nm = 6.67×10^{14} Hz 6.67×10^{14} Hz < 8.45×10^{14} Hz		 C1 M1 A1	

Q23.

7	(a)	wavelength associated with a particle	M1	
		that is moving	A1	[2]
	(b) (i)	kinetic energy = $1.6 \times 10^{-19} \times 4700$	C1	
		$= 7.52 \times 10^{-16}$ J		
		either energy = $p^2/2m$ *or* $E_K = ½mv^2$ *and* $p = mv$	C1	
		$p = \sqrt{(7.52 \times 10^{-16} \times 2 \times 9.1 \times 10^{-31})}$	C1	
		$= 3.7 \times 10^{-23}$ N s		
		$\lambda = h/p$	C1	
		$= (6.63 \times 10^{-34}) / (3.7 \times 10^{-23})$		
		$= 1.8 \times 10^{-11}$ m	A1	[5]
	(ii)	wavelength is about separation of atoms	B1	
		can be used in (electron) diffraction	B1	[2]

Q24.

7	(a)	*either* if light passes through suitable film / cork dust etc.	M1	
		diffraction occurs and similar pattern observed	A1	
		or concentric circles are evidence of diffraction	(M1)	
		diffraction is a wave property	(A1)	[2]
	(b)	(speed increases so) momentum increases	M1	
		$\lambda = h/p$ so λ decreases	M1	
		hence radii decrease	A1	[3]
		(*special case: wavelength decreases so radii decreases – scores 1/3*)		
		or		
		(speed increases so) energy increases	(B1)	
		$\lambda = h / \sqrt{(2Em)}$ so λ decreases	(M1)	
		hence radii decrease	(A1)	
	(c)	electron and proton have same (kinetic) energy	C1	
		either $E = p^2 / 2m$ *or* $p = \sqrt{(2Em)}$	C1	
		ratio = $p_e / p_p = \sqrt{(m_e / m_p)}$	C1	
		$= \sqrt{\{(9.1 \times 10^{-31}) / (1.67 \times 10^{-27})\}}$		
		$= 2.3 \times 10^{-2}$	A1	[4]

Q25.

7	(a)	(i)	minimum photon energy	B1	
			minimum energy to remove an electron (from the surface)	B1	[2]
		(ii)	*either* maximum KE is photon energy – work function energy		
			or max KE when electron ejected from the surface	B1	
			energies lower than max because energy required to bring electron to the surface	B1	[2]
	(b)	(i)	threshold frequency = 1.0×10^{15} Hz (*allow* $\pm 0.05 \times 10^{15}$)	C1	
			work function energy $= hf_0$	C1	
			$= 6.63 \times 10^{-34} \times 1.0 \times 10^{15}$		
			$= 6.63 \times 10^{-19}$ J	A1	[3]
			(*allow alternative approaches based on use of co-ordinates of points on the line*)		
		(ii)	sketch: straight line with same gradient	M1	
			displaced to right	A1	[2]
		(iii)	intensity determines number of photons arriving per unit time	B1	
			intensity determines number of electrons per unit time (not energy)	B1	[2]

Q26.

8	(a)	discrete and equal amounts (of charge)	B1	[1]
		allow: discrete amounts of 1.6×10^{-19} C/elementary charge/e		
		integral multiples of 1.6×10^{-19} C/elementary charge/e		
	(b)	weight $= qV/d$		
		$4.8 \times 10^{-14} = (q \times 680)/(7.0 \times 10^{-3})$	C1	
		$q = 4.9 \times 10^{-19}$ C	A1	[2]
	(c)	elementary charge = 1.6×10^{-19} C (*allow* 1.6×10^{-19} C to 1.7×10^{-19} C)	M0	
		either the values are (approximately) multiples of this		
		or it is a common factor	C1	
		it is the highest common factor	A1	[2]

Q27.

9	(a)		e.g. no time delay between illumination and emission		
			max. (kinetic) energy of electron dependent on frequency		
			max. (kinetic) energy of electron independent of intensity		
			rate of emission of electrons dependent on/proportional to intensity		
			(*any three separate statements, one mark each, maximum 3*)	B3	[3]
	(b)	(i)	(photon) interaction with electron may be below surface	B1	
			energy required to bring electron to surface	B1	[2]

(ii) 1. threshold frequency = 5.8×10^{14} Hz — A1 [1]

2. $\Phi = hf_0$ — C1
$= 6.63 \times 10^{-34} \times 5.8 \times 10^{14}$
$= 3.84 \times 10^{-19}$ (J) — C1
$= (3.84 \times 10^{-19})/(1.6 \times 10^{-19})$
$= 2.4$ eV — A1 [3]

or

$hf = \Phi + E_{MAX}$ — (C1)
chooses point on line and substitutes values E_{MAX}, f and h into equation with the units of the hf term converted from J to eV — (C1)
$\Phi = 2.4$ eV — (A1)

Q28.

8 (a) photon energy $= hc/\lambda$
$= (6.63 \times 10^{-34} \times 3.0 \times 10^{8})/(590 \times 10^{-9})$ — C1
$= 3.37 \times 10^{-19}$ J — C1

number $= (3.2 \times 10^{-3})/(3.37 \times 10^{-19})$
$= 9.5 \times 10^{15}$ (allow 9.4×10^{15}) — A1 [3]

(b) (i) $p = h/\lambda$ — C1
$= (6.63 \times 10^{-34})/(590 \times 10^{-9})$
$= 1.12 \times 10^{-27}$ kg m s^{-1} — C1

total momentum $= 9.5 \times 10^{15} \times 1.12 \times 10^{-27}$
$= 1.06 \times 10^{-11}$ kg m s^{-1} — A1 [3]

(ii) force $= 1.06 \times 10^{-11}$ N — A1 [1]

Q29.

8 (a) photon 'absorbed' by electron — B1
photon has energy equal to difference in energy of two energy levels — B1
electron de-excites emitting photon (of same energy) in any direction — B1 [3]

(b) (i) $E = hc/\lambda$ — C1
$= (6.63 \times 10^{-34} \times 3 \times 10^{8})/(435 \times 10^{-9})$ — C1
$= 4.57 \times 10^{-19}$ J (*allow 2 s.f.*) — C1
$= (4.57 \times 10^{-19})/(1.6 \times 10^{-19})$ (eV)
$= 2.86$ eV (*allow 2 s.f.*) — A1 [4]

(ii) arrow pointing in either direction between –3.41 eV and –0.55 eV — B1 [1]

Q30.

7 (a) *either* charge exists in discrete and <u>equal</u> quantities
or multiples of elementary charge / e / 1.6×10^{-19} C — B1 [1]

(b) (i) force due to magnetic field must be upwards — B1
B-field into the plane of the paper — B1 [2]

(ii) sketch showing: deflection consistent with force in **(b)(i)** — B1
reasonable curve — B1 [2]

Q31.

8 (a) discrete amount / packet / quantum of <u>energy</u> — M1
of electromagnetic radiation / EM radiation — A1 [2]

(b) (i) $E = hc / \lambda$
$= (6.63 \times 10^{-34} \times 3.0 \times 10^{8}) / (570 \times 10^{-9}) = 3.49 \times 10^{-19}$ J — A1 [1]

(ii) **1.** number $= (2.7 \times 10^{-3}) / (3.5 \times 10^{-19})$ — C1
$= 7.7 \times 10^{15}$ — A1 [2]

2. momentum of photon $= h / \lambda$ — C1
$= (6.63 \times 10^{-34}) / (570 \times 10^{-9})$
$= 1.16 \times 10^{-27}$ kg m s^{-1} — C1

change in momentum $= 1.16 \times 10^{-27} \times 7.7 \times 10^{15}$
$= 8.96 \times 10^{-12}$ kg m s^{-1} — A1 [3]

(*allow $E = pc$ route to 9×10^{-12}*)

(c) pressure = (change in momentum per second) / area — C1
$= (8.96 \times 10^{-12}) / (1.3 \times 10^{-5})$
$= 6.9 \times 10^{-7}$ Pa — A1 [2]

Q32.

1 (a) charge is quantised/enabled electron charge to be measured — B1 [1]

(b) <u>all</u> are (approximately) n x (1.6×10^{-19} C) — M1
so $e = 1.6 \times 10^{-19}$ C (allow 2 sig. fig. only — A1 [2]
summing charges and dividing ten, without explanation scores 1/2

Total [3]