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 $v = \sqrt{(2E/m)}$, hence	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 from surface		
			either with zero k.e *or* photon energy is minimum	A1	[2]
		(ii)	correct conversion eV → J or J → 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 × 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* $p = mv$ and $E_K = ½mv^2$		
		momentum $= \sqrt{(1.36 \times 10^{-16} \times 2 \times 9.11 \times 10^{-31})}$	M1	
		$= 1.6 \times 10^{-23}$ Ns	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} eV s	A1	
	= 6.6×10^{-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 = $(9.0 \times 10^{-19}) / (6.63 \times 10^{-34})$		
	= 1.4×10^{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 and 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 change in energy — M1
discrete energy change / 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 → –3.4 = 1.9 eV
–0.85 → –3.4 = 2.55 eV (allow 2.6 eV)
–0.54 → –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 M1
of electromagnetic energy / radiation A1 [2]

(ii) discrete wavelengths mean photons have particular energies M1
energy of photon determined by energy change of (orbital) electron M1
so discrete energy levels A0 [2]

(c) (i) three energy changes shown correctly B1
arrows 'pointing' in correct direction B1
wavelengths correctly identified B1 [3]

(ii) chooses λ = 486 nm C1
$\Delta E = hc / \lambda$ C1
$= (6.63 \times 10^{-34} \times 3.0 \times 10^{8}) / (4.86 \times 10^{-9})$
$= 4.09 \times 10^{-19}$ J (*allow 2 s.f.*) A1 [3]

Q17.

7 (a) each line corresponds to a (specific) photon energy B1
photon emitted when electron changes its energy level B1
discrete energy changes so discrete levels .... B1 [3]

(b) (i) $E = hc / \lambda$ …(*allow ratio ideas*) C1
$= (6.63 \times 10^{-34} \times 3.0 \times 10^{8}) / (486 \times 10^{-9})$
$= 4.09 \times 10^{-19}$ J .... A1 [2]

(ii) four transitions to/from -5.45×10^{-19} J level B1
all transitions shown from higher to lower energy (level) .... 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 $E = hf$ and $c = f\lambda$	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	M1	
		of electromagnetic radiation	A1	[2]
	(ii)	minimum energy to cause emission of an electron (from surface)	B1	[1]
	(b) (i)	$hc/\lambda = \Phi + E_{max}$	M1	
		c and h explained	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 $hc/\lambda = \Phi + E_{max}$	C1	
		$\Phi = 4.0 \times 10^{-19}$ J (allow $\pm 0.2 \times 10^{-19}$ J)	A1	[2]
	2.	*either* gradient of graph is $1/hc$	C1	
		gradient = $4.80 \times 10^{24} \rightarrow 5.06 \times 10^{24}$	M1	
		h = 1/(gradient × 3.0×10^{8})		
		= 6.6×10^{-34} J s $\rightarrow$ 6.9×10^{-34} J s	A1	
		or chooses point close to the line and substitutes values of $1/\lambda$ and E_{max} into $hc/\lambda = \Phi + E_{max}$	(C1)	
		values of $1/\lambda$ and E_{max} are correct within half a square	(M1)	
		h = 6.6×10^{-34} J s $\rightarrow$ 6.9×10^{-34} J s	(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		B1	
		energy of photon = Planck constant × frequency		B1	[2]
	(b)	threshold frequency	(1)		
		rate of emission is proportional to intensity	(1)		
		max. kinetic energy of electron dependent on frequency	(1)		
		max. kinetic energy independent of intensity	(1)		
		(*any three, 1 each, max 3*)		B3	[3]

(c)	*either* $E = hc/\lambda$	*or* $hc/\lambda = eV$	C1	
	λ = 450 nm to give	work function of 3.5 eV		
	energy = 4.4×10^{-19} or 2.8 eV	to give λ = 355 nm	M1	
	2.8 eV < 3.5 eV so no emission	355 nm < 450 nm so no	A1	[3]
	or work function = 3.5 eV			
	threshold frequency = 8.45×10^{14} Hz		C1	
	450 nm = 6.67×10^{14} Hz		M1	
	6.67×10^{14} Hz < 8.45×10^{14} Hz		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	
	$= 3.7 \times 10^{-23}$ Ns		
	$\lambda = h/p$	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]