1. (a) The following equation describes the release of electrons from a metal surface illuminated by electromagnetic radiation.

\[ hf = k.e_{\text{max}} + \phi \]

Explain briefly what you understand by each of the terms in the equation.

- \( hf \)  
  Energy of a photon  (1)

- \( k.e_{\text{max}} \)  
  Kinetic energy of emitted electron/equivalent  (1)

- \( \phi \)  
  Energy to release electron from surface / equivalent  (1)

(3 marks)

(b) Calculate the momentum \( p \) of an electron travelling in a vacuum at 5% of the speed of light.

\[ p = mv \]  
\[ = 9.11 \times 10^{-31} \text{ kg} \times 0.05 \times 3 \times 10^8 \text{ m s}^{-1} \]  
(no ecf for incorrect mass)

\[ p = 1.37 \times 10^{-23} \text{ N s/kg m s}^{-1} \]  
(1) Unit penalty

(3 marks)

What is the de Broglie wavelength of electrons travelling at this speed?

\[ \lambda = \frac{6.63 \times 10^{34}}{1.37 \times 10^{-23}} \text{ ecf (b)} \]  
\[ \lambda = 4.84 \times 10^{-11} \text{ m} \]  
Unit penalty  (1)

(2 marks)

Why are electrons of this wavelength useful for studying the structure of molecules?

\( \lambda \approx \) similar to size / spacing atoms / molecules  (1)

Diffraction occurs  (1)

(2 marks)

[Total 10 marks]
2. The graph shows how the maximum kinetic energy $T$ of photoelectrons emitted from the surface of sodium metal varies with the frequency $f$ of the incident radiation.

![Graph showing the relationship between kinetic energy $T$ and frequency $f$.]

A parallel line starting at a higher frequency

Why are no photoelectrons emitted at frequencies below $4.4 \times 10^{14}$ Hz?

Photon energy too small/less than $\phi$ (1)

Calculate the work function $\phi$ of sodium in eV.

If using $\phi = hf - T$

then a valid pair of points (1)

with both points in the same units (1)

OR

If using $hf_0 = \phi$

with $f_0 = 4.4 \times 10^{14}$ Hz (1)

Work function = 1.8 eV (1)

(3 marks)

Explain how the graph supports the photoelectric equation $hf = T + \phi$

$T = hf - \phi$ is similar to $y = mx + c$ (1)

Straight line shows $T/f$ relationship (1)

Negative intercept $T$ axis shows $\phi$ (1)

Any two (2 marks)

How could the graph be used to find a value for the Planck constant?

From the gradient (1)

(not necessary to mention conversion factor)

(1 mark)

Add a line to the graph to show the maximum kinetic energy of the photoelectrons emitted from a metal which has a greater work function than sodium. (See graph.)

(2 marks)

[Total 9 marks]
3. Experiments on the photoelectric effect show that

- the kinetic energy of photoelectrons released depends upon the frequency of the incident light and not on its intensity,
- light below a certain threshold frequency cannot release photoelectrons.

How do these conclusions support a particle theory but not a wave theory of light?

**Particle theory:** \( E = hf \) implied packets/photons  
One photon releases one electron giving it k.e.  
Increase \( f \) \( \Rightarrow \) greater k.e. electrons  
Lower \( f \); finally \( ke = 0 \) ie no electrons released

**Waves**

Energy depends on intensity \( / (amplitude)^2 \)  
More intense light should give greater k.e–NOT SEEN  
More intense light gives more electrons but no change in maximum kinetic energy  
Waves continuous \( \therefore \) when enough are absorbed electrons should be released–NOT SEEN

(6 marks)

Calculate the threshold wavelength for a metal surface which has a work function of 6.2 eV.

\[ 6.2 \text{eV} \times 1.6 \times 10^{-19} \text{C} \]  
Use of \( \lambda = \frac{hc}{E} \)  
Threshold wavelength = \( 2.0 \times 10^{-7} \text{m} \)

To which part of the electromagnetic spectrum does this wavelength belong?

UV ecf their \( \lambda \)

(4 marks)

[Total 10 marks]

4. The diagram shows monochromatic light falling on a photocell.

As the reverse potential difference between the anode and cathode is increased, the current measured by the microammeter decreases. When the potential difference reaches a value \( V_s \), called the stopping potential, the current is zero.
Explain these observations.

**Photons release e\(^-\) at photocathode; e\(^-\) travel to anode making a current** (1)

**Photon energy > work function of photocathode** (1)

**OR All energy of A photon goes to an electron** (1)

**Electrons released with a range of kinetic energies** (1)

**So smaller kinetic energy electrons stopped at lower pds** (1)

**PD opposes kinetic energy electrons stopped at lower pds** (1)

**Vs supplies enough energy to stop electrons with kinetic energy max** (1)

(MAX 5 marks)

(5 marks)

What would be the effect on the stopping potential of

(i) increasing only the intensity of the incident radiation, **No effect** (1)

(ii) increasing only the frequency of the incident radiation? **Increases stopping potential** (1)

(2 marks)

[Total 7 marks]

5. **Particle theory:**

One photon releases one electron giving it kinetic energy (1)

Increase \(f\) \(\rightarrow\) greater k.e. electrons (1)

Lower \(f\) finally k.e. = 0 i.e. no electrons released (1)

**Waves:**

More intense light should give greater k.e. (1)

More intense light gives more electrons but no change in maximum kinetic energy (1)

**Waves continuous \(\therefore\) when enough are absorbed electrons should be released (1) Max 5**

**Quality of written communication**

1

Line parallel to existing line
to left of existing line

2

[8]

6. **Calculation:**

\[ E = \frac{hc}{\lambda} \quad \text{[seen or implied]} \] (1)

physically correct substitutions (1)

\[ \div 1.6 \times 10^{-19} \text{ eV J}^{-1} \] (1)

\[ 5.78 \text{ eV} \] (1)

**Maximum kinetic energy:**

3.52 eV [ecf but not if –ve.] (1)
Stopping potential:
3.52 V [Allow e.c.f., but not signs] (1) 2

Annotated graph:
Position of S (1)
Cuts V axis between origin and existing graph (1) 3
Similar shape [i.e. levels off/up/below existing line] (1) [9]

7. Photoelectric effect
   (a) Explanation:
   Particle theory: one photon (interacts with) one electron (1)
   Wave theory allows energy to ‘build up’, i.e. time delay (1) 2
   (b) Explanation:
   Particle theory: $f$ too low then not enough energy (is released by
   photon to knock out an electron) (1)
   Wave theory: Any frequency beam will produce enough energy (to release an electron, i.e.
   should emit whatever the frequency) (1) 2 [4]

8. Planck constant
   Realise that $h$ is the gradient
   Correct attempt to find gradient [but ignore unit errors here]
   $h = (6.3 \text{ to } 6.9) \times 10^{-34} \text{ J s}$ [No bold answers] 3
   Work function
   Use of $hf_0$ / use intercept on $T$ axis/use of $\phi = hf - T$ (1)
   $\phi = (3.4 \text{ to } 3.9) \times 10^{-19} \text{ J [ -1 if –ve]} [2.1 \text{ to } 2.4 \text{ eV}] (1) 2$
   Stopping potential
   $T = 2.3 \times 10^{-19}$ [Use of $T = hf - \phi$ (1)
   Use of $V =$ their energy $\div 1.6 \times 10^{-19}$ (1)
   $V = 1.44 \text{ V } // V = 1.1 - 1.8 \text{ V [ignore –ve sign] [ecf h]} (1) 3 [8]