

Answers to Coursebook questions – Chapter 6.4

- 1 a** The emission of electrons from a metallic surface when light or other forms of electromagnetic radiation are incident on the surface.
- b** From the Einstein formula $E_{\max} = hf - \phi$. At the critical frequency, $E_{\max} = 0$ and so $hf_c - \phi = 0 \Rightarrow f_c = \frac{\phi}{h} = \frac{3.00 \times 1.6 \times 10^{-19}}{6.63 \times 10^{-34}} = 2.83 \times 10^{14}$ Hz.
- 2 a** Evidence for photons comes from the photoelectric effect, Compton scattering and others.
- b** From **Q1**, $\phi = hf_c = 6.63 \times 10^{-34} \times 2.25 \times 10^{14} = 1.49 \times 10^{-19}$ J.
Then $E_{\max} = hf - \phi = 6.63 \times 10^{-34} \times 3.87 \times 10^{14} - 1.49 \times 10^{-19} = 1.08 \times 10^{-19}$ J.
The stopping voltage is $qV_s = E_{\max} \Rightarrow V_s = \frac{E_{\max}}{q} = \frac{1.08 \times 10^{-19}}{1.6 \times 10^{-19}} = 0.675$ V.
- 3 a** Light consists of photons.
When light is incident on the metal an electron from within the metal may absorb one photon and so its energy will increase by an amount equal to the photon energy.
If this energy is sufficient to overcome the potential well the electron finds itself in, the electron may be free itself from the metal.
- b** The number of electrons emitted per second is 10^{15} and so the charge that leaves the metal per second, i.e. the current, is $10^{15} \times 1.6 \times 10^{-19} = 1.6 \times 10^{-4}$ A.
- c** From $E_{\max} = hf - \phi$ we get
- $$\begin{aligned} \phi &= hf - E_{\max} = \frac{hc}{\lambda} - E_{\max} \\ &= \frac{6.63 \times 10^{-34} \times 3.0 \times 10^8}{5.4 \times 10^{-7}} - 2.1 \times 1.6 \times 10^{-19} \\ &= 3.23 \times 10^{-19} \text{ J} \\ &= \frac{3.23 \times 10^{-20}}{1.6 \times 10^{-19}} \\ &= 0.20 \text{ eV} \end{aligned}$$
- d** The energy is independent of intensity and so we still have $E_{\max} = 2.1$ eV.
- e** The current will double since current is proportional to intensity.

- 4 a** The electrons are emitted without delay. In the photon theory of light the energy is supplied to an electron by a single photon in an instantaneous interaction.

There is a critical frequency below which no electrons are emitted. The energy of the photon depends on frequency, so if the photon energy is less than the work function the electron cannot be emitted.

The intensity of light has no effect on the energy of the emitted electrons. The intensity of light depends on the number of photons present and so this will affect the number of electrons emitted, not their energy.

b

$$qV_s = \frac{hc}{\lambda} - \phi \Rightarrow \phi = \frac{hc}{\lambda} - qV_s = \frac{E_{\max}}{q}$$

$$= \frac{6.63 \times 10^{-34} \times 3.0 \times 10^8}{2.08 \times 10^{-7}} - 1.6 \times 10^{-19} \times 1.40 = 7.32 \times 10^{-19} \text{ J}$$

The longest wavelength corresponds to the smallest frequency, i.e. the critical frequency:

$$\frac{hc}{\lambda_c} - \phi = 0 \Rightarrow \lambda_c = \frac{hc}{\phi} = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^8}{7.32 \times 10^{-19}} = 2.7 \times 10^{-7} \text{ m.}$$

- 5 a** Increasing the intensity of light increases the number of electrons emitted, i.e. the photocurrent. It has no influence on the energy of the emitted electrons.

b We have that $qV_s = \frac{hc}{2.3 \times 10^{-7}} - \phi$ and $q(2V_s) = \frac{hc}{1.8 \times 10^{-7}} - \phi$.

Subtracting, $qV_s = \frac{hc}{1.8 \times 10^{-7}} - \frac{hc}{2.3 \times 10^{-7}} \Rightarrow V_s = 1.50 \text{ V.}$

Hence, $\phi = \frac{hc}{2.3 \times 10^{-7}} - qV_s = 6.25 \times 10^{-19} \text{ J} = \frac{6.25 \times 10^{-19}}{1.6 \times 10^{-19}} = 3.9 \text{ eV.}$

- 6 a** The work function is $\phi = 3.0 \times 1.6 \times 10^{-19} = 4.8 \times 10^{-19} \text{ J.}$

The power incident on the given area is

$$P = 5.0 \times 10^{-4} \times 1.0 \times 10^{-18} = 5.0 \times 10^{-22} \text{ W.}$$

To accumulate the energy equal to the work function we need a time of

$$5.0 \times 10^{-22} \times t = 4.8 \times 10^{-19}, \text{ i.e. } t = \frac{4.8 \times 10^{-19}}{5.0 \times 10^{-22}} = 960 \text{ s or 16 minutes.}$$

b Since in photoelectric experiments there is no time delay in the emission of electrons, light cannot be treated as a wave as this calculation has.

c In the photon theory of light, the energy carried by a photon is given to the electron in one go, not gradually.

- 7 a** Extending the graph, we find a horizontal intercept of about 5.0×10^{14} Hz .
- b** The work function and the critical frequency are related through:
 $hf_c - \phi = 0 \Rightarrow \phi = hf_c = 6.63 \times 10^{-34} \times 5.0 \times 10^{14} = 3.3 \times 10^{-19}$ J = 2.1 eV .
- c** Reading off the graph we find about 2.0×10^{-19} J = 1.25 eV .
- d** It will be a line parallel to the original with a horizontal intercept at 6.0×10^{14} Hz .
- 8 a** $\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{0.250 \times 10} = 2.7 \times 10^{-34}$ m .
- b** No, because to show diffraction effects, the brick would have to go through openings of size similar to the wavelength, and this is not possible.
- 9 a** The Davisson–Germer experiment (see page 395 in *Physics for the IB Diploma*).
- b** $p = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{680 \times 10^{-9}} = 9.75 \times 10^{-28}$ N s .
Hence $v = \frac{p}{m} = \frac{9.75 \times 10^{-28}}{9.1 \times 10^{-31}} = 1.1 \times 10^3$ ms⁻¹ .
- 10 a** The kinetic energy of the electron will be $E_K = qV$ and so
 $\frac{p^2}{2m} = qV \Rightarrow p = \sqrt{2mqV}$.
Then $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mqV}}$.
- b** $\frac{\lambda_p}{\lambda_\alpha} = \frac{\frac{h}{\sqrt{2m_p q_p V}}}{\frac{h}{\sqrt{2m_\alpha q_\alpha V}}} = \sqrt{\frac{m_\alpha q_\alpha}{m_p q_p}} \approx \sqrt{4 \times 2} = \sqrt{8}$.
- c** From $E_K = \frac{p^2}{2m}$ we find
 $p = \sqrt{2mE_K} = \sqrt{2 \times 9.1 \times 10^{-31} \times 520 \times 1.6 \times 10^{-19}} = 1.23 \times 10^{-23}$ N s .
Hence $\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{1.23 \times 10^{-23}} = 5.4 \times 10^{-11}$ m .



- 11 a** The intensity is $I = \frac{P}{A} = \frac{nhf}{A}$, where n is the number of photons incident per second.

Then $I = \Phi hf$, where $\Phi = \frac{n}{A}$ is the number of photons per second per unit area.

b
$$I = \Phi hf = \frac{\Phi hc}{\lambda} = \frac{3.8 \times 10^{18} \times 6.63 \times 10^{-34} \times 3.0 \times 10^8}{5.0 \times 10^{-7}} = 1.5 \text{ W m}^{-2}.$$

c
$$\frac{\Phi hc}{\lambda} = \frac{\Phi' hc}{\lambda'} \Rightarrow \Phi' = \frac{\lambda'}{\lambda} \Phi = \frac{4.0 \times 10^{-7}}{5.0 \times 10^{-7}} = 3.0 \times 10^{18} \text{ m}^{-2} \text{ s}^{-1}.$$

- d** Since the intensity is the same, the flux for the shorter wavelength is less and hence fewer electrons will be emitted since fewer photons are incident.
- e** This assumes that the fraction of photons that eject electrons is the same for both wavelengths. This fraction is called the quantum efficiency, which in general does depend on wavelength in a complex way.

Additional problems

- A1 a** Assume that a current I is established in a conductor of cross-sectional area A and that there are n free electrons per unit volume of the conductor. Show that the current in the conductor is given by the expression $I = neAv$, where v is the drift velocity of the electrons.
- b** Photons are incident on a photosurface of area A and electrons are emitted from the surface at a rate of r electrons per unit area per unit time. Show that the current leaving the photosurface is $I = rAe$.
- c** More energetic photons are now incident on the photosurface at the same rate as in **b** and so the emitted electrons have a greater speed. By reference to the results in **a** and **b** discuss the effect of the greater electron speed on the photocurrent.

Solution

- a** In 1 second the number of electrons that will go past a cross-sectional area of the conductor is $1 \times nAv$ and so the charge per unit time crossing this area, i.e. the current, is $I = neAv$.
- b** Since we have r electrons per unit area per unit time, the number of electrons leaving an area A per unit time is rA and hence the charge they carry per unit time, i.e. the current, is $I = erA$.
- c** According to $I = erA$ speed should play no role but according to $I = neAv$ it looks like speed does play a role!

In time dt the number of emitted electrons from an area A is $rAdt$. These electrons are confined within a cylinder of cross-sectional area A and height vdt . Therefore the electron number density is $n = \frac{rAdt}{Avdt} = \frac{r}{v}$.

Substituting in the current formula, $I = nevA = \frac{r}{v}evA = reA$ just as in **b**, so speed plays no role.