Quantum Physics

A Level Physics 9702

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By the end of this topic I can...

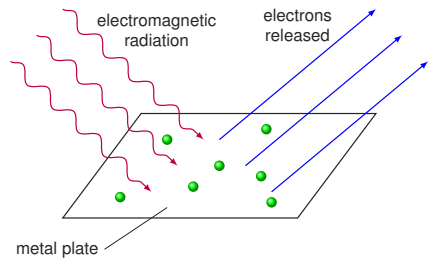
- use the photon model $E = hf = hc/\lambda$ and the electronvolt
- explain the photoelectric effect; use $hf = \Phi + E_{k,\text{max}}$
- use photon momentum and the de Broglie wavelength
- explain line spectra, energy levels and energy bands

Light: particle or wave?

- Newton (1671): **corpuscles**; fails for interference and diffraction
- Huygens (1678): **waves** in the aether; aether disproved
- Maxwell (1865): an **electromagnetic wave**, $c = 1/\sqrt{\epsilon_0 \mu_0}$
- the photoelectric effect breaks the wave model

The photoelectric effect

- electrons released if $f > f_0$ (**threshold frequency**)
- emission is **immediate**
- greater **intensity**: more electrons, same maximum K.E.
- higher **frequency**: greater maximum K.E.
- wave theory predicts none of these



Photons

Photon

A packet (quantum) of **electromagnetic energy**.

- $h = 6.63 \times 10^{-34}$ J s
- $1\ \text{eV} = 1.60 \times 10^{-19}$ J

$$E = hf = \frac{hc}{\lambda}$$

$$I = \frac{nhf}{A}$$

Example: laser photons

Example: laser photons

(a) $E = \dfrac{hc}{\lambda} = \dfrac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{650 \times 10^{-9}} = 3.06 \times 10^{-19}\ \text{J}$

(b) $N = \dfrac{P}{E} = \dfrac{2.0 \times 10^{-3}}{3.06 \times 10^{-19}} = 6.5 \times 10^{15}\ \text{s}^{-1}$

Einstein's photoelectric equation

Work function

The **minimum energy** needed for an electron to **escape** the metal.

- one photon gives its energy to **one** electron
- $f < f_0$: no emission

$$hf = \Phi + E_{k,\max}$$

$$hf_0 = \Phi$$

Example: gold

Example: gold

$$f_0 = \frac{\Phi}{h} = \frac{4.9 \times 1.60 \times 10^{-19}}{6.63 \times 10^{-34}} = 1.18 \times 10^{15} \text{ Hz}$$

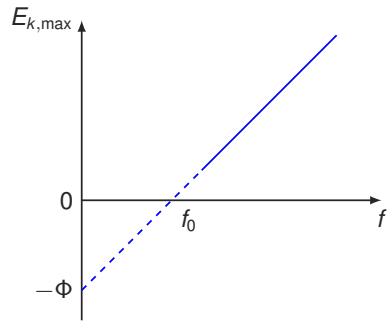
$$\lambda_0 = \frac{c}{f_0} = \frac{3.00 \times 10^{8}}{1.18 \times 10^{15}} = 2.54 \times 10^{-7} \text{ m (ultraviolet)}$$

Stopping voltage and the graph

Reverse p.d. that stops the fastest electrons:

$$E_{k,\max} = eV_{\text{stop}}$$

- plot $E_{k,\max}$ against f
- gradient $= h$; y-intercept $= -\Phi$
- x-intercept $= f_0$

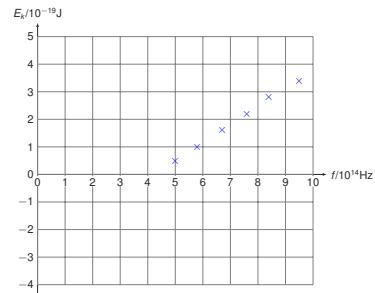


Question: reading the graph

The graph shows the maximum K.E. of photoelectrons against the frequency of the radiation. Use it to find (a) the threshold frequency and (b) a value of the Planck constant.

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(a) The best-fit line cuts the f-axis at about 4.2×10^{14} Hz.

(b) Gradient $= \dfrac{(3.4 - 0.5) \times 10^{-19}}{(9.5 - 5.0) \times 10^{14}} \approx 6.4 \times 10^{-34}$ J s, so $h \approx 6.4 \times 10^{-34}$ J s (accepted value 6.63×10^{-34}).

Photon momentum

Photons carry momentum (Compton, 1923):

$$p = \frac{h}{\lambda}$$

$$p = \frac{P}{cA}$$

- radiation exerts a **pressure**
- small normally, noticeable on spacecraft

Example: light pressure

Example: light pressure

$$E = \frac{hc}{\lambda} = 3.32 \times 10^{-19}\ \text{J}$$

(a) $N = \dfrac{5.0 \times 10^{-3} \times 1.0}{3.32 \times 10^{-19}} = 1.5 \times 10^{16}$

(b) $p = \dfrac{h}{\lambda} = 1.11 \times 10^{-27}\ \text{kg m s}^{-1}$ each, so $\Delta P = Np = 1.67 \times 10^{-11}\ \text{kg m s}^{-1}$

(c) $F = \dfrac{\Delta P}{\Delta t} = 1.67 \times 10^{-11}\ \text{N}$, $p = \dfrac{F}{A} = \dfrac{1.67 \times 10^{-11}}{0.16 \times 10^{-4}} = 1.0 \times 10^{-6}\ \text{Pa}$

de Broglie wavelength

de Broglie wavelength

All matter has a **wave** nature, with wavelength set by its **momentum**.

- a person: $\lambda \sim 10^{-36}$ m, unobservable
- an electron at 50 V: $\lambda \sim 10^{-10}$ m, like an atom

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

Example: accelerated electron

Example: accelerated electron

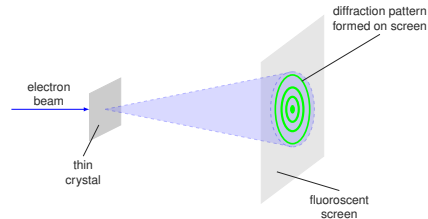
$\frac{1}{2}mv^2 = eV$: $v = \sqrt{\dfrac{2 \times 1.60 \times 10^{-19} \times 50}{9.11 \times 10^{-31}}} = 4.19 \times 10^6 \text{ m s}^{-1}$

$\lambda = \dfrac{h}{mv} = \dfrac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 4.19 \times 10^6} = 1.74 \times 10^{-10} \text{ m}$

This is about an atomic spacing, so crystals can **diffract** the electrons.

Electron diffraction

- electrons through a thin crystal give **rings**
- proves the **wave nature** of electrons (Davisson, Thomson 1927)
- shorter wavelength than light: better **resolution**
- higher p.d.: smaller λ, smaller rings

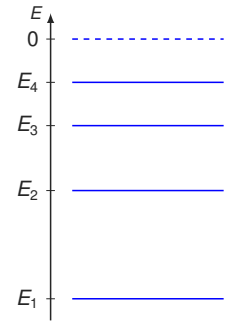


Wave-particle duality

- light and electrons **propagate** as waves
- they **interact** as particles
- applies to all matter

Energy levels

- electron energies are **quantised**
- lowest level: **ground state**; higher: excited states
- levels are **negative** ($E = 0$ means free)
- transitions emit or absorb a photon

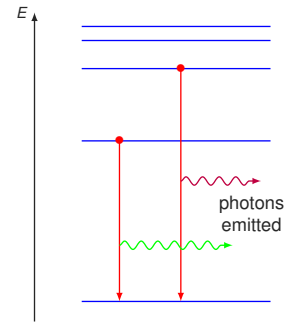


Photon energy and transitions

Photon energy equals the level difference:

$$hf = E_{\text{high}} - E_{\text{low}}$$

- **emission**: electron falls; bright lines
- **absorption**: electron rises; dark lines
- each element has a unique spectrum



Line spectra

- continuous spectrum: white light
- emission: bright lines on dark
- absorption: dark lines on continuous

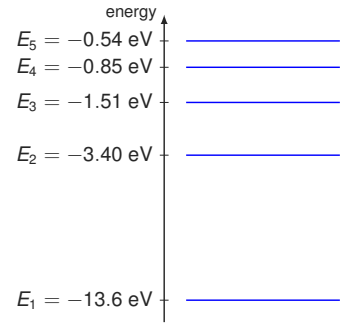


Example: hydrogen wavelengths

Some energy levels of hydrogen are shown ($E_1 = -13.6$, $E_2 = -3.40$, $E_3 = -1.51$, $E_4 = -0.85$, $E_5 = -0.54$ eV). Find the longest and shortest wavelengths produced by transitions between them.

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Smallest ΔE gives the longest wavelength: $E_5 \to E_4$:

$$\lambda = \frac{hc}{\Delta E} = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{(0.85 - 0.54) \times 1.60 \times 10^{-19}} =$$

4.0×10^{-6} m (infrared)

Largest ΔE: $E_5 \to E_1$:

$$\lambda = \frac{hc}{(13.6 - 0.54) \times 1.60 \times 10^{-19}} = 9.5 \times 10^{-8} \text{ m}$$

(ultraviolet)

Example: visible lines

Example: visible lines

$E_{\text{max}} = \dfrac{hc}{380\ \text{nm}} = 5.23 \times 10^{-19}\ \text{J} = 3.27\ \text{eV}; \quad E_{\text{min}} = \dfrac{hc}{740\ \text{nm}} = 2.69 \times 10^{-19}\ \text{J} = 1.68\ \text{eV}$

Look for level differences between 1.68 and 3.27 eV:

$E_3 \to E_2$: $3.40 - 1.51 = 1.89$ eV (656 nm, H_α)

$E_4 \to E_2$: $3.40 - 0.85 = 2.55$ eV (486 nm, H_β)

$E_5 \to E_2$: $3.40 - 0.54 = 2.86$ eV (435 nm, H_γ)

Example: a dark line

Example: a dark line

$$E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{435 \times 10^{-9}} = 4.57 \times 10^{-19}\ \text{J} = 2.86\ \text{eV}$$

$3.40 - 0.54 = 2.86$ eV, so the electron moves $E_2 \rightarrow E_5$ (absorption).

Question: helium in the Sun

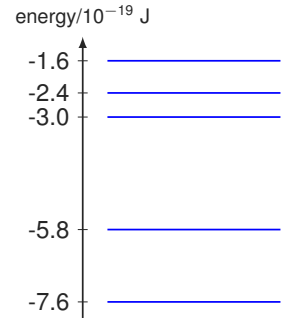
Sunlight shows a dark line at 590 nm. Using the helium energy levels (in 10^{-19} J: -7.6, -5.8, -3.0, -2.4, -1.6), suggest how this shows helium in the Sun's atmosphere.

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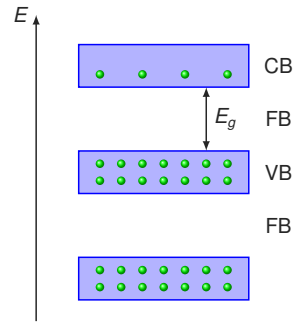
$$E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{590 \times 10^{-9}} = 3.4 \times 10^{-19} \text{ J}$$

This equals the gap between the -5.8 and -2.4 levels ($5.8 - 2.4 = 3.4$), so helium atoms in the cool outer atmosphere absorb this wavelength by an electron transition from the -5.8 level to the -2.4 level.



Energy bands

- levels split into **bands** in a solid
- **valence band** (VB), **conduction band** (CB)
- gap between them: **band gap** E_g
- metals: bands overlap
- insulators: large E_g; semiconductors: small E_g



Example: silicon in red light

Example: silicon in red light

$E = \dfrac{hc}{\lambda} = 3.32 \times 10^{-19}\ \text{J} = 2.1\ \text{eV} > E_g$

Photons can lift valence electrons into the conduction band, creating electron–hole pairs, so silicon **becomes conducting**.

Key equations

photon	$E = hf = \dfrac{hc}{\lambda}$	de Broglie	$\lambda = \dfrac{h}{p} = \dfrac{h}{mv}$
photoelectric	$hf = \Phi + E_{k,\max}$	transition	$hf = E_{\text{high}} - E_{\text{low}}$
momentum	$p = \dfrac{h}{\lambda}$		