# Quantum Physics

Name _____ Date _____

**By the end of this topic I can…**

- use the photon model: $E = hf = hc/\lambda$, and the electronvolt
- explain the photoelectric effect and use $hf = \Phi + E_{k,\max}$
- use photon momentum $p = h/\lambda$ and the de Broglie wavelength $\lambda = h/p$
- explain energy levels and line spectra, and use band theory for conductors, insulators and semiconductors

## From classical models to photons

Four ideas take us beyond classical physics: photons and the photoelectric effect, matter waves, atomic energy levels and spectra, and energy bands in solids.

### Particle and wave models

• **particle model**: a system of particles obeying _____ (electric current, ideal gas pressure, radioactive decay)

• **wave model**: energy transferred by vibrations of a medium or field (water, sound, light). The characteristic wave behaviours come from _____: _____ and _____.

### A history of light

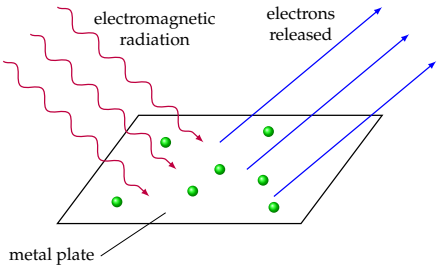
• **Corpuscular theory** (Newton, 1671): light is a stream of particles. It explains straight lines and reflection, but not _____.

• **Wave theory** (Huygens, 1678): light is a wave in the _____. It explains interference (Young's double slit) and diffraction, but the aether was disproved.

• **Electromagnetic theory** (Maxwell, 1865): light is an _____, travelling at $c = \dfrac{1}{\sqrt{\epsilon_0 \mu_0}} = 3.00 \times 10^8 \text{ m s}^{-1}$ with no medium needed.

By the late 1800s, everything known about light seemed explained by waves…

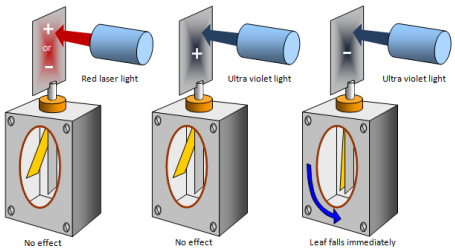
# Photons and the photoelectric effect




## The photoelectric effect

When electromagnetic radiation of high enough frequency falls on a metal, the _____ releases electrons, called _____, from the surface (first seen by Hertz, 1887).

- **observations**:
- there is a minimum _____ $f_0$: no electrons are emitted if $f < f_0$
- emission is _____, even for very faint light above $f_0$
- a greater _____ gives more electrons per second, but _____ in their maximum energy
- a higher _____ gives electrons of greater maximum energy
- **wave theory fails**: it predicts that electrons gradually build up energy (so any frequency should work with enough time), that dim light needs a delay, that greater intensity gives greater K.E., and that frequency should not affect K.E.




- **demonstration**: a clean zinc plate on a gold-leaf electroscope. Charged _____, the leaf falls under UV light (electrons leave). Charged _____, the leaf is unaffected (the electrons are attracted back).

## Photon theory

Einstein (1905) proposed that radiation is delivered in packets of energy.

A _____ is a packet (quantum) of _____.

- energy of one photon, with the _____
$h = 6.63 \times 10^{-34}$ J s:

• higher frequency (shorter wavelength) means _____ photon energy

• the _____ of a beam is power per unit area. With $n$ photons per second:

• **electronvolt**: 1 eV is the energy gained by an electron moving through a p.d. of 1 V, so 1 eV = _____

**Example 29.1** A laser emits red light of wavelength 650 nm at a power of 2.0 mW. (a) What is the energy of one photon? (b) How many photons are emitted per second?

**Question 29.1** Calculate the energy, in eV, of a photon of wavelength 440 nm.

**Question 29.2** The red laser is replaced by a green laser of the same power. How does the number of photons emitted per second change?

## The photoelectric effect explained

• the _____ $\Phi$ is the minimum energy needed for an electron to _____ from the metal surface

• one photon is absorbed by _____ electron (all or nothing). If $hf > \Phi$ the electron escapes and the excess becomes kinetic energy:

This is _____; $E_{k,\max}$ is the maximum K.E. (electrons from deeper below the surface lose extra energy).

- at the threshold frequency the photon has just enough energy:

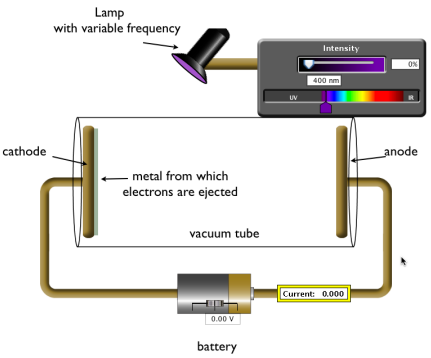
- **observations explained**: $f < f_0$ gives photon energy $< \Phi$, so _____; one-to-one interaction means _____; more intensity means more photons so more _____; higher $f$ means more photon energy so greater _____

**Example 29.2** The work function of gold is 4.9 eV. Find the longest wavelength of radiation that releases electrons from gold.

**Question 29.3** Sodium has a work function of $3.8 \times 10^{-19}$ J. (a) Find its threshold frequency. (b) Can light of wavelength 500 nm release electrons?

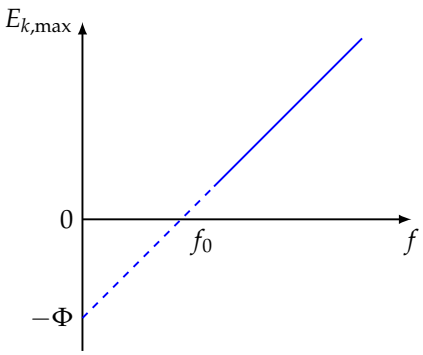
**Question 29.4** Radiation of wavelength 1200 nm releases electrons of maximum K.E. $5.4 \times 10^{-20}$ J from a metal. What is the work function?

**Question 29.5** Light of one frequency and intensity releases electrons from a metal. Light of the same intensity but higher frequency is used. What happens to the rate of emission?



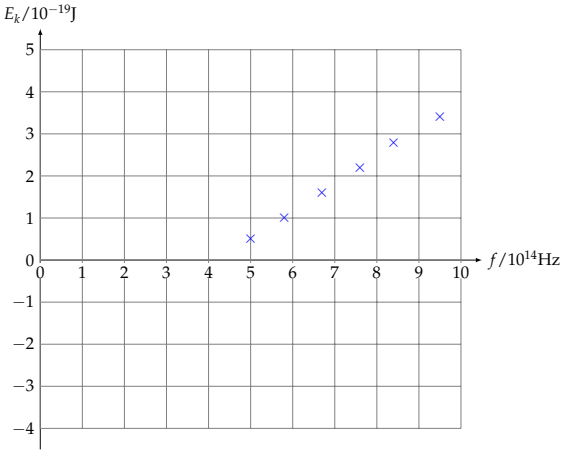

## Measuring $h$ and the work function

• photocell: illuminate the metal with (nearly) _____ light of known frequency and raise the reverse p.d. until the current is _____: this is the _____ $V_{\text{stop}}$:




• repeat for several frequencies, plot $E_{k,\max}$ against $f$. Comparing $E_{k,\max} = hf - \Phi$ with $y = mx + c$: gradient = _____, $y$-intercept = _____, $x$-intercept = _____

**Question 29.6** A metal with a greater work function is used. Describe the change to the $E_{k,\max}$–$f$ line.




**Question 29.7** 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.

## Photon momentum

Photons have _____ even though they have no mass (Compton, 1923):

This follows from $E = pc$ for photons and $E = hf$. Radiation exerts _____, small in everyday life but noticeable on spacecraft and comet tails.

**Example 29.3** A beam of wavelength 600 nm, power 5.0 mW and cross-sectional area 0.16 $cm^2$ falls normally on a surface and is completely absorbed. For 1.0 s, find (a) the number of photons, (b) the change of momentum, (c) the pressure.

**Question 29.8** Show that a laser of power $P$ on a spot of area $A$ (fully absorbed) causes pressure $p = \frac{P}{cA}$.

**Question 29.9** An electron and a positron with negligible K.E. annihilate to produce two $\gamma$-photons. Explain why the photons move off in opposite directions with equal energies.

# Wave–particle duality

## Matter waves

Inspired by photons, de Broglie (1924) suggested that all matter has a _____ nature.

The _____ of a particle of momentum $p = mv$:

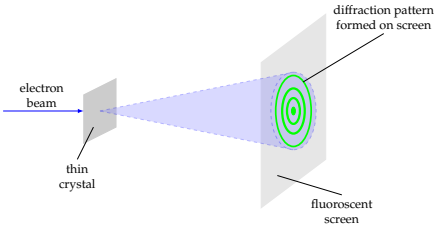
**Example 29.4** What is the wavelength of a 70 kg human walking at 2.0 m $s^{-1}$?

**Example 29.5** An electron is accelerated from rest through 50 V. What is its de Broglie wavelength?

**Question 29.10** An $\alpha$-particle has K.E. $2.4 \times 10^{-15}$ J. Find its speed and de Broglie wavelength.

**Question 29.11** A proton and an electron are accelerated through the same voltage. Compare (a) their energies and (b) their wavelengths.

## Electron diffraction




Davisson and Thomson (1927) fired electrons at a thin crystal and saw _____ on a fluorescent screen: a diffraction pattern, which proves the _____ nature of electrons. Electron wavelengths are much shorter than light, so an electron microscope has _____.

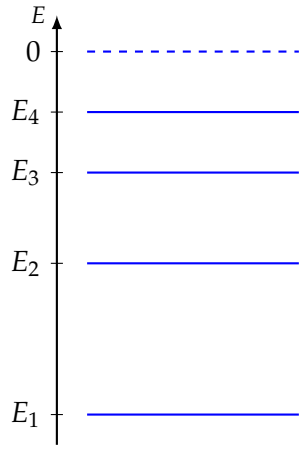
**Question 29.12** A higher accelerating p.d. is used in the electron diffraction experiment. How does the pattern change?

## Wave–particle duality

| | radiation | electron |
|---|---|---|
| particle-like | _____, radiation pressure | deflection in fields, collisions |
| wave-like | interference, diffraction, refraction | _____ |

Moving through space, light and electrons behave like _____; when they interact, they behave like _____. This is _____, and it applies to all matter.

# Energy levels and spectra



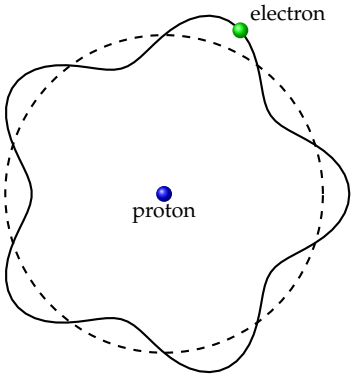

## Quantised energy levels

An electron in an atom behaves as a wave. Only orbits where it can _____ with itself exist, so the electron can only have certain _____: energy levels.

• energy is _____: no values between the levels. The lowest level is the _____; higher levels are _____.

• levels are _____: energy must be supplied to pull the electron away. At infinity $E = 0$ (a free electron).

• electrons _____ between levels by emitting or absorbing a photon




## The hydrogen atom (Bohr model, extension)

Electrostatic attraction provides the centripetal force: $\frac{e^2}{4\pi\epsilon_0 r^2} = \frac{m_e v^2}{r}$.

The orbit must fit a whole number of de Broglie wavelengths: $2\pi r = n\lambda = \frac{nh}{m_e v}$.

Eliminating $v$: [ ] with

$a_0 = \frac{h^2\epsilon_0}{\pi m_e e^2} = 5.29 \times 10^{-11}$ m

Total energy $E = E_k + E_p = -\frac{e^2}{8\pi\epsilon_0 r}$ gives

[ ] $R_E = 2.18 \times 10^{-18}$ J $= 13.6$ eV

## Emission and absorption

Photon energy equals the _____:

[ ]

• **emission spectrum**: hot gas; electrons fall to _____ levels emitting photons; _____ on a dark background. Each element has its own _____ set of lines.

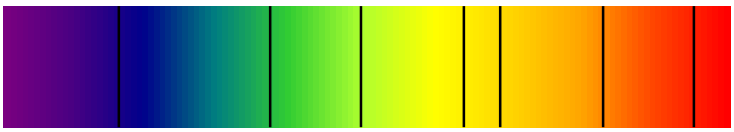
• **absorption spectrum**: white light through cool gas; photons of the right energy are absorbed (electrons move _____); _____ on a continuous spectrum. Re-emitted photons go in random directions.



*Continuous spectrum (white light).*

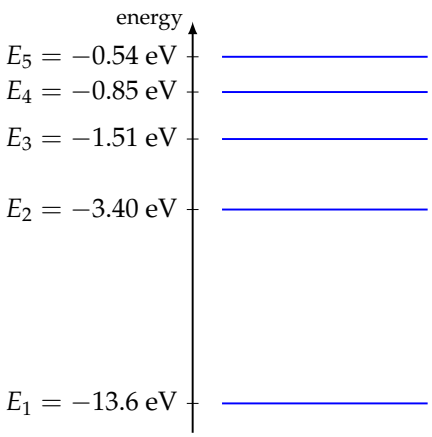


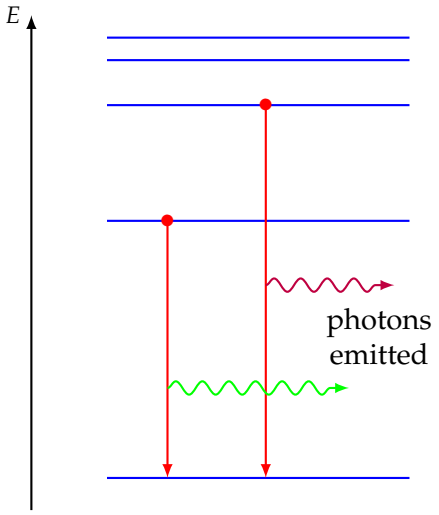
*Emission line spectrum (hydrogen).*



*Absorption line spectrum.*

• uses: flame colours, identifying elements, gas-discharge lamps, composition of stars






**Example 29.6** 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.

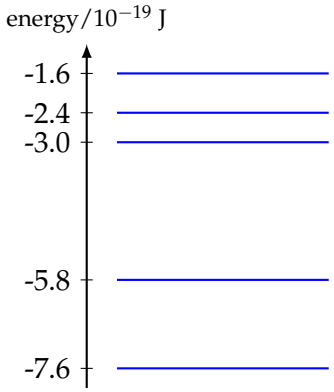
**Example 29.7** Visible light has wavelengths 380 nm to 740 nm. Find the energies of visible photons produced by transitions between the levels shown.

**Example 29.8** White light passes through cool hydrogen gas. A dark line appears at 435 nm. Which transition causes it?

**Question 29.13** With only the five levels in the example, how many different wavelengths can appear in the emission spectrum?

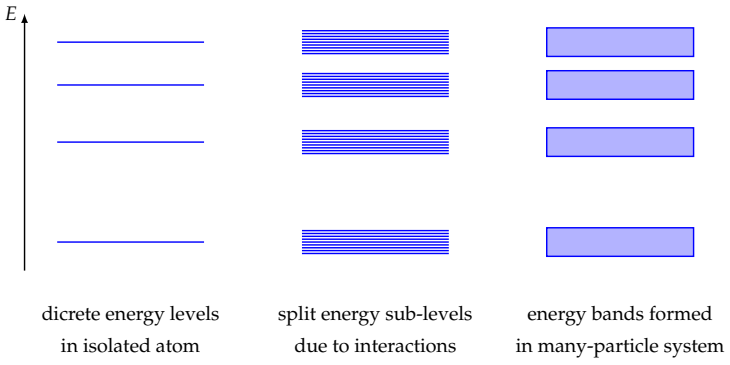
**Question 29.14** Hydrogen lines are seen at 486 nm, 656 nm and 1880 nm. (a) Calculate the photon energies. (b) Draw an energy level diagram with three labelled levels showing these transitions.

**Question 29.15** 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.



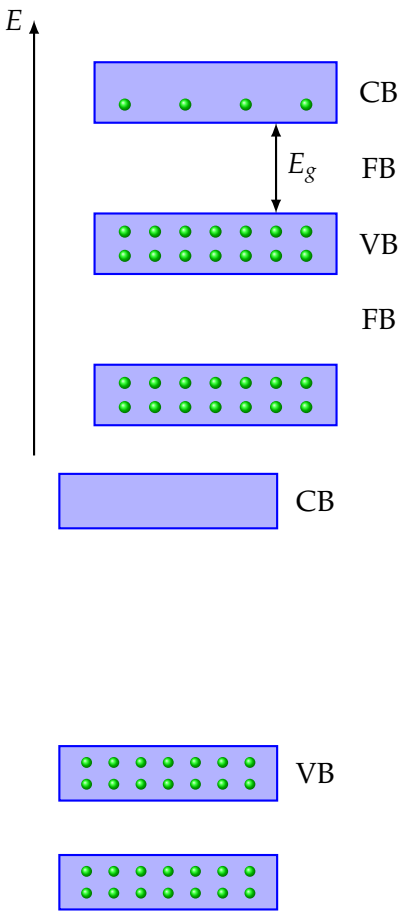

## Band theory (extension)

### Energy bands




In a solid, interaction between atoms splits each level into many closely spaced sub-levels (one per atom), forming _____, separated by _____.

• the highest filled band is the _____ (VB); the next band is the _____ (CB); the gap between them is the _____ $E_g$



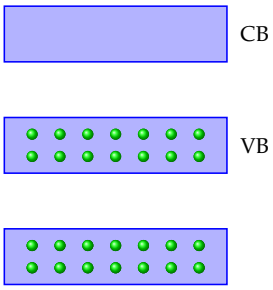

## Conductivity

• **metals**: the CB _____ the VB (no gap), so there are many free electrons. Resistance _____ with temperature (more lattice vibrations). Metals are _____ to visible light, which is absorbed by conduction electrons, but transparent to X-rays.

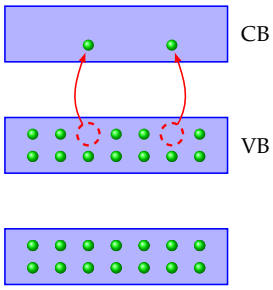
• **insulators**: VB full, CB empty, and a _____ band gap ($\gtrsim$ 5 eV). Thermal energy cannot promote electrons, so very few charge carriers.

**Question 29.16** Diamond has $E_g \approx 6.0$ eV. Explain why it is transparent to visible light.




band structure of an intrinsic semiconductor at low temperature




at higher temperature VB electrons cross band gap and enter CB

• **intrinsic semiconductors** (Si, Ge): similar to insulators but with a _____ band gap. As temperature rises, VB electrons cross into the CB, leaving _____ in the VB (positive charge carriers). More carriers means _____ resistance.

**Example 29.9** Silicon has $E_g \approx 1.1$ eV. Does it become conducting in 600 nm red light?

**Question 29.17** Use band theory to explain why an LDR has high resistance in the dark but low resistance in the light.