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 _____.

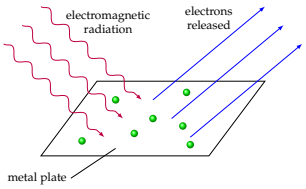
• **Wave theory** (Huygens, 1678): light is a wave in the _____. It explains interference (Young's double slit) and diffraction, but the aether was disproved.

• **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…

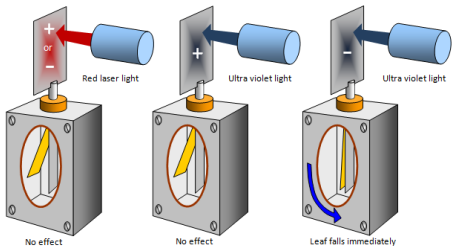
Photons and the photoelectric effect

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 _____ Φ 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 _____

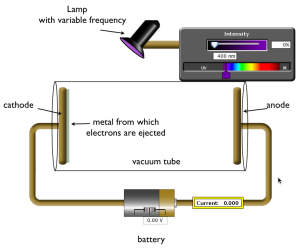
Example 29.2 The work function of gold is 4.9 eV. Find the longest wavelength of radiation that releases electrons from gold.

Question 29.3 Sodium has a work function of 3.8×10^{-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. 5.4×10^{-20} J from a metal. What is the work function?

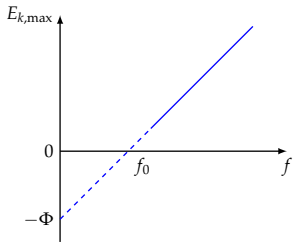
Question 29.5 Light of one frequency and intensity releases electrons from a metal. Light of the same intensity but higher frequency is used. What happens to the rate of emission?

Measuring h and the work function

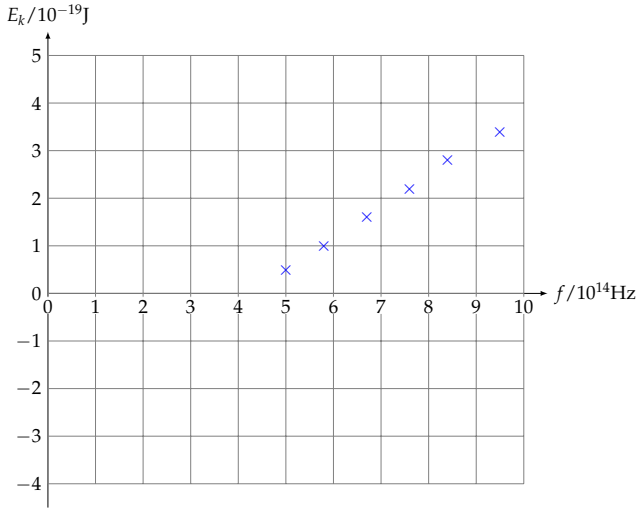


• photocell: illuminate the metal with (nearly) _____ light of known frequency and raise the reverse p.d. until the current is _____: this is the _____ V_{stop}:

• 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 $p = \dfrac{P}{cA}$.

Question 29.9 An electron and a positron with negligible K.E. annihilate to produce two γ-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 $p = mv$:

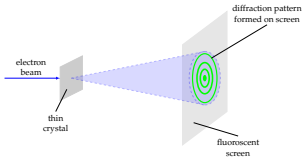
Example 29.4 What is the wavelength of a 70 kg human walking at 2.0 m s^{-1}?

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

Question 29.10 An α-particle has K.E. 2.4×10^{-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?

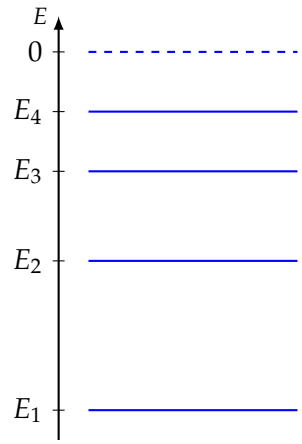
Wave–particle duality

	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.

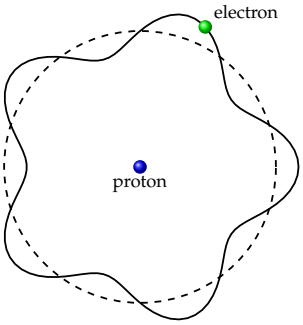
Energy levels and spectra

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

$R_E = 2.18 \times 10^{-18}\,\text{J} = 13.6\,\text{eV}$

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.

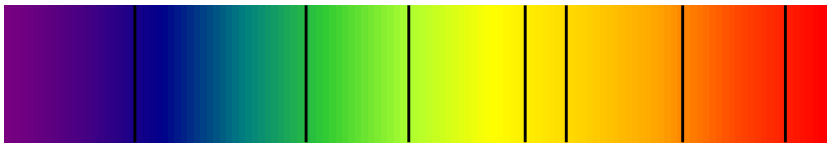
• **absorption spectrum**: white light through cool gas; photons of the right energy are absorbed (electrons move _____); _____ on a continuous spectrum. Re-emitted photons go in random directions.



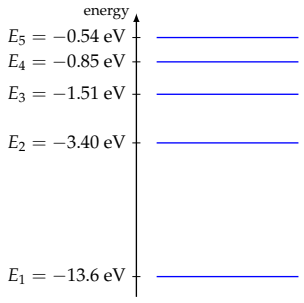
Continuous spectrum (white light).



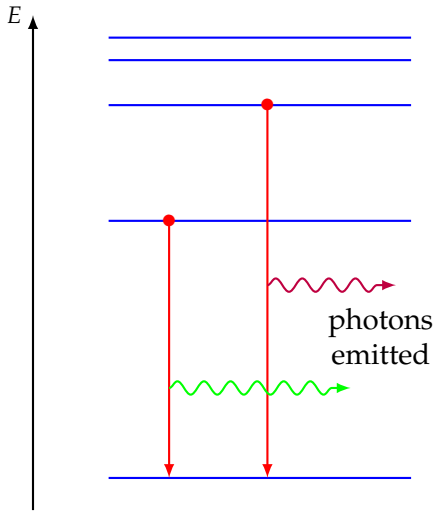
Emission line spectrum (hydrogen).



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.

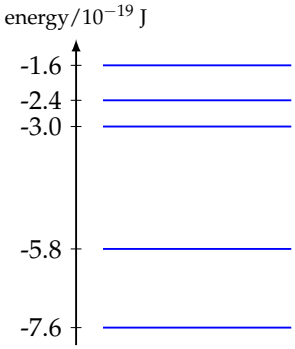
Example 29.7 Visible light has wavelengths 380 nm to 740 nm. Find the energies of visible photons produced by transitions between the levels shown.

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?

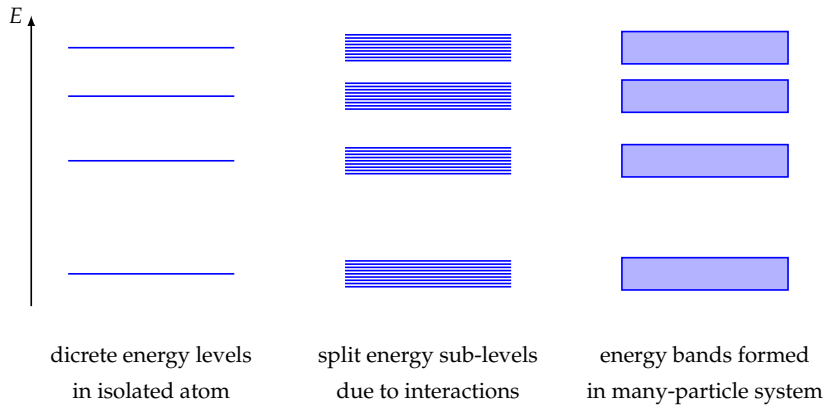
Question 29.14 Hydrogen lines are seen at 486 nm, 656 nm and 1880 nm. (a) Calculate the photon energies. (b) Draw an energy level diagram with three labelled levels showing these transitions.

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.



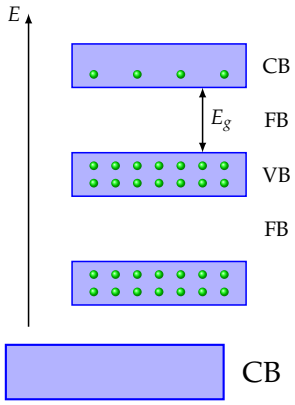
Band theory (extension)

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

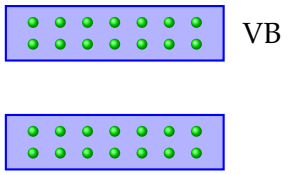


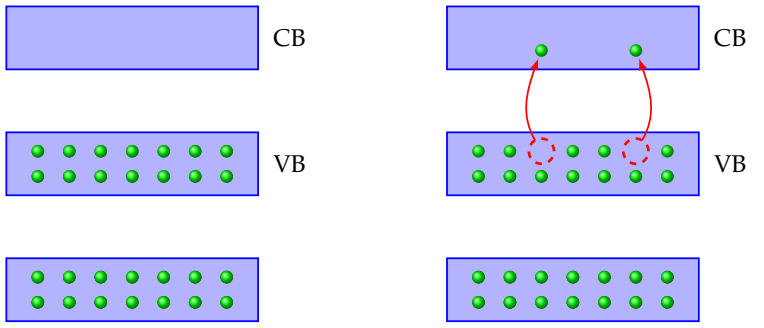
Conductivity

• **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.