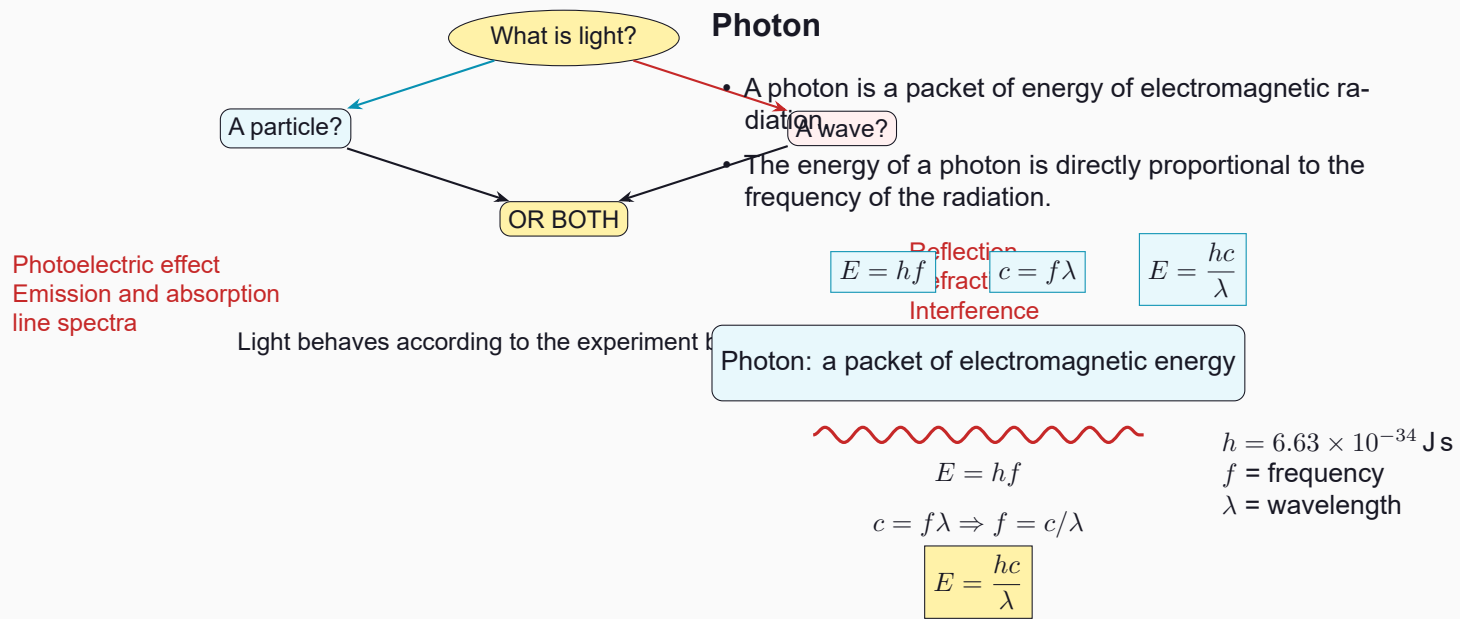


Quantum Physics

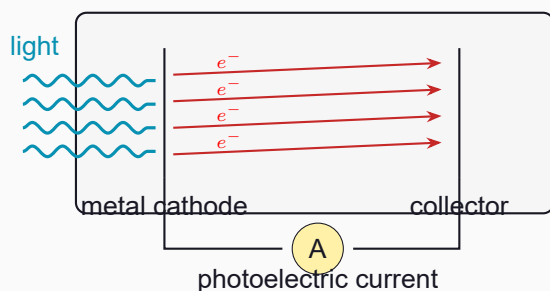
Chapter 12 / A2 Level / Apollo Physics 9702



What is light? Photon energy



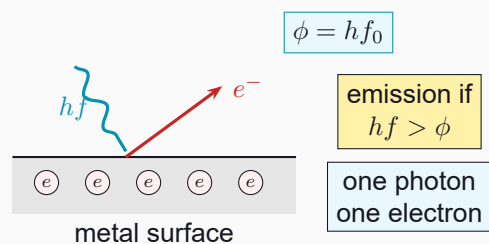
Photoelectric effect: photon energy and work function



No emission occurs if $hf < \phi$. If $hf > \phi$, one photon releases one electron and the excess energy becomes kinetic energy.

Threshold frequency and work function

- Work function energy ϕ : minimum photon energy required to remove an electron from a metal surface with negligible kinetic energy.
- Threshold frequency f_0 : minimum frequency needed for photoelectric emission.
- Planck's constant: $h = 6.63 \times 10^{-34} \text{ J s}$.
- $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$.



Einstein's photoelectric equation

If photon energy is less than the work function

The electron absorbs the photon inside the metal atom, gains vibration energy, collides with neighbouring atoms, and the temperature of the metal increases. No electron leaves the surface.

If photon energy is greater than the work function

$$E = \phi + E_{k \text{ max}}$$

$$hf = \phi + E_{k \text{ max}}$$

Examples from the notes:

$$12 \text{ eV} = 10 \text{ eV} + 2 \text{ eV}, \quad 15 \text{ eV} = 10 \text{ eV} + 5 \text{ eV}.$$

Intensity idea

$$\text{Intensity} = \frac{\text{Energy}}{\text{Area} \times \text{time}}$$

Total energy depends on the number of photons and the energy of each photon:

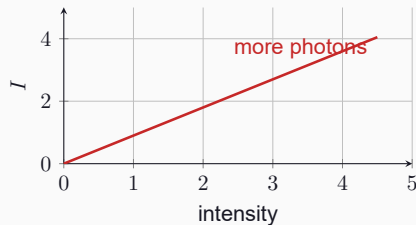
$$\text{Energy} = N \times hf.$$

Increasing frequency increases energy per photon. Increasing intensity at the same frequency increases the number of photons.

Changing intensity and frequency

Intensity increased at the same frequency

- More photons arrive per second.
- $E_{k \text{ max}}$ remains the same because each photon has the same energy.
- Photoelectric current increases because more electrons are emitted per second.



Frequency increased but intensity kept constant

- Photon energy increases.
- $E_{k \text{ max}}$ increases.
- The number of photons must decrease to keep total intensity constant.
- Photoelectric current decreases.

$$400 \text{ eV} = 1000 \times 0.40 \text{ eV} = 200 \times 2.0 \text{ eV}$$

Graph of maximum kinetic energy against frequency

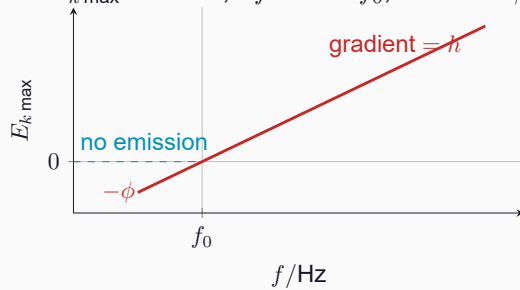
Linear form

$$E_{k \max} = hf - \phi$$

This matches $y = mx + c$:

$$\boxed{y = E_{k \max}}, \quad \boxed{x = f}, \quad \boxed{m = h}, \quad \boxed{c = -\phi}.$$

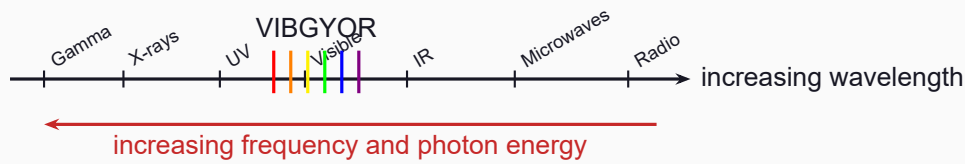
At $E_{k \max} = 0$, $f = f_0$, hence $\phi = hf_0$.



Changing metal

Replacing a red-sensitive metal by a blue-sensitive metal changes the work function and threshold frequency; the gradient remains Planck's constant.

Electromagnetic spectrum and definitions



Photoelectric effect

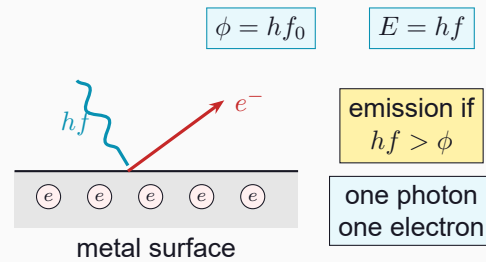
The emission of electrons from the surface of a metal by the incidence of light.

Work function

Minimum energy of a photon needed to remove an electron from the metal surface with negligible kinetic energy.

Threshold frequency

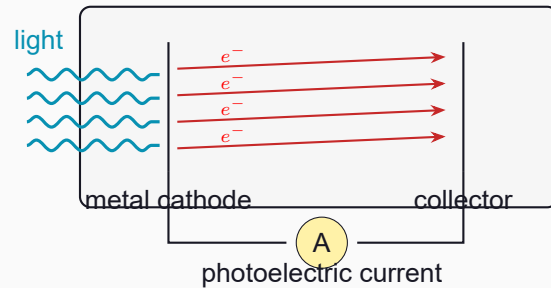
Minimum frequency needed to remove an electron from the metal surface with negligible kinetic energy.



Characteristics of the photoelectric effect

1. Not all electromagnetic radiations produce photoelectric effect. It depends on both the radiation and the metal.
2. If the frequency of the radiation is below the threshold frequency of the metal, no photoelectric effect occurs.
3. One electron absorbs only one photon at a time.
4. There is no time delay between absorption of a photon and emission of an electron if $hf > \phi$.
5. Increasing intensity at fixed frequency increases the rate of emission, not the kinetic energy of electrons.
6. Increasing frequency increases the maximum kinetic energy of emitted electrons.

If $hf < \phi$, the electron does not accumulate photons one by one. The absorbed energy is transferred as internal energy through collisions in the metal.



Electron volt and photoelectric equation

Maximum kinetic energy

$$E = \phi + E_{k \max}$$

$$hf = hf_0 + \frac{1}{2}mv_{\max}^2$$

where m is the mass of electron and v is the electron velocity.

quantity	symbol	meaning
photon energy	hf	incident photon
work function	ϕ	energy to remove electron
maximum kinetic energy	$E_{k \max}$	excess energy
threshold frequency	f_0	just enough frequency

Electron volt

An electron volt is a unit of energy. It is the energy gained by an electron when it moves through a potential difference of 1 V.

$$\text{energy} = \text{voltage} \times \text{charge}$$

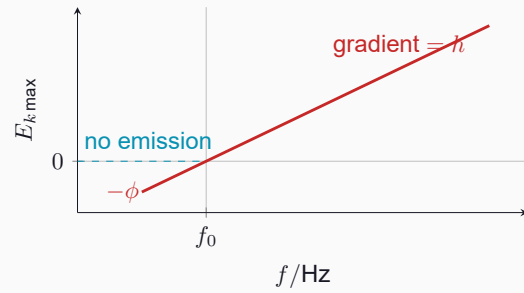
$$1 \text{ eV} = 1 \text{ V} \times e = 1.6 \times 10^{-19} \text{ J}$$

Increasing frequency of incident radiation

Effect on $E_{k \text{ max}}$

If the frequency of the incident radiation is increased, $E_{k \text{ max}}$ increases because the energy of each photon increases while the work function remains the same.

$$E_{k \text{ max}} = hf - \phi$$



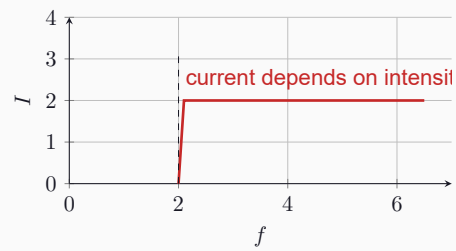
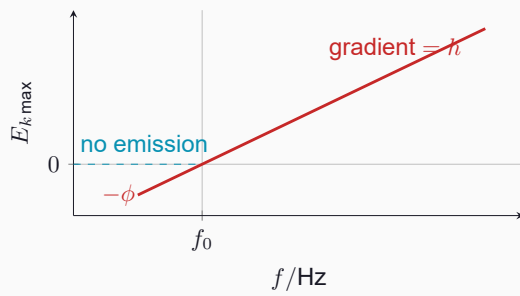
Effect on photoelectric current

The photoelectric current is the rate of emission of electrons from the surface of metal.

- More current: more electrons leave per second.
- Less current: fewer electrons leave per second.

Increasing frequency alone does not necessarily increase current; current mainly depends on photon arrival rate, i.e. intensity.

Variation of current and $E_{k\text{ max}}$ with frequency



Important readings from graph

- Gradient = h .
- y -intercept = $-\phi$.
- x -intercept = f_0 .
- Below f_0 , no photoelectric effect occurs.

Same intensity assumption

When intensity is held fixed, increasing frequency can reduce current because fewer photons are needed to carry the same energy per second.

Increasing intensity at fixed frequency

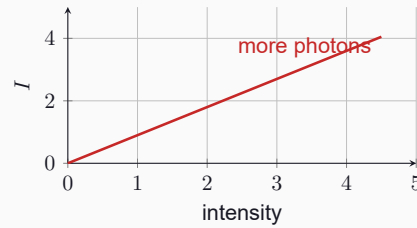
Intensity of electromagnetic radiation

The energy transmitted per unit area per unit time:

$$I = \frac{E}{At}$$

Increasing intensity at fixed frequency means increasing the number of photons incident per second.

- $E_{k \text{ max}}$ stays constant.
- Photoelectric current increases.



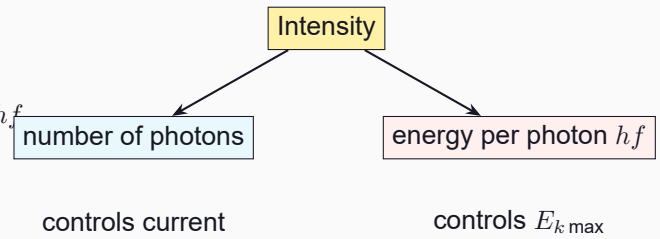
Energy of each photon depends on frequency. Brightness/intensity controls the number of photons when frequency is fixed.

Intensity as number of photons times photon energy

$$\text{Intensity} = \frac{\text{Energy}}{\text{Area} \times \text{time}}$$

Energy = number of photons $\times$ energy of each photon = Nhf

For a particular frequency, increasing intensity means increasing N , not hf .



Consequences

- $E_{k \text{ max}}$ is unchanged.
- Photoelectric current increases.

Same blue light: brighter source

Same blue light means same frequency, hence same photon energy:

$$E = hf = \text{constant}.$$

If the intensity of the same blue light is increased:

- number of photons increases,
- photoelectric current increases,
- maximum kinetic energy stays the same.

same frequency



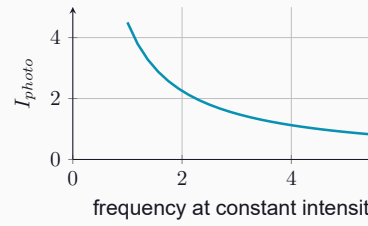
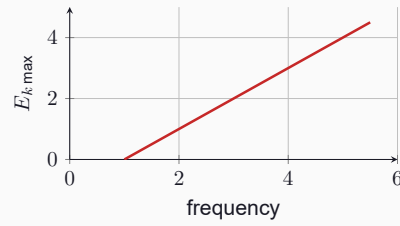
More photons, same energy per photon.

Increasing frequency while keeping intensity constant

At constant intensity

$$I \propto (\text{number of photons}) \times hf.$$

If f increases and I remains constant, the number of photons decreases.



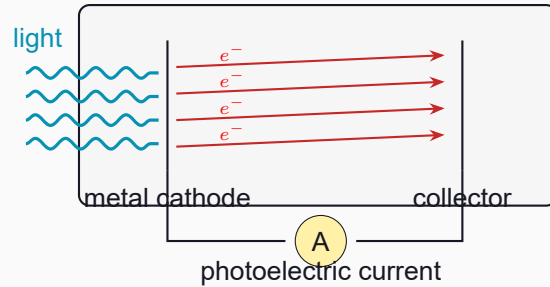
Results

- $E_{k\text{max}}$ increases.
- Photoelectric current decreases.
- Stopping potential increases.

Why photoelectric effect rejects pure wave theory

1. Low-intensity light of high frequency can produce photoelectric effect, whereas high-intensity light of low frequency cannot.
2. Low-frequency light incident for a long time still does not produce emission if $f < f_0$.
3. Wave theory predicts that increasing intensity should increase maximum kinetic energy, but experiments show it increases current instead.
4. There is no time delay between incident light and emission of electrons if $hf > \phi$.

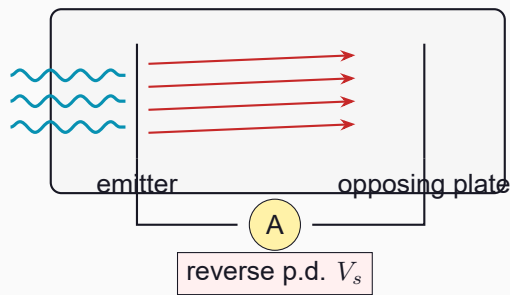
Wave view: energy is continuous.
Particle/photon view: energy arrives in discrete packets.
Photoelectric effect supports the photon model.



Stopping potential

Increase opposite potential difference until current becomes zero.

$$E_{k \max} = eV_s$$



Only electrons with maximum kinetic energy define the stopping potential; slower electrons are stopped earlier.

Meaning

Stopping potential is the minimum opposing potential difference needed to stop the most energetic emitted electrons from reaching the collector.

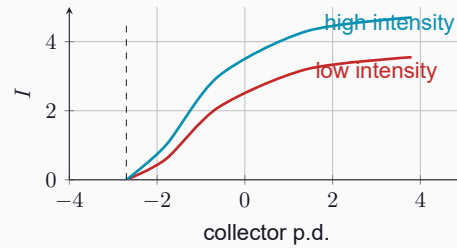
- Electrons are emitted with a range of kinetic energies.
- Increasing the reverse p.d. reduces the current.
- At V_s , the current becomes zero.

Stopping potential: frequency and intensity effects

Increasing frequency

- photon energy increases,
- $E_{k \text{ max}}$ increases,
- more work is needed to stop electrons,
- stopping potential increases.

$$E_{k \text{ max}} = eV_s$$



Increasing intensity

- more electrons are emitted,
- current increases,
- $E_{k \text{ max}}$ is unchanged,
- stopping potential is unchanged.

Work done against stopping potential

Work done against stopping potential equals the loss in kinetic energy of the electron with maximum kinetic energy:

$$V_s q = E_{k \max}$$

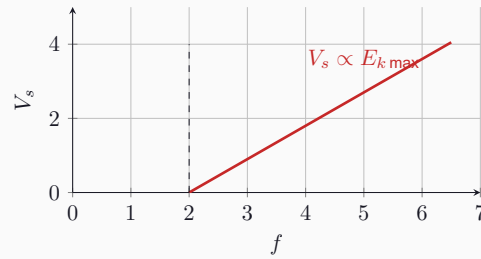
For electron charge $q = e$,

$$E_{k \max} = eV_s$$

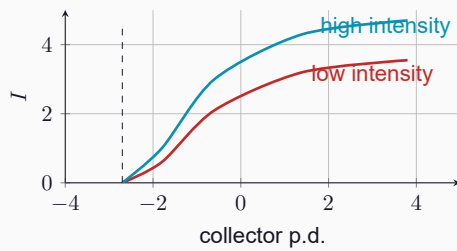
$$\frac{1}{2}mv_{\max}^2 = eV_s$$

Therefore,

$$v_{\max} = \sqrt{\frac{2eV_s}{m}}$$



Current against stopping potential curves



Reading the graph

- High intensity gives a higher saturation current.
- Same frequency gives the same stopping potential.
- Higher frequency shifts the stopping potential to a larger magnitude.

Current reaches zero only when even the fastest photoelectrons are stopped.

Frequency and intensity: final stopping-potential statements

Increasing frequency

Increasing frequency of radiation increases the stopping potential. Electrons now have more kinetic energy, so more work needs to be done to stop them.

$$E_{k\text{ max}} = hf - \phi = eV_s$$

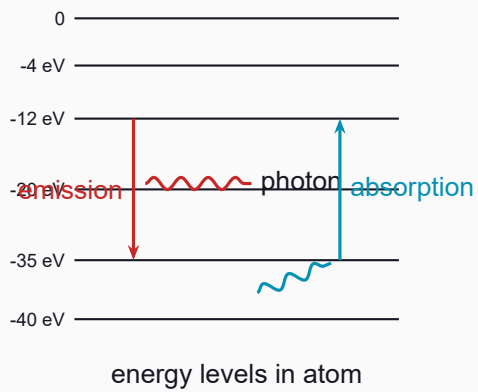
change	$E_{k\text{ max}}$	photoelectric current
increase f	increases	depends on intensity
increase intensity at same f	same	increases
increase intensity and f fixed	same V_s	larger saturation current

Increasing intensity

Increasing intensity of radiation of a fixed frequency only increases the number of photons and therefore more electrons are emitted. The kinetic energy of each electron is still the same because photon energy is unchanged.

$$V_s = \text{unchanged.}$$

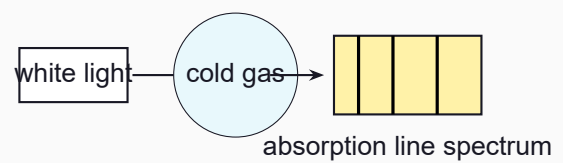
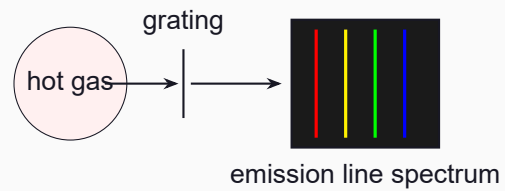
Emission and absorption line spectra



Energy of photon

When an electron changes energy level, a photon is emitted or absorbed:

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



De Broglie wavelength preview

Every moving particle has a wave associated with it.

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

$$p = mv$$

It is inversely proportional to momentum.

For electrons accelerated through V :

$$eV = \frac{1}{2}mv^2 \text{ and } p = \sqrt{2meV}$$

$$\lambda = \frac{h}{\sqrt{2meV}}$$

Interference by electrons

The notes introduce the idea that electrons can behave as waves and produce constructive and destructive interference, giving rings on a fluorescent screen.

thin graphite
rings = constructive interference
empty spaces = destructive interference

fluorescent screen

Energy levels and photons

Hot gas and emission

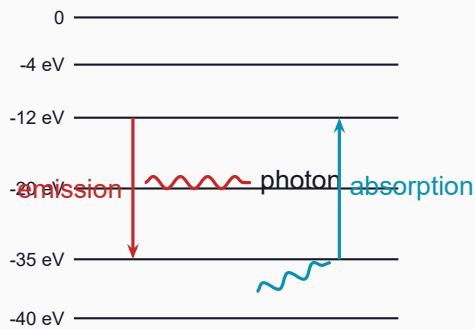
When an electron transits from a higher energy state to a lower energy state, it emits a photon whose energy equals the energy gap.

$$\Delta E = hf$$

Blue/violet photons correspond to larger energy gaps; red photons correspond to smaller energy gaps.

Cold gas and absorption

When an electron transits from a lower energy state to a higher energy state, it absorbs a photon with energy equal



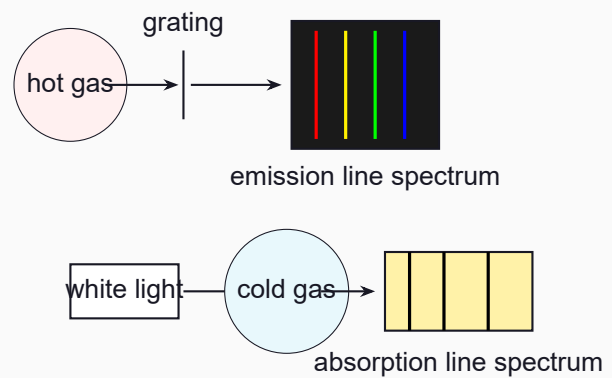
to the gap.

energy levels in atom

Emission line spectra

During the formation of an emission line spectrum, discrete lines of specific colours are observed on a black screen.

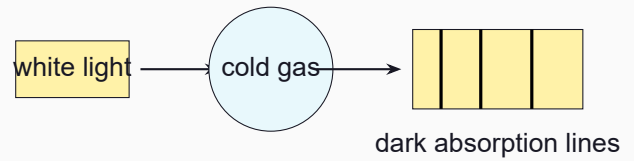
- A cloud of hot gas is used.
- Electrons in the hot gas exist at higher energy states due to high temperature.
- As electrons drop back to more stable lower states, they emit photons of energy equal to the energy gap.
- Hence colours of specific frequencies are observed.



Absorption line spectra

When white light passes through a cloud of cold gas, photons with energy equal to allowed energy gaps are absorbed by electrons.

- Electrons jump from lower to higher energy states.
- Photons of only those specific energies and frequencies are missing from the continuous spectrum.
- Electrons later drop back down and emit photons in random directions, so dark lines remain in the transmitted beam.



Negative energy levels and transition examples

Why energy levels are negative

The negative sign indicates a deficiency of energy in the electron. It tells how much energy must be supplied for the electron to escape the pull of the nucleus.

Transition calculations

$$\Delta E = E_{\text{final}} - E_{\text{initial}}, \quad E_{\gamma} = |\Delta E| = hf = \frac{hc}{\lambda}.$$

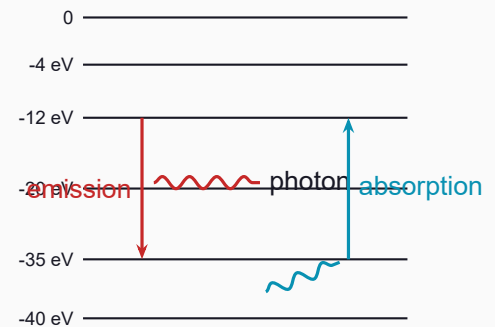
Example style from notes:

$$\Delta E = -0.54 - (-3.40) = 2.86 \text{ eV}$$

$$2.86 \text{ eV} = 2.86(1.6 \times 10^{-19}) \text{ J} = 4.57 \times 10^{-19} \text{ J}.$$

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

If $\lambda \approx 4.34 \times 10^{-7} \text{ m}$, the line is blue. The notes compare absorption and emission transitions through the same



energy gaps.

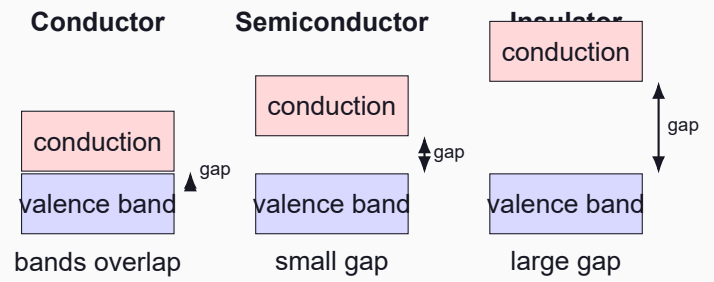
energy levels in atom

Band theory

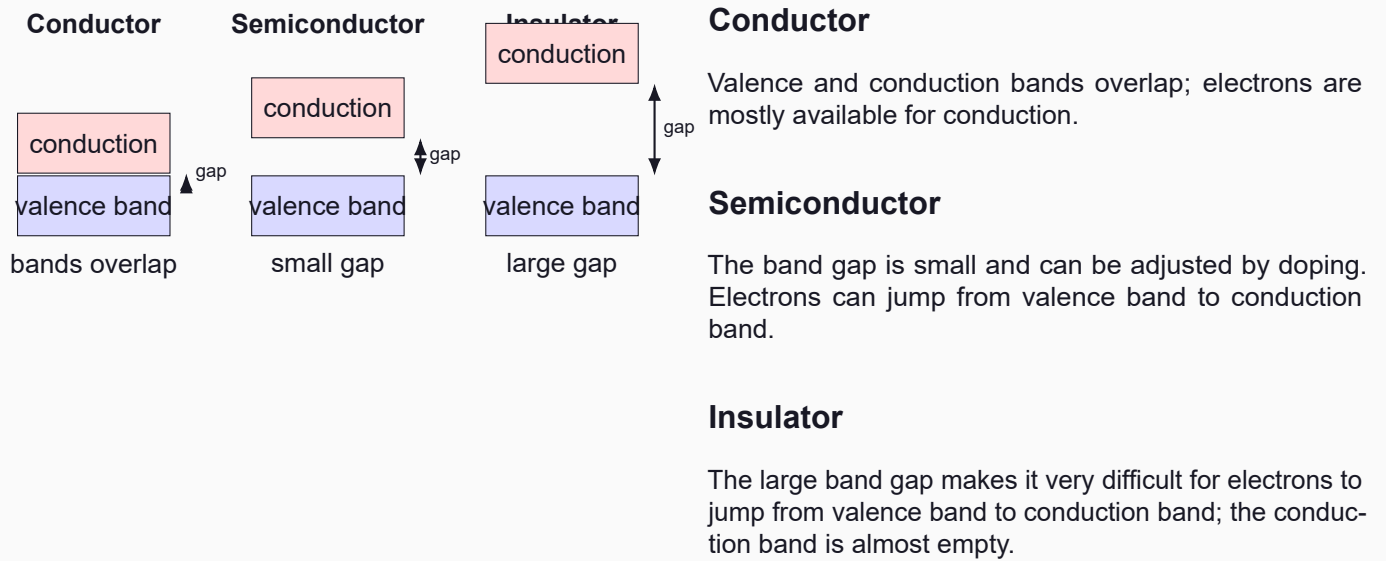
Energy bands in solids and liquids

In gases, atoms are far apart and have distinct energy levels. In solids and liquids, nuclei are close together; neighbouring atoms interfere with each other's energy levels.

- Numerous very close energy levels are produced.
- These levels combine into energy bands.
- Conduction band: electrons here are available for conduction.
- Forbidden band / band gap: region where no electron can exist.
- Valence band: band for valence-shell electrons.



Conductors, semiconductors and insulators



LDR, thermistor and metallic conductors

LDR

- LDR is made from a semiconductor.
- Semiconductors have a small band gap.
- Light provides photons to electrons.
- Electrons gain energy and jump from valence band to conduction band.
- Number density of charge carriers increases, so current increases and resistance decreases.

Thermistor

Increasing temperature gives electrons thermal energy to cross the band gap, increasing number density and decreasing resistance.

Metallic conductor

In metals, valence and conduction bands overlap. The conduction band is already saturated with electrons. When temperature increases, lattice ions vibrate more, causing more collisions with electrons; resistance increases.

Semiconductor: temperature/light increases carriers.

Metal: temperature increases scattering.

De Broglie's wavelength and electron diffraction

Every moving particle has a wave associated with it, which is inversely proportional to momentum.

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

$$p = mv$$

For electrons accelerated through V :

$$eV = \frac{1}{2}mv^2 \text{ and } p = \sqrt{2meV}$$

$$\lambda = \frac{h}{\sqrt{2meV}}$$

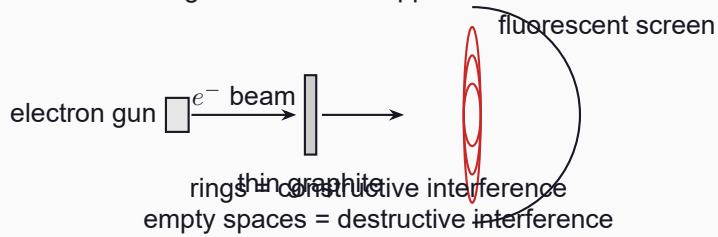
$$\lambda = \frac{h}{p}$$

$$p = mv$$

The energy of a particle can be treated as equivalent to photon energy of the associated wave.

Electron diffraction

A thin sheet of graphite and a fluorescent screen are used. Rings of electrons appear on the screen.



Accelerating electrons and diffraction rings

Electrons are accelerated by an electric field through a potential difference V .

gain in K.E. = work done by electric field

$$\frac{1}{2}mv^2 = eV$$

Since $p = mv$,

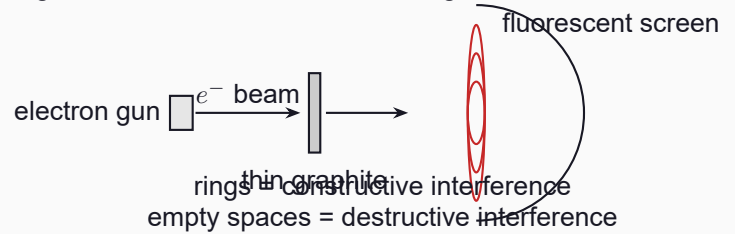
$$E_k = \frac{p^2}{2m} \Rightarrow p = \sqrt{2meV}$$

Therefore,

$$\lambda = \frac{h}{\sqrt{2meV}}$$

Ring spacing

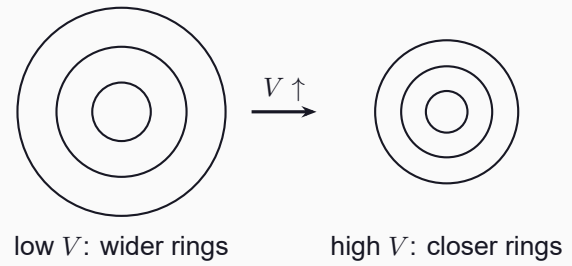
For diffraction, $n\lambda = d \sin \theta$ and $\lambda = h/p$. Larger accelerating voltage gives larger momentum and smaller wavelength, so the diffraction angle becomes smaller and rings come closer.



Increasing accelerating voltage

If the accelerating voltage is increased:

1. Momentum of electrons increases.
2. De Broglie wavelength decreases because $\lambda = h/p$.
3. Wavelength becomes smaller compared with slit/lat-tice spacing, so diffraction is less.
4. The diffraction angle becomes smaller.
5. Ring radius becomes smaller.
6. Rings come closer together and more rings may be observed on the screen.



Blank/checkpoint page

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This page is intentionally sparse to match the source sequence and avoid inventing additional notes.

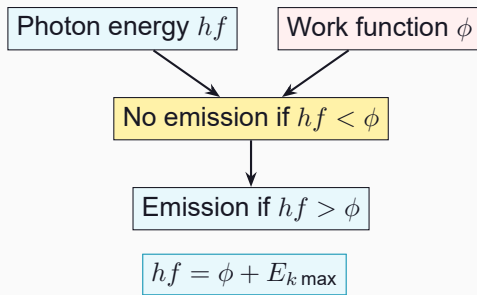
Checkpoint

- Photon model: $E = hf$.
- Photoelectric equation: $hf = \phi + E_{k\text{ max}}$.
- Stopping potential: $E_{k\text{ max}} = eV_s$.
- Energy levels: $\Delta E = hf$.
- De Broglie wavelength: $\lambda = h/p$.
- Accelerated electron: $\lambda = h/\sqrt{2meV}$.

Photoelectric effect summary

Photoelectric chain

photon energy hf compared with work function ϕ

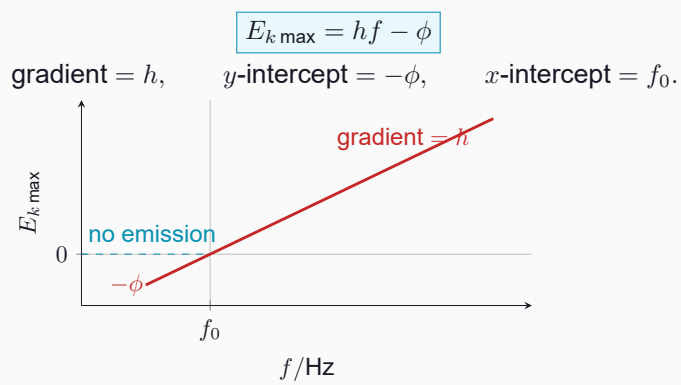


Key effects

- If frequency of radiation increases, $E_{k \max}$ increases.
- If intensity of radiation of the same frequency increases, $E_{k \max}$ stays the same and photoelectric current increases.
- Intensity depends on number of photons and energy of each photon.

$$I = \frac{Nhf}{At}$$

Final $E_{k \text{ max}}$ vs frequency summary



Metal comparison

Different metals have different work functions and threshold frequencies. For all metals, the gradient of an $E_{k \text{ max}}$ vs f graph is Planck's constant.

