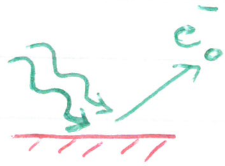
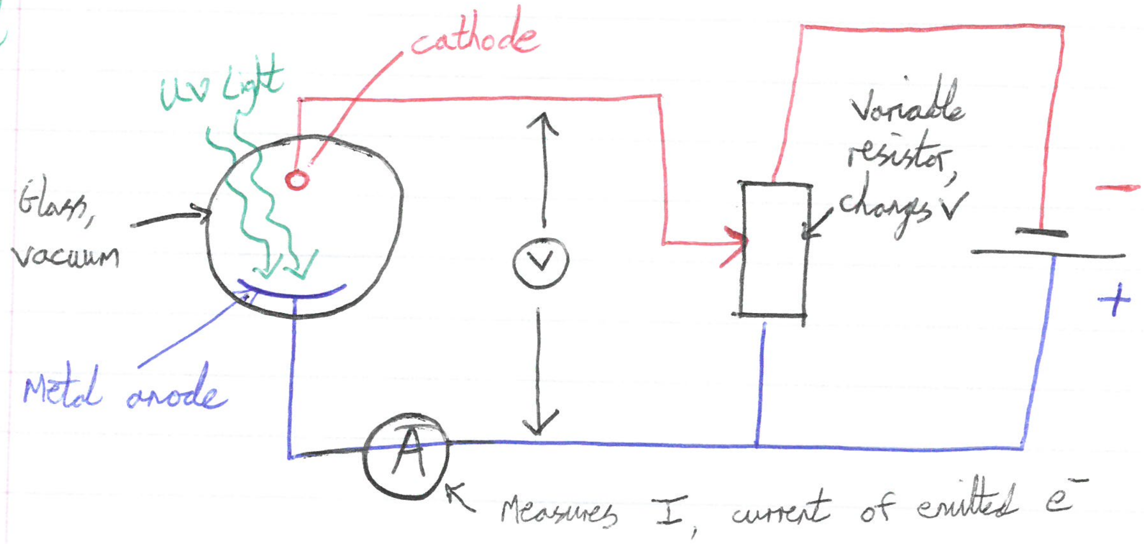
L3 # The Photoelectric Effect

- Shine UV light on a metal, electrons are emitted

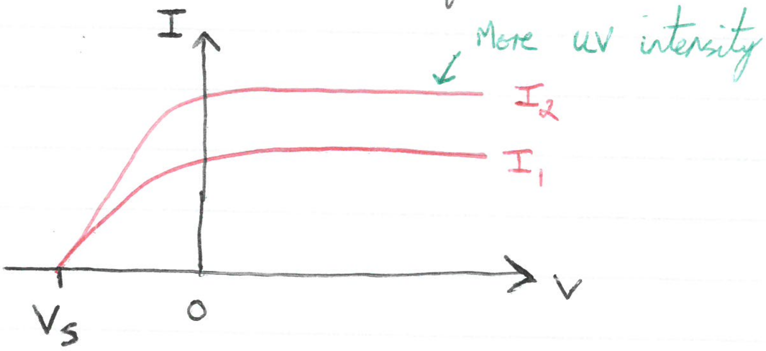


- Must be in vacuum or the e^- just hits air molecules

Photoelectric Effect



Result ① - For fixed UV wavelength:



- Increasingly negative potential on cathode decreases photocurrent

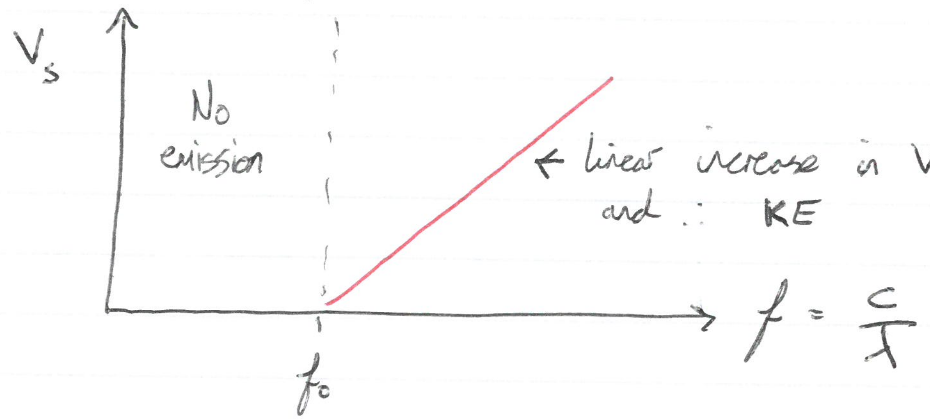
- Current drops to zero at voltage V_s ('stopping potential' - electrons emitted now get stopped or "blown" downwards, don't make it to the cathode)

→ V_s tells us the maximum kinetic energy of the electrons:

$$KE_{Max} = eV_s$$

- stopping potential independent of UV intensity! More UV makes current go up ($I_2 > I_1$), but doesn't give more energy to the electron...

Result ② - changing UV wavelength



- For a given metal, we find a threshold frequency f_0 - no emission of electrons below this - no matter the intensity of light
- Above the threshold, electron energy depends on UV frequency, not intensity (cf result ①)

- Classically
  - ⇒ Energy $\propto$ Intensity - V_s should increase
  - ⇒ No link between energy and frequency
    - → No threshold
  - ⇒ Expect time delay as electrons soak up energy

✗ not observed!

- Einstein's proposal (1905) - Nobel Prize
  - Energy of light comes in $E = hf$ photons
  - Minimum energy needed for electrons to escape the surface of a metal, the work function, ϕ

$$KE_{max} = hf - \phi = eV_s$$

- Now :
  - Higher intensity = more photons (but energy unchanged)
  - $E = hf$ so frequency changes energy.
  - Cutoff because we can't have the e^- gradually soak up energy - a single photon needs to kick it straight out - so no delay either. Photon has enough energy or it doesn't. More of them doesn't help.

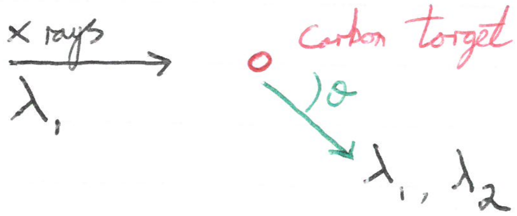
|| Photoelectric effect - results

|| ARPES

Compton Scattering

- Scattering of x-rays off atoms (carbon)

Compton Scattering - Setup



Surprise result - observe 2 wavelengths in scattered beam, not just original λ_1
⇒ Classically, λ shouldn't change...

Compton Scattering - Results

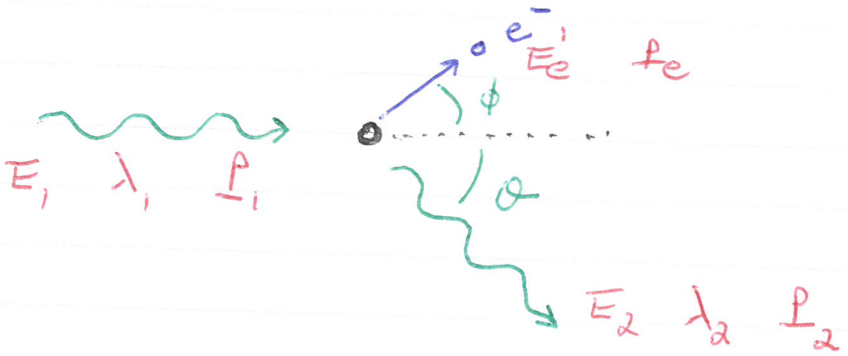
- Difference between λ_1 and λ_2 increases with scattering angle θ
  - Can explain this if the x-ray beam is a stream of particles

Both:

- **Elastic** scattering events - no energy change → λ_1
- **Inelastic** - an electron gets fired out of the target, carrying energy and momentum. Photon loses energy → λ_2

Compton Scattering - Diagram

- Compton's equation derivation:



Find relationship between λ_1 and λ_2 as a function of θ

→ Need relativistic treatment

$$E^2 = p^2c^2 + m^2c^4$$

For photon ($m=0$): $E = pc$

and $E = \frac{hc}{\lambda}$ $\Rightarrow$ $\boxed{p = \frac{h}{\lambda}}$ (1)

- conservation of momentum

$$\underline{p}_1 = \underline{p}_e + \underline{p}_2$$

$$\underline{p}_e = \underline{p}_1 - \underline{p}_2$$

square both sides:

$$p_e^2 = p_1^2 + p_2^2 - 2\underline{p}_1 \cdot \underline{p}_2$$

$$p_e^2 = p_1^2 + p_2^2 - 2p_1p_2\cos\theta \qquad (2)$$

- conservation of energy

$$E_1 + E_e = E_2 + E_e'$$

E_e: energy of electron 'at rest' in atom, before

E_1: Incoming photon energy

$$p_1 c + m_e c^2 = p_2 c + \sqrt{p_e^2 c^2 + m_e^2 c^4}$$

$$p_1 - p_2 + m_e c = \sqrt{p_e^2 + m_e^2 c^2}$$

Square both sides:

$$(p_1 - p_2)^2 + \cancel{m_e^2 c^2} + 2m_e c(p_1 - p_2) = p_e^2 + \cancel{m_e^2 c^2}$$

Sub in 2 for p_e^2:

$$(p_1 - p_2)^2 + 2m_e c(p_1 - p_2) = p_1^2 + p_2^2 - 2p_1 p_2 \cos\theta$$

Exercise: show:

$$m_e c(p_1 - p_2) = p_1 p_2 (1 - \cos\theta)$$

and 1, $p = h/\lambda$:

$$\boxed{\lambda_2 - \lambda_1 = \underbrace{\frac{h}{m_e c}}_{\text{Compton wavelength}} (1 - \cos\theta)}$$

- L3 conclusion: Both photoelectric effect and Compton scattering cannot be explained by classical, wave, light - need $E = hf$ photons