

Photons

OR How light interacts with atoms

OR the wave-particle duality problem.

The beginning of "modern" physics = "quantum" physics

1900 Max Planck → explains thermal (Blackbody) radiation

1905 A. Einstein → explains photoelectric effect using Planck's photons

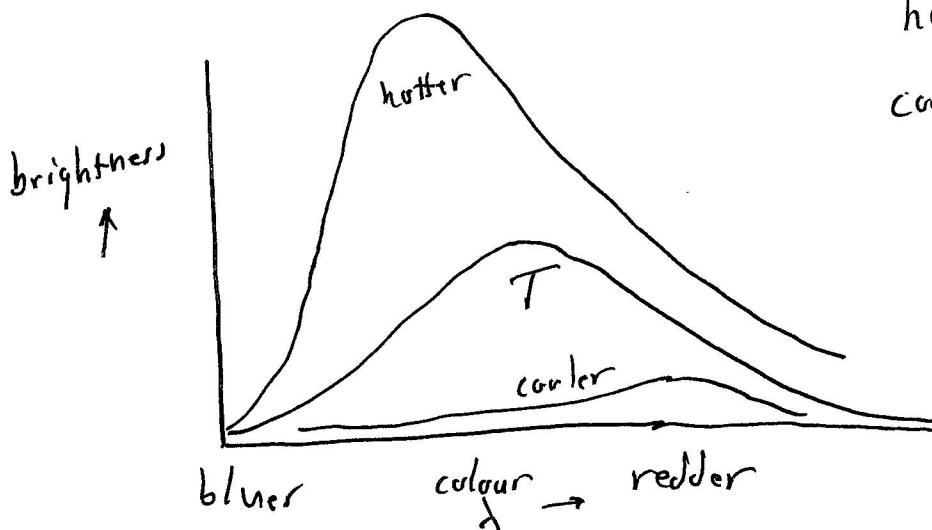
1913 Niels Bohr → explains Hydrogen atom

1923/24 Compton/deBroglie - wave/particle duality

Maxwell's equations imply a wave solution is correct \Rightarrow Intensity = $\frac{\text{Power}}{A}$

$$\text{Power} = \frac{\text{Energy}}{\text{time}} \propto E^2 \quad [\text{electric field}]$$

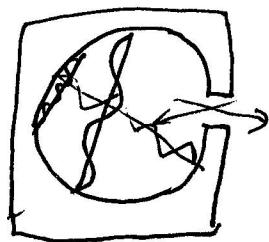
Thermal (Blackbody) radiation : every body with an absolute temperature above absolute zero will radiate energy.



hotter = brighter + bluer

cooler = fainter + redder

classical explanation: cavity radiation



1. determine the number of waves between λ and $\lambda + \Delta\lambda$

then sum over all the possible wavelengths

2. $\propto kT$ per wave ($\frac{1}{2}kT$ per degree of freedom)

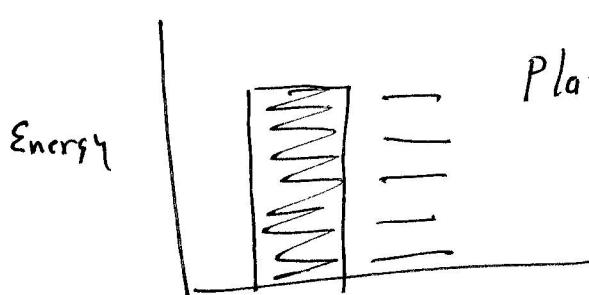
oscillators = 2 degrees of freedom

3 \div volume

$(KE + PE)$

$\rightarrow P \propto \frac{1}{\lambda^4}$ as $\lambda \rightarrow 0$ Power "explodes"
 \Rightarrow ultraviolet catastrophe

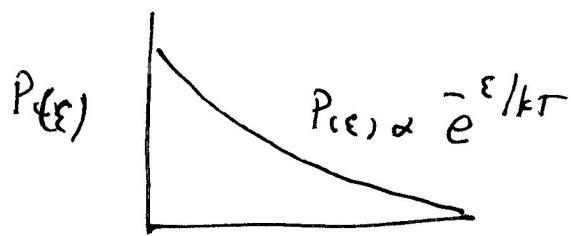
classical solution \Rightarrow all energies and frequencies are possible



Planck worked backwards and found if he limited oscillators to discrete energies:

$$\epsilon_0, 2\epsilon_0, 3\epsilon_0, \dots E_n = n\epsilon_0$$

such that they follow the Boltzmann distribution:



states of higher energy ϵ are less probable to be occupied

So Planck postulated that energy is found in discrete packets

$$E_n = n \epsilon_0, \quad n = 1, 2, 3, \dots$$

$$\text{where } \epsilon_0 = hf$$

$$h = \text{"Planck's" constant} = 6.63 \times 10^{-34} \text{ J.s}$$

$$= 4.14 \times 10^{-15} \text{ ev.s}$$

$$[\text{using } 1\text{eV} = (1.6 \times 10^{-19} \text{ C})(1 \text{ volt}) = 1.6 \times 10^{-19} \text{ J}]$$

$$f = \text{frequency} = \frac{1}{\text{sec}} = \text{Hertz}$$

$$c = f\lambda \rightarrow \quad f = \frac{c}{\lambda}, \quad hf = \frac{hc}{\lambda} = E$$

And light is a stream of "photons"

$$\text{Power} = \frac{\# \text{ photons}}{\text{sec}} \times \frac{\text{energy}}{\text{photon}}$$

$$= \frac{\text{energy}}{\text{sec}} = \text{watt}$$

$$P = \frac{n}{t} \cdot E_\lambda$$

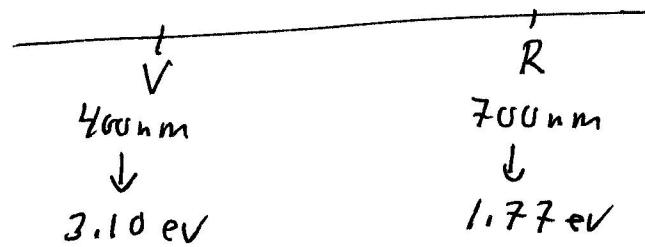
$$E_\lambda = hf = \frac{hc}{\lambda}$$

$$\text{Short cut: } E = \frac{hc}{\lambda} = \frac{(4.14 \times 10^{-15} \text{ ev.s})(3 \times 10^8 \text{ m/s})}{\lambda \text{ nm}} \left(10^9 \text{ m/nm} \right)$$

$$E_\lambda = \frac{1240 \text{ ev.nm}}{\lambda \text{ nm}}$$

for "light" photons only.

visible

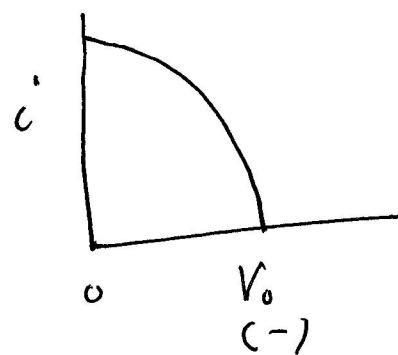
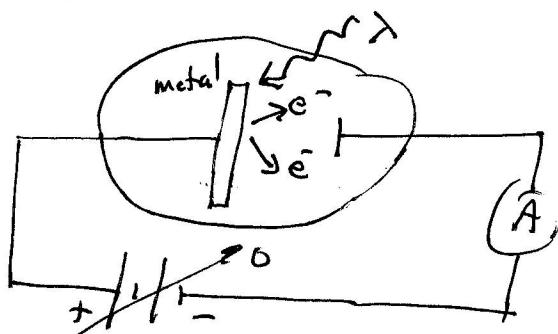


$$\frac{1240 \text{ eV nm}}{400 \text{ nm}} = 3.1 \text{ eV}$$

$$\frac{1240 \text{ eV nm}}{700 \text{ nm}} = 1.77 \text{ eV}$$

Photo electric effect

When light is incident on a metal surface, under the right conditions, photo electrons can be emitted.

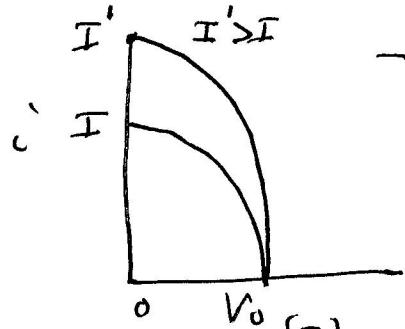


Problems

1. Colour dependency:

- if incident light is blue enough, photo electrons are emitted
- if the incident light is too red, no photoelectrons are emitted \rightarrow regardless of the intensity
*remember Power $\propto E^2$!

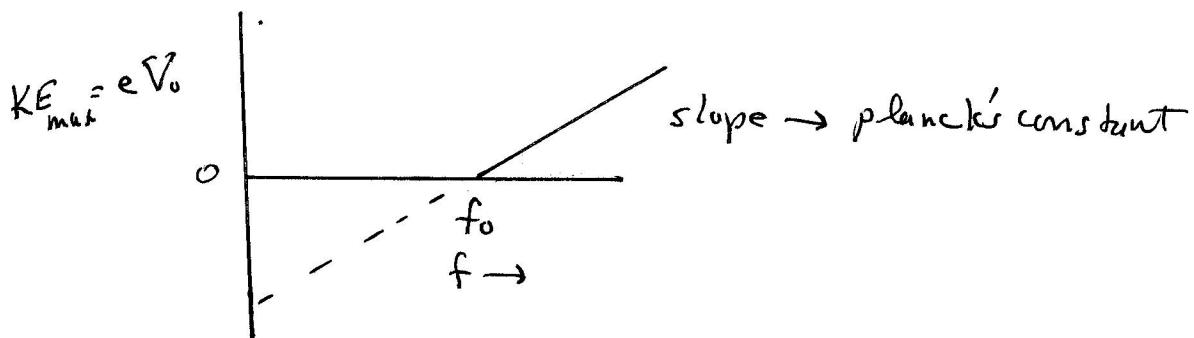
2. If the incident light is blue enough, and the colour is kept constant, but intensity is changed



- more photoelectrons are emitted initially, but the maximum KE ($= eV_0$) remains a constant!

3. If the incident light is blue enough, then even the faintest source will cause photoelectrons within $\sim 10^{-9}$ s [way below the intensity predicted by $P \propto E^2$].

4. Minimum frequency for photoelectron emission, then $KE_{\text{max}} \propto \text{frequency}$



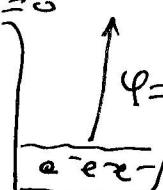
Einstein postulated that Planck's view that a light beam was a stream of "photons"

$\dots \rightarrow P = \frac{n}{t} \cdot E_\lambda$ so each photon had the same energy, only "brighter" meant more photons/sec

he postulated the interaction between photons and electrons were 1 photon \leftrightarrow 1 electron

so! either the photon could remove the electron, or it could not. (no time delay)

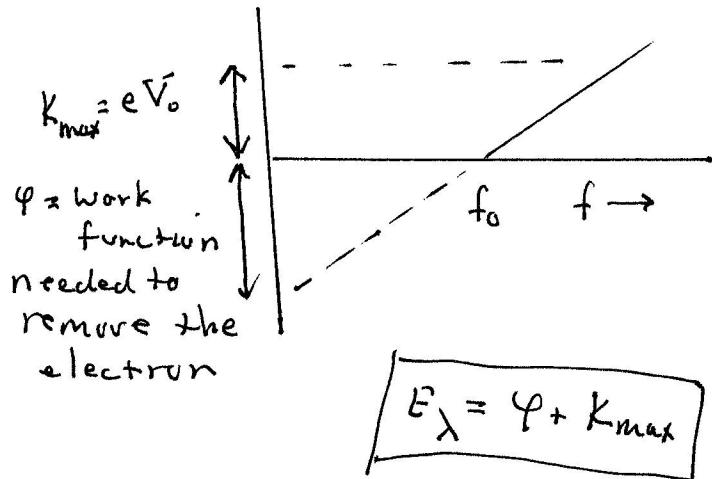
"free" electron theory $E=0$



work function = energy needed to remove the electron

② if the photon could remove the electron, a brighter beam would mean more photoelectrons would be emitted, but

③ the maximum kinetic energy would not change.



f_0 = cutoff frequency

or

λ_0 = cutoff wavelength

⇒ defines the least energy needed to remove an electron

$$\varphi = hf_0 = \frac{hc}{\lambda_0}$$

$$E_\lambda = \frac{1240 \text{ ev} \cdot \text{nm}}{\lambda \text{ nm}}$$

27.10 for Zinc: $\varphi = 4.31 \text{ eV}$:

$$\text{a)} E_\lambda = \frac{1240 \text{ ev} \cdot \text{nm}}{\lambda_0} \rightarrow \lambda_0 = \frac{1240 \text{ ev} \cdot \text{nm}}{4.31 \text{ eV}} = 288 \text{ nm}$$

$$\text{b)} \text{lowest frequency: } c = f_0 \lambda_0, f_0 = \frac{c}{\lambda_0} = \frac{3 \times 10^8 \text{ m/s}}{288 \times 10^{-9} \text{ m}} = 1.04 \times 10^{15} \text{ Hz}$$

$$\text{c)} E_\lambda = \varphi + K_{\max}, E_\lambda = 5.50 \text{ eV}$$

$$K_{\max} = E_\lambda - \varphi = 5.50 \text{ eV} - 4.31 \text{ eV} = 1.19 \text{ eV}$$

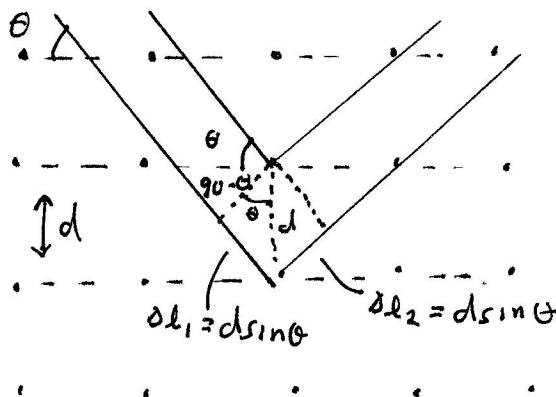
$$\underline{27.12} \quad \varphi_{Li} = 2.30 \text{ eV} \quad \lambda = 400 \text{ nm}, E_\lambda = \frac{1240 \text{ ev} \cdot \text{nm}}{400 \text{ nm}} = 3.10 \text{ eV}$$

$$\varphi_{Be} = 3.90 \text{ eV}$$

$\varphi_{Hg} = 4.50 \text{ eV}$ for photoelectrons to be emitted $E_\lambda > \varphi$
* so, only for Lithium will photoelectrons be emitted

$$E_\lambda = \varphi + K_{\max}, K_{\max} = E_\lambda - \varphi = 3.10 \text{ eV} - 2.30 \text{ eV} = 0.80 \text{ eV}$$

Bragg Scattering: for x-rays



for constructive interference

$$\Delta l_1 + \Delta l_2 = m\lambda, \quad m=1, 2, \dots$$

$d\sin\theta_1 + d\sin\theta_2$

$$2ds\sin\theta = m\lambda$$

Bragg Scattering

27.18

$$\lambda = .129 \text{ nm}$$

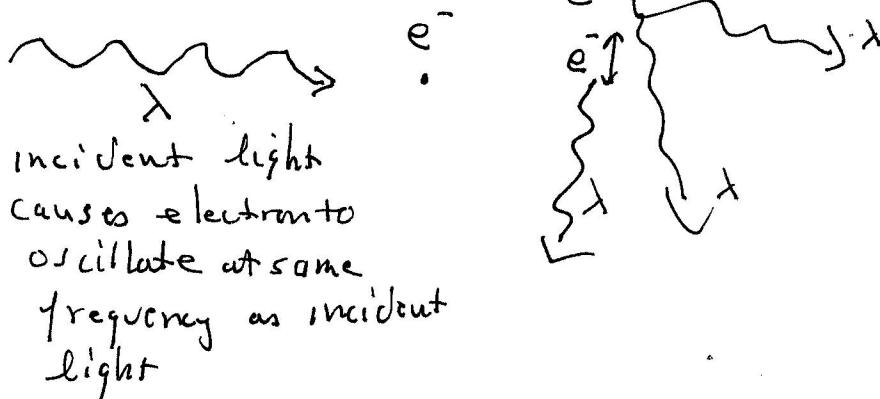
1st order scattering
 $\theta = 8.15^\circ$

$$2ds\sin\theta_1 = (1)\lambda$$

$$d = \frac{\lambda}{2\sin\theta} = \frac{.129 \text{ nm}}{2\sin 8.15^\circ} = .455 \text{ nm}$$

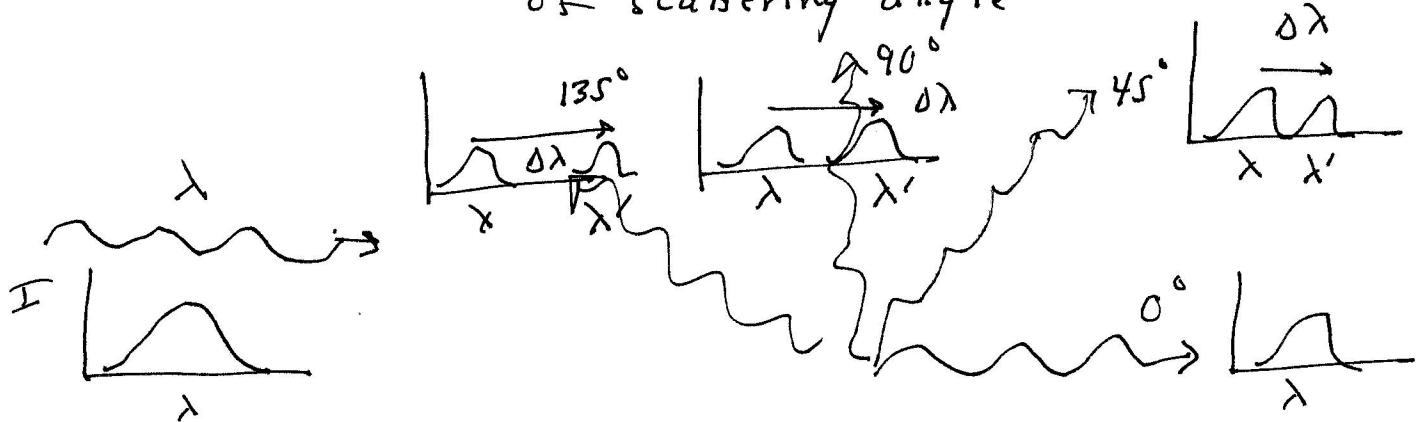
Compton Scattering: Incident photons scatter off (loosely bound) electrons

classically

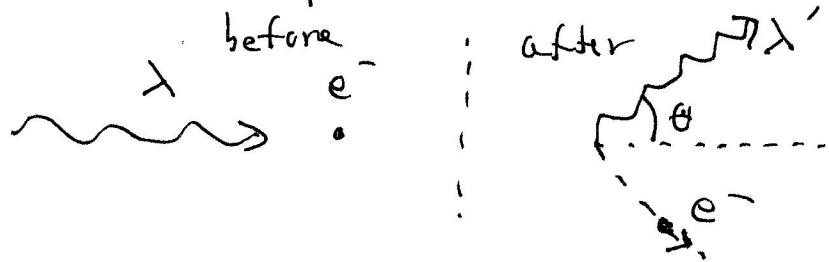


Incident light causes electrons to oscillate at same frequency as incident light

actual observation: a frequency shift as function of scattering angle



solution: like Planck + Einstein, treat photon as a particle → and do 2-dim. collision



(1) Conserve energy $E_i = E_f$ but use relativity

$$E_{tot} = KE + m_0 c^2 \quad \begin{matrix} \text{rest mass} \\ \text{energy} \end{matrix}$$

$$E_\lambda + E_{ie} = E_{\lambda'} + E_{fe}$$

$$E_\lambda + m_0 c^2 = E_{\lambda'} + \sqrt{p_e^2 c^2 + (m_0 c^2)^2}$$

$$p_\lambda c + m_0 c^2 = p_{\lambda'} c + \sqrt{p_e^2 c^2 + (m_0 c^2)^2}$$

for photons, $h\nu$ rest mass $m_\nu = 0$

$$E_{tot} = pc$$

$$E_\lambda = p_\lambda c$$

for photon

$$p_\lambda = \frac{E}{c} = \frac{h\nu}{\lambda} = \frac{h}{\lambda}$$

and (2) Conserve linear momentum

$$\vec{p}_i = \vec{p}_f$$

$$\vec{p}_\lambda + \vec{e} = \vec{p}_{\lambda'} + \vec{p}_e$$

Solving these we get

$$\Delta\lambda \doteq \boxed{\lambda' - \lambda = \frac{h}{m_ec} (1 - \cos\theta)}$$

" compton wavelength for electron = $\frac{6.63 \times 10^{-34}}{(9.11 \times 10^{-31})(3 \times 10^8)} = 2.43 \times 10^{-12} \text{ m}$
 $= 0.0243 \text{ nm}$

27.22 $\theta = 55^\circ$

$$\Delta\lambda = 2.43 \text{ pm} (1 - \cos 55^\circ) = 1.04 \text{ pm} = \boxed{1.04 \times 10^{-3} \text{ nm}}$$

Matter waves - Louis de Broglie (1924)

his postulate: if light (which we knew as a wave) now has particle properties,
 why can't particles have wave properties

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

$$\text{or by kinetic energy: } K = \frac{1}{2}mv^2 = \frac{1}{2}\frac{m}{m}v^2 = \frac{(mv)^2}{2m} = \frac{P^2}{2m}$$

$$\text{for } p = \frac{h}{\lambda} \rightarrow \boxed{K = \frac{h^2}{2m\lambda^2}}$$

However, this wave nature raises several important issues → the main one is "localization,"
 that is "where is the particle?"



n/m



? exactly, where
 (at what specific location)
 is a wave?

this leads to the : Uncertainty Principle

you cannot simultaneously measure momentum and position to infinite precision

$$\Delta p_x \Delta x \geq \frac{\hbar}{2} , \quad \hbar = h - bar = \frac{h}{2\pi}$$