PHY 114

Quantum Physics

Lecture 1-B-2

Waves as Particles

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Prediction of Classical vs Planck for $u(\nu)$?

We know ***Maxwell's EM Theory*** *&* ***Boltzmann's Classical Thermodynamics*****.**

Calculate the number density of oscillators in a cavity, and multiply the average energy of each oscillator.

	<u>*Classical*</u>	<u>*Planck's Quantum*</u>
Density of Modes:	$g(\nu) = \frac{8\pi}{c^3}\upsilon^2$	$g(\nu) = \frac{8\pi}{c^3}\upsilon^2$
Average Energy :	$\langle\epsilon\rangle = k_B T$	$\langle\epsilon\rangle = \frac{h\nu}{e^{h\upsilon/k_B T} - 1}$
Energy density u_ν *:*	$u_\nu = \frac{8\pi}{c^3}\,\upsilon^2\, k_B T$	$\boxed{u_\nu = \frac{8\pi}{c^3}\,\upsilon^2\,\frac{h\nu}{e^{h\upsilon/k_B T} - 1}}$

Perfect Match with Experiment

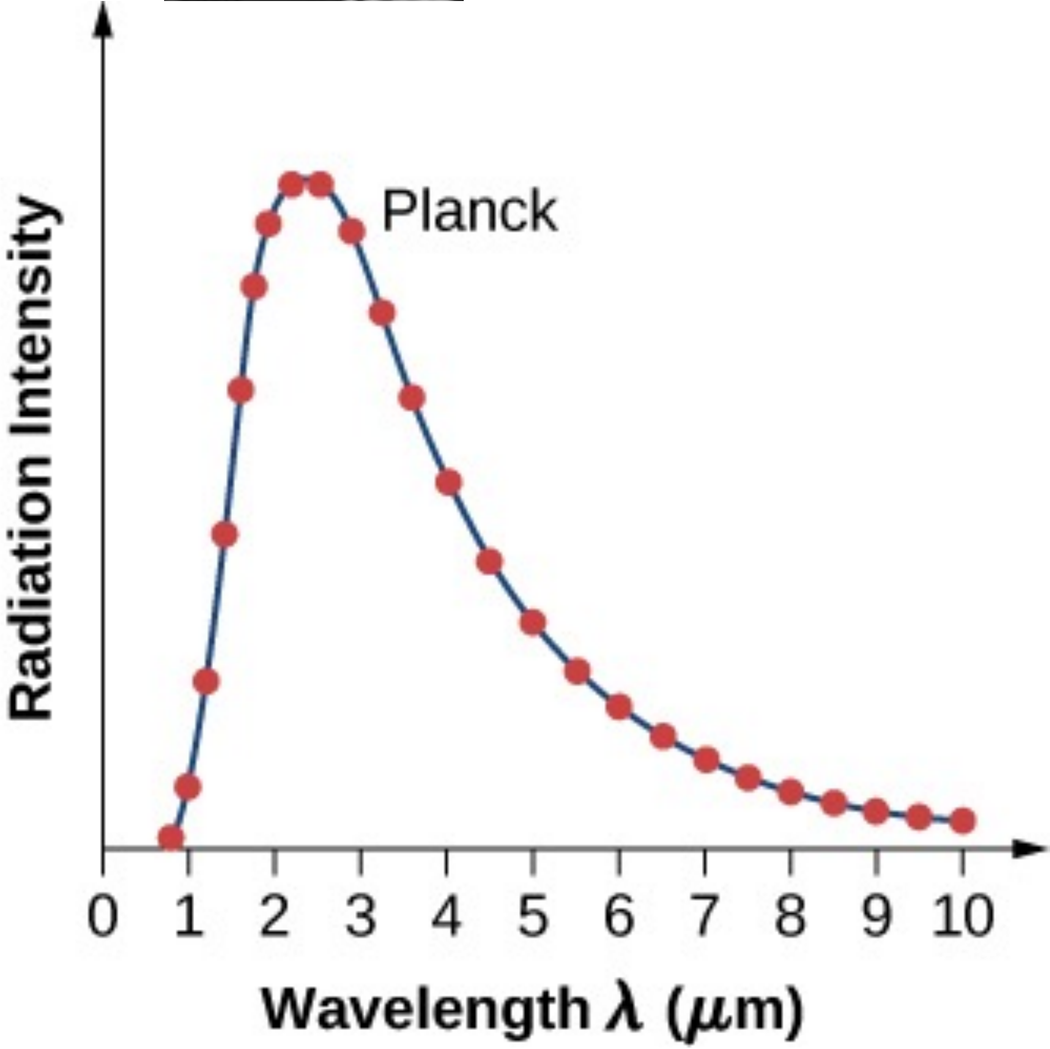
- *Energy of oscillator discrete* $E_n = n\,h\nu$
- *A new universal constant is born* h
- *Indication of a* <u>*new*</u> *occupation statistics.*

- *With* h quantum age came into being !

- *But,* h *is quantum of which Physical Quantity ?*

h= 6.62607015×10^{-34} J-s

QUANTUM of ACTION !!



An Act of Desperation………..

“Kurz zusammengefasst, kann ich die ganze Tut nur als einen Akt der Verzweiflung bezeichnen.”

“In summary, I can only characterize the entire work as an act of desperation.”

- Max Planck in 1931

Heat Capacity of Solids :

Dulong-Petit : $U = 3N_A k_B T \quad c_v = 3N_A k_B$

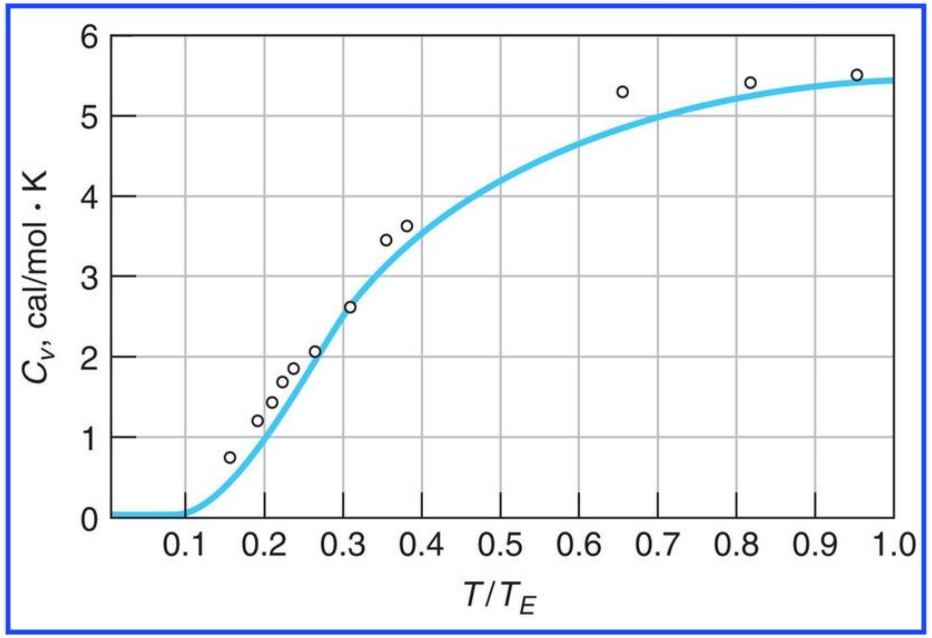
A simple <u>single frequency</u> model.

$$\boxed{U = N_A \frac{3\,h\nu}{e^{h\nu/k_BT} - 1}}$$

$$\boxed{c_v = 3N_A k_B \frac{x^2 e^x}{(e^x - 1)^2}} \qquad x \equiv \frac{h\nu}{k_BT} \equiv \frac{T_E}{T}$$

Einstein Model: C_V for Diamond

Einstein, Annalen der Physik 22 (4), 180 (1907)



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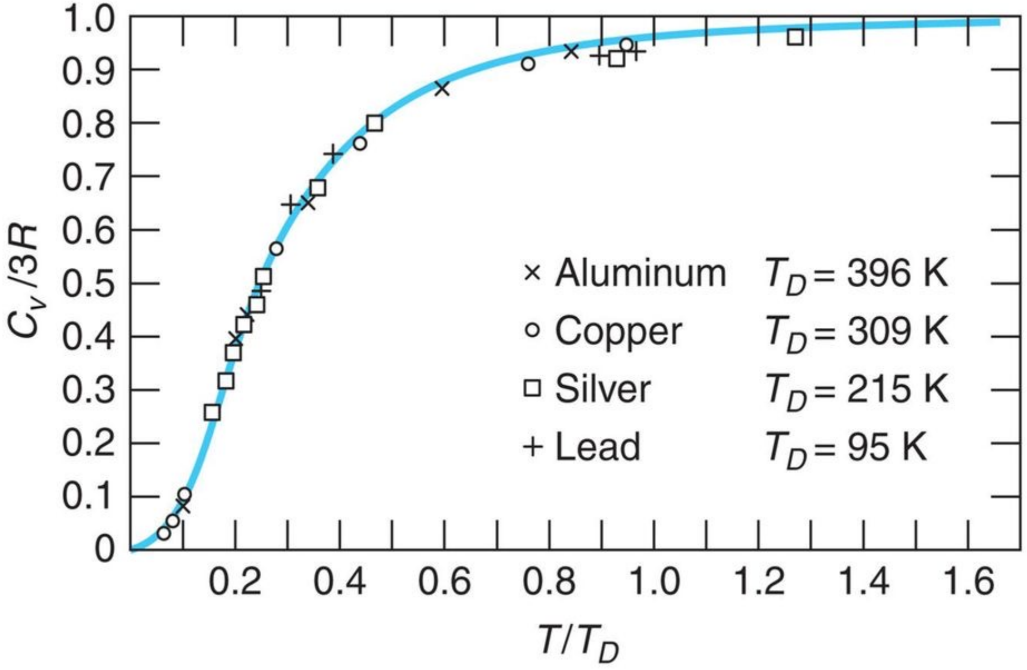
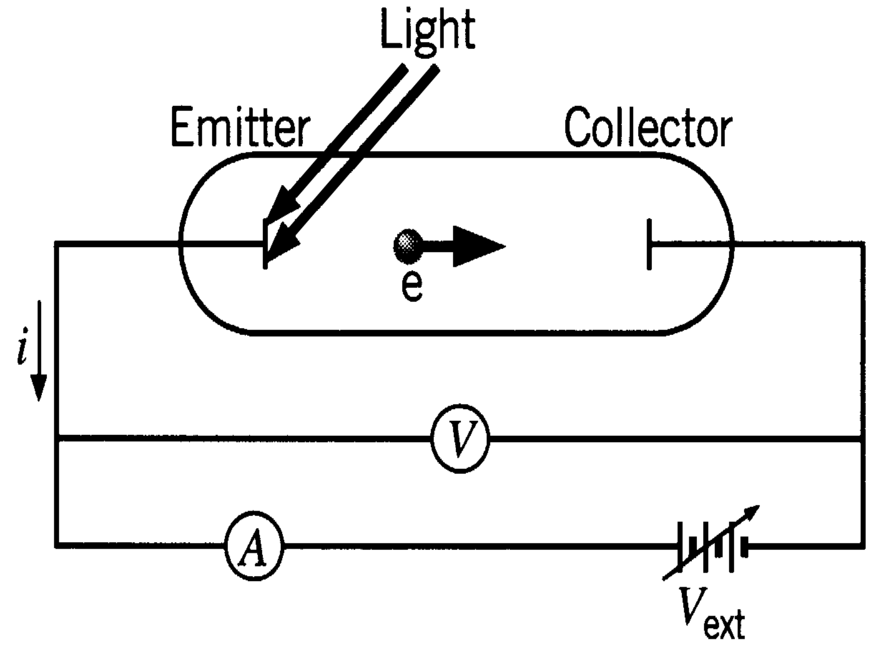
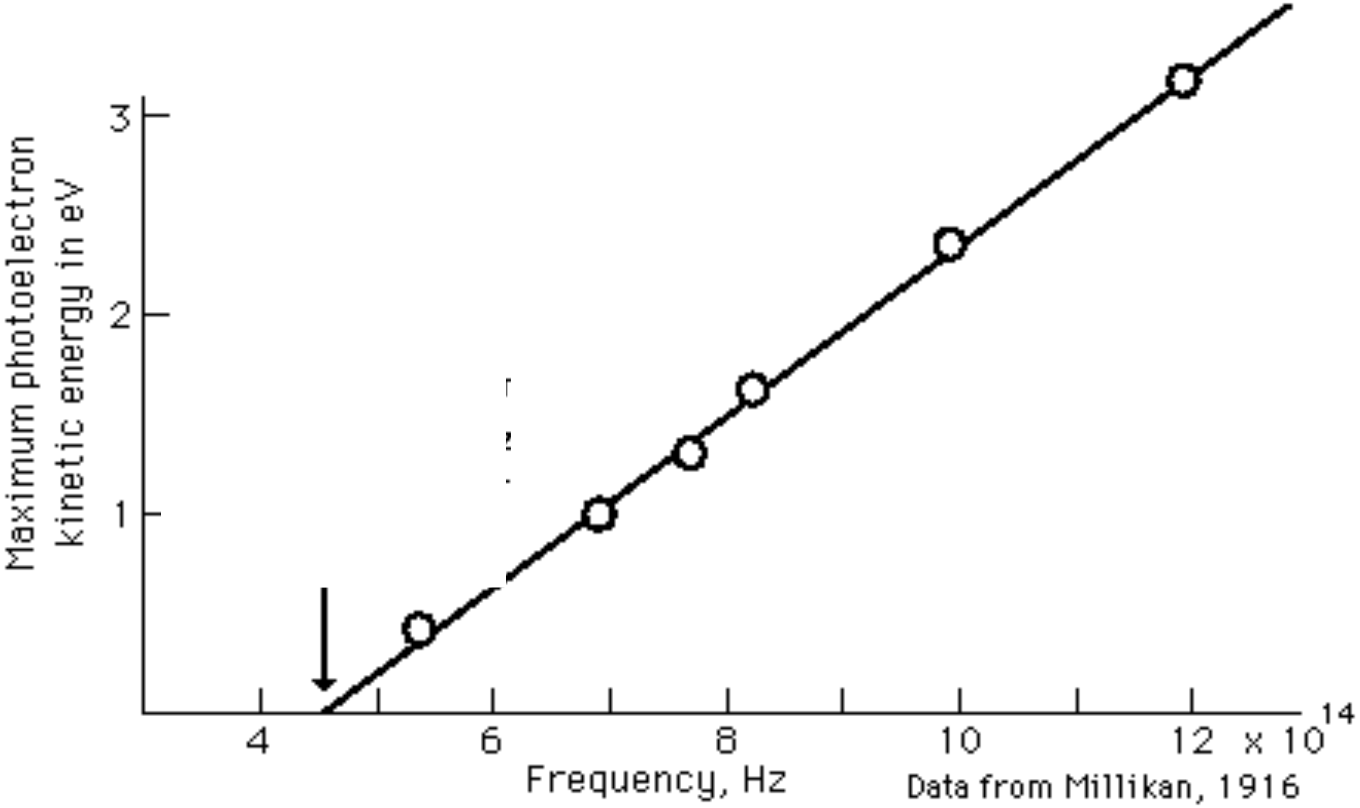
Debye Model of Heat Capacity of Solids



Photoelectric Effect :

Light consists of packet of energy : $h\upsilon$





Potassium : No emission below 2eV

What did Photoelectric Effect prove ?

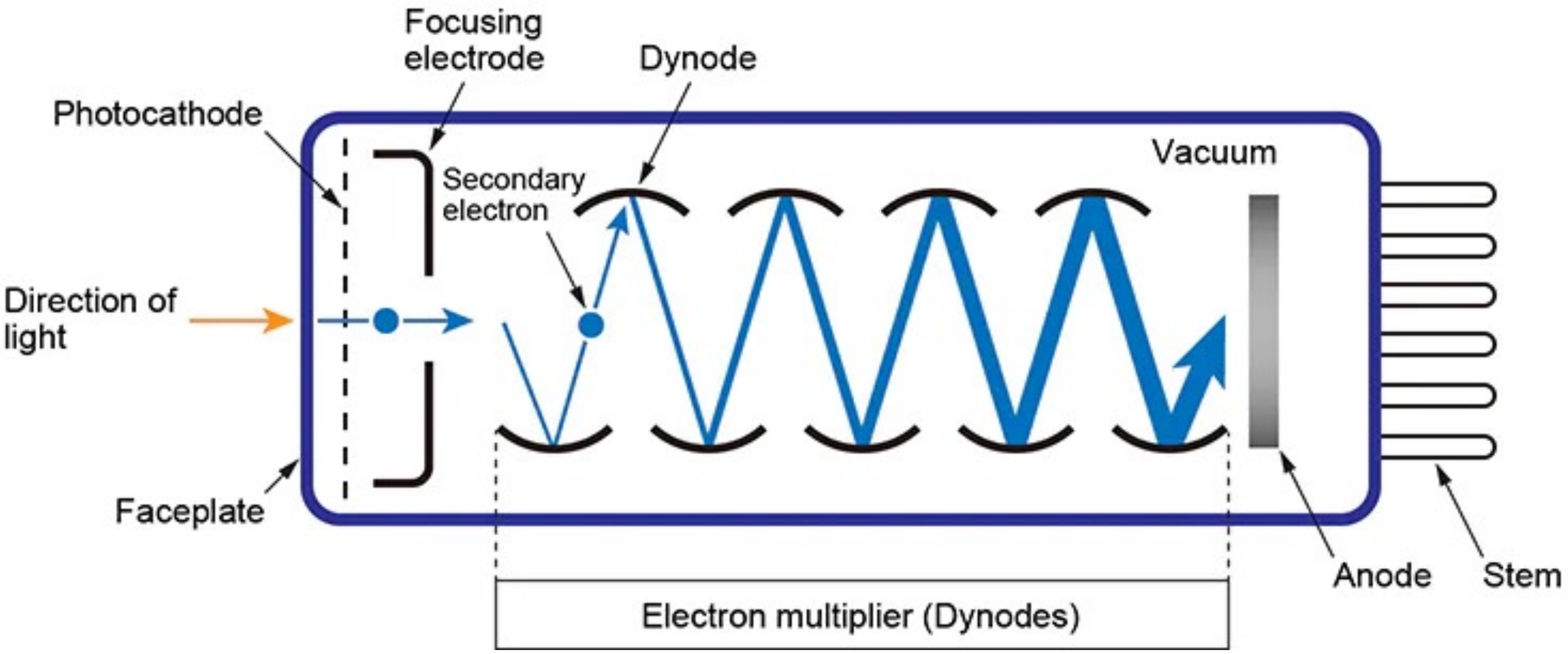
Light comes as ‘packets of energy’ : $h\nu$

Context: Light interacting with matter

Annus Mirabilis papers of Einstein

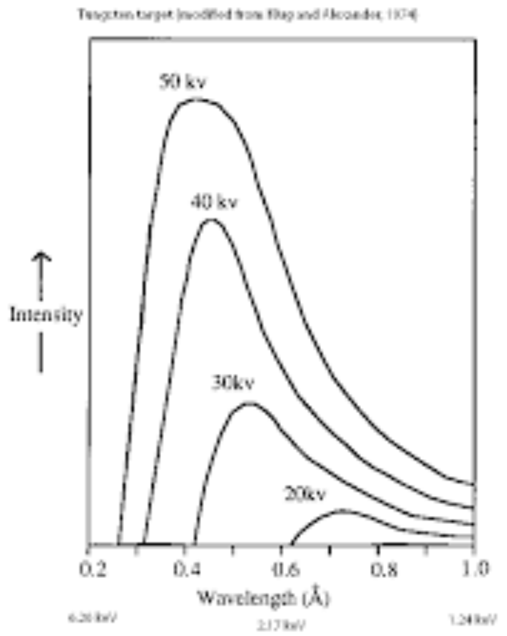
$$\begin{cases} Brownian\ Motion \\ Specail\ Relativity \\ E = mc^2 \end{cases}$$

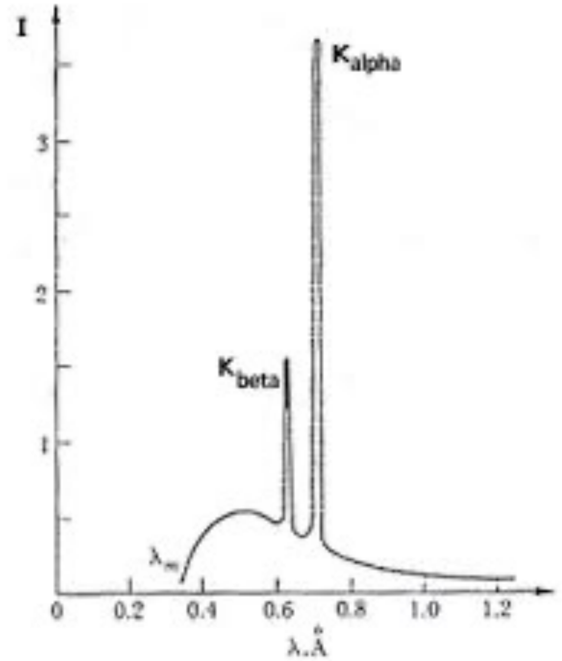
Photomultiplier Tube (PMT)

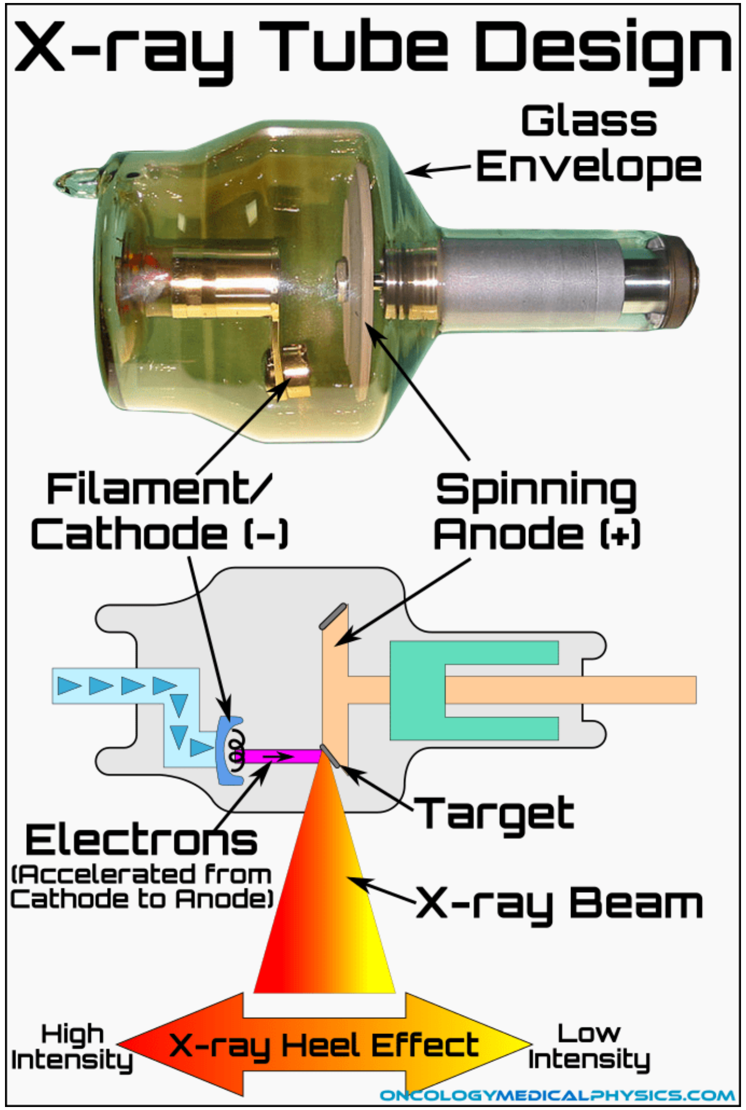


Inverse Photo-electric Effect ?

Generating X-Rays

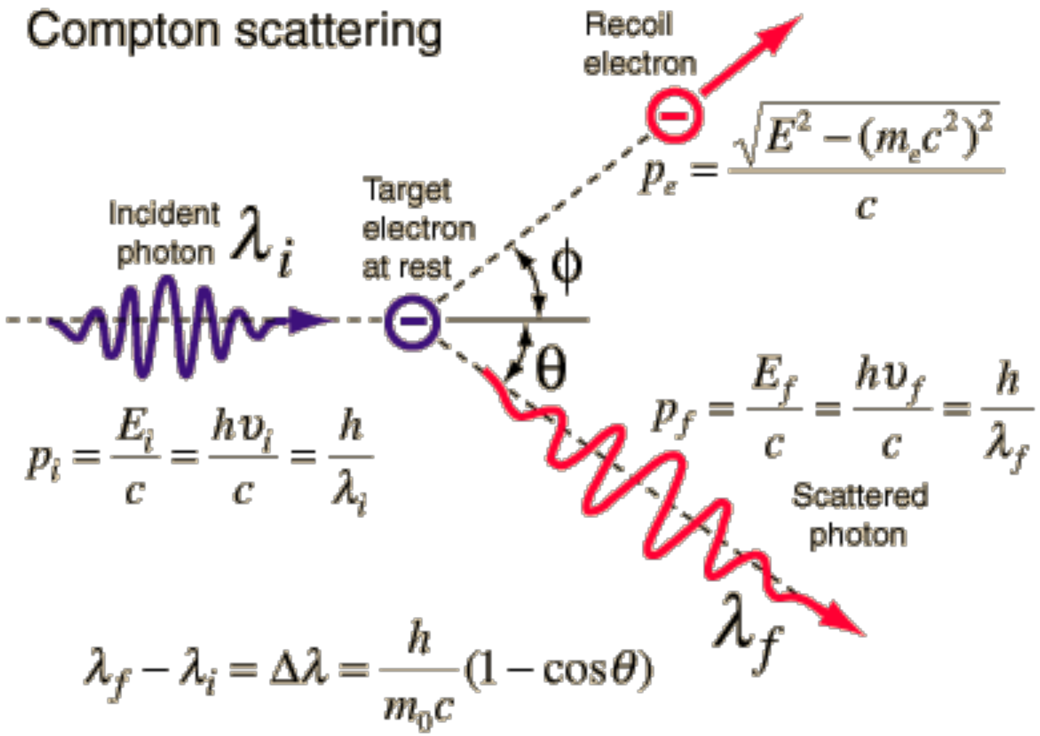






Photon as a particle ? Need solid proof?

Compton Effect (1923) Nobel in 1927



$$m_e c^2 + h\upsilon_i = h\nu_f + \sqrt{(m_e c^2)^2 + (p_e c)^2}$$

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

$$p_e^2 = (\vec{p}_i - \vec{p}_f) \cdot (\vec{p}_i - \vec{p}_f) = p_i^2 + p_f^2 - 2p_i p_f cos\theta$$

$$(p_e c)^2 = (h\upsilon_i)^2 + (h\upsilon_f)^2 - 2h^2\nu_i\nu_f cos\theta$$

$$(p_e c)^2 = (h\upsilon_i)^2 + (h\upsilon_f)^2 - 2h^2\nu_i\nu_f + 2m_e c^2(h\upsilon_i - h\upsilon_f)$$

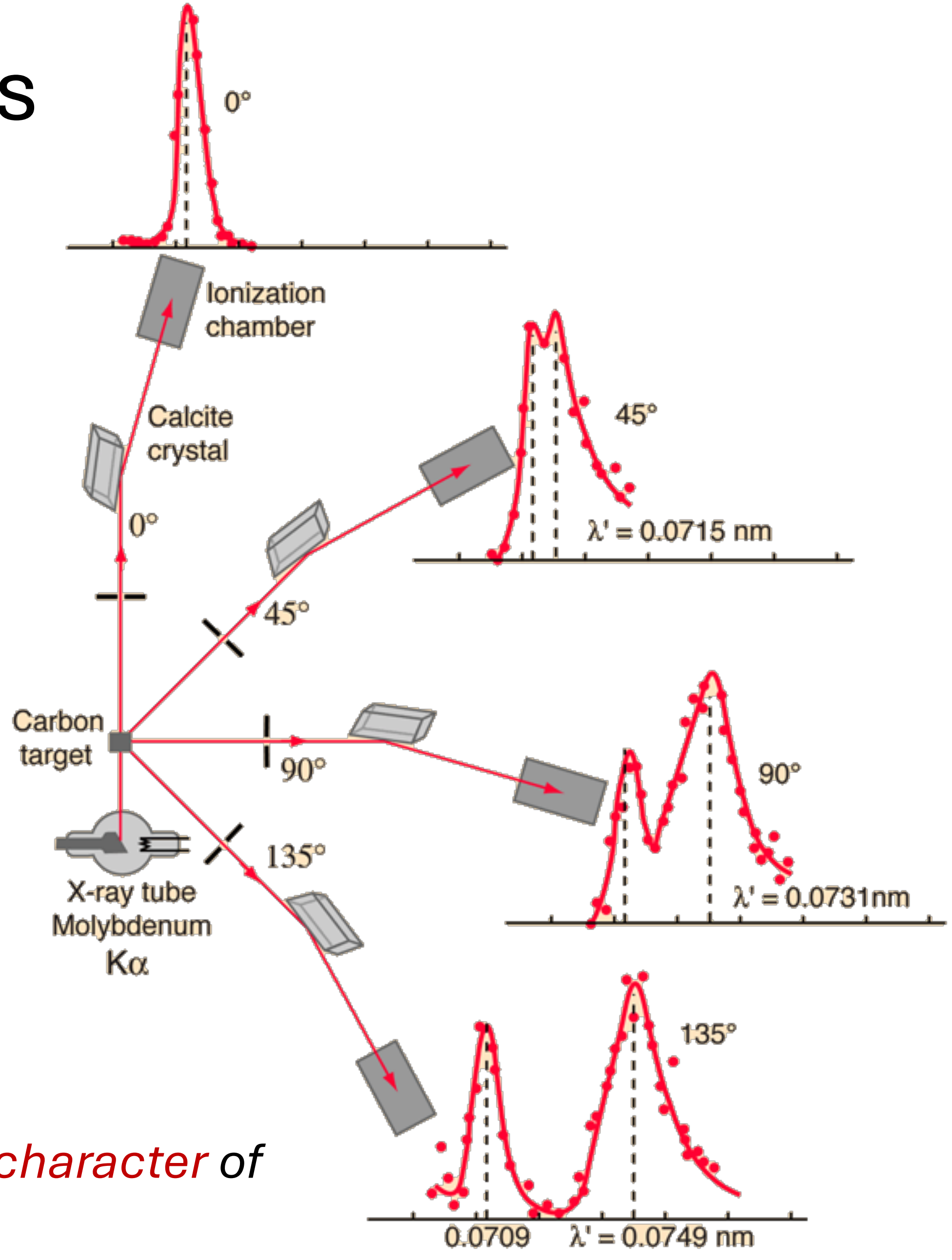
$$\boxed{\frac{1}{h\upsilon_f} - \frac{1}{h\upsilon_i} = \frac{1}{m_e c^2}(1 - cos\theta)}$$

$$\boxed{\lambda_f - \lambda_i = \frac{h}{m_e c}(1 - cos\theta)}$$

- *Shift $\Delta\lambda$ is independent of λ.*
- *Lighter the target particle larger is the shift.*
- *For electron, the Compton wavelength is* $\mathbf{2.42\times10^{-3}}$ ***nm***.

Compton's Experimental Results

- For convenient detection, X-rays (0.1 to 0.1) convenient.
- Compton used 0.0709 nm (Molybdenum K_α). The first peak is as per classical expectation due to Rayleigh scattering.
- The Compton shift increases with scattering angle with excellent agreement with prediction.



Though wavelength is measured,
it is the most convincing demonstration of particle-like character of Electromagnetic radiation.

In Summary,

Mounting evidence of EM radiation and waves behave like packets of energy or particles :

- Blackbody Radiation energy density spectrum (Oscillators)
- Specific Heat of solids: T- dependence. (Oscillators)
- Photoelectric Effect
- X-ray production
- Compton Scattering

Above all, birth of Planck's Constant

Do particles also behave like waves?