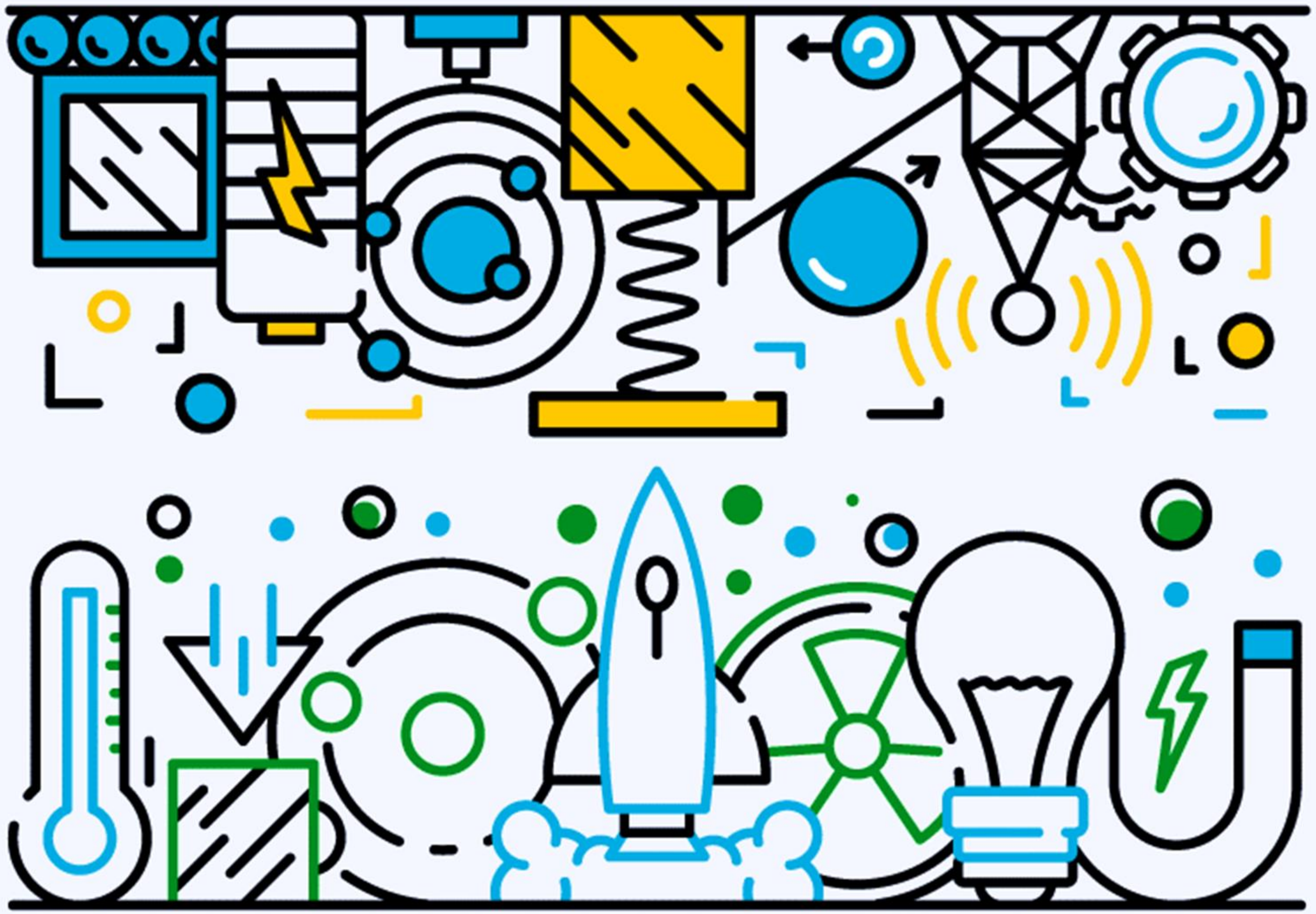
Engineering Physics (FIC 102)

UNIT-III



CONTENT

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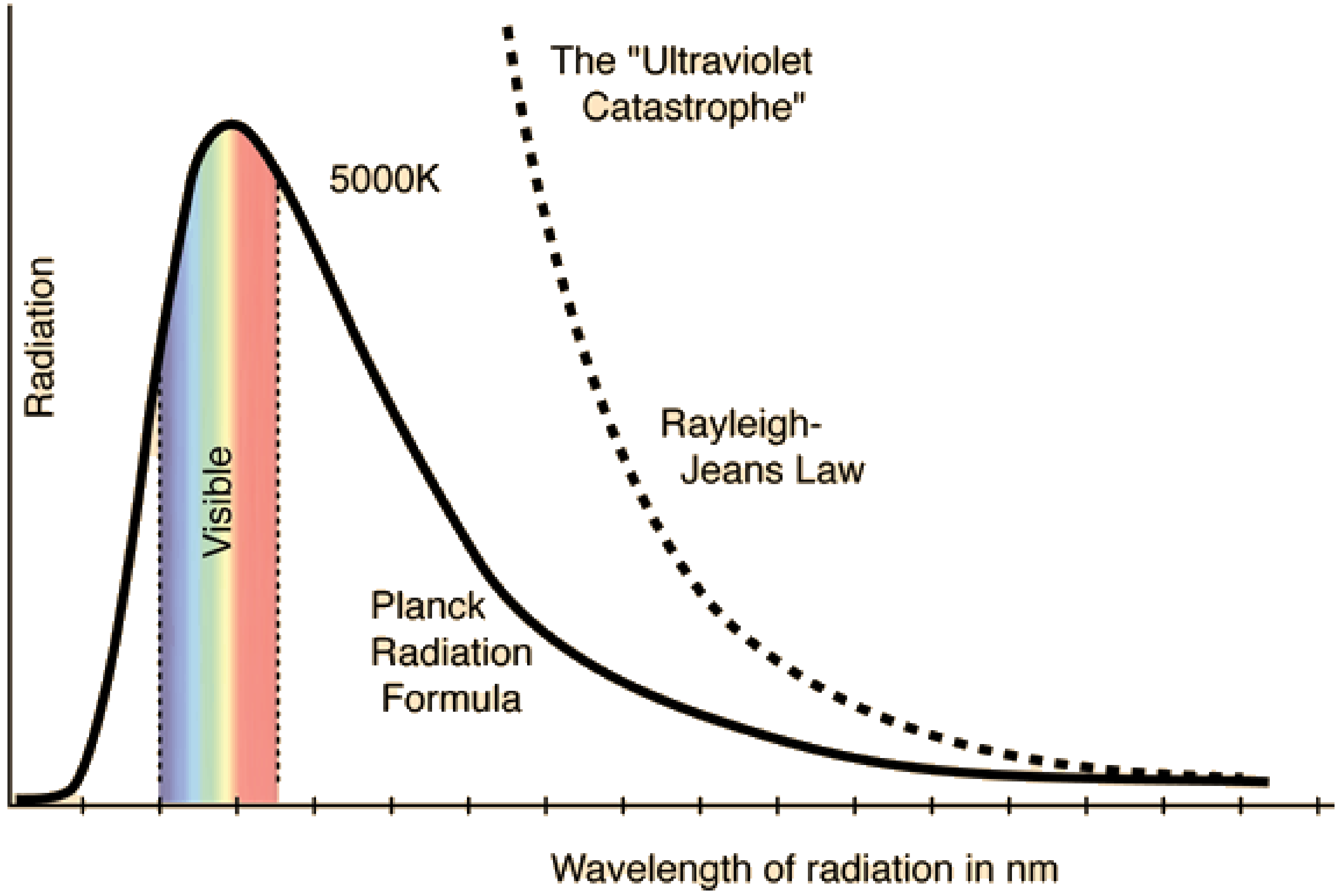


Black Body Radiation

LECTURE-01

NATURE OF LIGHT

1801

- **Thomas Young.**
- Wave Nature of Light is demonstrated.

1873

- **James C. Maxwell.**
  - Maxwell's Equation.
  - Light as an EM Wave is proposed.

1887

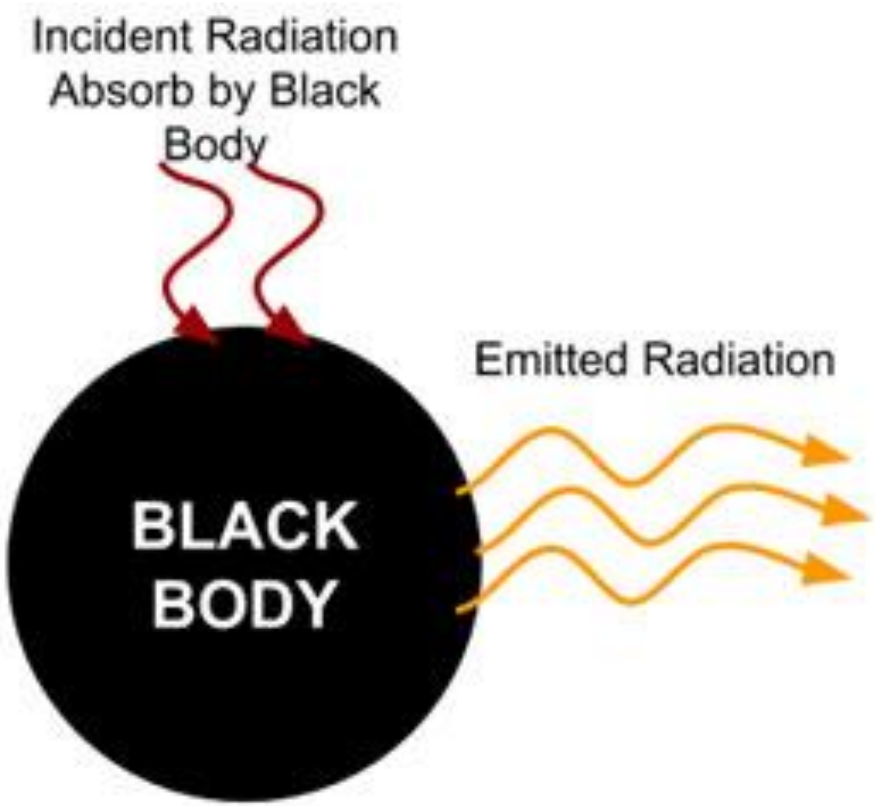
- **Heinrich Hertz.**
  - Experimental proof of Light as an EM Wave.

By the end of nineteenth century wave nature of light was firmly established!

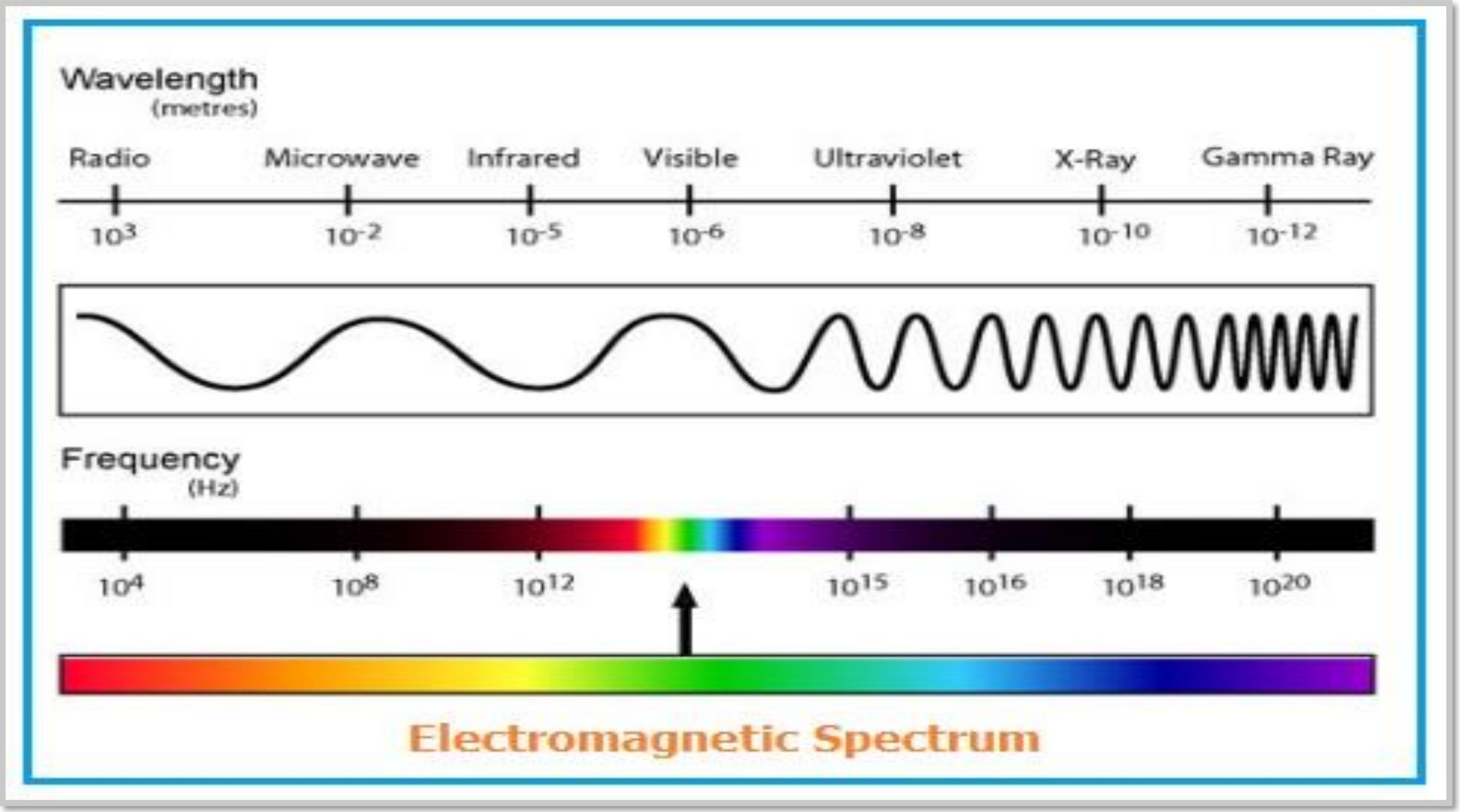
However, This certainty lasted only a decade or so!

BLACKBODY

- Initial theoretical complication came from attempts to explain the origin of the radiation emitted by bodies of matter.
- We are all familiar with the glow of a hot piece of metal, which gives off visible light whose color varies with the temperature of the metal, going from red to yellow to white as it becomes hotter and hotter.
- The ability of a body to radiate is closely related to its ability to absorb radiation.
- It is convenient to consider as an ideal body one that absorbs all radiation incident upon it, regardless of frequency.
- **Such a body is called a blackbody.**

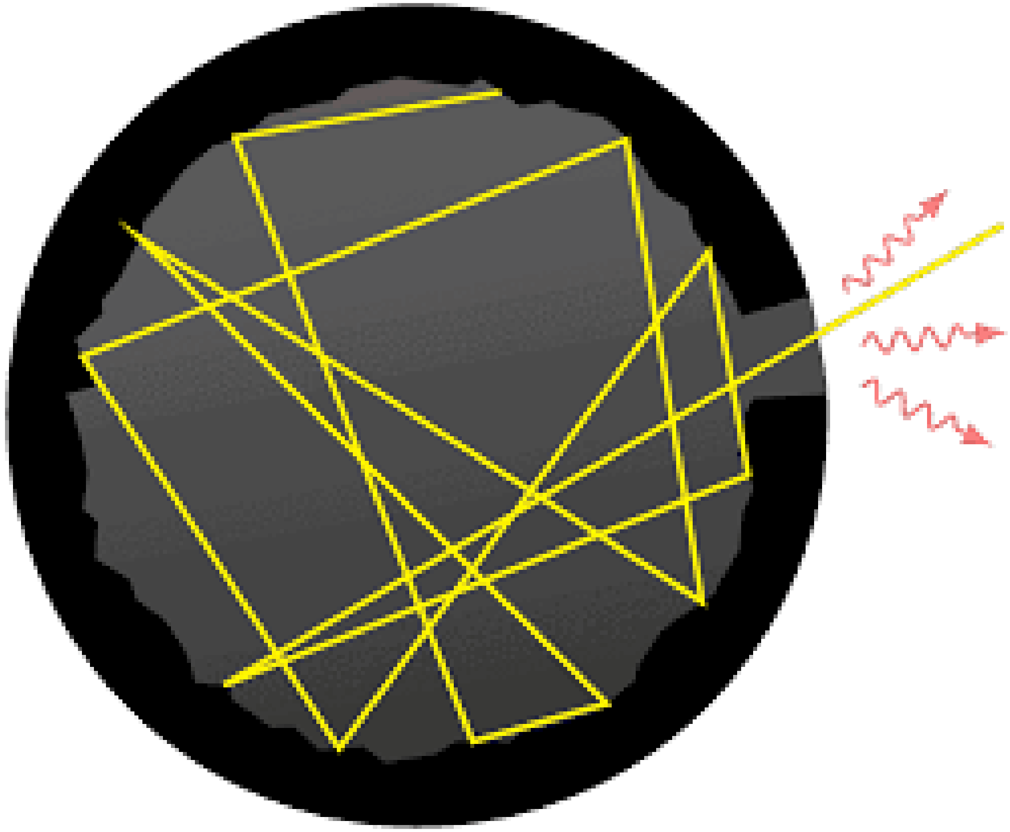


REVISITING EM WAVE SPECTRA



Visible light – Wave length (380 to 740 nm)/Frequency range (430–770 THz)

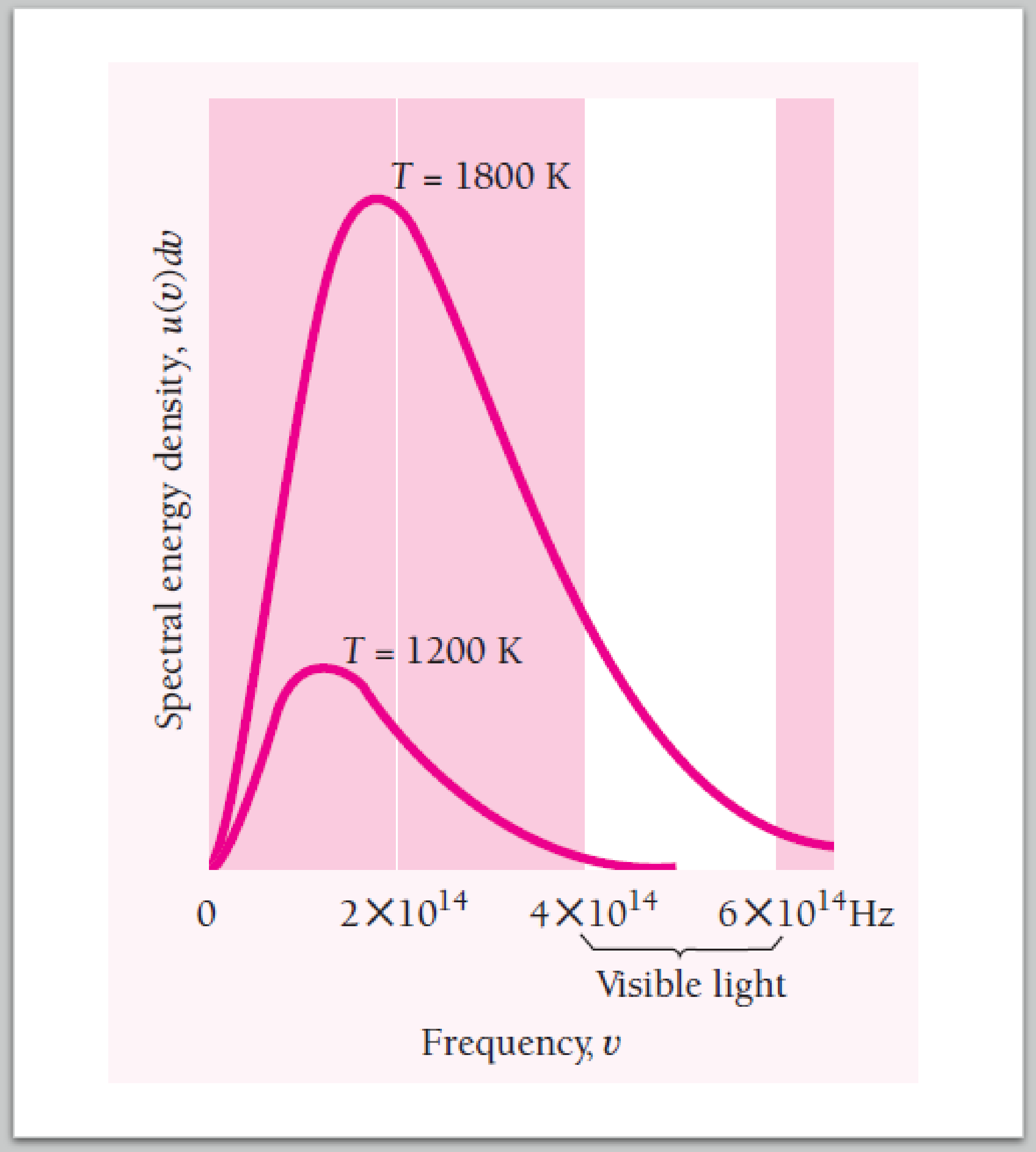
BLACKBODY



- A blackbody can be approximated by a hollow object with a very small hole leading to its interior.
- Any radiation striking the hole enters the cavity, where it is trapped by reflection back and forth until it is absorbed.
- The cavity walls are constantly emitting and absorbing radiation.
- It is in the properties of this radiation (***blackbody radiation***) that we are going to study here.

BLACKBODY SPECTRA

- Experimentally we can study blackbody radiation simply by inspecting what emerges from the hole in the cavity.
- The spectral distribution of energy in the radiation depends only on the temperature of the body.
- The *higher the temperature, the greater the amount of radiation* and *the higher the frequency at which the maximum emission occurs*.



BLACKBODY SPECTRA

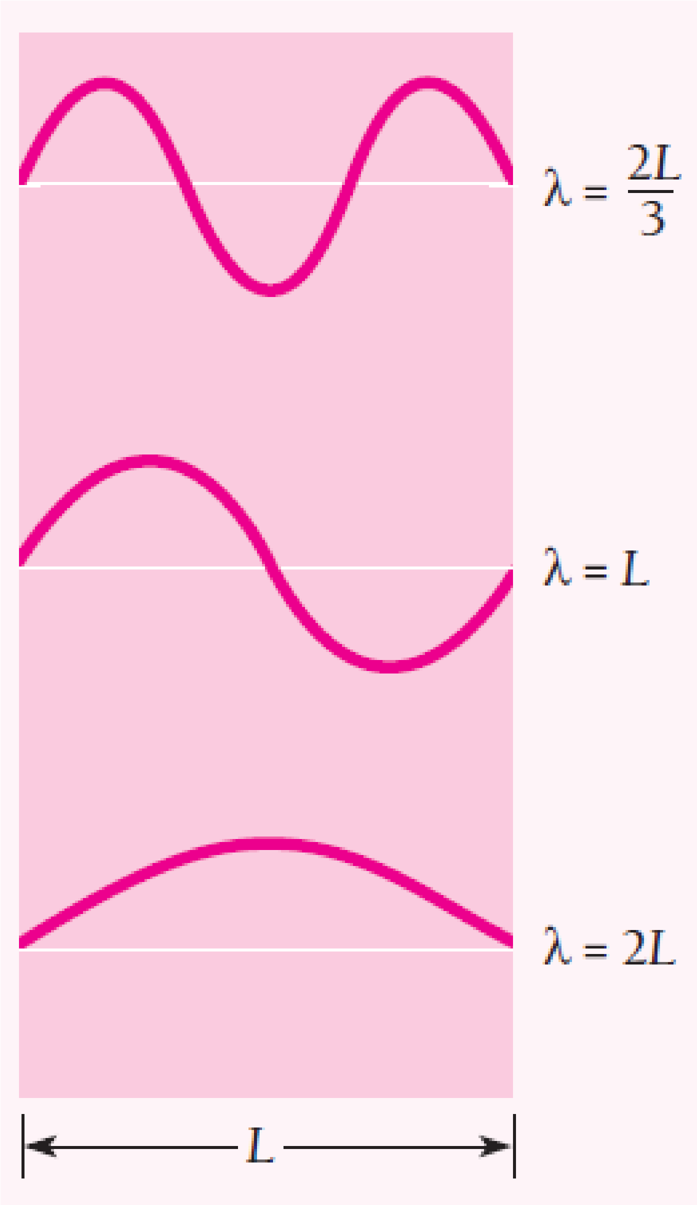
Classical Prediction

- The was examined at the end of the nineteenth century by ***Lord Rayleigh*** and ***James Jeans***.
- They started by considering the radiation inside a cavity of absolute temperature T whose walls are perfect reflectors.
- So, Electromagnetic Waves inside the cavity can form a series of standing waves after many reflections.
- This is a three-dimensional generalization of standing waves in a stretched string.

Rayleigh-Jeans formula

- These standing waves that have nodes at the walls, which restricts their possible wavelengths.
- Lord Rayleigh and Sir Jeans used these properties of the 3D standing waves to calculate *the number of independent standing waves $G(v)dv$ in the frequency interval between v and dv per unit volume in the cavity:*

$$G(v)dv = \frac{8\pi v^2 dv}{c^3}$$



Rayleigh-Jeans formula

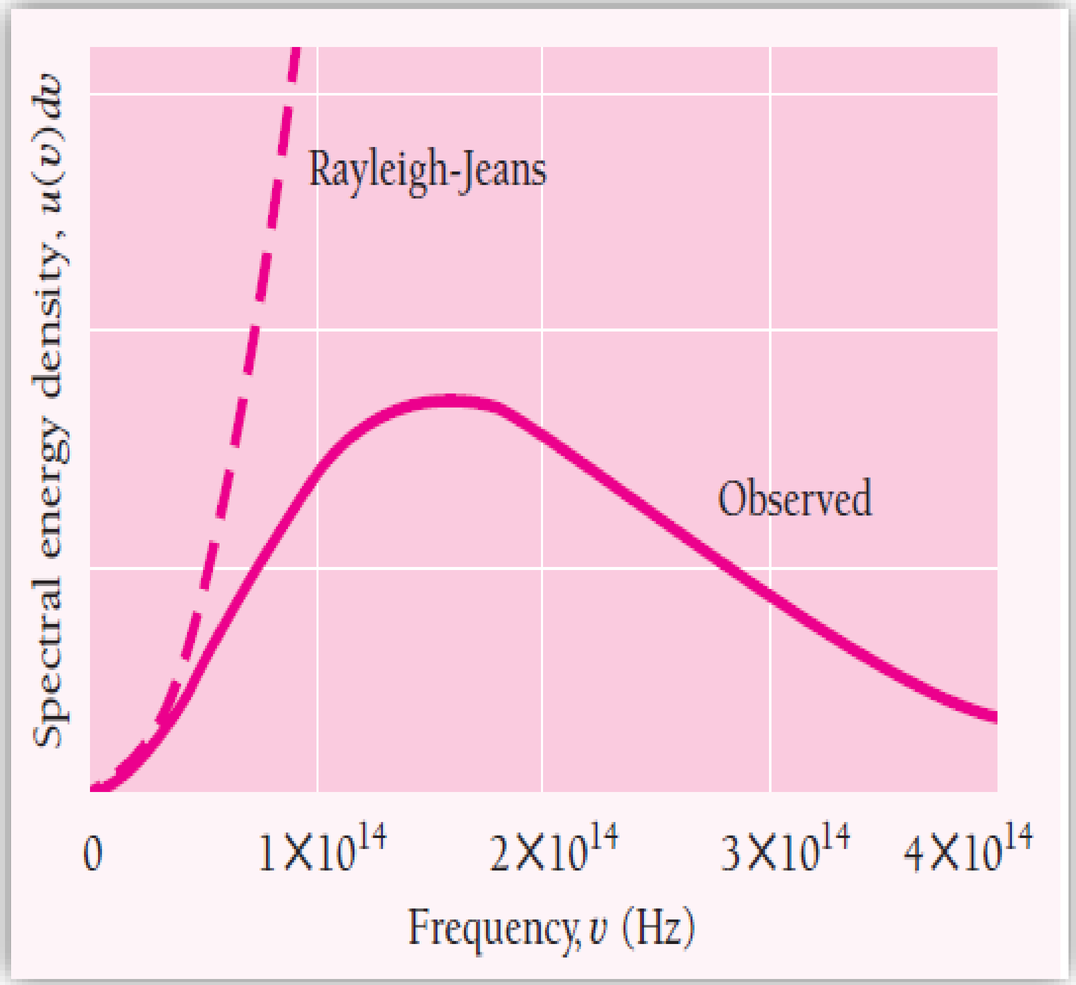
- Using the *theorem of equipartition of energy* and *assuming that the cavity is filled with monatomic ideal gas* they have estimated the energy per standing wave

$$\epsilon_{avg} = k_B T$$

$$Boltzman\ Const. \Rightarrow k_B = 1.381 \times 10^{-23} J/K$$

- So, the total energy $u(\nu)d\nu$ in the frequency interval between ν and $d\nu$ per unit volume in the cavity

$$u(\nu)d\nu = \epsilon_{avg} \cdot G(\nu)d\nu = \frac{8\pi\nu^2 k_B T\, d\nu}{c^3}$$



Rayleigh-Jeans formula

UV Catastrophe

- Rayleigh-Jeans formula of classical radiation:

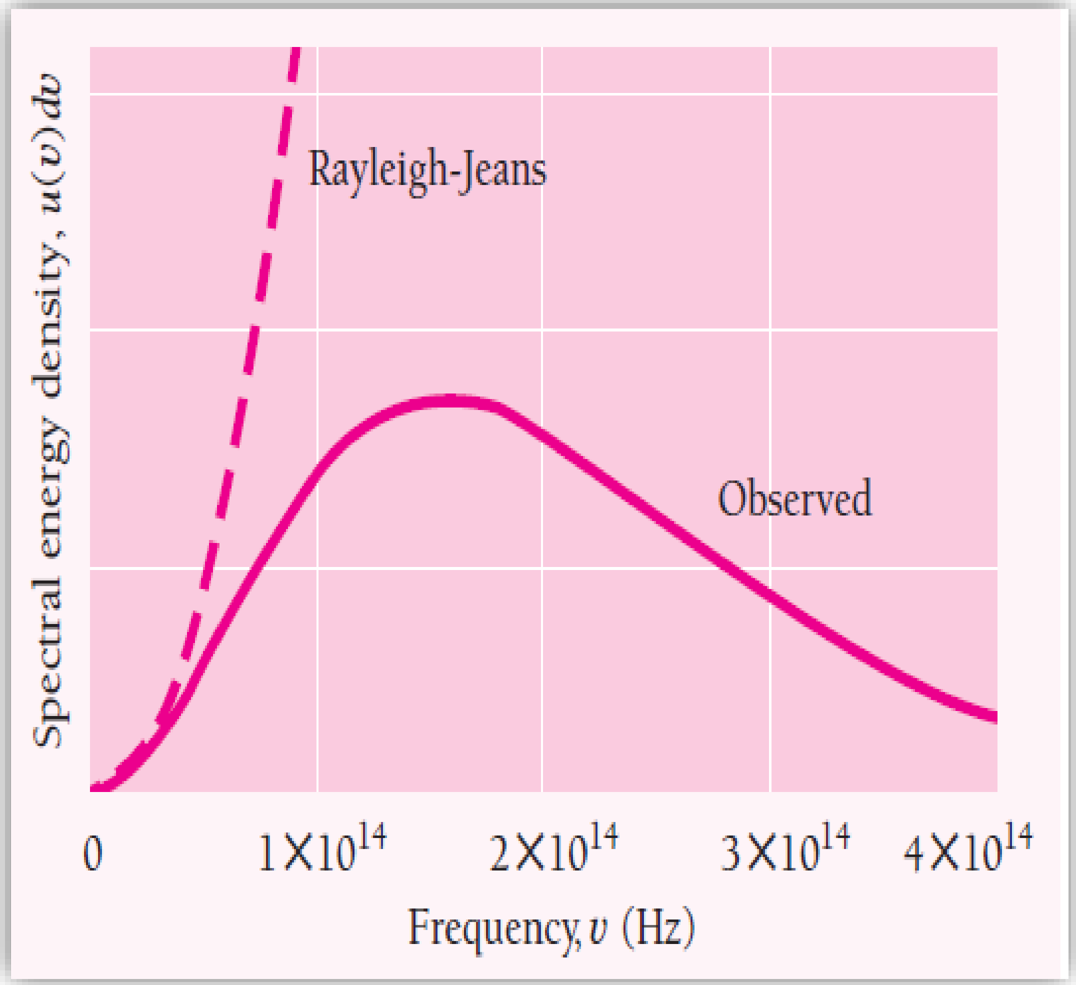
$$u(\nu)d\nu = \frac{8\pi\nu^2 k_B T\, d\nu}{c^3}$$

- However, a quick look at the prescribed theory and experimental data suggests some serious discrepancy among them!

As per theory as $\nu \to \infty \Rightarrow u(\nu)d\nu \to \infty$.

Experimentally, as $\nu \to \infty \Rightarrow u(\nu)d\nu \to 0$!!

- This discrepancy is formally called *Ultraviolet Catastrophe* of Classical Physics.
- Where did Rayleigh and Jeans go wrong?



BLACKBODY SPECTRA

Quantum Reality

- In 1900 the German physicist ***Max Planck*** produced his brilliant solution:

Planck Radiation Formula

$$\Rightarrow \mathrm{u}(\nu)d\nu = \frac{8\pi h}{c^3} \cdot \frac{\nu^3\, d\nu}{e^{h\nu/kT} - 1}$$

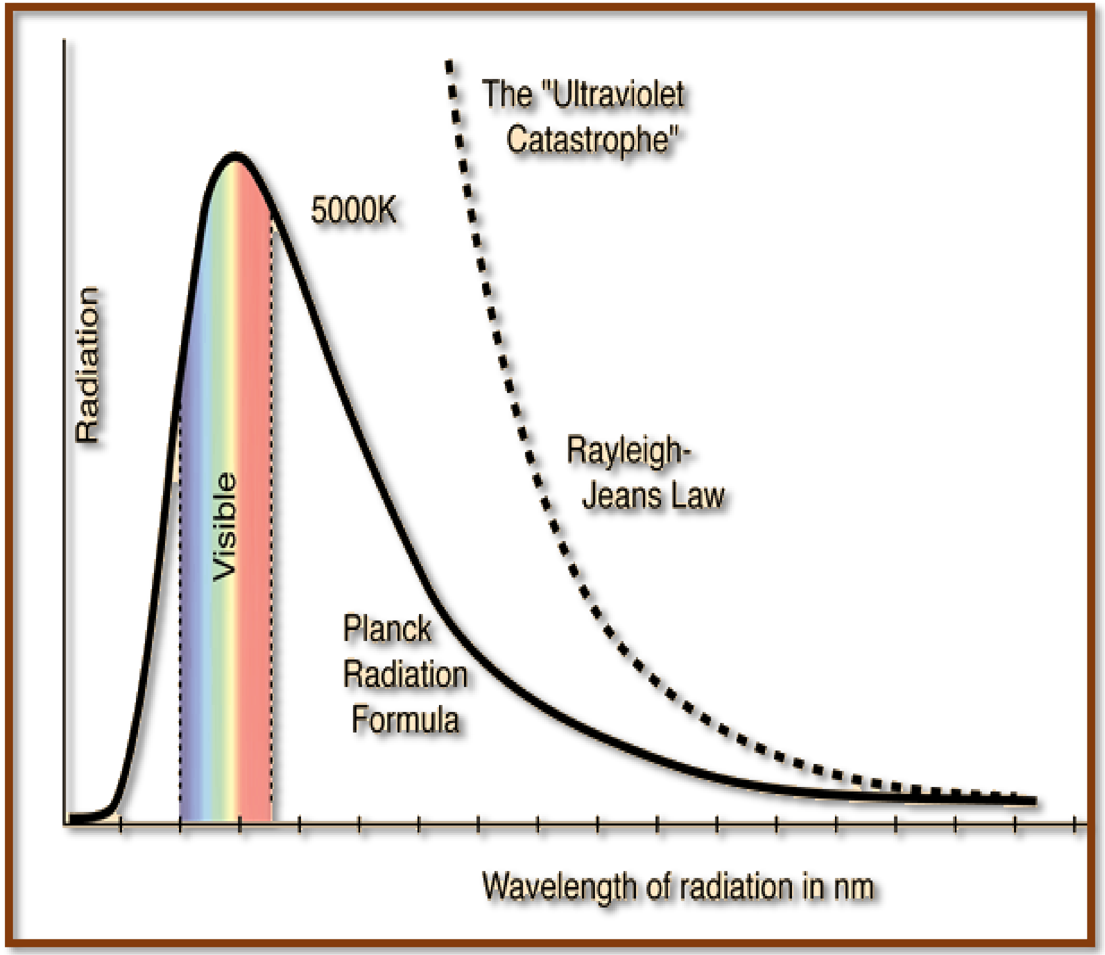
- Here h is the Planck Constant

$$h = 6.626 \times 10^{-34} J \cdot s$$

Planck Radiation Formula

$$u(\nu)d\nu = \frac{8\pi h}{c^3} \cdot \frac{\nu^3\, d\nu}{e^{h\nu/kT} - 1}$$

- $When\ h\nu \gg kT \Rightarrow e^{h\nu/kT} \to \infty$
- $\Rightarrow u(\nu)d\nu \to 0.$
- No Ultraviolet Catastrophe!
- $When\ h\nu \ll kT \Rightarrow e^{h\nu/kT} \to \left(1 + \frac{h\nu}{kT}\right)$
- $\Rightarrow u(\nu)d\nu \to Rayleigh - Jeans\ Formula.$
- So, Planck developed a complete theoretical framework.



Concept of Quanta

$$u(\nu)d\nu = \frac{8\pi h}{c^3} \cdot \frac{\nu^3\, d\nu}{e^{h\nu/kT} - 1}$$

- Planck arrived at his formula assuming average energy per standing wave:

$$\epsilon_{avg} = \frac{\nu}{e^{h\nu/kT} - 1}$$

- To have this type of average energy distribution ***Planck realised that the oscillators in the cavity walls could not have a continuous distribution of possible energies!***

- Possible energies of the oscillators, ϵ_n must have only the specific energies

$$\epsilon_n = nh\nu$$

- An oscillator emits radiation of frequency ν, when it drops from one energy state to the next lower one,
- and it jumps to the next higher state when it absorbs radiation of frequency ν.
- ***Each discrete bundle of energy hν is called a quantum (plural quanta)*** from the Latin for “how much.”

Fascinating and mysterious world of Quantum Physics opened in front of humanity!

Wien's Displacement Law

- Remember Blackbody radiation:

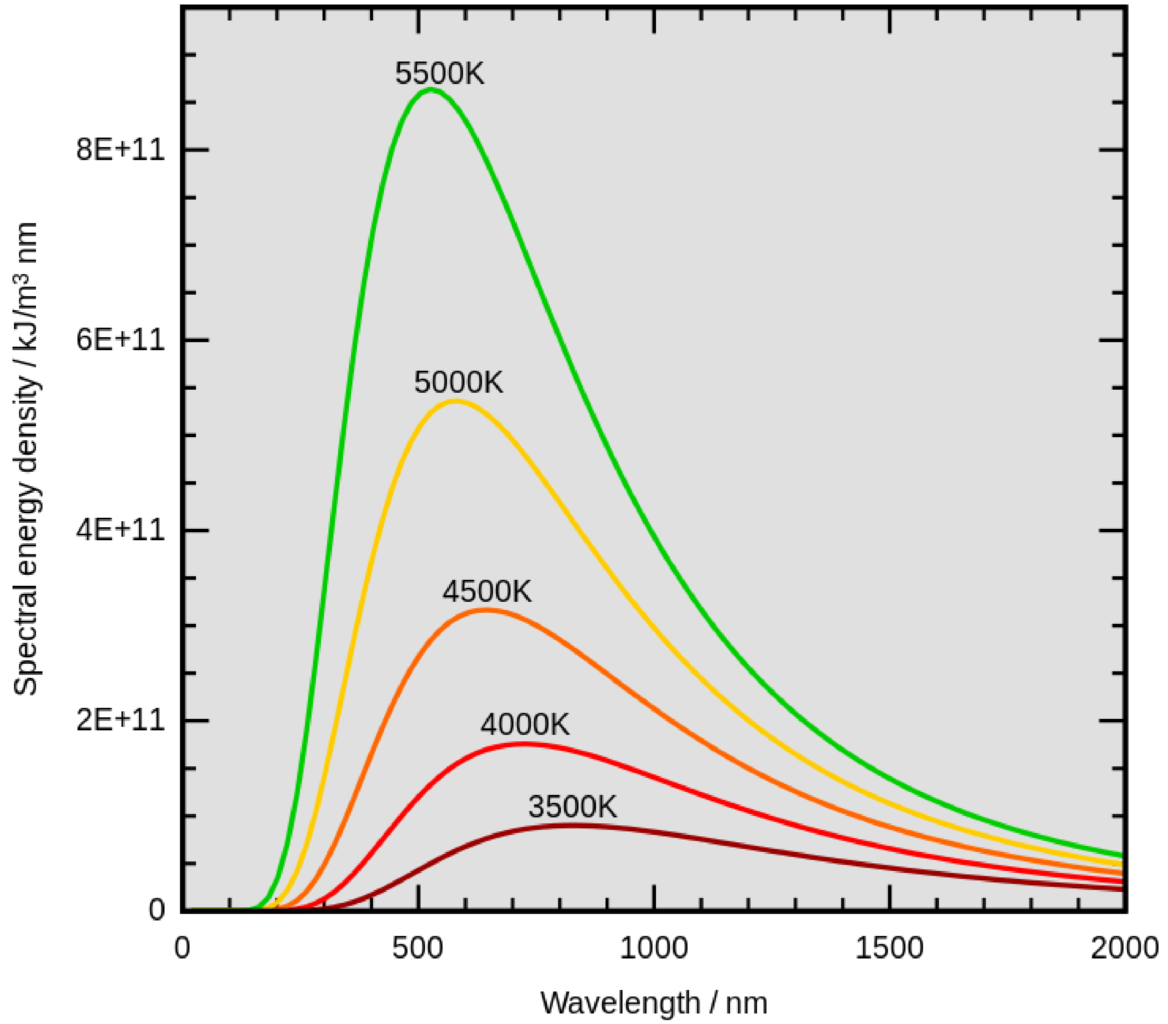
✓The higher the temperature, the greater the amount of radiation and *higher the frequency at which the maximum emission occurs.*

$$Now, Frequncy\ (\nu) \propto {}^{1}/_{wavelength\ (\lambda)}$$

- *And we find the Wien's Law:*

$$\lambda_{Peak} = \frac{b}{T}$$

$$b = 2.897 \times 10^{-3}\ m.K$$



- The wavelength of maximum solar emission is observed to be approximately $0.475\ \mu m$. *What is the surface temperature of the sun (assumed as a blackbody)?*

Solution: Given $\lambda_{\max} = 4.75 \times 10^{-7}$ m. Apply Wien's displacement law to get surface temperature of the sun $T = b/\lambda_{\max} = 6100\mathrm{K}$.

- The plots of intensity versus wavelength for three black bodies at temperatures T_1, T_2 and T_3, respectively are as shown in figure.

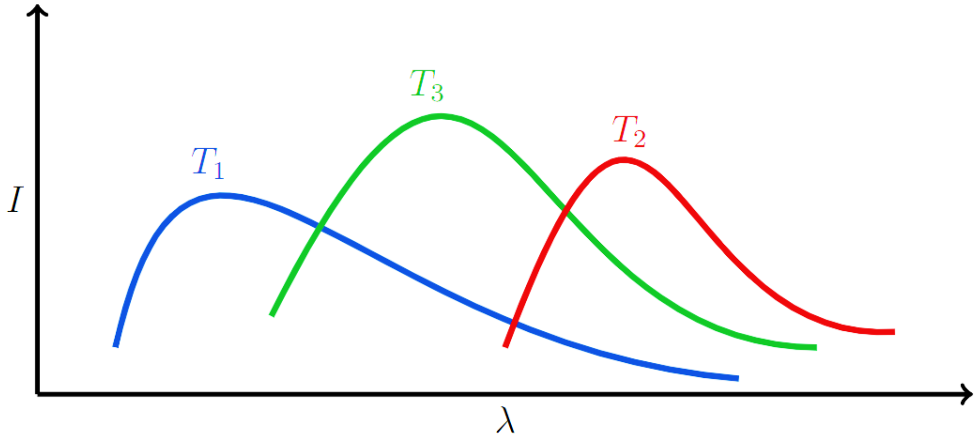
Their temperatures are such that,

a) $T_1 > T_2 > T_3$

b) $T_1 > T_3 > T_2$

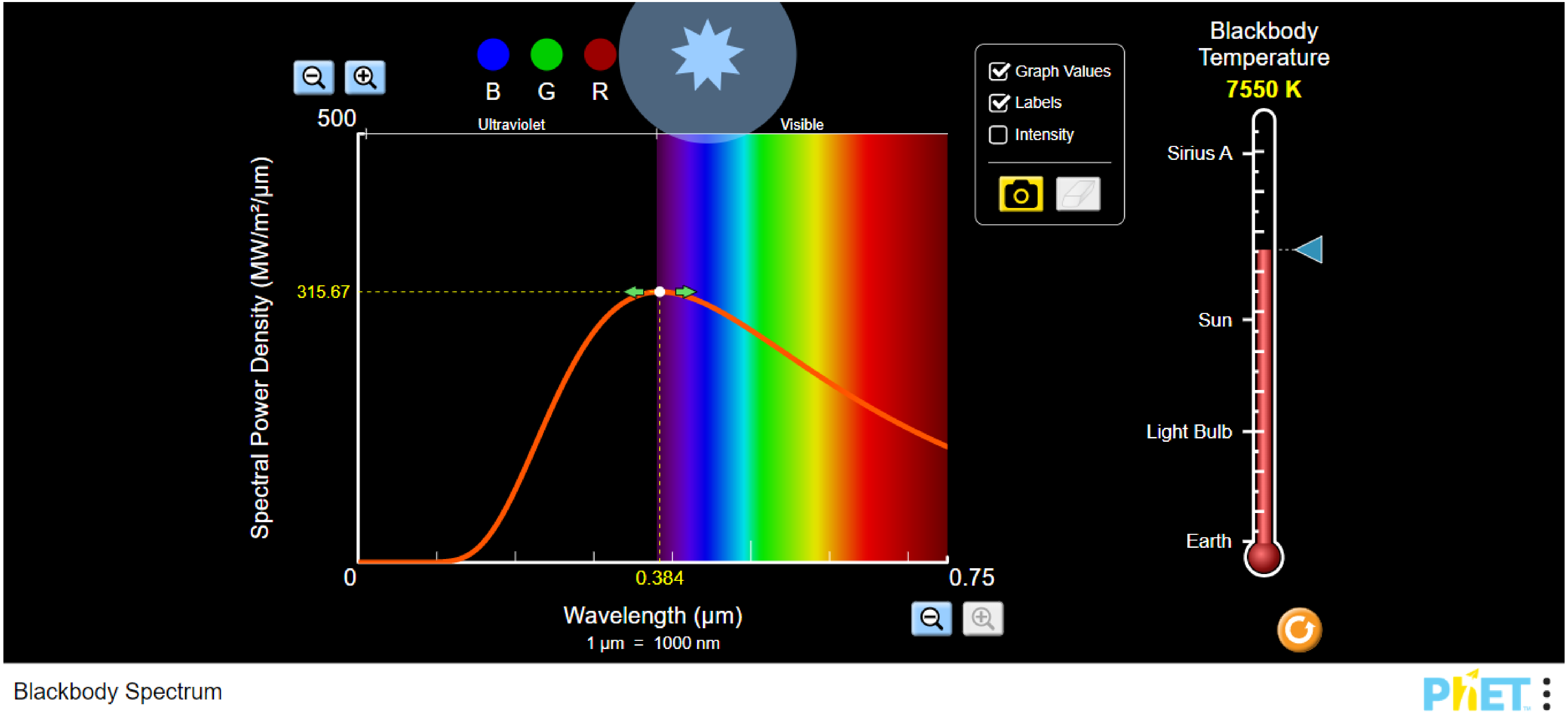
c) $T_2 > T_3 > T_1$

d) $T_3 > T_2 > T_1$



$\lambda_m T = b$. In given cases, $\lambda_{m,1} < \lambda_{m,3} < \lambda_{m,2}$ and hence $T_1 > T_3 > T_2$.

INTERACTIVE PRESENTATION



POLL QUESTIONS

Using Classical Physics and assuming that an ideal black body is filled with ideal monatomic gas molecules, calculate the average energy of a standing wave when the temperature of the blackbody is 600°C

A. $\varepsilon_{avg} = 300 \cdot k_B$

B. $\varepsilon_{avg} = 600 \cdot k_B$

C. $\varepsilon_{avg} = 573 \cdot k_B$

D. $\boxed{\varepsilon_{avg} = 873 \cdot k_B}$

POLL QUESTIONS

Calculate the value of associated energy quanta of an atomic oscillator that emits and absorbs orange light whose frequency is *5.00×10^{14} Hz.*

A. $\varepsilon = 1.45 \times 10^{-18}\,J$

B. $\varepsilon = 2.62 \times 10^{-19}\,J$

C. $\boxed{\varepsilon = 3.32 \times 10^{-19}\,J}$

D. $\varepsilon = 4.04 \times 10^{-19}\,J$

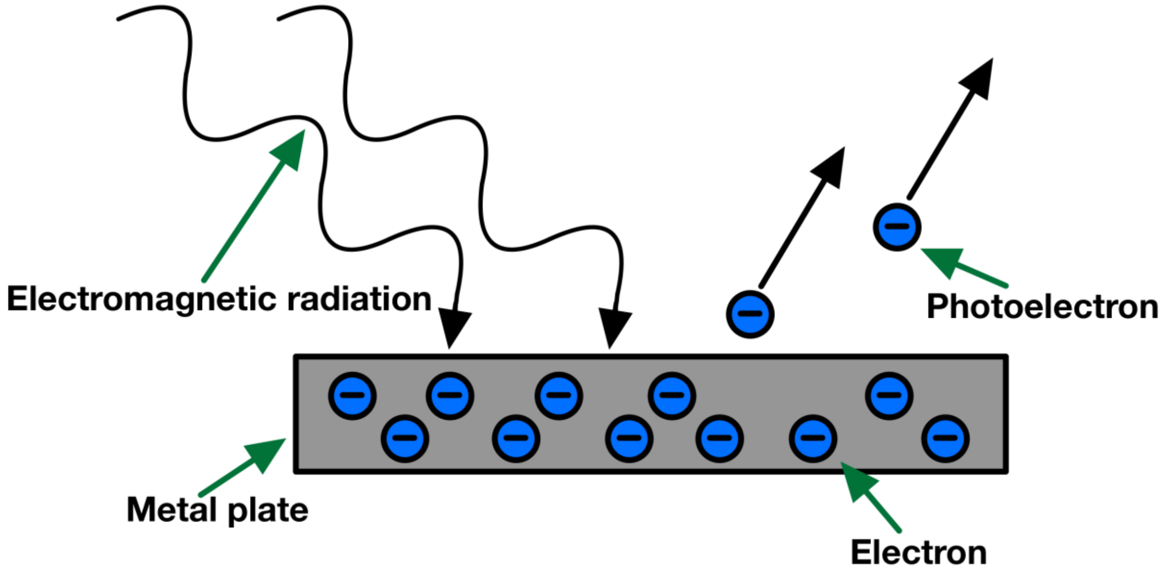
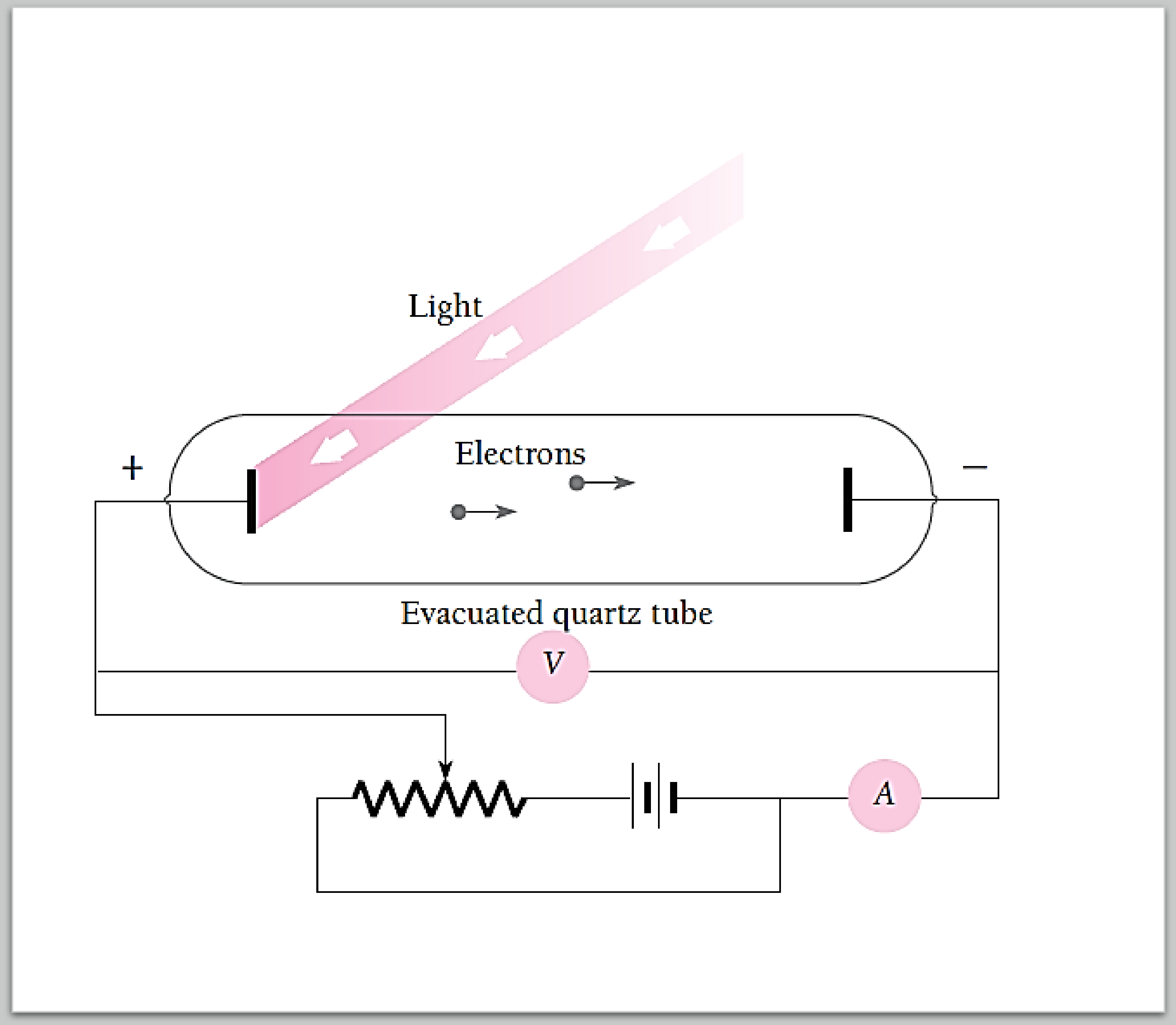


Photo Electric Effect
and concept of Photon

LECTURE-02

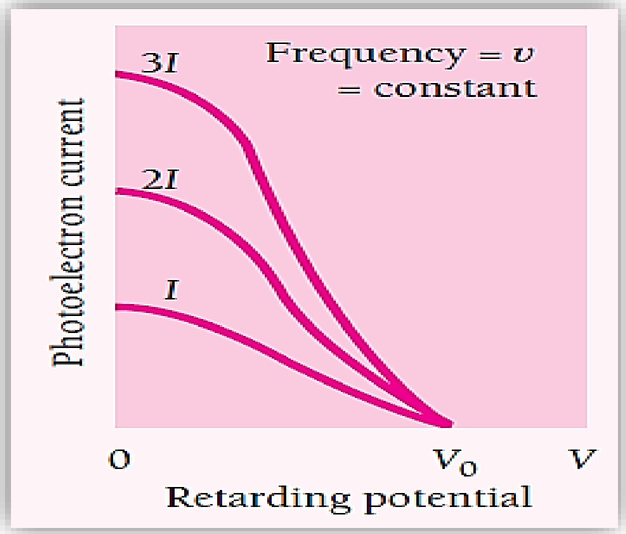
Photo-electric Effect

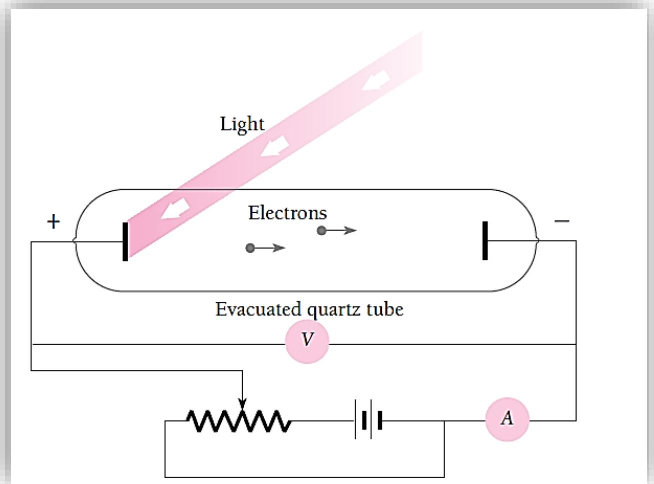
- In the early twentieth century, it has been repeatedly observed that *electrons were emitted from a metal surface kept in a vacuum/low pressure when the frequency of the light was sufficiently high*!
- This phenomenon is known as the ***photoelectric effect*** and the emitted electrons are called ***photoelectrons***.



Experimental Set-up

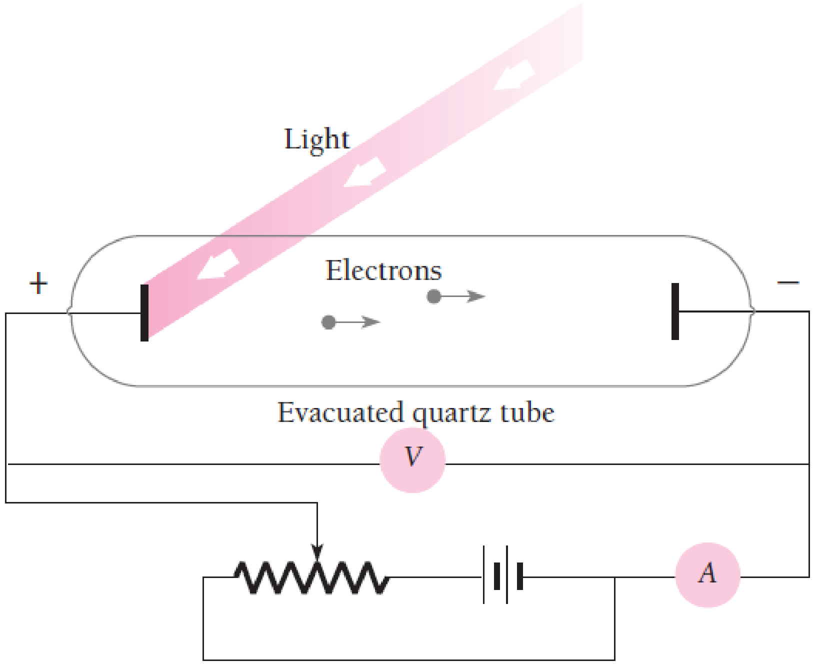
- ✓ An evacuated tube contains two electrodes connected to a source of variable voltage, with the metal plate whose surface is irradiated as the anode.
- ✓ Some of the photoelectrons that emerge from this surface have enough energy to reach the cathode - which create the ***Photo-current***.
- ✓ The slower photoelectrons are repelled before they get to the cathode.
- ✓ When the voltage is increased to a certain value V_0, of the order of several volts, no more photoelectrons arrive and the phot-current drops to zero.
- ✓ This extinction voltage is called the ***Stopping Potential*** and it corresponds to the ***maximum kinetic energy of the photoelectrons.***



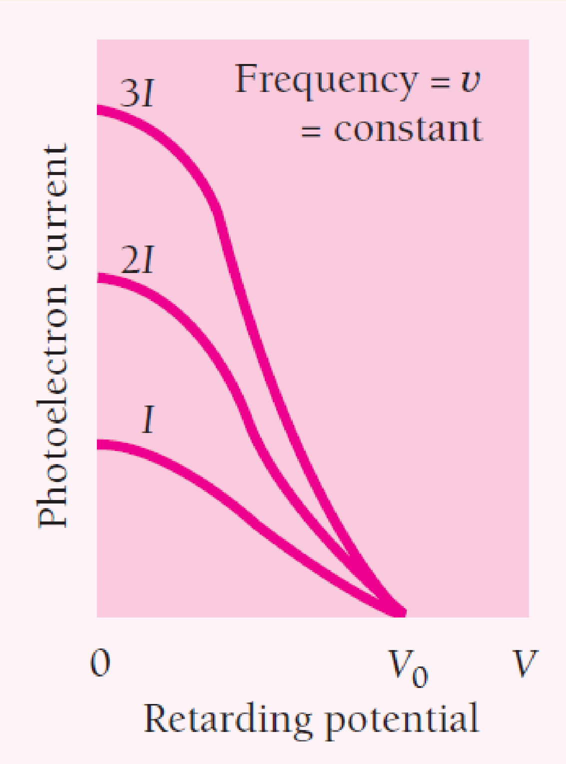


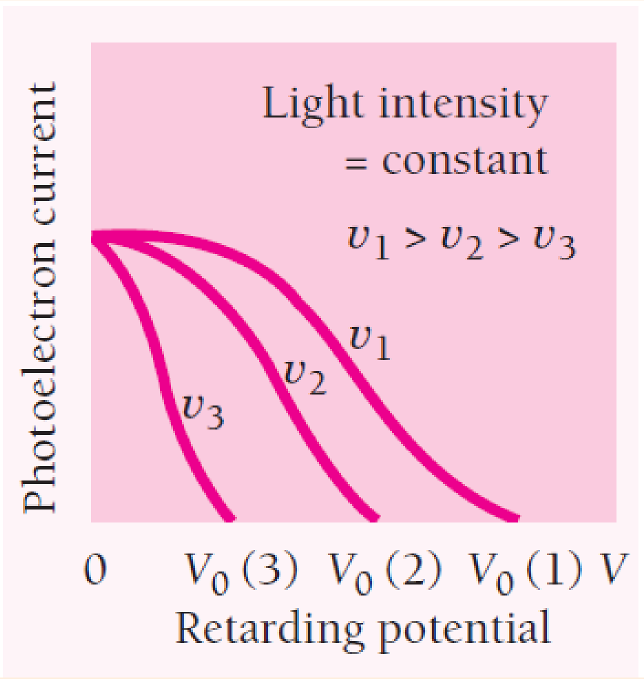
Classical Attempt

- The existence of the photoelectric effect was not surprising.
- After all, light waves carry energy, and some of the energy absorbed by the metal may somehow concentrate on individual electrons and reappear as their kinetic energy.
- Something like water waves dislodging pebbles from a beach.



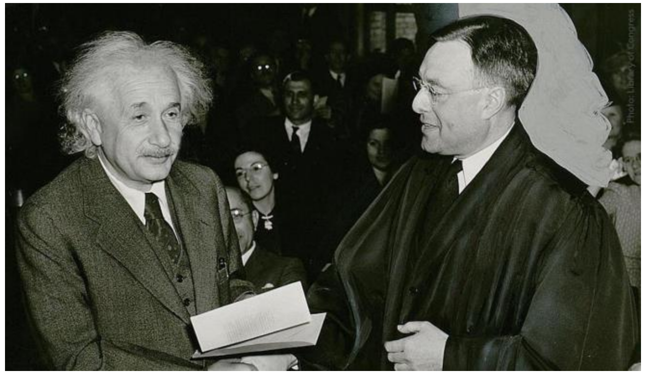
Critical Observations





However, following observations can't be explained by the classical wave interpretation.

- Why there is no delay?
- Why higher light intensity does not change photo-electron energy?
- Why there is a threshold frequency above which only photo-electron emission starts?
- Why higher the frequency of the light, more energy of the photoelectrons?



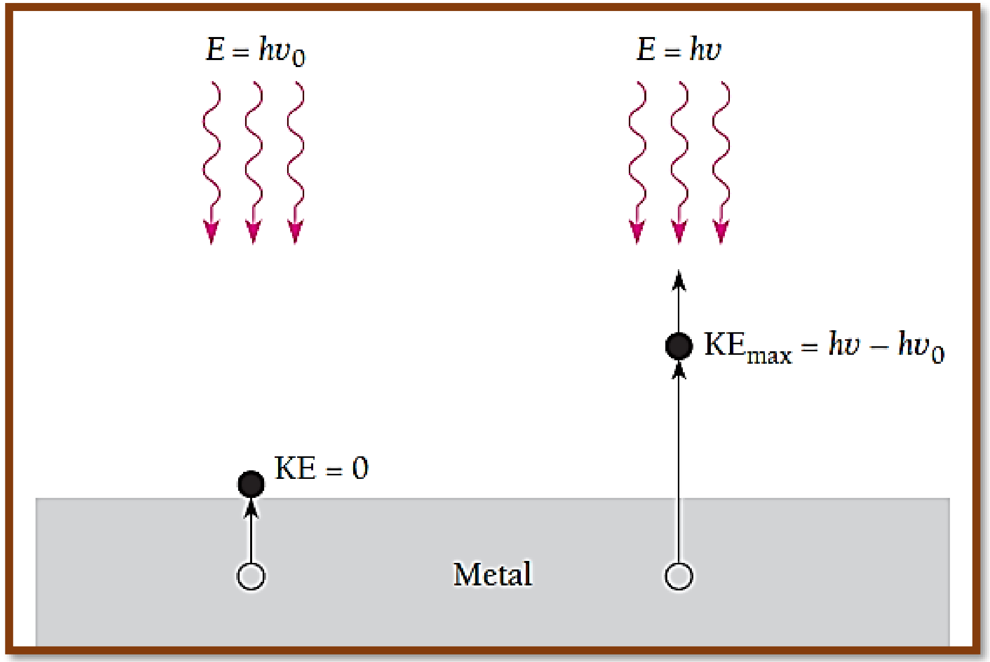
Quantum Theory of Light

- In early 20th century, ***Albert Einstein*** realized that the photoelectric effect could be understood if the energy in light is not spread out over wavefronts but is concentrated in small packets, or ***photons***.
- Each ***photon*** of light of frequency $\boldsymbol{\nu}$ has the energy $\boldsymbol{h\nu}$, the same as Planck's quantum energy.

$$\boldsymbol{E = h\nu = \frac{hc}{\lambda}}$$

- Einstein received ***Noble Prize in Physics in 1905*** for this pathbreaking discovery.

Quantum Theory of Light



Three experimental observations listed above follow directly from Einstein's hypothesis.

(1) Because EM wave energy is concentrated in photons and not spread out over wave-fronts, there should be no delay in the emission of photoelectrons.

(2) All photons of frequency $\boldsymbol{\nu}$ *has same energy, so changing the intensity of a monochromatic light beam will change the number of photoelectrons but not their energies.*

(3) The higher the frequency $\boldsymbol{\nu}$*, the greater the photon energy* $\boldsymbol{h\nu}$ *and more energy for the photoelectrons.*

Work Function

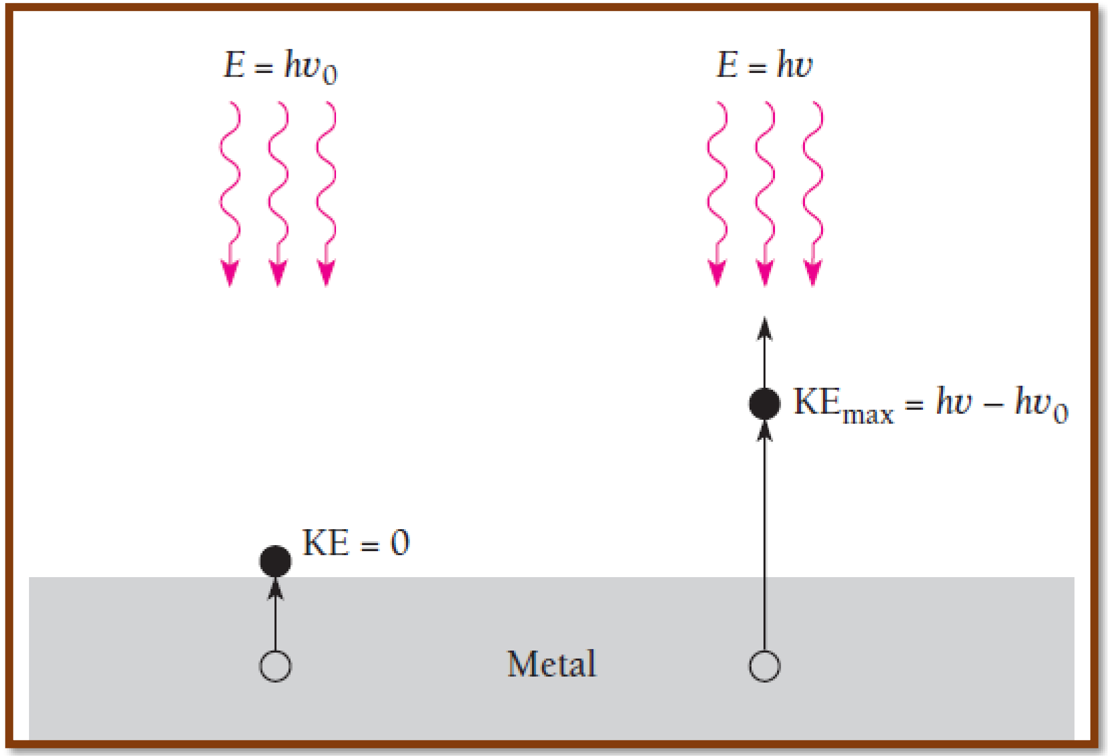
Metal	Symbol	Work Function, eV
Cesium	Cs	1.9
Potassium	K	2.2
Sodium	Na	2.3
Lithium	Li	2.5
Calcium	Ca	3.2
Copper	Cu	4.7
Silver	Ag	4.7
Platinum	Pt	6.4

1eV = 1.602 x 10^{-19} Joules

Greater the Φ, more energy is required for PE Effect, higher is the ν_0.

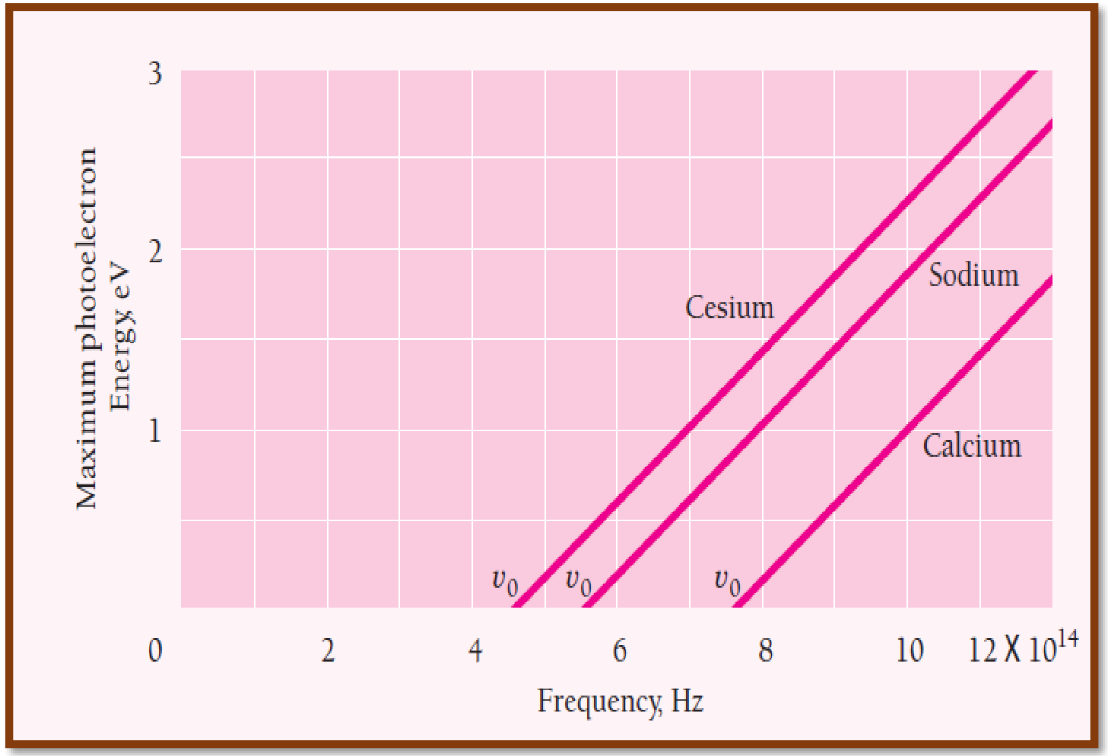
- Photo-electrons need to overcome a critical energy *Φ* to come out of the metal surface.
- Otherwise, electrons will always come out of a metal surface destabilizing it's crystalline order!
- This critical energy (*Φ*) is called the ***Work Function*** of the metal.
- Work Function $\boldsymbol{\Phi = h\nu_0}$, *where* ν_0 *is the threshold frequency above which photo-electron emission starts.*

Work Function and Photoelectron Energy



$$Acc.\,to\ Einstein\ for\ a\ given\ metal$$

$$\Rightarrow\ photon\ energy\ h\nu = KE_{max} + \Phi$$

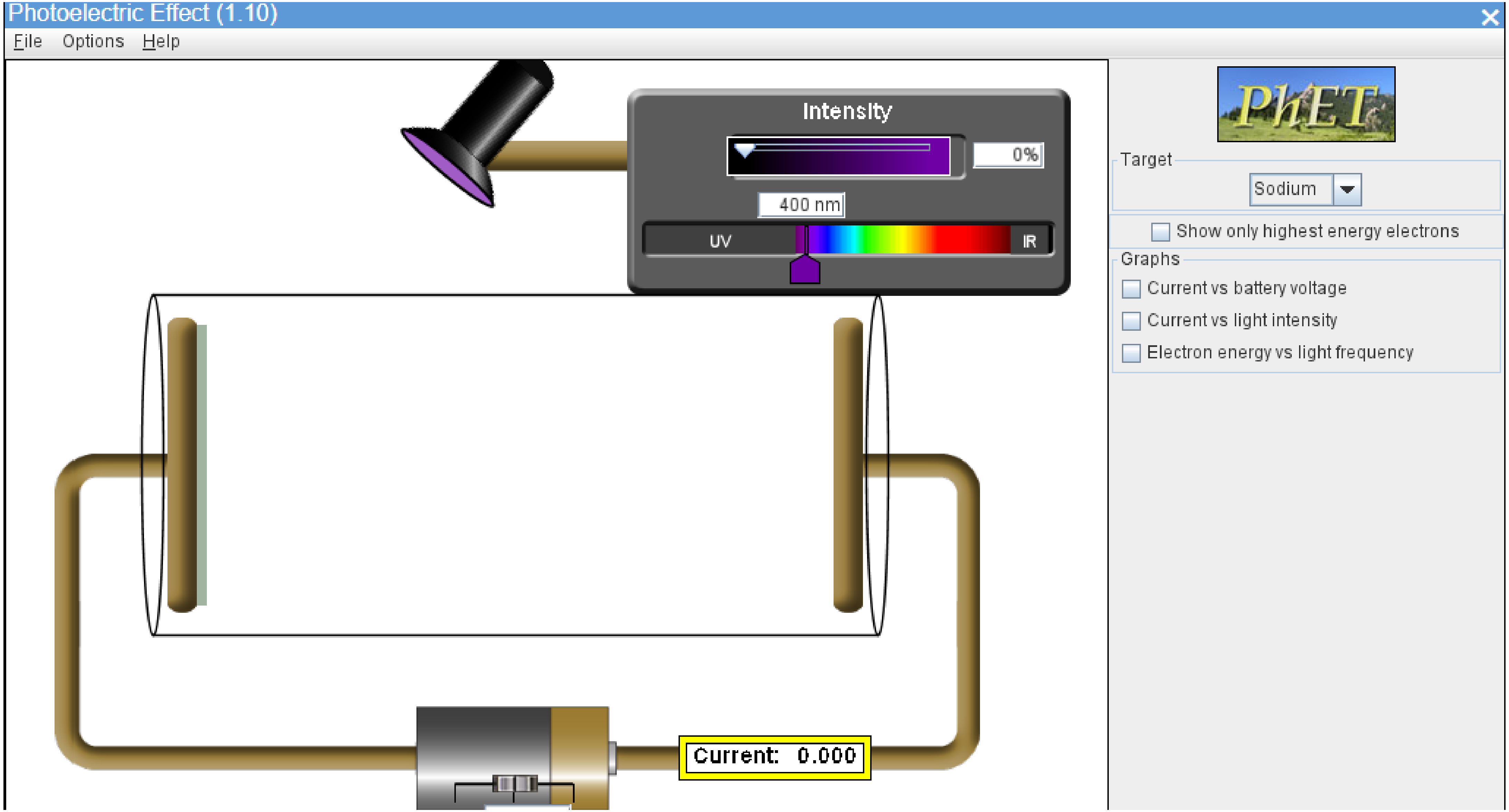


$$Photo\ electron\ energy$$

$$\Rightarrow KE_{max} = h\nu - \Phi \Rightarrow h\nu - h\nu_0$$

$$\Rightarrow KE_{max} = h(\nu - \nu_0)$$

INTERACTIVE PRESENTATION



Solution:

Using the values of

1. electron-volt (eV),

2. Planck const h and

3. Velocity of light in free space (c) ;

we can re-write energy equation:

$$\boldsymbol{E = \frac{1240 \times 10^{-6} eV.m}{\lambda}}$$

$$\boldsymbol{E} = [(4.136 \times 10^{-15}) \cdot \mathrm{v}] eV \cdot s$$

Use these formulae to rapidly convert frequency, wavelength and energy in eV.

POLL QUESTIONS

Calculate energy of a 700nm photon

A. 1.35eV

$\boxed{B.\ 1.77eV}$

C. 1.89eV

D. 1.97eV

$$HINT: \boldsymbol{E = h\nu = \frac{hc}{\lambda}}$$

1eV = 1.602 x 10^{-19} Joules

POLL QUESTIONS

Calculate the critical wavelength (λ_0) for photo-electron emission for Sodium metal surface *(Work Function = 2.3eV)*

A. $\lambda_0 = 360$ nm

B. $\lambda_0 = 470$ nm

C. $\lambda_0 = 540$ nm

D. $\lambda_0 = 720$ nm

$$HINT: \boldsymbol{\Phi = h\nu_0} \equiv \frac{\boldsymbol{hc}}{\boldsymbol{\lambda_0}}$$

1eV = 1.602×10^{-19} Joules

POLL QUESTIONS

Calculate maximum kinetic energy of the emitted photo-electrons from Li (Φ = 2.5eV) if bluish-violet light of 350nm is used for photo-current generation.

A. $KE_{max} \approx 0.5$ eV

B. $KE_{max} \approx 0.8$ eV

C. $KE_{max} \approx 1.0$ eV

D. $KE_{max} \approx 1.3$ eV

HINT: Find out Photon Energy in eV