Brian Wecht, the TA, is away this week. I will substitute for his office hours (in my office 3314 Mayer Hall, discussion and PS session.

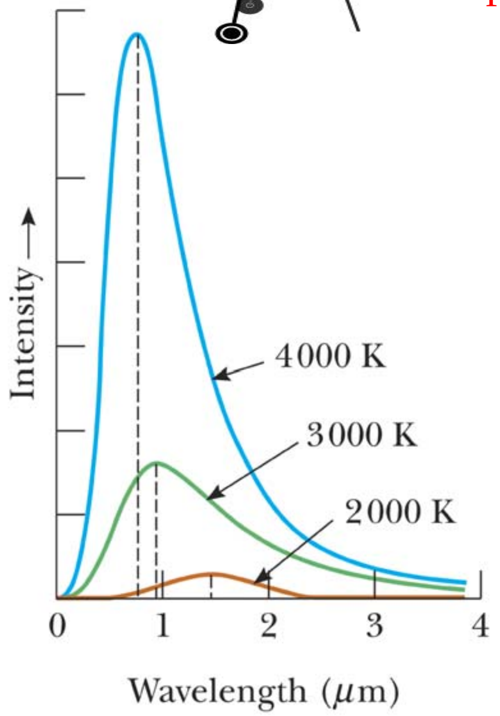
Pl. give all regrade requests to me this week (only)

Quiz 3 is This Friday

Physics 2D Lecture Slides
Lecture 11: Jan 27th 2004

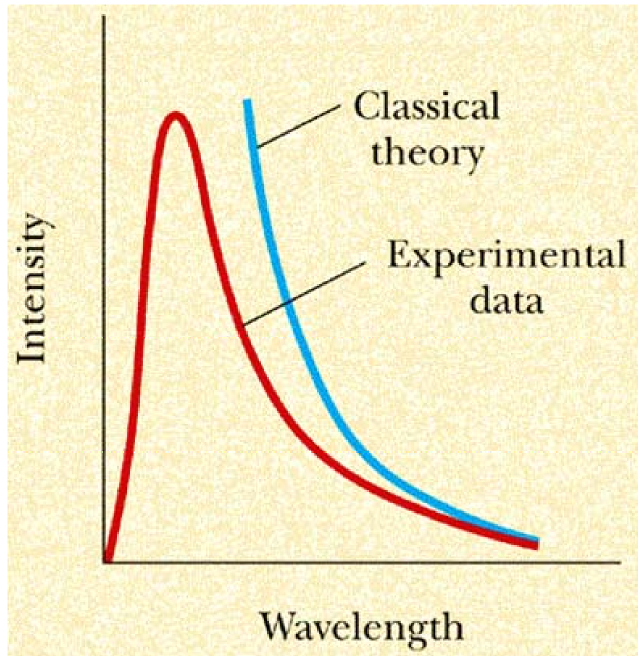
Vivek Sharma
UCSD Physics

Ultra Violet (Frequency) Catastrophe



$$\text{Radiancy } R(\lambda) = \frac{c}{4}u(\lambda) = \frac{c}{4}\frac{8\pi}{\lambda^4}kT = \frac{2\pi c}{\lambda^4}kT$$

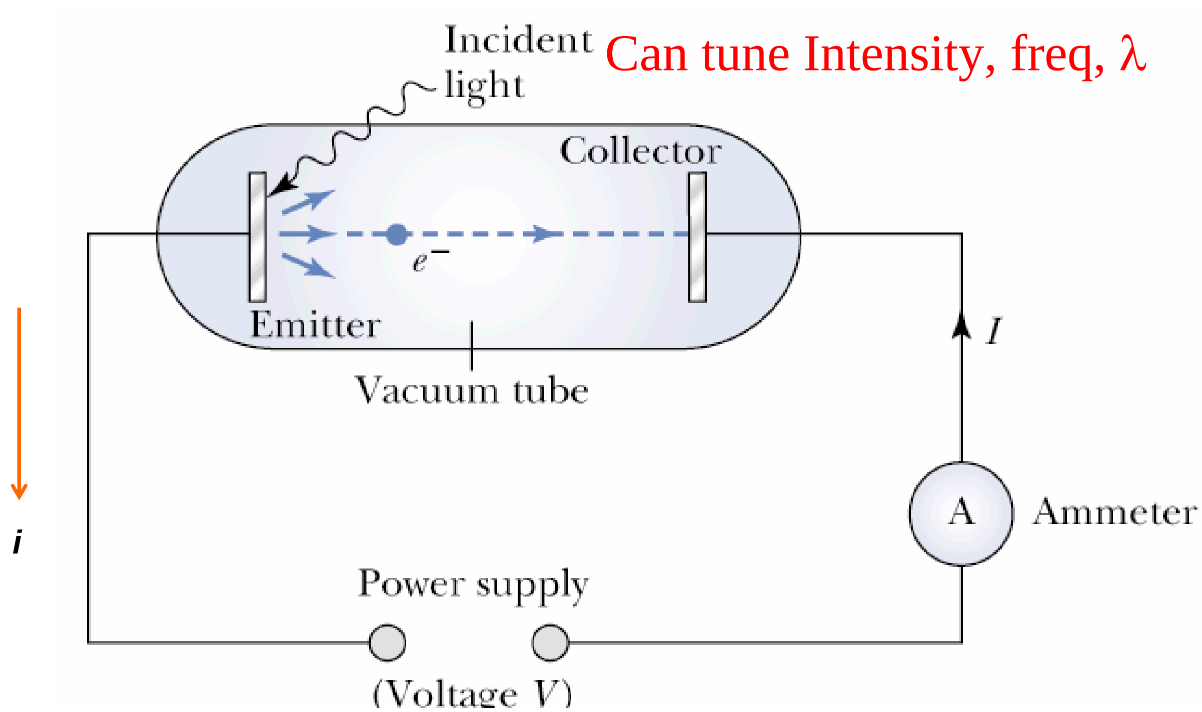
Radiancy is Radiation intensity per unit λ interval



Disaster # 2 : Photo-Electric Effect

Light of intensity I, wavelength λ and frequency ν incident on a photo-cathode

Can tune Intensity, freq, λ



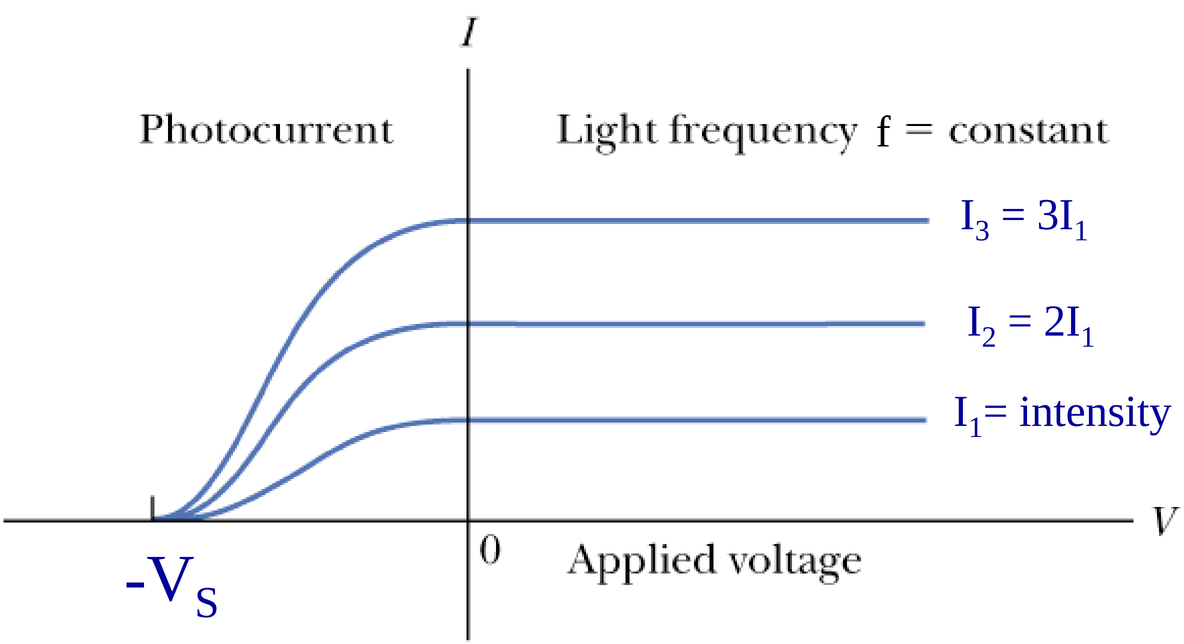
Measure characteristics of current in the circuit as a fn of I, f, λ

Photo Electric Effect: Measurable Properties

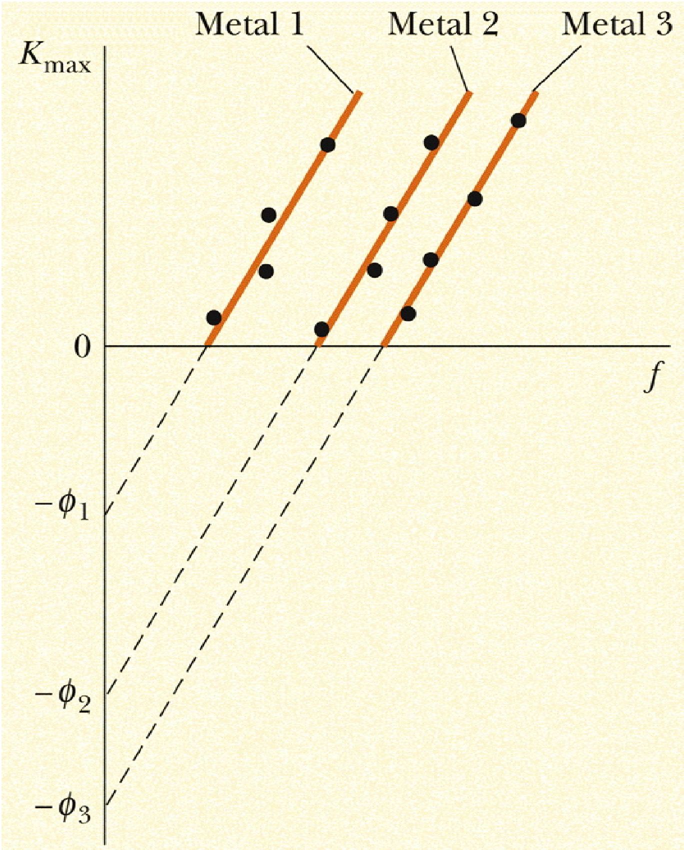
- Rate of electron emission from cathode
  - From current *i* seen in ammeter
- Maximum kinetic energy of emitted electron
  - By applying retarding potential on electron moving towards Collector plate
    - » **$K_{MAX} = eV_S$ (V_S = Stopping voltage)**
    - » **Stopping voltage → no current flows**
- Effect of different types of photo-cathode metal
- Time between shining light and first sign of photo-current in the circuit

Observation: Photo-Current Vs Frequency of Incident Light

Stopping voltage V_S is a measure of the Max kinetic energy of the electron



Stopping Voltage V_s For Different Photocathode Surfaces



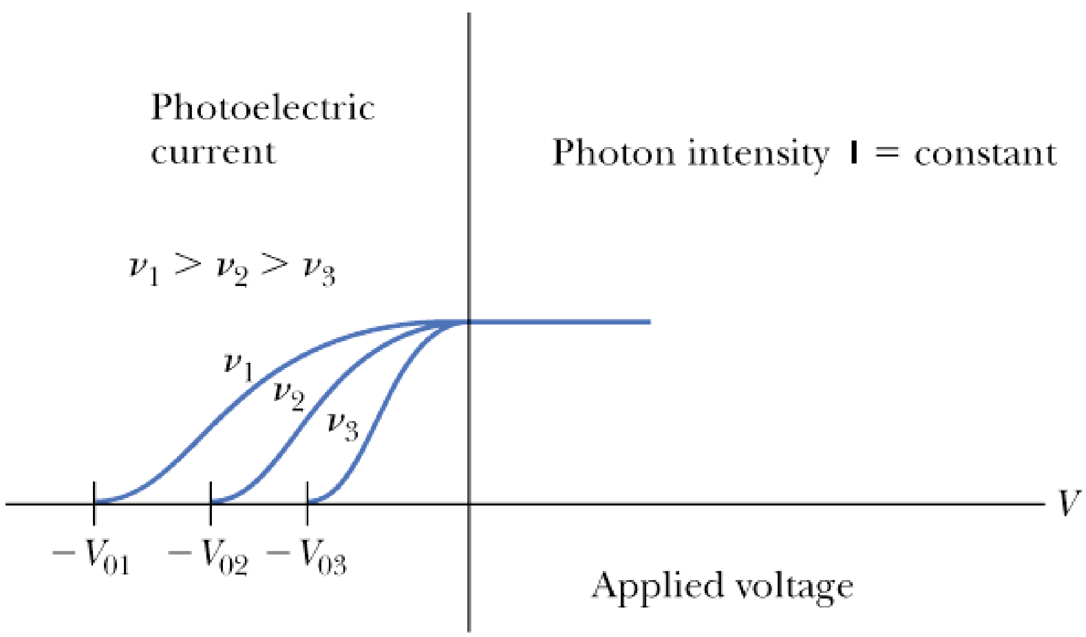
$eV_S = K_{MAX} = \text{max KE}$

Retarding Potential Vs Light Frequency (f)

Shining Light With Constant Intensity But different frequencies

Larger the frequency of light, larger is the stopping voltage (and thus the kinetic energy of the "photoelectrons")

*Current **i** in circuit*



Conclusions from the Experimental Observation

- Max Kinetic energy K_{MAX} independent of Intensity I for light of same frequency
- No photoelectric effect occurs if light frequency f is below a threshold no matter how high the intensity of light
- For a particular metal, light with $f > f_0$ causes photoelectric effect IRRESPECTIVE of light intensity.
  - f_0 is characteristic of that metal
- Photoelectric effect is instantaneous !...not time delay

Can one Explain all this Classically !

Classical Explanation of Photo Electric Effect

- As light Intensity increased $\Rightarrow$ $\vec{E}$ field amplitude larger
  - E field and electrical force seen by the "charged subatomic oscillators" Larger
    - $\vec{F} = e\vec{E}$
    - More force acting on the subatomic charged oscillator
    - $\Rightarrow$ More energy transferred to it
    - $\Rightarrow$ Charged particle "hooked to the atom" should leave the surface with more Kinetic Energy KE !! The intensity of light shining rules !
- As long as light is <u>intense enough</u> , light of ANY frequency f should cause photoelectric effect
- Because the Energy in a Wave is uniformly distributed over the Spherical wavefront incident on cathode, thould be a noticeable time lag ΔT between time is incident & the time a photo-electron is ejected : Energy absorption time
  - How much time ? Lets calculate it classically.

Classical Physics: Time Lag in Photo-Electric Effect

- Electron absorbs energy incident on a surface area where the electron is confined ≅ size of atom in cathode metal
- Electron is "bound" by attractive Coulomb force in the atom, so it must absorb a minimum amount of radiation before its stripped off
- Example : Laser light Intensity I = 120W/m^2 on Na metal
  - Binding energy = 2.3 eV= "Work Function"
  - Electron confined in Na atom, size ≅ 0.1nm ..how long before ejection ?
  - Average Power Delivered P_{AV} = **I . A**, A= $\pi r^2 \cong 3.1 \times 10^{-20}$ m^2
  - If all energy absorbed then $\Delta E = P_{AV} \cdot \Delta T \Rightarrow \Delta T = \Delta E / P_{AV}$

$$\Delta T = \frac{(2.3eV)(1.6\times10^{-19}\ J/eV)}{(120W/m^2)(3.1\times10^{-20}\ m^2)} = 0.10\ S$$

  - Classical Physics predicts Measurable delay even by the primitive clocks of 1900
  - But in experiment, the effect was observed to be instantaneous !!
  - Classical Physics fails in explaining all results

That's Disaster # 2 !

Max Planck & Birth of Quantum Physics

Back to Blackbody Radiation Discrepancy

Planck noted the UltraViolet Catastrophe at high frequency

"Cooked" calculation with new "ideas" so as bring:

$R(\lambda) \rightarrow 0$ as $\lambda \rightarrow 0$

$f \rightarrow \infty$

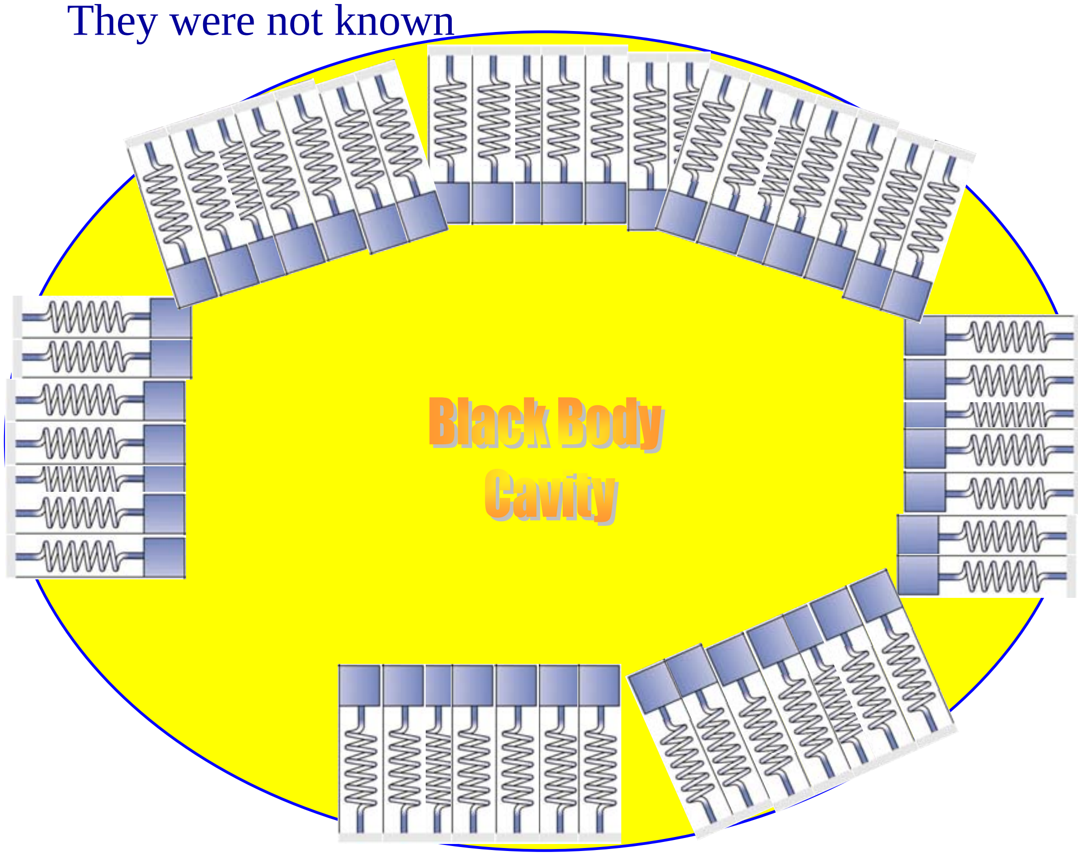
- Cavity radiation as equilibrium exchange of energy between EM radiation & "atomic" oscillators present on walls of cavity
- Oscillators can have any frequency f
- But the Energy exchange between radiation and oscillator NOT continuous and arbitarary…it is discrete …in packets of same amount
- $E = n\,hf$, with n = 1,2 3…. ∞

  h = constant he invented, a very small number he made up

Planck's "Charged Oscillators" in a Black Body Cavity

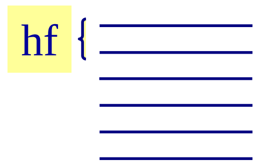
Planck did not know about electrons, Nucleus etc:

They were not known

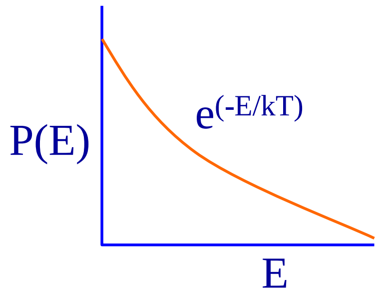


Planck, Quantization of Energy & BB Radiation

- Keep the rule of counting how many waves fit in a BB Volume
- Radiation Energy in cavity is quantized
- EM standing waves of frequency f have energy
  - E = n hf (n = 1,2 ,3 …10 ….1000…)



- Probability Distribution: At an equilibrium temp T, possible Energy of wave is distributed over a spectrum of states: $P(E) = e^{(-E/kT)}$
- Modes of Oscillation with :
  - Less energy E=hf = favored
  - More energy E=hf = disfavored



By this statistics, large energy, high f modes of EM disfavored

Planck's Calculation

$$R(\lambda) = \left(\frac{c}{4}\right)\left(\frac{8\pi}{\lambda^4}\right)\left[\frac{hc}{\lambda}\left(\frac{1}{e^{\frac{hc}{\lambda kT}} - 1}\right)\right]$$

Odd looking form

$$\text{When } \lambda \to \text{large} \Rightarrow \frac{\text{hc}}{\lambda\text{kT}} \to \text{small}$$

$$\text{Recall } \boxed{e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + ...}$$

$$\Rightarrow e^{\frac{hc}{\lambda kT}} - 1 = (1 + \frac{hc}{\lambda kT} + \frac{1}{2}\left(\frac{hc}{\lambda kT}\right)^2 + ...] - 1$$

$$= \frac{hc}{\lambda kT}$$ plugging this in $R(\lambda)$ eq:

$$\boxed{R(\lambda) = \left(\frac{c}{4}\right)\left(\frac{8\pi}{\lambda^4}\right)\frac{hc}{\lambda kT}}$$

Graph & Compare With BBQ data

Planck's Formula and Small λ

When λ is small (large f)

$$\frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \cong \frac{1}{e^{\frac{hc}{\lambda kT}}} = e^{-\frac{hc}{\lambda kT}}$$

Substituting in R(λ) eqn:

$$R(\lambda) = \left(\frac{c}{4}\right)\left(\frac{8\pi}{\lambda^4}\right) e^{-\frac{hc}{\lambda kT}}$$

$$\text{As } \lambda \to 0,\ e^{-\frac{hc}{\lambda kT}} \to 0$$

$$\Rightarrow R(\lambda) \to 0$$

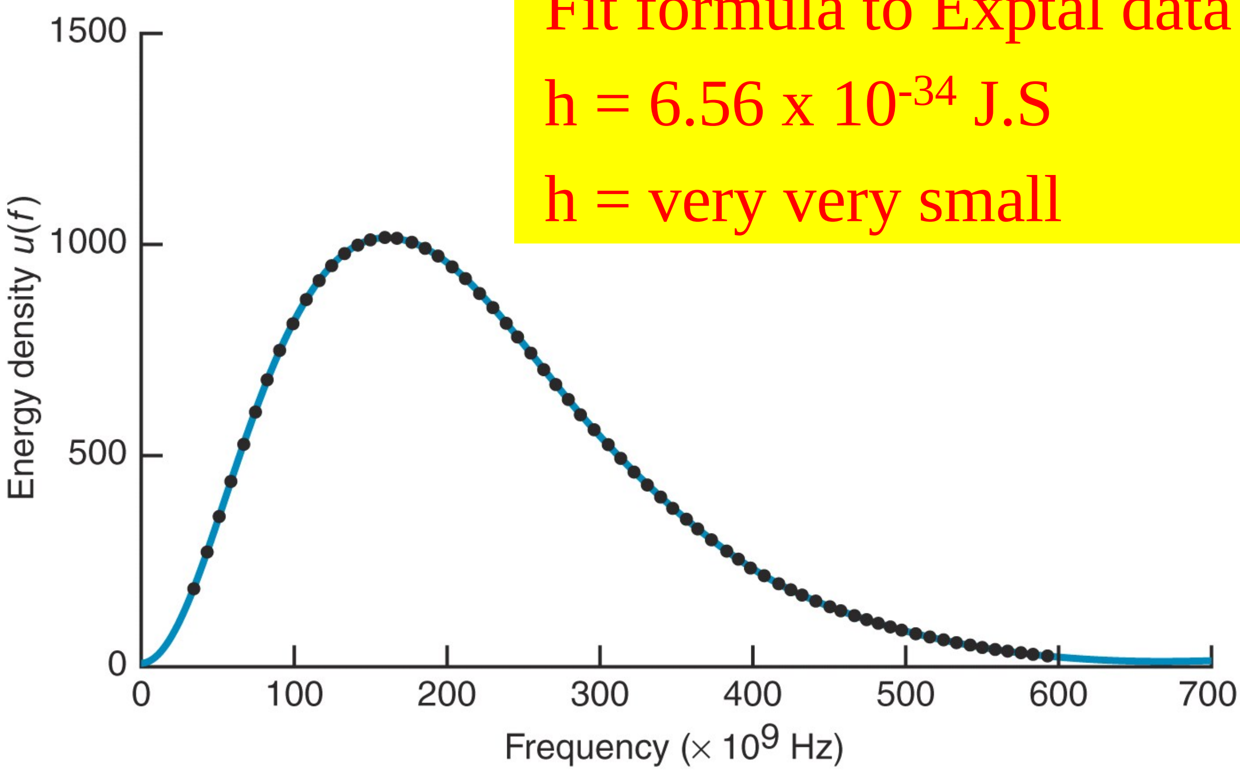
Just as seen in the experimental data

Planck's Explanation of BB Radiation

Fit formula to Exptal data

h = 6.56 x 10^{-34} J.S

h = very very small



Major Consequence of Planck's Formula