PARTICLE PROPERTIES OF WAVES

1. Electromagnetic Waves.
2. Blackbody Radiation.
3. Photoelectric Effect.
4. What is Light?
5. X-Rays.
6. X-ray Diffraction.
7. Compton Effect.
8. Pair Production.
9. Photons and Gravity.

BLACKBODY RADIATION

What is the fundamental nature of light?

EM waves that obeyed Maxwell's theory and proved by Young.

People were happy ☺ for a dozen of years and then…. ☹

Scientist tried to understand the origin of radiation emitted by bodies of matter and found that something is seriously amiss!!!

BLACKBODY RADIATION

Color varies with temperature..
Red → yellow → white…. Not to mentions other frequencies our eyes can't see!!

ALL objects (including our selves) **radiate** such energy continuously whatever their temperature.

Which frequencies predominate depends on the temperature.

At room temperature most of the radiation is in the infrared (invisible) part of the spectrum.

BLACKBODY RADIATION

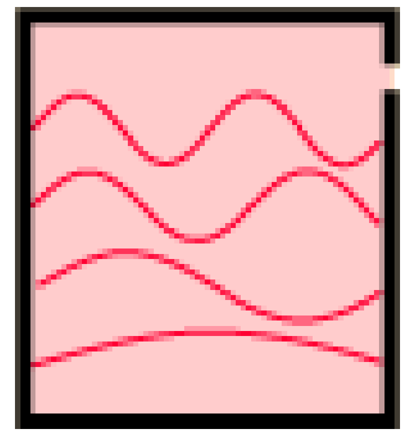
A body at constant T is in thermal equilibrium with its surroundings ← it must absorb energy at the same rate it emits energy!

That is, the ability a body to radiate is related to its ability to absorb radiaiton.

An ideal body is the one that absorbs ALL radiation incident upon it, regardless of frequency. ← this body is called **BLACKBODY**!

BLACKBODY RADIATION

A blackbody can be approximated by a hollow object with a very small hole leading to its interior.



Any radiation entering the hole is trapped by reflection back and forth until it is absorbed.

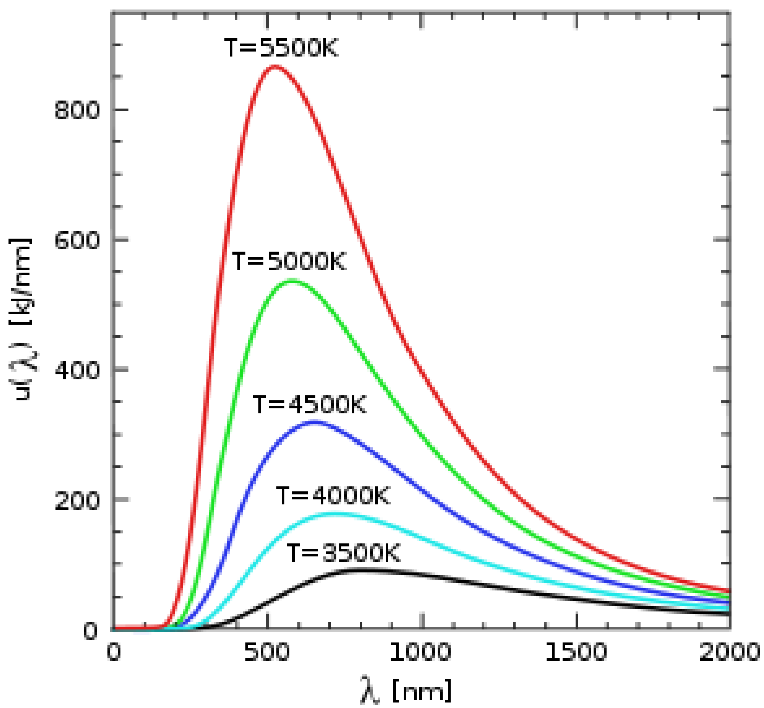
The cavity walls are constantly emitting and absorbing radiation.

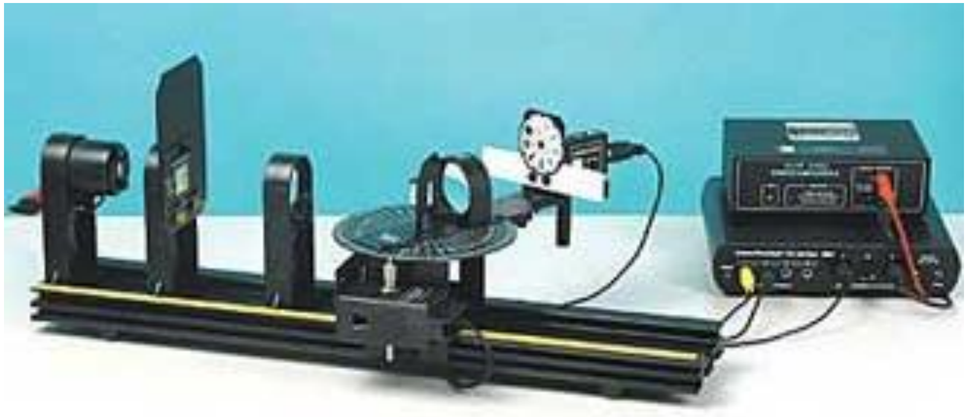
We are interested in the properties of this radiation ← the **BLACKBODY RADIATION**!

BLACKBODY RADIATION

What did the spectrum of a blackbody looked like?

• BB radiates more when it is hot than when it is cold.
• The spectrum of a hot BB has its peak at higher frequencies. ← remember red → yellow → white.

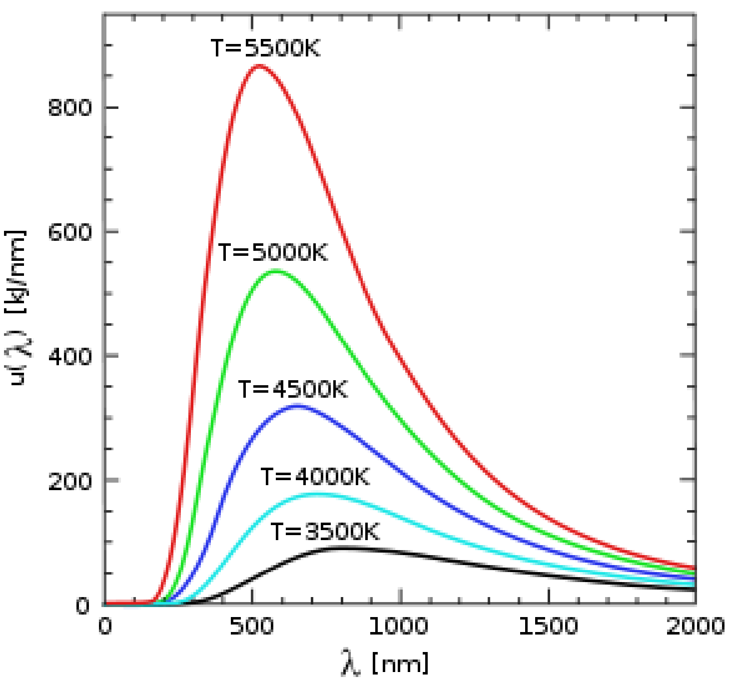


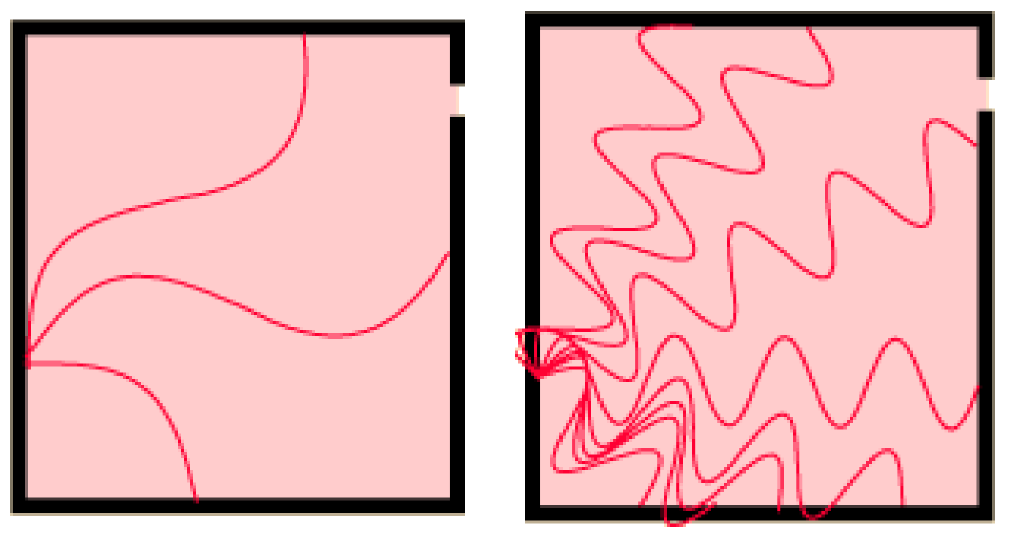


BLACKBODY RADIATION

Why does a BB spectrum look as it does?

- Rayleigh and Jeans tried to explain it.
- They considered radiation inside a cavity of absolute temp *T* whose walls are perfect reflectors as standing EM waves.





BLACKBODY RADIATION

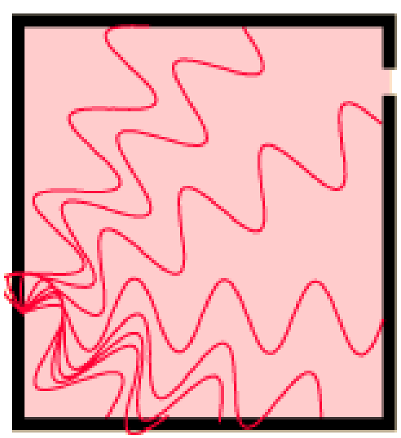
What are standing waves?

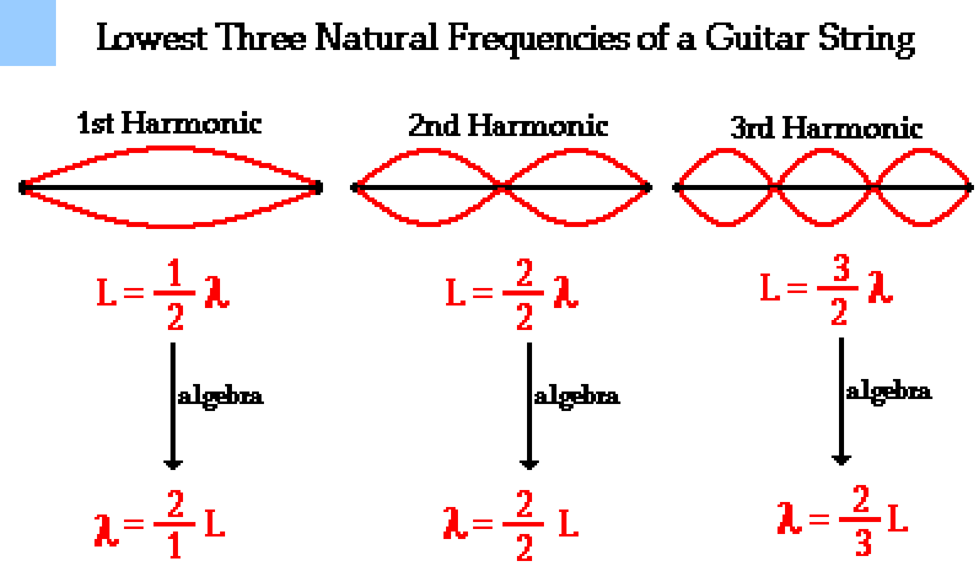
• Conditions of a standing wave:

- The path length from wall to wall = nλ/s , n integer.
- nodes occur at each reflecting surface.

• The number of independent standing waves $G(\nu)d\nu$ in the frequency interval between ν and $d\nu$ per unit volume in the cavity is:

$$G(\nu)d\nu = \frac{8\pi\nu^2 d\nu}{c^3}$$





BLACKBODY RADIATION

How to find the total energy in a BB spectrum?

• To find the total energy $u(\nu)d\nu$ per unit volume in the cavity in the frequency interval from ν to $\nu+d\nu$ we need to know:

- Number of independent standing waves.

$$\boxed{G(\nu)d\nu = \frac{8\pi\nu^2 d\nu}{c^3}}$$

- Average energy per standing wave.

BLACKBODY RADIATION

How to find the average energy per standing wave?

• Remember the **theorem of equipartition of energy**??

- The average energy per **degree of freedom** of an entity in thermal equilibrium at temperature T is ½ kT.
- k is Boltzmann constant.
- A degree of freedom is a mode of energy possession.
- A monoatomic ideal gas molecule has 3 degrees of freedom ← average total energy 3/2 kT.
- A one dimensional harmonic oscillator has two degrees of freedom ← average energy 2(½) kT.

$$\bar{\varepsilon} = kT$$

Classical average energy per standing wave

BLACKBODY RADIATION

What is then the total energy?

$$G(\nu)d\nu = \frac{8\pi\nu^2 d\nu}{c^3}$$

$$\bar{\varepsilon} = kT$$

$$u\nu)d\nu = \bar{\varepsilon}\, G(\nu)d\nu = \frac{8\pi kT}{c^3}\nu^2 d\nu$$

Rayleigh-Jeans formula

This formula is based on classical physics. Does it reproduce the experimental finding?

BLACKBODY RADIATION

Theory vs. experiment…

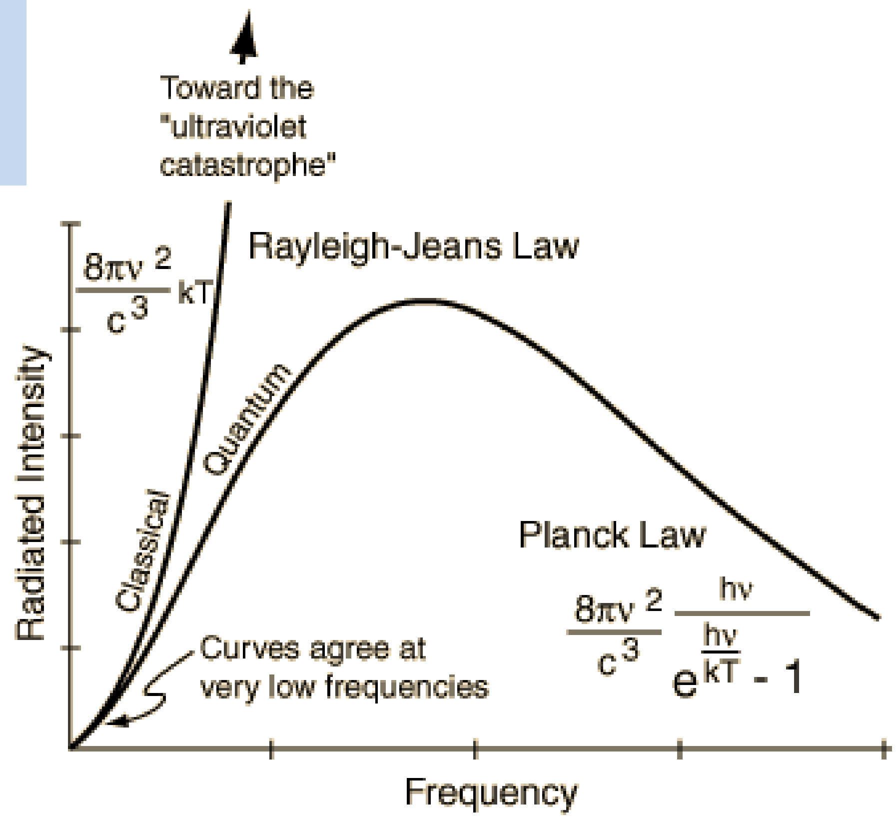
$$u\nu)d\nu = \bar{\varepsilon}\, G(\nu)d\nu = \frac{8\pi kT}{c^3}\nu^2 d\nu$$

Ultraviolet catastrophe!!

Planck came up with a formula for the spectral energy density of BB radiation.

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

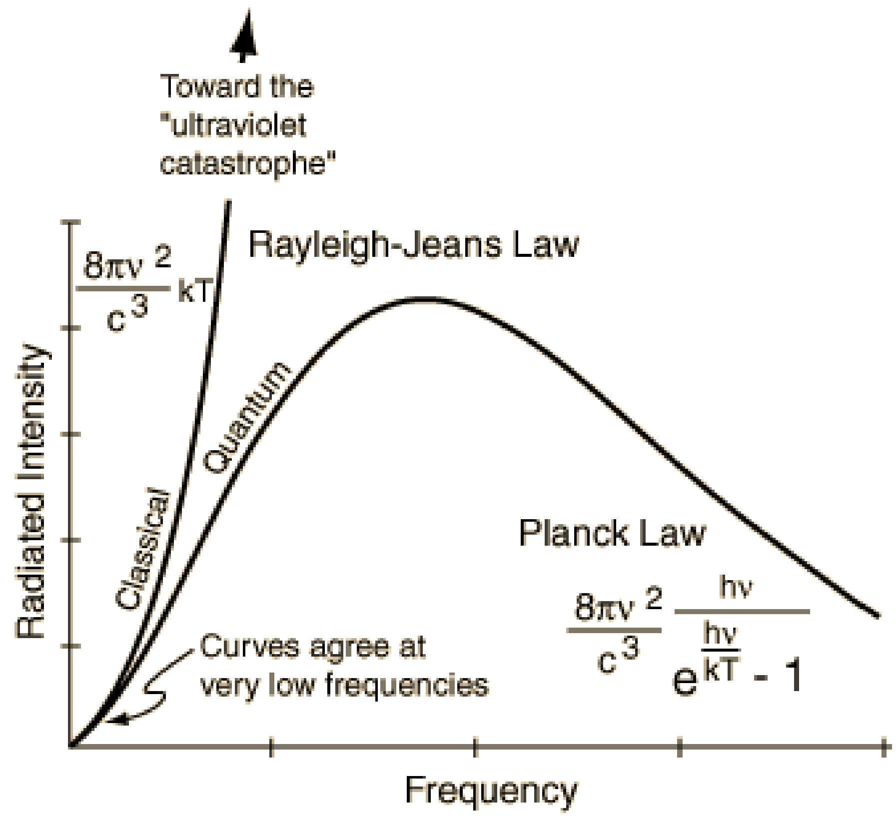
h is Planck constant.



BLACKBODY RADIATION

Theory vs. experiment…

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



- **At high frequencies:**

$h\nu >> kT$ we have $e^{h\nu/kT} \rightarrow \infty$. Hence, $u(\nu)d\nu \rightarrow 0$ as observed.
NO ULTRAVIOLET CATASTROPHE!

- **At low frequencies:**

$h\nu << kT$, $h\nu/kT << 1$

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \ldots$$

$$\frac{1}{e^{h\nu/kT}-1} = \frac{1}{1+\frac{h\nu}{kT}-1} \approx \frac{kT}{h\nu}$$

$$u(\nu)d\nu = \frac{8\pi h}{c^3}\nu^3\left(\frac{kT}{h\nu}\right)d\nu \approx \frac{8\pi kT}{c^3}\nu^2 d\nu$$

BLACKBODY RADIATION

What was left for Planck?

- He had to justify his formula in terms of physical principles.
- A new principle seemed needed!

The oscillators in the cavity walls could not have continuous distribution of possible energies ε but must have only specific energies

$$\varepsilon_n = nh\nu$$

- 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 o energy h ν is called a **quantum**.
- Hence, the average energy per oscillator in the cavity wall…

$$\bar{\varepsilon} = kT \Longrightarrow \varepsilon = \frac{h\nu}{e^{h\nu/kT} - 1}$$

BLACKBODY RADIATION

Example 2.1:

Assume that a certain 660 Hz tuning fork can be considered as a harmonic oscillator whose vibrational energy is 0.04 J. Compare the energy quanta of this tuning fork with those of an atomic oscillator that emit and absorbs orange light whose frequency is 5×10^{14} Hz.

BLACKBODY RADIATION

Remember….

Only the quantum theory of light explained the origin of the blackbody radiation…

Quote

"The important thing is not to stop questioning. Curiosity has its own reason for existing."

Albert Einstein