PHY 1203 General Physics II

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Modern Physics (18 hrs)

- Introductory Quantum Physics (4 hrs)
- Atomic Physics (4 hrs)
- Nuclear Physics (8 hrs)
- Elementary Particles (2 hrs)

Introductory Quantum Physics

At the end of the 19th century, attempts to apply laws of classical physics to explain the behaviour of matter in atomic scale were totally unsuccessful. Various phenomena could not be explained using classical physics.

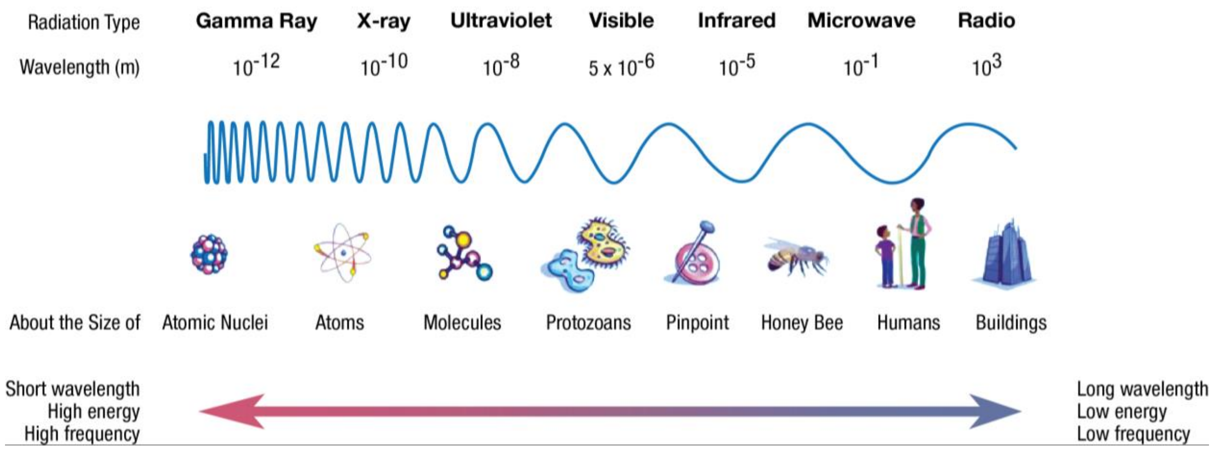
The experiments that led the development of Quantum Mechanics.

- Blackbody Radiation
- Photoelectric Effect
- Compton Effect

Blackbody Radiation

We know that energy from the Sun reaches us on the earth, even through the vacuum. This type of energy propagation is known as electromagnetic radiation.

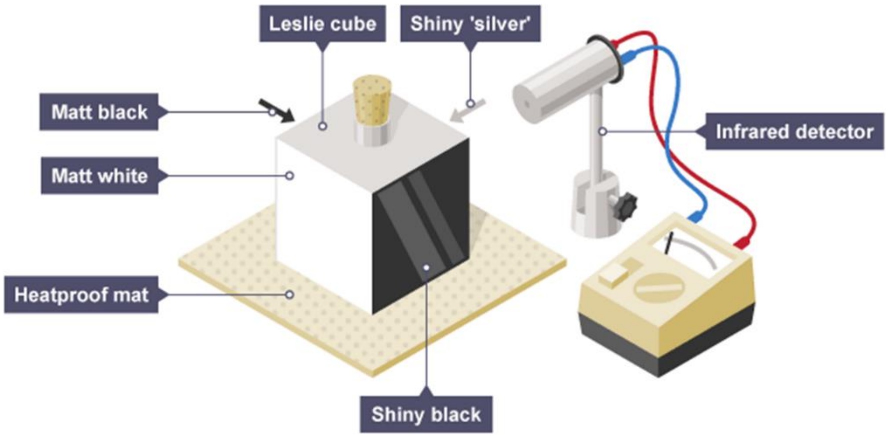
All bodies at a temperature above absolute zero emit electromagnetic waves.



The rate of e-m radiation energy emitted from a hot body depends on

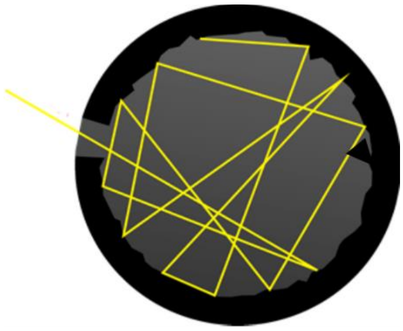
1. The absolute temperature of the body (T in K)
2. The surface area (A)
3. The nature of the surface (ε)

This can be demonstrated using a Leslie's cube



A body that absorbs all the e-m radiation falling on it (at all wavelengths) is called a black body. The blackbody is a perfect absorber as well as a perfect emitter.

By blackening the inner surface of a spherical shell with a hole made from a hard material, such as tungsten or ceramic, it can be used as a model blackbody. Since all the e-m radiation entering from the hole is absorbed, it acts as a blackbody.



Stefan-Boltzmann Law

The thermal energy radiated by a blackbody per unit time per unit area is proportional to the fourth power of the absolute temperature (*T*) of the body.

$$\frac{E}{t} = P \ \text{(watt)} \quad \rightarrow \quad \frac{P}{A} = I \ (\mathrm{W\,m^{-2}})$$

$$I \propto T^4$$

$$I = \sigma T^4$$ (Radiation intensity of a blackbody)

where σ is known as the Stefan-Boltzmann constat.

$$\sigma = 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}K^{-4}}$$

For a blackbody with area A → Power emitted $P = \sigma A T^4$

For any object → Power emitted $P = \varepsilon \sigma A T^4$

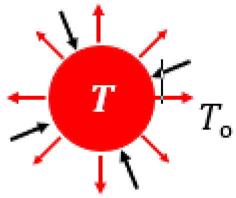
where ε is known as the emissivity of the surface. It has no unit or dimensions.

For an ideal blackbody $\varepsilon = 1$

For any other object $0 < \varepsilon < 1$

If a hot object is at a temperature T (K) and the surrounding temperature is T_o (K)

then



Power emitted by the object $P_{out} = \varepsilon\sigma A T^4$

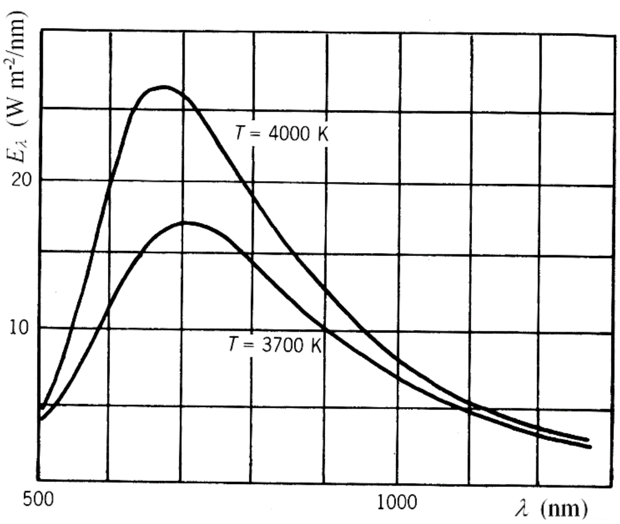
Power absorbed from the surrounding by the object $P_{in} = \varepsilon\sigma A T_o^4$

Rate of heat energy (power) dissipated by the object $P = P_{out} - P_{in}$

$$P = \varepsilon\sigma A(T^4 - T_o^4)$$

Spectral radiance is a measure of the radiant power emitted (or received) by a surface, per unit area at a particular wavelength.

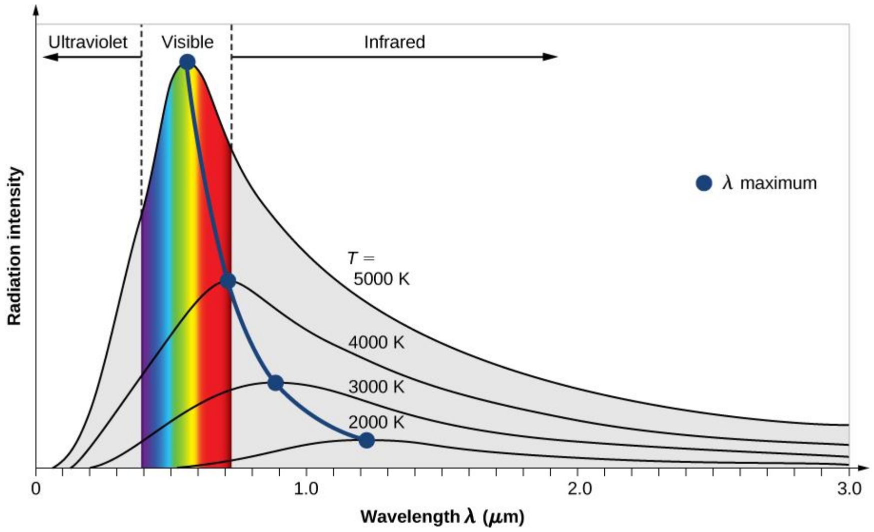
The graph of spectral radiance I_λ $(\mathrm{W\,m^{-2}/nm})$ versus $\lambda\,(\mathrm{nm})$ for blackbody radiation



The area between two wavelengths λ_1 and λ_2 gives the power of the radiation intensity emitted with those wavelengths.

Total power per unit area is given by $P(\lambda, T) = \int I_\lambda \, d\lambda$

Characteristics of the blackbody radiation:



- There is a peak (or maxima λ_m) for the intensity curve of radiation
- As temperature increases the intensity increases for all wavelengths
- As temperature increases the value of λ_m shifts towards lower wavelength (higher energy) direction.

Base on the above experimental observation Wein introduce a relationship.

Wein's (Displacement) Law

The peak wavelength of the radiation emitted by a blackbody is inversely proportional to the absolute temperature of the body.

$$\lambda_m \propto \frac{1}{T}$$

$$\lambda_m T = C$$

where C is known as the Wein's constant. $C = 2.90 \times 10^{-3}\ \mathrm{m\ K}$

Once the maximum wavelength blackbody radiation of a hot object is known the Wein's law can be used to determine the temperature the object.

e.g.: The peak wavelength of radiation emitted from the Sun is **483 nm** which represent green colour. Calculate the temperature of the surface of the Sun.

$$\lambda_m = 483\ \mathrm{nm} = 4.83 \times 10^{-7}\mathrm{m}$$

$$\text{Substitute in } \lambda_m T = C$$

$$T = \frac{2.90\times10^{-3}}{4.83\times10^{-7}}$$

$$\underline{\underline{T \approx 6000\ \mathrm{K}}}$$

Classical physics fails to explain blackbody radiation because it predicts an infinite amount of energy emitted at short wavelengths, known as the "ultraviolet catastrophe". This contradicts experimental observations, which show a peak in the radiation spectrum at a certain wavelength that shifts with temperature. The resolution came with quantum mechanics, which proposed that energy is emitted in discrete packets (quanta) rather than continuously, as assumed by classical physics.

Here's a more detailed explanation:

Classical Physics' Prediction:

- Classical physics, based on wave theory of light, treated electromagnetic radiation as continuous waves.
- It predicted that as the frequency of the emitted radiation increases (and wavelength decreases), the energy emitted would also increase infinitely, leading to the "ultraviolet catastrophe".
- This prediction was based on the idea that all modes of vibration of electromagnetic waves in a blackbody would be equally excited, regardless of frequency.

Experimental Observations:

- Experiments showed that blackbodies emit radiation with a spectrum that peaks at a certain wavelength, and this peak shifts towards shorter wavelengths as the temperature increases.
- The total energy emitted by a blackbody is finite and depends on its temperature.

The Breakdown of Classical Physics:

- Classical physics failed to reconcile the observed blackbody radiation spectrum with its theoretical predictions.
- The predicted infinite energy at short wavelengths was not observed, highlighting a fundamental flaw in the classical understanding of electromagnetic radiation.

The Quantum Mechanical Solution:

- Max Planck introduced the concept of energy quantization to resolve the ultraviolet catastrophe.
- He proposed that energy is not emitted or absorbed continuously, but in discrete packets called quanta.
- The energy of each quantum is proportional to its frequency ($E = hf$, where h is Planck's constant).

- This quantization of energy successfully explained the observed blackbody radiation spectrum, with the energy of higher frequency modes being limited by the energy of the quanta.

In essence, classical physics failed because it treated energy as a continuous entity, while the reality is that energy comes in discrete packets, and this difference in perspective is crucial for understanding blackbody radiation.

Rayleigh Jeans Law is a classical law that defines the spectral radiance of electromagnetic radiation at all frequencies emitted by a black body in thermal equilibrium. The expression for the energy density can be denoted as:

$$u(f,T) = \frac{8\pi f^2}{c^3} kT$$

$$I(\nu,T) = \frac{8\pi \nu^2}{c^3} kT$$

where f represents the frequency, T the absolute temperature, c the speed of light and k the Boltzmann constant.

$$I(\lambda,T) = \frac{2hc^2}{\lambda^5} e^{-\frac{hc}{\lambda k_B T}},$$

$$I(\nu,T) = \frac{2h\nu^3}{c^2} \exp\left(-\frac{h\nu}{kT}\right)$$

$$I(\nu,T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}.$$

$$I(\nu,T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

$$\frac{1}{e^{\frac{h\nu}{kT}} - 1} \approx e^{-\frac{h\nu}{kT}},$$