Modern Physics Lab PHYS 396 — "The Blackbody radiation "

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Introduction

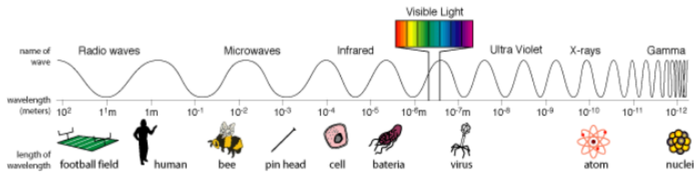
A blackbody is defined as an object that perfectly absorbs all (and thus reflects none) of the radiation incident on its surface. When a blackbody is in thermal equilibrium with its surroundings, it must also be a perfect emitter so that the temperature of the blackbody stays the same. But this emitted light is not at the same frequency as the light that was initially absorbed; rather it is distributed between different frequencies in a characteristic pattern called the blackbody spectrum.

The measurement of the blackbody spectrum was the center of a crisis in physics during the early 20th century known as the ultraviolet catastrophe. Different classical models could explain the blackbody spectrum over some frequency ranges, but broke down (in one case predicting infinite radiation at some frequencies). Max Planck eventually resolved the crisis by introducing the quantization of energy, giving birth to the quantum revolution in the process.

In this lab, we shall discover the relation between the wavelength of light emitted from the blackbody and its temperature

1 Background

The concept of blackbody radiation is seen in many different places.The intensity of the energy coming from the radiator is a function only of temperature. A good example of this temperature dependence is a flame. The flame starts out with a low frequency emitting red light in the visible range, as the temperature increases the flame turns white and then blue as is moves across the visible spectrum with an increasing temperature. Also, with each temperature corresponds a new maximum radiance which can be emitted. As the temperature increases, the total radiation emitted also increases due to an increase in the area under the curve. Lord Rayleigh



Electromagnetic spectrum:click for citation

and J. H. Jeans developed an equation which explained blackbody radiation at low frequencies.The equation which seemed to express blackbody radiation was built upon all the known assumptions of physics at the time. The big assumption which Rayleigh and Jean implied was that infinitesimal amounts of energy were continuously added to the system when the frequency was increased. Classical physics assumed that energy emitted by atomic oscillations could have any continuous value. This was true for anything that had been studied up until that point, including things like acceleration, position, or energy.They came up with Rayleigh-Jeans law and the equation they derived was

$$d\rho(\nu, T) = \rho_\nu(T) d\nu = \frac{8\pi k_B T}{c^3}\nu^2 d\nu \tag{1}$$

Experimental data performed on the black box showed slightly different results than what was expected by the Rayleigh-Jeans law. The law had been studied and widely accepted by many physicists of the day, but the experimental results did not lie, something was different between what was theorized and what actually happens.The experimental results showed a bell type of curve but according to the Rayleigh-Jeans law the frequency diverged as it neared the ultraviolet region.This inconsistency was termed the ultraviolet catastrophe.

2 Quantum theory

During the 19th century much attention was given to the study of heat properties of various objects. An idealised model that was considered was the Black Body, an object which absorbs all incident radiation and then re-emits all this energy again. We can think of the radiating energy as standing waves inside our blackbody cavity. The energy of the radiating waves at a given frequency Îi, should be proportional to the number of modes at this frequency. Classical physics states that all these modes have the same energy kT (a result derived from classical thermodynamics) and as the number of modes is proportional to ν^2

$$E \propto \nu^2 k_B T \tag{2}$$

This implies that we would expect most of the energy at higher frequency, and this energy diverges with frequency. If we try and sum the energies at each frequency we find that there is an infinite energy in ths system! This paradox was called the ULTRAVIOLET CATASTROPHE.

It was left to Planck to resolve this gaping paradox, but postulated that the energy of the modes could only come in discrete packets - **quanta** - of energy:

$$E = h\nu,\ 2h\nu,\ 3h\nu, \ldots \tag{3}$$

Using statistical mechanics Planck found that the modes at higher frequency were less likely excited so the average energy of these modes would decrease with the frequency. The exact expression for the average energy of each mode is given by the Planck distribution:

$$\bar{E} = \frac{h\nu}{\exp(\frac{hv}{k_B T}) - 1} \tag{4}$$

You can see that if the frequency is low then the average energy tends towards the classical result, and as frequency goes to infinity we get that the average energy goes to zero as expected, recall that $e^x \sim 1 + x + \ldots$ for $x << 1$:

$$\bar{E} \sim k_B T \quad \nu \to 0$$
$$\bar{E} \sim 0; \quad \nu \to \infty$$

Max Planck was the first person to properly explain this experimental data. Rayleigh and Jean made the assumption that energy is continuous, but Planck took a slightly different approach. He said energy must come in certain unit intervals instead of being any random unit or number. He instead âĂIJquantizedâĂİ energy in the form of $E = nh$ where n is an integer, h is a constant, and ν is the frequency. This assumption proved to be the missing piece of the puzzle and Planck derived an expression which could explain the experimental data

$$d\rho(\nu, T) = \rho_\nu(T)\, d\nu = \frac{8\pi k_B T}{c^3} \frac{nu^2}{e^{\frac{hv}{K_b T}} - 1} d\nu \tag{5}$$

This now famous equation is known as the Planck Distribution Law for Blackbody Radiation.The h in this equation is the famous PlanckâĂŹs constant, which has a value of $h = 6,63 \times 10^{-34} J\, s$

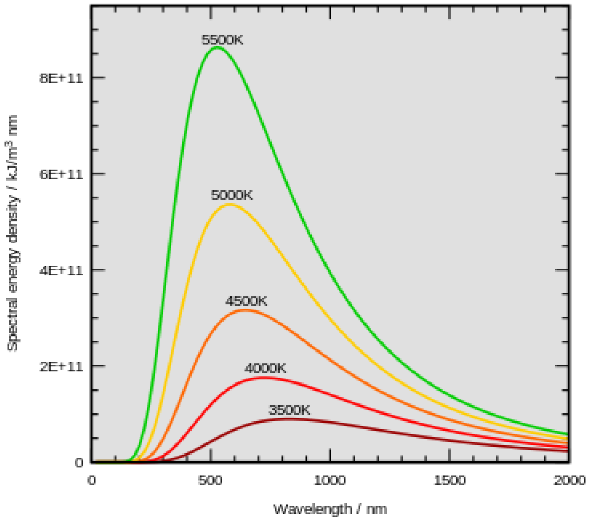


Figure 1: The spectrum of black body radiation

Reference

Bowler, M. G. (2012). *Lectures on statistical mechanics*. Newnes.

Eisberg, R. M., Resnick, R., Lea, S. M., and Burke, J. R. (1961). *Modern Physics*. New York: John Wiley and Sons.

Heisenberg, W. (1958). Physics and philosophy: The revolution in modern science.

Jauch, J. M. and Morrow, R. A. (1968). Foundations of quantum mechanics. *American Journal of Physics*, 36(8):771–771.

Mandl, F. (1971). *Statistical Physics*. Wiiley.