# Experiment 7

# Blackbody radiation spectra

## 7.1 Introduction

The constant $h = 6.62559 \times 10^{-34}$Js was introduced by Planck in 1900 to provide the first satisfactory theoretical basis for the temperature and wavelength dependence of the radiation from a black body. An idealized non-reflecting blackbody absorbs all the radiation that falls upon it, while the rate of all its energy emissions, summed over all wavelengths, is $\propto T^4$ where $T$ is the thermodynamic temperature. Since there is no reflection off an ideal blackbody, the emitted spectrum, *i.e.* the distribution of the radiation intensity as a function of wavelength, is due to emission only. The radiative intensity depends on $T$, with a maximum in the emission versus wavelength curve such that the product of the characteristic wavelength of the maximum emission varies inversely with temperature, shifting to lower wavelengths (*i.e.* to higher frequencies) with increasing temperature. These relations are known as Stefan's Law and Wien's Law, respectively. In 1893, W.Wien showed from thermodynamic considerations that the form of the radiation curve was given by

$$E_\lambda = \frac{1}{\lambda^5} \times f\left(\frac{1}{\lambda T}\right) \tag{7.1}$$

where $E_\lambda$ is the energy emitted in range $d\lambda$ centered at wavelength $\lambda$, and $f$ is some function to be determined. The experimental data were obtained by W.Coblentz in 1914–16, who measured the emissions from a small aperture in a fully enclosed body (a metallic cylinder) with walls maintained at a constant temperature, which is a good approximation of a perfect blackbody because radiation that enters the hole from outside has an exceedingly small chance to escape before it is absorbed at the walls of the cavity (see A.C.Parr's article). The rate of emission is independent of the material that forms the walls of such a cavity. At the temperatures available in the laboratory the shortest wavelength radiation of measurable intensity is in the near-ultraviolet.

In 1900, Planck introduced the assumption that each mode of vibration of frequency $\nu$ ($\nu = c/\lambda$) of the electromagnetic field in the cavity could change its energy by a definite amount $h\nu$ (where $h$ was a constant to be determined) rather than by continuously variable amounts. He was then able to derive the explicit form of the radiation curve and to show that Stefan's Law and the Wien Law followed from his form. Planck's formula for the power radiated by a black body at wavelength and temperature $T$ is

$$\rho(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda k_B T} - 1} \tag{7.2}$$

where the spectral radiance $\rho(\lambda, T)$ is the power (energy per second) radiated per solid angle and per unit area normal to the propagation, at frequency $\lambda$ and temperature $T$, $k_B$ is Boltzmann constant and $c$ is the velocity of light. The form of the Planck's radiation curve is shown in Figure 7.1. The form determined by Coblentz matches the predictions of Plank's theory and his data yielded the value of $h$ within 0.8% of the correct value. Planck's assumption was the first use of the idea of quantization in the radiation field and, later, in the interaction of radiation with atoms.

If a body is not a black body radiator, so that it does not absorb all radiation that falls upon it, the power radiated is less than the amount predicted by the Planck's formula, by a factor called emissivity, $0 < \varepsilon < 1$. However, if the emissivity $\varepsilon$ coefficient at each wavelength is independent of the temperature, the emitted power is reduced by a constant factor for all temperatures. In addition, for the wavelength in

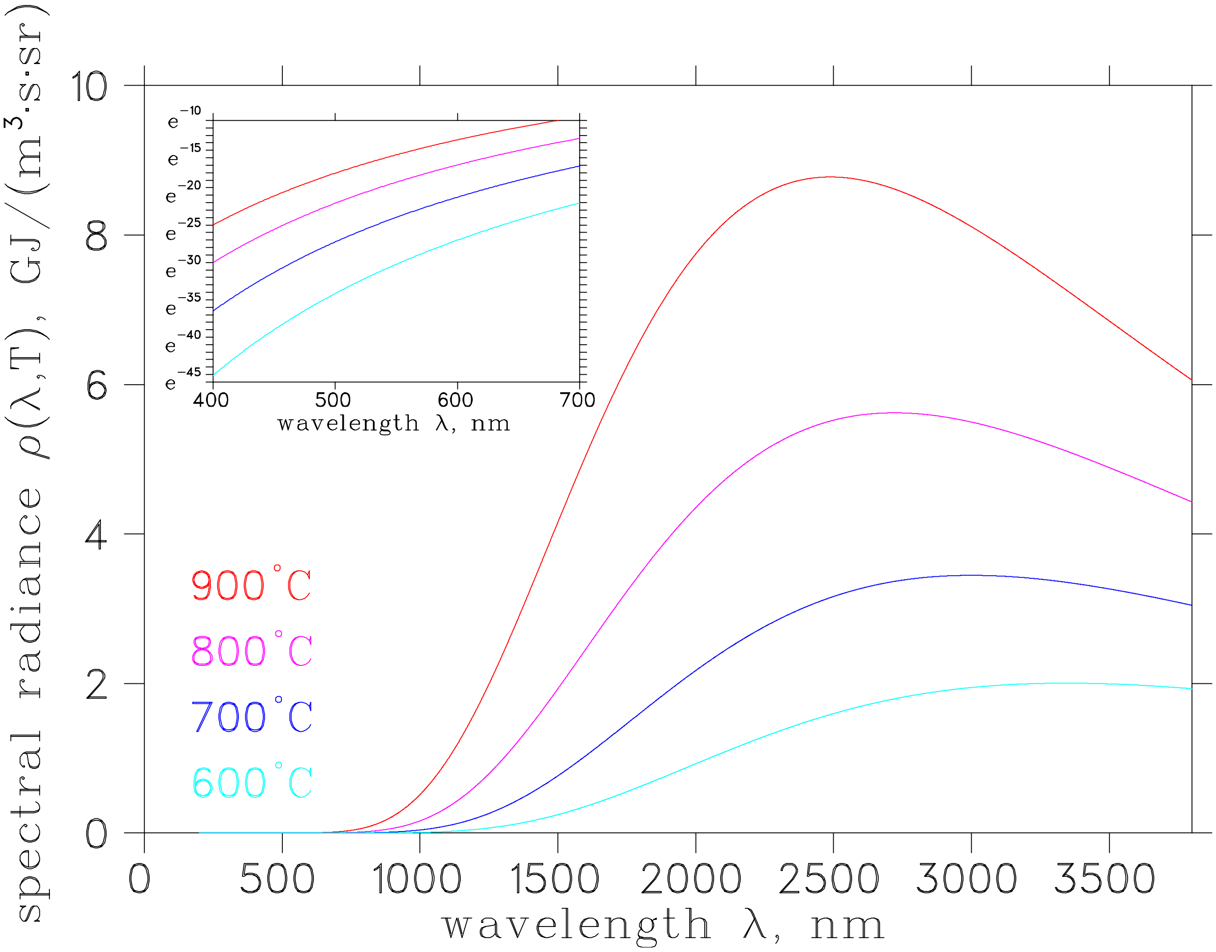

Figure 7.1: Temperature-dependent energy emission by a blackbody. The insert shows fragments of the same curves, on a logarithmic scale, in the range of visible light, 400–700nm. At those wavelengths, the spectral radiance is many orders of magnitude weaker than the peak intensity at each temperature, but it does exhibit a strong temperature dependence.

the visible,$\exp(hc/\lambda k_B T) \gg 1$. Thus

$$\rho(\lambda, T) \propto \exp\left(-\frac{hc}{\lambda k_B T}\right), \tag{7.3}$$

and a graph of $\ln\rho$ versus $1/T$ should be a straight line of slope $-hc/\lambda k_B T$. Using independently known values of $c$ and $k$, a value for $h$ can be obtained.

If the Planck's constant is known, one can use measurements of radiance performed at multiple wavelengths to estimate the temperature from the spectral radiance, using the so-called "two-colour method" used in various pyrometric instruments:

$$\frac{\rho_1}{\rho_2} = \frac{\varepsilon_1}{\varepsilon_2} \times \left(\frac{\lambda_2}{\lambda_1}\right)^5 \times \frac{e^{-hc/\lambda_1 k_B T}}{e^{-hc/\lambda_2 k_B T}} \tag{7.4}$$

which can be rewritten as

$$T = \frac{hc/k_B(1/\lambda_2 - 1/\lambda_1)}{\ln(\rho_1/\rho_2) + \ln(\varepsilon_2/\varepsilon_1) + 5\ln(\lambda_1/\lambda_2)}, \tag{7.5}$$

where the ratio of two emissivities $\varepsilon_1/\varepsilon_2 \simeq 1$ if the two wavelengths $\lambda_{1,2}$ are chosen sufficiently close to each other which simplifies the calculations. Fitting to measurements at more than two wavelengths would allow for a simultaneous determination of both $h$ and $T$.

## 7.2 The apparatus

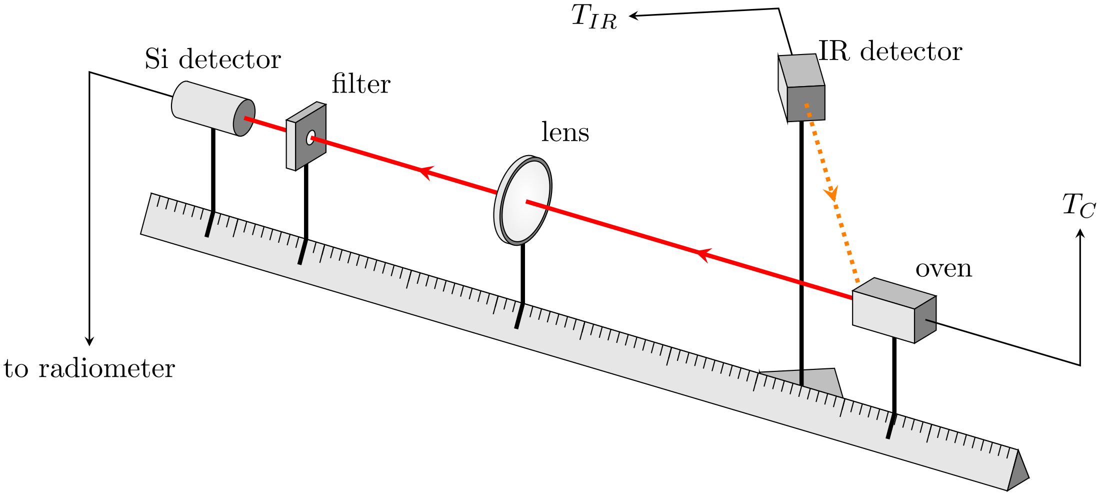

Figure 7.2: Experimental setup for determining Planck's constant from blackbody radiation. A hot $MoSi_2$ oven mounted on an optical bench emits thermal radiation through a narrow slit. The radiation passes through a lens focused on the Si detector. A narrow band-pas filter restricts the spectrum to be essentially monochromatic. The temperature of the oven is measured two different ways: using a Pt thermocouple ($T_C$) and with an infrared sensor ($T_{IR}$). Tikz figure by C.Wilson.

In the experiment we detect the intensity of the radiation reaching the Si photodetector attached to a radiometer. An oven cavity is a blackbody radiation source with a $MoSi_2$ heater element, controlled with a Variac. This oven can reach temperature as high as $1500°C$. The temperature of the oven can be measured using several methods:

- directly using the S-type Pt thermocouple inside the oven;

- with an infrared pyrometer (by Omega Engineering) aimed and focused on the inside of the oven; the detector has a built-in aiming laser that can be used to align the detection direction exactly;
- using a glowing-filament radiometer, where an image of a glowing tungsten wire at a known temperature is superimposed and colour matched to the remote image of the inside of the oven.

In addition, the entire setup can be replaced with a USB spectrometer (by Ocean Optics), measuring the entire spectrum emitted from the oven. The spectrometer is uncalibrated and does not provide properly normalized spectrum (that could be used to fit to a Planck's distribution function to determine the temperature), but it does provide multiple regions in the visible where the dependence $\propto \exp(-hc/\lambda k_B T)$ can be observed, providing another way of analysing the data.

## 7.3 Measurement checklist

Review this manual, and the reference materials provided, to develop your own checklist before coming to the lab. Be sure to include it in your lab report, and comment on how well it worked. Devise a plan to explore several ways of measuring the temperature and discuss their relative merit. Determine Planck's constant.

## References

Note that some of the links below require the class password for access.

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