Lab Report 1

PHY 2020: Physics Lab 3

Aditya Malhotra

February 5, 2024

Instructor: Dr Susmita Saha

Graduate Assistant: Archana

Teaching Assistants: Anjali Madangarli, Satwik Wats

Dates of Experiment: 22 January, 29 January, 3 February, 4 February

Lab Partner: Yashsas Shende

Senior Lab Superintendent: Sudarshana Banerjee

Senior Lab Technician: Pradip Chaudhari

1 Aim

1. To verify Wien's Displacement Law from the given blackbody and to calculate the value of Wien's constant.
2. To evaluate the value of Planck's constant given the value of the Boltzmann constant.

2 Theoretical Background

2.1 Thermal Radiation and Blackbodies

The radiation emitted by an object due to its temperature is known as thermal radiation. Every object radiates and absorbs heat. As long as a temperature difference exists in between the object and its surroundings radiation continues to be emitted and absorbed. Matter in the solid or liquid phase emits a continuous spectrum of radiation. The nature of this spectrum is almost completely independent of the composition of the object but depends strongly on the temperature of the object. The spectrum of thermal radiation of an object can tell us about the temperature and the chemical composition of that object.

While thermal radiation of most object depends, to a small extent, on the composition of the object there are a class of objects that emit radiation of a universal character. These object are known as blackbodies. They are called so since they absorb all the radiation incident upon them. The radiation emitted by a blackbody can be characterized by a physical quantity called the spectral radiancy ($R_T(v)$). Thus the energy per unit time emitted from a differential surface area element of an object is given by $R_T(v)dv$ and. The relation between radiancy and temperature for a blackbody was first given by Josef Stefan and also by Ludwig Boltzmann and it is,

$$R_T = \sigma T^4$$

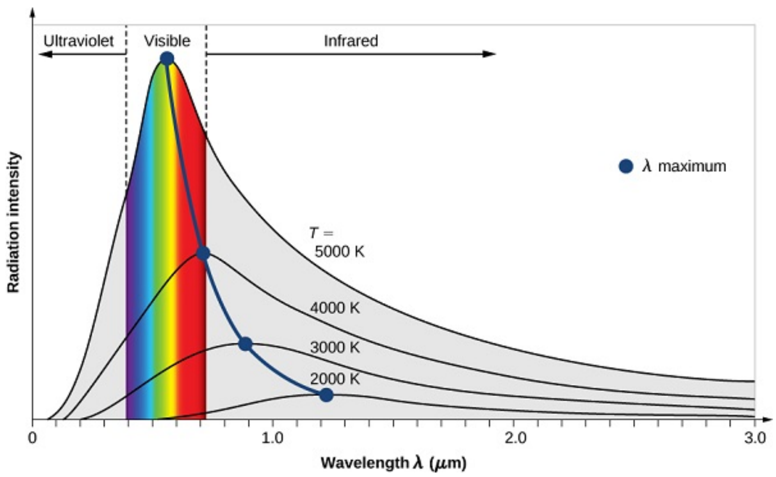

Figure 1: Radiation pattern of a blackbody

Where σ is the Stefan-Boltzmann constant and its value is $5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$.

The radiation of a blackbody follows the general trend as, Figure 1 shows that the peak wavelength (wavelength of light of highest intensity) shifts towards the left as the temperature increases. This relation is known as Wien's Displacement Law which in mathematical terms is,

$$\lambda_{max} T = b$$

Where b is the Wien's constant.

To calculate the value of the Planck's constant two different wavelengths are compared. The equation that is used to measure the value is,

$$h = \ln\left(\frac{I_1}{I_2}\right)\lambda\left(\frac{T_1 T_2}{T_1 - T_2}\right)\left(\frac{k_B}{c}\right)$$

Where h is Planck's constant, I_1 is the intensity of one wavelength, T_1 is the temperature of the filament for that wavelength, I_2 and T_2 are the corresponding values for the second wavelength, λ is the average of the 2 wavelengths being considered, k_B is Boltzmann's constant and c is the speed of light.

2.2 Blackbody in the laboratory

Blackbodies are theoretical objects. In reality there is no object that is a true blackbody but all are approximations. To study the spectrum of a blackbody in the laboratory a cavity with a small hole can be constructed. This object has the properties of a blackbody and can emit blackbody radiation.

Radiation that is incident upon the hole enters the cavity and is reflected inside the cavity itself. If the hole is small enough a very small amount of the incident radiation will be reflected out of the hole. Thus the hole has the properties of the surface of a blackbody. Now if the walls of the cavity are heated up to a certain temperature then the walls will emit radiation that will be reflected within the cavity. A small fraction of that radiation will be emitted from the hole. Since the hole has the properties of the surface of a blackbody it means that the radiation from the hole is also analogous to blackbody radiation and the spectrum of that radiation must be that of a blackbody. Furthermore, since the hole is only an outlet for the radiation emitted by the walls of the cavity it means that the spectrum obtained is that of a blackbody at the same temperature as the walls of the cavity. Thus this object has the same kind of radiation as a blackbody at the particular temperature.

3 Equipment

1. Light sensor by PASCO
2. Optical spectrometer without telescope
3. Tungsten filament in a cavity (acts as blackbody)
4. Prism
5. Screen with a mount
6. Magnifying glass
7. Torch

4 Procedure

4.1 Initial Setup

1. The source of light was placed in line with a collimator. The sensor with its reference screen was also placed in line with the collimator and the light was switched on. The reading on the scale was noted and was used as the reference to measure all other angles.
2. The prism was then placed on the prism table such that the light from the collimator fell on one of the polished surfaces. The dispersed light from the other polished surface was seen by moving the reference screen.
3. Once the spectrum was obtained on the screen the prism table was rotated both clockwise and anti-clockwise till the spectrum flipped its direction of movement. The position of the prism where this happened is the angle of minimum deviation and the prism was set to this position for the rest of the experiment.

4.2 Part A

1. The voltage is set to 180 V at first. The sensor arm is rotated till it is at $320°$ on the circular scale. The light was switched off and the sensor was tared at that point to obtain the 0 intensity reading. Following this the sensor was rotated at increments of 20 arc-seconds and the intensity reading at each of these points was taken.
2. The readings were taken using the PASCO Capstone software on a laptop. The sensor was connected to the laptop using a USB. Following this the Manual Sampling option was chosen on the application. The Preview button was clicked and the sensor was then tared to get the 0 reading. Step 1 was followed and at each point the intensity reading was noted on PASCO.
3. These angles were then converted into the corresponding dispersed wavelengths using the Sellmeier equation and then the intensity was plotted against the wavelength to check the trend of the data.

4. The temperature for each setting was calculated using the formula,

$$T = T_0 + \frac{(R/R_0) - 1}{\alpha}$$

Where T_0 is the temperature of the room, R is the resistance of the tungsten filament, R_0 is the resistance of the tungsten filament at settings corresponding to temperature T_0 and α is the temperature coefficient of resistance of the conducting material.

5. From this plot the maximum dispersed wavelength (λ_{max}) was obtained. This process was repeated for 3 different values of voltage and current. For each of the 3 the value of Wien's constant was calculated using the formula written above.

4.3 Part B

1. The data gathered in the last part is what was used for the analysis in this part. 3 curves were obtained. Out of these pairs were compared and Planck's constant was calculated using the formula given above.
2. This was repeated to get 3 values of the Planck's constant.

5 Data

The values of the constants in each measurement are,

1. $R_0 = 37\,\Omega$
2. $T_0 = 295.25\,K$
3. $\alpha = 0.0045\,K^{-1}$

5.1 Least Counts of Instruments

1. Spectrometer: 20"

5.2 Part A

Temperature (K)	Dispersed Wavelength of maximum intensity (nm)
2491.645	12.075
2574.391	12.130
2682.761	12.023

Table 1: Dispersed wavelength of maximum intensity for different temperatures of the Tungsten filament

5.3 Part B

The data for Part B is the same as Part A. However 2 other constants, the Boltzmann constant (k_B) and the speed of light were used in the calculations for this part.

6 Graphs and Analysis

6.1 Part A

The 3 values of the Wien's constant obtained are,

Temperature (K)	Dispersed Wavelength of maximum intensity (nm)	Wien's Constant (mK)
2491.645	12.075	0.00030087
2574.391	12.130	0.00031228
2682.761	12.023	0.00032254

Table 2: Value of Wien's constant for different temperatures of the Tungsten filament and dispersed wavelengths of maximum intensity.

The raw data obtained are a range of angles and the intensity values of different wavelengths. The wavelengths were obtained using the Sellmeier equation. Following this the wavelength with the highest intensity was determined by finding the index of the highest intensity value in the intensity array on Python. This index was also the index corresponding to the wavelength with the highest intensity.

6.2 Part B

The suitable wavelength used for analysis was the average of the 2 wavelengths being compared. Doing so and applying the formula 3 different values of the Planck's constant were obtained as,

Wavelengths compared (nm)	Planck's constant ($\times 10^{-34}$Js)
12.075 & 12.130	2.475
12.130 & 12.023	0.594
12.023 & 12.075	1.437

Table 3: Planck's constant by comparing different wavelengths at different temperatures.

The plot showing the shape of the curve for different wavelengths and temperatures is,

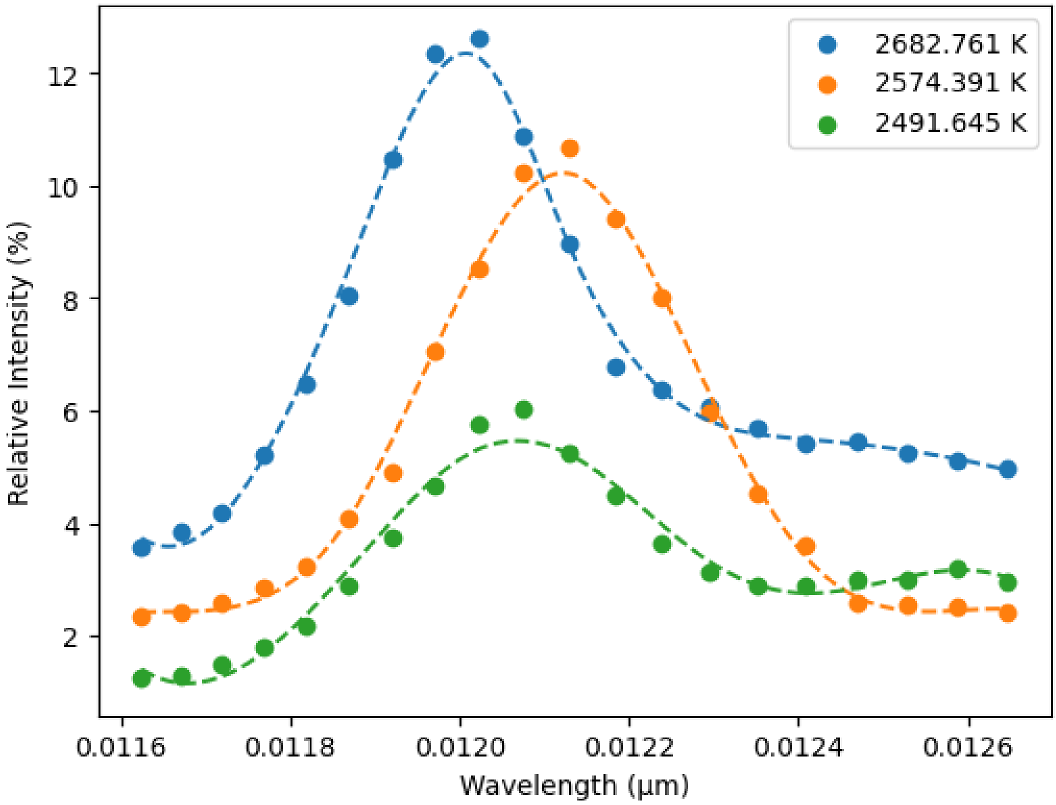

Figure 2: The spectrum obtained for the Tungsten filament at different temperatures

The shape of the curves is as expected. However the curve for 2574.391 K looks like an anomaly. That is so since it is not supposed to intersect the other curves at any point and the peak is shifted more than that of 2491.645 K which is not supposed to occur. The possible reasons are addressed in the section on Error Analysis below

7 Error Analysis

The value of the Wien's constant for each temperature is off by an order which is a large amount of error. The equation used to convert the recorded angles into the wavelength is the Sellmeier Equation which has coefficients that depend on the material of the prism being used. This equation is derived from the Cauchy equation,

$$\mu = \frac{A}{\lambda^2} + B$$

Here B is the refractive index of the material being used. The value of A was calculated by fitting a curve to the data obtained from Thor Labs. This data comprised of the maximum dispersed wavelength for different refractive indices of various kinds of prisms. Using `scipy.optimize.curve_fit()` on this data the value of A and B were obtained. It is possible that the fit was not performed properly since the value of B obtained from the plot was 1.588 which is wrong since that value would give negative values of the wavelength from the Sellmeier equation. Thus the value of A might be wrong which leads to the value of the Wien's constant to be wrong by an order of magnitude.

The actual value of the Wien's constant is supposed to be 0.0029 mK. From this value using the general relation for finding the error we get,

Wien's Constant (mK)	Relative Error (%)
0.00030087	863.864
0.00031228	828.665
0.00032254	799.110

Table 4: Relative error in calculating the value of Wien's constant.

The qualitative errors in part B arise due to the same reasons as outlined above. Using the general formula for calculating the relative error in calculating the value of Planck's constant is,

Planck's Constant ($\times 10^{-34}$Js)	Relative Error (%)
1.437	361.058
2.475	167.685
0.594	1015.481

Table 5: Relative error in calculating the value of Planck's constant.

These errors can also be attributed to the sensitivity of the PASCO sensor. The values it showed fluctuated very rapidly.