Experiments in Modern Physics P451: Black Body Radiation

David Baxter
Indiana University, Bloomington, IN 47405
(Dated: April 21, 2016)

The development of a satisfacotry description of the radiation emitted from an ideal "Black Body" was a fundamental step in Modern Physics, and the result plays important roles in Astronomy, Cosmology, and technology to this day. In the early part of the 20^{th} century, two Nobel prizes were awarded for work associated with the emission of electromagnetic waves from hot objects (Wien in 1911 and Planck in 1918). Although Planck's formula is a very useful and important result (it led directly to the development of Quantum Mechanics), the spectra observed from real hot objects often show departures from this ideal spectrum. Nevertheless, even in the absence of detailed quantitative agreement with this ideal spectrum, the tungsten filament from a projector bulb can be used to confirm the fundamental physics contained in Planck's formula, and to determine the a particular combination of three fundamental physical constants (hc/k_B). In this experiment you will determine this ratio, and explore some of the systematic effects that cause measured spectra to deviate from the ideal behavior you read about in text books.

A. Introduction

The famous Planck radiation law describes how electromagneitc waves are emitted from a physical body at a well-defined temperature T, assuming that all wavelengths of light are absorbed by the body in the same manner (that is why such a body is described as an ideal "Black Body"). The derivation of Planck's law is given in most introductory Quantum or Statistical Mechanics and Modern Physics texts (e.g. see [1]) and more details associated with the physical realization of a Black Body in the laboratory are discussed in [2]. In the somewhat more general case, where the interactions of the body with electromagnetic radiation are not constant, a modified description can be written as:

$$I(\lambda) = \frac{8\pi hc\lambda^{-5}}{e^{hc/\lambda k_B T} - 1}\epsilon(T,\lambda) \tag{1}$$

where $\epsilon(T,\lambda)$ is the emissivity, which is a number between 0 and 1 (which is in general different for each wavelength and temperature). Perhaps the most famous application of this result has been the measurement of the temperature and anisotropy of the Cosmic Microwave Background, and the remarkable fidelity with which that spectral ghost from the Big Bang follows (1) [3] (another couple of Nobel prizes can be associated with this). The emissivity in (1) is used to desribe the manner in which the body deviates from an ideal black-body, but in typical applications its variation with T and λ is slow so it can be taken to be a constant (you might want to check whether this assumption is reasonable for the case of the tungsten filament you will be studying in this lab).

In the limit where $hc/\lambda k_B T >> 1$ the above formula simplifies somewhat to:

$$I(\lambda) = 8\pi hc\lambda^{-5}\epsilon(T,\lambda)e^{-hc/\lambda k_B T} \tag{2}$$

To the extent that you can ignore the temperature dependence of the emissivity, this formula predicts a linear dependence of the log of the intensity on the inverse of the absolue temperature [2]. Decide for yourself the range of temperatures and wavelengths for which (1) may be safely replaced by (2) and keep that in mind as you perform the experiments below.

B. Equipment

The primary apparatus for this experiment is an Ocean Optics USB4000 optical spectrometer with a fiber-optic input device, a tungsten-filament projection bulb mounted above a fan. You can vary the power fed to the filament, and the current going to the bulb and voltage dropped across the bulb can be monitorered with digital meters (note that the current is AC, and the current reading is taken from a "clamp" style meter so you don't have to worry about blowing a fuse as you would have to with a standard "in-series" ammeter). The temperature of the filamemt may be derived from these voltage and current readings, provided that you make reasonable precautions for accounting for the lead resistance inside the bulb (see section C below), but you can also make use of a disappering filament pyrometer (Spectrodyne model DFP2000) if you so choose. The projector bulb power is controlled by a variac on the wedge-shaped control box. To turn it on, you must turn on both switches at the bottom of the control box (which also activate a cooling fan) and then raise the power on the variac. If the fan does not come on, contact your instructor.

C. Temperature Calibration

A key element in this experiment is the proper determination of the tempartures of the tungsten filament at a particular power. The data in table 1 can be used to determine the temperature, if you can determine the ratio of the filament temperature at a given power to that of the filament at room temperature (with the further as-

TABLE I. Electrical resistivity of Tungsten from table 7.1 of Preston and Dietz [2]

T (K)	ρ ($\mu\Omega cm$)	r_{300}	T (K)	ρ ($\mu\Omega cm$)	r_{300}	T (K)	ρ ($\mu\Omega cm$)	r_{300}
300	5.65	1.00	1300	34.06	6.26	2300	66.91	12.39
400	8.06	1.43	1400	37.19	6.83	2400	70.39	13.04
500	10.56	1.90	1500	40.36	7.42	2500	73.91	13.70
600	13.23	2.40	1600	43.55	8.02	2600	77.49	14.36
700	16.09	2.92	1700	46.76	8.62	2700	81.04	15.02
800	19.00	3.45	1800	50.05	9.23	2800	84.70	15.69
900	21.94	4.00	1900	53.35	9.85	2900	86.33	16.37
1000	24.93	4.56	2000	56.67	10.48	3000	92.04	17.06
1100	27.94	5.12	2100	60.06	11.11			
1200	30.96	5.68	2200	63.48	11.75			

sumption that thermal expansion and any change in the lead resistance can be neglected). To determine the temperature using this technique, determine the resistance of the bulb at room temperature by monitoring the current and voltage across the bulb at very low current. Consider how you might determine how low a current you need to use for this step. This measurement will include both the resistance of the filament, and some resistance from the leads connecting your voltage probes to the filament itself (which will include some contribution from wires in the box, but will be dominated by the contact resistance to the pins of the bulb, and the resistance of the leads connecting those pins to the filament itself).

If R_o is the resistance you measure at room temperature, we can let $R_L = \alpha R_o$ be the lead resistance for some value of α between 0 and 1. Now measure the resistance of the bulb ($R_M(T) = R_L + R_F(T)$) at several different power settings covering the full range of temperatures you wish to use for your tests of Planck's law. You can then put some limits on the likely value of α by checking your temperature scales against the expected relationship between power and temperature below.

$$P_{in} = IV = a(T - T_o) + b * (T^4 - T_o^4) = P_{out} \tag{3}$$

Take a moment to consider what each term in the above equation corresponds to, and to ask yourself how you might check to see how well your data conforms to this relationship (and therefore how you might determine the "best" value for α).

It is also possible to determine the temperature of the filament directly using a pyrometer (a thermometer that works by analysing the light coming from the hot object). The lab has available a disappearing filament optical pyrometer that you can use for this purpose [5]. The disadvantage of this method is that it is far more subjective than the resistance reading, and it tends to be more suitable for measuring the temperature of objects with a uniform temperature over a flat surface of constant emissivity than to the measurement of a small object like the tungsten filament in our projector bulb. If you are so inclined, you might find it interesting to compare the temperature scale you obtain from the pyrometer with the one that you get from measuring the resistance of the light bulb.

Wavelengths in μ

Temperature °K	0.25	0.30	0.35	0.40	0.50	0.60	0.70
1600	.448*	.482	.478	.481	.469	.455	.444
1800	.442*	.478*	.476	.477	.465	.452	.44
2000	.436*	.474	.473	.474	.462	.448	.436
2200	.429*	.470	.470	.471	.458	.445	.431
2400	.422	.465	.466	.468	.455	.441	.427
2600	.418	.461	.464	.464	.451	.437	.423
2800	.411	.456	.461	.461	.448	.434	.419

Temperature °K	0.80	0.90	1.0	1.1	1.2	1.3	1.4
1600	.431	.413	.39	.366	.345	.322*	.300*
1800	.425	.407	.385	.364	.344	.323*	.302*
2000	.419	.401	.381	.361	.343	.323	.305
2200	.415	.396	.378	.359	.342	.324	.306
2400	.408	.391	.372	.355	.340	.324	.309
2600	.404	.386	.369	.352	.338	.325	.310
2800	.400	.383	.367	.352	.337	.325	.313

Temperature °K	1.5	1.6	1.8	2.0	2.2	2.4	2.6
1600	.279*	.263*	.234*	.210*	.19*	.175*	.164*
1800	.282	.267*	.241*	.218*	.20*	.182*	.174*
2000	.288	.273	.247	.227	.209	.197	.175
2200	.291	.278	.254	.235	.218	.205	.194
2400	.296	.283	.262	.244	.228	.215	.205
2600	.299	.288	.269	.251	.236	.224	.214
2800	.302	.292	.274	.259	.245	.233	.224

* Values by extrapolation.

FIG. 1. Data taken from the 75th editon of the CRC Handbook of Chemistry and Physics [4].

Your report should include some discussion about how you have determined your temperature scale, including any rationale you have for choosing one of the available methods over the other. Your report should also include measurements of the optical spectra from the Sodium and Mercury lamps provided. This will provide measurements of the calibration and resolution of the spectrometer used (and your report should also comment on whether either of these will have a significant impact on your final results).

D. Experiments

The Ocean Optics USB4000 spectrometer is accessed through the "Overture" software on the computer to which the spectrometer is connected via a USB cable. In order to get used to this software, as well as to calibrate and characterise the spectrometer, you should start the program and collect spectra from the sodium and mercury lights provided. Keep in mind that the mercury light emits significant amounts of UV light, so you should not remove the UV filter from the aperture to the lamp and you should not stare at the light. Note that the spectrum varies with time as the lamps warm up (over 5 to 10 minutes) and that the fiber optic input to the spectrometer has to be aligned with the aperture from the lamp to maximize the signal. A stand and clamp system is provided to facilitate this alignment. Note also that you do not want to saturate the spectrometer's detector, so you should use a combination of increased distance between the lamp and the optic fiber input and/or decreased integration time for the spectrometer to prevent saturation. What can you say about the calibration of the spectrometer and its resolution from your measurements of these two spectra?

After you have finished characterising the spectrometer, use it to investigate the light from the tungsten filament of the projector bulb. Here too you should be careful to line up the optic fiber's input with the filament. You may have to use different integration times for different power settings in order to get a signal that does not saturate or get lost in the noise floor of the detector. How should you account for this in your analysis, and how might you check that your proposed method is adequate? Do you expect the spectrum provided by the USB4000 to follow equation (1) (why, or why not)? Collect spectra from the projector bulb at several different power levels covering as wide a range of temperatures as you can manage. Do your data exhibit the famous Wien displacement law (can you think of reasons why it might not, and do you remember how that result comes from equation (1))? Determine the ratio hc/k_B for several different wavelength bands (how might you choose the width and location of the bands you propose to use?). Once you have determined this ratio, and investigated any systematic variation there may be with wavelength, determine your best estimate for this ratio and compare it to the accepted value. Feel free to explore any other physics you can think of with this apparatus if you have the time.

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[1] P. A. Tipler and R. A. Llewellyn "Modern Physics, 5th ed.", W. H. Freeman, New York, NY (2008).
[2] D. W. Preston and E. R. Dietz, "The Art of Experimental Physics", Wiley, New York, NY (1991).
[3] G. Smoot and D. Scott, "Cosmic Microwave Background", European Physical Journal **C3**, 127 (1998).
[4] "Handbook of Chemistry and Physics 75^{th} edition", Chemicl Rubber Company (1995)
[5] "DFP 2000 Disappearing Filament Optical Pyrometer," Spectrodyne Inc., Comar, PA (2001)