BlackBody Radiation Lab Report*

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(Dated: December 6, 2021)

Abstract: A blackbody, first proposed by Gustav Kirchhoff, is an object that is a perfect emitter and absorber of radiation. A black body in thermal equilibrium emits electromagnetic blackbody radiation that is described by Planck's law, whose spectrum is determined by the temperature alone. Planck's law itself indicates the Boltzmann Law and Wien's law. Though a blackbody is an idealized object, many bodies are very close to being black bodies and can be expressed as such without losing much accuracy. In this lab, we perform experiments studying the black body radiation using heated objects that are approximately blackbodies. An electric oven with a black body accessory is used in the first experiment. We observe that the oven's temperature is directly proportional to the output voltage measured by Moll's thermopile, which qualitatively predicts the Stefan Boltzmann Law. A light bulb with a spectrometer device is used in the second experiment. We observe that the light intensity increases universally for every wavelength of the light bulb spectrum as its temperature increases and that the wavelength which corresponds to the highest light intensity decreases as temperature increases, which are in good agreement with Planck's Law and Wien's displacement Law.

I. INTRODUCTION

The history of black body radiation begins with the study of thermal radiation. In early 1800, astronomer William Herschel tested different filters to pass sunlight through. He noticed that filters of different colors seemed to generate varying amounts of heat [3], which implies that thermal radiation is related to wavelength. He passed the light through a prism to measure the temperature of different colors of light. He detected the highest temperature below the visible red light, leading to his discovery of infrared light[4], which we currently know is the maximum wavelength of most bodies on earth.

In 1858 Balfour Stewart compared the thermal radiative emissive and absorptive powers of lamp-black surfaces with the power of polished plates of various substances at the same temperature. He found that the lamp-black surfaces had the greatest absorption of radiation, as well as the greatest intensity of emission radiation from themselves and concluded that in a cavity in

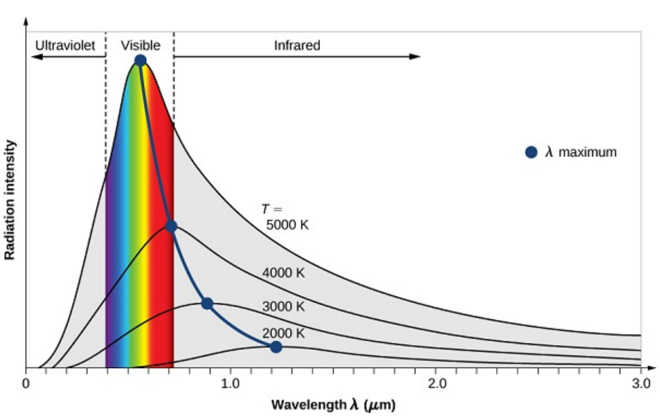

FIG. 1. The blackbody radiation. Image Credit: [1]

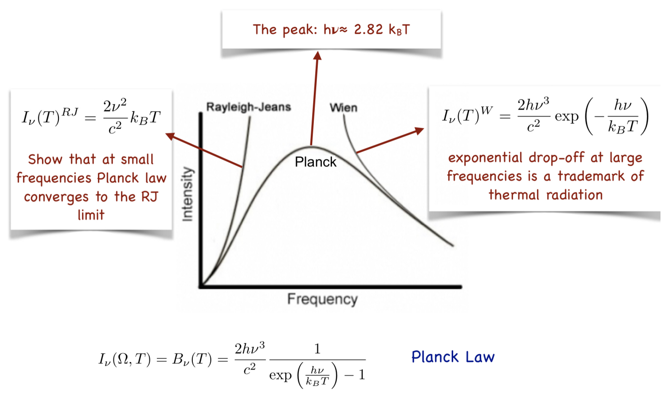

FIG. 2. Planck's Law, Wien's Limits, and Rayleigh-Jeans Limits. Image Credit: [2]

thermal equilibrium, the heat radiated from any part of the interior bounding surface, no matter of what material it might be composed, was the same as would have been emitted from a surface of the same shape and position that would have been composed of lamp-black[5]. However, he didn't mention thermodynamics, and his mathematics was not rigorously valid[5].

The term "black body" was first proposed by a German physicist, Gustav Kirchhoff. In 1859, he discovered the same phenomenon as Balfour's and expanded on them with his theory, known as Kirchhoff's law of thermal radiation. His theory states that "for any material at all, radiating and absorbing in thermodynamic equilibrium at any given temperature T, for every wavelength, λ, the ratio of emissive power to absorptivity has one universal value, which is characteristic of a perfect black body and is an emissive power which we here represent by $B_\lambda(\lambda, T)$ (Kirchhoff's original notation was simply e)[5]." Due to experimental difficulties, the function of $B_\lambda(\lambda, T)$ was not determined until 1900 by German physicist Max Planck. Before the discoveries of Planck's Law, which gave the precise mathematical form of $B_\lambda(\lambda, T)$, the function has been called "Kirchhoff's function." The science historian

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Helge Kragh has commented that "Quantum theory owes its origin to the study of thermal radiation, particularly the "black-body" radiation that Robert Kirchhoff had first defined in 1859–1860."[6]

In 1896, German Physicist Wilhelm Wien published his form of the emissive power function. But Wien's Law can only fit the experimental data at short wavelengths (high frequency) and completely broke down for long wavelengths (low frequency). In 1900, as an improvement of Wien's approximation, Max Planck combined Wien's approximation with the expression of energy for low-frequency derived by Lord Rayleigh, known as Rayleigh-Jeans law, in the simplest possible way, and derived a formula relating the energy of the radiation to its frequency. Planck's formula fitted the observational data for all wavelengths remarkably well and was confirmed experimentally by Rubens and Kurlbaum. The concept of energy quanta was used in the derivation of Planck's law, which most physicists did not fully appreciate at first[7]. However, the evidence for its validity gradually became overwhelming as its application accounted for many discrepancies between observed phenomena and classical theory, among them Einstein's explanation of the photoelectric effect. And in 1918, Planck's fundamental contribution was recognized with the awarding of the Nobel Prize in Physics, "for the discovery of energy quanta."[7]. In other words, Planck's law of black-body radiation contributed to Einstein's concept of quanta of light carrying linear momentum, which became the fundamental basis for the development of quantum mechanics[8].

In this lab, we perform experiments studying the black body radiation using heated objects that are approximately blackbodies. We analyze the light bulb spectrum with different temperatures and the energy intensity from the electric heating oven. The results are all in good agreement with Planck's Law. We will introduce the theory of Planck's Law in section II and the theory of the apparatus we use. Then we will demonstrate our experiments' procedure and present the data analysis in sections III and IV.

II. THEORETICAL CONSIDERATIONS

A. Planck's Law

Every physical body spontaneously and continuously emits electromagnetic radiation, and the spectral radiance of a body, B, describes the spectral emissive power per unit area, per unit solid angle for particular radiation frequencies. The spectral radiance of a body for wavelength λ at absolute temperature T is given by Planck's radiation law [8]:

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5 e^{\frac{hc}{\lambda kT}} - 1} \quad (1)$$

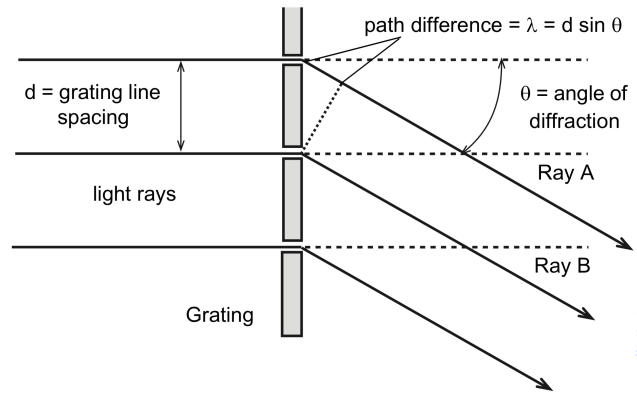

FIG. 3. Ray diagram for a singly wavelength. Source: [9]

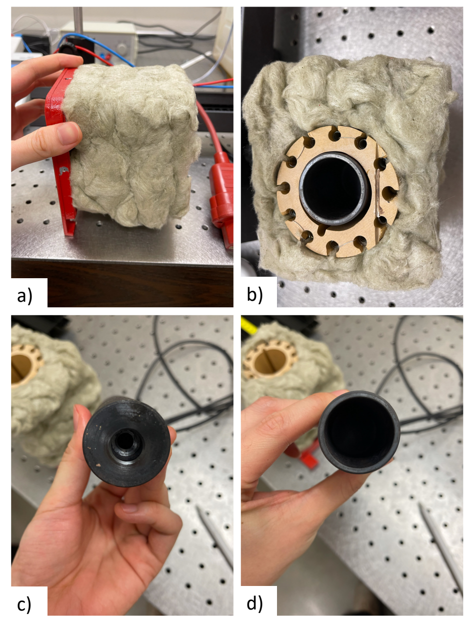

FIG. 4. The interior of the black body accessory. a) the thermal insulator is surrounded. b) the oven and the brass cylinder. c) the brass cylinder back view. d) the brass cylinder front view.

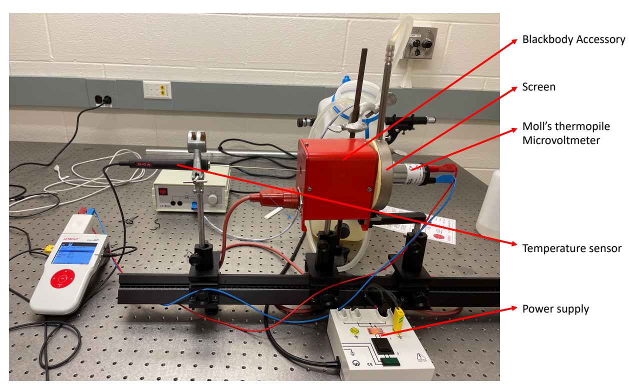

FIG. 5. The overall setup of the Electric Oven experiment.

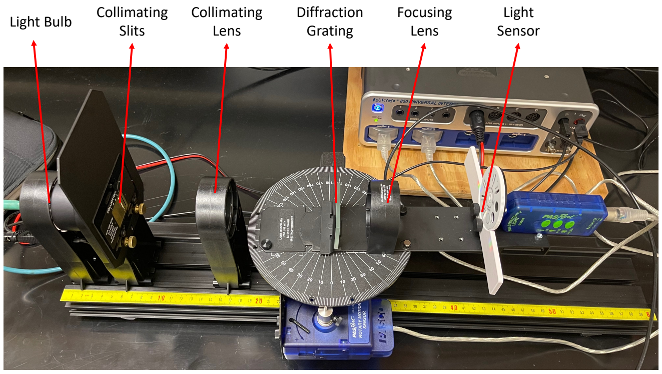

FIG. 6. The equipment Setup of the Light Bulb and a Grating Spectrometer

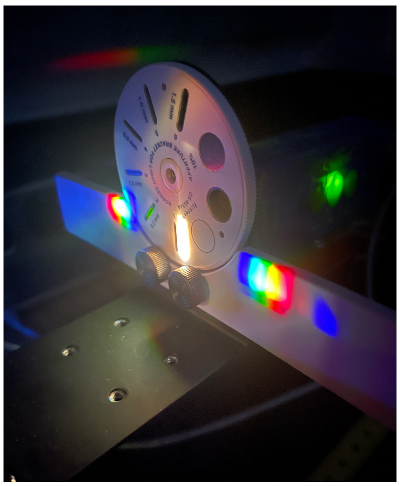

FIG. 7. The example spectrum of light bulb on the light sensor screen

, where $k = 1.38 \times 10^{-23} J/K$ is the Boltzmann constant, $h = 6.63 \times 10^{-34} J \cdot s$ is the Planck constant, and $c = 3 \times 10^8 m/s$ is the speed of light in the medium. With increasing temperature, the total radiated energy of a body increases (Stefan Boltzmann Law) and the peak of the emitted spectrum shifts to shorter wavelengths (Wien's Law). Figure 1 shows the plots of spectral radiation in terms of wavelength for four different temperature values. Planck's Law is the combination of Wien's approximation of energy in high-frequency (low wavelength) and Rayleigh-Jeans approximation of energy in low-frequency (high wavelength). Figure 2 illustrates how Planck's Law combined the two limits. The peaks of Planck's function is described by the Wien's Displacement Law, which gives the maximum light intensity wavelength emitted by a blackbody where 1 is at its maximum:

$$\lambda_{max} = \frac{0.29(K \cdot cm)}{T} \quad (2)$$

The Stefan-Boltzmann law describes the total power emitted per unit area at the surface of a black body (the flux F), which can be found by integrating the Planck distribution 1 with all wavelength:

$$F = \sigma T^4 \quad (3)$$

, where $\sigma = 5.67 \times 10^{-8} J s^{-1} m^{-2} K^{-4}$ is the Stefan-Boltzmann constant.

B. Temperatures of Light Bulb

The light bulb uses Tungsten as filament. Its temperature is related to the resistivity of the Tungsten. A function that approximates the data in the table of the CRC handbook of chemistry and physics([10]) for resistivity of Tungsten over a broad range of temperature is:

$$T = 103 + 38.1\rho - 0.095\rho^2 + 0.000248\rho^3 (K) \quad (4)$$

, where $\rho (10^{-8} \Omega \cdot m)$ is the resistivity of the Tungsten, which is directly proportional to the resistance given by the equation:

$$\rho = \rho_o \left(\frac{V}{I} - R_{holder}\right) / R_o \quad (5)$$

, where $\rho_o = 5.65 \times 10^{-8} \omega \cdot m$ is the resistivity of Tungsten, $R_o = 0.93\Omega$ is the resistance of the Tungsten filament at room temperature, R_{holder} is the resistance of the lamp holder. BY measuring the V, I, and R_{holder}, the temperature of the filament of the light bulb can be determined.

C. Diffraction Grating

(Same theory as the diffraction grating for the Franck-Hertz Experiment we did before) The diffraction grating is a useful tool to separate the different spectral lines associated with the different atomic transitions for the incident light. It is a large number of parallel slits that are spaced equally by distance d. The incident light can be diffracted by the grating at all angles. Only a specific angle can form a light spot (a maximum) on the screen. Figure 3 shows the diffraction pattern for light rays with wavelength λ. The path difference between the adjacent diffraction rays needs to be exactly equal to the incident wavelength so that they can have constructive interference and make a maximum light spot on the screen.

The constructive interference requires:

$$\lambda = d \sin\theta \quad (6)$$

The diffraction angle can also be zero and $-\theta$ to have constructive interference. All the other diffraction angles will be completely destructive. If the incident light is a combination of various different rays with different wavelengths, they can be separated by the grating because the constructive angles are different for different rays. All

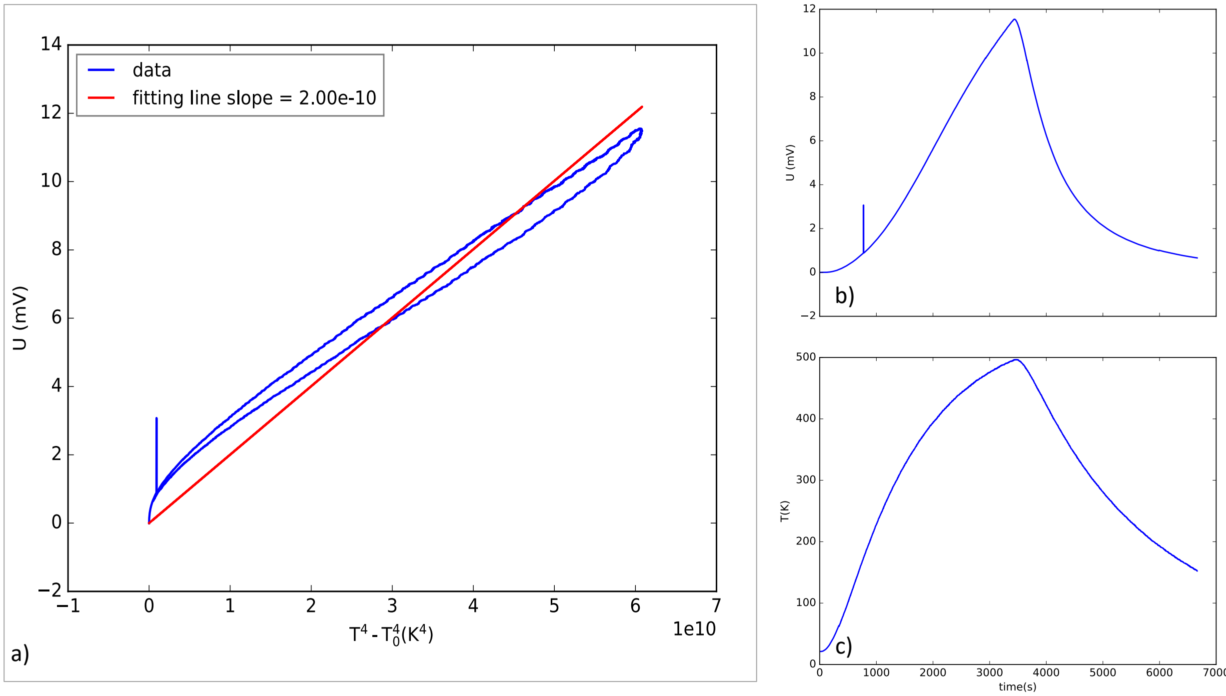

FIG. 8. a)The output voltage U as a function of temperature difference to the fourth power. b)The output voltage changes with time. c) The temperature changes with time.

the light sources are in phase at the middle peak (m = 0). The spectral image on the screen is symmetric about the middle peak. The different spectral lines in one side of the middle line represent light rays with a different wavelength from the incident light. The light intensities can be measured by scanning the spectrum on the screen using a spectrometer as a function of angle. Using the equation 6, we can relate the wavelength to the angle.

III. EXPERIMENTAL METHODS

A. Electric Oven

The first experiment uses an electric oven with a black body accessory as the "blackbody." The black body accessory is made of a burnished brass cylinder that is slid into the electric oven. Figure 4 shows the interior materials of the black body accessory. The screen is arranged in front of the blackbody accessory so that only the thermal radiation of the burnished cylinder is measured by the microvoltmeter and not the outer wall of the hot oven. The microvoltmeter is connected to Moll's thermopile, which contains a number of thermocouples connected in series. The measuring points absorb the incident radiation almost completely. The output voltage of the thermopile can be used as a relative measure of the radiation flux from the blackbody. As the blackbody adsorbs the radiation from its environment, the measured flux is the radiant exitance. The radiation from the environment is $\sigma \times T_0^4$, where T_0 is the absolute temperature of the environment. Hence, the measured flux is $F = \sigma \times (T^4 - T_0^4))$. A NiCr-Ni temperature sensor is connected to the back of the brass cylinder to measure the temperature. Figure 5 shows the overall setup of this experiment.

The electric oven is heated by the external power supply to around 500^oC. Then, the power supply is switched off to have the black body naturally cooled down. The data of measured temperature and the output voltage while heating and cooling are collected by the digital sensor CASSY. We will discuss the data analysis in section IV.

B. Light Bulb

The second experiment uses a Tungsten light bulb as the "black body." The spectrum of the light bulb is scanned by hand using a refraction grating spectrometer with grating line spacing $d = 1666nm$ that measures relative light intensity as a function of angles. The wavelengths corresponding to the angles can be calculated using the equation 6. The light bulb is powered by the external voltage of 4V, 7V, and 10V. The light source of the light bulb transmits through the Collimating slits and lens, which change the large opening source into a narrow beam in the direction perpendicular to the diffraction grating (Figure 6 shows the experiment setup). The

TABLE I. calculation results for temperature of light bulb

output current (A)	output voltage (V)	resistivity ($10^{-8}\Omega \times m$)	Temperature (K)
0.39	3.9	54	1942
0.59	6.8	64	2215
0.76	9.8	72	2458

spectra for the three different power supplies for the light bulb are scanned by the light sensor in the middle of the screen that was rotated slowly in one direction of the central ray (Figure 7). The data for relative light intensity and the angles are collected during the scanning process. The temperature of the filament of the bulb can be determined by the equation 4 and 5. We will analyze the data in section IV.

IV. DATA ANALYSIS

A. Electric Oven: Stefan-Boltzmann Law

We plot the data of output voltage as a function of $T^4 - T_0^4$ in the figure 8. The data contains a noise voltage at around 1000s. This may be due to a sudden environmental change; for example, a flashlight containing high energy photons accidentally pointed to the microvoltmeter. More investigation is needed to evaluate the real cause of this noise. We excluded this noise data and plotted a best fit straight line in figure a) of 8, as predicted by the Stefan-Boltzmann law. However, there is a large deviation of the straight line at the beginning of the experiment. We think this may be due to the measurement with the thermopile. At the beginning of the experiment, the temperature change is not very stable, and the radiation may be convective. The influence of the radiation from the outside of the brass cylinder and the heat built up in the comparison points in the thermopile may also be the cause of this deviation.

B. Light Bulb: Planck's Law

We first calculate the temperature of the filament of the light bulb for three different voltages using the equation 4 with $R_{holder} = 1\Omega$. The calculation results are shown in the table Then we calibrate the angles with the center and use the equation 6 to convert angels to wavelength. The graphs of the scanned spectra for relative intensity as function of wavelength is shown in figure 9. The shape of the spectra is in good agreement with Planck's law. The light intensity of all the wavelengths is higher for higher temperatures. The peak of the curves shifted to a lower wavelength as the temperature increased. We select the spectrum for $U = 10V$ and compare it with the theoretical spectrum predicts by the equation 1 for $T = 2500K$ in the figure 10.

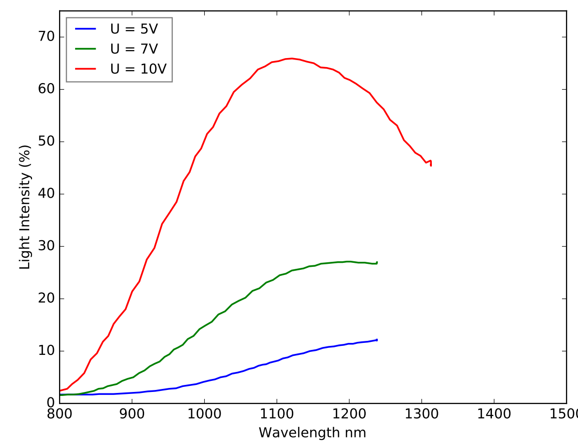

FIG. 9. The spectra of the light bulb

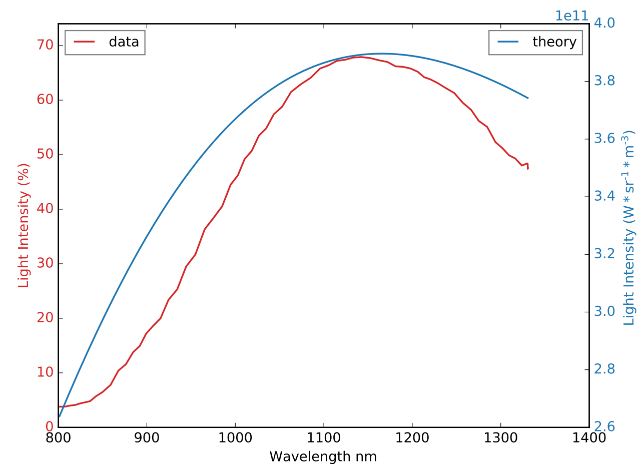

FIG. 10. Compare with Planck's Law

The experimental data matches reasonably well with Planck's law but is not perfect. The reason for the deviation is that Tungsten is not an idealized blackbody. In addition, the diffraction grating decreases the intensity of the light for higher angles.

V. CONCLUSION

In this lab, we directly observed Planck's Law. The experimental data agree with the theory well. The deviation exists because the body we used is not the idealized "black body." In the first experiment, we noticed that the brass cylinder was not perfectly aligned with the hole of the red box. Also, as the temperature increased to around 400^o, the thermal insulator emitted a burnt smell, which may lead to the higher error of the measurement for the output voltage. In the second experiment, we noticed that the second-order spectrum appeared on the screen at an angle of around 40^o. For this reason, we didn't scan over a large angle, which led to the earlier cut-off for the spectrum of $V = 4$ and $V = 7V$ in figure 6. A better calibration could have been done for the collimating lens and focusing lens to have a sharper first-order image so that a larger range of angles could be scanned.

[1] Libretexts, *1.1: Blackbody Radiation Cannot Be Explained Classically* (Libretexts, 2021).

[2] T. Bogdanociv, *PHY4347 PowerPoint Lecture Slides* (Georgia Tech, 2021).

[3] *William Herschel* (Wikimedia Foundation, 2021).

[4] *herschel discovers infrared light*.

[5] *Black-body radiation* (Wikimedia Foundation, 2021).

[6] H. Kragh, *Quantum generations: a history of physics in the twentieth century* (Princeton University Press, 2002).

[7] *October 1900: Planck's Formula for Black Body Radiation*.

[8] Planck's law (2021).

[9] Atomic spectra experiment • ex-5546b.

[10] R. C. Weast, *CRC handbook of chemistry and physics: a ready-reference book of chemical and physical data* (CRC Press, 1983).