Final Report: Observation of Black-body Radiation and Flame Emission Spectra of Alkali Metals by Using Visible Light Spectroscopy

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Two of the main concepts which demonstrate quantization of energy are black-body radiation and emission spectra of atoms. Purposes of this experiment are observing the flame emission spectra of some alkali metals and the variation Planck's distribution law for the black-body radiation by the change of temperature. The intensity and wavelength distribution of black-body radiation of an tungsten filament in an incandescent light bulb and light emission of alkali metals excited by flame will be measured by using the visible light spectrometer we have built.

INTRODUCTION

One of the most prominent concepts which introduced the world of quantum physics to scientists is black-body radiation. In the late 1800s, there was an emerging problem with the emission of light by heated matter. The problem of ultraviolet catastrophe which born from the classical interpretation of the phenomena suggested that intensity of the emitted electromagnetic wave should increase as the wavelength decreases due to decreased energy of lower wavelengths. But, this was not the case when experimental observations are considered. Therefore, German physicist Max Planck introduced the idea of quantization of energy which means that energy is not continuous but rather packed. Thanks to introduction of this idea he was able to theoretically explain the distribution of black-body radiation and solve the problem of ultraviolet catastrophe. Idea of quantization later led to quantum physics.[1].

Identification of alkali metals by flame emission spectroscopy dates back to early 1800s, by Herschel and Talbot. Basically, flame emission spectroscopy is a technique which uses high temperature produced by flame to excite the atoms and detect the electromagnetic radiation emitted during the transition process of electrons. Since every element has a unique emission spectra, it is possible to detect the presence of elements in a solution[2]. Therefore, flame emission spectroscopy is a significant technique to identify specific elements in solutions, especially for alkali metals[3].

Black-body radiation and emission spectra of atoms are fundamental phenomena that gives insights into the quantum nature of light, matter and energy. These concepts are used in many areas of physics and engineering. For example, in astrophysics, properties such as the elements contained in the stars and the temperature of the star can be determined by analyzing the wavelengths and intensities of the light coming from stars. In addition, thermal imaging technologies, such as night vision devices, are dependent on the principles of black-body radiation. Also, the fundamentals of emission spectra are essential to physical chemistry and crystallography to analyze elements or crystals.

Matter emits light of various wavelengths, corresponding to visible, infrared, and ultraviolet light, because it transfers energy via radiation [4]. The wavelength of the emitted radiation depends on the matter's temperature. While the temperature increases, when the emitted light becomes visible, its colors change to grey (faint glow), red, yellow, and finally white. [5]. In addition, as an excited atom returns to its previous state, it emits its energy as photons corresponding to certain wavelengths. The purpose of this experiment is to analyze blackbody radiation at varying temperatures and observe flame emission spectra of sodium, potassium and lithium. Firstly, black body radiation of a tungsten light bulb at different temperatures will be detected. Secondly, flame emission spectra of sodium, potassium and lithium will be observed. During the experiment, a digital camera will be used as a spectrometer to observe the spectrum of visible-light. Finally, the experimental results will be analyzed and compared with the theory and corresponding data tables.

THEORY

Black Body Radiation

In nature, objects emit a distribution of electromagnetic waves which depends only on their temperature. Scientists introduced the idea of energy density (u) which demonstrates the energy of electromagnetic waves per unit volume in a certain region to declare this phenomenon.

$$du(\lambda, T) = \rho(\lambda, T) d\lambda \tag{1}$$

The function $\rho(\lambda, T)$ represents the density of energy states at specific wavelength λ and temperature T. At a fixed temperature, the higher $\rho(\lambda, T)$ means that more energy states present between λ and $\lambda + d\lambda$. If the both sides are integrated, total energy density u is derived as:

$$u(T) = \int_0^\infty \rho(\lambda, T) d\lambda \tag{2}$$

which depends on only T as expected. The total energy $E(T)$ is:

$$E(T) = V u(T) \tag{3}$$

where V corresponds to the volume of a given region. Here, the German physicist Max Planck introduced the concept of discrete energy which is the principle known as quantization of energy. Eventually, he was able to derive a formula for distribution of electromagnetic radiation emitted from a black-body as a function of wavelength λ and temperature T, which is called Planck distribution:

$$\rho(\lambda, T) = \frac{8\pi hc}{\lambda^5 (e^{\frac{hc}{\lambda kT}} - 1)} \tag{4}$$

where h is Planck's constant and k is the Boltzmann's constant. This idea later led the birth of quantum mechanics.

In this project, an incandescent light bulb will be used. The tungsten filament of the light bulb can go over 2000°C. Planck distribution of an object with 1500°C, 2000°C and 2500°C is given below as example:

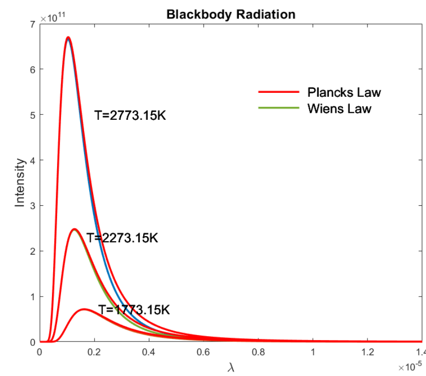

FIG. 1. Planck's and Wien's Distribution at 1500°C, 2000°C and 2500°C which is Expected to be Observed.

By Equation 4, this distribution will shift to left as the temperature of specimen increase. It is aimed to observe this shift by using visible light spectroscopy [6].

Heat Transfer via Radiation

Total energy density $u(T)$ per unit volume can be found by integrating Equation 4 along its whole λ axis:

$$u(T) = \int_0^\infty \frac{8\pi hc}{\lambda^5 (e^{\frac{hc}{\lambda kT}} - 1)} d\lambda = \frac{8\pi^5 k^4}{15(hc)^3} T^4 \tag{5}$$

This equation can also be written as:

$$u(T) = \sigma \frac{T^4}{c}$$

where $\sigma = \frac{8\pi^5 k^4}{15(h^3c^2)} = 5.6704 \times 10^{-8}\ W/m^2 \cdot K^4$ Here, energy flux density which is the rate of energy emission per unit area is defined as:

$$J_u(T) = \frac{cU(T)}{V} = cu(T)$$

If $u(T)$ is put in this equation, it is obtained that:

$$J_u(T) = \sigma T^4$$

This equation is consistent for ideal black-bodies. Since tungsten is not a ideal black-body radiator, a individual emissivity coefficient ε is needed to add.

$$J_u(T) = \sigma \varepsilon T^4$$

So if both sides are multiplied by the surface area of the blackbody, the total power derives as [7]:

$$P(T) = \sigma \varepsilon A T^4 \tag{6}$$

When the system reaches thermal equilibrium, Equation 6 and power output of the circuit $P_c = I^2R$ will be equal. Using equation, it is aimed to find the temperature of the tungsten wire with simple circuit components such as current, resistance, voltage. Which can be measured easily using power supply used to power the incandescent lamp. A incandescent lamp of $24W$ has used and according to data it provides on its box it reaches $2700K$ at $24W$. Using this information and Equation 6, it is possible to calculate the temperature of tungsten filament at any arbitrary power output governed by $P_c = IV$ where I is the current and V is the voltage. By solving the Equation 6 for $P(T) = 24W$ and $T = 2700K$, it is found that the constant in front of the T^4 term in Equation 6 is $\sigma\varepsilon A = 4.516 \times 10^{-13} W/K^4$.By solving Equation 6 for T the equation simplifies to

$$T = \left(\frac{P_c}{\sigma \varepsilon A}\right)^{\frac{1}{4}} = \left(\frac{P_c}{4.516 \times 10^{-13} W/K^4}\right)^{\frac{1}{4}} \tag{7}$$

P_c is the power output of supplied by power supply.

Emission Spectra

Atom can be excited using temperature, high voltage, photon-electron collision, or electron-electron collision. When electrons return to their initial state, they emit light with certain wavelengths corresponding to the energy difference between these states. These energy states can be acquired by solving the Schrodinger equation. Since the atoms are stationary systems, which means does not evolve or change by time, it is sufficient to solve time independent Schrodinger equation for atoms. Time independent Schrodinger equation is as follows:

$$E\psi(\overrightarrow{r}) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\overrightarrow{r})\right]\psi(\overrightarrow{r}) \tag{8}$$

Where V is the potential energy, $-\frac{\hbar^2}{2m}\nabla^2$ is the kinetic energy operator and E is the total energy. So, it basically is a energy balance equation. It is easy to calculate the energy levels and differences for hydrogen atom, which is relatively simple, but for elements planned to use, which are alkali metals, it is very involved to calculate those levels and differences. Because interactions between electrons involves and makes Equation 8 extremely complex to solve. Therefore, it is hard to explain such emission spectra theoretically but corresponding data tables will be used to compare with acquired data.

Data tables for flame emission spectroscopy of lithium, potassium and sodium are as follows[3]:

Lithium

2741.20	5
3232.61	17
4602.86	13
4971.99	8
6103.64	320
6707.84	3600
8126.52	48

FIG. 2. Data Table of Light Emission Spectra of Lithium [3]

First row of the data table corresponds to wavelengths of emitted light in angstrom units, and second row of the table corresponds to intensities. As it can be seen from the table, it is expected to observe a wavelength of 670.784nm due to its relatively high intensity for lithium.

Potassium

4044.14	21
4047.20	16
5782.60	1
5801.96	1.4
6911.30	2.5
6938.98	5
7664.91	1800
7698.98	900

FIG. 3. Data Table of Light Emission Spectra of Potassium [3]

Rows are corresponds to same values as in Figure 2. As it can be seen in the table, wavelengths of 766.491 nm and 769.898 nm are expected because of their relatively high intensities for potassium.

Sodium

3302.32	30
3302.99	15
5682.66	7
5688.22	14
5889.95	2000
5895.92	1000
6160.76	6
8183.27	110
8194.81	220

FIG. 4. Data Table of Light Emission Spectra of Sodium [3]

Rows are corresponds to same values as in Figure 2. As it can be seen in the table, wavelengths of 588.995 nm and 589.592 nm are expected because of their relatively high intensities for sodium.

Diffraction Grating

Diffraction gratings simply diffracts light to use phase difference to create destructive and constructive interferences of light. Since the wavelength of light affects the diffraction angle, it is possible to determine the wavelength of light by basically find where it falls after it diffract. Between two types of gratings, which are transmission phase grating and reflection phase grating, reflection grating has chosen to be used due to high compatibility with the intended experimental setup. The equation for the reflection grating is as follows:

$$d \cdot (\sin\theta_m - \sin\theta_i) = m\lambda \tag{9}$$

where d is spacing between grooves, m is diffraction order, θ_m is the mth order diffraction angle, θ_i is the incidence angle and λ is the wavelength of the light.[8] In the experimental setup, a CD has used as a reflection grating. For CD grooves are located in a spiral shape starting from the middle of the CD and has a spacing of 1510nm[9].

METHODOLOGY

The experimental setup for the spectrometer is composed of an isolated box with a single slit for light to pass through, a light diffuser to get a more homogeneous light, a diffraction grating to diffract and reveal the spectra of the light, and a digital camera (a 2K resolution webcam from an arbitrary brand) to observe the spectra and transfer it to the digital. A computer with Theremino spectrometer software is used to analyze the spectra data transferred by digital camera.

1. Most of the digital cameras have an infrared filter in front of their optical censors. By removing that filter it is possible to detect near infrared regions with digital cameras. Therefore, removal of those filter is helpful to build a spectrometer. In this setup, that optical filter has removed from used digital camera. This allowed us to have a detection range up to 950nm from our observations.

2. Slit was formed by the sharp edges of two razors. In this way, a thin and precise slit has obtained. By using this slit it is possible to obtain the light coming from specimen in a fixed direction. But it was not enough to make a thin slit to make light come in a fixed direction so, a light diffuser is used with slit to make light coming from the specimen more homogeneous and also a tunnel like area has put in front of the slit to hinder the light coming from unwanted directions. In addition, the amount of light entering was controlled by adjusting the slit width. In this way, the brightness was kept at an optimal level and the best spectrum was tried to be obtained. The surface of a CD was used as a diffraction grating. Then, the position and angle of the diffraction grating were set to reflect and diffract incoming light from the slit to the lens of the camera according to Equation 9. Spectra taken by the camera were analyzed by Theremino Spectrometer software.

3. Theremino spectrometer software allows the processing of the image that is obtained from the webcam in real time. The software processes the picture of spectra, pixel by pixel on a linear axis. Location of the pixels on the linear axis which the picture processed on gives the wavelength and the brightness of those corresponding pixels gives the intensity of that wavelength. Than using those data, software also plots the spectra accordingly.

4. The webcam was calibrated with the tests from different locations and angles by using various lights with known wavelengths having sharp peaks, such as monochromatic lasers, gaseous emission lamps, or LED's with different colors. Calibration of the used software done by using two monochromatic lasers with wavelengths of 532 ∓ 10nm and 655 ∓ 10nm. Than, calibration of the software is verified by the found peak wavelength values (blue:463nm, green:523nm, red:610nm) for spectra of an AMOLED screen of a phone [10]. In this way, the optimal distance and angle values were found and the resolution of the spectrometer was enhanced. Then the intensity and wavelength data were plotted and gave the spectrum of the light used.

5. Once the calibration process is done, any visible light can be used as specimen. Black-body radiation of a tungsten filament in an incandescent light bulb is used

as a specimen for the experiment. By varying the current and voltage passing from the bulb using a power supply, it is possible to change the temperature of the tungsten filament in the incandescent lamp. Afterward, it is possible to calculate the temperature by using Equation 6. So, black-body radiation of tungsten filament is observed in various temperatures by varying the current and voltage, and by using those values and a known initial temperature at a specific power outcome of used incandescent lamp the temperatures at every step is calculated. Using those temperatures, corresponding black-body distributions has plotted by using Equation 4. Finally, observation and theory is compared.

6. Flame emission spectra of lithium, potassium and sodium are observed. To observe the mentioned spectra, aqueous solutions of lithium, potassium and sodium salts, which are LiCl, NaCl and KBr, has excited with the flame of a Bunsen burner. After that, flame emission spectra of them is observed by the spectrometer built and acquired data is compared with the corresponding data tables. Peaks in flame emission spectra of lithium is compared with Figure 2, potassium is compared with Figure 3, and sodium is compared with Figure 4.

A photo of the final experimental setup is as follows:

FIG. 5. Photo of Final Experimental Setup

RESULTS

Measurements for both black-body radiation of tungsten filament and flame emission spectra of lithium, potassium and sodium has taken successfully with the visible light spectrometer built.

Results for Blackbody Radiation

A power supply which provides voltage and current to the incandescent light bulb is used and by Equation 7 temperature values at every step has calculated. Acquired data from each step and theoretical distribution with corresponding temperature by Equation 4 has plotted and compared.

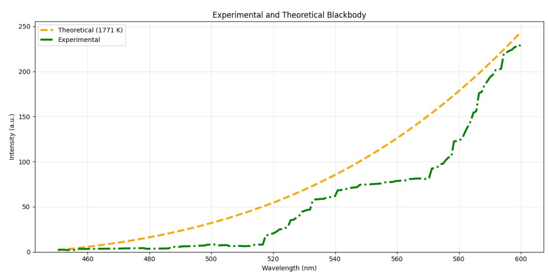

FIG. 6. Results at $10V$ Corresponding to $1771K$ and Theoretical Black-body distribution at $1771K$

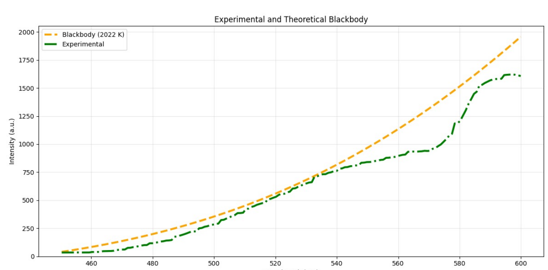

FIG. 7. Results at $14V$ Corresponding to $2022K$ and Theoretical Black-body distribution at $2022K$

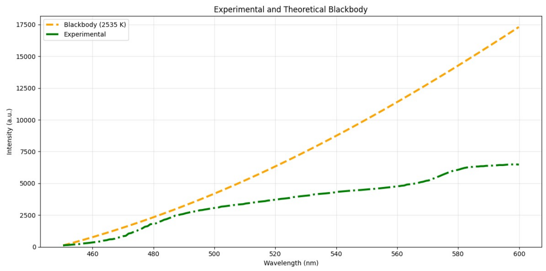

FIG. 8. Results at $22V$ Corresponding to $2535K$ and Theoretical Black-body distribution at $2535K$

As it can be seen from the figures provided, the data acquired is quite consistent with the theory at relatively lower temperatures. As the temperature rises it deviates from the theory more probably because of the non-ideality of the system or the limitations of the optical censor on the digital camera used. Since the aim is to observe the shift of distribution as the temperature rises, it is helpful to plot all of the data on same graph to visualize that shift.

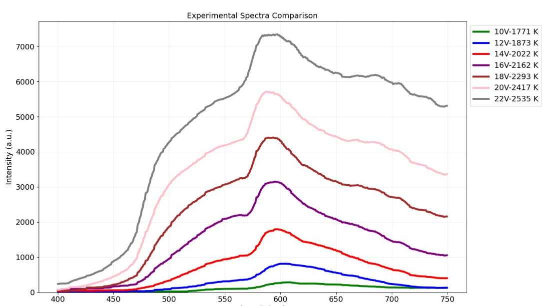

FIG. 9. Results Obtained from Each Run Plotted on Same Graph with Corresponding Voltage and Temperature Values

This plot demonstrates the data acquired from the black-body radiation of tungsten filament in used $24W$ incandescent lamp at each run. Each measurement has taken with voltage values from $10V$ to $22V$ by $2V$ increments. Even though it is not a perfect black-body radiation distribution it is still possible to observe the shift by looking at the slope at $400-600$nm region. As it can be seen from the Figure 9; as the temperature rises, the slope at the mentioned region of distribution increases which means the distribution shifts to left. Thus, it confirms our expectations.

Results for Flame Emission Spectra

To observe the flame emission spectra of lithium, potassium and sodium, aqueous solutions of their salts has burnt using a Bunsen burner. As it burns, flame of the Bunsen burner also excited the lithium, potassium and sodium atoms. Excited atoms of those emitted electromagnetic waves in certain wavelengths and those waves has observed by the visible light spectrometer built. Acquired spectra are as follows:

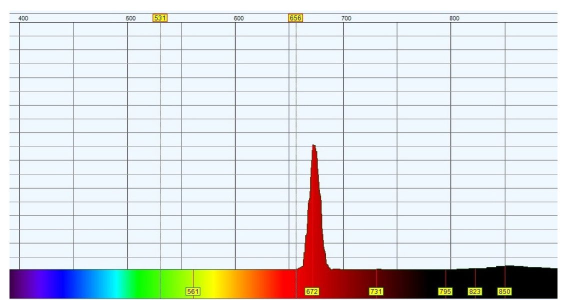

FIG. 10. Flame Emission Spectra of Lithium has a Peak at 672nm

As it can be seen from the Figure 10, lithium has a peak at the wavelength of 672nm. According to data table of flame emission spectra of lithium (see Figure 2) it should have a peak at the wavelength of 670.784nm. Thus the acquired data is sufficiently consistent with the known value of the wavelength of the peak value.

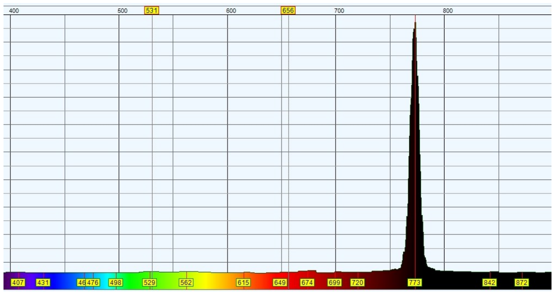

FIG. 11. Flame Emission Spectra of Potassium has a Peak at 773nm

As it can be clearly seen from the Figure 11, potassium has a peak at the wavelength of 773nm. According to data table of flame emission spectra of potassium (see Figure 3) it should have peaks at the wavelengths of 766.491nm and 769.898nm. Since the expected peaks are very close to each other, they observed as one peak with this experimental setup probably due to lack of precision. But, the acquired data is still consistent with the expected values.

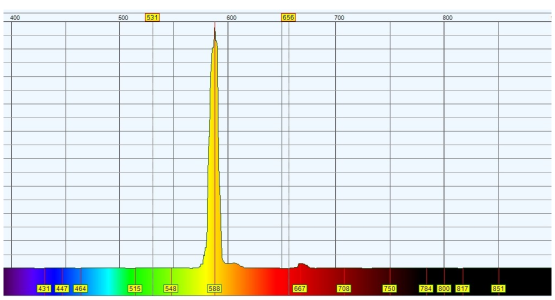

FIG. 12. Flame Emission Spectra of Sodium has a Peak at 588nm

As it can be clearly seen from the Figure 12, potassium has a peak at the wavelength of 588nm. According to data table of flame emission spectra of sodium (see Figure 4) it should have peaks at the wavelengths of 588.995nm and 589.592nm. Since the expected peaks are very close to each other, they observed as one peak with this experimental setup again like in the case of potassium probably due to lack of precision. But, the acquired data is still consistent with the expected values.

Even though the acquired data lacks some expected peaks for potassium and sodium, it still has approximately $\mp$5nm precision when the difference between data and expectation values considered.

ERROR ANALYSIS

Since the spectrometer built with the low budget equipment. It has lots of limitations and problems.

One of the limitations of the spectrometer is low resolution images taken by low budget webcam. If more advanced cameras used, it should be possible to overcome this limitation.

In addition, light diffuser used to acquire a more homogeneous light also negatively affected the intensity of light coming in. This could be the reason of absence of the other expected peaks in flame emission spectra of lithium, potassium and sodium. If more compatible optical equipment are used, this limitation can be overcome and intensity sensibility of the spectrometer can be enhanced.

Furthermore, low budget CD surface is not a perfect diffraction grating due to its spiral shaped grooves. This condition could distort the diffracted light and affect the precision of spectrometer. If more advanced diffraction gratings used, this limitation can be also overcame.

Imperfect black-body spectra of tungsten filament could be caused by the self emission spectra of tungsten or the absorption of the glass on the lamp and the gas inside of the lamp.

CONCLUSION

The results of the experiment mostly met with the expectations. For black-body radiation, observations were mostly consistent with the theory in the range of $450-600$nm and at lower temperatures. At relatively high temperatures and out of the mentioned region observations deviates from the theory. Best fit with the theory was at $14V$ corresponds to $2022K$. Nevertheless, it is still very clear by the observations that as the temperature increases black-body radiation distribution of the tungsten filament specimen shifts to left, to the lower wavelengths. For flame emission spectra of lithium, potassium and sodium which demonstrates the quantization of energy, observations were mostly consistent with the theory in terms of locations of the peaks. It is observed that the spectrometer in this experiment has a precision of $\mp$5nm. Even though observing the low intensity peaks and the peaks very close each other(closer than 5nm) was not possible due to lack of intensity sensibility and lack of precision of the low budget spectrometer, the acquired data was still sufficient to show quantized nature of energy by showing certain wavelengths of electromagnetic waves emitted from excited atoms.

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