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Using Natural and Artificial Light Sources to Illustrate Quantum Mechanical Concepts

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Abstract: We present here a discovery-based laboratory project that introduces elementary quantum mechanical concepts using the spectral distributions of natural and artificial light sources. The measured emission spectra of sunlight and interior/exterior lighting are explained using the electromagnetic spectrum, the phenomenon of blackbody radiation, and the quantization of light. This 4–5 week experiment is appropriate for the general chemistry laboratory or can be expanded for use in upper-division chemistry laboratories, and it uses modern spectroradiometric equipment that is readily available and increasingly used in the physical and biological sciences.

Introduction

The paradoxes of 19th-century classical physics and their resolution can be especially challenging concepts for introductory chemistry students. In particular, there is a lack ofof experiments that effectively demonstrate concepts such as blackbody radiation and atomic spectra while illustrating to students their practical importance. Here we describe an integrated laboratory project designed for an advanced (honors) general chemistry laboratory that demonstrates the relevance of quantum mechanics and spectroscopy to everyday lighting. The Appendix (34jg1897.pdf) provides more detailed information which can be used in adapting the project for a physical chemistry laboratory. In this experiment students collect spectral distributions of natural and artificial light sources in the visible and near-infrared regions of the electromagnetic spectrum. Natural light sources (sunlight and moonlight) and artificial light sources (incandescent, fluorescent, and low/high-pressure gas discharge lamps) are effective means of illustrating discrete and continuous emission spectra while applying the concepts of blackbody radiation to color lighting technologies.

Background and Theory

The nature of light as electromagnetic radiation and the development of modern quantum theory is treated in most introductory chemistry and physics textbooks. Prior to the laboratory, concepts such as electromagnetic radiation, atomic absorption/emission spectra, and the Bohr model of the hydrogen atom are discussed in the lecture portion of the general chemistry course. In addition, students have completed an experiment that introduced electromagnetic radiation and the line spectra of common elements (H, He, and Hg) prior to this project. During the first week's prelaboratory discussion, the phenomenon of blackbody radiation is introduced at the following level.

The emission spectra of many materials heated to glowing, or incandescence, are well-described by Planck's blackbody distribution (see Figure 1). For a radiating object, the plot of relative intensity against wavelength has a characteristic maximum. The wavelength corresponding to this maximum intensity is termed $\lambda_{\max}$. In some cases, this maximum wavelength lies in the visible part of the electromagnetic spectrum; for example, a "red-hot" object emits red light, which is of longer wavelength than the inner blue cone of a Bunsen burner flame. The color of a very hot object changes from red through white to blue as the object is heated to higher temperatures. The wavelength corresponding to the peak of the curve can be related to an absolute temperature using the Wien displacement law [1]:

$$\lambda_{\max} T = 2.90\times 10^{-3}\,\mathrm{m\cdot K} \qquad (1)$$

where $\lambda_{\max}$ is the wavelength in m, T is the absolute temperature, and 2.90×10^{-3} m·K is the Wien displacement constant. Wien's law shows that the radiant energy peak shifts toward shorter wavelengths with increasing temperature; thus, the spectral distribution of the light emitted by glowing sources (such as an incandescent filament or the surface of a star) can be indicated in terms of absolute temperature, also called color temperature [2]. The concept of color temperature is frequently used in photography and artificial-lighting technologies as the following experiments demonstrate.

Experimental

The emission spectrum of the sun, daylight at various times of the day, and artificial light sources found in the laboratory and in outdoor campus lighting were recorded using a Spectron Engineering, Inc. SE590 field-portable, data-logging spectroradiometer. A spectroradiometer measures the output (electromagnetic radiant energy) of a radiating source as a function of wavelength over a relatively narrow range of the electromagnetic spectrum [3]. Optical radiometry has found increasing use in the physical and biological sciences as a method for providing information on the changing UV component of sunlight due to the thinning of the ozone layer. Manufacturers of spectroradiometers include Spectron Engineering, Inc. (Denver, CO), PP Systems (Haverhill, MA), Optronics Laboratories (Orlando, FL), Oriel Instruments (Stratford, CT) and LI-COR (Lincoln, NB). The cost of the instruments varies widely (beginning near $5,000.00) depending on whether the spectroradiometer utilizes a scanning monochrometer or a multichannel detection scheme.

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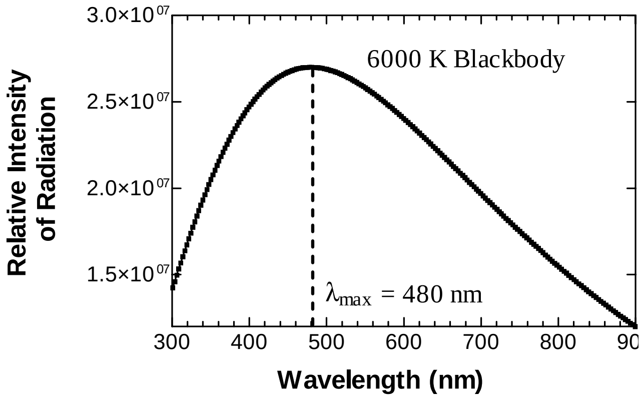

FIGURE 1. Spectrum of a blackbody radiator at 6000 K. The wavelength corresponding to the maximum of the curve can be determined using Wien's law.

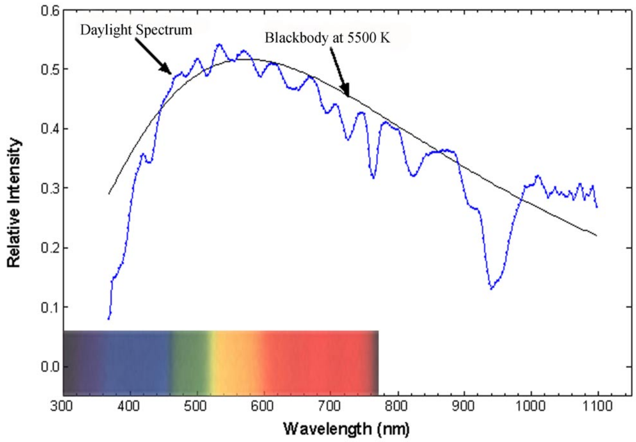

FIGURE 2. Spectrum of daylight (blue curve) fit to a 5500 K Planck blackbody distribution function.

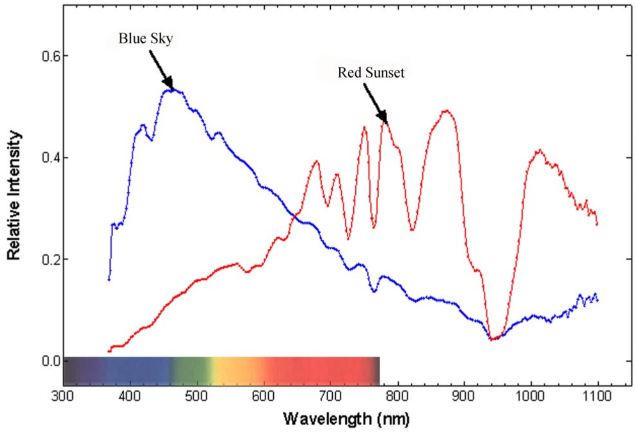

FIGURE 3. Comparison spectrum of blue sky to red sunset.

The photo-diode-array detection, battery-back-up feature, and compact design of our laptop-computer-controlled spectroradiometer allow fast (< 5 s) collection of spectra both inside the laboratory and at various locations outside on our college campus. A variety of different light sources were studied including sunlight, moonlight, incandescent lamps, fluorescent lamps, and gas discharge lamps. In addition, students were also encouraged to bring their own lighting sources (e.g., fluorescent desk lamps, halogen lamps, candles, car headlights, blacklights, etc.) for study.

The spectra of lighting sources were generally measured by collecting the reflection of the light off of a blank white card or a white reflectance calibration standard (Labsphere, Inc.) and directing it into the slit of the radiometer's camera. Although our spectroradiometer is capable of measuring spectra in the 200–1200 nm region, we report data from 350–1100 nm here only. It was convenient to mount the camera on a tripod for stability; alternatively, in several of the experiments students held the camera in various positions to collect the light and note the effect on signal intensity. Our spectroradiometer system software immediately displays the spectrum upon measurement, and intensity versus wavelength data can be imported into a spreadsheet program for further analysis. Although there are other features of the software that allow automatic blackbody temperature calculation for the light source measured, they were not used in this study. Instead, students calculated blackbody temperatures as previously described using equation 1.

Results and Discussion

Sunlight/Daylight. Daylight, the combination of sunlight and skylight, is the natural source of light that most artificial lighting attempts to emulate. The spectral distribution of daylight recorded by students in our laboratory is shown in Figure 2. In general, the daylight spectral distribution peaks at different wavelengths depending on a number of parameters, including the solar zenith angle and atmospheric conditions. The overall shape of the spectrum recorded on November 21, 1996 (4:04 p.m. PST), resembles that of a Planck blackbody radiator near 5500 K and is in excellent agreement with literature values [4, 5].

The attenuation ("dips") in the visible/near-IR portion of the spectral distribution of daylight is caused mainly by the scattering properties of molecules and particles suspended in the atmosphere, as well as absorption by ozone, oxygen, and water vapor (see appendix 34jg1897). Due to the resolution of our spectroradiometer (a few nm), and the altitude at which the spectrum was taken (near sea level), only the most intense Fraunhofer lines are visible. In the early 1800s, the German physicist Joseph Fraunhofer found some 700 dark lines in the solar spectrum, later determined to be due to absorption by gaseous elements in the outer portions of the sun's atmosphere [6]. The most easily identified Fraunhofer line is the red line of atomic hydrogen (Hα, the 656.3 nm Balmer series line) [6]. Students can confirm their assignment by placing a hydrogen discharge lamp in between the spectroradiometer camera and the sunlight source in a manner reminiscent of Fraunhofer's original experiments [6].

The scattering of sunlight by molecules and colloidal particles in the air is illustrated by taking direct spectra of the blue sky and a red sunset. Because blue light is scattered more effectively than red by the molecules in air (oxygen and nitrogen), the sky is blue, and the peak of the blue-sky spectral distribution is near 400 nm (Figure 3). When the sun is low in the sky (sunrise and sunset), its rays must travel through a greater thickness of the atmosphere and the blue components of sunlight are scattered out of the direct beam, resulting in a reddish-orange color; therefore, the red-sunset spectral distribution has less spectral intensity in the blue end of the visible region and more in the red (Figure 3). In the red-sunset spectrum, the "dips" are very prominent because the sun's pathlength through the atmosphere is longer; that is, a large proportion of the sun's intensity has been absorbed by water vapor, oxygen, and ozone. By comparing the spectral

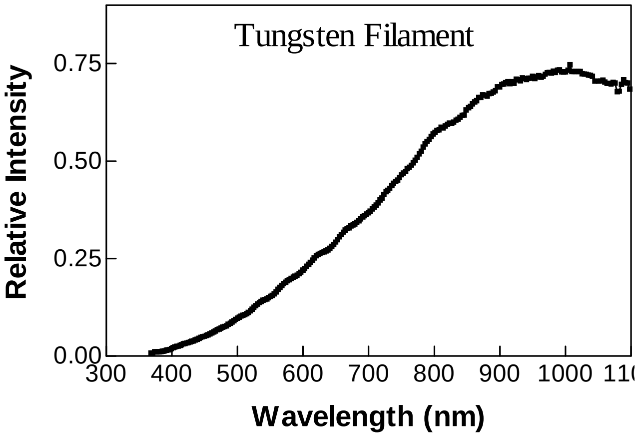

FIGURE 4. Spectrum of a tungsten filament within a white light bulb.

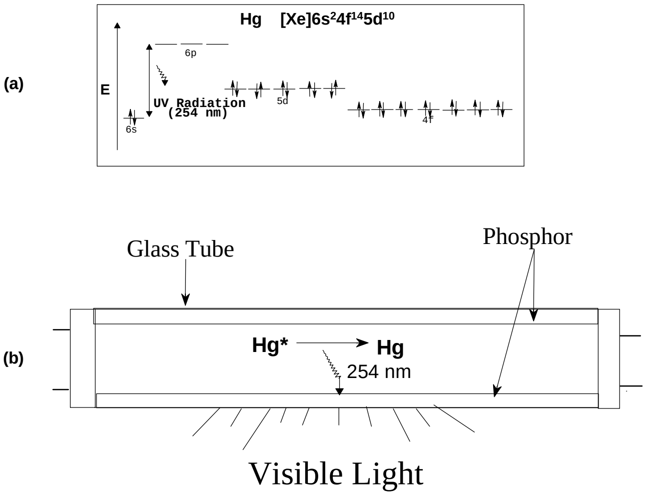

FIGURE 5. (a) Partial energy level diagram for Hg. (b) Schematic diagram of a fluorescent lamp and its operation.

distributions of daylight, blue sky, and red sunset in Figures 2 and 3, students can discover the practical meaning of color temperature. Daylight films are color-balanced for a 5500 K light source and so give good results with the color temperature of midday sun [7]. Skylight without direct sun has a much higher color temperature, and red light from sunrise or sunset has a much lower color temperature. Students can verify this by noting the $\lambda_{\max}$ of spectral distributions collected at various times of the day and using Wien's law to calculate the absolute color temperature.

Tungsten Filament. White light bulbs of various wattages were used to obtain spectra of a glowing tungsten filament. The spectral distribution of light from incandescent lamps is continuous and follows a blackbody distribution very closely. The spectral distribution of a 60 W white light bulb is shown in Figure 4 and peaks near 1000 nm. Students note that in addition to the visible light output, the emission of IR radiation is also detected. The poor efficiency of incandescent lamps is attributed to the large proportion of thermal radiation which lies in the infrared. One consequence of the infrared output is that incandescent lamps are suitable for heating applications (e.g., food-warming lamps). By testing different incandescent bulbs and using Wien's law (equation 1), students find that general purpose incandescent lamps used in the home usually possess a color temperature of 2820–3200 K. In photography, most indoor color films are tungsten-balanced; that is, they are designed specifically for light of 3200 K color temperature, but generally produce acceptable results with any household incandescent light bulb [7].

Fluorescent Lamp. The fluorescent lamp is a low-pressure gas discharge lamp that requires three basic elements to produce visible light: (1) electrodes, (2) gases, and (3) solid phosphor(s), which coat the lamp tube. It contains a highly purified noble gas (usually a few torr of argon) and a small amount of mercury (about 50 mg), which vaporizes during lamp operation [8]. Figure 5 shows schematically how visible light is produced from a fluorescent lamp. Electrons in the fluorescent lamp travel at high speeds through the tube until they collide with a Hg atom. This impact excites a Hg valence 6s electron to the 6p state, after which the electron returns to the ground state, giving off a photon of UV radiation. The 6p → 6s electronic transition provides UV radiation at 253.7 nm. This UV radiation within the lamp tube causes the phosphor coating on the walls of the lamp to glow. Other possible electronic transitions in the Hg atom lead to the emission of visible light. The spectrum of a fluorescent lamp thus consists of discrete lines from the mercury emission superimposed on a continuous spectrum from the solid phosphor coating the inside of the lamp. Students can compare the lamp spectrum to that of a mercury discharge lamp in order to note the discrete Hg lines in the visible region (404.7, 435.8, 546.1, and 578.0 nm). The fluorescent lamp would be blue/violet in color if it were not for the phosphor coating of the tube wall. When the phosphor is excited by 254-nm radiation, it produces visible photons. By changing the composition of the phosphor mixture, lamp manufacturers can produce lamps of slightly different colors (cool white, warm white, etc.). Although fluorescent lamps do not behave as blackbody radiators, the color of the light they emit is characterized by a *correlated* color temperature, the temperature of the corresponding blackbody [8].

Spectra were recorded for a variety of different fluorescent lamps showing the effects of different phosphor compositions on the light output (Figure 6). Cool white lamps have a greater proportion of their spectral intensity in the blue region of the visible spectrum than do natural white lamps, which emit a more yellowish color. Sylvania Gro-Lux lamps, used in plant growth chambers or greenhouses, have a spectral distribution that peaks in the red and blue regions because these colors of light are useful for photosynthesis. By limiting the green light in the lamp, which is largely reflected by chlorophyll, more power can be directed into the useful regions of the spectrum.

Modern fluorescent lamps use blends of red-, green- and blue-emitting phosphors to achieve a "white" output and are called "triphosphor" lamps. These phosphors are generally complex stoichiometric metal oxides that emit light in a narrow region of the visible spectrum. For example, a cool white fluorescent-lamp phosphor blend may use $Y_2O_3{:}Eu^{3+}$ for the red emission, $BaMg_2Al_{16}O_{27}Eu^{2+}$ for the blue, and $Ce_{0.67}Tb_{0.33}MgAl_{11}O_{19}$ for the green [9]. The precise color output of the phosphor depends not only upon the energy separation of the rare earth ions' valence levels (particularly the 5*d* and 4*f* levels) but on the nature of the host lattice as well [8–10].

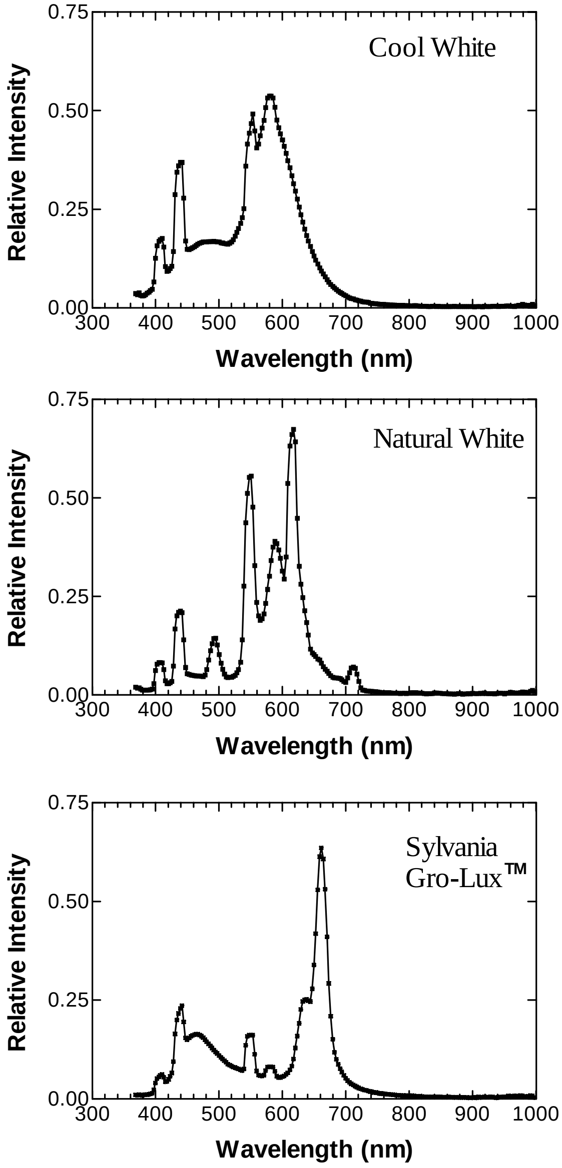

FIGURE 6. Spectra of three different types of fluorescent lamps: cool white, natural white, and Gro-Lux.

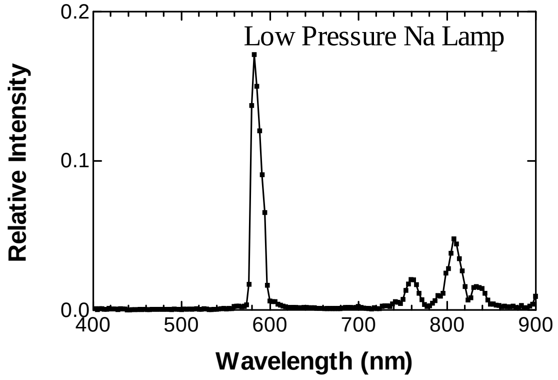

FIGURE 7. Spectrum of a low-pressure sodium vapor lamp.

Low Pressure Sodium Vapor Lamp. The sodium vapor lamp can often be found both inside and outside the laboratory; the low-pressure lamp is commonly used as a polarimeter reference lamp and in outdoor applications such as streetlighting. Like the fluorescent lamp, sodium vapor lamps are gas discharge lamps. They contain mercury and xenon in addition to sodium metal, which is housed in small reservoirs throughout the length of the lamp tube [8]. Radiation is produced by passing an electric current through vaporized sodium under pressure at a high temperature. Electron bombardment of the sodium metal excites the Na 3*s* electron to the 3*p* level. A yellow photon of light is produced when the excited electron returns to the ground state. Because the light emission results from a discrete transition, a line spectrum results (see Figure 7). The visible light consists of the Na D lines and is nearly monochromatic, yellow light. Because the lamp output is yellow light only, all colors illuminated by the lamp appear as different shades of gray or brown except for yellow objects; thus, the lamp is said to provide poor color rendering [8]. Students can note this by attempting to discriminate different colors under the low-pressure sodium lamp. The use of this lamp is confined to locations which do not demand color discrimination, such as in streetlighting. High-pressure sodium vapor lamps are used more widely in outdoor lighting, and more information about their spectral distribution can be found in the Appendix (34jg1897).

Conclusion

Because of their abstract nature, quantum mechanical concepts traditionally introduced in freshman chemistry courses can often be difficult for students to grasp. We have described here a laboratory experiment that uses natural and artificial indoor/outdoor lighting to provide tangible examples of the electromagnetic spectrum and the quantization of light and the importance of these topics in color-lighting technologies.

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