# Light Sources and the Particle Nature of Light

# 7

*The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.*

—Albert A. Michelson

## 7.1 Unsettling Discoveries

As the nineteenth century was coming to a close, Newtonian mechanics could explain and predict the motion of objects ranging in size from pebbles to planets while Maxwell's theory of electromagnetism unified electricity, magnetism, and optical phenomena. Kinetic molecular theory provided an explanation of the behavior of gases, successfully linking the microscopic and macroscopic worlds. For these reasons, and others, many scientists felt that the end of physics was near. In the words of Sir William Thomson: "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

That view would be short-lived, for in 1895 W.K. Rontgen produced a form of invisible radiation, today known as X-rays, capable of penetrating the human body and affecting a photographic plate. Shortly thereafter, Henri Becquerel discovered naturally occurring radioactivity emanating from uranium salts. Just a few months later, J.J. Thompson observed evidence for the electron, the first known subatomic particle. And then there were the lingering problems regarding the transmission of electromagnetic waves through the void of space and discrete nature of light emitted by atoms.

Not only was classical physics unable to explain these discoveries and enigmas, it was also incapable of explaining a rather vexing problem involving thermal radiation, namely, how to explain the spectrum of electromagnetic radiation emitted from a hot object.

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Few expected that the solution to these problems would give birth to a new physics. However, the period that started with the late 1800s and extended through the 1920s produced such an upheaval in how the physical world was perceived that it has been referred to as 30 years that shook physics.

The radical new paradigm that resulted from a solution to the thermal radiation problem became known as quantum physics. What made the tenets of this "modern physics," as it is often called, initially hard to accept was its central premise that light, and all other forms of electromagnetic energy, comes in the form of particle-like bundles, or quanta, rather than in continuous waves. This flew in the face of everything that was known about light at the time. It took two famous scientists, Max Planck and Albert Einstein, to provide irrefutable evidence in support of the quantum hypothesis.

## 7.2 Blackbody Radiation

A closed box with a small hole in it and a glowing filament in an incandescent light bulb each approximate an object known as a *blackbody*. A blackbody is an ideal absorber of light; all radiation falling on a blackbody, irrespective of wavelength or angle of incidence, is absorbed. A blackbody is also an ideal emitter. No object at the same temperature can emit more radiation at any wavelength than a blackbody. One of the rather remarkable features of blackbody radiation is that the blackbody spectrum depends only on the temperature of the object, and not on what it is made of.

The spectral distribution of power emitted by blackbodies at several temperatures is shown in Fig. 7.1. Note that only a portion of the emitted power lies within the visible spectrum, which extends from about 400 to 700 nm (0.4–0.7 μm).

Blackbody behavior is approached, in practice, by blackened surfaces and by small apertures in cavities, as shown in Fig. 7.2. This is true regardless of whether the interior is black or white. Another good example of this is the human eye; the pupil looks black because most light entering it is trapped and absorbed (An exception is light from a photographic flashlamp that is reflected by the retina so that it exits the pupil and results in "red eye" on the photograph.). The surface of sharp edges of a stack of razor blades pretty well approximates a blackbody, interestingly enough, because the array of blade edges effectively traps incident light, resulting in almost complete absorption.

A newly developed material called Vantablack, "Vanta" being an acronym for "vertically aligned nanotube array," is the closest thing to a blackbody on Earth. A Vantablack sample is shown in Fig. 7.3. Developed by Britain's Surrey NanoSystems, Vantablack absorbs virtually all the light incident upon it, 99.965 percent to be precise. Consisting of a microscopic forest of densely packed, extremely thin rods of carbon, the ultra-absorbent material reflects only a tiny

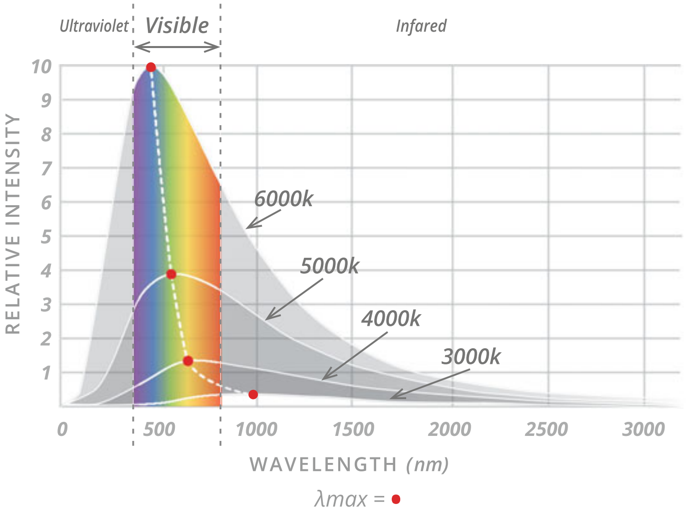


**Fig. 7.1** Spectral distribution of light radiated by blackbodies at several temperatures. Raising the temperature shifts the maximum to shorter wavelength (to the left). Visible range is shown in color

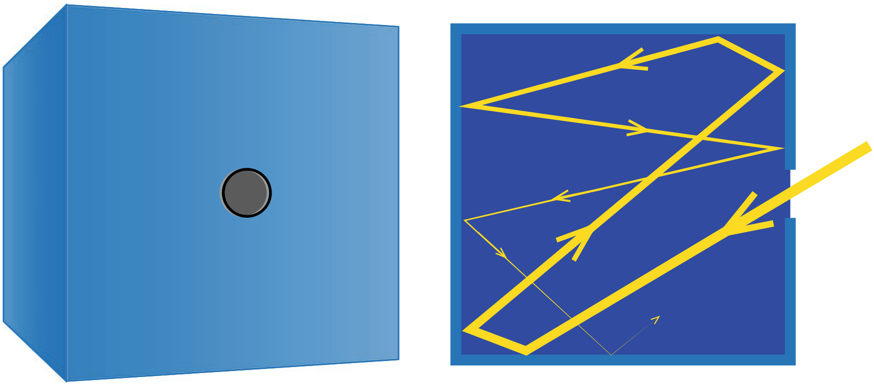


**Fig. 7.2** The black hole in the box's center suggests that the inside of the box is black; however, it can be any color. Light entering the box is absorbed before it can leave through the hole

fraction of the light that strikes it. The remainder of the light bounces back and forth between the nanotubes' vertical surfaces, ultimately being converted into thermal energy.

Additional interesting facts about blackbody radiation are:

1. The total radiation (represented by the area under the spectral distribution curve) is proportional to the fourth power of the absolute temperature.

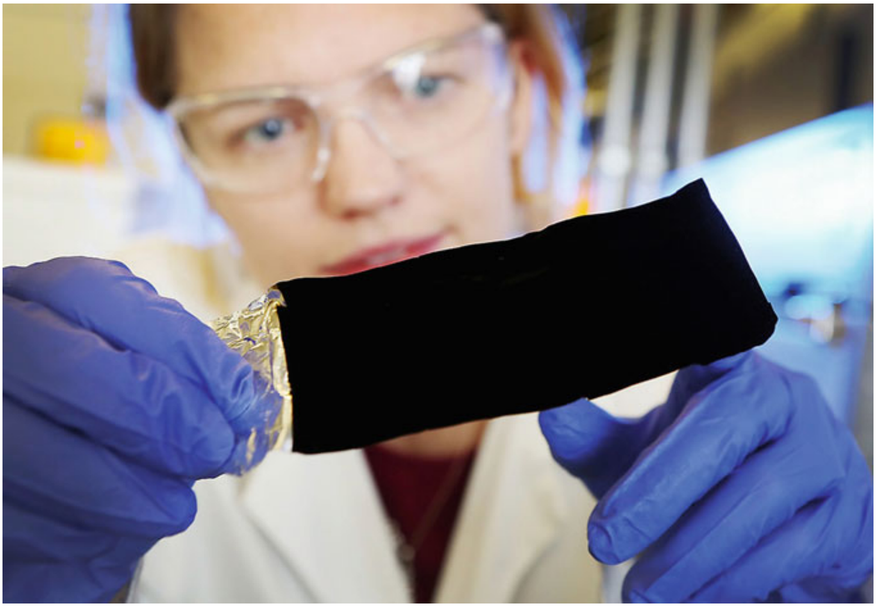


**Fig. 7.3** Experiencing Vantablack has been likened to looking into a black hole (Courtesy of Surrey Nanosystems)

2. The wavelength at which the peak in each spectral distribution curve occurs (indicated by the dashed line in Fig. 7.1) is inversely proportional to the absolute temperature.

The first fact about blackbody radiation in the preceding list is usually expressed mathematically by the Stefan–Boltzmann law: $E = \sigma T^4$, where $\sigma = 5.67 \times 10^{-8}$ W/m$^2$K$^4$ is the Stefan–Boltzmann constant and $T$ is the temperature of an object in degrees above absolute zero. In describing light sources, as in many areas of physics, it is logical to use the *absolute temperature scale*, in which temperature is expressed in *kelvins* (K) or degrees above absolute zero. On the absolute scale, which uses the same size of degrees as the Celsius scale, the freezing point of water is 273 K and the boiling point of water is 373 K (as compared to 0 and 100 degrees on the Celsius scale). Room temperature is about 300 K, the filament of an incandescent light bulb is about 2700 K, and the surface of the Sun is about 6000 K. The conversion from Celsius to absolute temperature merely requires adding 273 (273.16, to be exact).

It should be noted that the radiation from real (nonideal) surfaces, always less than from a blackbody, can be described by their *emissivity* $\epsilon$, which is the ratio of the radiant power $E$ to that of a blackbody $E_{bb}$ at the same temperature: $\epsilon(T) = E/E_{bb}$. The emissivity of the tungsten wire filament in a light bulb, for example, is about 0.4–0.5. The *color temperature* of a light source is the temperature of the blackbody with the closest spectral power distribution.

According to the Stefan–Boltzmann law, a surface at temperature $T$ in an environment at temperature $T'$ will emit and absorb radiation equal to $E = \epsilon\ \sigma T^4$ and $E = \epsilon\ \sigma T'^4$, respectively. Thus the net radiation from the system equals:

$$E = \epsilon\sigma(T^4 - T'^4). \tag{7.1}$$

### ▲ Example

Determine the net radiant power per unit area radiated by a human being with a body temperature of 37 °C (310 K) in a room at 20 °C (293 K). Assume the emissivity $\epsilon$ of the human body to be 0.97.

*Solution* With an emissivity $\epsilon$ of 0.97, the skin covering the human body closely approximates an ideal blackbody. Thus, the Stefan–Boltzmann law (Eq. [7.1]) may be used to obtain the net radiant power per unit area.

$$\begin{aligned} E &= \epsilon\sigma(T^4 - T'^4) = (0.97)(5.67 \times 10^{-8}\mathrm{W/m^2 \cdot K^4})[(3.10 \times 10^2)^4 - (2.93 \times 10^2)^4] \\ &= 1.02 \times 10^2\mathrm{W/m^2}. \end{aligned}$$

For a person with a surface area of 1.8 $\mathrm{m^2}$, the net radiant power would be equal to the radiant power, $E$, times the surface area of the body, $A$. In this situation, $EA = (1.02 \times 10^2\ \mathrm{W/m^2}) \times (1.8\ \mathrm{m^2}) = 1.84 \times 10^2$ W or 184 W. This is a bit more than the thermal radiation produced by a 150 W incandescent light bulb. However, as the following example illustrates, the human body emits very little radiation in the visible region of the spectrum.

The second fact is expressed by the Wien displacement law:

$$\lambda_{\max} T = 2898\,\mu\mathrm{m} \cdot \mathrm{K}. \tag{7.2}$$

Both of these laws are clearly illustrated in Fig. 7.1. Note that raising the temperature greatly increases the total radiated power $E$, and it also shifts the peak wavelength $\lambda_m$ of the radiation distribution curve toward the blue (short wavelength) end of the spectrum.

Wien's law may be applied to find the peak wavelength of light radiated by objects ranging from the human body to stars, as the following example illustrates. Alternately, knowing the wavelength of the light emitted by a blackbody, it is possible to determine the radiating object's temperature.

### ▲ Example

Determine the peak wavelength of light radiated from the human body.

*Solution* Taking the temperature of the human body to be 37 °C, the peak wavelength is calculated from Wien's displacement law as follows:

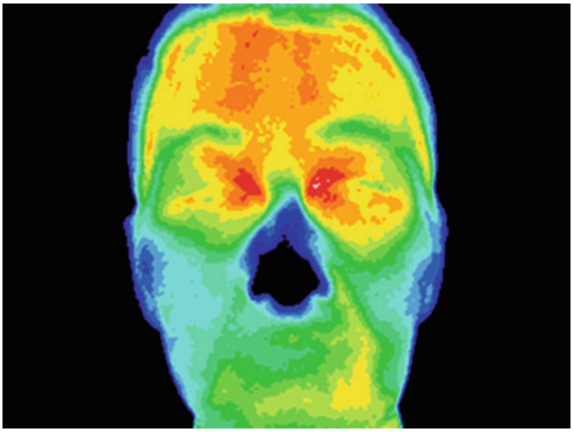


**Fig. 7.4** Thermographic image of a human face showing different temperatures in a range of colors from blue showing cold to red showing hot (Anita van der Broek/Shutterstock.com)

$$\lambda_{\text{peak}} = \frac{2.898 \times 10^{-3}\,\text{m} \cdot \text{K}}{\text{T}} = \frac{2.898 \times 10^{-3}\,\text{m} \cdot \text{K}}{(273 + 37)\,\text{K}} = 9.41 \times 10^{-6}\,\text{m} = 9350\,\text{nm}.$$

Thus, the radiation from the human body is primarily in the infrared region of the electromagnetic spectrum and cannot be perceived by the human eye. While our eyes are not sensitive to light of this wavelength, there are cameras that are. Infrared thermographic cameras produce colored images in which each color corresponds to a particular temperature, typically blue indicating cold to red indicating hot (see Fig. 7.4).

The spectral distribution of light radiated by blackbodies, embodied in the two aforementioned laws, could not be explained by classical physics. On classical grounds, there should be no limit to the energy of the light produced at short wavelengths. This failure of classical physics is called the ultraviolet catastrophe because the breakdown between theory and experiment occurs at short wavelengths.

The distribution of electromagnetic radiation from blackbodies remained an enigma until 1900 when German scientist Max Planck arrived at a completely unorthodox solution. Even though he had no basis for his assumption, he proposed that blackbodies consist of atomic oscillators that emit and absorb electromagnetic energy only in discrete amounts he called quanta. Central to Planck's postulation was that each individual packet possesses an energy equal to $nhf$, where $n$ is a positive integer, $f$ is the frequency of the oscillator, and $h$, now called Planck's constant, is equal to $6.626 \times 10^{-34}$ J·s. This ad hoc solution to the blackbody problem, for which it is said that Planck was never comfortable, was what was needed to bring theory in line with the experiment.

## 7.3 Einstein and the Photoelectric Effect

In 1887, Heinrich Hertz, while performing experimentswith with electromagnetic waves, found that he could increase the sensitivity of his apparatus by shining ultraviolet light on the metal spheres that served as antennae. Later, J.J. Thompson, the discoverer of the electron, proposed that electrons in the atoms in the spheres were being shaken free from the metal by electromagnetic waves. Thompson concluded, correctly, that the freed electrons increased the conductivity between the spheres.

The liberation of electrons when light shines on a metal surface is known as the photoelectric effect, and the freed electrons as photoelectrons. The process, shown in Fig. 7.5, by which this occurs remained a mystery until Albert Einstein realized that light was made up of discrete bundles of energy, later called photons. This was seen as the only way to make sense of the photoelectric effect.

Prior to Einstein's quantum hypothesis, it was thought that electromagnetic waves, that is, light incident on a metal, jostle surface electrons, providing them with the energy needed to break away from the metal. It was reasoned that the time required for the ejection of the first electrons would be dependent on the intensity of the incident light. Therefore, brighter light of any color should result in higher energy photoelectrons. However, these ideas did not agree with the experiment.

According to Einstein's explanation, light quanta behave like particles, each having an energy proportional to frequency of the light: $E = hf$, where $h$ is the proportionality constant introduced by Planck as part of his treatment of blackbody radiation. This is a departure from the wave theory that posits that light energy and intensity are related. Based on the photon theory of light, an electron will leave a metal only if the photon energy absorbed by the electron is equal to or greater than the minimum energy needed to pull an electron from the metal's surface. This minimum energy, known as the work function, depends on the nature of the metal and the condition of the metal's surface.

### ▲ Example

Determine the energy of a photon of ultraviolet light with a wavelength of 296 nm.

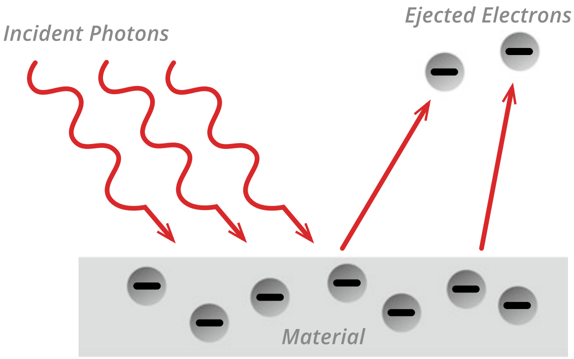


**Fig. 7.5** The photoemission of electrons from a metal plate

*Solution* The energy of a photon may be calculated using the relationship $E = hf$, where $E$ is the photon energy, $h$ is Planck's constant equal to $6.626 \times 10^{-34}$ J·s, and $f$ is thefrequency of the light. Before determining $E$, it is necessary to find $f$. Using the relationship $c = f\lambda$, the frequency is calculated as

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}\text{m/s}}{2.96 \times 10^{-7}\text{m}} = 1.01 \times 10^{15}\text{s}^{-1}.$$

It follows that the energy of the photon is

$$E = hf = (6.63 \times 10^{-34}\text{J} \cdot \text{s})(1.01 \times 10^{15}\text{s}^{-1}) = 6.69 \times 10^{-19}\text{J}.$$

Photons possessing energies of this magnitude are capable of breaking molecular bonds and altering DNA molecules, the result, in some cases, being skin cancer.

## 7.4 Spectra of Light Sources—Optical Fingerprints

When listening to an orchestra, it is possible to focus on a particular instrument and listen to what that instrument is playing. This demonstrates the human ability to analyze, or dissect, a composite sound into its component parts. This rather amazing capability explains what is sometimes referred to as "the cocktail party effect." Most people can zero in on a particular conversation in a room even though there are many people speaking.

Our ability to analyze complex sounds is quite astounding. And while human vision is equally remarkable, it isn't quite so analytical. When you look at a white light bulb, you have no reason to suspect that the light actually consists of virtually every color in the rainbow. Likewise, light from a red neon sign does not reveal its spectral composition. In order to breakdown light into its constituent colors, it is necessary to extend our sense of vision by using optical tools such as prisms or diffraction gratings, optical elements found at the heart of devices called spectroscopes.

From Fig. 7.1 it is clear that an ordinary incandescent lamp (with a filament temperature of about 2700 K) is not a very efficient light source, since most of its radiated power or energy is at wavelengths too long to be seen (we call such radiation *infrared*, since it lies outside the red end of the spectrum). Some photographic films will record infrared radiation, but we experience it mainly as "radiant heat." Raising the temperature of an incandescent lamp filament to increase the efficiency is not too practical, since the metal evaporates rapidly at the higher temperature, coating the interior of the glass with an opaque layer and greatly shortening the life of the filament. In "quartz-halogen" bulbs, the filament is surrounded by a quartz enclosure containing a little iodine gas, which inhibits filament evaporation and makes it possible to operate at a higher temperature than ordinary incandescent bulbs. Even at 4000 K, however, there is little power radiated at the short-wavelength (blue) end of the spectrum, and all incandescent lamps are considerably richer in red and orange than sunlight.

An important class of light sources makes use of radiation from gas discharge, the conduction of electricity through an ionized gas contained in a glass tube or bulb. The light from such gas discharges has a characteristic color (e.g., red from neon, green from argon, blue from krypton), familiar to us from outdoor advertising signs. If we analyze the spectrum of light from a gas-discharge tube (by means of a prism or a diffraction grating) , we will find that it consists of a series of spectral lines, each having a different wavelength. Each of these spectral lines corresponds to some transition between energy levels in the gas ion (atom). In fact, analytical chemists examine such spectra to detect small traces of gaseous impurities. It is interesting to photograph the gas-discharge tubes in signs through an inexpensive diffraction grating in order to see the various spectral colors displayed individually.

Viewing the blue light from a mercury vapor discharge tube through a diffraction grating reveals strong yellow, green, and blue spectral lines, and weaker ones in the red and violet portions of the spectrum. In addition to these lines in the visible portion of the spectrum, there are strong lines in the ultraviolet portion (wavelengths shorter than violet) that are not visible to the eye (but which can produce

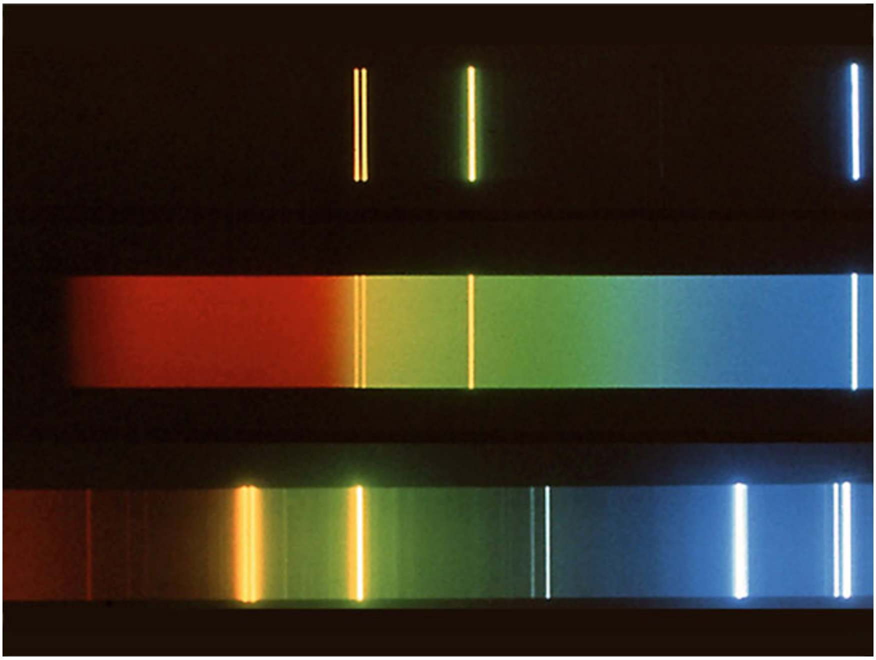


**Fig. 7.6** Top: spectrum of mercury (low pressure); center: spectrum of fluorescent lamp showing mercury lines in addition to continuous spectrum from the fluorescent coating; bottom: spectrum from a high-pressure mercury vapor lamp, showing line spectrum and a continuous spectrum at the blue end (Courtesy of Kodansha, Ltd.)

sunburn). Fluorescent tubes are mercury-discharge tubes that have been coated on the inside surface with a phosphor to convert the ultraviolet light into visible light. Atoms of the phosphor absorb the ultraviolet radiation and reradiate some of this energy as visible light. This is quite an energy-efficient process, and fluorescent lamps give greater efficiency or *efficacy* (more lumens per watt) than incandescent bulbs. Under high pressure, mercury produces both a line and continuous spectra. Figure 7.6 shows the spectra that can be produced by mercury vapor under various conditions.

Other gas-discharge lamps, such as those filled with sodium vapor, are very efficient, but their spectrum of color is not so satisfactory, especially for viewing paintings and other objects with color.

## 7.5 Atoms

What happens when an electric current passes through a gas-filled tube (such as a neon-filled sign or the mercury vapor in a fluorescent tube) and causes it to produce light? Physicists in the nineteenth century were puzzled by this question. The simple element hydrogen was studied in great detail in the hope that understanding its spectrum would lead to understanding the spectra of more complex elements. In 1884, a Swiss schoolteacher, Johann Balmer, found that the wavelengths of some of the lines in the spectrum of hydrogen could be represented by the simple formula: $\lambda = (346.6 \text{ nm})\ m^2/(m^2 - 4)$, where $m$ takes on the values 3, 4, 5, … for different spectral lines; we now call these lines the *Balmer series* of hydrogen. Other series of spectral lines were found in hydrogen, and they all fit into the general formula:

$$\lambda = 364.6(nm)\frac{m^2}{m^2 - n^2}. \tag{7.3}$$

When $n = 2$, this formula gives the wavelengths corresponding to the Balmer series; other series result for other values of $n$.

This orderly arrangement of spectral lines in hydrogen led to the understanding of the structure of the hydrogen atom. Early in the twentieth century, Ernest Rutherford and his colleagues in England developed the idea of a planetary structure of the atom with an extremely dense nucleus surrounded by orbiting electrons, somewhat as the planets of the solar system orbit the Sun. In 1913, Danish physicist Niels Bohr developed a quantum model for the planetary atom that explained the spectral series. The *Bohr model*, in its simple form, has the electrons moving stably in "allowed orbits" or "quantum levels," each with a definite amount of energy, as shown in Fig. 7.7. If an atom is excited, by the passage of electric current, for instance, electrons might take on extra energy and move to a higher level. Such an excited electron would normally fall back to a lower level, radiating its excess energy as light. The Balmer series consists of electrons falling from various higher levels into the $n = 2$ level, as shown in Fig. 7.7.

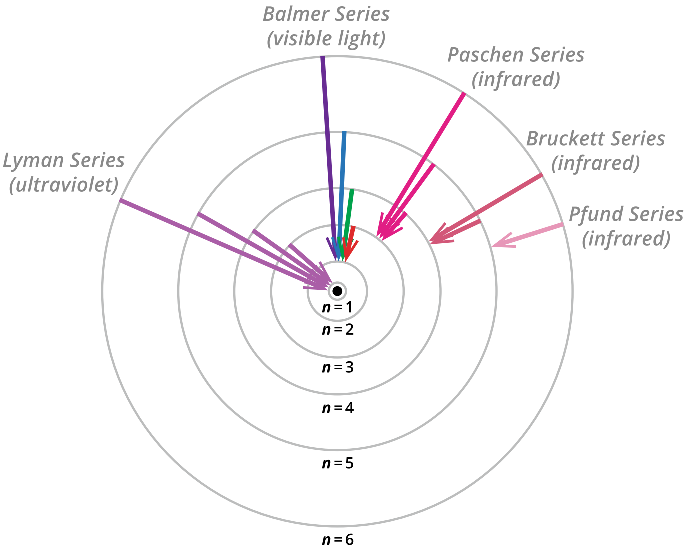


**Fig. 7.7** Spectral series in a hydrogen atom correspond to transitions to a quantum level from a higher level

### ▲ Example

Determine the wavelength of light produced for a transition in the hydrogen atom from the fourth level ($n = 4$) to the second level ($n = 2$).

Solution The wavelength of the spectral lines of hydrogen may be calculated using the Balmer formula (Eq. 7.3). For the transition from the fourth level ($n = 4$) to the second level ($n = 2$),

$$\lambda = 364.6(\text{nm})\,[16/(16-4)] = 486.1\,\text{nm}.$$

This corresponds to blue light. Other transitions in the Balmer series give red, blue-green, and violet light.

The energy levels in a hydrogen atom, according to the Bohr model, are given by $E_n = -(13.6\ \text{eV})/n^2$, where the energy levels are negative with respect to the reference level of a highly excited electron that is able to "escape" from the atom. Energy levels are often expressed in a unit called the *electron volt* (eV), which is the energy that an electron would acquire in traveling from the negative to the positive terminal of a 1-V battery. Based on Einstein's theory, light is emitted from an atom as *photons* or quanta of light, each photon having an energy given (in eV) by $E_\lambda = hc/\lambda = 1240/\lambda$, where $\lambda$ is the wavelength in nanometers, $h$ is Planck's constant, and $c$ is the speed of light.

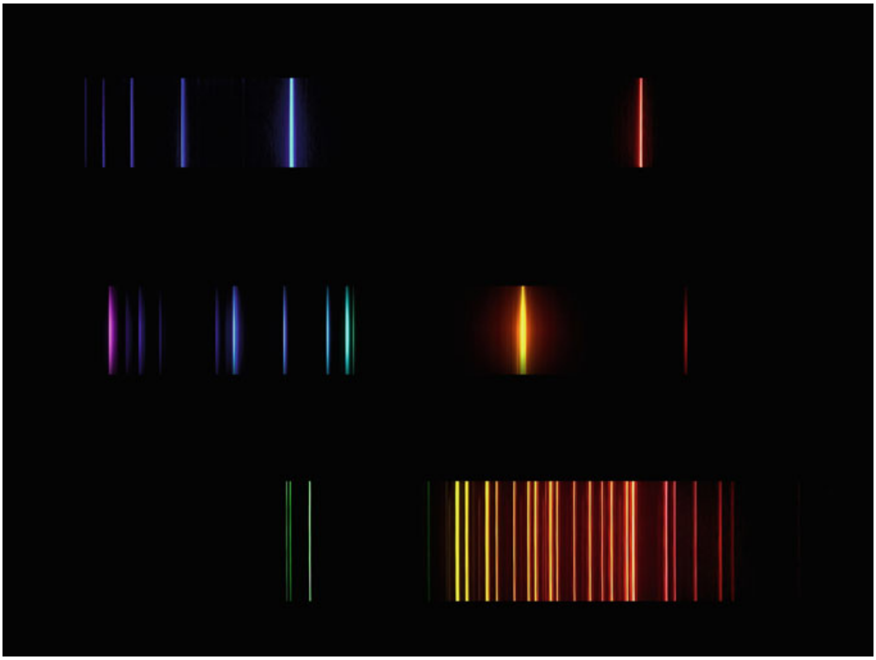


**Fig. 7.8** Top: spectrum of hydrogen; the strong lines are from hydrogen atoms (Balmer, Lyman, and other series); center: spectrum of helium; bottom: spectrum of neon (Courtesy of Kodansha, Ltd.)

Although Bohr's simple quantum model is quite successful in explaining the spectrum of hydrogen, more sophisticated models are required for atoms having more than one electron. The basic idea still remains, however: Atoms have definite energy levels, and when electrons change levels they radiate (or absorb) photons of light. Atoms can be excited (so that one or more electrons move to higher levels) in several ways, such as through the passage of an electric current, collisions with other atoms, absorption of radiation, and so on. As is shown in Fig. 7.8, the energy level structure is different in different atoms (or molecules), so each atom produces a distinctive spectrum when it is excited. Analytical chemists make use of this fact to identify traces of elements. By exciting atoms of paint in a painting so that they radiate their characteristic spectra, for example, much can be learned about the type of pigments used.

The spectra of the light from distant stars tell astronomers a great deal about the character of the stars. It is possible to determine, with a fair degree of certainty, what chemical elements are in the star. By determining small shifts in the wavelengths of familiar elements (known as Doppler shifts, see Sect. 2.7), it is possible to determine the speed at which distant stars are moving toward us or away from us (much the same way police officers use the Doppler shift of reflected radar to determine the speed of a moving automobile). It is remarkable how much we know about our universe just by analyzing the light from distant stars, some of which was radiated millions of years ago and has been traveling through space ever since!

## 7.6 Fluorescence and Phosphorescence

In a gas-discharge lamp, such as those filled with gaseous mercury or sodium, the atoms are excited by atomic collisions due to an electric current. Atoms can also become excited (i.e., their electrons move up to higher quantum levels) by absorbing light. In some cases, the atoms then radiate a photon of longer wavelength (lower energy) as they return to their normal state. This process is called *fluorescence*.

The most familiar example of fluorescence is the fluorescent lamp, which is filled with mercury vapor. Along with visible light (consisting of blue, green, yellow, and other colors), a mercury-discharge tube emits strong ultraviolet light, whose wavelength is too short to be seen by our eyes. However, the inside of the lamp is coated with fluorescent material that absorbs the ultraviolet light and reradiates it as visible light. If the coating is chosen carefully, the fluorescent light will be essentially white. It is possible to make fluorescent coatings that give blue-rich ("cool") white, red-rich ("warm") white, lots of violet for plant growth, yellow to repel insects, or other special tints.

Material whose atoms decay very slowly back to their normal state is called *phosphorescent*. Phosphorescence is really delayed fluorescence. Phosphorescent materials with long decay times are used to paint watch dials and safety tape that glow for hours in the dark.

*Luminescence* is a term that includes both fluorescence and phosphorescence. A prefix is sometimes attached to describe the way in which atoms are excited, such as electroluminescence, chemiluminescence, thermoluminescence, or bioluminescence (e.g., the firefly).

Fluorescent paints are used to create posters that glow brightly under "black light." A so-called black light is a mercury lamp that has been coated with a material that strongly absorbs visible light while allowing much of the ultraviolet light to pass through. Many natural materials, such as human teeth, are strongly fluorescent under ultraviolet light. Tonic water appears clear and colorless under normal light, but, as Fig. 7.9 shows, the liquid appears blue under ultraviolet radiation. This is due to the quinine it contains.

Fluorescent dyes are sometimes added to laundry soap so that clothes will absorb ultraviolet light from the Sun and "glow." Objects that glow white in sunlight, due to fluorescent dyes, can correctly be described as "whiter than white" because they emit more white light than the most efficient white paint reflects. These same dyes cause some white clothing to glow in black light.

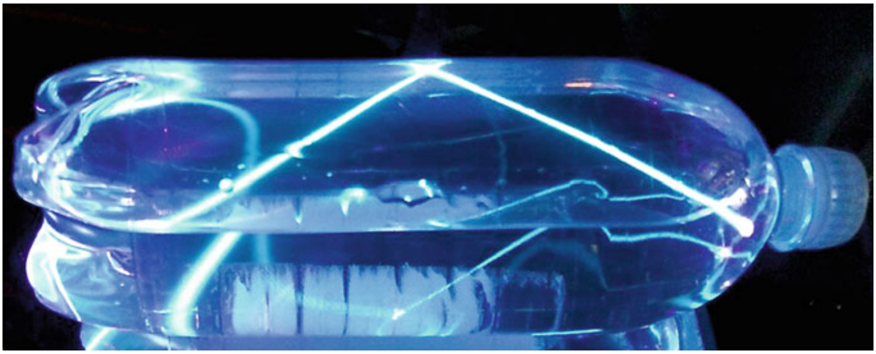
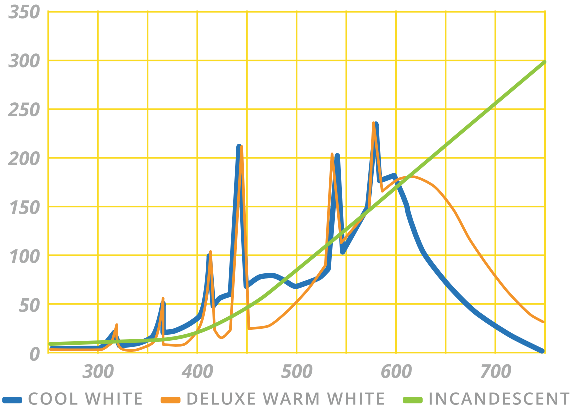


**Fig. 7.9** Light from a blue-violet laser produces fluorescence as it passes through tonic water

Examples of spectra from incandescent and fluorescent lamps are shown in Fig. 7.10. The spectra of fluorescent lamps include discrete spectral lines from the mercury gas combined with continuous spectra due to the phosphorescent coating on the inside of the tube. The peak output from an incandescent lamp lies in the infrared part of the spectrum (not shown), and the visible light output increases toward the red end of the spectrum.

A type of fluorescent lamp, the compact fluorescent lamp or CFL, emerged commercially in 1985 as a convenient and efficient replacement for the conventional incandescent bulb. In essence, a CFL is a standard fluorescent lamp bent into a helical shape capable of fitting into a light fixture designed to accommodate a standard incandescent bulb. In addition to its compact size, the CFL's advantages include substantially less power consumption (one-fifth the electrical power of an incandescent lamp producing the same visible light) and a much longer life (up to 15 times).

**Fig. 7.10** Spectra of: **a** cool white fluorescent lamp; **b** warm white fluorescent lamp; **c** incandescent lamp. The spectral lines of mercury gas are seen in the spectra of the fluorescent lamps



While a boon to energy conservation, the CFL has its detractors. Many users, accustomed to the light produced by incandescent lamps, find the light produced by some CFLs unpleasant due to its spectral content. Concern has been voiced about the possible environmental and health consequences of the mercury contained in CFLs. As a result, many governmental agencies have instituted recycling schemes that insure safe disposal of mercury.

With improvements in brightness and drop in price, light-emitting diodes (LEDs) have become the lighting option of choice. As a result, General Electric and other manufacturers have begun phasing out CFL production.

## 7.7 Light-Emitting Diodes

Luminescent light sources produce practically no heat. A widely used form of this type of light source is the light-emitting diode (LED) . When current flows through an LED, electrons combine with virtual positive charges called "holes." In the process, electrons drop to a state of lower energy. The energy change produces a photon. The color of light produced depends on the materials used to create the LED.

At the heart of an LED are materials known as semiconductors. Virtually all materials in our world can be categorized as conductors, insulators, or semiconductors. Electrons move freely through conductors and with considerable difficulty through insulators. Semiconductors fall in the middle of these two conductive extremes. As the name implies, they have electrical properties that lie between low-resistance conductors and high-resistance insulators. The elements silicon, selenium, and germanium as well as the compounds copper oxide, zinc oxide, and lead sulfide are common semiconductors.

A typical LED is shown in Fig. 7.11. The semiconductor chip, typically a cube 0.25 mm on each side, is mounted on one of the electrical leads. A clear epoxy dome serves as a lens to focus the light as well as to protect the semiconductor.

An LED consists of two semiconducting materials placed back to back. Each of the semiconductor materials has trace amounts of certain impurities added to enhance their conductivity. One type of "doping" leaves one of the semiconductors with what are called "holes." Holes result from the absence of electrons and behave like free positive charges. This semiconductor is called a positive or p-type material. The other semiconductor has had an impurity added that produces an abundance of free electrons and is referred to as a negative or n-type semiconductor.

When p- and n-type semiconductors are sandwiched together, a p-n junction is created. At this junction, some free electrons from the n-type region drift into the p-type region and some holes from the p-type region drift into the n-type region. As a result, a neutralization of positive and negative charges occurs. In the neutral region between the n- and p-type semiconductors, a kind of electrical barrier, called the depletion layer, is formed. The neutralization process does not continue

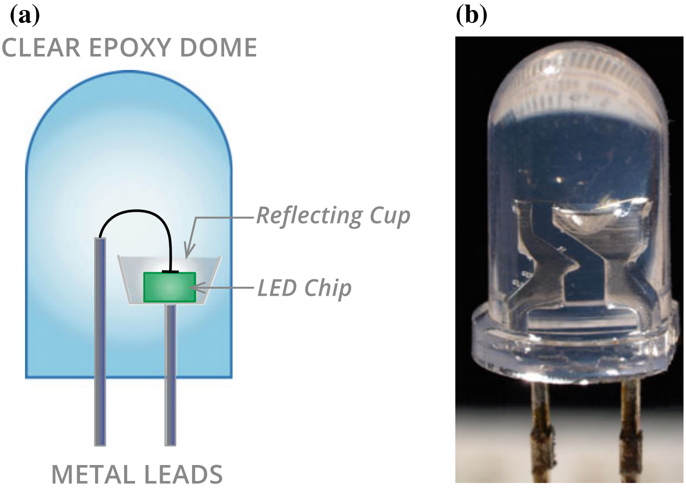


**Fig. 7.11** **a** Drawing of a typical LED lamp. The LED chip is mounted in a reflecting cup attached to one of the leads. Clear epoxy acts as a lens. **b** Enlarged image of an LED (Grapetonix (https://commons.wikimedia.org/wiki/File:Uvled_highres_macro.jpg), "Uvled highres macro", https://creativecommons.org/licenses/by/3.0/legalcode

indefinitely. An electric field develops between the two semiconductors that limit further charge movement.

If the positive terminal of a battery is connected to the p-type semiconductor and the negative terminal to the n-type, the charges in each of the two semiconductors will be repelled toward inward, thus reducing the width of the depletion layer. With sufficient voltage applied to the junction, charges will move across the depletion layer. When this occurs, electrons and holes will combine and in the process the electrons will lose energy. The energy given up by the electron appears in the form of a photon of light. Hence the p-n junction functions as a light source—a light-emitting diode. This process is shown in Fig. 7.12.

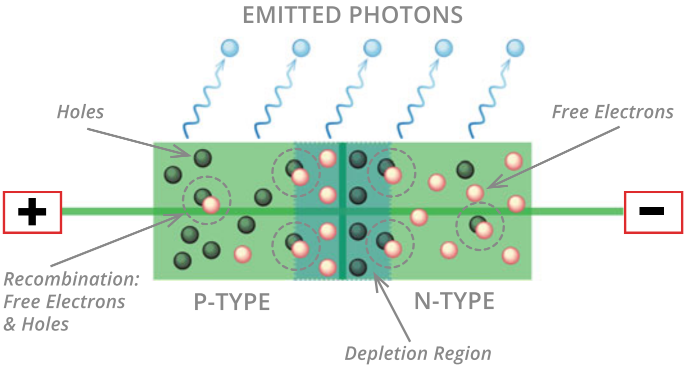


**Fig. 7.12** Electrons and holes combine and in the process produce light

Because the first LEDs weren't very bright, they were primarily used as indicators in devices such as electronic calculators. Early LEDs also had another drawback: prior to 1996, they were only available in a limited number of colors. Blue or white LEDs were not available. Things have changed dramatically since then. LEDs now come in virtually every color and produce light with extreme efficiency.

The range of applications of LEDs continues to grow rapidly as diodes with ever greater efficiency, greater range of color, and lower cost are developed. LEDs are now widely used in such common consumer items as clocks, radios, TV-channel remote controls, toys, holiday lighting, and flat screen televisions. Outside the home, LEDs are used in street lighting, traffic signals, and automotive tail lights and turn signals. A prominent use for LEDs is in large-area outdoor displays, the so-called "jumbotrons." These displays may be as large as several meters high and wide. Visible in even bright sunlight, these large-scale screens are well suited for use in concert venues, for advertising, and at sporting events.

Today, it is almost impossible to find an electronic or lighting device that doesn't employ LEDs. LEDs have replaced incandescent and fluorescent lights in most applications. One is hard pressed to find incandescent bulbs or CFLs in stores anymore.

While LEDs have only been commercially available since the 1960s, the history of the LED can be traced to a 1907 discovery. It was then that British engineer H. J. Round, while working with radio pioneer Guglielmo Marconi, found that a crystal detector that he was using in a radio receiver emitted light when a current was passed through it. This is the first time light was produced by a process known as electroluminescence, the emission of light by a material in response to an electric current.

Starting in 1924, Russian engineer Oleg Vladimirovich Losov published several papers describing his research on light emission from zinc oxide and silicon carbide crystal rectifiers. In his writings, Losov detailed a variety of aspects of these diodes, including their spectra. He is often credited with the creation of the first LED.

While LED research and development continued throughout the twentieth century, it wasn't until 1962 that red GaAsP LEDs were first introduced commercially by General Electric. They had efficiencies of only 0.1 lumens/watt (1/100 that of an incandescent lamp) and were used mainly as indicator lights on equipment. In the mid-1970s, it was discovered that by adding nitrogen, red-orange, yellow, and green LEDs with performance in the range of 1 lumens/watt could be produced. By 1990, efficiencies had increased to 10 lumens/watt, greater than filtered incandescent lamps, and they began to replace light bulbs in many outdoor lighting displays.

## 7.8 Blue, Ultraviolet, and White LEDs

Although red and green LEDs had been around for many years, blue LEDs continued to be a challenge for scientists until 1993 when bright blue LEDs were demonstrated by Shuji Nakamura of Japan's Nichia Corporation. The event revolutionized LED lighting, making high-power, highly efficient blue light sources practical. The breakthrough was based on the use of gallium nitrate growth process and lead to the development of technologies such as Blu-ray.

Nakamura and collaborators Hiroshi Amano and Isamu Akasaki were awarded the Nobel Prize in Physics in 2014 for the invention of the blue LED. According to the Nobel Award Committee, the technological advance ushered in a "fundamental transformation of lighting technology."

Using compounds of AlGaN and AlGaInN, even shorter wavelengths are achievable. Ultraviolet LEDs in a range of wavelengths are available. Near-UV emitters at wavelengths around 375–395 nm are inexpensive and are frequently used in lieu of so-called black lights often used in security applications.

Many common lighting applications require white light. However, LEDs only emit light in a very narrow range of wavelengths, emitting light of a color characteristic of the semiconductor material used to make the LED. To produce white light, some means of producing a much broader band of colors must be employed.

One approach to the problem is to place red, green, and blue LEDs in close proximity and properly adjust the intensity of each. This additive mixing approach makes the production of white light and virtually all other colors possible. This method is commonly used in large video displays.

White light may also be produced by using phosphors in conjunction with short-wavelength light. By including appropriate phosphors in a blue LED, yellow light may be produced through the process of fluorescence. The yellow light combines with the blue light not absorbed by the phosphors to produce white.

## 7.9 Laser Light

The laser is one of the most important technological achievements of the twentieth century. *Laser* is an acronym that stands for **l**ight **a**mplification by the **s**timulated **e**mission of **r**adiation. The key words are *amplification* and *stimulated emission*. Einstein predicted stimulated emission in 1916, and the principle was applied to light in 1958 by Arthur Schawlow and Charles Townes when they proposed the optical maser, or laser.

The first laser was constructed by Theodore Maiman in 1960. Maiman's laser used a ruby crystal, excited by a xenon-filled flashtube, as the amplifying medium, and the laser emitted intense flashes of red light with a wavelength of 694.3 nm. Ruby is a transparent crystal of $Al_2O_3$ with a small amount (about 0.05 percent) of chromium. It appears red because the chromium ions have strong absorption bands

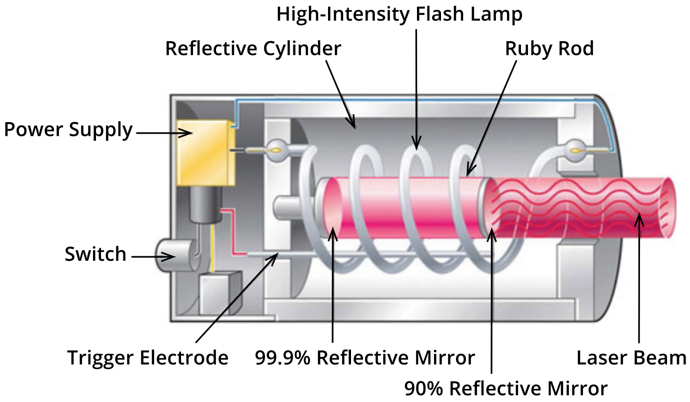


**Fig. 7.13** Schematic of a ruby laser

in the blue and green regions of the spectrum. A schematic diagram of a ruby laser is shown in Fig. 7.13.

When the flashtube is fired, light is absorbed and atoms are raised from the ground state to a short-lived excited state, as shown in Fig. 7.14. They then quickly relax, giving up a portion of their energy to the crystal lattice by nonradiative transitions (i.e., transitions that don't give off light) to a longer-lived, metastable state (i.e., a state in which atoms can remain for a small fraction of a second). Eventually, they decay from the metastable state back down to the ground state by emitting photons with an energy of 1.79 eV and a wavelength of 694.3 nm. In addition, some of these photons stimulate other atoms to emit photons with the same energy and wavelength.

In a system of many atoms (solid, liquid, or gas), most atoms occupy the lowest available energy levels. If a large number of atoms end up in a metastable state, a *population inversion* occurs in the numbers of atoms in the metastable and ground

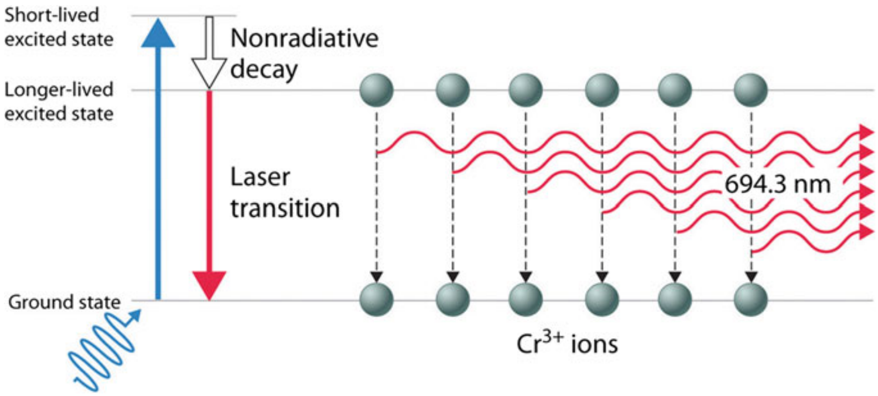


**Fig. 7.14** Transitions between energy levels in ruby laser

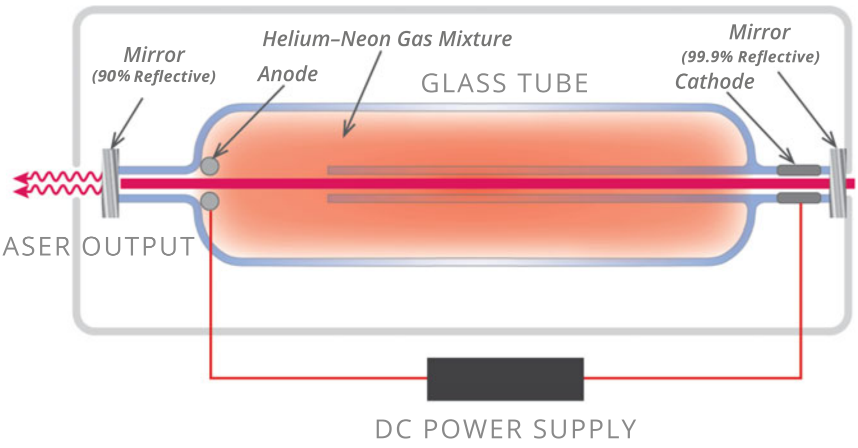


**Fig. 7.15** HeNe laser components include a gas-discharge tube, two mirrors, and a power supply

states. This is a nonequilibrium condition, like balancing a concrete block on the top of a stick; anything that disturbs the block will cause it to fall. A photon of the right wavelength striking the atom does just that; it causes the atom to "fall" to its ground state, emitting a photon of the same wavelength (i.e., it *stimulates* radiation). Now we have two photons that can, in turn, stimulate two more atoms to radiate, and the light builds up very rapidly.

As Fig. 7.13 indicates, both ends of the ruby crystal are silvered, such that one end is almost totally reflecting (about 99.9 percent) and the other end reflects about 90 percent of the light. If the mirrors are parallel, standing waves of light are set up, and an intense beam of coherent light emerges through the partially silvered end. During each pass through the crystal, the photons stimulate more and more atoms to emit, so the light becomes very intense. The light is *coherent* because all the photons have the same phase and the same wavelength.

A few months after Maiman's ruby laser was announced, Javan, Bennet, and Herriott developed the first gas-filled laser, a helium-neon laser that emitted continuous light in both the visible ($\lambda = 632.8$ nm) and infrared ($\lambda = 1150$ nm) portion of the electromagnetic spectrum. TheHeNe laser, which has been widely used for the past 30 years, includes a gas-discharge tube with a mixture of 15 percent He and 85 percent Ne, two mirrors, and a high-voltage power supply (see Fig. 7.15).

Populationinversion inversion among the atomic states is achieved somewhat differently in the HeNe laser than in the ruby laser. Helium atoms are excited by the electrical current, and these excited helium atoms excite neon atoms by collisions. This leads to an excess of neon atoms in the excited states, and these atoms decay back to a lower level by emitting photons. The light is not nearly so intense as that from a ruby laser because the density of atoms is much lower in a gas than in a solid crystal; however, the emission is continuous rather than intermittent.

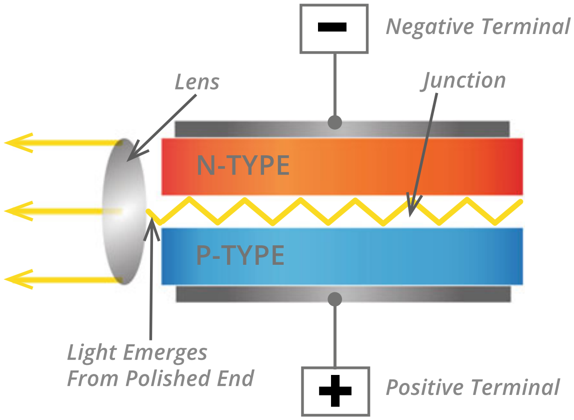


**Fig. 7.16** In a diode laser, light is produced in a narrow p-n junction

Diode lasers, using semiconducting materials similar to those used in LEDs and transistors, are the most efficient type of lasers. In a ruby or HeNe laser, a concentrated light beam is produced by repeatedly reflecting the light emitted from atoms between two mirrors to create a population inversion. In a laser diode, an equivalent process happens when the photons bounce back and forth in a roughly 1-μm wide junction between p-type and n-type semiconductors, as shown in Fig. 7.16. The amplified laser light eventually emerges from the polished end of the gap in a beam parallel to the junction.

Diode lasers are inexpensive and very compact, and thus they have found their way into many commercial and consumer products, such as optical pickups for reading compact discs, pointers, and barcode readers in stores. Diode lasers emit light with wavelengths throughout much of the visible spectrum and beyond.

## 7.10 Gas-Filled Arc Lamps

In a gas-discharge lamp, electrical current flowing through the ionized gas provides the energy to excite the gas atoms so that they emit light. The process can be made to be very efficient. A modern sodium arc lamp, for example, produces about seven times as many lumens per watt as an incandescent lamp. A modern high-pressure sodium arc lamp radiates yellowish light (2100 K color temperature) with a broad enough spectrum to be acceptable for street lighting. A sealed ceramic tube contains a liquid amalgam of sodium and mercury, as well as a starting gas, xenon. When the arc is started by a pulse of about 2500 volts, the light first appears bluish-white due to the discharge in mercury and xenon and then shifts to yellow-orange as the sodium atoms become excited. As the sodium warms and its pressure increases to atmospheric, the spectrum broadens.

Mercury arc lamps also offer long life and high efficiency. The mercury, together with a starter gas, argon, is enclosed in a quartz tube. The lamp is started by applying a high voltage between one of the main electrodes and a starting electrode nearby; the arc heats and vaporizes the mercury, which then carries the main discharge. It takes several minutes for the mercury to heat up so that the arc is stable. High gas pressure in a gas-discharge lamp broadens out the spectral lines (due to the Doppler effect described in Sect. 2.7), which gives a more usable light for general illumination. High-pressure mercury lamps give a broad continuous spectrum slightly slanted toward the blue end.

A xenon arc lamp is still another example of a discharge lamp. In this type of arc lamp, shown in Fig. 7.17, a high-voltage power supply is used to ionize xenon gas contained within a glass tube, resulting in the production of positively charged ions and negatively charged electrons. These charges move in opposite directions along the tube, with electrons being attracted to the positive electrode and ions moving to the negative electrode. The collision of these charged particles with each other and the electrodes produces light.

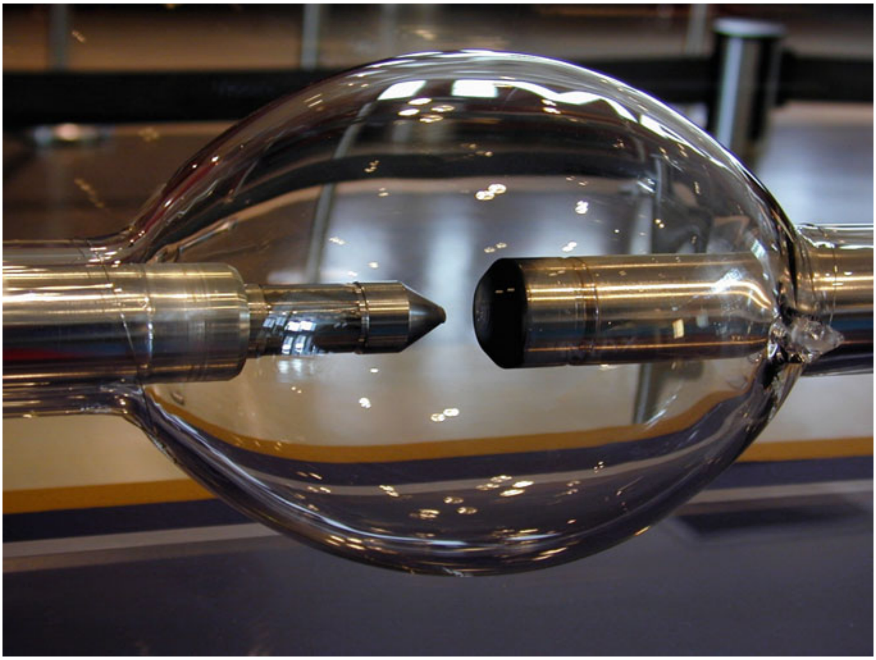


**Fig. 7.17** A 15-kW xenon arc lamp used in movie projection systems (Atlant (https://commons.wikimedia.org/wiki/File:Xenon_short_arc_1.jpg), "Xenon short arc 1", https://creativecommons.org/licenses/by/2.5/legalcod)

In addition to a line spectrum, high-pressure xenon arc lamps have a broad continuous spectrum closely resembling sunlight. This makes them useful in a variety of applications that include use in movie projectors and situations requiring simulated sunlight.

When short, high-intensity bursts of light are required, a capacitor, which gives a short pulse of high current, is used to produce ionization. For this reason, capacitor-energized xenon arc lamps are used in photography, as high-intensity stroboscopic light sources, and as exciters for pulsed lasers.

## 7.11 Nanoscale Light Sources

Richard Feynman, Nobel laureate in physics, once said, "There's plenty of room at the bottom." Feynman's prophetic statement made over a half century ago referred to the possibility of manipulating individual atoms and molecules, something that is now routinely being done. Known as nanotechnology, this relatively new field of research and development represents the design, production, and application of devices and systems at the nanometer scale.

One area where nanotechnology shows great promise is in the production of light, for researchers have found ways to produce light with devices in many cases not much bigger than a small cluster of atoms. These miniature nanophotonic devices include light-producing nanocrystal quantum dots, carbon nanotubes, and carbon nanowires.

A quantum dot is a nanostructure made from a semiconducting material such as silicon, cadmium selenide, cadmium sulfide, or indium arsenide. Quantum dots are sometimes referred to as artificial atoms, since a quantum dot has bound, discrete energy states, such as those found in atoms and molecules. As in an ordinary LED, a quantum dot produces light when an electron and a positively charged hole combine. There is one big difference, however: size. Quantum dots have diameters ranging from 2 to 10 nm. These dimensions correspond to the size of a bundle of 10–50 atoms.

The wavelength of light emitted by a quantum dot is related to their size: the smaller the quantum dot, the shorter the wavelength of the emitted light. This enables the production of a wide range of wavelengths merely by changing the size of the quantum dot. The quantum dot samples shown in Fig. 7.18 range in size from 2 nm (blue light emitter) to 4.2 nm (red light emitter).

The ability to fine tune the size of and, therefore, the color emitted by quantum dots is a particularly useful feature when it comes to creating monochromatic light sources and vivid color displays such as those found in quantum light-emitting display (QLED) televisions. Beyond display applications, quantum dots are predicted to provide a way of increasing the efficiency of solar cells, detecting and treating cancer, and serving as switches in quantum computers.

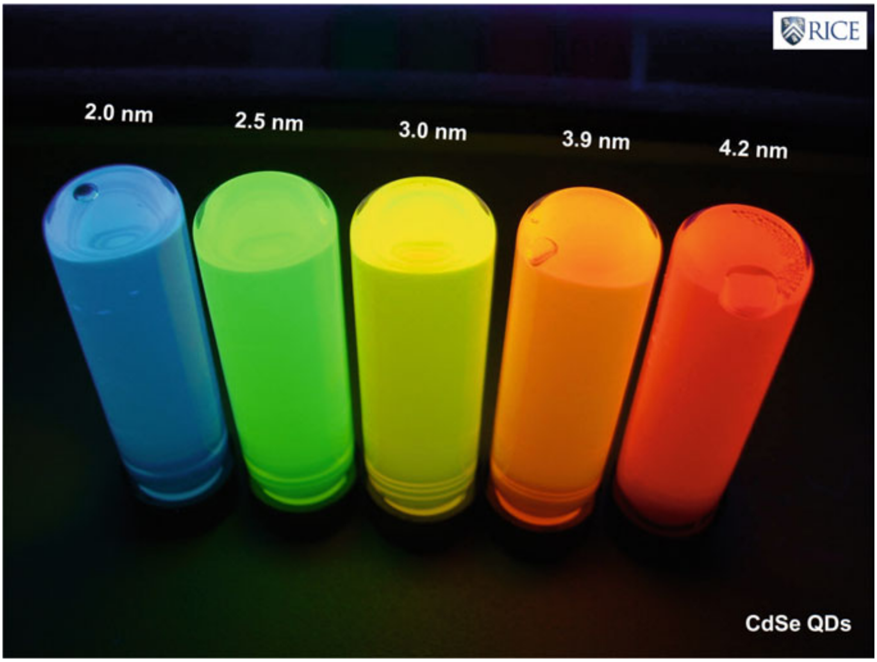


**Fig. 7.18** Cadmium selenide (CdSe) quantum dots (Prof. Michael S. Wong (https://commons.wikimedia.org/wiki/File:CdSe_Quantum_Dots.jpg), "CdSe Quantum Dots", https://creativecommons.org/licenses/by-sa/3.0/legalcode)

Carbon nanotubes are long, extremely thin cylinders of carbon that can be thought of as a single layer of carbon atom rolled into a cylinder. The diameter of a nanotube is on the order of only a few nanometers; however, they can be up to several millimeters in length. An artist's rendering of a nanotube's hexagonal structure is shown in Fig. 7.19.

Considering their size, nanotubes have amazing physical properties. When produced from pure carbon, they are extremely strong (about 100 times stronger than steel!), and exhibit diverse electrical and thermal conductivity properties. Depending upon its diameter, a pure carbon nanotube can conduct an electrical current as if it were a metal or it can act as a semiconductor.

Carbon nanotubes are seen as a replacement for silicon in the production of highly efficient semiconductors. This application has been demonstrated by scientists at Japan's Tohoku University who have developed a light source using carbon nanotubes whose power consumption is about 100 times lower than that of a conventional LED.

Unlike other semiconductor-based light sources that are assembled by forming p-n junctions, the single-nanotube device doesn't require doping or fabrication. The nanotube serves as a semiconducting channel, capable of carrying both electrons

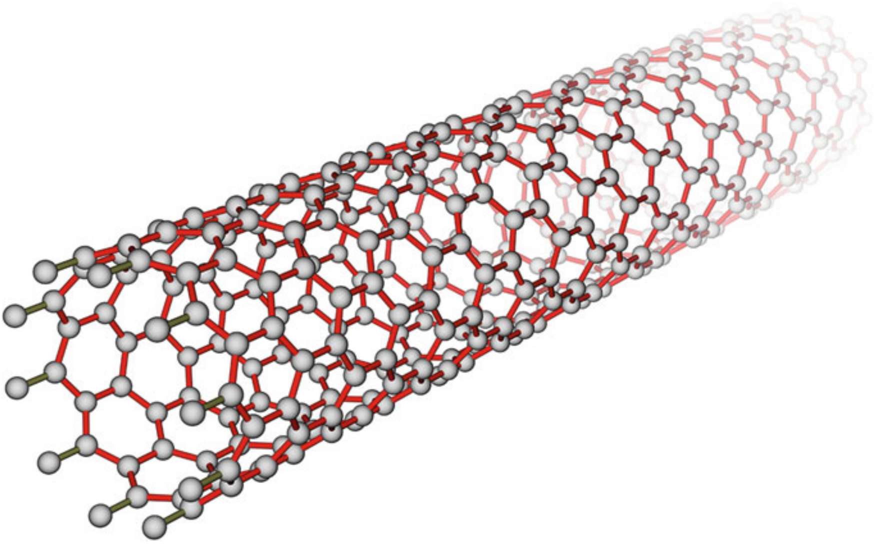


**Fig. 7.19** A carbon nanotube can function as a metal or semiconductor (Leonid Andronov/Shutterstock.com)

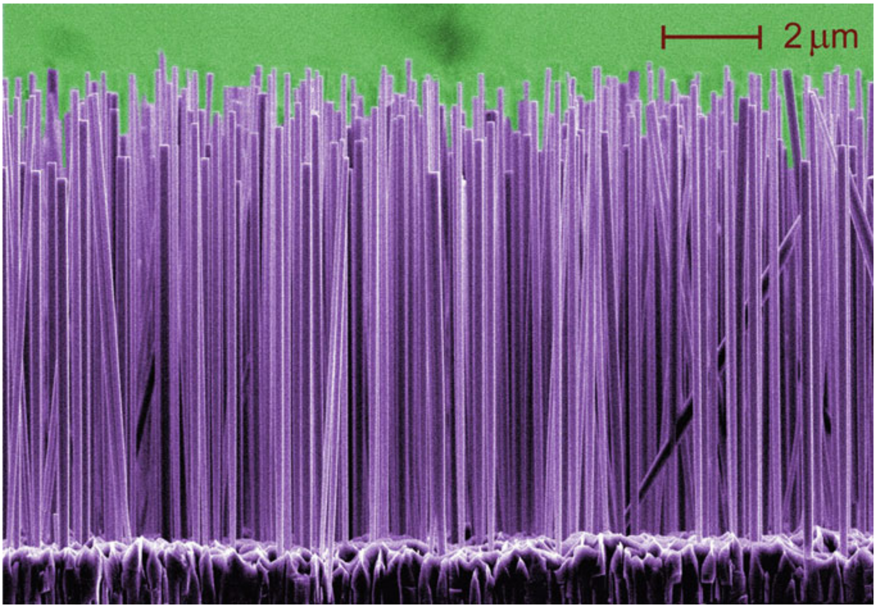


**Fig. 7.20** Semiconductor nanowires that emit ultraviolet light are part of a project to make prototype nanolasers and other devices (By National Institute of Standards and Technology (Nanowires that Emit UV Light) [Public domain], via Wikimedia Commons)

and holes. When these two charge types are introduced into the nanotube, they combine and, in the process, produce light.

What appear to be dense-packed thin rods in the photograph in Fig. 7.20 are actually nanowires, wires with diameters on the order of a few nanometers. Nanowires can function as insulators, semiconductors, or metals depending on the material from which they are made. The photograph is of a color-enhanced electron micrograph of gallium nitride wires growing on a silicon substrate. Demonstrated to be capable of producing infrared and ultraviolet light, these highly efficient devices are envisioned to have applications in telecommunications and optical computing.

## 7.12 Illumination

*Radiometry* is the measurement of the energy content of electromagnetic radiation, including visible light, infrared and ultraviolet radiation, radio waves, microwaves, X-rays, and so on. The unit of energy in the standard international (SI) system of units is the *joule*, which is the energy required to lift 1 kg of mass a distance of 10.2 cm.

The *radiant flux* is the amount of radiation that leaves an object or is received by an object each second, and it is measured in *watts*; 1 W is equal to 1 joule per second. A 100-W light bulb radiates approximately 100 joules of energy per second. However, it might radiate only 5 W of this as visible light, the remainder being radiated mainly as infrared radiation or radiant heat. The *irradiance*, expressed in $W/m^2$, is a measure of the radiation intensity on a surface.

*Photometry* is concerned with measuring radiation energy and other quantities in the visible portion of the electromagnetic spectrum. It takes into account the sensitivity of the eye to different wavelengths of light. The *luminous flux*, expressed in *lumens*, scales the radiant flux up or down at each wavelength, according to the sensitivity of the eye to that wavelength. The *illuminance* expresses the eye-weighted intensity of visible light striking a surface in $lumens/m^2$ (lux) (In English units, the illuminance is expressed in $lumens/ft^2$ [foot-candles]. One foot-candle is equal to 0.0929 lx.) Photographers use illuminance meters, also called *photometers*, to determine the proper exposure time. Photometers are generally fitted with a filter to tailor the spectral response to match that of the CIE (Commission Internationale).

## 7.13 Summary

A blackbody is an ideal absorber and emitter of light to which other light sources can be compared. The total radiation of a blackbody is proportional to the fourth power of its absolute temperature, and the wavelength of its maximum radiation is inversely proportional to the absolute temperature. The color temperature of a light source is the temperature of the blackbody with the closest spectral distribution. The spectral sensitivity of the eye is well matched to the spectral distribution of sunlight.

An ordinary incandescent lamp is not a very efficient light source; since its radiation peak lies in the infrared, it radiates more heat than light. Fluorescent tubes, which convert radiation from a mercury discharge tube to visible light by means of a phosphor coating on the inside of the tube, are much more efficient light sources.

The Bohr model of the atom, inspired in part by earlier work of Balmer and Rutherford, explains spectral lines as being due to transitions between energy levels in the atom. The Bohr model is quite successful in explaining the radiation from hydrogen atoms, although more sophisticated models are required for atoms and molecules with more than one electron. Lasers, which use stimulated emission from atoms to create intense, monochromatic, coherent light, have found their way into many commercial and consumer products.

Light-emitting diodes (LEDs) are very efficient sources of light and are finding many new applications, such as instrument displays, automobile tail lights, and large outdoor displays ("electronic billboards"). Blue LEDs, which were developed in the early 1990s, have many applications including being the central component in white LEDs.

Gas-filled arc lamps, especially sodium and mercury, are also very high-efficient light sources, and xenon-filled strobe lamps are useful in photography and as exciters for pulsed lasers.

Nanotechnology is involved with the design, production, and application of devices at the nanometer scale. Optical devices at the nanoscale include light-producing nanocrystal quantum dots, carbon nanotubes, and carbon nanowires.

Radiometry is the measurementof the energy content of electromagnetic radiation, including visible light. The luminous flux, expressed in lumens, scales the radiant flux up or down at each wavelength, according to the sensitivity of the eye to that wavelength.

## ◆ Review Questions

1. What is a blackbody? Sketch a typical blackbody spectral distribution curve.
2. Describe how you would construct a simple device that approximates a blackbody.
3. What is the approximate temperature of something that is "white hot"?
4. What is meant by the term *color temperature*?
5. When an electric range is turned on, it becomes red; the filament in an incandescent light bulb appears white. Which is hotter? Use Wien's law to explain your answer.
6. An incandescent lamp filament having a temperature of 2700 K radiates its maximum spectral power at a wavelength of 1070 nm (compare Fig. 7.1). Is radiation of this wavelength visible to the eye?
7. Given a choice of light bulbs having color temperatures of 3000, 4000, 5000, and 6000 K, which one would you choose to provide illumination most like sunlight?

8. When you look at most people's eye pupils, they appear black. Use your knowledge of blackbody radiation to suggest an explanation for this phenomenon.
9. Why are different types of color film used for indoor and outdoor photography?
10. Discuss the Bohr model of the atom. What are some successes of this model? What are its shortcomings?
11. What is the difference between line spectra and continuous spectra?
12. What type of light sources produce continuous spectra? Line spectra? Both?
13. What is fluorescence? What is phosphorescence?
14. If light from different gas-discharge tubes is viewed through a diffraction grating, what differences will be apparent?
15. Why are sodium vapor lamps generally not used for indoor lighting?
16. What is the difference between photometry and radiometry?
17. Provide a detailed description of a ruby laser's light production process.
18. What are some differences between laser light and light from a fluorescent lamp?
19. What is the relationship between the size of a quantum dot and the light it emits?

## ▼ Questions for Thought and Discussion

1. Window glass is transparent to visible light but opaque to most infrared radiation. Use this information and your knowledge of blackbody radiation to explain why the interior of a greenhouse becomes hot.
2. If you were in charge of selecting the lighting system for an art gallery, what characteristics would you want your light sources to possess?
3. List some uses of atomic and molecular spectra.
4. Discuss the advantage (if any) of a 100-W red heat lamp over a 100-W white heat lamp.
5. Describe a situation where the color of an object appears to change as the light used to illuminate the object is changed.

## ■ Exercises

1. State the Stefan-Boltzmann law and Wien's law in words and as formulas.
2. The peak in the spectral distribution curve for radiation from "radio stars" occurs in the microwave region of the electromagnetic spectrum ($\sim 10^{-2}$ m). Assuming that this radiation originates mainly from thermal emission, determine the approximate surface temperature of such stars.
3. What is the peak wavelength radiated by a blackbody at room temperature ($\sim 300$ K)? Is this wavelength visible to the eye?
4. **a.** Calculate the total power radiated per unit area by an incandescent lamp filament at 2700 K.

   **b.** Determine the surface area of the filament if the lamp radiates 100 W (mostly as infrared radiation).

5. Use Balmer's formula to calculate the wavelengths of the first three spectral lines of the Balmer series.
6. Compute the energy of a photon of red light ($\lambda = 650$ nm) and a photon of ultraviolet light ($\lambda = 400$ nm). Why is ultraviolet light potentially more harmful to the skin than red light?
7. When a food containing sodium spills into an open flame on a stove, a characteristic orange color is produced. Determine the difference in energy between the two levels in a sodium atom responsible for the emission of this light (Use 589.6 nm as a representative wavelength for this light.).

## ● Experiments for Home, Laboratory, and Classroom Demonstration

### Home and Classroom Demonstration

1. **Dissecting fluorescent light**. The inside of a fluorescent light tube is coated with a variety of phosphors that produce different colors. The combination of these colors is perceived as white light. Each phosphor absorbs ultraviolet light and emits visible light, but they do it at different rates, so the intensity of different colors varies slightly. To see the component colors, examine fluorescent light reflected from the blades of an electric fan as you turn the fan on and off so that its speed changes. When the blade passage rate of the fan coincides with the flash rate of the fluorescent lamp (120 times per second) , colors can be seen (the effect is subtle, so look carefully). Similarly, a vibrating guitar string illuminated with fluorescent light may reflect colors.
2. **Compact disc diffraction grating**. The tracks of pits on a compact disc, by acting as a grating, can produce colorful interference effects (see Sect. 5.9). In fact, a CD can be used to observe the spectra of everyday light sources, such as incandescent bulbs, fluorescent tubes, compact fluorescent bulbs, LEDs, and even sodium and mercury street lamps. To observe this, hold a CD as close as possible to the source and note the interference colors of the reflected light. Which sources show a continuous spectrum? Line spectra? If you have a laser pointer, bounce the light off the CD onto a white wall or screen. Do you see interference colors? What does this suggest about the laser light?
3. **Fluorescent plastics**. Fluorescent dyes are sometimes added to clear plastic objects to give them a vibrant "neon" appearance. Examples include plastic cups and clipboards. Examine a fluorescent plastic object in light from a variety of sources. Is the fluorescence more pronounced in a particular type of light? If so, why does this occur? The fluorescent clipboards have another interesting feature: They act as "light pipes." Due to total internal reflection, a portion of the light that enters the clipboard is piped to the edges of the board, making them appear bright. A similar effect may be noticed around the rim of a plastic cup.
4. **Invisible graffiti**. Many liquid laundry detergents contain fluorescent dyes. These dyes serve as whitening agents that are intended to make yellowed clothing look whiter and brighter. When illuminated with ultraviolet light, these liquids fluoresce, giving off a cool blue light. By mixing roughly equal parts of

liquid detergent and water, you can produce a “paint” that is invisible in white light but fluoresces dramatically under black (ultraviolet) light. You may write a message or produce some art work with your finger tip or brush on a tabletop, wall, or sheet of paper. Once it has dried, your painting will be invisible most of the time but readily visible in ultraviolet light.

5. **Detecting ultraviolet light**. The human eye does not detect ultraviolet radiation. However, certain dyes that change color when exposed to ultraviolet can be used to detect UV radiation. The dyes are not affected by visible light and remain white until exposed to ultraviolet. Inexpensive ultraviolet detecting beads, nail polish, and T-shirts are available from several suppliers of science education materials. You can use the dyes to look for UV output from TV screens, computer monitors, incandescent and fluorescent light sources, and camera flashlamps. Observe the change in dye color when taken outdoors. Do the dyes have to be in direct sunlight for a color change to occur? (What does this imply about getting a suntan or sunburn on a cloudy day?) Use the UV-sensitive dyes to determine whether sunglasses offer UV protection. Does the window glass on your car transmit UV radiation? Use the dyes to test suntan lotions for UV protection.
6. **Blacker than black**. Find the blackest sheet of paper you can and cut out a four-inch square. With a sharp pencil make a tiny hole in the center of the square and place it on top of a coffee cup that is all white inside. Observe that the hole clearly is blacker than the paper! Light entering the tiny hole can exit only after undergoing so many reflections inside the cup that almost no radiation escapes even though the surface of the cup is quite a good reflector.
7. **Whiter than white**. Compare a white sheet of paper with paper that has been coated with invisible paint (laundry detergent and water), as in Experiment 4. Make the comparison in different types of light. What makes the coated paper appear whiter than white?
8. **Spectrum as a function of temperature**. Remove the shade from a dimmer-controlled lamp (preferably with a clear incandescent light bulb). View the lamp filament through a diffraction grating as you slowly increase the brightness of the bulb. What do you observe? Which colors are visible through the grating when the bulb is glowing dull red? Bright red? Which colors do you see when the filament is white hot? How do you explain these observations?
9. **Spectra of common sources**. Use a diffraction grating to observe the spectra of light sources you encounter daily. Sources to consider include incandescent bulbs, fluorescent lamps, sodium street lamps, neon signs, and so on. **Do not look directly at the Sun!** Viewing a street scene at night may reveal a variety of spectra. Which light sources appear to have continuous spectra? Which have discrete spectral lines?
10. **Photography through a grating**. Take color pictures through a diffraction grating and notice how spectra of various light sources appear.

11. **Making infrared radiation visible**. The unaided human eye is sensitive to a very limited range of the electromagnetic spectrum. However, it is possible to detect radiation that lies beyond our normal vision by using a digital camera or smartphone. Use either device to view the infrared LED at the end of a remote control unit while depressing any button on the remote. What do you see?

### Laboratory (See Appendix J)

7.1 Spectrum Analysis with a Diffraction Grating

### Glossary of Terms

***absolute temperature*** Temperature on a scale that begins at absolute zero and measures temperature in kelvins (K). Celsius temperature is converted to absolute temperature by adding 273 K.

***blackbody*** An ideal absorber and emitter of light.

***Bohr model*** Model of the atom in which electrons move in stable orbits around the nucleus.

***coherent light*** Light in which all photons have the same phase and wavelength (such as laser light) .

***color temperature*** The temperature of the blackbody with the closest spectral energy distribution to a given light source.

***efficacy*** Measure of the power efficiency (lumens per watt) of a light source.

***electron volt*** Unit of energy equal to the energy that an electron would acquire traveling from the negative to positive terminal of a 1-volt battery.

***emissivity*** Ratio of the radiant energy from a nonideal surface to that of a blackbody at the same temperature.

***fluorescence*** Absorption of light and subsequent reemission at a longer wavelength.

***illuminance*** Measure of the light intensity striking a surface in lumens/m$^2$ (lux) .

***irradiance*** Measure of the radiation intensity on a surface.

***joule*** Unit of energy in SI system.

***kelvin*** One degree on the absolute temperature scale.

***laser*** Coherent monochromatic light source that utilizes the stimulated emission of radiation.

***light-emitting diode (LED)*** A very efficient semiconductor light source used especially in outdoor displays, radios, TVs, home appliances, and automobile tail lights.

***lumen*** Unit for measuring luminous flux or output of light sources.

***luminescence*** Absorption of energy and emission of light; includes fluorescence and phosphorescence.

***luminous flux*** Radiant flux scaled according to the sensitivity of the eye at each wavelength.

***nanoscale light source*** Light-emitting device having dimensions on the order of 10 to 100 nm.

***phosphorescence*** Absorption of light and delayed emission at longer wavelength.

***photometer*** Illuminance meter used by photographers, illumination engineers, and others.

***photometry*** Measurement of energy content in the visible portion of the electromagnetic spectrum.

***photon*** A particle of light having an energy $hc/\lambda$.

***population inversion*** A condition in which more atoms are in the higher energy state than in the lower one (a nonequilibrium condition).

***quantum dot*** A nanoscale semiconductor that emits light in wavelengths that are determined by its size.

***radiometry*** Measurement of radiant energy of electromagnetic radiation.

***stimulated emission of radiation*** A photon triggers an atom to emit a photon of the same wavelength (as in a laser).

***watt*** Unit of power in SI system.

## Further Reading

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