CHAPTER 21
The Quantum Nature of Light

Figure 21.1 In Lewis Carroll's classic text Alice's Adventures in Wonderland, Alice follows a rabbit down a hole into a land of curiosity. While many of her interactions in Wonderland are of surprising consequence, they follow a certain inherent logic. (credit: modification of work by John Tenniel, Wikimedia Commons)

Chapter Outline

INTRODUCTION At first glance, the quantum nature of light can be a strange and bewildering concept. Between light acting as discrete chunks, massless particles providing momenta, and fundamental particles behaving like waves, it may often seem like something out of Alice in Wonderland.

For many, the study of this branch of physics can be as enthralling as Lewis Carroll's classic novel. Recalling the works of legendary characters and brilliant scientists such as Einstein, Planck, and Compton, the study of light's quantum nature will provide you an interesting tale of how a clever interpretation of some small details led to the most important discoveries of the past 150 years. From the electronics revolution of the twentieth century to our future progress in solar energy and space exploration, the quantum nature of light should yield a rabbit hole of curious consequence, within which lie some of the most fascinating truths of our time.

21.1 Planck and Quantum Nature of Light

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe blackbody radiation
- Define quantum states and their relationship to modern physics
- Calculate the quantum energy of lights
- Explain how photon energies vary across divisions of the electromagnetic spectrum

Section Key Terms

blackbody	quantized	quantum	ultraviolet catastrophe

Blackbodies

Our first story of curious significance begins with a T-shirt. You are likely aware that wearing a tight black T-shirt outside on a hot day provides a significantly less comfortable experience than wearing a white shirt. Black shirts, as well as all other black objects, will absorb and re-emit a significantly greater amount of radiation from the sun. This shirt is a good approximation of what is called a **blackbody**.

A perfect blackbody is one that absorbs and re-emits all radiated energy that is incident upon it. Imagine wearing a tight shirt that did this! This phenomenon is often modeled with quite a different scenario. Imagine carving a small hole in an oven that can be heated to very high temperatures. As the temperature of this container gets hotter and hotter, the radiation out of this dark hole would increase as well, re-emitting all energy provided it by the increased temperature. The hole may even begin to glow in different colors as the temperature is increased. Like a burner on your stove, the hole would glow red, then orange, then blue, as the temperature is increased. In time, the hole would continue to glow but the light would be invisible to our eyes. This container is a good model of a perfect blackbody.

It is the analysis of blackbodies that led to one of the most consequential discoveries of the twentieth century. Take a moment to carefully examine Figure 21.2. What relationships exist? What trends can you see? The more time you spend interpreting this figure, the closer you will be to understanding quantum physics!

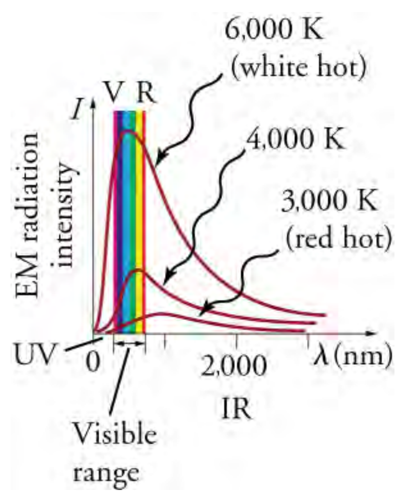

Figure 21.2 Graphs of blackbody radiation (from an ideal radiator) at three different radiator temperatures. The intensity or rate of radiation emission increases dramatically with temperature, and the peak of the spectrum shifts toward the visible and ultraviolet parts of the spectrum. The shape of the spectrum cannot be described with classical physics.

TIPS FOR SUCCESS

When encountering a new graph, it is best to try to interpret the graph before you read about it. Doing this will make the following text more meaningful and will help to remind yourself of some of the key concepts within the section.

Understanding Blackbody Graphs

Figure 21.2 is a plot of radiation intensity against radiated wavelength. In other words, it shows how the intensity of radiated light changes when a blackbody is heated to a particular temperature.

It may help to just follow the bottom-most red line labeled 3,000 K, red hot. The graph shows that when a blackbody acquires a temperature of 3,000 K, it radiates energy across the electromagnetic spectrum. However, the energy is most intensely emitted at a wavelength of approximately 1000 nm. This is in the infrared portion of the electromagnetic spectrum. While a body at this temperature would appear *red-hot* to our eyes, it would truly appear 'infrared-hot' if we were able to see the entire spectrum.

A few other important notes regarding Figure 21.2:

- As temperature increases, the total amount of energy radiated increases. This is shown by examining the area underneath each line.
- Regardless of temperature, all red lines on the graph undergo a consistent pattern. While electromagnetic radiation is emitted throughout the spectrum, the intensity of this radiation peaks at one particular wavelength.
- As the temperature changes, the wavelength of greatest radiation intensity changes. At 4,000 K, the radiation is most intense in the yellow-green portion of the spectrum. At 6,000 K, the blackbody would radiate *white hot,* due to intense radiation throughout the visible portion of the electromagnetic spectrum. Remember that white light is the emission of all visible colors simultaneously.
- As the temperature increases, the frequency of light providing the greatest intensity increases as well. Recall the equation $v = f\lambda$. Because the speed of light is constant, frequency and wavelength are inversely related. This is verified by the leftward movement of the three red lines as temperature is increased.

While in science it is important to categorize observations, theorizing as to why the observations exist is crucial to scientific advancement. Why doesn't a blackbody emit radiation evenly across all wavelengths? Why does the temperature of the body change the peak wavelength that is radiated? Why does an increase in temperature cause the peak wavelength emitted to decrease? It is questions like these that drove significant research at the turn of the twentieth century. And within the context of these questions, Max Planck discovered something of tremendous importance.

Planck's Revolution

The prevailing theory at the time of Max Planck's discovery was that intensity and frequency were related by the equation $I = \frac{2kT}{\lambda^2}$. This equation, derived from classical physics and using wave phenomena, infers that as wavelength increases, the intensity of energy provided will decrease with an inverse-squared relationship. This relationship is graphed in Figure 21.3 and shows a troubling trend. For starters, it should be apparent that the graph from this equation does not match the blackbody graphs found experimentally. Additionally, it shows that for an object of any temperature, there should be an infinite amount of energy quickly emitted in the shortest wavelengths. When theory and experimental results clash, it is important to re-evaluate both models. The disconnect between theory and reality was termed the **ultraviolet catastrophe**.

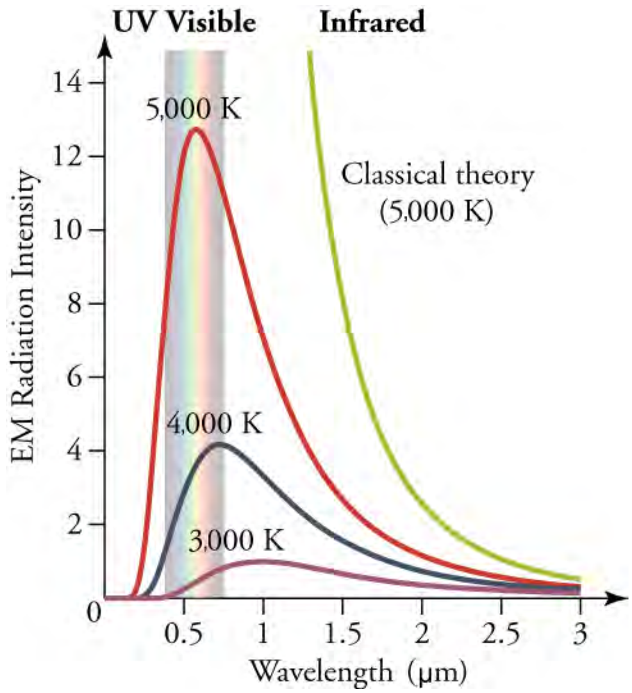

Figure 21.3 The graph above shows the true spectral measurements by a blackbody against those predicted by the classical theory at the time. The discord between the predicted classical theory line and the actual results is known as the ultraviolet catastrophe.

Due to concerns over the ultraviolet catastrophe, Max Planck began to question whether another factor impacted the relationship between intensity and wavelength. This factor, he posited, should affect the probability that short wavelength light would be emitted. Should this factor reduce the probability of short wavelength light, it would cause the radiance curve to not progress infinitely as in the classical theory, but would instead cause the curve to precipitate back downward as is shown in the 5,000 K, 4,000 K, and 3,000 K temperature lines of the graph in Figure 21.3. Planck noted that this factor, whatever it may be, must also be dependent on temperature, as the intensity decreases at lower and lower wavelengths as the temperature increases.

The determination of this *probability factor* was a groundbreaking discovery in physics, yielding insight not just into light but also into energy and matter itself. It would be the basis for Planck's 1918 Nobel Prize in Physics and would result in the transition of physics from classical to modern understanding. In an attempt to determine the cause of the *probability factor,* Max Planck constructed a new theory. This theory, which created the branch of physics called quantum mechanics, speculated that the energy radiated by the blackbody could exist only in specific numerical, or **quantum**, states. This theory is described by the equation $E = nhf$, where n is any nonnegative integer (0, 1, 2, 3, …) and h is Planck's constant, given by $h = 6.626 \times 10^{-34} \text{J} \cdot \text{s}$, and f is frequency.

Through this equation, Planck's probability factor can be more clearly understood. Each frequency of light provides a specific quantized amount of energy. Low frequency light, associated with longer wavelengths would provide a smaller amount of energy, while high frequency light, associated with shorter wavelengths, would provide a larger amount of energy. For specified temperatures with specific total energies, it makes sense that more low frequency light would be radiated than high frequency light. To a degree, the relationship is like pouring coins through a funnel. More of the smaller pennies would be able to pass through the funnel than the larger quarters. In other words, because the value of the coin is somewhat related to the size of the coin, the probability of a quarter passing through the funnel is reduced!

Furthermore, an increase in temperature would signify the presence of higher energy. As a result, the greater amount of total blackbody energy would allow for more of the high frequency, short wavelength, energies to be radiated. This permits the peak of the blackbody curve to drift leftward as the temperature increases, as it does from the 3,000 K to 4,000 K to 5,000 K values. Furthering our coin analogy, consider a wider funnel. This funnel would permit more quarters to pass through and allow for a reduction in concern about the *probability factor*.

In summary, it is the interplay between the predicted classical model and the quantum probability that creates the curve depicted in Figure 21.3. Just as quarters have a higher currency denomination than pennies, higher frequencies come with larger amounts of energy. However, just as the probability of a quarter passing through a fixed diameter funnel is reduced, so is the probability of a high frequency light existing in a fixed temperature object. As is often the case in physics, it is the balancing of multiple incredible ideas that finally allows for better understanding.

Quantization

It may be helpful at this point to further consider the idea of quantum states. Atoms, molecules, and fundamental electron and proton charges are all examples of physical entities that are **quantized**—that is, they appear only in certain discrete values and do not have every conceivable value. On the macroscopic scale, this is not a revolutionary concept. A standing wave on a string allows only particular harmonics described by integers. Going up and down a hill using discrete stair steps causes your potential energy to take on discrete values as you move from step to step. Furthermore, we cannot have a fraction of an atom, or part of an electron's charge, or 14.33 cents. Rather, everything is built of integral multiples of these substructures.

That said, to discover quantum states within a phenomenon that science had always considered continuous would certainly be surprising. When Max Planck was able to use quantization to correctly describe the experimentally known shape of the blackbody spectrum, it was the first indication that energy was quantized on a small scale as well. This discovery earned Planck the Nobel Prize in Physics in 1918 and was such a revolutionary departure from classical physics that Planck himself was reluctant to accept his own idea. The general acceptance of Planck's energy quantization was greatly enhanced by Einstein's explanation of the photoelectric effect (discussed in the next section), which took energy quantization a step further.

Figure 21.4 The German physicist Max Planck had a major influence on the early development of quantum mechanics, being the first to recognize that energy is sometimes quantized. Planck also made important contributions to special relativity and classical physics. (credit: Library of Congress, Prints and Photographs Division, Wikimedia Commons)

WORKED EXAMPLE

How Many Photons per Second Does a Typical Light Bulb Produce?

Assuming that 10 percent of a 100-W light bulb's energy output is in the visible range (typical for incandescent bulbs) with an average wavelength of 580 nm, calculate the number of visible photons emitted per second.

Strategy

The number of visible photons per second is directly related to the amount of energy emitted each second, also known as the bulb's power. By determining the bulb's power, the energy emitted each second can be found. Since the power is given in watts, which is joules per second, the energy will be in joules. By comparing this to the amount of energy associated with each photon, the number of photons emitted each second can be determined.

Solution

The power in visible light production is 10.0 percent of 100 W, or 10.0 J/s. The energy of the average visible photon is found by substituting the given average wavelength into the formula

$$E = nhf = \frac{nhc}{\lambda}.$$

By rearranging the above formula to determine energy per photon, this produces

$$E/n = \frac{(6.63 \times 10^{-34}\,\mathrm{J \cdot s})(3.00 \times 10^{8}\,\mathrm{m/s})}{580 \times 10^{-9}\,\mathrm{m}} = 3.43 \times 10^{-19}\,\mathrm{J/photon}. \quad (21.1)$$

The number of visible photons per second is thus

$$\frac{\text{photons}}{\text{sec}} = \frac{10.0\text{J/s}}{3.43 \times 10^{-19}\text{J/photon}} = 2.92 \times 10^{19}\text{photons/s.}$$

Discussion

This incredible number of photons per second is verification that individual photons are insignificant in ordinary human experience. However, it is also a verification of our everyday experience—on the macroscopic scale, photons are so small that quantization becomes essentially continuous.

WORKED EXAMPLE

How does Photon Energy Change with Various Portions of the EM Spectrum?

Refer to the Graphs of Blackbody Radiation shown in the first figure in this section. Compare the energy necessary to radiate one photon of infrared light and one photon of visible light.

Strategy

To determine the energy radiated, it is necessary to use the equation $E = nhf$. It is also necessary to find a representative frequency for infrared light and visible light.

Solution

According to the first figure in this section, one representative wavelength for infrared light is 2000 nm (2.000×10^{-6} m). The associated frequency of an infrared light is

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}\text{m/s}}{2.000 \times 10^{-6}\text{m}} = 1.50 \times 10^{14}\text{Hz.} \tag{21.2}$$

Using the equation $E = nhf$, the energy associated with one photon of representative infrared light is

$$\frac{E}{n} = h \cdot f = \left(6.63 \times 10^{-34}\text{J} \cdot \text{s}\right)\left(1.50 \times 10^{14}\text{Hz}\right) = 9.95 \times 10^{-20}\frac{\text{J}}{\text{photon}}. \tag{21.3}$$

The same process above can be used to determine the energy associated with one photon of representative visible light. According to the first figure in this section, one representative wavelength for visible light is 500 nm.

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}\text{m/s}}{5.00 \times 10^{-7}\text{m}} = 6.00 \times 10^{14}\text{Hz.} \tag{21.4}$$

$$\frac{E}{n} = h \cdot f = \left(6.63 \times 10^{-34}\text{J} \cdot \text{s}\right)\left(6.00 \times 10^{14}\text{Hz}\right) = 3.98 \times 10^{-19}\frac{\text{J}}{\text{photon}}. \tag{21.5}$$

Discussion

This example verifies that as the wavelength of light decreases, the quantum energy increases. This explains why a fire burning with a blue flame is considered more dangerous than a fire with a red flame. Each photon of short-wavelength blue light emitted carries a greater amount of energy than a long-wavelength red light. This example also helps explain the differences in the 3,000 K, 4,000 K, and 6,000 K lines shown in the first figure in this section. As the temperature is increased, more energy is available for a greater number of short-wavelength photons to be emitted.

Practice Problems

1. An AM radio station broadcasts at a frequency of 1,530 kHz . What is the energy in Joules of a photon emitted from this station?
   a. 10.1×10^{-26} J
   b. 1.01×10^{-28} J
   c. 1.01×10^{-29} J
   d. 1.01×10^{-27} J
2. A photon travels with energy of 1.0 eV. What type of EM radiation is this photon?
   a. visible radiation

b. microwave radiation
c. infrared radiation
d. ultraviolet radiation

Check Your Understanding

3. Do reflective or absorptive surfaces more closely model a perfect blackbody?
   a. reflective surfaces
   b. absorptive surfaces

4. A black T-shirt is a good model of a blackbody. However, it is not perfect. What prevents a black T-shirt from being considered a perfect blackbody?
   a. The T-shirt reflects some light.
   b. The T-shirt absorbs all incident light.
   c. The T-shirt re-emits all the incident light.
   d. The T-shirt does not reflect light.

5. What is the mathematical relationship linking the energy of a photon to its frequency?
   a. $E = \frac{hf}{n}$
   b. $E = \frac{nh}{f}$
   c. $E = \frac{nf}{h}$
   d. $E = nhf$

6. Why do we not notice quantization of photons in everyday experience?
   a. because the size of each photon is very large
   b. because the mass of each photon is so small
   c. because the energy provided by photons is very large
   d. because the energy provided by photons is very small

7. Two flames are observed on a stove. One is red while the other is blue. Which flame is hotter?
   a. The red flame is hotter because red light has lower frequency.
   b. The red flame is hotter because red light has higher frequency.
   c. The blue flame is hotter because blue light has lower frequency.
   d. The blue flame is hotter because blue light has higher frequency.

8. Your pupils dilate when visible light intensity is reduced. Does wearing sunglasses that lack UV blockers increase or decrease the UV hazard to your eyes? Explain.
   a. Increase, because more high-energy UV photons can enter the eye.
   b. Increase, because less high-energy UV photons can enter the eye.
   c. Decrease, because more high-energy UV photons can enter the eye.
   d. Decrease, because less high-energy UV photons can enter the eye.

9. The temperature of a blackbody radiator is increased. What will happen to the most intense wavelength of light emitted as this increase occurs?
   a. The wavelength of the most intense radiation will vary randomly.
   b. The wavelength of the most intense radiation will increase.
   c. The wavelength of the most intense radiation will remain unchanged.
   d. The wavelength of the most intense radiation will decrease.

21.2 Einstein and the Photoelectric Effect

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe Einstein's explanation of the photoelectric effect
- Describe how the photoelectric effect could not be explained by classical physics
- Calculate the energy of a photoelectron under given conditions
- Describe use of the photoelectric effect in biological applications, photoelectric devices and movie soundtracks

Section Key Terms

electric eye	photoelectric effect	photoelectron	photon

The Photoelectric Effect

Teacher Support
[EL]Ask the students what they think the term *photoelectric* means. How does the term relate to its definition?

When light strikes certain materials, it can eject electrons from them. This is called the **photoelectric effect**, meaning that light (*photo*) produces electricity. One common use of the photoelectric effect is in light meters, such as those that adjust the automatic iris in various types of cameras. Another use is in solar cells, as you probably have in your calculator or have seen on a rooftop or a roadside sign. These make use of the photoelectric effect to convert light into electricity for running different devices.

Figure 21.5 The photoelectric effect can be observed by allowing light to fall on the metal plate in this evacuated tube. Electrons ejected by the light are collected on the collector wire and measured as a current. A retarding voltage between the collector wire and plate can then be adjusted so as to determine the energy of the ejected electrons. (credit: P. P. Urone)

Revolutionary Properties of the Photoelectric Effect

When Max Planck theorized that energy was quantized in a blackbody radiator, it is unlikely that he would have recognized just how revolutionary his idea was. Using tools similar to the light meter in Figure 21.5, it would take a scientist of Albert Einstein's stature to fully discover the implications of Max Planck's radical concept.

Through careful observations of the photoelectric effect, Albert Einstein realized that there were several characteristics that could be explained only if *EM radiation is itself quantized*. While these characteristics will be explained a bit later in this section, you can already begin to appreciate why Einstein's idea is very important. It means that the apparently continuous stream of energy in an EM wave is actually not a continuous stream at all. In fact, the EM wave itself is actually composed of tiny quantum packets of energy called **photons**.

In equation form, Einstein found the energy of a photon or **photoelectron** to be

$$E = h\mathrm{f},$$

where E is the energy of a photon of frequency f and h is Planck's constant. A beam from a flashlight, which to this point had been considered a wave, instead could now be viewed as a series of photons, each providing a specific amount of energy see Figure 21.6. Furthermore, the amount of energy within each individual photon is based upon its individual frequency, as