12

The Quantum Idea

Anyone who has not been shocked by quantum physics has not understood it.

Niels Bohr

Chapters 12 and 13 present science's most accurate and complete description of the physical world: quantum physics—often called quantum mechanics because it replaces Newtonian mechanics. As you will see, however, quantum physics is anything but "mechanical." Originating during 1900–1930 and still under active development, quantum physics is the set of ideas and experiments that scientists use to study the microscopic world. Its central notion is that, at the microscopic level, some physical quantities such as energy are discontinuous or "quantized," rather than continuous. Using language from our computerized culture, the microscopic world is "digital" rather than "analog." Quantization represents a radical break with Newtonian physics, leading to fundamental new developments in physics and its philosophical impacts.

Section 12.1 sets the stage with a broad description of the general nature, aims, and cultural role of quantum physics. Section 12.2 takes a closer look at an old experiment, Young's double-slit interference experiment (Chapter 9), to introduce the quantization of the electromagnetic field and the quantum theory of radiation. Section 12.3 discusses aspects of the quantum theory of light, especially "uncertainty" and "nonlocality." Section 12.4 presents another specific experiment, the double-slit experiment with electrons, which requires us to introduce a second kind of quantized field called a matter field, leading to a new way of looking at matter. Section 12.5 discusses the meaning of this theory. Section 12.6 looks more carefully at quantum uncertainty for both matter and radiation.

12.1 THE QUANTUM REVOLUTION

The quantum idea slipped nearly unnoticed into physics in 1900. Although nobody realized it at the time, it was the dawn of the post-Newtonian era. It's remarkable that a second revolutionary but entirely different post-Newtonian idea, Einstein's relativity, was announced only five years later. The special theory of relativity was fairly complete when first announced in 1905, and its revolutionary nature was already clear.

Quantum physics describes the nature and behavior of matter and radiation, particularly at the microscopic level. It developed slowly, but its impact ultimately went far beyond special relativity's impact, and today it is far from being a closed book. Although the theory's main principles had appeared by 1930, and despite the theory's wide testing and application, it's still not clear what the theory really means.

Because it predicts such a wide variety of phenomena so accurately, quantum physics is probably history's most successful scientific theory. Its practical impact extends to everything that depends on the details of the microscopic world: electronic devices such as transistors, silicon chips, and integrated circuits, and so all the information and communication technologies such as television and computers; most of modern chemistry and some of biology; lasers; our understanding of different types of matter ranging from superconductors to neutron stars; and nuclear physics, nuclear power, and nuclear weapons. Central to the entire high-tech world is an elusive and highly non-Newtonian particle: the electron.

Perhaps more significant but certainly less appreciated is the philosophical impact of quantum physics. Quantum physics represents a more radical undoing of the Newtonian worldview than does relativity. I have emphasized throughout this book that a scientific worldview is by no means a trivial academic matter. Newtonian views are woven subtly into the entire fabric of Western civilization. The mechanical worldview has dominated Western culture for centuries and has been assimilated so deeply that it's accepted without even realizing that it is a worldview.

You'll discover that contrary to the Newtonian worldview, quantum physics implies that randomness, or chance, is built into nature at the microscopic level. Nature doesn't know what she will do next! No longer can the universe be a predictable machine in which the future is "hard-wired" into the present. Quantum physics also implies, contrary to the Newtonian worldview, that nature is deeply interconnected, that such parts of nature as electrons, protons, and light waves cannot be separated from their surroundings without fundamentally altering their character. No longer can the universe be viewed as a machine at all, even an unpredictable one, for the most basic feature of the machine metaphor has always been its separable parts.

Quantum physics holds that changes in nature occur discontinuously, rather than continuously as Newtonian physics predicts. Here's an example, at the macroscopic level: Suppose you are swinging in a child's swing, and that you then stop pumping and let the swing die down to smaller and smaller oscillations. The process of dying down is continuous, gradual, and this continuous process is exactly what Newtonian physics predicts. It would be surprising if, without pumping, you maintained an amplitude (width of oscillation) of say 4 m for several oscillations and then instantaneously "jumped" to an amplitude of only 2 m, where you remained for several more oscillations without pumping, after which your swing suddenly stopped. Such a discontinuous process is not predicted by Newtonian physics, and it is not observed in the macroscopic world around us. But such discontinuous processes are the norm at the microscopic level. For example, nature requires an atom to vibrate at only certain precise energies, just as our imaginary swing could oscillate only at amplitudes of 4 m, 2 m, or 0 m. When an atom loses energy, it must do so in sudden jumps from one of its "allowed" energies to a lower one. In doing so, it must release an instantaneous burst or quantity or "quantum" of energy. This is a central new feature of the theory, and it is the origin of the term *quantum physics*. The energy of a microscopic system is "digital" rather than "analog."

The discovery of quantum mechanics in the mid-1920s was the most profound revolution in physical theory since the birth of modern physics in the seventeenth century.

Steven Weinberg, in *Dreams of a Final Theory*

12.2 RADIATION HAS WAVE AND PARTICLE PROPERTIES

Let's review what you learned about light in Chapter 9. The **double-slit experiment with light** (Section 9.3) showed that light is a wave. In this experiment, light from a single source passes through two narrow slits and then impacts a viewing screen.[1] **Figure 12.1** shows the experimental setup, and **Figure 12.2** shows the experimental result; both figures are reproduced from Chapter 9. Figure 12.2 is an interference pattern, caused by the wave-interference of light waves spreading out from the two slits. The brightly lit lines in Figure 12.2 are places where the waves from the two slits are exactly "in sync," where wave crests from one slit meet crests from the other, and valleys meet valleys, to create big light waves (bright light). The dark lines in Figure 12.2 are places where crests from one slit meet valleys from the other, so that the waves cancel. This alternating reinforcement and cancellation of light shows that light is a wave phenomenon.

This led to the question of what's doing the waving. The answer was that an **electromagnetic (EM) field** is waving, an invisible force field that is created by charged objects and exerts forces on other charged objects. An EM field is the effect that every electrically charged object has on the space around it. The field fills the space around electrically charged objects, the way that smoke fills a room, and exists everywhere that a charged object *would* feel an EM force *if* a charged object were present.

So much for our review. Now, I want to tell you something new about light: Light is "quantized," meaning that it comes in tiny parcels or bundles. First, I'll present the experimental evidence for this, and then I'll discuss what it means.

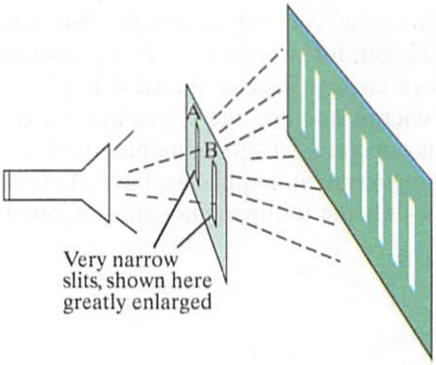

Figure 12.1
The double-slit experiment with light: the experimental setup and result.

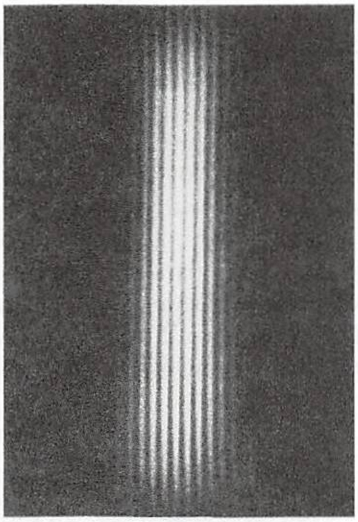

Figure 12.2
The double-slit experiment with light: experimental result.

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[1] As in Chapter 9, the light must be single-frequency and synchronized.

How do we know light is quantized? Imagine performing the double-slit experiment with extremely dim light. You might expect that the result would be just like Figure 12.2 only a lot dimmer. But that's not what happens. **Figure 12.3** shows what happens. In sufficiently dim light and with a short exposure time, *light impacts only at a few tiny points on the screen* [Figure 12.3(a)]! There is no trace of an interference pattern. If we extend the exposure time, we simply get more tiny impacts [Figure 12.3(b)] and still no trace of an interference pattern. With a longer exposure, we get more impacts [Figure 12.3(c)] and *we begin to see an interference pattern in the pattern of individual impacts*. Finally, with longer exposure times, we see that the interference pattern is a consequence of a huge number of individual tiny impacts [Figures 12.3(d) and 12.3(e)].

Figure 12.4 shows another example of the same phenomenon. Dim light and a short exposure time allow us to see individual particle-like impacts in an ordinary photograph. Figure 12.4 shows the photo emerging from these impacts.

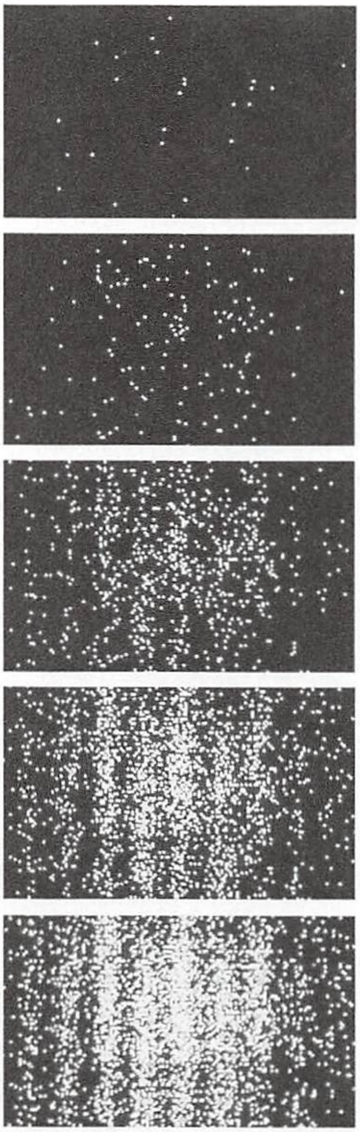

Figure 12.3
Close inspection using extremely dim light with time-lapse photography shows that the double-slit interference pattern of Figure 12.2 is formed by light striking at individual tiny points all over the screen. The five photos use exposures of about 0.2 s (when about 30 tiny impacts have occurred), 1 s (150 impacts), 5 s (800 impacts), 20 s (3000 impacts), and 2 minutes (20,000 impacts).

So the wave-interference pattern of Figure 12.2 builds up from tiny individual particle-like impacts of light on the screen. The process is analogous to the way painters of the pointillist school of impressionist painting made their pictures from tiny dots of color. It's natural to hypothesize, from the tiny impacts, that light is after all made of tiny particles. But we've already seen that light is an extended wave in a spread-out EM field that comes through both slits, so this hypothesis must be discarded. After all, every impact must occur preferentially within the brightly lit lines of the interference pattern. Such impacts cannot be made by particles traveling from the light source to the viewing screen, because a single individual tiny particle coming through one or the other slit cannot "know" that both slits are open and that it is therefore supposed to hit preferentially within the brightly lit lines.

So just what *is* coming through the double slits? How can we explain the particle-like impacts of light upon the screen? The answer has a long history, but rather than dwelling on the history I'll present the answer as it's understood today. The answer is that no particles come through the slits; instead, a spread-out EM field comes through both slits and interferes at the viewing screen, as described in Chapter 9. But EM fields are not quite what physicists had thought they were during the nineteenth century, not quite as they are described in Chapter 9. The new feature is that all EM fields are *quantized*.

Like the rest of modern physics, this new concept is simple, but odd. A **quantized EM field** is simply an EM field that, for reasons nobody understands, is not allowed to have just any old quantity of energy. Instead, the field is allowed to have just certain particular quantities of energy, and no others, just like the dying-down swing of Section 12.1. To make this concrete, let's imagine pure yellow light with a frequency of 5×10^{14} Hz. According to quantum physics, the EM field that carries this yellow light is allowed to have only the following amounts of energy:

$$\begin{gathered} 0\ \text{J} \\ 3.2 \times 10^{-19}\ \text{J}, \\ 6.4 \times 10^{-19}\ \text{J}, \\ 9.6 \times 10^{-19}\ \text{J}, \\ 12.8 \times 10^{-19}\ \text{J, and so on} \end{gathered}$$

You can probably see the pattern in these energies.[2] They are all simple multiples of 3.2×10^{-19} J. If we call this energy E, then the allowed energies are simply 0, E,

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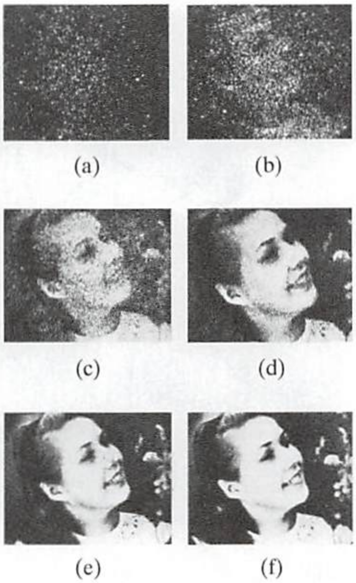
[2] I've simplified the numbers a little to make it easier to follow. The lowest possible energy level should not be 0 joules, but should instead be 1.6×10^{-19} J, with the other levels all raised accordingly (by 1.6×10^{-19} J). Electromagnetic fields are not allowed to have zero energy, but this fact will not be needed in Chapters 12 and 13.

$2E$, $3E$, $4E$, etc. No other energy is allowed for an EM field carrying pure yellow light. For instance, $1.3E$ or $15.71E$ are not allowed.

This example illustrates the general rule: The total energy of an EM field carrying radiation (it can be light, infrared, X-ray, etc.) must be a simple multiple of some single energy value. The German physicist Max Planck (**Figure 12.5**) made the first and most important contribution toward the eventual discovery of this general rule, and he found a formula for the allowed energy increment that we called E above. The following statement gives this formula and summarizes the general rule:


(a) (b)

(c) (d)

(e) (f)

Figure 12.4
A photo emerges from individual particle-like impacts. Each photo in the sequence has a longer exposure time. The approximate number of impacts in each photo is (a) 3×10^3, (b) 10^4, (c) 10^5, (d) 8×10^5, (e) 4×10^6, and (f) 3×10^7.

The Quantum Theory of Radiation

All EM fields are quantized. More specifically, when carrying radiation of frequency f, an EM field is allowed to have only the following particular values of total energy:

$$\text{total energy} = 0, hf, 2hf, 3hf, 4hf, \text{and so on}$$

That is, the field's energy must be a simple multiple of the energy increment $E = hf$, where f is the frequency (in hertz) of the radiation, and h is a universal constant called **Planck's constant:** $h = 6.6 \times 10^{-34}$ joules per hertz.[3]

So EM fields are "digitized": They can't have just any old energy, but must instead have either 0, 1, 2, 3, and so on, units of the basic energy increment hf. Instead of "digitized," physicists say that EM fields are "quantized" (restricted to particular *quantities* of energy). The smallest energy increment hf is referred to as one **quantum** (or quantity, or parcel) **of energy.** Here's an analogy: If water were quantized in 1 liter increments, then your bathtub would only be able to hold 0, 1, 2, 3, etc. liters of water. Just as the quantized water fills the tub from side to side, the quantized EM field fills the entire region between source of light and the viewing screen, but it can only have a total energy of 0, hf, $2hf$, $3hf$, etc.

Armed with the key concept of the quantized EM field, let's return to the double-slit experiment. When radiation strikes the screen, the EM field transfers some of its energy to the screen. But the field cannot transfer just any old amount of energy, because quantization implies that the field's energy can only change by a whole number of quanta. The tiny impacts seen in Figures 12.3 and 12.4 are these individual quanta of EM field energy. Let me explain.

Suppose the light is so extremely dim that the EM field can deposit, on average, only a single quantum of EM field energy on the screen during a span of, say, 5 seconds. The entire spread-out field comes through both slits and fills the region between source and screen, but during the full 5-second time span it can transfer at most one quantum of energy. This field must deposit its quantum of energy all at once, in a single instant, because the field cannot carry some fraction of one quantum—it must always contain either exactly one or exactly zero quanta. When the field deposits its quantum on the viewing screen, the *entire spread-out field* must instantaneously lose this much energy. In our bathtub analogy, the entire spread-out body of water would instantaneously reduce its volume by 1 liter.

This energy must be deposited at only a single point in the screen, because the screen is made of atoms and, as you will see in Chapter 13, these atoms are also quantized so that each one must either absorb or not absorb one whole quantum of energy. An atom can't absorb half of an energy quantum. For example, each of the

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[3] The unit "joules per hertz" (or, equivalently, joule-seconds) needs to be attached so that when multiplied by a frequency measured in hertz, the result will be an energy measured in joules.

Figure 12.5
Max Planck. His introduction of the formula $E = hf$ at a meeting of the German Physical Society on December 14, 1900, is usually taken as the birthdate of quantum physics. In Planck's theory, hf represented the smallest unit of exchange of thermal energy into radiant energy, that is, the smallest amount of energy that a microscopic particle could give up in order to produce light.

roughly 30 impacts seen in Figure 12.3a imparts one quantum of energy to an atom in the screen.

So that's the explanation of the particle-like behavior of light observed in Figures 12.3 and 12.4. Since the tiny impacts have energy, and occur at fairly precise points, they have a particle-like nature even though they aren't really particles but are simply increments of the energy of the entire spread-out EM field. These energy quanta that act like particles are called **photons** and are often thought of as microscopic particles of light even though "particles" might be a misleading word. Insofar as it's proper to think of them as particles, photons are parcels of EM field that travel at lightspeed and carry an energy (radiant energy, of course) hf, where f is the frequency of the oscillating EM field that carries the radiation. Since they travel at speed c, relativity tells us that photons must have a rest-mass of zero. Notice that the energy of a photon increases with its frequency—higher frequency implies higher energy, as expected from our general study of waves in Chapter 9.

It's important to remember that photon's aren't really particles. A photon is simply an energy increment of a spread-out EM field, analgous to a spread-out liter of water in a bathtub. Speaking precisely, there is no photon in the double-slit experiment until the instant an impact (on the screen, or on an airborne dust particle, or anywhere else) occurs. Don't imagine that individual particles move from the light source, through the slits, to the screen. If an impact occurs at some point, don't imagine that a photon was approaching that point just a moment earlier. A photon is nothing like, say, a tiny fast-moving pea. What really happens is that the entire space-filling EM field instantaneously loses one quantum of energy, and at the same instant that quantum of energy shows up at a particular point on the screen.

Figure 12.6 will help you visualize this. The figure shows the emission, transmission, and impact of one quantum of light, at five different instants during the double-slit experiment. At (a), a light source (a laser is used for this kind of experiment) has just emitted a small amount of light, or EM field, having hf joules of energy. At (b) this

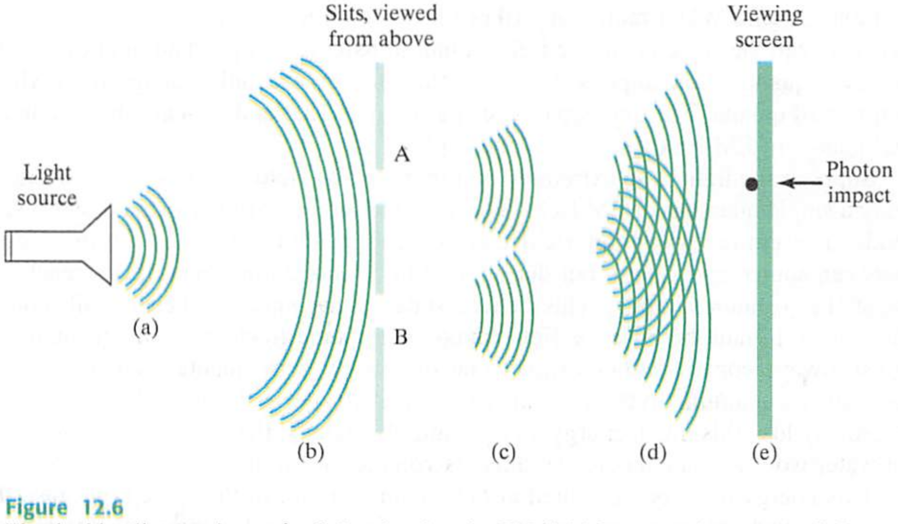

Figure 12.6
The double-slit experiment for light, showing the EM field for a very low energy light beam (a laser is used for this kind of experiment) at five different instants. The diagram shows the experiment as viewed from above, with the openings at A and B representing the *narrow* dimensions of the long narrow slits. The light beam is emitted at (a), approaches the slits at (b), emerges from the slits at (c), approaches the viewing screen at (d), and impacts the screen at a specific point at (e). The impact is referred to as "a photon." At the instant of impact, the entire spread-out field vanishes.

field is approaching the double slits. At (c) a portion of the field has passed through the slits (we don't show the remaining portion that reflects from the partition). At (d) the part that passed through the slits is approaching the viewing screen. At (e), a single impact—a photon—appears on the viewing screen. At the instant the photon appears, the entire spread-out field vanishes. Physicists often describe this as the "collapse" of the field. But as you'll see inChapter 13, the energy doesn't collapse to a true mathematical point having zero volume. Quantum physics demands that it be spread out over at least a certain minimal volume, a volume that is usually of atomic dimensions.

And these fifty years of conscious brooding have brought me no nearer to the question of "What are light quanta [photons]?" Nowadays every clod thinks he knows it, but he is mistaken.

Einstein, Near the End of His Life

CONCEPT CHECK 1 During the double-slit experiment with light, the region between the slits and the screen contains (a) electrons; (b) an EM field; (c) photons; (d) energy; (e) none of the above.

CONCEPT CHECK 2 Radiation made of yellow light, red light, and infrared radiation enters your camera and strikes the photographic film. Which of the three forms of radiation deposits the most energy per photon? (a) Yellow. (b) Red. (c) Infrared. (d) All three deposit the same energy per photon.

12.3 QUANTUM RADIATION

Scientists don't know why radiation is quantized, nor why Planck's constant has the particular value it does have. The small number h plays a role in quantum physics that's analogous to the role played by the large number c in relativity theory. The universe would be quite different if either h or c had a very different value.

Although the patterns made by light waves are due to large numbers of photon impacts, keep in mind that each photon "knows" about the entire spread-out field because each photon represents an increment of energy of the entire field. As we see in Figures 12.3 and 12.4, photons strike the screen fairly randomly, the first hitting in one place, the second in quite another place, and so forth. But there's a pattern in this randomness: Photons strike preferentially in the regions that will emerge as bright regions. The interference pattern is best described as a statistical pattern formed by large numbers of individual impacts. Judging from Figure 12.3, the precise impact point of any individual photon is unpredictable even though the emerging statistical pattern is predictable. This reminds us of dice throws, or insurance statistics, in which individual outcomes are unpredictable but the long-term statistics are predictable. As we'll see, this unpredictability or *uncertainty* within an overall pattern is characteristic of quantum physics.

Besides quantization and uncertainty, another key characteristic of quantum physics shows up in the double-slit experiment with light. One of this experiment's oddities is that at the precise instant a photon impacts the screen, the *entire space-filling EM field* suddenly shifts its energy downward by hf. How can, for example, the field in the vicinity of the two slits (Figure 12.1) suddenly lose energy precisely when the photon impact occurs on the screen? After all, it's some distance between the screen and the slits. In principle, the distance could be interstellar, or intergalactic. How can the field at the slits "know" instantaneously that the photon impact occurred, when relativity says that lightspeed is the limiting velocity? This puzzling situation relates to another general quantum phenomenon known as *nonlocality*. We'll study quantum uncertainty and nonlocality in more detail in Chapter 13.

One quantum is ridiculously small. For yellow light, it's only 3.2×10^{-19} J, as you can see by multiplying h and f together, with $f = 5 \times 10^{14}$ Hz for yellow light. For example, a typical lightbulb emits around 10 J of light every second. Assuming that all of this is yellow light, this amounts to more than 10^{19} (10 million trillion) photons every second, as you can see by dividing 10 J by 3.2×10^{-19} J. So one quantum of energy—a single photon—is really tiny. There's no way you could tell the difference between a bulb emitting 10^{19} photons every second and one emitting $10^{19} + 1$. This smallness of the typical quantum of energy is the reason scientists didn't notice quantization before 1900, and why you don't notice it in your everybody life.

CONCEPT CHECK 3 If Planck's constant were ten times larger than it is, quantum effects would be (a) easier to detect; (b) more difficult to detect; (c) neither of the above.

CONCEPT CHECK 4 Suppose the light source in Figure 12.1 is turned on so briefly that only a single quantum of energy passes through the double slits. When it arrives at the screen, this energy is deposited (a) all over the white bands in the drawing; (b) at one small point within the white bands; (c) at one small point, which could be anywhere on the screen; (d) at one small point on the screen, lying directly behind the slit through which the energy passed.

MAKING ESTIMATES On a clear day at noon, the sunlight striking each square meter of ground during each second carries 1000 J of energy. Estimate the number of photons striking 1 square meter during 1 second. Estimate the number of photons striking your hand during 1 second when you hold your hand open to bright sunlight.

12.4 MATTER HAS WAVE AND PARTICLE PROPERTIES

Sections 12.2 and 12.3 presented the quantum theory of radiation. Now let's turn to matter. Recall that radiation has no rest mass while matter has rest mass. The conventional view until 1900 was that radiation is made of waves in an EM field while matter is made of particles. But we've just learned that the EM field is quantized and this means that, even though radiation is a wave, it behaves in some respects like particles. What about matter?

Louis de Broglie (pronounced "de Broy"; **Figure 12.7**), a Ph.D. student at the University of Paris in 1923, felt that there should be a kind of symmetry, or balance, between radiation and matter. He thought it ugly that radiation should exhibit both wave and particle properties while matter behaved always as particles and suggested that matter should also have both wave and particle properties. This was weird. Despite the lack of experimental evidence at that time to support it, he found his weird idea so beautiful that he included it in his Ph.D. dissertation. De Broglie's Ph.D. committee didn't know what to make of it and sent the dissertation to Einstein for his opinion. Einstein was impressed and commented later that "it is a first feeble ray of light on this worst of our physics enigmas." The committee approved de Broglie's dissertation.

Waves of matter? How could an individual particle of matter such as one electron or one atom also be spatially extended waves? Nevertheless, de Broglie pursued his

Figure 12.7
Louis de Broglie. Feeling that there should be symmetry between matter and radiation, he predicted that matter should display the same wave-particle nature as radiation.

SOLUTION TO MAKING ESTIMATES Sunlight is made mainly of visible radiation with a frequency around 10^{15} Hz (Figure 9.27). The energy of one photon of this radiation is $(6.6 \times 10^{-34}) \times 10^{15}$, or 6.6×10^{-19} joules, or about 10^{-18} joules. To get 1000 joules of energy, we would then need $1000/10^{-18}$ or 10^{21} photons. I measure my hand to be roughly 9 cm × 18 cm, or about 200 cm^2. One square meter is 100 × 100 cm, or 10,000 cm^2, in area. So a hand is about 200/10,000 m^2, or 0.02 m^2, and the number of photons falling on a hand in 1 second is about 0.02×10^{21} or 2×10^{19} − 20,000,000,000,000,000,000 photons every second.

notion. Based on the symmetry that he envisioned between radiation and matter and working from Planck's formula $E = hf$ that connects the wave and particle aspects of radiation, he deduced a formula that predicted the wavelength of the wave associated with every material particle:

$$\text{wavelength of material particle} = \frac{\text{Planck's constant}}{\text{(particle's mass)(particle's velocity)}}$$

$$\lambda = h/mv$$

[The double-slit experiment is] a phenomenon which is impossible, absolutely impossible, to explain in any classical [Newtonian] way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery. We cannot make the mystery go away by explaining how it works.

Richard Feynman

This formula for these **matter waves** is analogous to the formula $E = hf$ for quanta of radiation. Both connect a particle property to a wave property. Planck's constant plays an important role in both formulas. The smallness of h implies that the wavelength λ of a material particle is very small, just as it implies that the energy E of a photon is very small. The smallness of λ means that the wave aspects of matter are difficult to detect, just as the smallness of E means that the particle aspects of radiation are difficult to detect. That's why we normally assume that matter is made of particles while radiation is made of waves.

If we apply de Broglie's formula to a typical macroscopic object like a 1 kg baseball rolling across the floor at 1 m/s, we get a wavelength of

$$\lambda = \frac{6.6 \times 10^{-34}\ \text{J/hz}}{(1\ \text{kg}) \times (1\ \text{m/s})} = 6.6 \times 10^{-34}\ \text{m}$$

The baseball's wavelength is about a billionth of a trillionth of a trillionth of a meter! This is far smaller than an atom and far too small to detect. It's no wonder that we have never noticed the wave aspects of baseballs.

The wavelengths of microscopic particles are much larger. Since mass shows up in the denominator of de Broglie's formula, the least massive material particles generally have the largest wavelengths. One of the least massive material particles is the electron. Electrons typically move at velocities of 10^7 or 10^8 m/s. At these velocities, de Broglie's formula predicts an electron's wavelength to be about 10^{-11} m. Although this is very small—about one-tenth the size of a typical atom—it's large enough to be detected in careful experiments.

Note that de Broglie's idea says *every* material particle has wave properties, not just electrons but also protons, gold nuclei, molecules, and so on. At this point, you might wonder what's going on here. How can a single material particle have a wavelength? An individual electron isn't even spread out in space, while a wave requires an extended medium, so how can one electron be a wave? Let's turn to experiment for guidance. We're going to look at two experiments that answer these questions and that confirm de Broglie's ideas, but in a completely unexpected way.

How do we know matter has wave properties? **Figure 12.8** shows the experimental arrangement for a double-slit experiment that's just like the double-slit experiment with light but that uses matter instead of light. I will assume that the experiment uses electrons, although any other material particles such as neutrons, protons, atoms, or molecules could be used and the results would be similar. The apparatus on the left side of the diagram represents an electron source plugged into a power supply. This source could be a metal wire, enclosed in a vacuum tube, heated electrically until electrons "boil off" of it; a similar electron source is central to TV picture tubes. We'll call this setup the **double-slit experiment with electrons.**

An "electron beam"—which you can think of for now as a fast-moving stream of billions of electrons per second—emerges from the electron source and spreads out as it travels toward the double slits.[4] When it gets to the two slits, marked A and B in the diagram, a portion of the beam goes through each slit and the rest of the beam is stopped by the partition. So a narrow electron beam emerges from each slit and travels on toward the viewing screen at the right. What will we see on the screen?

Figure 12.9 shows the experimental outcome. Although this outcome had been predicted since de Broglie's work in 1923, it's not easy to actually make the experimental setup because the slits must be extremely small, and so the experiment was not carried out until 1974, by physicist Claus Jonsson working in Germany. Just to reinforce what you're looking at here, **Figure 12.10** shows the experimental arrangement and the result.

The experimental outcome looks just like the outcome of the double-slit experiment with light, Figures 12.1 and 12.2! The pattern seen on the screen is a wave-interference pattern, showing that waves come through the two slits and interfere as they approach the viewing screen. This certainly confirms de Broglie's idea that electrons and other material particles have wave properties, and in fact the quantitative results agree entirely with de Broglie's formula for the wavelength of these waves.

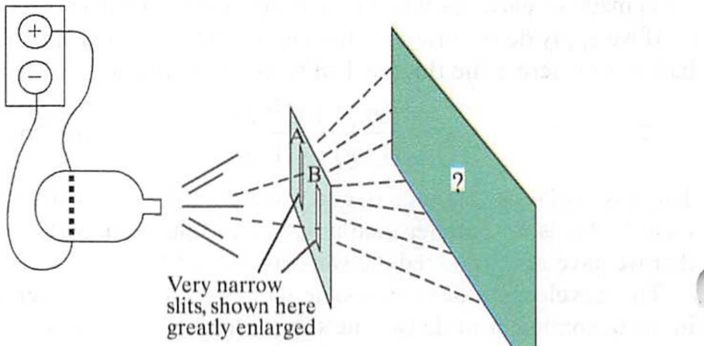

Figure 12.8
The double-slit experiment with electrons. The electron source is a thin tungsten metal wire that is heated electrically until electrons "boil" off it. A similar electron beam is central to TV picture tubes. In the experiment shown, what will we see on the screen?

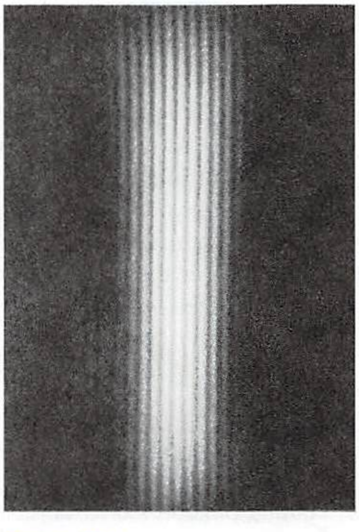

Figure 12.9
A wave-interference pattern made by electrons.

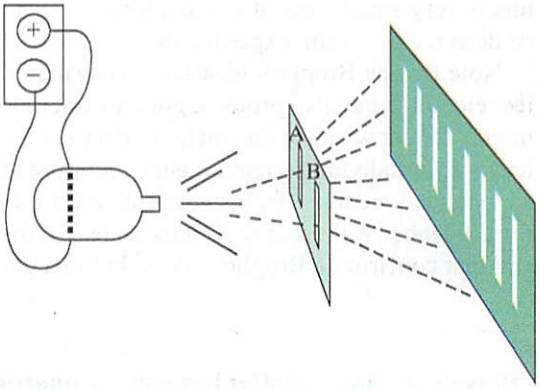

Figure 12.10
Outcome of the double-slit experiment with electrons. The electron beam creates the white bands shown on the screen. Compare this with the similar experiment using photons (in other words, light) instead of electrons, Figure 12.1.

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[4] The electrons must all have the same velocity, in other words the same wavelength.

But it's pretty puzzling. In Chapter 2, and probably as far back as grade school, you learned that matter is made of particles such as protons, neutrons, and electrons. Yet here is an experiment that fires electrons through a couple of slits, and it turns out that they must be waves! What's going on? To answer this, we again ask nature.

How do we know matter has particle properties? Now we're going to look at the double-slit experiment with electrons again, but using a much lower-intensity electron beam—you could call it a much "dimmer" beam (although we're talking here about electrons, not light). Physicists have predicted the outcome of this experiment since about 1930, but this difficult experiment wasn't actually performed until A. Tonomura and his Japanese colleagues performed it in 1989. With a dimmer electron beam, you might expect the experimental result to look like Figure 12.9, only a lot dimmer. But that's not what happens. **Figure 12.11** shows what does happen. With a sufficiently low-intensity electron beam and a short exposure time, *the electron beam impacts only at a few tiny points on the screen* [Figure 12.11(a)]! There is no trace of an interference pattern. If we extend the exposure time a little, we simply see more impact points and still no trace of an interference pattern [Figure 12.11(b)]. But with longer exposure times *we discover an interference pattern showing up in the pattern of individual impacts.* The interference pattern is a consequence of a huge number of individual tiny impacts.

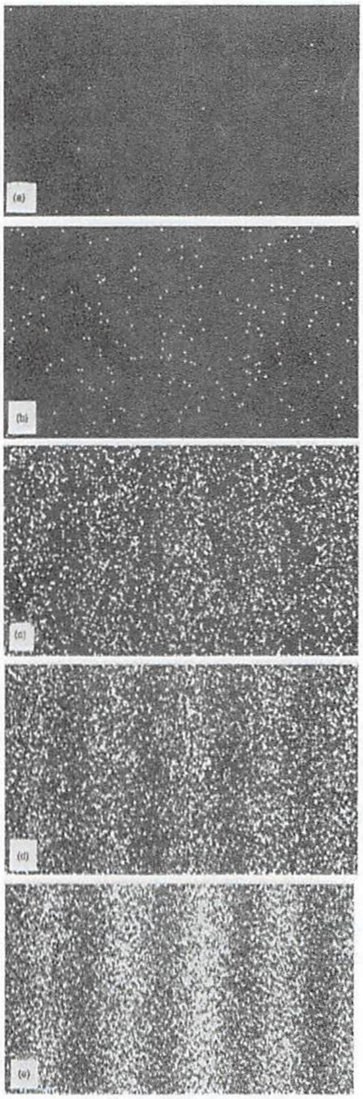

Figure 12.11
The buildup of an interference pattern in the electron wave-interference experiment by individual impacts of electrons. The five photos use exposures of 0.01 s (when only 10 electrons have hit), 0.1 s (100 electrons), 3 s (3000 electrons), 20 s (20,000 electrons), and 70 s (70,000 electrons).

You might have already guessed the name given to these individual impacts. They are electrons! And you might have noticed that the two experimental outcomes in Figures 12.9 and 12.11 are just like the outcomes in Figures 12.2 and 12.3—except that now we're using an electron beam instead of a light beam so the impacts are made by electrons, not photons.

To ward off a possible misconception, the interference pattern is not the result of interactions between different electrons. This pattern shows up even for a beam so dim that at most one electron at a time comes through the slits. Even if only one electron came through per hour, the cumulative impacts over many hours would still form an interference pattern.

The experiment shows that the wave-interference pattern of Figure 12.9 is built up from tiny individual electron impacts on the screen. Notice carefully that, like the double-slit interference experiment with light, each impact tends to occur only within the brightly lit constructive interference part of the figure.[5] This means that each individual electron "knows" that it's "supposed" to contribute to the double-slit interference pattern—each electron "knows" that both slits are open. But we are accustomed to thinking of electrons as tiny particles, much smaller than either slit, particles that would necessarily come through either one slit or the other and certainly not both slits. How could a single tiny electron, coming through either one or the other slit, "know" that the other slit is open and that it is therefore supposed to contribute to the double-slit interference pattern?

Quantum physics gives the same answer to this dilemma that it gave in Section 12.2 for the double-slit interference experiment with light: The explanation of the Figure 12.9 is that a spread-out *field* comes through the two slits and interferes in the region between the slits and the screen. But what kind of field? It cannot be an EM field as it was for light, because an electron beam is not an EM wave. In fact, the experiment has basically nothing to do with electromagnetism, despite the fact that the electron is an electrically charged particle. Even when this experiment is done with uncharged particles such as neutrons, the result is still a double-slit interference experiment pattern like Figure 12.9.

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[5] You might have noticed that the pattern seen in Figure 12.11(e) is not as simple as the pattern shown in Figure 12.10. For instance, some impacts occur in the "dark" regions between the bright lines. This is because the predicted pattern in Figure 12.10 is simplified. The actual predicted pattern is graphed in Figure 12.13.

The field that comes through the two slits is something entirely new, something that nobody knew existed until de Broglie and others discovered it during the 1920s. We'll call it a **matter field**.[6] De Broglie's matter waves are waves in a matter field, just as EM waves are waves in an EM field. And just like EM fields, matter fields are quantized.

Since we've already discussed quantized EM fields, it's not difficult to understand a **quantized matter field:** First of all, like EM fields and gravitational fields, a matter field fills up a region of space, such as the region between the slits and the screen in Figure 12.10. When we say that matter fields are quantized, we mean that, for reasons nobody understands, a matter field is not allowed to have just any old quantity of energy. Instead, the field is allowed to have only certain particular quantities of energy, and no others. For an electron beam, this energy can be mc^2, $2mc^2$, $3mc^2$, $4mc^2$, and so on, where m means the mass of one electron. Recall from Chapter 10 that, if m represents the mass (i.e., the total inertia) of a motionless or moving electron, then mc^2 is its total energy (including kinetic energy). So when we say that the allowed energies of the matter field are mc^2, $2mc^2$, and so on, we're simply saying that the matter field must contain enough energy for one electron, or two electrons, or three electrons, and so on, and nothing in-between.

Matter is quantized, just as radiation is quantized! Just as the quanta of the EM field are called photons, the quanta of the matter field are called electrons. In other words, electrons are not particles at all. They are not even remotely like a small pea, not like a small "thing" held rigidly together that maintains a fixed shape and follows a path from the electron source through the slits to the screen. An electron is simply an increment of matter field energy that acts in a unified way. When the matter field interacts with the viewing screen of Figure 12.11, one such increment instantly and entirely absorbs into the screen and the entire matter field in the space outside the screen reduces its energy by mc^2. Just as in the analogous EM field experiment, the interaction point on the screen is not predictable, and the process is non-local because the matter field loses energy everywhere at the instant of interaction.

As mentioned earlier, the same idea applies to all other material particles: Protons, neutrons, atoms, and molecules are all matter field quanta, all parcels of a spread-out field energy, all capable of going through both slits in the double-slit experiment.[7] There's a beautiful symmetry here: Everything, all matter and all radiation, is made of spread-out fields, but these fields are quantized and this is why there are particle-like parcels of light (photons) and particle-like parcels of matter (electrons, protons, etc.)

For me, the main purpose of doing experiments is to show people how strange quantum physics is. Most physicists are very naive; most still believe in real waves or particles.

Anton Zeilinger, Physicist

I'll summarize this idea as follows:

The Quantum Theory of Matter

A new type of field called a matter field exists in nature. Like EM fields, matter fields are quantized. For example, the matter field for electrons is allowed to possess enough energy for either 0 electrons, or 1 electron, or 2 electrons, and so on. Electrons (and other material particles) exist because matter fields are quantized in just these energy increments.

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[6] The matter field has a long history and goes by a variety of names: psi, wave function, electron field, electron-positron field, and matter wave.

[7] As the particles get more massive, it gets harder to demonstrate this experimentally. But in 2003, Austrian physicist Anton Zeilinger demonstrated wave interference for C_{60} molecules, showing that these large molecules (60 carbon atoms!) are quanta of a matter field.

CONCEPT CHECK 5 According to quantum physics, what's really happening when we say that an electron passes through the double-slit apparatus and hits the viewing screen? (a) A single tiny particle passes through one or the other slit (not both) and impacts the screen. (b) A single tiny particle passes through both slits and impacts the screen. (c) A spread-out matter field passes through one or the other slit (not both) and an increment of the field interacts with the screen. (d) A spread-out matter field passes through both slits and an increment of the field interacts with the screen.

CONCEPT CHECK 6 Suppose the electron source in Figure 12.10 is turned on so briefly that only a single quantum of energy passes through the double slits. When it arrives at the screen, this energy (a) spreads out all over the white bands in the drawing; (b) strikes at one small point within the white bands; (c) strikes at one small point, which could be anywhere on the screen; (d) strikes at a small point on the screen, lying directly behind the slit through which the energy passed.

12.5 QUANTUM MATTER

Figure 12.12 will help you visualize all this. The figure is analogous to Figure 12.6, but for matter instead of EM radiation. The figure shows the emission, transmission, and impact of a very low intensity matter wave, at five different instants. At (a), an electron source has just emitted a small amount of an electron beam, or matter field, having just mc^2 joules of energy, where m is the total inertial mass of one electron. This field approaches the double slits, passes through the slits, and approaches the viewing screen. At (e), a single impact—an electron—appears on the viewing screen. At the instant the electron appears, the entire spread-out matter field vanishes.

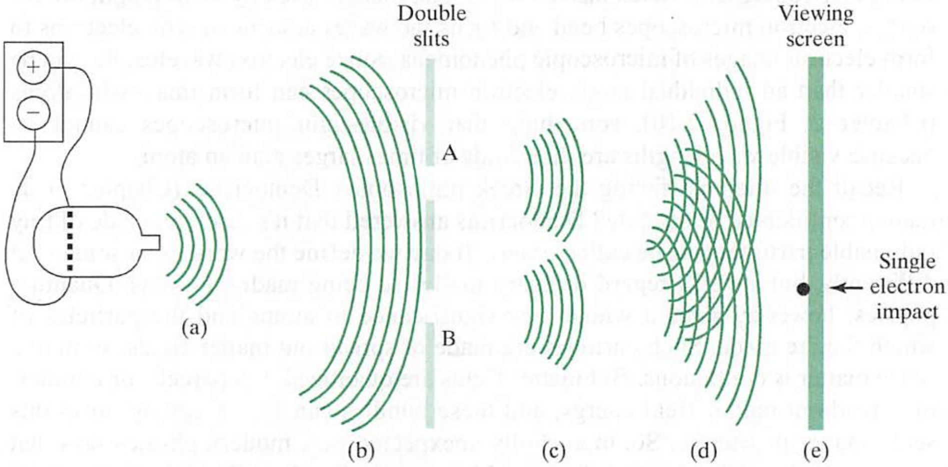

Figure 12.12
The double-slit experiment with electrons, showing the matter field for a very low-intensity electron beam at five different instants. The diagram shows the experiment as viewed from above, with the openings at A and B representing the narrow dimensions of the long narrow slits. The electron beam is emitted, approaches the slits, emerges from the slits, approaches the viewing screen and, at (e), impacts the screen at a specific point. The impact is referred to as "an electron." At the instant of impact, the entire spread-out field vanishes.

In its mature form, the idea of quantum field theory is that quantum fields are the basic ingredients of the universe, and particles are just bundles of energy and momentum of the fields. Quantum field theory hence led to a more unified view of nature than the old dualistic interpretation in terms of both fields and particles.

Steven Weinberg

To repeat some of the earlier remarks about light: Physicists view matter fields, rather than electrons and protons and so on, as the fundamental entity. That is, a matter field is physically real, just as an EM field is physically real. Just as photons are merely quanta of an EM field, electrons and so on are merely quanta of a matter field. The reason nature has a particle-like aspect is that it is made of quantized fields. Although it's legitimate to think of electrons, protons, and so on as particles, it's important to remember that they are not particles in the simple Newtonian sense. An electron is simply an energy increment of a spread-out matter field. When an impact occurs at some point, do not imagine that an electron was approaching that point just a moment earlier. Before that time, there was only a spread-out matter field.

You may have seen the narrow paths or "tracks" of electrons or other microscopic particles made in high-energy physics experiments (you'll find photographs of such tracks in Chapter 17). Although these tracks are convincing evidence that electrons exist, they do not invalidate the view that only a matter field exists between impacts. The tracks are made by successive individual interactions between a matter field and gas or water molecules. The matter field collapses into a tiny electron impact each time it interacts with a molecule, while spreading out as a matter field between impacts.

Keep in mind that, although an interference pattern such as Figure 12.9 is created by billions of electrons impacting the viewing screen during every second, each *individual* electron "knows" about the entire experimental arrangement because each electron is simply an energy increment—a quantum—of an entire spread-out matter field that comes through both slits. Note also the unpredictable nature of the individual electron impacts, just like the unpredictable nature of photon impacts in the double-slit experiment for light. We also see the characteristic nonlocality noted in the experiment with light: At the instant the electron impact occurs, the *entire* spread-out matter field *instantaneously* deposits an entire quantum of energy at the impact point.

Matter waves are exploited every day in such devices as the **electron microscope.** Using electromagnetic fields instead of the glass lenses used by visible-light microscopes, electron microscopes bend and focus the waves associated with electrons to form electron images of microscopic phenomena. Since electron wavelengths can be smaller than an individual atom, electron microscopes can form images of atoms (Chapter 2, Figure 2.10), something that visible-light microscopes cannot do because visible wavelengths are thousands of times larger than an atom.

Recall the dilemma facing the Greek philosopher Democritus (Chapter 2): Is matter continuous, or discrete? Democritus answered that it's discrete, made of tiny indivisible particles that he called *atoms*. Today we define the word *atom* somewhat differently, but we still regard ordinary matter as being made of atoms. Quantum physics, however, gives a whole new significance to atoms and the particles of which they're made. Such particles are made of spread-out matter fields, so in this sense matter is continuous. But matter fields are quantized into parcels, or bundles, of spread-out matter field energy, and these bundles can act separately, so in this sense matter is discrete. So, in a wholly unexpected way, modern physics says that matter is both continuous and discrete. More precisely, it's made of discrete quanta of a continuous matter field.

CONCEPT CHECK 7 How is an electron similar to a photon? (a) Both contain electric charge. (b) Both move at lightspeed. (c) Both impact at a tiny point on a viewing screen. (d) Both are quanta.

12.6 NATURE IS NONLOCAL AND UNCERTAIN

In the double-slit experiments with light and matter, we noted that the entire EM field or matter field changed its character instantaneously when an impact appeared on the screen, a behavior called **quantum nonlocality.** In addition, the position of each individual impact on the screen was unpredictable, even though the overall pattern was predictable. Unpredictability and nonlocality are two significant and characteristic features of quantum physics. I'll begin discussing unpredictability, or **quantum uncertainty,** in this section and continue in Chapter 13, where we'll also discuss nonlocality.

In order for a pattern like Figure 12.9 to emerge from billions of tiny electron impacts, different impacts must occur at different places. If you think in Newtonian ways, you might suppose that electrons impact at different places because they started out differently from the electron source. Could we then adjust the source so as to prepare every electron identically in order to make them all hit the same point on the screen? Experimentally, the answer is "no." Even if we prepare the electron source identically prior to every impact, the impacts still occur at different points all over the interference pattern.

A philosopher once said "It is necessary for the very existence of science that the same conditions always produce the same results." Well, they don't!

Richard Feynman

We expect—and Newtonian physics teaches us—that identical physical conditions lead to identical outcomes. But this expectation, and Newtonian physics, are wrong. Contrary to Newtonian physics, there is an inherent uncertainty in nature. Identical causes can lead to different outcomes. The matter field is spread all over the interference pattern, and the impact point—the point where the field deposits a quantum of energy—can occur at any point within this pattern. There is no way of predicting the precise impact point, because even nature doesn't know the precise point ahead of time. Newtonian physics had it wrong: The future is not encoded in the present. And this is not just a matter of microscopic physics; quantum uncertainties can be magnified into big, easily observed impacts in the macroscopic world, impacts such as radioactive decay (Chapter 14). The universe even has quantum uncertainties imprinted on its large-scale structure (Chapter 11).

A few physicists disagree with the notion that the future is undetermined, arguing instead that our current understanding (quantum physics) is simply not deep enough to penetrate the true principles governing the microscopic world and that these true principles would restore predictability to nature. Einstein argued forcefully during the 1930s that "God does not play dice," citing detailed examples to try to show that an irreducible uncertainty would be absurd. But quantum physics continues to have a perfect record of experimental success, and the quantum predictions that Einstein believed to be absurd have now been tested and found to actually occur.

I believe in the possibility of a theory which is able to give a complete description of reality, the laws of which establish relations between the things themselves and not merely between their probabilities. . . . Quantum mechanics is very impressive. But an inner voice tells me that it is not yet the real thing. The theory produces a good deal but hardly brings us closer to the secret of the Old One. I am at all events convinced that He does not play dice.

Einstein. His Friend Niels Bohr Replied, "Albert, Stop Telling God What to Do."

Note that, despite the randomness of individual impacts, the overall double-slit interference pattern *is* predictable. We get the same interference pattern every time we do the experiment. Since the pattern represents the overall statistics of billions of impacts, *the overall statistics are predictable, even though individual impacts are not.* The precise pattern is not quite as simple as the one shown in Figure 12.10. **Figure 12.13** shows the observed overall statistical pattern in more detail; the graph at the right shows the average number of impacts versus position on the screen. The points marked "o" on the screen are the positions of the dark lines in Figure 12.9, where no impacts occur.

God not only plays dice. He also sometimes throws the dice where they cannot be seen.

Stephen Hawking, Physicist

Figure 12.14
Max Born. He was the first to conclude that the wave patterns observed in experiments involving microscopic material particles were probability patterns.

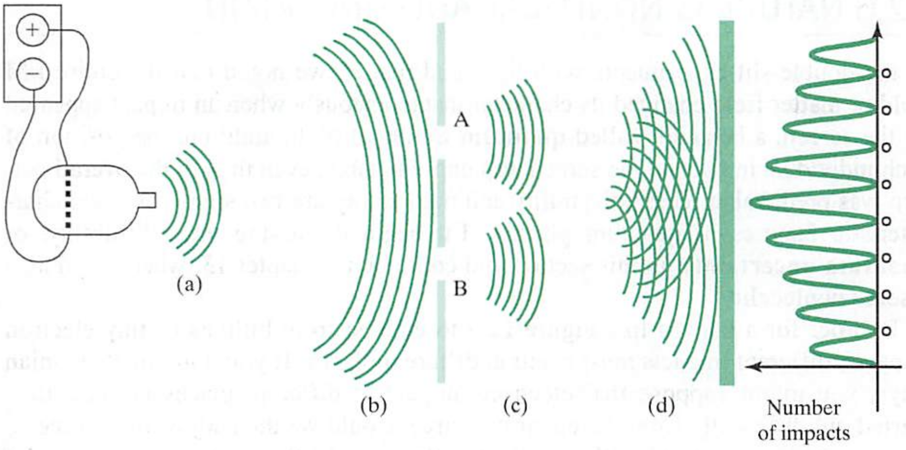

Figure 12.13
The right side of this diagram shows a graph of the distribution of impacts after millions of electrons have impacted the viewing screen. Figures 12.9 and 12.11 are photographs of this distribution of impacts. The points marked "o" are the positions of the dark lines in Figure 12.9.

In 1926, German physicist Max Born (**Figure 12.14**) was the first to conclude that data such as the graph in Figure 12.13 give the *probabilities* for a single electron to strike at various points on the screen, in the same way that "50% probability of heads and 50% probability of tails" gives the probabilities for the outcome of a single coin flip. More precisely, *the intensity*[8] *of the matter field at any particular point represents the probability that an electron impact will occur at that point if a viewing screen or some other detecting device happens to be at that point.* For example, Figure 12.9 shows the intensity of the matter field at various points on the screen, and this intensity (or brightness) represents the probability that any individual electron will impact at that point.

Probabilities were invented long before quantum physics and usually have nothing to do with quantum physics. Probabilities are useful whenever the outcome of a particular experiment is uncertain but the overall statistics of many repetitions are predictable. A simple example, having nothing to do with quantum physics, is the flip of a coin. What "50% probability of heads" means is that, in a long series of tosses, roughly 50% will be heads. This probability, 50% or 0.5, can be regarded as a statistic, a number representing the pattern that emerges in many repeated trials of the experiment.

But there is a difference between the probabilities observed in macroscopic experiments such as coin flips and the probabilities referred to in quantum physics. Because coin flips obey Newtonian physics to an excellent approximation, the outcome is predictable in principle. That is, with enough information regarding the tension in the flipper's thumb, the initial height of the coin above the table, the elastic properties of table and coin, and so forth, you can use Newtonian physics to predict the outcome. Our uncertainty about a coin flip arises only from ignorance of the precise details. But quantum events are not predictable even in principle. Quantum unpredictability arises from a fundamental uncertainty in nature, rather than simply from our own inability to predict nature. Nature herself doesn't know what she will do next.

God rolls the dice every time a quantum interaction takes place.

Heinz Pagels, Physicist

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[8] Quantitatively, *intensity* means the square of the matter field's amplitude.

The predictability of the statistical patterns shows that matter waves are predictable, even though individual impacts are not. In 1926, Austrian physicist Erwin Schroedinger (Figure 12.15) invented a method of predicting the motion of matter waves. Schroedinger began with a well-known formula that had been used to describe waves in other situations not involving quantum physics. Into this wave formula, he inserted de Broglie's relation $\lambda = h/mv$, along with some judicious guesswork. The result was a formula, now called **Schroedinger's equation,** that correctly describes the motion of the matter wave for electrons or any other material particles in a wide variety of situations. Most important historically, Schroedinger showed that his equation could be applied to electrons within atoms and that the predicted results agree with atomic experiments (Chapter 13).

Figure 12.15
Erwin Schroedinger. He invented the equation that predicts the statistical pattern, or matter wave, in a wide variety of situations involving microscopic material particles.

CONCEPT CHECK 8 During the double-slit experiment using a beam of *neutrons*, the region between the slits and the screen contains (a) a matter field; (b) individual neutrons; (c) an EM field; (d) a stream of photons; (e) none of the above.

"ACTUALLY I STARTED OUT IN QUANTUM MECHANICS, BUT SOMEWHERE ALONG THE WAY I TOOK A WRONG TURN."

Answers to Concept Checks and odd-numbered Conceptual Exercises and Problems can be found in the back of the book.

Review Questions

THE QUANTUM REVOLUTION

1. What is quantum physics?
2. Describe at least one way in which the philosophical implications of quantum physics differ from those of Newtonian physics.

QUANTUM RADIATION

3. Describe the double-slit experiment with light and its outcome.
4. What is an electromagnetic field?
5. If we perform the double-slit experiment with dim light and a short exposure time, what will we see on the screen?
6. Following up on the preceding question, what will we see after a longer exposure time?
7. What do we mean by a quantized electromagnetic field?
8. How big is the smallest allowed energy increment in a quantized EM field?
9. What do we mean by a quantum (or energy quantum) of the EM field?
10. What is a photon? What is its speed? Its rest-mass?
11. Why don't we normally notice that light is made of photons?
12. How does quantum uncertainty enter into the double-slit experiment with light?
13. How does quantum nonlocality enter into the double-slit experiment with light?

QUANTUM MATTER

14. Can a single electron have a wavelength?
15. How do we know that material particles are associated with waves?
16. What name do we give to the waves that are associated with material particles?
17. Which detects the smallest objects: a visible light microscope or an electron microscope? Why?
18. Describe the double-slit experiment with electrons and its outcome.
19. If we perform the double-slit experiment with electrons using a low intensity beam and a short exposure time, what will be see on the screen?
20. Following up on the preceding question, what name do we give to the individual impacts?
21. What evidence is there that a field called a "matter field" exists?
22. What do we mean when we say that matter fields are quantized?

QUANTUM UNCERTAINTY

23. Describe an example in which identical causes do not result in identical outcomes.
24. How does quantum uncertainty differ from the ordinary uncertainty in the outcome of a coin flip?

Conceptual Exercises

THE QUANTUM REVOLUTION

1. Name the two revolutionary physics theories of the first decade of the twentieth century.
2. What are some practical ways in which quantum physics has impacted modern life?

QUANTUM RADIATION

3. How do we know light is quantized?
4. In what sense are EM fields "digital" rather than "analog"?
5. A photon impact appears on the screen in the double-slit experiment with light. What happens to the EM field?
6. We don't ordinarily notice photons. Suppose that Planck's constant were much larger than it actually is. Would we then be more likely, or less likely, to notice photons?
7. Which has higher energy: a photon of red light or a photon of yellow light?
8. Which has lower energy: a photon of ultraviolet radiation, or a photon of infrared radiation?
9. In the double-slit experiment with light, are tiny photons actually coming through the slits? What is coming through the slits?
10. When we greatly dim the light used in a double-slit experiment, we don't simply get a dimmer interference pattern. What do we get?
11. Suppose a red light beam has a variable intensity, or brightness. As you increase the intensity, do the energies of the individual photons increase, decrease, or remain the same?
12. In the preceding question, does the number of photons emitted each second increase, decrease, or remain the same?
13. As you increase the frequency of a light beam, does the color change? Do the energies of the individual photons increase, decrease, or remain the same?
14. In the preceding question, do the speeds of the photons change?
15. What kind of waves are demonstrated by the experimental result shown in Figure 12.2? Waves in what (what is the medium called)?

QUANTUM MATTER

16. What kind of waves are demonstrated by the experimental result shown in Figure 12.9? Waves in what?
17. Which has a shorter wavelength, an electron or a proton moving at the same speed?
18. Which has a shorter wavelength, a slow electron or a fast electron?
19. Suppose we use a very low intensity beam in the double-slit experiment with electrons, so low that only one electron appears per minute. Will we see an interference pattern on the screen? What will we see?

20. List some similarities between an electron beam and a light beam.
21. List some similarities between an electron and a photon.
22. List some differences between an electron and a photon.
23. The impact point of each electron is unpredictable in the double-slit experiment with electrons. What is predictable?
24. If an electron traveling through a double-slit apparatus strikes directly behind slit A, is it correct to say that the electron came through slit A?
25. If electrons behaved only like particles and not like waves, would you observe an interference pattern in the double-slit experiment?
26. You don't notice the wave aspect of a pitched baseball. Is this because the baseball's wavelength is very long or because it is very short?
27. Arrange these in order from shortest to longest wavelength, assuming that they all have the same speed: helium atom, automobile, DNA molecule, electron, neutron, baseball.
28. If a "proton microscope" could be devised, how would you expect its wavelength to compare with the wavelength of an electron microscope?

QUANTUM UNCERTAINTY

29. When you flip a coin, the outcome is uncertain. Does this arise from quantum uncertainty? Explain.
30. What is the percentage probability of getting two heads in a row in fair coin tosses? How could you experimentally test this prediction?
31. In the double-slit experiment with electrons, is the impact point predictable?
32. In the double-slit experiment with electrons, are there any points where we can predict that an electron will certainly not hit?
33. What is predictable in the double-slit experiment with electrons?
34. Would the answers to the preceding three questions be different if we were talking about photons instead of electrons?
35. List at least two differences between Newtonian physics and quantum physics.

Problems

QUANTUM RADIATION

1. A light source emits two colors simultaneously: orange and violet. Which color has the higher energy per photon?
2. In the preceding problem, the frequencies are 5×10^{14} Hz (orange) and 7×10^{14} Hz (violet). Find the energies of the photons.
3. Which has greater energy, a microwave photon or a visible photon? About how many times greater (consult Figure 9.27)?
4. You charge an object by rubbing it, and then shake it at 1 Hz, creating EM radiation. How much energy does each photon carry?
5. How much energy does one photon of 10^{24} Hz gamma radiation carry?
6. **MAKING ESTIMATES** About how many visible photons would be needed to have enough energy to lift a 1 newton (about 1/4 pound) weight through 1 meter (consult Figure 9.27)?
7. **MAKING ESTIMATES** About 10 visible photons are needed to cause a single photosynthesis reaction in living plants. About how much energy is carried by these 10 photons?
8. **MAKING ESTIMATES** The human eye can detect as few as 10,000 photons per second entering the pupil. About how much energy is this per second?

QUANTUM MATTER

9. If you double the speed of a proton, how does this affect its wavelength?
10. How would the wavelength of a proton compare with the wavelength of a deuteron (a proton and neutron held together by nuclear forces), assuming that both the proton and the deuteron have the same speed?
11. An electron and a proton are moving at the same speed. Which has the longer wavelength? How much longer? (Protons are about 1800 times more massive than electrons.)
12. Suppose we fire a high-velocity pellet gun that accelerates 1 gram (10^{-3} kg) pellets to speeds of 1000 m/s (three times the speed of sound). Find the wavelength of the pellet's matter wave.
13. Find the wavelength of an electron that strikes the back of a TV screen at a speed of $0.1c$. The mass of an electron is 9.1×10^{-31} kg.
14. Individual electrons have been slowed down to speeds as low as several centimeters per second. The mass of an electron is 9.1×10^{-31} kg. What is the wavelength of a single electron moving at 0.1 m/s (10 cm/s)? Express your answer in millimeters.
15. In a recent experiment, sodium atoms were cooled until they were moving at only a few meters per second. The mass of a sodium atom is 38×10^{-27} kg. What is the wavelength of a single sodium atom moving at 2 m/s? Express your answer in millimeters.

CHAPTER

13 The Quantum Universe

In order to understand atomic structure, we must accept the idea that the future is uncertain. It is uncertain to the extent that the future is actually created in every part of the world by every atom and every living being. This point of view, which is the complete opposite of machinelike determinism, is something that I believe should be realized by everyone.

Edward Teller, Physicist

This chapter delves more deeply into quantum physics. Section 13.1 takes a closer look at quantum uncertainties and presents the uncertainty principle. Section 13.2 discusses the surprising effect of macroscopic observation on the behavior of microscopic systems. I've mentioned quantum nonlocality in Chapter 12; Section 13.3 takes a closer look at this phenomenon, which could lay claim to being the oddest notion that has cropped up yet in physics. Sections 13.4 and 13.5 ponder the kind of reality that quantum physics describes and ask how quantum physics affects, or might in the future affect, the Newtonian worldview that still pervades modern culture. Finally, Sections 13.6 and 13.7 study perhaps the most significant practical application of quantum physics: the quantum atom.

13.1 THE UNCERTAINTY PRINCIPLE: THE FUTURE IS NOT DETERMINED BY THE PAST

You saw in Chapter 12 that one of quantum theory's most characteristic features is the microworld's inherent **quantum uncertainty.** That is, identical physical conditions often give rise to varying and thus unpredictable observed outcomes. It's a feature that's radically at odds with the predictably of nature according to Newtonian physics. You also saw that, despite this uncertainty, the overall statistics of large numbers of outcomes follows predictable patterns.

German physicist Werner Heisenberg (**Figure 13.1**) found, in 1927, that quantum uncertainty can be quantified. To get a feel for Heisenberg's argument, consider a quantized matter field containing enough energy for just one electron, moving through empty space along a direction that we will call the x-axis. As you know, the matter field's intensity at any particular point represents the probability that an electron will be found at that point. You've seen in Chapter 12 that matter fields are spread out in space and generally have a wavelike character, as shown in **Figure 13.2**. In quantum physics, this figure is the natural way to represent the matter field for an individual particle such as an electron. I will call a matter wave such as is shown in Figure 13.2 a **wave packet.** The range of possible positions is indicated in the figure by the symbol Δx ("delta x").

Keep in mind that there is no tiny particle called "an electron" traveling with, or in, the wave packet. Rather, the electron *is* the wave packet. The spread-out wave packet is a single quantum, a single parcel of matter field energy as discussed in Chapter 12. It contains the total energy, and therefore the total inertial mass, as well as the other features such as charge, of a moving electron. "Particles" such as "one electron" are not really particles at all; they are quanta of spread-out fields, such as the wave packet shown. It's only when the wave packet interacts with another system (such as a viewing screen) that the packet collapses to impart a tiny, particle-like impact. Δx is the range within which such an impact is likely to occur.

Quantum theory (the Schroedinger equation) predicts that a wave packet cannot be at rest. Furthermore, a wave packet cannot just move at a single velocity; it must instead move with a range of different velocities.[1] This means that not only is an electron's position uncertain, its velocity is also uncertain. A particle's range of possible velocities is abbreviated Δv.

So a single moving electron (or any other material particle) has two kinds of uncertainties, Δx and Δv. Let's compare one wave packet A with another wave packet B that has been squeezed into half of A's length (**Figure 13.3**). As you can see, B's wavelengths are shorter. But de Broglie's formula, $\lambda = h/mv$, tells us that shorter wavelengths correspond to higher velocities. So wave packet B represents a higher-velocity electron than does packet A. And it turns out that larger velocities mean a larger *uncertainty* in velocity and that in fact the halving of Δx implies a doubling of Δv.[2]

Figure 13.1
Werner Heisenberg. Using the Schroedinger equation, he derived the famous uncertainty principle according to which every material particle has inherent and irreducible uncertainties in position and velocity. Thus, in the microscopic world, the future is not entirely determined by the past.

This illustrates a general feature of quantum physics: Whenever a particle's Δx is squeezed by some amount, Δv expands by the same amount, and vice versa: Squeezing Δv expands Δx. Quantitatively, Heisenberg showed that the *product* of Δx and Δv remains unchanged.

Working through these ideas in detail, Heisenberg found that this rule holds for every material particle (not just electrons) in every physical situation (not just when moving freely). Here is his result:

The Uncertainty Principle

The position and velocity of every material particle are uncertain. Although either uncertainty can take on any value, its product must approximately equal Planck's constant divided by the particle's mass. In symbols,

$$(\Delta x) \cdot (\Delta v) \approx h/m$$

where h is Planck's constant and m is the particle's mass.[3]

---

[1] Here's why: According to the branch of mathematics known as "Fourier analysis," a wave packet is a superposition of many different infinitely long waves, each having a definite wavelength. But de Broglie's formula $\lambda = h/mv$ tells us that different wavelengths correspond to different velocities. Thus, a wave packet has a range of possible velocities.

[2] Here's why: Since B is squeezed to half of A's length, B's wavelengths are half as long as A's. So B's component velocities are twice as big as A's, because $\lambda = h/mv$ says that wavelength and velocity are inversely proportional. So the range of velocities, Δv, is twice as big for B as for A.

[3] More precisely, $(\Delta x) \cdot (\Delta v) \geq h/4\pi m$. The product can be greater than $h/4\pi m$ but not less.

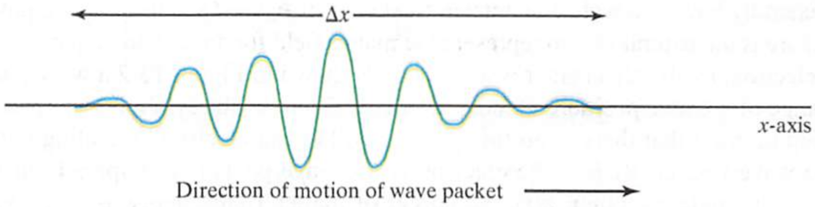


Figure 13.2
The matter wave representing a single particle whose uncertainty in position is Δx, moving along the x-axis. A matter wave like this, which is spread out over only a limited distance, is called a wave packet.

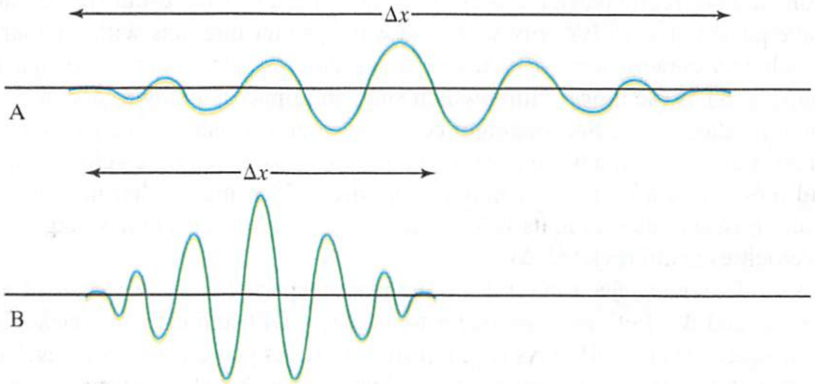
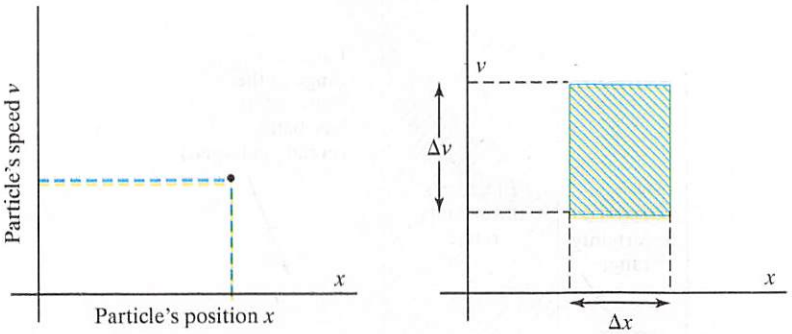


Figure 13.3
Two wave packets, having different values of Δx. Packet B can be constructed by squeezing packet A to half its size. In this process, all of A's wavelengths get squeezed to half their original length, which means that the velocities and also the uncertainty in velocity get doubled.

> I remember discussions with Bohr which went through many hours till very late at night and ended almost in despair; and when at the end of the discussion I went alone for a walk in the neighbouring park I repeated to myself again and again the question: Can nature possibly be as absurd as it seemed?
>
> Werner Heisenberg

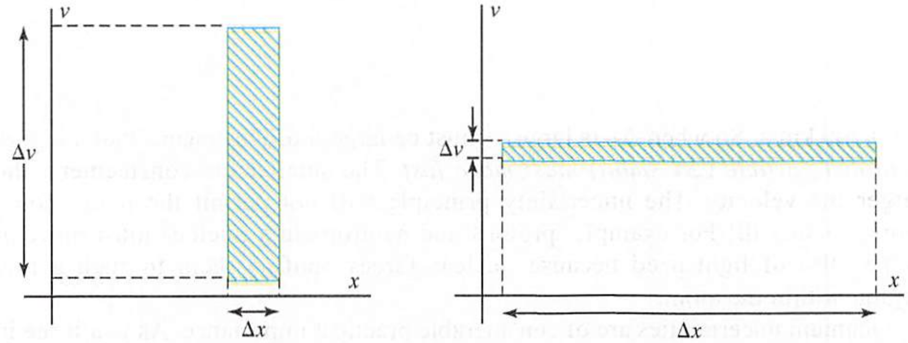
We refer to a particle's Δx and Δv as its **uncertainty range.** You can visualize a particle's uncertainty range in a velocity-versus-position diagram (**Figure 13.4**). A single point on such a diagram represents a precise position x and velocity v [Figure 13.4(a)]. Newtonian physics assumes that every object has a precise x and v. For example, the location and motion of the center of a baseball can be described, according to Newtonian physics, by a particular x and a particular v. Newton's law of motion is basically a method for predicting an object's future x and v from its present x and v. For example, given the position and velocity of the center of a falling baseball at one time, we can predict the center's position and velocity at any later time during the fall.

But microscopic particles do not have precise positions and velocities, for the simple reason that the so-called "particles" are really quanta of a matter field, spread out over a range of positions and velocities. Quantum theory demands that an object's position and velocity have uncertainties Δx and Δv whose product is roughly h/m. In an x-versus-v diagram, this product is the area formed by the rectangle whose sides are Δx and Δv, as shown in Figure 13.4(b). If for any reason Δx is reduced, then Δv must expand to yield the same product $\Delta x \cdot \Delta v$, as shown in Figure 13.4(c). And if Δv is reduced, Δx must expand, as in Figure 13.4(d). Either x or v can be as highly predictable as you like, but if one is highly predictable, the other must be highly uncertain. You can think of these diagrams as rough pictures of a particle's matter field. Like other physical fields, a matter field is spread out over a range of positions in space, and different parts of the field move at different velocities. An uncertainty range such as Figure 13.4(b) simply shows those ranges of positions and velocities.



(a) A single point on an *x*-versus-*v* diagram, such as the point shown here, represents a precise value of both *x* and *v*. Quantum theory does not allow such precise values.

(b) An uncertainty range for a single particle. According to quantum theory, the total area of the shaded region, $(\Delta x)\cdot(\Delta v)$, must be roughly equal to h/m.



(c) If for any reason Δx is reduced, then Δv must expand to fill up an uncertainty range having the same area.

(d) And if Δv is reduced, Δx must expand.

Figure 13.4
Position and velocity uncertainty ranges.

This again emphasizes a subjective element in the description of atomic events, since the measuring device has been constructed by the observer. . . . We have to remember that what we observe is not nature in itself but nature exposed to our method of questioning.

Werner Heisenberg

The belief in an external world independent of the perceiving subject is the basis of all natural science.

Einstein

Since the uncertainty principle says that $(\Delta x)\cdot(\Delta v) \approx h/m$, more massive particles have smaller uncertainty ranges. A proton, with a mass 2000 times larger than an electron's mass, has an uncertainty range 2000 times smaller (in area) than does an electron (**Figure 13.5**). Because *x* and *v* are both needed in order to predict an object's future behavior, a proton is more predictable than an electron. And a baseball, one million trillion trillion times more massive than an electron, is so predictable that quantum uncertainties are negligible (Figure 13.5). That's why the macroscopic world is Newtonian! Even a grain of sand is so massive (it contains some 10^{18} atoms) that quantum uncertainties are negligible. Macroscopic objects such as baseballs and dust grains are predictable, but the atoms, electrons, and protons of which they are made are not predictable.

Suppose a particle's Δx has been squeezed into a very small range. This particle must then have a large Δv. But you can't have a large Δv without at the same time having a large *v*; for instance, if Δv were 1000 km/s, the lowest (slowest) uncertainty range for *v* alone would be 0 to 1000 km/s, so the average *v* must be at

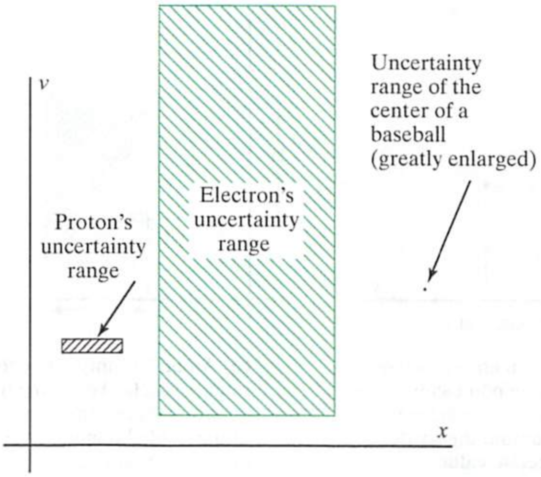


Figure 13.5
More massive objects have smaller uncertainties. That's why quantum uncertainties are negligible for such macroscopic objects as baseballs.

least 500 km/s. So when Δv is large, v must be large too. This means that *a highly confined particle* (Δx *small*) *must move fast.* The smaller the confinement, the larger the velocity. The uncertainty principle will not permit the microscopic world to sit still! For example, protons and neutrons in a nucleus must move at some 10% of lightspeed because nuclear forces confine them to such a tiny region within the atom.

Quantum uncertainties are of considerable practical importance. As you'll see in Section 13.3, they might someday be used to practical advantage in quantum computers. Quantum uncertainties lie at the heart of the nuclear phenomenon known as radioactive decay (Chapter 14) and cause this process to be fundamentally unpredictable. When a child is conceived, the DNA molecules of each parent are randomly combined in a process in which quantum phenomena play a role. Thus, quantum uncertainty played a role in your genetic inheritance. As you saw in Chapter 11, microscopic quantum uncertainties during the big bang formed the "seeds" for the later gravitational gathering of matter into the great clusters of galaxies that you see today. The expansion of the universe stretched these initially tiny seeds to astronomical sizes, and matter gravitated toward these seeds. Today we see, forever imprinted on the overall layout of the universe, microscopic quantum uncertainties writ large.

We are, in these and many other subtle ways, in the hands of the god who plays dice.

▶ CONCEPT CHECK 1 Which of these has the largest quantum uncertainties? (a) Proton. (b) Automobile. (c) Helium atom. (d) Water molecule.

▶ CONCEPT CHECK 2 Referring to Figure 12.13, *just* after the matter wave passes through the slits, its uncertainty range (a) covers the entire range of positions from above slit A to below slit B in the figure; (b) is broken into two separate pieces, one of them behind slit A and the other behind slit B; (c) is located either behind slit A or behind slit B, but not both.

CONCEPT CHECK 3 A particle having a very precise velocity has a wave packet that (a) occupies a wide region of the x-axis; (b) occupies only a narrow region of the x-axis; (c) moves with a wide variety of velocities; (d) moves with a narrow range of velocities.

13.2 THE EFFECT OF DETECTORS

Einstein was among those who found quantum theory too counterintuitive to believe. He and two other physicists showed in 1935 that quantum theory predicts nonlocal phenomena that are, as he put it, so "spooky" that "no reasonable definition of reality could be expected to permit this." Einstein and others took these predictions as evidence that the theory needed repair. However, Einstein did not suggest a way to put quantum theory's spooky predictions to an experimental test.

Because quantum theory proved so gloriously successful in practice, few physicists worried much about such untested objections. Among those who did worry were David Bohm and John Bell (**Figure 13.6**). Bohm began publishing his analysis during the 1950s. Working from Bohm's ideas, Bell showed in 1964 that some of quantum theory's spooky predictions are experimentally testable. John Clauser (Figure 13.6) carried out the first such test in 1972 and found that contrary to the expectations of Einstein and others, the spooky phenomena actually occur! In 1982, Alain Aspect (Figure 13.6) refined Clauser's test so as to leave little doubt that the real world is stranger than Einstein and others had thought.

The spooky predictions are related to sudden alterations in the quantized EM and matter fields. Consider, for example, a single freely moving electron approaching a viewing screen. As you've seen, up until the moment of impact the "electron" is really a wave packet—a ripple in a matter field—approaching the screen; the impact that we call "an electron" is really just the deposit of a quantum of energy from the matter field to the atoms of the screen. The packet can be quite spread out, stretching even over macroscopic distances. For example, the wave packet responsible for any one of the impacts in Figure 12.11 was about 1 cm wide as it approached the viewing screen. Compared with atomic dimensions, this is enormous, as wide as 100 million atoms placed side by side.

Now think about what happens when this 1 cm wide wave packet for a single electron hits the viewing screen: The interaction between the packet and one of the atoms of the screen causes a single "grain" (similar to a sand grain) of the screen to emit a burst of light. At this instant, the entire spread-out wave packet suddenly alters radically because the entire energy of the quantized packet must be delivered to a single atom. The electron's uncertainty range is now confined to one atom within the grain that emitted the burst of light, about a billionth of a meter in size. The packet suddenly becomes 100 million times smaller. Such an instantaneous reduction in the size of a wave packet upon detection of a particle is called **collapse of the wave packet.**

There has always been lots of controversy about this process and about other cases in which microscopic particles interact with macroscopic devices such as viewing screens. Such a process is called a **measurement** for obvious reasons, but this term need not refer only to cases in which a human observer is actually present to record the measurement. It refers, rather, to any situation in which a *micro*scopic particle causes a *macro*scopic event such as a visible flash, whether or not a human is present to observe it.

The world thus appears as a complicated tissue of events, in which connections of different kinds alternate or overlap or combine and thereby determine the texture of the whole.

Werner Heisenberg

Marvelous, what ideas the young people have these days. But I don't believe a word of it.

Einstein, After Heisenberg's 1927 Lecture Enunciating the Uncertainty Principle

I cannot seriously believe in [the quantum theory] because it cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at a distance.

Einstein

Attempts have been made to add laws to quantum mechanics to eliminate uncertainty. Such attempts have not only been unsuccessful, they have not even appeared to lead to any interesting results.

Edward Teller

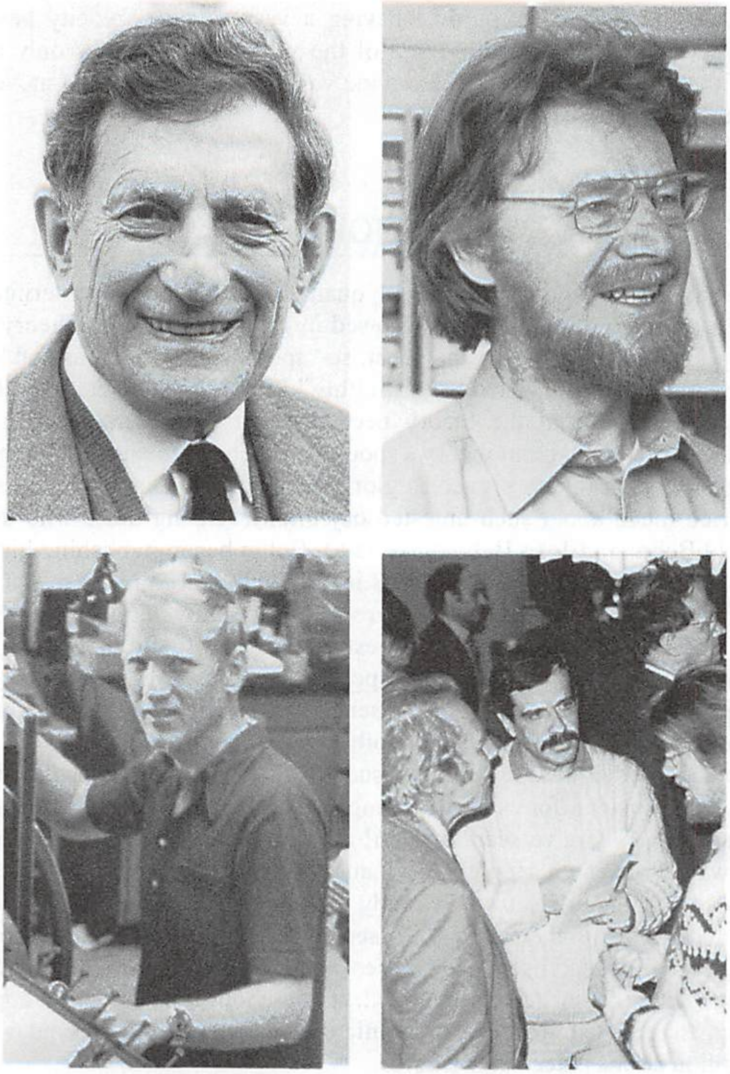


Figure 13.6
Four explorers of quantum theory: Clockwise from upper left: David Bohm, John Bell, Alain Aspect talking with Bell (r.) and physicist Albert Messiah (l.), John Clauser.

Collapse of the wave packet can occur over large regions. For example, the EM field for each wave packet from any very distant star is spread out over *many kilometers* by the time it reaches Earth. British physicist Robert Hanbury Brown confirmed this prediction in 1965 by measuring, for the light from an individual star, interference patterns that were over 100 meters in diameter. Despite each photon wave packet's large size, the field for each photon instantaneously collapsed to atomic dimensions when the photon hit a detector.

Collapse of the wave packet is controversial among physicists because of its instantaneous and "nonlocal" character: The entire wave packet vanishes, simultaneously, over an extended region. I'll discuss nonlocality further in the next section.

The double-slit experiment with electrons offers interesting examples of quantum measurement issues. Based on Newtonian ways of thinking, one might suppose that we could place a detector near one or both of the slits and thus detect individual electrons coming through one or the other slit, in contradiction to our discussion of Figure 12.13, where we said that the matter field for each electron comes through both slits. What will such a detector observe, and what will be the pattern on the viewing screen?

Before answering these questions, we need to see what happens when we completely close either one or the other slit. With one slit closed, the wave packet for each electron must obviously come through the other slit, either slit A or slit B. **Figure 13.7** shows each of these single-slit patterns: Part (a) is the pattern when only slit A is open, and part (b) is the pattern when only slit B is open. Each pattern shows the intensity of an individual electron's wave packet (the intensity of the matter field, or the probability that the impact will occur at various points on the screen) as the packet approaches the screen. There is no trace of interference. Schroedinger's equation predicts these patterns, and they can be observed experimentally as the statistical result obtained after millions of electron impacts. Part (c) is simply the sum of the first two graphs. It shows what would happen if, contrary to the discussion in Chapter 12, each electron wave packet in the double-slit experiment actually came through one or the other slit and not both. Finally, part (d) shows what actually happens when both slits are open, but there is no detector to see which slit the electron goes through. What actually happens, as you saw in Chapter 12, is an interference pattern.

Now you'll see what happens in the double-slit experiment when a detector determines the slit through which the electron came. **Figure 13.8** shows the detector (it's supposed to look like an eye seen from the side) located at point D just behind slit B. Such detectors are usually electromagnetic devices designed to have as little effect as possible on the motion of the electron, allowing it to pass nearly unimpeded to the viewing screen. As long as such a detector is switched off so that it cannot detect electrons, the usual interference pattern appears on the screen [Figure 13.8(a)]. But when the detector is switched on, it immediately begins indicating that about half of the electrons are coming through slit B and half are not! This makes us think that

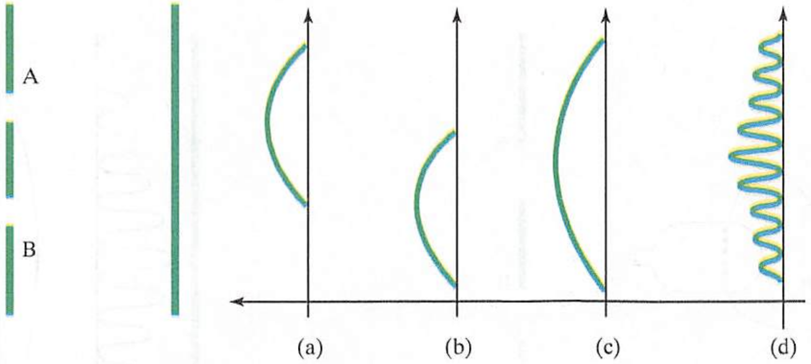


Figure 13.7

Results of different *single*-slit experiments with electrons. (a) The pattern of electron impacts on the viewing screen for the case that slit A only is open and slit B is closed. (b) The pattern for the case that slit B only is open and slit A is closed. (c) The patterns (a) and (b) added together to show what would happen in the double-slit experiment if each electron wave packet simply came through one or the other slit rather than through both slits. (d) The actual result of the double-slit experiment, from Figure 12.13.

Newtonian physics has it right after all: Electrons do come through one or the other slit but not both. However, precisely when the switch is turned on, the interference pattern vanishes and the "noninterference pattern" (b) appears on the screen. This is precisely the pattern that we saw, in Figure 13.7(c), should be the net effect of electrons coming through either slit A or slit B but not both! Apparently, detectors have strong and instantaneous effects on matter waves: When the "slit detector" is turned off, each electron comes through both slits; turning on the detector causes each electron to come through one or the other (but not both) slits.

Can the effect of the detector be reduced? For example, researchers might place the detector further from the slits (**Figure 13.9**). Again, the entire pattern shifts from (a) to (b) as soon as the detector is switched on. Extremely fast switching devices have even been devised to turn on the detector only *after* an electron must have *already* come through the slits. And still, pattern (a) switches

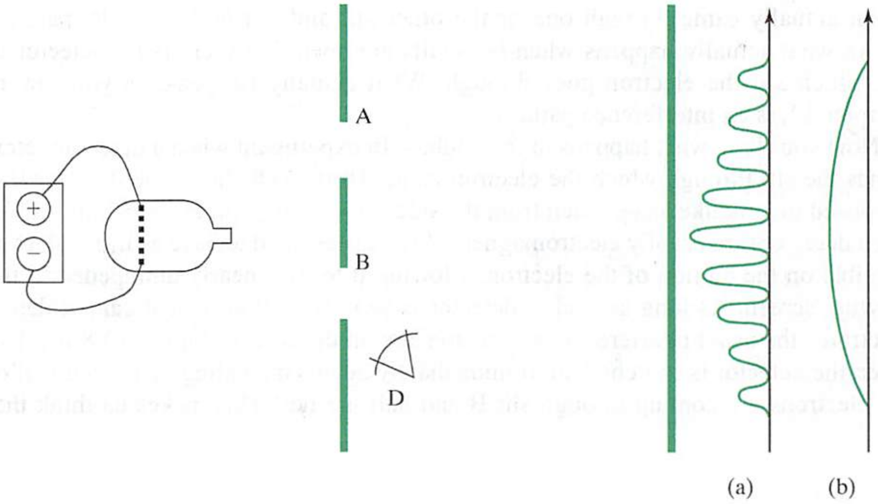


Figure 13.8
Merely switching on a particle detector at a point such as D causes the matter field to jump from the interference pattern (a) to the noninterference pattern (b).

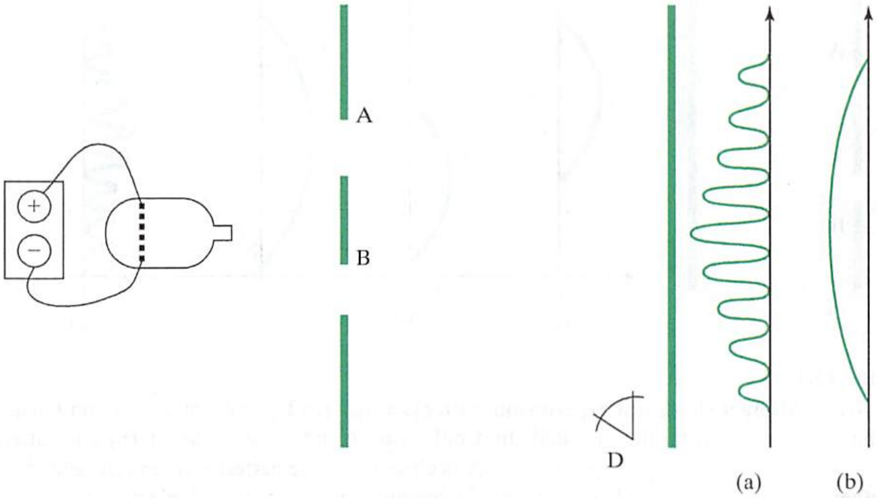


Figure 13.9
Even if the detector is placed far behind the slits, near the screen, the pattern still jumps from pattern (a) to (b) whenever the detector is activated.

to pattern (b) as soon as the detector is switched on! The detection device causes the packet to instantly shift from the interference pattern to the noninterference pattern *after* it has already passed through the slits. This strange influence of the detector is actually predicted by the standard rules of quantum physics, and observed in experiments.

▶ CONCEPT CHECK 4 Suppose that, in Figure 13.8, two detectors were used, one behind each slit. The pattern that the matter field makes on the screen would then be (a) an interference pattern that is broken into two separate parts, one behind each slit; (b) a noninterference pattern that is broken into two separate parts, one behind each slit; (c) an interference pattern like the one shown in the figure; (d) a noninterference pattern like the one shown in the figure.

13.3 QUANTUM ENTANGLEMENT: SPOOKY ACTION AT A DISTANCE

So far, we've discussed quantum uncertainty and nonlocality only in situations involving separate particles that don't interact with each other. Recall that **quantum nonlocality** refers to the instantaneous alteration of an entire spread-out EM field or matter field, even at some distance from the interaction (energy exchange) that caused the alteration. Now we're going to look at the consequences of quantum uncertainty and nonlocality when applied to two or more particles. We'll just consider two particles, but the same conclusions apply to any number of particles. If two particles physically interact with each other, quantum theory predicts that their matter fields (remember that a particle *is* its matter field) usually become intimately connected and remain connected even after the particles have separated. The two particles become a single quantum system with a single shared matter field. Such particles are said to be **entangled.** Figure 13.10 is a way to picture this. The figure shows wave packets for two particles. The two packets are entirely separate initially, then they move close enough together to interact, and then they separate. Quantum physics predicts that their matter waves get mixed up with each other during the interaction so that, even after separation, the two packets form a *single two-particle wave packet*. I've tried to indicate this in Figure 13.10 by coloring the two initial packets black and green. When they separate, part of each packet goes to the right and part of each packet goes upward. After the interaction, both packets contain both black and green and are really two "subpackets" of a *single* black-and-green packet, even though the two subpackets might be widely separated in space. Entangled particles are part of a single quantum object, namely a two-particle wave packet. They form a single thing, but in two different places.

Now suppose that one of the two entangled packets in Figure 13.10 impacts a viewing screen. This wave packet instantly collapses everywhere. But this would have to affect the other wave packet because the two packets really form a single connected packet. *This instantly alters the other, second particle*, even if the two particles are light-years apart. This is the action at a distance that seemed so "spooky" to Einstein. Experiments since 1972 have amply confirmed the reality of entanglement at distances up to 144 kilometers.

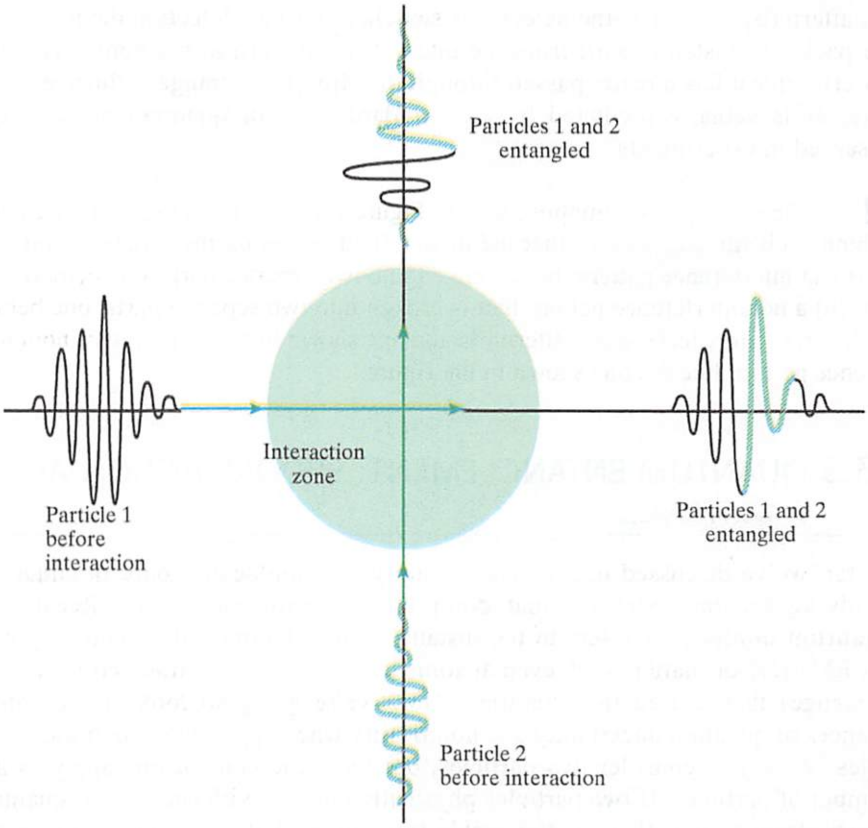


Figure 13.10
When two particles interact and then separate, their matter fields usually become entangled. See the text for explanation.

One is led to a new notion of unbroken wholeness which denies the classical idea of analyzability of the world into separately and independently existing parts. We have reversed the usual notion that the independent "elementary parts" of the world are the fundamental reality. Rather, we say that the interconnectedness of the whole universe is the fundamental reality, and that the "parts" are merely particular and contingent forms within this whole.

David Bohm

How do we know that nature is nonlocal?[4] In 1990, British physicists John Rarity and Paul Tapster performed an entanglement experiment based on double-slit interference. This experiment begins with the creation of two entangled photons (the experiment would be harder to do with electrons, but quantum physics predicts that the result would be the same) whose wave packets then move directly away from each other, as shown in **Figure 13.11**. The two packets then pass through separate double-slit apparatuses and, with the help of the mirroring devices shown, impact on separate viewing screens. Rarity and Tapster observed the overall pattern formed by millions of such entangled pairs.

As in the ordinary double-slit experiment, each particle's wave packet goes through both slit A and slit B. If the two particles were not entangled, the left-hand screen and the right-hand screen would each show the usual double-slit interference pattern.

Because the two photons move in opposite directions, if they had been ordinary Newtonian particles they would have impacted at identical distances x below the midpoint of the first screen, and y above the midpoint of the second screen (see the figure). That is, x would have been equal to y. But, because of quantum uncertainties, y does not necessarily equal x and the second impact point y can't be predicted from knowledge of the first point x. In fact, quantum physics predicts that the *difference* $y - x$ should form a typical interference pattern as shown in **Figure 13.12**.

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[4] This experiment was suggested in 1986 by Michael Horne and Anton Zeilinger; a similar experiment was performed by Z. Y. Ou and Leonard Mandel.

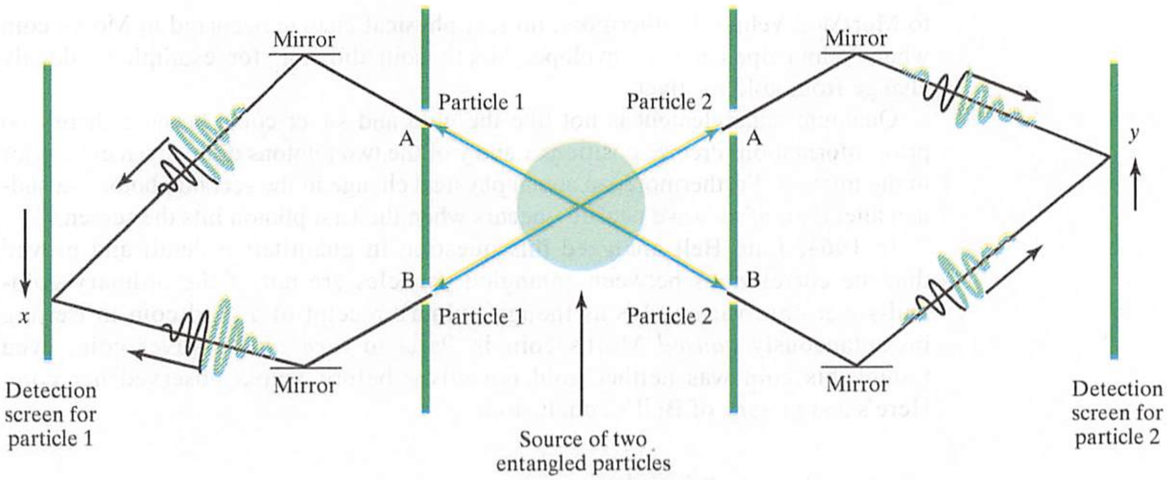

Figure 13.11

The position-entanglement experiment. Because of their entanglement, particles 1 and 2 coordinate their impact points x and y instantaneously, regardless of the distance between them. The wave packets shown are created at the "source" at the center of the figure. The mirrors only reflect these wave packets and are introduced only to bring each packet back together.

According to Figure 13.12, the two photons must mutually correlate their impact points x and y so as to make $y - x$ form an interference pattern, despite that fact that neither a precise x nor a precise y even existed (because of the uncertainty principle) prior to impact. Suppose that the experiment were altered slightly to allow the first photon to impact its screen just before the second photon impacts its screen (this would not change the experiment's outcome). Despite the fact that a precise x doesn't exist prior to impact, as soon as the first photon impacts its screen at some point x, the second photon's wave packet (which could be light-years away) must instantly alter itself to just "fit" the first particle's impact point, as shown in Figure 13.12. To see the significance of this, suppose that the interference pattern of Figure 13.12 has high points that are 1 mm apart, so that constructive interference occurs when $y - x$ equals 0 mm, 1 mm, 2 mm, 3 mm, and so forth. Then, after photon 1 impacts at some particular point x, photon 2 must impact preferentially at a point y that differs from x by 0 mm, 1 mm, 2 mm, etc., and must avoid the points that differ from x by 0.5 mm, 1.5 mm, 2.5 mm, etc. How can the second photon "know" which points to hit and which to avoid, when a specific x didn't even exist prior to the first photon's impact, and when the two photons are some distance (even light-years) apart? The second photon instantaneously obtains "knowledge" about the first photon's impact point, and alters its wave packet accordingly, despite their separation. Spooky, indeed!

Maybe this cooperation between different particles across a distance is not spooky. Maybe it's merely an example of the following common type of correlation between separated events: Suppose I inform Mort in Paris and Velma in Beijing that I've mailed one of them a gold coin and the other a silver coin. Without further information, neither one knows which coin they'll receive. But as soon as Velma opens her envelope she knows immediately what kind of coin Mort received, because the two coins must be different. There's nothing spooky about this correlation between separated events; it's due entirely to the prior information that I gave

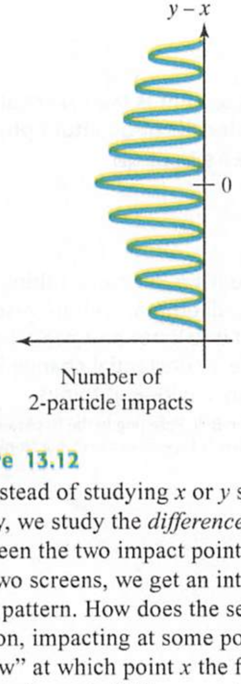

Figure 13.12

If, instead of studying x or y separately, we study the *difference* $y - x$ between the two impact points on the two screens, we get an interference pattern. How does the second photon, impacting at some point y, "know" at which point x the first photon impacted? The second photon instantly coordinates its impact pattern with the first photon's impact point, despite the fact that the uncertainty principle says that both impact points are uncertain in advance.

to Mort and Velma. Furthermore, no real physical change occurred in Mort's coin when Velma opened her envelope. Mort's coin did not, for example, suddenly change from gold to silver.

Quantum entanglement is not like the gold and silver coins because there's no prior information. Precise positions x and y of the two photons didn't even exist prior to the impacts. Furthermore, an actual physical change in the second photon—a sudden alteration of its wave packet—occurs when the first photon hits the screen.

In 1964, John Bell analyzed this question in quantitative detail and proved that the correlations between entangled particles are not of the ordinary gold-and-silver-coin variety. It's as though Velma's receipt of a gold coin in Beijing instantaneously *caused* Mort's coin in Paris to *turn into* a silver coin, even though his coin was neither gold nor silver before Velma observed her coin. Here's a summary of Bell's conclusion:

Non-locality means that we cannot discuss the different parts of space independently.

John Bell

The Nonlocality Principle

Quantum theory predicts that entangled particles exhibit behavior that can be explained only by the existence of real nonlocal (that is, instantaneous and distant) correlations between the particles. That is, a physical change in one particle causes instantaneous physical changes in all other particles that are entangled with that particle, no matter how far away those other particles may be.

Entanglement is *the* essential characteristic of quantum physics.

Erwin Schroedinger

For me it's a dilemma. I think it's a deep dilemma, and the resolution of it will not be trivial; it will require a substantial change in the way we look at things.

John Bell, Referring to the Implications of Aspect's Experiment Verifying Nonlocality

Bell also discovered ways in which the quantum predictions about entanglement could be experimentally tested. Clauser was the first to carry out such tests. Alain Aspect was the first to show that the connection occurs at faster than lightspeed and appears to be instantaneous, just as quantum theory predicts. The "two" particles literally form a single unified object, described by some physicists as a "two-particle." Two entangled particles do not coordinate their actions by means of communication between them; rather, their actions *must* be coordinated because they are a single unified object, but in two different places. Such a conclusion might seem to contradict relativity theory's prohibition on faster-than-light motion. But relativity says only that energy (matter or radiation) cannot travel faster than light. The connections referred to in Bell's principle do not transfer energy, so Bell's principle does not contradict relativity.

Quantum entanglement is quickly destroyed if one of the entangled particles contacts the external world. In the Rarity-Tapster experiment, for example, the entanglement is destroyed when either particle hits a screen. Despite this fragility, Danish physicists in 1999 proposed a practical method for entangling any number of ions (electrically charged atoms) by trapping them in electromagnetic fields and using lasers to create entanglements between them. This method was used in 2001 to entangle two tiny separated gas clouds, each containing a trillion cesium atoms. The two clouds were only a few millimeters apart and were demonstrated to remain entangled for only 0.0005 seconds, but larger distances and times are expected in the future, perhaps using solid samples rather than gases.

Entanglement and uncertainty could lead to powerful **quantum computers.** Conventional computers are built from many simple individual physical devices such as electronic switches that can have two values, namely "on" and "off." Such physical devices are called **bits** and their two states are labeled "0" and "1." Quantum computers would be built from many individual *quantum* systems, such as a single ion trapped in an electromagnetic field, that have two possible quantum states, such as a higher-energy state and a lower-energy state. Such a quantum system is called a **qubit** and, like ordinary bits, the two quantum states are labeled "0" and "1." But qubits exploit the quantum nature of these states. To understand this, let's return to the double-slit experiment where we saw that quantum uncertainties allow each individual electron to come through *both* slits. In this same sense, quantum uncertainties allow a qubit (such as an ion) to be in *both* its possible states, 0 and 1, at the same time. Physical operations carried out on such a qubit then operate on *both* states simultaneously.

The lesson to be learned from ... the origin of quantum mechanics is that ... somewhere in our doctrine is hidden a concept, unjustified by experience, which we must eliminate to open up the road.

Max Born

This doesn't sound terribly impressive, until you begin to consider the implications of more than a single qubit. Consider two qubits. A conventional computer built from two bits would have four possible states: 00, 01, 10, and 11. The computer can be in only one of these states at any one time. But a quantum computer, with each qubit in *both* the states 0 and 1, is in all four of its possible states simultaneously, and thus it can perform calculations on all four simultaneously instead of one at a time. And three qubits can be in eight states simultaneously. The number of simultaneous states increases enormously as the number of qubits increases, providing far more computational power.

Quantum computers would operate on the quantum states of their qubits by employing "control" qubits that would be connected with the computational qubits via quantum entanglement. If a quantum computer turns out to be feasible, it will be the quintessential quantum device, depending crucially on the two characteristic quantum phenomena: uncertainty and entanglement.

▶ CONCEPT CHECK 5 How many simultaneous operations could a 10 qubit quantum computer perform? (a) 10. (b) 100. (c) 8. (d) 64. (e) 512. (f) 1024.

▶ CONCEPT CHECK 6 If two electrons are entangled then (a) if one of the particles suddenly alters its wave packet, the other must also; (b) they must exert forces on each other; (c) they will become less entangled as they move farther apart; (d) both are part of a single matter wave; (e) they will become more entangled as they move farther apart.

13.4 WHAT DOES IT MEAN? QUANTUM REALITY

Quantum physics has a well-deserved reputation for being odd. Quantum uncertainty, nonlocality, and the surprising effect of detectors are about as far-removed as you can get from the world described by Newtonian physics. The odd results come from the non-Newtonian view that the world is made not of rigid, unchanging, pointlike particles but rather of continuous fields, and that these fields come in unified parcels or "quanta" of energy.

The oddness of quantum physics has stimulated unfounded rumors that there is something paradoxical or even mystical about quantum physics. The simultaneous appearance of wave and particle properties, for example, leads some to believe that it's impossible to consistently describe what's really going on in the microworld. But you've seen that quantum physics is basically about fields, and that particle-like aspects such as the tiny flashes on the screen seen in Figure 12.11 are really fields spread out over a Δx of atomic dimensions. There's no paradox here.

In a completely deterministic world, what we know as free will in humans is reduced to a mere illusion.... According to quantum mechanics, we cannot exclude the possibility that free will is a part of the process by which the future is created.

Edward Teller

As another example, one sometimes hears that quantum physics necessarily involves human observation, especially in connection with the surprising effects of detectors, as though some quantum phenomena couldn't occur without humans present to witness them. But the detector effect depends only on the interaction between an inanimate macroscopic device called a detector and a microscopic system such as an electron. It occurs perfectly well with no humans present to read the detector. In fact, the detector could be any macroscopic object upon which a microscopic object leaves a permanent mark. For instance, when a cosmic ray hits a moon rock and leaves a permanent mark, a similar "detection" process occurs even though no human is involved.

The quantum uncertainty of matter arises because each material quantum, an electron for example, is spread out in both position and velocity simply because it's a *field*. When we say that an electron's position is uncertain, we simply mean that its matter field is spread out over a range Δx of positions. The electron really has no definite position.

In the double-slit experiment with electrons, for example, each electron (each quantum) comes through both slits. Just after passing through the slits, the quantum has two separated parts, one near each slit, yet the entire quantum acts as a single unified object. When it arrives at the screen, its two parts form a spread-out interference pattern that's seen in the overall pattern formed by many individual interactions (Figure 12.9). But the quantized nature of the matter field demands that each individual quantum's energy transfer is "all or nothing," so all its energy transfers to a single atom (Figure 12.11). At the instant of the transfer, the entire spread-out quantum (it might be 1 cm wide for example) instantaneously collapses to atomic dimensions. Electrons are still spread-out quanta even after being absorbed by an atom, but with a Δx that's now spread over a region of only atomic dimensions.

A similar collapse occurs whenever any detector measures the position of an electron or any other particle. The electron wave packet interacts with an atom or molecule in the detector, and thus the packet collapses to a small Δx around that location. The electron resided all over a much larger region just before the measurement occurred, and the measurement *created* a position (to within a Δx of atomic dimensions) for the electron. Measurements partly create the properties they detect. A position measurement creates an (approximate) position, and a velocity measurement creates an (approximate) velocity (**Figure 13.13**).

The surprising effect of detectors, noted in connection with Figures 13.8 and 13.9, happens for reasons similar to the collapse of the wave packet in the double-slit experiment. You'll recall that each electron (each quantum) goes through both slits so long as the detector is in the "off" mode, but as soon as the detector is switched on, half the electrons go through slit A and the other half go through slit B. This is because each electron (each quantum) must either entirely interact, or not interact, with the switched-on detector, and the interaction (or non-interaction) causes each quantum to collapse to the vicinity of one or the other slit.

Non-locality is written all over these phenomena, even though this section so far has related only to non-interacting particles. But when two or more particles interact, non-locality can become quite explicit via quantum entanglement. Entanglement means that two or more particles share a single wave packet. The two must then behave as a single unified object. If something happens to one of them, the entire two-particle wave packet collapses and so some other corresponding thing must instantaneously happen to the other. This has been demonstrated with pairs of photons.

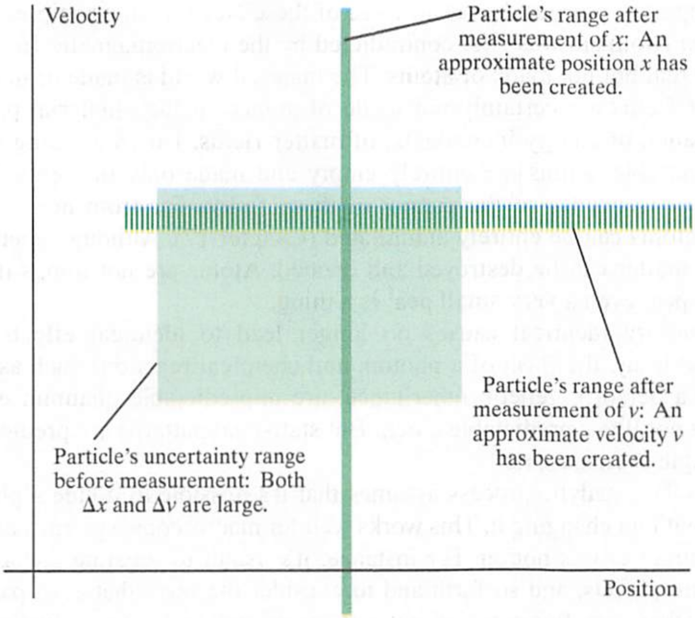

Figure 13.13
The effect of a position measurement or of a velocity measurement is to create a position and velocity for the measured particle.

Quantum physics predicts that any pair of particles that have ever, at anytime in the past, interacted with each other are entangled with each other, although the degree of entanglement might be tiny. In fact, if particles A and B are entangled, and if another particle C then interacts with B, not only will B become entangled with C but A will also become entangled with C. Thus the entire universe, which was created in a single microscopic event—just the sort of thing that creates entangled particles—might be entangled with itself. But such a statement is hypothetical to say the least, because it's always dangerous to extrapolate the theories of physics to the entire universe.

I think that what we will eventually make of all this is still anybody's guess. We haven't yet worked out a "post-Newtonian viewpoint" of how the world works, a viewpoint having the philosophical grandeur of the Newtonian clock-like universe, and maybe we don't need such a viewpoint. There have been attempts to align these quantum phenomena with religious or psychological notions—efforts that have in my opinion been interesting but dubious. In the next section, I'll discuss a few notions that are directly tied to what we already know about quantum physics.

There are two sorts of truth: trivialities, where opposites are obviously absurd, and profound truths, recognized by the fact that the opposite is also a profound truth.
Niels Bohr

When it comes to atoms, language can be used only as in poetry. The poet, too, is not nearly so concerned with describing facts as with creating images.
Niels Bohr

13.5 TOWARD A MODERN WORLDVIEW

Recall three key features of the **Newtonian worldview** (Chapter 5):

Atomism Atoms form the fundamental reality. Newton called them "solid, massy, hard, impenetrable particles" that "never wear or break in pieces."

Predictability The future is hard-wired into the present. Once it got started, the clockwork universe had to evolve precisely as it has evolved, right down to you scratching your nose just now.

Analysis Science progresses by separating phenomena into their simplest components and studying those components. Thus we can understand the universe by understanding its simplest component particles.

We shall always be able to imagine other [false] theories—like the boring world of particles governed by Newtonian mechanics.
Steven Weinberg, Physicist, in *Dreams of a Final Theory*

Not exist—not exist! Why I can see the little beggars there in front of me as plainly as I can see that spoon!

Ernest Rutherford around 1915, When Asked over a Dinner Table Whether He Believed That Atomic Nuclei Really Existed

I don't think there's one unique real universe.... Even the laws of physics themselves may be somewhat observer dependent.

Stephen Hawking

Contemporary physics denies all three of these Newtonian principles:

Atomism Atomism was first contradicted by the electromagnetic field, which is physically real but not made of atoms. The material world is made of matter fields, and matter fields are certainly not made of atoms. In fact, material particles are merely quanta, or energy increments, of matter fields. Far from being solid, hard, and impenetrable, atoms are entirely empty and made only of fields. Their rest-mass is a consequence of the energy of these fields. Far from never wearing or breaking, atoms can be entirely annihilated (Chapter 17). Although energy is indestructible, matter can be destroyed and created. Atoms are not things in the same way that a pea, even a very small pea, is a thing.

Predictability Identical causes no longer lead to identical effects. A single radioactive decay, the flash of a photon, and chemical reactions such as those that determine a person's genetic inheritance, are unpredictable quantum events. The universe is not like a predictable clock. But statistical patterns are predictable, even though single events are not.

Analysis The analytic process assumes that it's possible to divide a phenomenon into parts without changing it. This works well for macroscopic systems, but quantum theory contradicts this notion. For instance, it's useful to separate the solar system into the sun, planets, and so forth and to consider the ways that each part interacts with each other part. But quantum entanglement implies that we cannot always consider a microscopic system to be made of separable parts. Two entangled particles are so closely connected that it is not possible even to think of them as independent particles. There is a microscopic wholeness that is not obvious to our macroscopic eyes.

In short, **the quantum worldview** asserts that the universe is made of nonmaterial fields, the particles of the microscopic world are merely quantized increments of these fields, the future is inherently unpredictable, and nature is deeply interconnected and indivisible. This is radically different from the Newtonian view of the world as a machine or a clock.

Despite more than a century of modern physics, a post-Newtonian worldview is still not in sight, and the metaphor of the mechanical universe continues to deeply and inappropriately influence our culture's view of physical reality. Will we construct a scientifically accurate and humane worldview that can sustain us in the modern age? Humankind has barely scratched the surface of this task.

13.6 HOW DO WE KNOW? OBSERVING ATOMIC SPECTRA

So far, Chapters 12 and 13 have presented the fundamental principles of quantum physics and their significance. Now let's study perhaps the most significant practical example of quantum physics: the quantum atom. I'll begin by presenting what scientists know experimentally, and how they know it.

The most accurate scientific measurements known are made with **spectroscopes,** devices that measure the frequencies or wavelengths present in radiation. **Figure 13.14** shows how a spectroscope studies the visible radiation emitted by a light source such as a heated, glowing gas. Radiation from the source passes through a single thin slit and emerges as a narrow beam. This beam passes through a glass prism or other device that can separate the light beam's different frequencies (colors). Light beams bend when they pass from one medium into another, such as from air into glass. You might have noticed this effect in a pool of water, where partly submerged objects appear to bend at the water's surface. The reason a prism separates a light beam's frequencies is that different

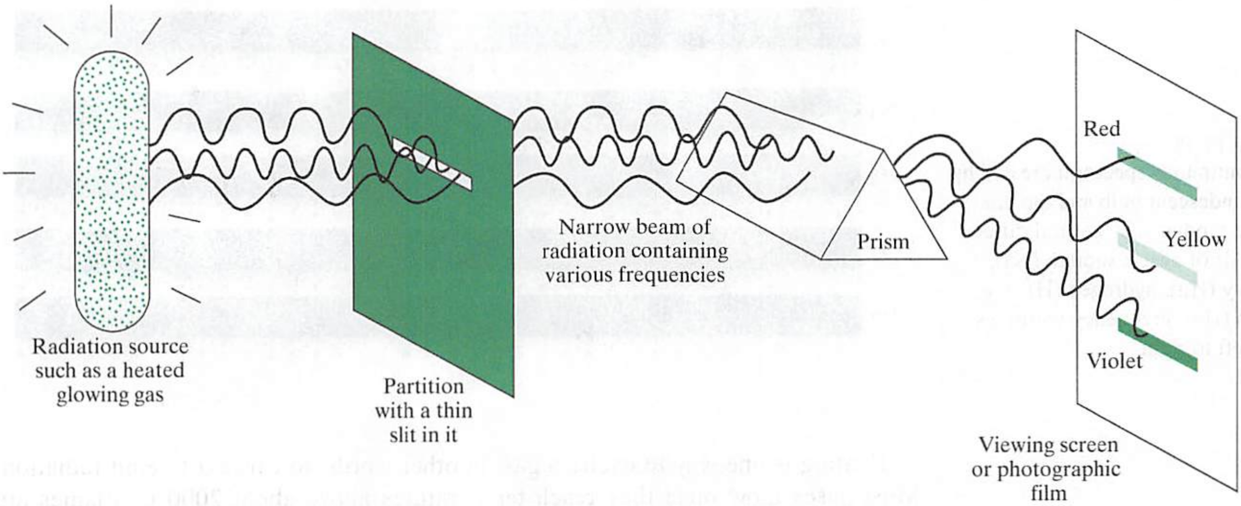

Figure 13.14
One type of spectroscope.

frequencies bend by different amounts at each glass surface. This separation of frequencies is also seen in a rainbow, where each raindrop acts like a small prism for sunlight.

By the time the light beam exits the far side of the prism, it has separated into many beams, one for each frequency present in the original beam. A screen or photographic film intercepts all these light beams and displays their various colors. Each beam's frequency or wavelength can be determined by measuring the position at which it strikes the screen. The set of frequencies measured in such an experiment is called the **spectrum** of the source that emitted the radiation.

Different kinds of spectroscopes operate in every part of the electromagnetic spectrum. For example, a radio receiver is a kind of spectroscope for separating and detecting the frequencies of radio radiation present in a room. Spectral measurements yield an enormous quantity and variety of information. For instance, by placing a spectroscope at the viewing end of a telescope, astronomers can infer information about the mass, temperature, motion, chemical composition, and other properties of stars and galaxies. Most of our data about the microscopic world come from spectral measurements.

A glowing solid or liquid, such as a lightbulb's metal filament heated to 3000°C, emits a **continuous spectrum,** one that contains an unbroken range of visible frequencies and spreads out in a continuous band of color. Rainbows show the continuous spectrum of the sun. But surprisingly, if a dilute (low pressure) gas is heated until it glows, it emits a spectrum that is not continuous. Instead, it is restricted to a limited number of precise frequencies, each frequency appearing on the screen as a narrow slit-shaped line (Figure 13.14). Such a collection of precise separated frequencies is called a **line spectrum.** Figure 13.15 shows a continuous spectrum and four line spectra from four different gases. As you can see, the line spectra for different gases are different. Because each gas has its own characteristic spectrum, it's possible for spectroscopy to identify different gases. This is, for example, how we know the chemical compositions of stars.

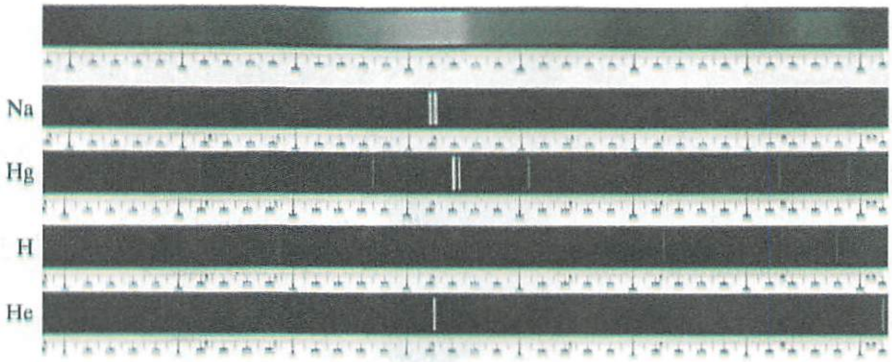

Figure 13.15
The continuous spectrum created by an incandescent bulb and the line spectra produced by several different kinds of gases: sodium (Na), mercury (Hg), hydrogen (H), and helium (He). Frequency increases from left to right.

Heating is one way to **excite** a gas, in other words, to cause it to emit radiation. Most gases glow once they reach temperatures above about 2000°C. Flames are glowing gases of this sort, heated by combustion. The sun's light comes from hot gases on its visible surface, which has a temperature of 5500°C. A second way to excite a gas is to send an electric current through it. This process, called **electric discharge,** creates the light seen in neon tubes, mercury or sodium vapor bulbs, sparks, and lightning strokes. Electric discharge tubes containing a dilute gas can be used to study the gas's spectrum (**Figure 13.16**).

How can we explain the observed spectra? As you know, when any substance is heated, the random kinetic energy of its atoms increases. The Greek model of the atom offers no reason why this should cause materials to glow, but the planetary model of the atom does: Heating energizes the subatomic parts of the atom, some of these parts are electrically charged, and these vibrating and orbiting charged particles should send out EM radiation. But why do gases emit line spectra rather than continuous spectra? Why are only some wavelengths emitted, rather than all wavelengths? What determines which wavelengths are emitted? The planetary atom offers no clue.

There is an even more glaring problem with the planetary atom. As explained in **Figure 13.17**, an orbiting electron can be thought of as vibrating along two directions at once. But you know (Chapter 9) that vibrating charged particles emit radiation, so an orbiting electron should radiate electromagnetic energy all the time! But observation shows that atoms do not radiate all the time. Worse yet, if an electron did radiate all the time, it would have to continually lose energy, which would cause it to spiral into the nucleus and cease orbiting. So the planetary model predicts that atoms should collapse! Something's wrong.

Atoms are completely impossible from the classical [Newtonian] point of view.
Richard Feynman

One can imagine a universe in which Newtonian physics would be correct even down to the smallest sizes, but it would be a pretty boring place. Atoms could not exist, so there would be no chemistry, so life would be impossible. The universe would be a predictable, lifeless, machine.

CONCEPT CHECK 7 You might have noticed that as you heat a metal hot plate, it first glows dark red and then becomes brighter and whiter. Just before it begins to glow, we might expect such a hot plate to emit (a) ultraviolet radiation; (b) infrared radiation; (c) no radiation at all.

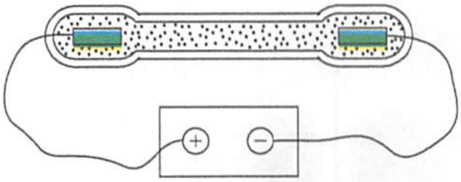

Figure 13.16
An electric discharge tube containing a dilute gas. With a large enough charge on the two *electrodes* at the ends of the tube, the electrodes *discharge* by forcing electrons off the negative electrode. These electrons excite atoms of the gas by colliding with them as the electrons move through the tube toward the positive electrode. The gas atoms then lose their energy of excitation by emitting photons having the characteristic frequencies of these atoms.

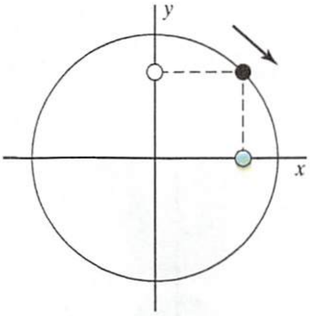

Figure 13.17
An orbiting electron (black circle) can be thought of as making two vibrational motions: When viewed from below, it appears to be vibrating along the x-axis (green circle), and when viewed from the side, it appears to be vibrating along the y-axis (white circle).

CONCEPT CHECK 8 As the hot plate in the preceding Concept Check goes from dark red to white, its spectrum would (a) change from a spectrum containing only red lines to one containing only white lines; (b) change from a spectrum containing only red lines to one containing many different colors; (c) change from a dim continuous red spectrum to an intense continuous white spectrum; (d) change from a dim continuous red spectrum to an intense continuous spectrum that included all the colors.

13.7 THE QUANTUM ATOM

To see how quantum physics describes atoms, we'll examine only the simplest atom, hydrogen, made of one proton and one electron. Because the electron is 2000 times less massive than the proton, it does nearly all the moving, orbiting in the electromagnetic field of a nearly stationary proton. To a good approximation, you can ignore the proton's motion, treating it as a tiny material particle at rest. The **quantum model of the atom** describes the electron's matter field.

Imagine a hydrogen atom that's been at rest and isolated for some period of time. Since there is no reason for anything to be changing in such an atom, you would expect the electron's matter field to have a stationary, unchanging shape. A detailed mathematical study of the Schroedinger equation for a hydrogen atom yields precise predictions as to the allowed shapes, or patterns, for the electron's matter field. There turn out to be many such allowed patterns. Figure 13.18 is one way of picturing a few of these **quantum states of the hydrogen atom.** Each of the 10 patterns

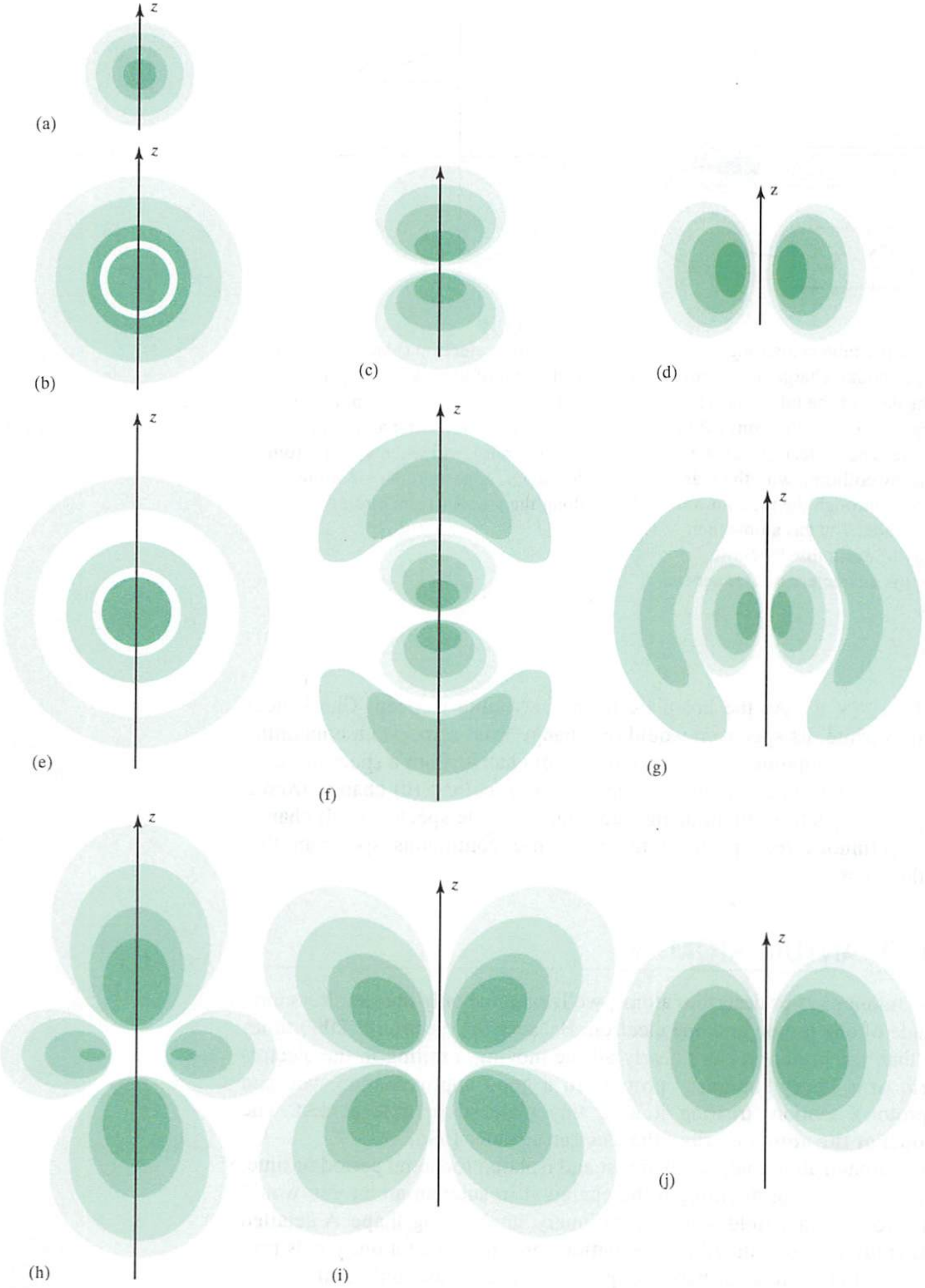

Figure 13.18
Patterns of the microworld. Ten different allowed matter waves, or quantum states, for the electron in a hydrogen atom. If the electron's position were measured, it would have a greater probability of being found in the darker regions where the matter field is more intense.

shown is an allowed pattern for the electron's matter field. Darker regions are regions of higher intensity, and unshaded regions are regions of low or zero intensity. To visualize the full three-dimensional patterns, imagine rotating the two-dimensional diagram around the vertical z-axis shown in each diagram.

Recall, from Chapter 12 (Section 12.6), what the intensity of a matter field means. If you measure an electron's position sufficiently precisely, you'll find it to be at some fairly precise point x within the hydrogen atom. The intensity of an electron's matter field at any particular point x is the probability that, when a sufficiently precise measurement is made, the electron will be found to be at that point x. Briefly, the electron is more likely to be found in the darker regions of Figure 13.18 and less likely to be found in the lighter regions. However, don't let the language of the preceding sentence mislead you into thinking that "the electron" was actually at point x before the measurement was made; as you know, "the electron" is a field quantum and the position measurement *creates* a position x for it. Before the measurement, the quantum had one of the shapes shown in Figure 13.18.

Let's discuss some of these shapes. State (a) occupies a smaller volume than does any other state. In this state, the electron is highly likely to be found close to the nucleus and is equally likely to be found in any direction out from the nucleus (upward, downward, to the left, etc.).

State (b) is larger, so the electron is likely to be found farther from the nucleus than is an electron in state (a). State (b) has an interesting gap partway out from the nucleus, representing a distance from the nucleus at which the electron will never be found. It is interesting that an electron in state (b) can be found inside or outside this distance but never at this distance. How can an electron be sometimes inside and sometimes outside this distance without sometimes being at this distance? The answer is that a tiny particle-like electron is not present except when a position measurement is made; between measurements, only the matter field shown in the figure exists. State (e) is larger still. The electron is likely to be found still farther from the nucleus and there are now two gaps where the electron will not be found.

Unlike states (a), (b), and (e), the remaining seven states shown are not the same in every direction. State (d) is shaped like a fat doughnut circling the z-axis and is reminiscent of the planetary model of the atom. State (c) is shaped like a dumbbell (two spheres) along the z-axis. It is separated into two parts, between which the electron is not found.

The figure shows 10 of the most common quantum states of hydrogen, nature's simplest atom. There are many more states, not shown in the figure. Each pattern represents one state (or condition) in which a hydrogen atom can exist.[5] Atoms with more than one electron have more complex quantum states, but they all are found by solving the Schroedinger equation in the form appropriate to that particular atom.

In addition to predicting these states, the Schroedinger equation predicts that each of them has just one specific energy. That is, the energy of each state shown in Figure 13.18 has no quantum uncertainty. From the figure, we can even make educated guesses about the **energy level** (the amount of energy) of each state. Because the force by the proton on the electron is attractive, one would have to do work to pull an electron outward, away from the nucleus. So the electromagnetic energy of

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[5] A hydrogen atom can also exist in a combination of two or more of these allowed quantum states.

the atom increases as the electron gets farther from the nucleus. This is just like gravitational energy: Because Earth exerts an attractive force on a rock, the rock's gravitational energy increases when the rock is lifted upward. So the smallest matter field, the one bunched most tightly around the nucleus, should have the lowest energy. Judging from the figure, this is state (a). Because of the gravitational analogy, this is called the **ground state.** It is the state in which the electron is as close to the nucleus as it can be. Recall that if the universe obeyed Newtonian physics, atoms would collapse because orbiting electrons would radiate their energy away and fall into the nuclei. In contrast to this, there is a smallest possible quantum state of hydrogen, namely state (a). The atom cannot radiate energy when it is in this state, simply because there are no states of lower energy. An atom in its ground state is like a ball that's rolled all the way downhill and can't roll any lower. Quantum physics prevents atoms from collapsing!

Other states are called **excited states** because they are more energetic than the ground state. The precise energy of each quantum state can be calculated using Schroedinger's equation. Figure 13.19 shows the lowest five of these precise energies (but without showing any actual numerical values). As expected, state (a) has the lowest energy, labeled E_1. States (b) (c) and (d) all happen to have the same energy, labeled E_2. The remaining six states pictured in Figure 13.18 all happen to have the same energy, labeled E_3. Two further energy levels, labeled E_4 and E_5, corresponding to additional quantum states, are shown. Notice that the energy levels get closer together as the energy increases. An **energy-level diagram** like this Figure is a prime example of the quantum or "digital" nature of the microscopic world: If the energy of a hydrogen atom's electron is measured, it will be found to have one of these energies and no other. For instance, it cannot have an energy between E_1 and E_2.

> You surely must understand, Bohr, that the whole idea of quantum jumps necessarily leads to nonsense.... If we are still going to have to put up with these damn quantum jumps, I am sorry that I ever had anything to do with quantum theory.
>
> Schroedinger, during a Conversation with Niels Bohr

Each of these quantum states represents an isolated hydrogen atom that isn't changing. What happens when something does change? What happens, for example, when an atom emits radiation? As we know, radiation is quantized and so can be observed only in energy bundles called photons. An atom must emit at least one quantum of energy—one photon—whenever it radiates. This means that it must be in an excited state to begin with, and it must transition to a lower-energy state. The transition must be instantaneous, because the atom is not allowed to have any energy other than the ones shown in Figure 13.19. Such an instantaneous transition of an atom from one quantum state to another is called a **quantum jump.**

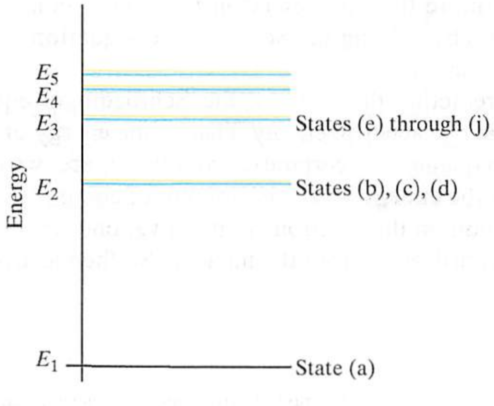


Figure 13.19

The lowest five energy levels for the electron in a hydrogen atom. When measured in joules, these atomic energy levels are quite small: The energy difference, $E_2 - E_1$, between the lowest two levels is only 1.6×10^{-18} joules.

Figure 13.20 shows a common way of representing quantum jumps. The transition is shown as an arrow on an energy-level diagram stretching from the initial to the final energy. The diagram represents an atom making a transition from the E_4 to the E_2 energy level and also indicates that a single photon is emitted, carrying away the energy. You can picture this by imagining that, in Figure 13.18, a state (not shown in Figure 13.18) having energy E_4 suddenly vanishes and is replaced by state (b), (c), or (d). The hydrogen atom truly jumps from one pattern to another.

Now you can understand atomic spectra and the **emission of radiation by an atom.** Atoms emit radiation when they quantum-jump to a lower energy level, creating and emitting a photon in the process. Recall (Chapter 12) that a photon's energy is hf, where h is Planck's constant and f is the photon's frequency. Conservation of energy tells us that the energy hf of the emitted photon must equal the energy difference in the quantum jump; that is,

$$hf = (\text{energy of high-energy state}) - (\text{energy of low-energy state})$$

So if you know the energies E_4 and E_2, you can find the frequency of the photon emitted in a quantum jump between these two levels. Physicists can calculate the precise energy levels from the Schroedinger equation and then find the frequency of the photon emitted in each possible quantum jump between pairs of energy levels.

How do we know Schroedinger's equation is reliable? **Figure 13.21** shows, on an energy-level diagram, the 10 downward quantum jumps that are possible between the lowest five energy levels for hydrogen. Since the photon's energy is equal to the atom's energy change, the length of the arrow representing each quantum jump is proportional to the frequency of the radiation emitted in that quantum jump. So a hydrogen atom can emit 10 different frequencies by quantum-jumping from the E_2, E_3, E_4, or E_5 levels downward into one of the lower levels. **Figure 13.22** shows these 10 frequencies quantitatively. Since Schroedinger's equation predicts the energy levels, it also predicts these frequencies.

When one uses a spectroscope to measure the spectrum of atomic hydrogen gas, the frequencies turn out to be precisely those indicated in Figure 13.22 and predicted by quantum theory. Schroedinger's equation first gained fame because Schroedinger was able to show that it correctly predicted these frequencies. For just one example, the Schroedinger equation predicts the wavelength (which can be calculated from the frequency) of the photon emitted when a hydrogen atom quantum jumps from energy E_2 to E_1 to be 1.21568×10^{-7} meters. Actual measurement shows it to be 1.21566×10^{-7} meters

> There is no part of chemistry that does not depend, in its fundamental theory, upon quantum principles.
>
> Linus Pauling, Chemist

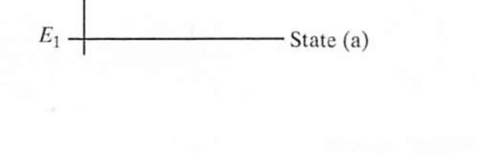


Figure 13.20
A symbolic representation of a quantum jump from one quantum state to another. A photon, carrying energy $E_4 - E_2$, is emitted at the instant the quantum jump occurs.

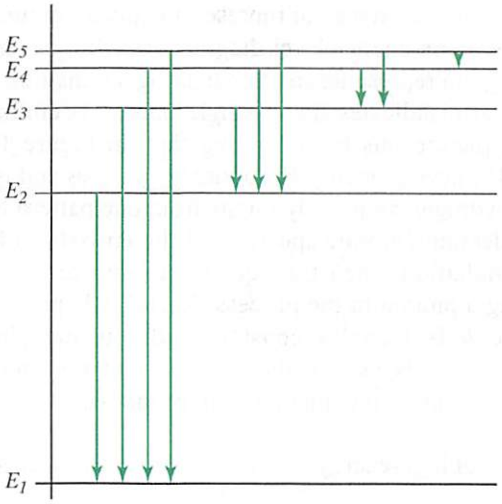


Figure 13.21
The possible downward quantum jumps between the lowest five energy levels of the hydrogen atom.

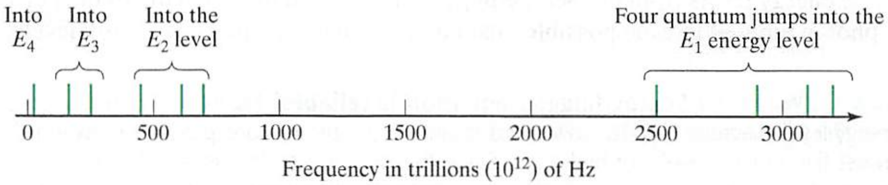


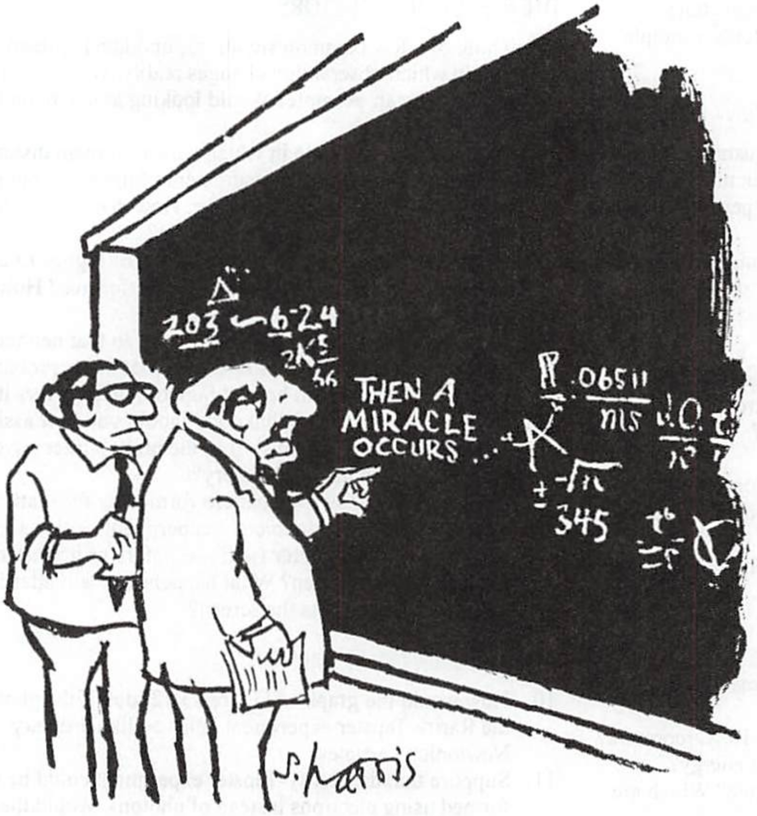
Figure 13.22
The frequencies of the photons that are given off during the quantum jumps shown in Figure 13.21.

plus or minus a small error. Many other hydrogen frequencies and wavelengths have been predicted and measured with similarly accurate agreement. Physicists know that there must be something right about any equation that can predict six-figure numbers.

CONCEPT CHECK 9 In three dimensions, the quantum state in Figure 13.18(h) is best described as having the shape of (a) a dumbbell; (b) a doughnut; (c) two dumbbells oriented in different directions; (d) two doughnuts oriented in different directions; (e) a dumbbell and a doughnut.

CONCEPT CHECK 10 Among the 10 quantum jumps between the five energy levels of hydrogen shown in Figure 13.21, the one that will create the photon with the highest frequency is (a) E_5 to E_4; (b) E_5 to E_1; (c) E_5 to E_2; (d) E_2 to E_1.

CONCEPT CHECK 11 How many different frequencies can be created by quantum jumps among only the lowest six energy levels of hydrogen? (a) 6. (b) 5. (c) 10. (d) 14. (e) 15.



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Answers to Concept Checks and odd-numbered Conceptual Exercises and Problems can be found in the back of the book.

Review Questions

THE UNCERTAINTY PRINCIPLE

1. Does the particle represented by the matter field of Figure 13.2 have a precise position? A precise velocity?
2. Which wave packet of Figure 13.3 has the more precise position? The more precise velocity?
3. Does the uncertainty principle say that a particle must have a Δx that is larger than some prescribed value? What does it say?
4. Does a baseball have large quantum uncertainties or small ones? Why?

THE EFFECT OF DETECTORS

5. What happens to a particle's wave packet when a position measurement is performed?
6. Is it possible for a single microscopic particle's matter field to be spread out over macroscopic dimensions, such as several meters or larger? Give an example.
7. Give an example in which the switching on of a detector causes a particle's matter field to quantum-jump.
8. What is meant by a nonlocal effect?

QUANTUM ENTANGLEMENT

9. What is entanglement?
10. What does Bell's principle tell us about entangled particles?

11. What does the Rarity-Tapster experiment demonstrate?
12. Can the nonlocal connections described by Bell's principle transfer energy instantaneously?

QUANTUM REALITY AND A MODERN WORLDVIEW

13. According to the standard interpretation of quantum theory, which of the following are actually inherent in nature: predictability, precise positions for microscopic particles such as electrons?
14. Describe at least two key ideas of the Newtonian worldview that are contradicted by quantum physics.

OBSERVING ATOMIC SPECTRA

15. What is the purpose of the prism in a spectroscope?
16. What is the purpose of the thin slit in a spectroscope?
17. Exactly what is measured by a spectroscope?
18. Describe two ways to excite a gas.
19. When we excite a gas, what happens to its atoms?
20. Describe one way in which the planetary model disagrees with observations of atomic spectra.
21. There's a really huge problem with the planetary model of the atom. What is it?

THE QUANTUM ATOM

22. Describe the three-dimensional shapes of some of the states in Figure 13.18.
23. Exactly what does one of the states in Figure 13.18 represent?
24. Which state(s) in Figure 13.18 has the lowest energy?
25. Which state(s) in Figure 13.18 is a ground state? Which are excited states?
26. Consider any one of the states in Figure 13.18. In this state, does the electron have a predictable energy? A predictable position? A predictable velocity?
27. Describe the process by which atoms create radiation.
28. What is meant by a quantum jump in an atom?
29. How many different frequencies are emitted in the quantum jumps shown in Figure 13.21?

Conceptual Exercises

THE UNCERTAINTY PRINCIPLE

1. Arrange the following objects in order, beginning with the object having the largest uncertainty range and ending with the one having the smallest: proton, glucose molecule $C_6H_{12}O_6$, helium atom, baseball, electron, grain of dust, water molecule, automobile.
2. If Planck's constant were smaller than it is, how would the uncertainty principle be affected? What if Planck's constant were zero?
3. How would it affect you if Planck's constant were 1 J/Hz instead of 6.6×10^{-34} J/Hz?
4. If Planck's constant were smaller than it is, would this affect the sizes of atoms? If so, how?

THE EFFECT OF DETECTORS

5. Think of a few common situations, unrelated to quantum theory, in which observation changes reality. Would public opinion polls be an example? Would looking at the moon be an example?
6. One everyday example in which a measurement disturbs the measured object is the measurement of the temperature of a pan of water using a thermometer. How does this disturb the temperature? Is this a quantum effect?
7. What would happen to the wave packet of Figure 13.2 if an accurate velocity measurement were performed? How would the measurement affect Δx and Δv?
8. Your friend flips a coin but covers it up so that neither of you can tell whether it is heads or tails. What odds (probability) would be fair to put on heads? Suppose he uncovers it and you see that it is tails. What odds should you now assign to heads? Does this sudden shift in the probabilities have anything to do with quantum theory?
9. Figure 13.8(a) shows the pattern formed by the matter wave on the screen in the double-slit experiment. Is this a graph of a single electron's matter field just before or just after the electron hits the screen? What happens to the matter field when the electron hits the screen?

QUANTUM ENTANGLEMENT

10. How would the graph of Figure 13.12 look if the photons in the Rarity-Tapster experiment behaved like ordinary Newtonian particles?
11. Suppose that the Rarity-Tapster experiment could be performed using electrons instead of photons. Would the outcome still be an interference pattern like Figure 13.12?

QUANTUM REALITY AND A MODERN WORLDVIEW

12. Electrons do not normally have precise positions. How can you cause an electron to have a (fairly) precise position?
13. Electrons do not normally have precise velocities. How can you cause an electron to have a (fairly) precise velocity?
14. List several general ways in which nature is non-Newtonian.
15. List several specific experiments that show that nature is non-Newtonian.
16. List several specific experiments that show that nature is Newtonian.

OBSERVING ATOMIC SPECTRA

17. In what ways is your radio a type of spectroscope?
18. In what ways does a radio (preceding exercise) differ from the spectroscope described in the text?
19. Why do spectroscopes use a thin slit (Figure 13.14) rather than, say, a round hole?
20. Why, when different materials burn, do they often create flames of different colors?
21. How might the chemical composition of a burning substance be determined?
22. If you compared the spectra from two sodium vapor lightbulbs, would they be the same? What if you compared a sodium vapor bulb with a mercury vapor bulb?

THE QUANTUM ATOM

23. Explain, in terms of inertia, why the electron does nearly all the moving in a hydrogen atom.
24. Describe the three-dimensional shape of the quantum state shown in Figure 13.18(f).
25. Describe the three-dimensional shape of the quantum state shown in Figure 13.18(g).
26. Describe the three-dimensional shape of the quantum state shown in Figure 13.18(i).
27. Describe the three-dimensional shape of the quantum state shown in Figure 13.18(j).
28. If a very accurate measurement of an atom's mass could be made in an excited state and in its ground state, would any difference be found? (*Hint*: Remember $E = mc^2$.)
29. What happens to an atom's mass when it emits a photon? (*Hint*: Remember $E = mc^2$.)
30. Among the 10 quantum jumps between the five energy levels of hydrogen shown in Figure 13.21, which one creates the lowest-frequency photon?
31. In Figure 13.21, which quantum jump creates the higher-frequency photon, E_4 to E_3 or E_4 to E_2? Which of the two photons has the longer wavelength?
32. In Figure 13.21, which quantum jump creates the highest frequency, E_5 to E_4, E_4 to E_3, E_3 to E_2, or E_2 to E_1? Which creates the longest wavelength?
33. The four spectral lines of hydrogen photographed in Figure 13.15 have wavelengths and frequencies that agree precisely with the four lowest-energy transitions into hydrogen's second energy level, E_2. Which three of these four lines are graphed in Figure 13.22?

Problems

THE UNCERTAINTY PRINCIPLE

1. An electron (mass = 9.1×10^{-31} kg) has a velocity uncertainty $\Delta v = 1$ m/s. How large must its position uncertainty be? Express your answer in millimeters.
2. A proton (mass = 1.7×10^{-27} kg) has a velocity uncertainty $\Delta v = 1$ m/s. How large must its position uncertainty be? Express your answer in millimeters. If you worked the preceding problem, then compare the two answers.
3. **MAKING ESTIMATES** The electron in a ground-state hydrogen atom remains within a sphere measuring roughly 10^{-10} meters across. An electron's mass is about 10^{-30} kilograms. Use this data along with Heisenberg's uncertainty principle to estimate the velocity of this electron. (*Hint*: In the ground state, the electron's velocity should be roughly equal to the uncertainty in its velocity, in other words $\Delta v = v$. See the discussion at the end of Section 13.1.) What fraction of lightspeed is this?

THE QUANTUM ATOM

4. For the hydrogen atom, the energy difference $E_2 - E_1$ between the lowest two levels (Figure 13.19) is 16×10^{-19} J. Find the frequency of the photon emitted when a hydrogen atom quantum-jumps from state 2 to state 1. In which region of the spectrum is this (Figure 9.27)?
5. For the hydrogen atom, the energy difference $E_3 - E_2$ between the second and third levels (Figure 13.19) is 3×10^{-19} J. Find the frequency of the photon emitted when a hydrogen atom quantum-jumps from state 3 to state 2. In which region of the spectrum is this (Figure 9.27)?
6. From the information given in the preceding two problems, find the energy difference $E_3 - E_1$ between the third and first energy levels of the hydrogen atom. Find the frequency of the photon emitted when a hydrogen atom quantum-jumps from state 3 to state 1. In which region of the spectrum is this?