12.1 Introducing Quantum Theory

How does the microscopic world differ from the world as you know it? The laws of classical physics govern the motion of everyday objects, such as baseballs, automobiles, and planets. Do these laws apply to the microscopic world?

In classical physics, Newton's laws describing forces and Maxwell's work on electromagnetic radiation form the basis for the study of mechanics, electricity, and magnetism. However, by the late 1800s, experiments applying these laws and theories to the study of newly discovered subatomic particles were leading to some very strange results.

Physicists such as J.J. Thomson discovered that Newton's laws failed to explain the behaviour of electrons and atoms. Similarly, although Maxwell correctly described electromagnetic phenomena in the everyday world, his equations failed to describe the microscopic world. This microscopic world is called the quantum world, where **quantum** refers to a very small increment of energy. The study of the behaviour of these very small bundles of energy, called **quantum theory**, shook the classical foundations of physics in the early twentieth century. In this section, you will see how quantum behaviour is different from anything described before.

quantum the smallest amount of energy that a particle can emit or absorb; the plural is quanta

quantum theory the theoretical basis of modern physics that explains the nature and behaviour of matter and energy at the atomic and subatomic levels

Particles and Waves

According to Newton's laws and Maxwell's equations, energy can be carried from one point to another in two ways: by particles (such as hockey pucks and tennis balls) and by waves (such as sound and earthquake waves). We have an understanding of particles and waves through our everyday experiences, and it is natural to use this intuition when we consider the behaviour of all objects. However, we will see that this intuition is not accurate in the quantum world.

How Do Waves and Particles Differ?

Consider the double-slit experiment, which you learned about in Chapter 9. **Figure 1(a)** shows light incident on an opaque barrier that contains two extremely narrow openings. Recall from Chapter 9 that during a double-slit experiment, an interference pattern consisting of a series of alternating bright and dark fringes forms on the screen on the right. The bright fringes are produced by constructive interference between light waves that pass through the two slits, and the dark fringes are produced at locations where destructive interference occurs. Other types of waves, such as sound and water waves, produce similar results.

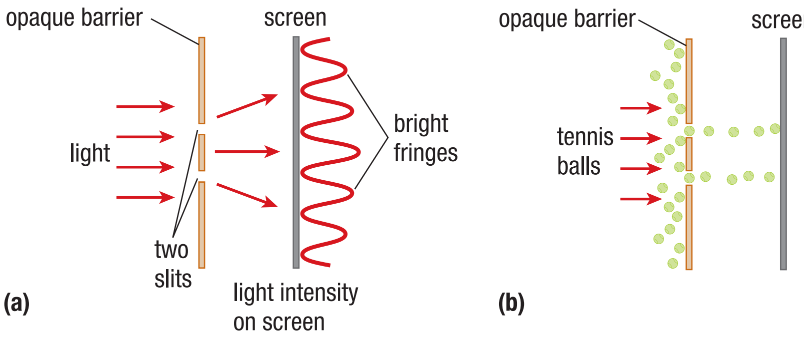


Figure 1 (a) When light passes through a double slit, constructive and destructive interference produces bright and dark fringes on the screen. (b) Classical objects such as tennis balls do not interfere when they pass through a double slit.

Figure 1(b) shows another double-slit experiment using tennis balls instead of light. You might predict that only tennis balls that pass through one or the other of the two slits will reach the screen on the right; the other tennis balls (the ones that strike the barrier) are stopped by the barrier. Your prediction would be correct. In addition, the pattern formed on the screen by the tennis balls that went through the slits will be quite different from the pattern formed by light waves. The tennis ball pattern corresponds only to the "shadows" of the slits. In this case, no constructive or destructive interference occurs.

The behaviour of the tennis balls in Figure 1 illustrates some important differences between particles and waves.

- Particles do not show interference effects.
- Waves do show interference effects.
- Particles deliver energy in discrete quantities, that is, separate, individual "parcels" of energy that transfer to the screen in the small area where the particle strikes. For example, when a tennis ball hits the screen, some energy instantly transfers to the screen at the spot where the tennis ball hit.
- Waves do not deliver energy in discrete quantities. Waves deliver their energy continuously over time and spread out over the screen.

The energy carried by a wave is described by its intensity, which equals the amount of energy the wave transports per unit time across a surface of unit area. For the light wave in Figure 1(a), the amount of energy absorbed by the screen depends on the intensity of the wave and the absorption time. The amount of absorbed energy can take on any non-negative value.

An Interference Experiment with Electrons

In classical physics, the experiment in Figure 1 shows the distinction between particles and waves. According to classical physics, only these two types of behaviour are possible: waves exhibit interference; particles do not. However, this separation of particles and waves is not found in the quantum world.

Figure 2 shows a double-slit experiment performed with electrons. (You will have a more detailed look at an actual electron double-slit experiment in Section 12.3.) A beam of electrons, all with the same speed, is incident from the left and passes through two slits. The electrons then travel to a screen on the right, which records where each electron strikes. Case 1 in Figure 2 shows the result after 20 electrons have passed through the slits. Each dot shows where a particular electron arrived at the screen—the arrival points seem to be distributed randomly. If you repeated this experiment with another 20 electrons, the precise arrival points would be different, but the general appearance would be the same.

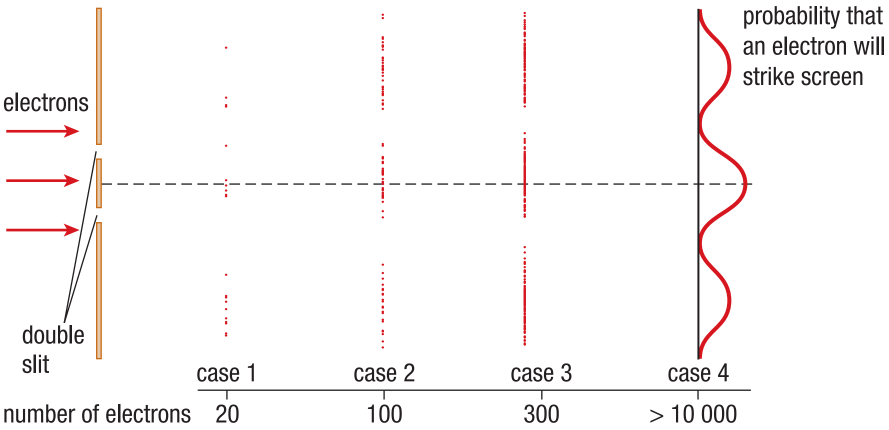


Figure 2 Each dot indicates where an electron hits the screen in an electron double-slit experiment.

If you proceed with the experiment and wait until 100 electrons have arrived, you will see the result shown in case 2. The arrival points are still spread out, but you can now see that the electrons are more likely to strike at certain points than at others. By the time 300 electrons have reached the screen in case 3, it is clear that electrons are much more likely to hit certain points on the screen.

In case 4, quite a large number of electrons have passed through the slits. This part shows the probability that electrons will arrive at different points. This probability curve has precisely the same form as the variation of light intensity in the double-slit interference experiment in Figure 1(a). The experiment shows that electrons constructively interfere at certain locations on the screen, giving a large probability for electrons to arrive at those locations. At other places, the electrons destructively interfere, and the probability for an electron to reach those locations is quite small or zero. **Figure 3** is an actual image taken during an electron double-slit experiment, and it shows how the electrons produce the same pattern as light in the double-slit experiment.

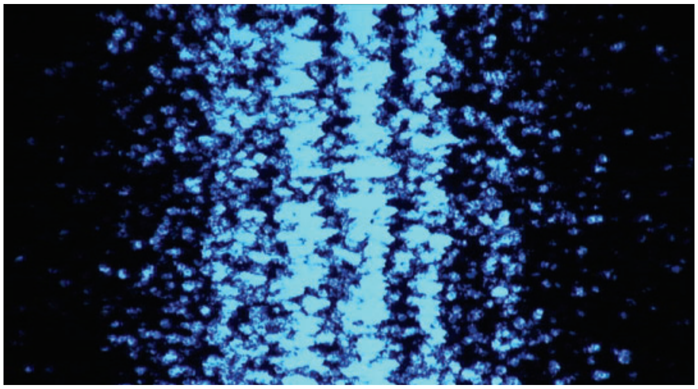


Figure 3 The electrons in the double-slit experiment produce the same pattern as light in a double-slit experiment.

The results in Figure 3 show that electrons can exhibit interference, a property that classical theory says is possible only for waves. This experiment also shows aspects of particle-like behaviour because the electrons arrive one at a time at the screen. Each dot in cases 1 through 3 in Figure 2 corresponds to the arrival of a single electron as it deposits its parcel of energy on the screen.

The behaviour in Figure 3 shows that electrons behave in some ways as both a classical particle and a classical wave. In fact, this behaviour is characteristic of the quantum world: Electrons, protons, atoms, and molecules all give the results shown in Figure 3. Even light and other electromagnetic radiation exhibit particle-like behaviour. The clear-cut distinction between particles and waves breaks down in the quantum world.

wave–particle duality the property of matter that defines its dual nature of displaying both wave-like and particle-like characteristics

The property of matter that defines its dual nature of exhibiting both wave-like and particle-like behaviours is sometimes called **wave–particle duality**, and includes the following properties:

- All quantum objects, including electromagnetic radiation and electrons, can exhibit interference.
- All quantum objects, including electromagnetic radiation and electrons, transfer energy in distinct, or discrete, amounts. These discrete "parcels" of energy are quanta.

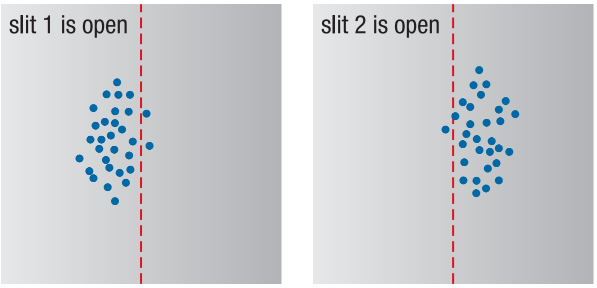
12.1 Review

Summary

- Classical physics refers to the everyday world of large objects where Newtonian mechanics and Maxwell's theory of electromagnetism apply.
- The quantum world is the world of microscopic particles and their behaviours.
- Many models in classical physics break down when applied to extremely small objects such as electrons.
- In classical physics, energy can be carried from one point to another by waves or by particles.
- In classical physics, waves exhibit interference; particles do not. Particles often deliver their energy in discrete amounts, but waves do not.
- In the quantum world, all objects, including electromagnetic radiation and electrons, can exhibit interference and transfer energy in discrete amounts called quanta.
- Wave–particle duality is the property of matter that defines its wave-like and particle-like characteristics.

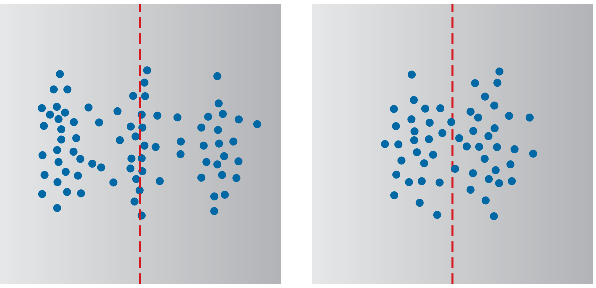
Questions

1. How is energy transferred according to classical physics? K/U
2. Describe the differences between the properties of classical particles and classical waves. K/U C
3. Describe what evidence the electron double-slit interference experiment provides that suggests that
   (a) electrons have particle properties
   (b) electrons have wave properties K/U T/I C
4. Explain why quantum theory revolutionized classical physics in the early twentieth century. T/I C
5. Describe the impact of the electron double-slit interference experiment on classical physics and the development of quantum theory. T/I C
6. Maxwell's theory describes the wave nature of light and all electromagnetic radiation. How is quantum theory more complete than Maxwell's theory? T/I C
7. You hit 50 golf balls at a barrier with 2 narrow slits in it. There is a wall directly behind the barrier. Draw a diagram that shows the distribution of golf balls hitting the wall. T/I C A
8. Imagine that you hit baseballs toward two slits, and that the balls leave marks on a wall after passing through the slits. **Figure 4** shows the distributions of the marks made on the wall when each slit is open. When slit 1 is open and slit 2 is closed, the baseballs hit the wall in the pattern shown in Figure 4(a). When slit 2 is open and slit 1 is closed, the baseballs hit the wall in the pattern shown in Figure 4(b). **Figure 5** shows sample distribution patterns. K/U T/I C A



(a) **(b)**

Figure 4



(a) **(b)**

Figure 5

   (a) Which distribution in Figure 5 best represents the distribution of baseballs when both slits are open at the same time?
   (b) Compare this pattern to the pattern that you would see if you used a beam of electrons instead of baseballs.
9. Explain why some of our intuitions about the macroscopic world do not apply to the quantum world. T/I C