12.2 Wave–Particle Duality

The photoelectric effect and the Compton effect revealed that light and X rays have a particle nature; that is, photons act like particles with a given energy and momentum. In earlier chapters, however, we saw that for the properties of reflection, refraction, diffraction, interference, and polarization, electromagnetic radiation acts like a wave. In this section, we will see how quantum theory reconciles these two apparently opposing viewpoints.

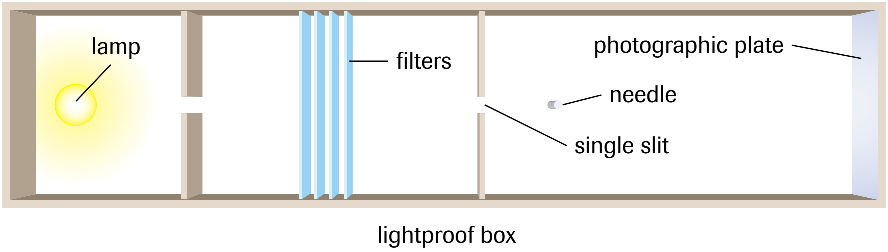
The Particle Nature of Electromagnetic Waves

In 1910, Geoffrey Taylor, a young student at Cambridge University, set up an experiment to find out whether the interference patterns of light resulted from the interactions of many photons or whether the behaviour of individual photons could be predicted from their wave properties. The basic equipment he used is illustrated in **Figure 1(a)**.

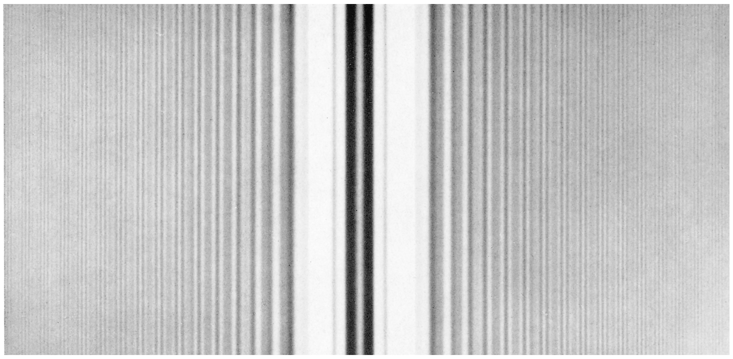
Light from a small lamp passed first through a slit, then through a series of dimming filters, which reduced the intensity of the light. After passing through another single slit, the light was diffracted by a vertical needle, and the resulting image was recorded on a photographic plate (**Figure 1(b)**). Taylor adjusted the dimensions of the box and its contents so that diffraction bands around the shadow of the needle were plainly visible in bright light, without any filters. Then he reduced the intensity of light by adding filters. He found that progressively longer exposures were needed to get a well-exposed photographic plate, since fewer and fewer photons passed through the slit per second as he made his stack of dimming filters progressively thicker. Finally, Taylor made a very weak exposure that lasted three months. Even on this plate, the diffraction interference fringes were perfectly clear. By calculation, Taylor was able to show that with such a dim source, two or more photons would rarely, if ever, be in the box at the same time. In other words, the behaviour of a single photon was governed by the wave theory.

Figure 1
(a) Lightproof box
(b) Diffraction pattern created by a needle

(a)



(b)

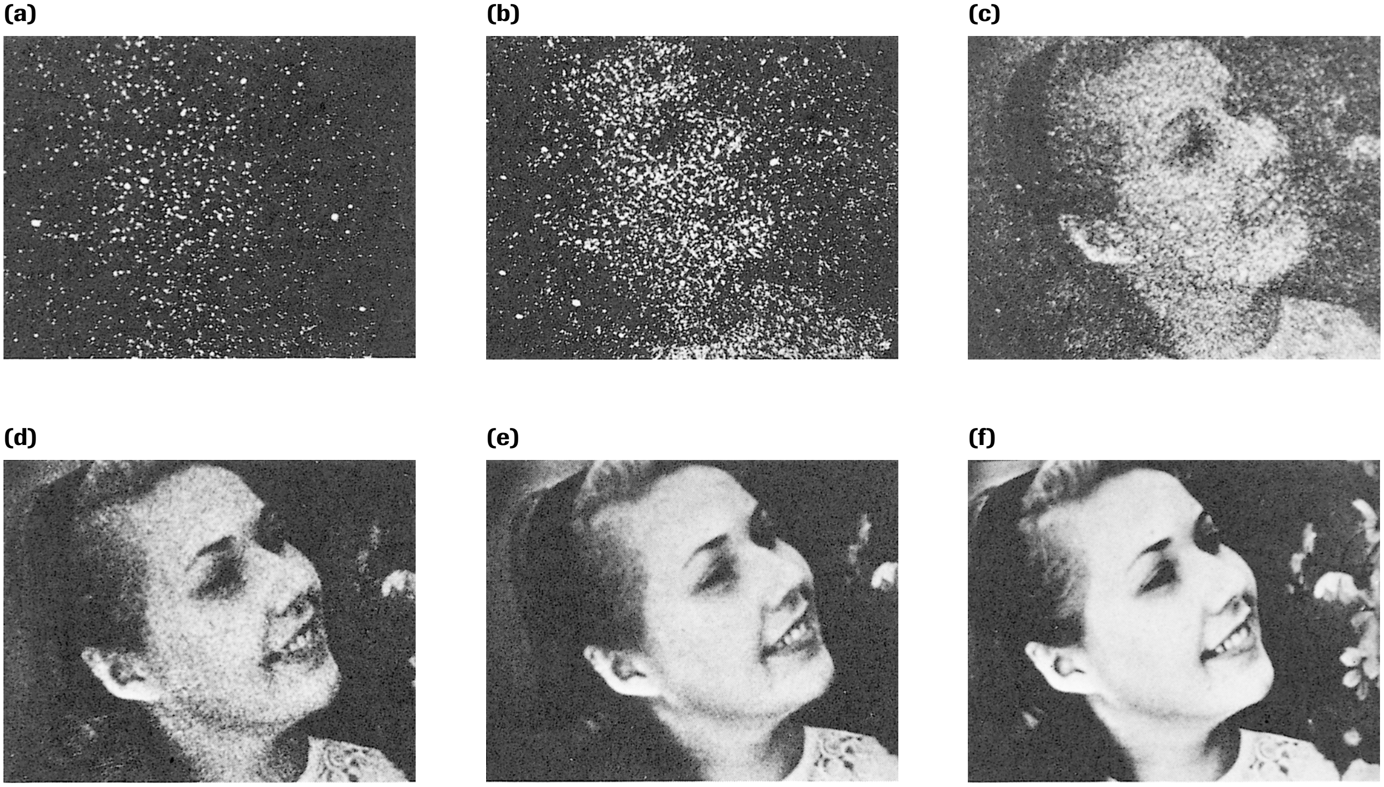


One way of visualizing the relationship between a photon and its electromagnetic wave is to consider that the electromagnetic wave acts as a “guide” that predicts the probable behaviour of the photon. The electromagnetic wave determines the chance, or probability, that a photon will be at a certain position in space at a given instant. For a classical particle the probability of being in certain places is either 100% (if it is there) or 0% (if it is not). We do not have this exactness for photons. We only know the probabilities determined by the electromagnetic wave. Quantum theory assumes that, at any instant, the photon has a probability of being in any position. The probability is greater in those regions where the amplitude of the electromagnetic wave interference pattern is greater and smaller in those regions where the amplitude of the electromagnetic wave interference pattern is smaller.

If an intense beam of light is directed through two adjacent slits, as in Young’s experiment (Section 9.6), a series of alternating bands of constructive and destructive interference is created on the screen. The photons pass through the two slits, and it is the probability of their arrival on the screen that is predicted by their electromagnetic waves. If two electromagnetic waves interfere destructively, the amplitude is smaller than either of the original waves, so the probability of a photon arriving is reduced. When conditions are such that the resultant amplitude is zero, as it is on a nodal line, the probability of finding a photon is zero. On the other hand, if the two electromagnetic waves interfere constructively, the resultant amplitude is larger and the probability is high that a photon will be in that position; that is, a bright area is found.

If a photographic film replaces the screen, the particle nature of photons becomes evident. A photographic film may be constructed of plastic film on which has been deposited a thin layer of very small silver bromide crystals. Each photon absorbed by a silver bromide crystal gives up a fixed amount of energy, freeing the silver, and producing a bright area on the resulting picture (**Figure 2**). The electromagnetic wave gives the probability of its falling on any part of the film. However, since a photon’s chance of registering in areas of constructive interference is high, many silver bromide crystals are

Figure 2
When a photograph is taken, the individual photons cause changes in the silver bromide molecules. As more and more photons strike the film, the image is gradually created. The number of photons applied to form each reproduction of the same image in this sequence of photos is as follows:
(a) 2×10^3 photons
(b) 1.2×10^4 photons
(c) 9.3×10^4 photons
(d) 7.6×10^5 photons
(e) 3.6×10^6 photons
(f) 2.8×10^7 photons



changed in these areas, and a bright area will be recorded on the image. In areas of near-total destructive interference, fewer crystals are changed, and a relatively dark area will be recorded on the image. On the nodal lines, no crystals change at all.

Today, using a photomultiplier (**Figure 3**), photon experiments can be performed with much greater speed and sensitivity than in Geoffrey Taylor's time. By placing the photomultiplier at various locations in an interference pattern, the number of individual photons arriving at the photocathode can be measured. All the results point to the same conclusion: even though the photons arrive one at a time, their distribution on the detecting screen is predicted by their wave properties.

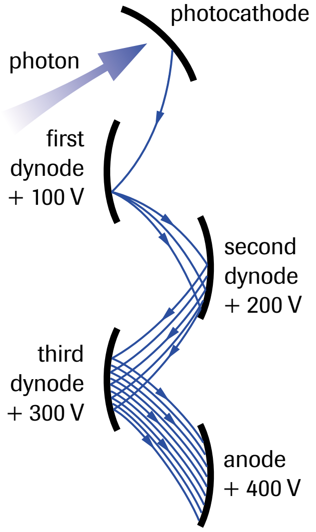


Figure 3
A photomultiplier is an instrument that takes a small amount of light energy and, using a series of electron-emitting surfaces, amplifies the signal many thousands of times. This is a three-stage photomultiplier.

The experimental evidence forces us to conclude that light does not have just a wave nature but also the nature of a stream of particles: photons with momentum. Physicists refer to this dual nature as **wave–particle duality**.

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

The two aspects of light complement one another, and understanding both aspects is essential to having a full understanding of light. Niels Bohr (1885–1962), the great Danish physicist, partially clarified the situation by proposing his *principle of complementarity:*

Principle of Complementarity

To understand a specific experiment, one must use either the wave theory or the photon theory but not both.

To understand how light interferes after it passes through two parallel slits, we must use the wave theory, as illustrated in Young's experiment, not the particle theory. To understand the photoelectric effect or why a photographic plate is exposed as it is, we must use the photon, or particle nature of light, not the wave theory. As a general rule, when light passes through space or through a medium, its behaviour is best explained using its wave properties. But when light interacts with matter, its behaviour is more like that of a particle. The limitations of human experience make it difficult for us to understand the dual nature of light. It is very difficult, if not impossible, for us to visualize this duality. We are used to creating wave pictures, or images, in some applications and particle pictures in others, but never both at the same time.

In the study of light, particularly as it transfers energy from place to place, we must base our knowledge on indirect experiments. We cannot see directly how light energy is transmitted as a wave or a particle. All we can observe are the results of the interaction of light and matter. Our knowledge is limited to indirect information. Therefore, to describe light's dual nature, we cannot use visual means. Further study of quantum mechanics uses mathematical models, not visual models.

The wave–particle model of light that we use today is much more subtle than Newton's particle theory or Maxwell's electromagnetic theory. These were both useful but limited in their applicability. They were important and contributed much to our understanding of the behaviour of light. But these models were inadequate in themselves for explaining all of the properties of light. Like all models or theories, they can be enhanced or even replaced when new information becomes available. This is the case with the two classical theories of light. They have been superseded by the wave–particle model of light, the only theory that we find acceptable today for a full understanding of the nature of light.

The Wave Nature of Matter

In 1923, Louis de Broglie (**Figure 4**), a young graduate student at the University of Paris, proposed a radical idea: he hypothesized that since the momentum of a photon was given by the relationship $p = \frac{h}{\lambda}$, any particle with momentum might also be expected to have an associated wavelength. He further suggested that this wavelength could be determined from the Compton relationship as follows: if $p = \frac{h}{\lambda}$ for photons, then for particles having nonzero mass,

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

This wavelength is known as the **de Broglie wavelength**. Since the wavelength is associated with particles having nonzero mass, they have become known as **matter waves**. The concept was so radical at the time that de Broglie's graduation was held up for one year. (Since Einstein supported the hypothesis, de Broglie duly graduated, in 1924.) Before discussing the implications of his hypothesis, it is important to determine the magnitudes of the associated wavelengths of a macroscopic object and a subatomic particle.

Figure 4
Prince Louis-Victor de Broglie (1892–1987) originally applied his hypothesis to the special case of the electron, using it to analyze the energy levels in hydrogen (see Section 12.5). He was awarded the 1929 Nobel Prize in physics for his electron analysis.

de Broglie wavelength the wavelength associated with the motion of a particle possessing momentum of magnitude p: $\lambda = \frac{h}{p}$

matter waves the name given to wave properties associated with matter

SAMPLE problem 1

What de Broglie wavelength is associated with a 0.10 kg ball moving at 19.0 m/s?

Solution

$m = 0.10$ kg
$v = 19.0$ m/s
$\lambda = ?$

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}\ \text{J}\cdot\text{s}}{(0.10\ \text{kg})(19.0\ \text{m/s})}$$

$$\lambda = 3.5 \times 10^{-34}\ \text{m}$$

The de Broglie wavelength of the ball is 3.5×10^{-34} m.

We see from this example that for macroscopic objects the wavelength is extremely small, even by subatomic standards (being a million-billion-billionth the approximate diameter of a typical atom).

SAMPLE problem 2

What de Broglie wavelength is associated with an electron that has been accelerated from rest through a potential difference of 52.0 V?

Solution

$m = 9.11 \times 10^{-31}$ kg
$\Delta V = 52.0$ V
$\lambda = ?$

$$\Delta V = \frac{\Delta E_e}{q}$$

$$\Delta E_e = q\Delta V$$

The loss of electric potential energy is equivalent to the gain in the electron's kinetic energy.

$$\Delta E_K = \Delta E_e$$

For an electron

$$E_K = e\Delta V$$

$$= (1.60 \times 10^{-19}\ \text{C})(52.0\ \text{J/C})$$

$$E_K = 8.32 \times 10^{-18}\ \text{J}$$

But $E_K = \frac{1}{2}mv^2$

$$v = \sqrt{\frac{2E_K}{m}}$$

$$= \sqrt{\frac{2(8.32 \times 10^{-18}\ \text{J})}{9.11 \times 10^{-31}\ \text{kg}}}$$

$$v = 4.27 \times 10^6\ \text{m/s}$$

Then $\lambda = \frac{h}{mv}$

$$= \frac{6.63 \times 10^{-34}\ \text{J·s}}{(9.11 \times 10^{-31}\ \text{kg})(4.27 \times 10^6\ \text{m/s})}$$

$$\lambda = 1.70 \times 10^{-10}\ \text{m}$$

The de Broglie wavelength of the electron is 1.70×10^{-10} m.

We see from this example that while for a low-momentum subatomic particle such as an electron the de Broglie wavelength is still small, it is no longer very small. For example, the diameter of a hydrogen atom is approximately 1.0×10^{-10} m, that is, *less* than the de Broglie wavelength associated with an electron. This is an issue of great importance, to which we will return in Section 12.5.

Practice

Understanding Concepts

1. Calculate the de Broglie wavelength associated with each of the following:
   (a) a 2.0-kg ball thrown at 15 m/s
   (b) a proton accelerated to 1.3×10^5 m/s
   (c) an electron moving at 5.0×10^4 m/s

2. Calculate the associated wavelengths, in metres, of a 3.0-eV photon and a 5.0-eV electron.

3. Calculate the de Broglie wavelength associated with an artillery shell having a mass of 0.50 kg and a speed of 5.00×10^2 m/s.

4. Calculate the energy, in electron volts, required to give an electron an associated de Broglie wavelength of 0.15 nm.

5. An electron is accelerated through a potential difference of 1.00×10^2 V. Calculate the associated de Broglie wavelength.

6. (a) Calculate the momentum of an electron that has an associated de Broglie wavelength of 1.0×10^{-10} m.
   (b) Calculate the speed of the same electron.
   (c) Calculate the kinetic energy of the same electron.

Answers

1. (a) 2.2×10^{-35} m
   (b) 3.0×10^{-12} m
   (c) 1.5×10^{-8} m
2. 4.1×10^{-7} m; 5.5×10^{-10} m
3. 2.7×10^{-36} m
4. 67 eV
5. 1.23×10^{-10} m
6. (a) 6.6×10^{-24} kg·m/s
   (b) 7.3×10^6 m/s
   (c) 2.4×10^{-17} J, or 1.5×10^2 eV

Matter Waves

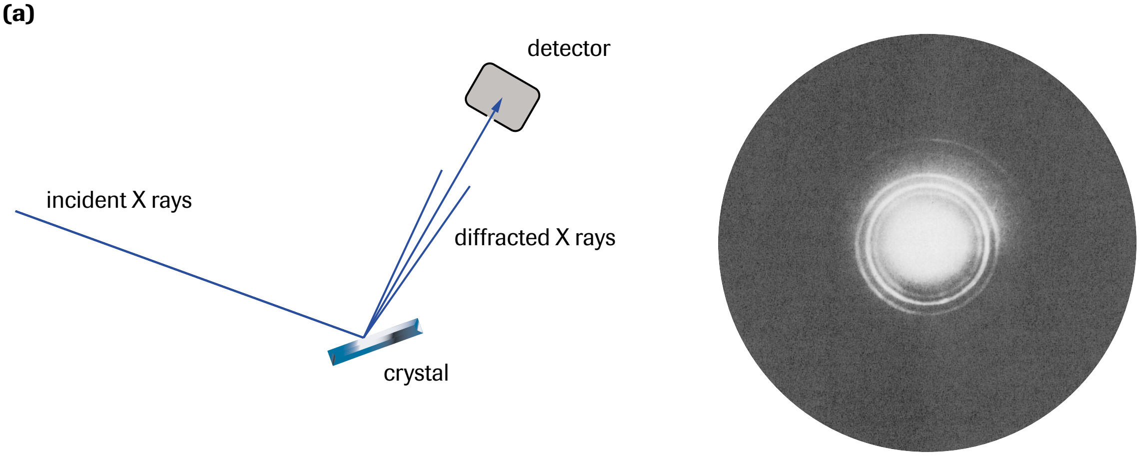
We saw in the preceding problems that the matter wavelengths of most ordinary objects, such as baseballs, are exceedingly small, even on atomic scales. We also saw that the matter wavelengths of objects such as electrons are small on macroscopic scales but appreciable on atomic scales (being comparable, in fact, with the wavelengths of some X rays). Recall that the wave nature of light was elusive until the time of Young because light has such short wavelengths. The matter wavelengths of macroscopic objects are so small they preclude detection. For subatomic particles, the matter wavelengths are still small enough to make detection challenging.

In 1927, two physicists in the United States, C.J. Davisson and L.H. Germer, showed that de Broglie's matter waves do exist. Earlier, in Britain, W.H. Bragg (1862–1942) and his son, W.L. Bragg (1890–1971), had developed equations that predicted the diffraction of X rays upon scattering by thin crystals. The intensity of the scattered radiation produced a maximum at a series of regularly spaced angles, as in **Figure 5(a)**. Davisson and Germer used the Bragg analysis to show that a beam of electrons could be diffracted in much the same way, thereby demonstrating the wavelike properties of particles. When they directed a beam of electrons at a single crystal of nickel, the observed diffraction pattern was in almost perfect agreement with calculations made using the de Broglie wavelength of the electrons. **Figure 5(b)** shows how the Davisson–Germer experiment gave convincing support to de Broglie's hypothesis.

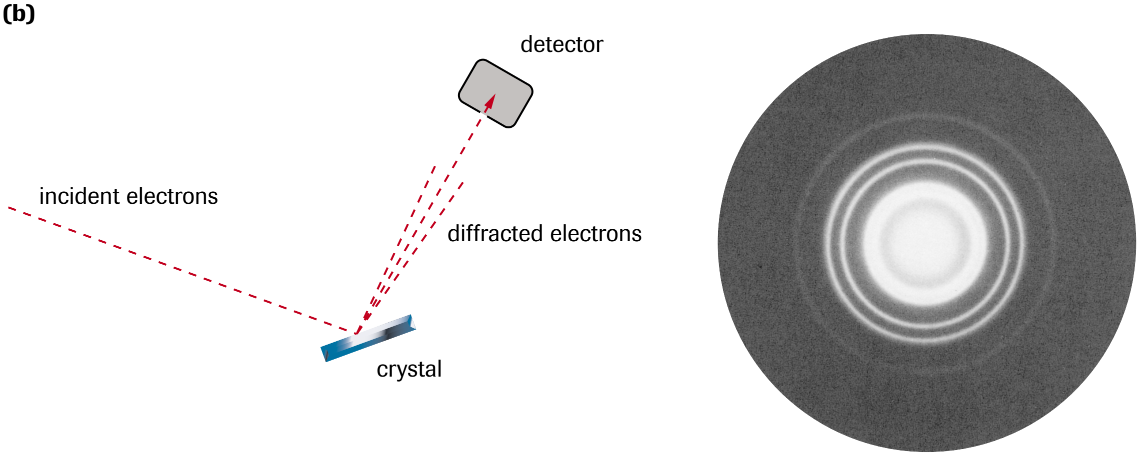
DID YOU KNOW?

Nobel Prize Winners

Clinton Davisson (1881–1958) and George Paget Thomson (1892–1975) shared the 1937 Nobel Prize in physics for pioneering work on electron diffraction.



diffraction of X rays (Bragg)



diffraction of electrons (Davisson and Germer)

Figure 5
The wave nature of photons and electrons
(a) X-ray diffraction due to a crystal of nickel
(b) Diffraction of electrons due to a gold film

In the same year, 1927, G.P. Thomson, in Britain, passed a beam of electrons through a thin metal foil. The diffraction pattern was the same as for X rays, once the correct wavelength was taken into account. The Davisson–Germer and Thomson experiments left little doubt that particles exhibit wavelike properties. Later experiments using protons, neutrons, helium nuclei, and other particles produced similar results. **Quantum mechanics**, the mathematical interpretation of the structure and interactions of matter based on the concept that particles have a wave nature, was vindicated.

quantum mechanics mathematical interpretation of the composition and behaviour of matter, based on the wave nature of particles

The wave–particle duality for small particles matched the wave–particle duality for the photon, as worked out by Compton. The principle of complementarity thus applies to matter as well as to radiation. We may now ask, as we did for light, under what general conditions does matter reveal its wavelike properties? Recall that for the wave property of diffraction to be evident in optics, an aperture comparable to the wavelength of light is needed. Otherwise, the light behaved like a beam of particles moving in a straight line through an opening or past an obstacle, showing little diffraction or interference. A similar requirement holds for matter waves.

Ordinary objects, such as baseballs, have associated matter waves whose wavelength is extremely short compared with the dimensions of other objects or openings that they encounter. Therefore, they act like particles, concealing their wave nature. Subatomic particles such as electrons, by contrast, have associated matter waves whose wavelength is of the same order of magnitude as the objects with which they interact. As a result, they produce diffraction patterns large enough to be observed.

What about the conceptual interpretation of matter waves? Like electromagnetic waves, matter waves predict the probability that a particle will follow a particular path through space. It is important to note that matter waves do not carry energy. They only predict behaviour. The particle carries the energy.

The fact that wave–particle duality exists for both matter and light reinforced Einstein's contention (Section 11.4) that mass is interconvertible with energy, under the relationship $E = mc^2$. By 1927, the concept that mass and energy were interrelated did not seem as astonishing as it had when Einstein proposed it in 1905. Furthermore, the wave characteristics of the electrons orbiting the nucleus of an atom could now be examined using quantum mechanics (see Section 12.5).

DID YOU KNOW?

George Unruh

George Unruh (1945–) was born in Winnipeg, Manitoba, and studied physics at the University of Manitoba and Princeton University. He is presently a physics professor at the University of British Columbia. Unruh's research applies quantum mechanics to the study of gravity and the forces that existed at the moment of creation, according to the Big Bang theory. He also pursues research in quantum computation, using quantum principles to design computers able to solve certain problems billions of times more quickly than traditional equipment.

Electron Microscopes

The resolution of an ordinary microscope is limited by the wavelength of the light used. The highest useful magnification obtainable, with an oil-immersion objective, is 2000×, with the best resolution approximately 2.0×10^{-7} m (about one-half the wavelength of visible light). On the other hand, a beam of electrons having an associated de Broglie wavelength of less than 1.0 nm could produce a resolution of approximately 0.5 nm. This means that if one could get electrons to behave as light does in a microscope, the magnification could be increased to as high as 2 million times or more.

Technological developments in the 1920s that involved the focusing of electron beams by means of magnetic coils permitted the development of a crude electron microscope in Germany, in 1931. The first North American electron microscope, and the first of immediate practical application anywhere, was designed and built in the winter of 1937–38 by James Hillier (**Figure 6**) and Albert Prebus, two young graduate students at the University of Toronto. By the summer of 1938, they were producing microphotographs with a magnification of 20 000× and a resolution of 6.0 nm (30 atomic diameters). The electronics manufacturer RCA soon used their design in the first commercial electron microscope.

DID YOU KNOW?

Richard Feynman

Richard Feynman (1918–1988), 1965 Nobel laureate with Tomonaga and Schwinger, once remarked, "I think I can safely say that nobody understands quantum mechanics." What he meant was that, although we can use the mathematical equations of quantum mechanics to make extremely accurate predictions, we cannot truly understand wave–particle duality and other implications of the quantum theory at an intuitive level.

A **transmission electron microscope** is similar in operation to an ordinary light microscope, except that magnetic "lenses" replace the glass lenses (**Figure 7**). The magnetic "lenses" are constructed of circular electromagnetic coils that create strong magnetic fields. These fields exert forces on the moving electrons, focusing them in much the same way that a glass lens focuses light. Electrons emitted from a hot cathode filament are accelerated by an anode through an electrical potential of 50 kV to 100 kV or more. The electrons are focused into a parallel beam by a condensing lens before they pass through the specimen, or object, being imaged. For transmission to take place, the specimen must be very thin (approximately 20 to 50 nm); otherwise, the electrons would be slowed down too much or scattered, and the resulting image would be blurred.

Next, the beam of electrons passes through the objective coil and finally through the projector coil (corresponding to the eyepiece in an optical microscope). The beam is projected onto a fluorescent screen or photographic plate, creating a two-dimensional image of the specimen. Since the powerful beam of electrons can degrade the specimen, short exposure times are necessary. Further, it is necessary to operate the whole system of coils, beams, and specimen in a high vacuum, to avoid scattering of the electron beam by collisions with air molecules.

Figure 6
In this 1944 photograph, a young James Hillier (standing) demonstrates an early electron microscope at RCA Laboratories where he was a research engineer. When he retired in 1978, he was executive vice-president and senior scientist at RCA Labs. Born in Brantford, Ontario, he received his physics Ph.D. in 1941, from the University of Toronto. A generation later, more than 2000 electron microscopes, some capable of magnifying more than 2 million times, were in use in laboratories around the world.

transmission electron microscope a type of microscope that uses magnetic lenses fashioned from circular electromagnetic coils creating strong magnetic fields

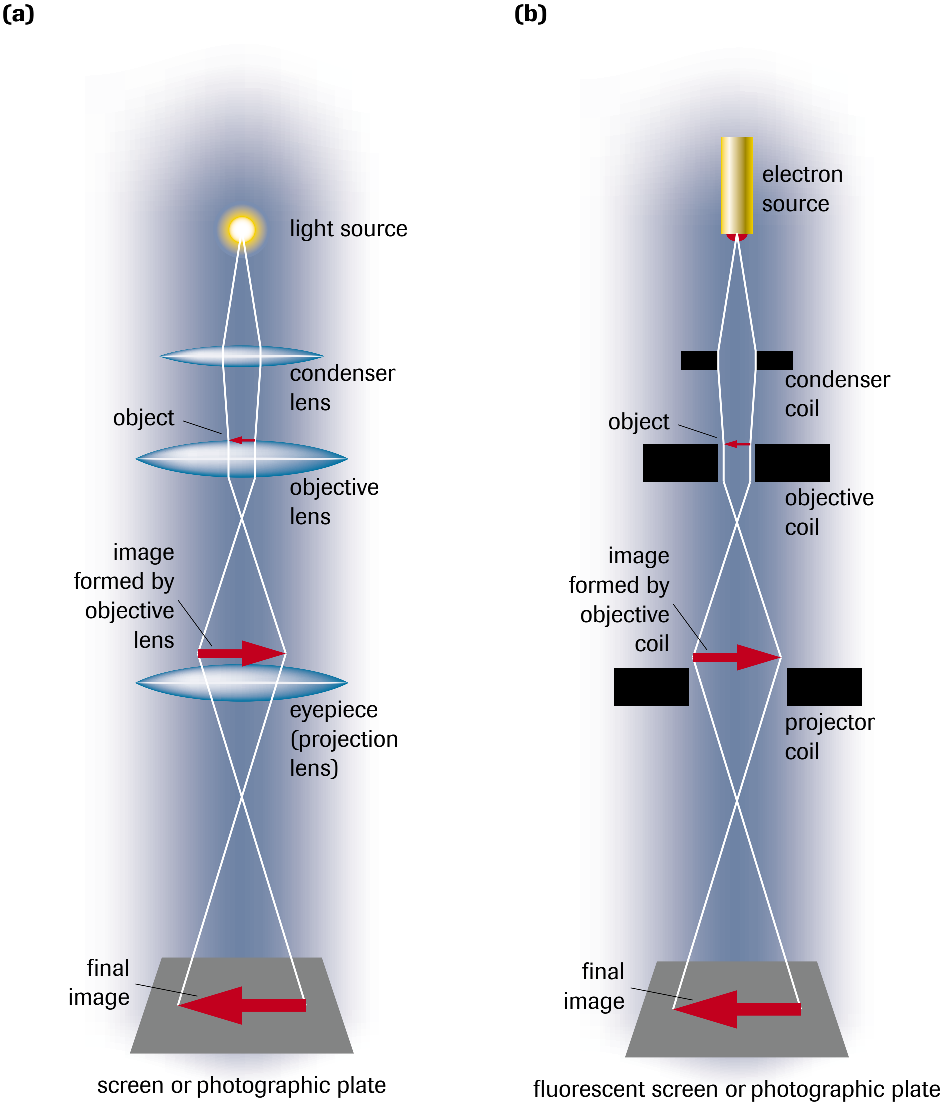


Figure 7
Design similarities of **(a)** a compound optical microscope and **(b)** an electron microscope. To help make the similarities evident, the optical microscope is depicted upside down.

scanning electron microscope a type of microscope in which a beam of electrons is scanned across a specimen

scanning tunnelling electron microscope a type of microscope in which a probe is held close to the surface of the sample; electrons "tunnel" between the sample and the probe, creating a current

Unlike the more traditional transmission electron microscope, with the **scanning electron microscope** three-dimensional, contoured images are possible. In this type of microscope, a carefully directed beam of electrons is moved across the specimen (**Figure 8(a)**). At each position on the specimen, the secondary electrons emitted from the surface are collected, controlling the intensity (brightness) of a picture element in a monitor. As a result, as the beam "sweeps" the specimen, a corresponding magnified, three-dimensional image is created on the monitor. Since the beam of electrons will damage a biological specimen, the time of exposure is generally limited. Further, it is usually necessary to coat the specimen with a thin layer of gold so that it does not accumulate negative charges from the electron beam. (Accumulated charge would repel the beam as it sweeps across the specimen, distorting the image.)

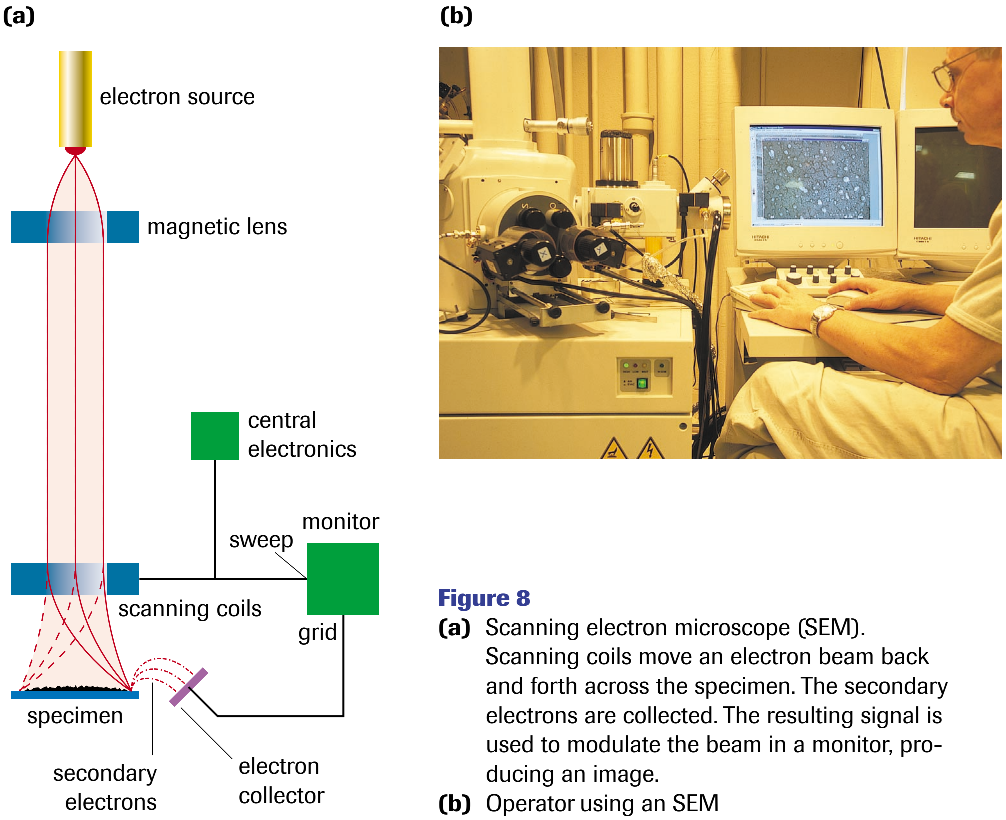


Figure 8
(a) Scanning electron microscope (SEM). Scanning coils move an electron beam back and forth across the specimen. The secondary electrons are collected. The resulting signal is used to modulate the beam in a monitor, producing an image.
(b) Operator using an SEM

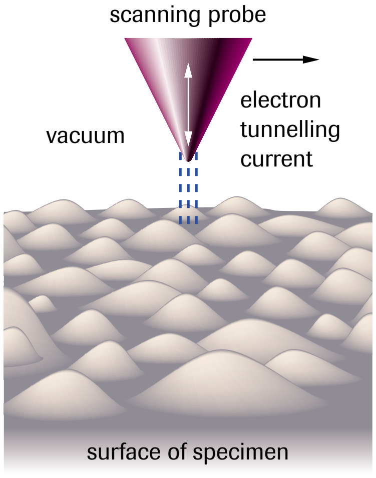


Figure 9
The tip of a probe in a scanning tunnelling electron microscope moves up and down to maintain a constant current, producing an image of the surface.

The **scanning tunnelling electron microscope** uses the tip of a probe, a few atoms thick, to scan very close to the specimen surface (**Figure 9**). During the scanning, a small potential difference between the tip and the surface causes surface electrons to leave, creating a current through the probe in a process called "tunnelling." This current is used to create a three-dimensional image, recording surface features as fine as the size of atoms. In fact, the images can actually "picture" the distribution of electrons; one of the images in **Figure 10** shows the structure of the DNA molecule.

Electron microscopes have extended the frontiers of research in the microscopic world. Although biological specimens produce some of the most dramatic images, microscopy of atomic and molecular structure holds even greater promise.

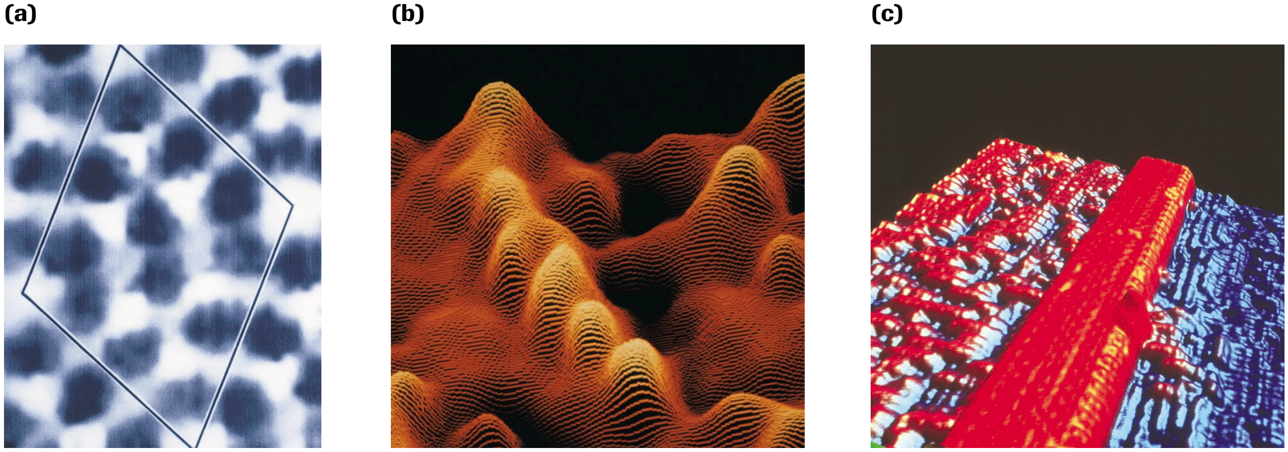


Figure 10
False-coloured images from a scanning tunnelling microscope
(a) Atoms and electron bonds in a crystal of silicon. The black spots are the individual silicon atoms in a single "unit cell." The bright regions between them show the position of electron bonds that hold the structure together.
(b) A strand of DNA
(c) This nanowire, just 10 atoms wide, could be used in a computer operating at the limits of miniturization. The wire is made of a rare-earth metal (lanthanide) combined with silicon.

SUMMARY Wave–Particle Duality

- The behaviour of a single photon was predicted by the wave theory. The electromagnetic wave predicts the probability that a photon will register at a certain position on a detecting surface at a given instant.
- Light is not just a wave and not just a particle but exhibits a "wave–particle duality."
- Understanding both the wave and the particle properties of light is essential for a complete understanding of light; the two aspects of light complement each other.
- When light passes through space or through a medium, its behaviour is best explained using its wave properties; when light interacts with matter, its behaviour is more like that of a particle.
- The wave–particle model of light has superseded Newton's particle theory and Maxwell's electromagnetic theory, incorporating elements of both.
- A particle of nonzero mass has a wavelike nature, including a wavelength λ, found by de Broglie to equal $\frac{h}{mv}$.
- Matter wavelengths of most ordinary objects are very small and thus unnoticeable.
- Matter waves predict the probability that a particle will follow a particular path through space. The diffraction of electrons revealed these wave characteristics.
- Electron microscopes use the principles of quantum mechanics and matter waves to achieve very high magnifications, in some cases exceeding 2 million times.

Section 12.2 Questions

Understanding Concepts

1. Describe one type of evidence for
   (a) the wave nature of matter
   (b) the particle nature of electromagnetic radiation
2. Explain how the equations for single-slit diffraction can be used to predict the behaviour of a photon passing through a single slit.
3. Compare and contrast a 2-eV electron and a 2-eV photon, citing at least four properties of each.
4. Calculate the associated de Broglie wavelength of
   (a) a neutron travelling at 1.5×10^4 m/s ($m_n = 1.67 \times 10^{-27}$ kg)
   (b) an electron travelling at 1.2×10^6 m/s ($m_e = 9.11 \times 10^{-31}$ kg)
   (c) a proton with kinetic energy 1.0×10^9 eV ($m_p = 1.67 \times 10^{-27}$ kg)
5. An electron beam in a certain electron microscope has electrons with individual kinetic energies of 5.00×10^4 eV. Calculate the de Broglie wavelength of such electrons.
6. Calculate the momentum and the equivalent mass of a 0.20 nm X-ray photon. (This does not imply a photon has mass!)
7. A certain microscopic object has a speed of 1.2×10^5 m/s. Its associated de Broglie wavelength is 8.4×10^{-14} m. Calculate its mass.
8. What would the slit width have to be before the matter wave effects would be noticeable for a 5.0-eV electron passing through the single slit?
9. A proton emerges from a Van de Graaff accelerator with a speed that is 25.0% the speed of light. Assuming, contrary to fact, that the proton can be treated nonrelativistically, calculate
   (a) the associated de Broglie wavelength
   (b) the kinetic energy
   (c) the potential difference through which the proton was accelerated if it started essentially from rest
10. In a television picture tube, electrons are accelerated essentially from rest through an appreciable anode-cathode potential difference. Just before an electron strikes the screen, its associated de Broglie wavelength is 1.0×10^{-11} m. Calculate the potential difference.

Making Connections

11. Research the use of tunnelling electron microscopes to determine the electron distribution in atoms. Write a short report on your findings.

GO www.science.nelson.com

12. Research electron microscopes and find out what precautions are necessary to protect the sample from damage.

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13. In Sections 12.1 and 12.2 you read about two significant accomplishments by Canadian scientists: Willard Boyle and the CCD, and James Hillier and the first commercial electron microscope. Choose one of these Canadian scientists (or another of your choosing who has contributed to modern physics), and prepare a summary that includes biographical information, the technology, background to the development of the technology, the physics behind it, and how it contributed to the respective field(s) of science and to society. Your summary can be in the form of a research paper, a web site, or a pamphlet designed to sell the technology.

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