Quantum Physics
In a Nutshell

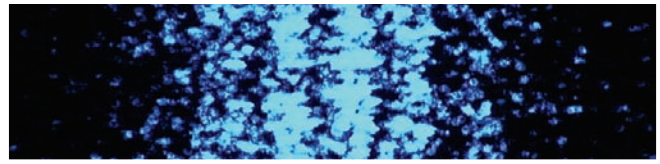
CLASSICAL PHYSICS

- Classical physics is the physics of the motion, energies, and interactions of objects in the everyday world around us.
- In the double-slit experiment, tennis balls and all other *classical particles* move as localized particles through the slits and once they hit the screen they produce the following distribution:

- If we use water waves, sound, or any other *classical waves* they spread out behind the double-slit barrier and produce an *interference pattern*.
- Light also spreads out behind the double-slit barrier and produces an interference pattern.

QUANTUM PHYSICS

- Quantum physics is revealed in the physics of isolated processes, typically with very small subatomic objects.
- In the electron double-slit experiment, each electron hits the detection screen as a particle.
- After many electrons hit, an interference pattern forms, demonstrating wave behaviour.
- The same interference pattern forms even when we fire electrons one at a time.



- These results show that electrons exhibit both wave and particle behaviour, i.e., *wave–particle duality*.
- The de Broglie wavelength describes the wave behaviour of particles such as electrons. It is given by the equation

$$\lambda = \mathrm{h}/p$$

- Light also exhibits wave–particle duality. In the double-slit experiment light hits the detection screen as an individual particle, but over time it forms an interference pattern like a wave.
- A particle of light is called a *photon* and its energy is given by

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

- All quantum objects, including protons, neutrons, atoms, and molecules, exhibit wave–particle duality.
- When we look at the electron to see what it is doing while passing through the double-slit barrier, we are making a measurement which perturbs the electron and destroys the interference pattern. This demonstrates *measurement disturbance*.
- We can predict the overall behaviour of the electrons in the double-slit experiment, but nobody really knows what the electrons are doing between the source and the detector. To complete the picture, physicists have proposed various interpretations, including:

i) thinking of electrons as spread-out waves that collapse to point-like particles once they are measured (Collapse Interpretation),
ii) thinking of electrons as particles that are guided by an invisible wave (Pilot Wave Interpretation),
iii) thinking of parallel universes that come into being when we make measurements at the quantum level (Many Worlds Interpretation)
iv) thinking exclusively about the direct results of measurements (Copenhagen Interpretation).

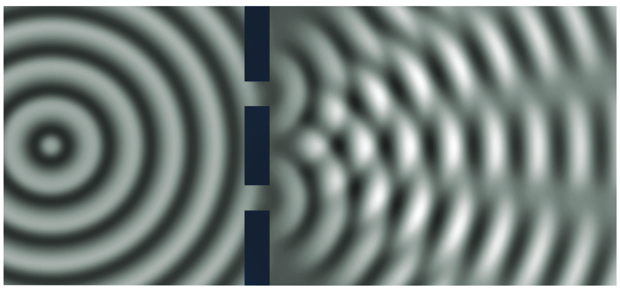
- In spite of these differing views, quantum physics plays a crucial role in a number of everyday technologies including computers, remote control devices, lasers, and cell phones.

Worksheet 01:
Video Summary

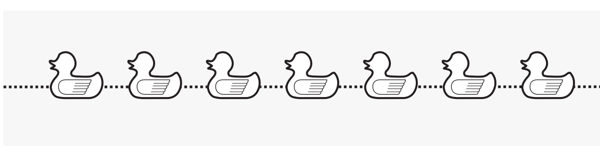
Useful equations: $\lambda = h/p$ $E = hf$

01. Baseballs are fired at a barrier with two narrow slits. Behind the barrier is a wall. Draw a distribution that shows where the baseballs hit the wall.

02. A water wave passes a two-slit barrier, as shown below, generating an interference pattern.

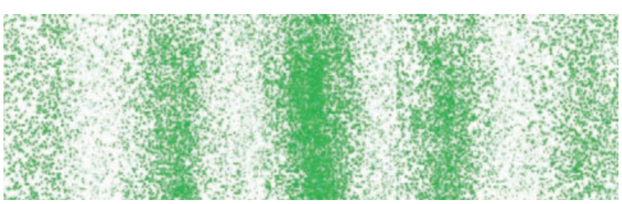


(a) Imagine a rubber duck is floating at each maxima and minima along the reference line shown. Using the diagram below, draw a vertical line for each duck that will show how its vertical position changes over time.



(b) The relative height each rubber duck moves is related to the amount of energy passing at that point. A longer vertical line represents more energy than a shorter line. Describe where the energy is greatest. How does the energy distribution between maxima mimic the energy distribution in a double-slit interference pattern for light?

03. The photograph below shows an interference pattern from the electron double-slit experiment.



(a) The distance between neighbouring interference maxima is 120 μm. Why is this distance so much smaller than the distance between maxima for water waves?
(b) What aspects of the image illustrate the particle nature of electrons?
(c) What aspects of the image illustrate the wave nature of electrons?
(d) How can an electron be a particle and a wave at the same time? Spend a few minutes formulating your explanation for what is going on and then discuss it with your neighbour.

04. The double-slit experiment is performed using light with a wavelength of 580 nm. The light's intensity is so low that only one photon passes through the slits each second. This means no two photons ever interact with each other in the experiment.

(a) What is the energy of each photon emitted?
(b) What aspects of this experiment demonstrate the particle nature of light?
(c) What aspects of this experiment demonstrate the wave nature of light?

05. One of the largest objects that physicists have used to produce an interference pattern is a molecule called PFD (perfluoroalkyl-functionalized diazobenzene, $C_{30}H_{12}F_{30}N_2O_4$). It has a mass of 1.7×10^{-24} kg. In the experiment, the molecule had a de Broglie wavelength of 2.8×10^{-12} m. Calculate the molecule's velocity.

06. What happens to the interference pattern created in the electron double-slit experiment when detectors are used to determine which slit an electron is passing through? How do the researchers explain this result?

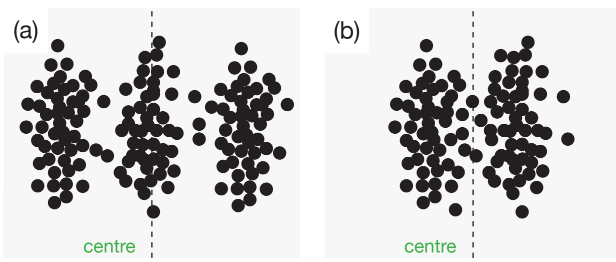
07. You are discussing the electron double-slit experiment with a friend. She says: "Physicists understand the experiment completely. Each electron leaves the source as a classical particle and hits the screen as a classical particle. All researchers agree that an electron is a classical particle in the experiment." Write a three to four line reply to your friend that explains why she is mistaken.

08. Quantum physics is part of your everyday life. List at least five of the technological applications discussed in the video.

Worksheet 02:
Concept Questions

01. Tennis balls are sent toward two slits. The distributions of the marks they make on a wall on the other side of the barrier when one slit is open are shown below.

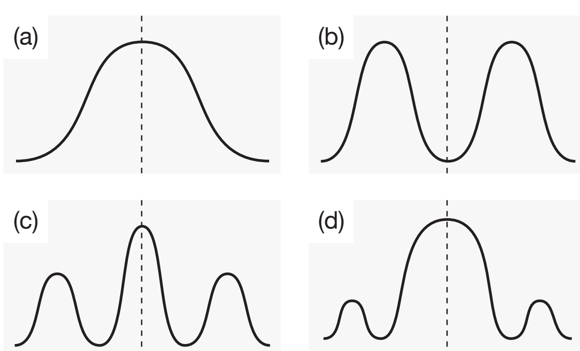
Which distribution would you expect to see if both slits are open at the same time?



02. Which statement correctly describes how waves behave when they occupy the same location at the same time?

(a) A crest overlapping with a crest will constructively interfere to produce a minima.
(b) A crest overlapping with a trough will constructively interfere to produce a minima.
(c) A trough overlapping with a trough will constructively interfere to produce a maxima.
(d) A trough overlapping with a trough will destructively interfere to produce a maxima.

03. A water wave passes through two slits. Which pattern best matches the amplitude of the resulting wave?



04. Classical particles are different from classical waves because classical particles

(a) are spread out and generate an interference pattern in the double-slit experiment.
(b) are localized and generate an interference pattern in the double-slit experiment.
(c) are localized and generate a distribution that is the sum of each single-slit distribution.
(d) are spread out and generate a distribution that is the sum of each single-slit distribution.

05. The video shows the interference of light of a single colour. What would you expect if white light were used?

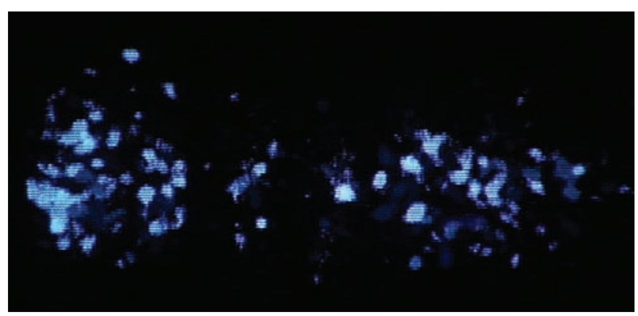
(a) bands of white light and darkness
(b) bands of different colours of light and darkness
(c) a white central maxima and alternating bands of different colours of light and darkness on either side
(d) no interference pattern

06. To better understand the double-slit experiment, it was important to send electrons through one at a time because

(a) the detector needed time to reset in order to detect the next electron.
(b) the slits were too narrow to allow two electrons to pass at the same time.
(c) this prevented the electrons from interacting with each other.
(d) time is needed to generate more electrons.

07. In the double-slit experiment, electrons

(a) behave like waves and behave like particles.
(b) split in half and go through both slits simultaneously.
(c) behave like particles, but are waves.
(d) are both waves and particles at the same time.



Actual image from the electron double-slit experiment

Worksheet 02:
Continued

08. You get sunburn from ultraviolet light but not from visible light. This is because UV photons have a greater

(a) mass.
(b) frequency.
(c) speed.
(d) wavelength.

09. Why have interference effects with tennis balls not been observed?

(a) The de Broglie wavelength equation, $\lambda = h/p$, is only for sub-microscopic objects.
(b) The experiment has not been done yet.
(c) The de Broglie wavelength for a tennis ball will be much smaller than for an atom.
(d) The de Broglie wavelength for a tennis ball will be larger than for an atom.

10. All quantum objects exhibit wave–particle duality. In the double-slit experiment this is shown by the fact that individual objects hit the screen

(a) at specific locations and build up an interference pattern after a large number have hit.
(b) in a spread-out way and build up an interference pattern after a large number have hit.
(c) at specific locations and build up a particle distribution after a large number have hit.
(d) in a spread-out way and build up a particle distribution after a large number have hit.

11. If we do measurements to determine which slit an electron went through, we find that

(a) half of the electron goes through each slit.
(b) the whole electron goes through both slits.
(c) the whole electron goes through one or the other slit.
(d) it is impossible to detect an electron.

12. With electrons in the double-slit experiment, physicists know

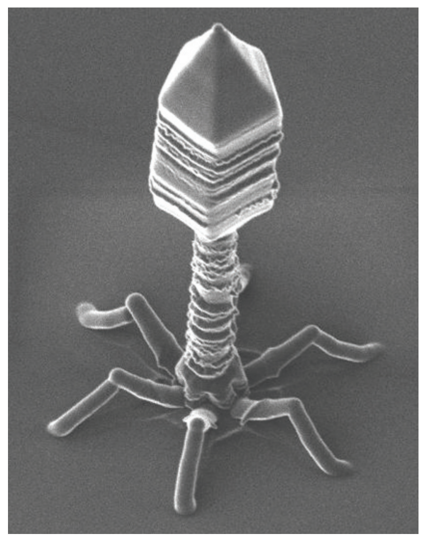
(a) where an electron will hit the screen.
(b) which slit the electron went through, without the aid of a detector.
(c) that the electron went through both slits.
(d) that all of the interpretations give the same predictions for the overall results.

13. There are competing ideas about what is actually happening between the source and the detector in the double-slit experiment. In which of the interpretations does a single electron go through one and only one slit?

(a) Pilot Wave and Collapse
(b) Pilot Wave and Many Worlds
(c) Collapse and Many Worlds
(d) Pilot Wave, Collapse, and Many Worlds

14. An electron microscope can produce clearer images of significantly smaller objects than a light microscope can because the electrons have a

(a) larger frequency.
(b) smaller size.
(c) slower speed.
(d) shorter wavelength.



Electron microscope image of a virus

15. Which quantum application has had the greatest effect on your life?

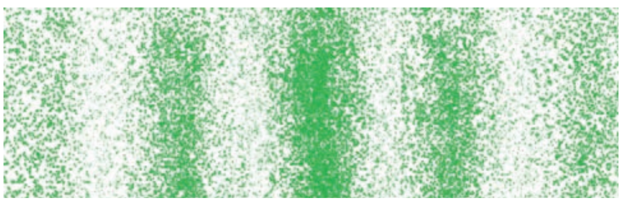
(a) solar panels
(b) transistors
(c) lasers
(d) other

Worksheet 03:
Mathematical Investigation of Wave-Particle Duality

Useful equations: $\Delta x = \frac{\lambda L}{d}$ $\lambda = \frac{h}{p} = \frac{h}{mv}$ $E = hf$ $V = \frac{E_Q}{q}$ $E_K = \frac{1}{2}mv^2 = \frac{p^2}{2m}$

$m_e = 9.11\times10^{-31}$ kg $c = 3.00\times10^{8}$ m/s $h = 6.626\times10^{-34}$ J·s $q_e = 1.602\times10^{-19}$ C 1 amu $= 1.6605\times10^{-27}$ kg

01. The photo below shows the interference pattern produced by an electron double-slit experiment. In this experiment, the electrons were sent through a double-slit apparatus with an effective slit separation of 200 nm. The detector screen was 79.0 cm from the double slits. The image has been magnified by a factor of 100.



3.60 cm

(a) Use Young's double-slit equation to determine the wavelength of the electrons.
(b) Use the de Broglie wavelength equation to determine the momentum and velocity for the electrons passing through the apparatus.
(c) The electrons were accelerated by an electric field. Calculate the potential difference needed to produce these results.

02. The resolving power of imaging devices is limited by the wavelength of radiation used. Optical microscopes use visible light, so they can only resolve objects down to a size of about 200 nm. Electron microscopes can resolve much smaller objects because the wavelength of the electrons can be made much shorter than the wavelength of visible light.

(a) A typical transmission electron microscope (TEM) accelerates the electrons through a potential difference of 30 kV. Calculate the velocity of the electrons incident on the sample.
(b) Determine the de Broglie wavelength for these electrons.
(c) Compare the electron wavelength to the wavelength for green light (550 nm).
(d) If resolving power depended only on wavelength, what would the resolving power of this TEM be?
(e) Using the Internet, research the resolving power for a typical electron microscope.

03. A standard He-Ne laser produces about 1.0 mW of light at a wavelength of 633 nm. To create a single-photon interference experiment the laser is shone through a series of filters that reduce the beam to a small fraction of the original number of photons.

(a) Calculate the number of photons produced by the laser every second.
(b) Determine the time taken for the photons to travel 0.30 m from the filters to the detector.
(c) Each filter absorbs 96% of the photons. How many photons per second pass through after seven filters?
(d) Compare the time taken by each photon to travel 0.30 m with the time between successive photons emerging from the final filter (assume the photons are equally spaced). Express your answer as a fraction. This fraction describes the chance that there is more than one photon in flight between the filters and the detector at any one time.

04. The experiment demonstrating interference of buckminsterfullerene, C_{60}, had the molecules moving at 210 m/s. Each molecule has an atomic mass of 720 atomic units and a diameter of 1 nm. The molecules passed through slits with widths of 50 nm and separations of 100 nm. After the slits, the molecules travelled 1.25 m before being detected.

(a) What is the mass of one molecule?
(b) What is the momentum?
(c) What is its wavelength?
(d) How does this wavelength compare with the size of the molecule?
(e) How does this wavelength compare with the size of the slits?
(f) What would the distance between fringe maxima be if the screen was 5.0 m from the slits?

Chapter 01
Classical Background

This chapter of the video:

- *uses the double-slit experiment to review the behaviour of classical particles, water waves, and light.*
- *shows that classical particles are localized. They pass through the slits as individual particles and strike a wall in a familiar and predictable distribution.*
- *shows that water waves are spread out. The slits act as individual sources that produce an interference pattern as the waves overlap.*
- *examines the results of Young's double-slit experiment to support the use of a wave model for light.*

The world of classical physics is relatively straightforward. There is matter and energy, particles and waves. Phenonmena can be described completely as one or the other.

CLASSICAL PARTICLES

In classical physics, matter is made up of particles. The particles are localized, which means their location can be described exactly and they can only be in one place at one time. Localized particles follow trajectories that can be predicted with mathematics using variables such as velocity, acceleration, etc. When two particles are in the same place at the same time they collide and their trajectories change. Careful measurements of a particle's location and trajectory allow us to make very precise predictions about the outcome of any event.

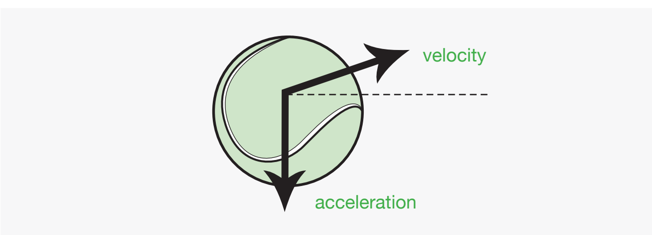


Figure 1.1 This tennis ball can only be in one place at one time. It follows a predictable path.

CLASSICAL WAVES

Energy can be transferred through a medium by the propagation of a wave. A wave is a disturbance that spreads out through the medium by making the particles of the medium move about an equilibrium position. These particles are localized and can only be in one place at one time. When two (or more) waves meet, the medium will add the amplitudes of the waves together and produce a superposition of the waves. Superposition of two (or more) waves can produce an interference pattern and this pattern can be described using geometry.

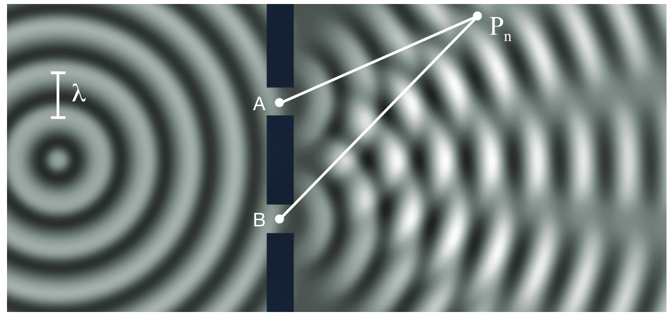


Figure 1.2 When two waves meet they produce an interference pattern.

In Figure 1.2 $$\left|\overline{P_nA} - \overline{P_nB}\right| = (n - \frac{1}{2})\lambda \qquad (1.1)$$

where

$\overline{P_nA}$ = the distance from point P on the *n*th nodal line to source A (m)

$\overline{P_nB}$ = the distance from point P on the *n*th nodal line to source B (m)

n = an integer identifying which nodal line the point is on

λ = wavelength (m)

LIGHT AS A WAVE

In 1803, Thomas Young described the interference of light using several experiments. The experiment that has survived with his name associated with it is the double-slit experiment, in which light shines through two narrow slits. His analysis of the pattern used the geometry of wave interference, and his conclusion was that light must be some sort of wave phenomenon. Young's double-slit experiment seemed to settle the debate about the nature of light in favour of Huygens's wave model.

Figure 1.3 Interference pattern produced by light.

Chapter 02
Wave–Particle Duality with Electrons

This chapter of the video:

- *presents an electron interference experiment using a double-slit.*
- *illustrates how the experiment provides evidence for both the particle nature and the wave nature of electrons.*
- *introduces de Broglie's wave equation for matter.*

WAVE–PARTICLE DUALITY

In classical physics, matter is modelled as a particle. However, in the subatomic world of quantum physics, things are different. The double-slit experiment with electrons highlights the dual nature of subatomic matter, illustrating both particle and wave behaviour, intrinsic to the quantum realm.

Dr. Herman Batelaan and his team at the University of Nebraska-Lincoln have successfully conducted an electron double-slit experiment. Dr. Batelaan's team fired electrons at two tiny slits, only 100 nm wide. Their investigation is the most recent version of an electron double-slit experiment and provides a concrete look into the wave–particle duality of matter on quantum scales

HOW THE EXPERIMENT WORKS

In the experiment, a tungsten filament is heated to a few thousand degrees, causing elections in the filament to be ejected at high speeds. The high-speed electrons pass through narrow apertures that collimate the beam. The beam of electrons is incident on a silicon nitride double-slit barrier. The slits are 100 nm wide and are separated by a distance of 200 nm. After passing through the slits each electron is detected by an electron multiplier that is used to generate a magnified image on a computer monitor. It is impossible to predict where an individual electron will hit the screen. After enough electrons have passed through the apparatus, however, a distinctive interference pattern emerges. Figure 2.3 is a simplified schematic diagram of the experimental set-up.

The intensity of the electron beam can be turned down so that there is only one electron in the apparatus at a time. Surprisingly, despite the fact that electrons are passing through the apparatus one electron at a time, an interference pattern will still develop over time. The interference pattern can be analyzed using the same equations used to investigate Young's double-slit experiment for light.

$$\lambda = \frac{\Delta x \cdot d}{L} \qquad (2.1)$$

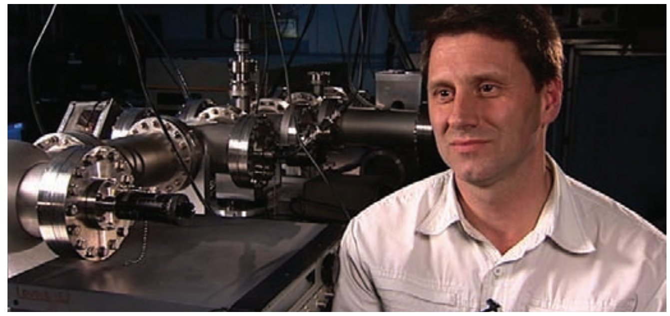


Figure 2.1 Dr. Herman Batelaan in front of the electron double-slit experiment at the University of Nebraska-Lincoln

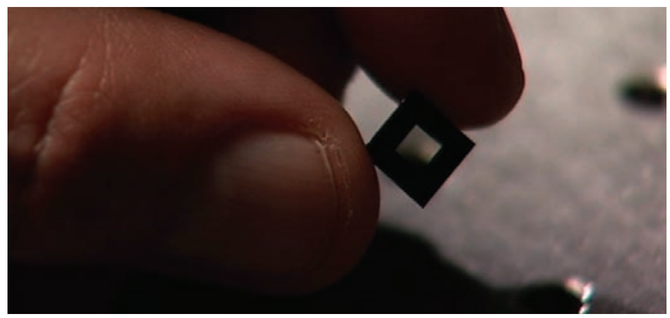


Figure 2.2 The photo shows the actual double-slit barrier used by Batelaan. The slit centres are separated by only 200 nm

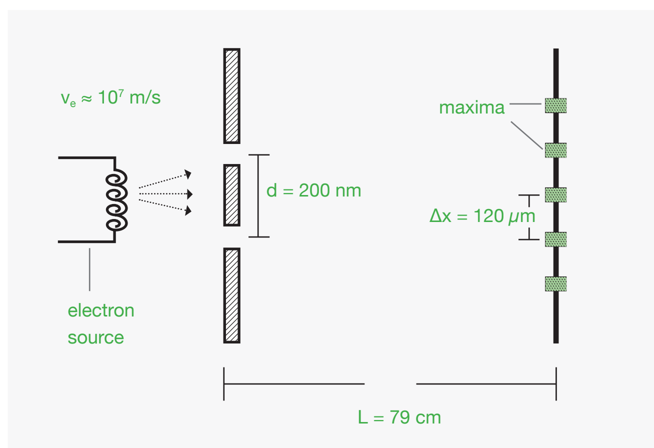


Figure 2.3 Dr. Batelaan's electron double-slit experiment at the University of Nebraska-Lincoln (not to scale)

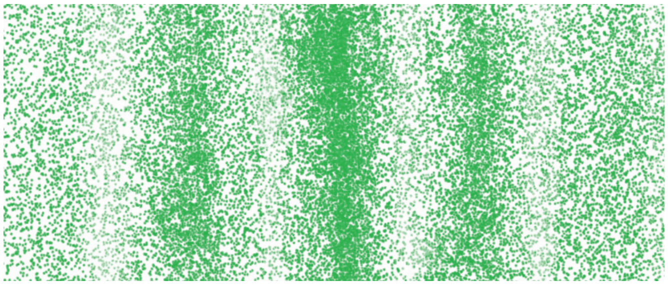


Figure 2.4 An interference pattern is evident after thousands of electrons have been detected

Electron Double-Slit Experiment Data

distance between slits, d	200 nm
width of each slit	100 nm
effective distance from slits to the detection screen, L	79 cm
distance from source to slits	30 cm
temperature of electron source	3000 to 4000 K
electron de Broglie wavelength, λ	3×10^{-11} m
electron velocity, $v_{electron}$	10^{7} m/s
maxima separation distance, Δx	120 µm

where λ = wavelength of electron (m)
Δx = distance between adjacent maxima or minima (m)
L = distance between the slits and the screen (m)
d = slit separation (m)

The interference pattern result raises deep questions about what the electron is actually doing as it travels through the double-slit apparatus, and how seemingly particle-like objects are able to produce an interference pattern. The mathematical formalism of quantum mechanics predicts the interference, but it does not answer any questions about what a specific electron is actually doing inside the apparatus. This ambiguity is what leads to the various interpretations presented in Chapter 5.

MATTER EXHIBITS WAVE PROPERTIES

The wave–particle duality of an electron was part of de Broglie's 1924 doctoral thesis, in which he derived his matter–wave equation (see equation 2.2). Interestingly, an electron interference experiment was not actually conducted until 1961 when Claus Jönsson of Tübingen, Germany finally verified the 1920s theoretical predictions. By then, the result was not at all surprising and received little fanfare.

The wave nature of matter is mathematically expressed by the de Broglie equation

$$\lambda = \frac{h}{mv} \qquad (2.2)$$

where λ = wavelength (m)
h = Planck's constant (6.626×10^{-34} J·s)
m = mass (kg)
v = velocity (m/s)

The variables contained in the de Broglie equation help illustrate the wave–particle duality of matter. The object's wavelength, a wave property, is determined from the object's mass and velocity (typically associated with a particle) and Planck's constant. Planck's constant is a common feature in equations dealing with quantum physics. The constant is extremely small and is related to the minimum size of the discrete units of energy, mass, spin, and other quantum descriptors.

It is important to emphasize that any quantum object exhibiting wave–particle duality only ever demonstrates one behaviour at a time. For example, in the double-slit experiment with electrons, the interference pattern is built up one electron at time and it is this pattern that provides the evidence for wave-like behaviour. However, the individual electrons that are emitted and strike the screen at localized spots provide evidence for particle-like behaviour. This dual nature is not observed in the macroscopic world, and it highlights a key difference between descriptions in classical physics and quantum physics. A classical particle always behaves as a particle, and never requires a classical wave model to describe its behaviour. A quantum object is not a classical particle or a classical wave. Careful use of language is required to correctly describe a quantum object. Phrases that describe the observed behaviour are preferred over statements about what a quantum object actually is. For example, it is safer to say that an electron "behaves like a particle" than an electron "is a particle." Interpretations about what an electron "is" are discussed in the Chapter 5 Summary.

THE WAVEFUNCTION – A MATHEMATICAL DESCRIPTION

Quantum physics mathematically addresses wave–particle duality and the behaviour of an electron by using a mathematical wave called a wavefunction. A wavefunction gives the probabilities for finding an electron at all of the possible locations that it can be observed. If the amplitude of an electron's wavefunction at a particular location is large, there is a high probability of finding the electron there. If the amplitude is small, there is a low probability of finding the electron there. The wavefunction is a mathematical description and, in the absence of a specific interpretation, does not answer the question about what an electron is.

Chapter 03
Wave – Particle Duality with Light

This chapter of the video:

- *shows how light, which had previously been modelled as a wave, also demonstrates wave–particle duality.*
- *introduces the formula for the energy of a photon.*
- *illustrates how this strange behaviour is also seen in protons, neutrons, atoms, and even very large molecules (buckyballs).*
- *presents the differing opinions of researchers on how big a quantum object can be.*

EVIDENCE FOR PHOTONS

The nineteenth century opened with the publication of Young's double-slit experiment, which firmly established the wave nature of light. As the century drew to a close there were several experiments that pointed to the need for a different model. By 1905, Einstein was using a particle model for light in his explanation of the photoelectric effect. The double-slit experiment showed that light came in packets whose energy could be calculated by the equation

$$E = \mathrm{h}f \qquad (3.1)$$

where E = the energy of the photon (J)
h = Planck's constant (6.63 x 10^{-34} J·s)
f = the frequency of the photon (Hz)

Note how the variables in this equation illustrate the wave–particle duality of light. A photon, which is detected as a localized object like a particle, has an energy that is proportional to its frequency, which is a wave-like property. The two aspects are connected by Planck's constant, the same constant that is in the de Broglie wavelength equation, $\lambda = h/p$. The de Broglie equation holds for all quantum objects, including photons, and therefore a photon has momentum even though it has no mass.

A demonstration of Young's double-slit experiment with individual photons was done by Geoffrey Ingram Taylor in 1909. He used extremely faint light, so that there was only one photon in the apparatus at a time. The light was so faint that it required a three-month exposure time before the many individual photons were able to form an interference pattern.

WAVE–PARTICLE DUALITY AND LIGHT

All of the wave-like properties of light can be demonstrated using individual photons. This means that all of the demonstrations and experiments that we do with light have quantum physics at their core. For example, thin-film interference seems quite reasonable as a wave phenomenon; part of the wave reflects from the top surface of the thin film and part reflects from the bottom. These two parts interfere with each other to produce maxima and minima that vary with the thickness of the film. But this interference pattern forms even for only one photon at a time. How can a single photon do this? It is the same counter intuitive result that is found in the double-slit experiment.

The model for light scientists use often depends on the energy of the radiation with which they are working. Individual photons are easiest to detect if they are high energy, and so physicists who work with low-energy radio waves rarely consider light's particle-like behaviour, and physicists who deal with high-energy gamma radiation rarely see the wave-like behaviour.

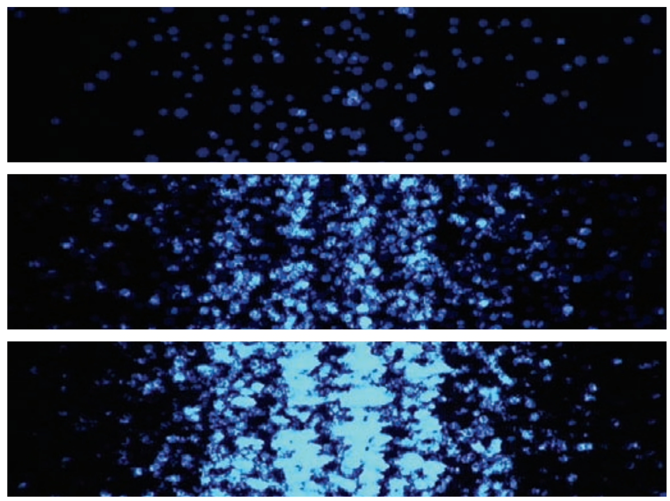


Figure 3.1 These photos show how an interference pattern forms from many individual photons.

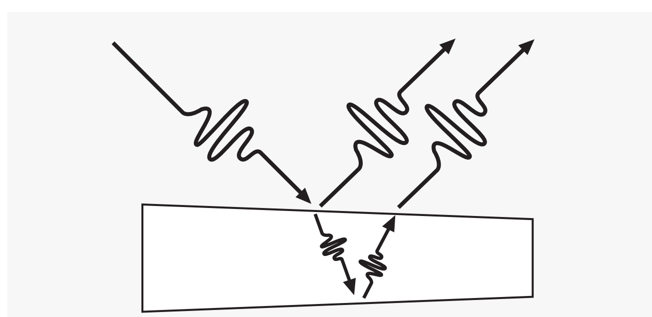


Figure 3.2 Thin film interference can be observed even when experimenters only use one photon at a time.

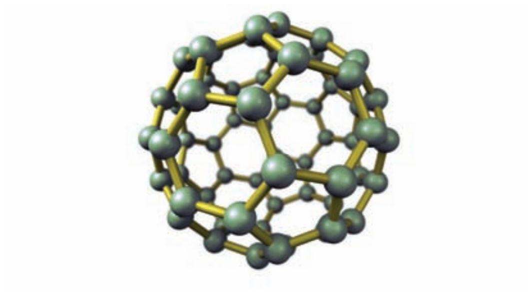


Figure 3.3 *Buckminsterfullerene or buckyballs consist of 60 carbon atoms*

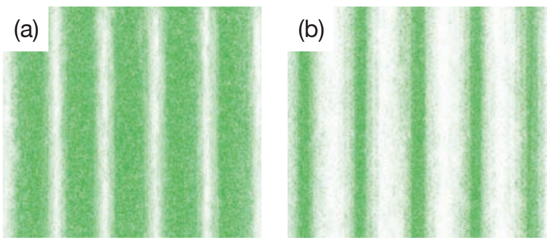


Figure 3.4 *Interference pattern produced by two slits (a) versus many slits (b)*

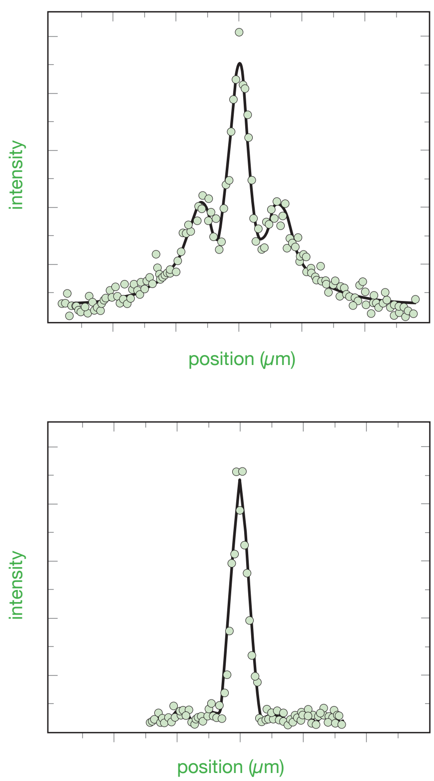


Figure 3.5 *The results of the buckyball experiment.The graphs show the results without (top) and with a diffraction grating (bottom).*

THE QUANTUM NATURE OF LARGE OBJECTS

Larger objects should also have de Broglie wavelengths, but these are much harder to demonstrate. Their wavelengths are smaller because their mass is greater. Recall the de Broglie equation:

$$\lambda = \frac{h}{p} = \frac{h}{mv} \qquad (3.2)$$

For example, buckminsterfullerene, or buckyballs, are made of 60 carbon atoms, so each one is about 600 000 times more massive than an electron. In order to make their wavelengths large enough to be detected, physicists had them travel much more slowly—200 m/s rather than 120 000 000 m/s. Even so, the wavelength of the balls was only 0.0025 nm, which is 400 times smaller than the 1 nm size of the molecule itself!

It gets more difficult to demonstrate interference as the wavelengths get smaller. Separation between the maxima is given by

$$\Delta x = \frac{\lambda L}{d} \qquad (3.3)$$

We can compensate somewhat for the tiny wavelength by using a very small slit separation, *d*. The slits in the buckyball experiment were 50 nm wide and separated by 100 nm. To make the separation of maxima even clearer, physicists used a diffraction grating with many slits, rather than just two. This does not change the separation between maxima, but it does make the maxima more concentrated and the minima more spread out (see Figure 3.4).

The results of the buckyball experiment are shown in Figure 3.5. The graphs show the results without a diffraction grating (top) and with (bottom). Note that there are only two interference maxima produced beyond the central one and these are really not all that clear. This shows how difficult it is to demonstrate the interference of such a “large” object. The same physicists have also shown interference with a fluorinated buckyball made of 60 carbon atoms plus 70 fluorine atoms, and they are trying for larger molecules. The physicists in the video disagree as to whether there is a theoretical limit or just a practical, technological limit to showing quantum effects with large objects. The answer is not known.

Chapter 04
Measurement Disturbance

This chapter of the video:

- *describes how detectors placed next to each slit reveal that half of the electrons went through each slit.*
- *describes how the act of measuring the electrons at the slits causes the interference pattern to disappear.*
- *outlines how researchers in Tübingen, Germany have verified these measurement disturbance results.*

In the double-slit experiment with tennis balls, each ball passes through just one slit and no interference pattern is observed. With water, the wave passes through both slits and an interference pattern is observed. An interference pattern is also observed with electrons. This surprising result raises a question about how each electron passes through the slits. The answer is not obvious. The fact that we always observe electrons as localized particles suggests that each electron goes through just one slit, like a tennis ball. However, if that was true, electrons would form the same distribution that the tennis balls make. Instead, they form an interference pattern. Does this mean that each electron somehow goes through both slits, like a wave?

To find out exactly how electrons pass through the slits, we can place detectors next to each slit. Physicists in Tübingen, Germany did just this in 2002. Their detector consisted of a slab of silicon placed near both slits. When a (negative) electron went through one of the slits it attracted positive charges in the silicon creating an electrical current, which caused the silicon to heat up. From the heating data, the Tübingen scientists were able to determine that an equal number of electrons went through each slit.

The electrons significantly above the silicon slab did not interact and were not measured, shown by the intact interference pattern at the top of Figure 4.1. However, electrons passing near the bottom of the slits were measured, and the interference pattern was destroyed and replaced by a completely random distribution of hits, shown at the bottom of Figure 4.1. The act of measuring the electrons had disturbed them and the pattern they produced on the screen. This phenomenon is called *measurement disturbance*. It is one of the defining features of quantum physics. In classical physics, we can measure an object without affecting it. For example, we can measure the speed of a car with a radar gun without altering the car's speed in any significant way. However, if we measure an electron, or any other quantum object, we change its behaviour in a significant way.

WHY DOES MEASUREMENT DISTURB?

To measure which slit an electron goes through, we have to physically interact with it. In the Tübingen experiment, electrical charges in the silicon "detector" exerted electromagnetic forces on the electrons. The interaction with each electron was largest when the electron passed close to the silicon, and it weakened as the distance increased. For example, if we measure which slit electrons go through by shining light on them, photons hit the electrons and bounce off them. Interactions like these have an effect on electrons. When a photon hits an electron, the electron rebounds and changes its direction of motion. As photons collide with each electron in a slightly different way, different electrons travel off in different directions. As a result, they hit the screen all over the place, destroying the interference pattern.

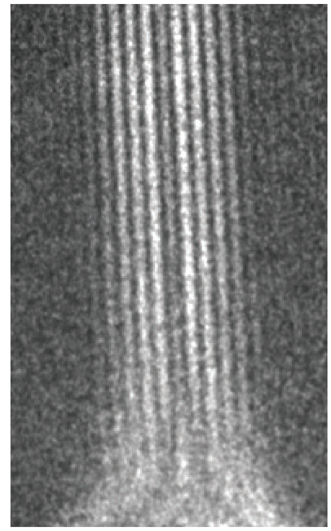


Figure 4.1 Measurement disturbance data from Tubingen. Notice how the clear interference pattern near the top is destroyed near the bottom due to the detector.

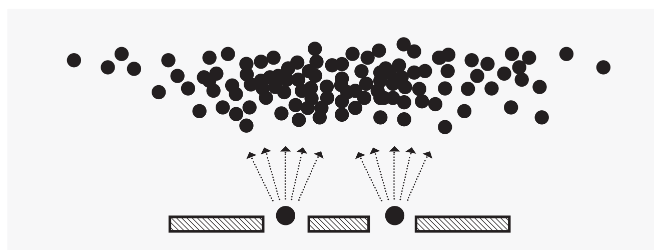


Figure 4.2 Electrons that have been detected by photons move in a wide range of directions due to their interaction with the photons.

HEISENBERG'S UNCERTAINTY PRINCIPLE

The concept of measurement disturbance is closely related to Heisenberg's uncertainty principle. This principle says there is a fundamental limit on how accurately we can make simultaneous measurements of the position and momentum of a quantum object. So, if we know the position of a quantum object with great accuracy, then we know very little about its momentum. When a detector measures which slit an electron passes through, we know its position with great accuracy. So Heisenberg's uncertainty principle says that its momentum is highly uncertain. This means that the electron could be moving in one of a wide range of directions, as shown in Figure 4.2. This leads to electrons hitting the screen all over the place and to the pattern at the bottom of Figure 4.1.

Chapter 05
Interpretations and Applications

This chapter of the video:

- *presents four different perspectives currently used to try to make sense of the quantum reality (Collapse, Pilot Wave, Many Worlds, and Copenhagen interpretations).*
- *highlights the surprising variety of technologies that owe their existence to the quantum nature of our world.*

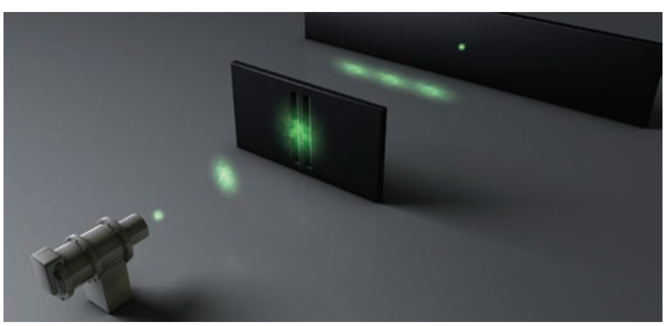
WHERE EXPERIMENTAL FACTS END AND INTERPRETATION BEGINS

The double-slit experiment demonstrates the way nature really behaves. The electron's dual wave and particle behaviour is a fact, as strange as it seems. When we use a measurement device and look at an electron to see what it is doing, we perturb it and actually change what happens. That leads to an understanding of nature at the quantum level which is very different from the familiar models of classical physics.

In the double-slit experiment, electrons are detected as particles at the screen, but while passing through the slits their behaviour seems to be governed by waves. Nobody really knows what the electrons are doing between the source and the detector. We have equations that make very accurate predictions about the results of the double-slit experiment, but quantum physics does not seem to answer the question about what is actually going on between the source and the detector. In the absence of a clear answer, physicists have developed various interpretations to complete the picture and describe what might be happening in the quantum world.

COLLAPSE INTERPRETATION

Scientists who subscribe to the Collapse interpretation make a choice. They believe that when you accept the electron's wave nature, you must give up on the electron's particle nature.



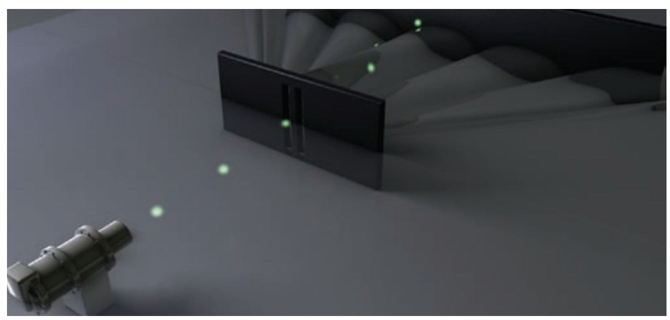
In this interpretation, the electron leaves the source as a particle that is governed by one set of laws, but then "expands" into a spread-out wave as it passes through the slits. The electron is now governed by new laws.

However, before we can measure this wavy, spread-out quantum electron it "collapses" back into a particle and arrives at only one of the many possible places on the screen.

The consequence of choosing the Collapse interpretation line of thinking is that you must accept that an electron physically changes from particle to wave and back again. These two realities, including the laws that describe them, alternate uncontrollably.

PILOT WAVE INTERPRETATION

The Pilot Wave interpretation avoids this unexplained collapse altogether. Scientists who subscribe to this interpretation choose to believe that the electron always exists as a classical particle and is only ever governed by one kind of physical law, for both the familiar classical as well as quantum phenomena. However, to account for the electron's wave behaviour this description requires the introduction of an invisible guiding wave.

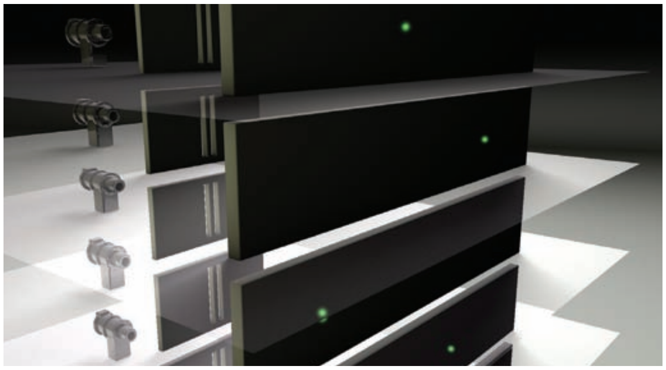


In this interpretation, wave-particle duality is explained by assuming that electrons are real particles all of the time, and are guided by an invisible wave. The electron's wave nature is attributed to this abstract wave, called a Pilot Wave, which tells the electron how to move. To obtain the interference pattern in the double-slit experiment, this wave must be everywhere and know about everything in the universe, including what conditions will exist in the future. For example, it knows if one or two slits are open, or if a detector is hiding behind the slits.

The Pilot Wave interpretation embodies all of the quantum behaviour, including all the interactions between classical objects like the electron, the two-slit barrier, and the measuring devices. In contrast to the Collapse interpretation where the collapsing electron wave was considered real, in the Pilot Wave interpretation the wave is an abstract mathematical tool. This interpretation has a consequence. The Pilot Wave interpretation, which was invented to deal with an electron as a real physical object, suffers the fate of being permanently beyond detection.

MANY WORLDS INTERPRETATION

Supporters of the Many Worlds interpretation, similar to the Pilot Wave idea, choose to accept that electrons are classical particles. Then they go even further, demanding that all elements of the theory must correspond to real objects—unlike the collapsing electron or the Pilot Wave. Supporters insist on only measurable, physical objects within the world. This world is constantly splitting into many copies of itself.



When electrons demonstrate wave behaviour they exist in a superposition of many different states. To Many Worlds supporters, who maintain the idea of an electron as a classical particle, a parallel universe must exist for each of the electron's possible states. When the electron reaches the slits, it has to choose which slit to go through. At that moment, the entire universe splits into two. In one universe, the electron passes through the left slit as a real particle. In the other universe it passes through the right slit as a real particle. The consequence of accepting the Many Worlds interpretation, with many quantum particles constantly facing similar choices, is the requirement that our universe must be constantly splitting into an almost infinite number of parallel universes, each having its own copy of every one of us.

COPENHAGEN INTERPRETATION

Advocates of the Copenhagen interpretation choose to limit their discussion directly to the experiment and to the measurements on physical objects. Questions are restricted to what can be seen and to what we actually do. They try to think about experiments in a very honest way, without invoking extra theoretical ideas like the on-off switching of the Collapse idea, or the guidance supplied by the invisible Pilot Wave, or the proposed splitting into Many Worlds.

It is tempting to come up with mental pictures about what is happening that go beyond the results of an experiment, and to try to interpret what is happening by means of those hidden theoretical mechanisms. The previous interpretations attributed the mysterious wave–particle duality to imaginative mathematics. In the Copenhagen interpretation much of this mystery is attributed to what happens when an experimenter enters the lab and interacts with the quantum mechanical system. With the Copenhagen perspective, the mathematics only deals with the experimenter's information about measurement interactions with the quantum mechanical system.

The consequence of accepting the Copenhagen interpretation is a fundamental restriction on how much you can read into experimental results. We know that electrons

Table 6.1 A summary of the choices physicists make and the resulting unsettling feature for each interpretation associated with wave–particle duality.

Interpretations	Assumptions that physicists choose to believe about reality			Unsettling feature
	One set of laws governs electrons.	Only one universe exists.	All objects are real.	
Collapse	X	✓	✓	Random switching between particles and waves, and between classical and quantum laws
Pilot Wave	✓	✓	X	Invisible, undetectable guiding wave that exists in a purely abstract mathematical space
Many Worlds	✓	X	✓	Infinite number of copies of the universe
Copenhagen	?	?	?	Accept that some questions cannot be asked
	Physicists choose to believe that descriptions of reality must be restricted to the measurements that they take.			

are particles when they are fired from the source, and we know that they are particles when they hit the screen. What happens to electrons in the middle, what they are "doing", or what they really "are" is not possible to know. In the Copenhagen interpretation these are unfounded questions. We may call an electron a wave or a particle, but ultimately those names are no more than suitable models.

Although the discussion about an adequate understanding of quantum physics is still unsettled, it is important to realize that all of the interpretations predict the observed experimental results. Leaving the unanswered questions about the foundations of the quantum universe temporarily aside, many physicists have gone on to put quantum physics to use. Engineers use quantum physics to make predictions about experiments, to construct devices, and to explore new technological applications.

APPLICATIONS OF WAVE–PARTICLE DUALITY

Quantum physics has revolutionized society with applications such as lasers, LEDs, and solar cells. Microelectronics led to computers, the Internet, and the Information Age. The electron microscope has opened the door to nanotechnologies. The next generation of innovators are exploring quantum cryptography, quantum computing, and many more possibilities.

ELECTRON MICROSCOPE: ELECTRON WAVES Resolution is the ability to form a clear image and is related to the wavelength of the incident radiation. A light microscope can resolve objects as small as 2×10^{-7} m, which is about half the wavelength of violet light. The de Broglie wavelength of electrons can be a thousand times smaller than violet light. This dramatic reduction in wavelength allows an electron microscope to resolve objects that are incredibly tiny.

The electron beam is focused by electric and magnetic fields instead of glass lenses. Eli Burton and his students built the first practical electron microscope at the University of Toronto in 1938. Today there are transmission (TEM), scanning (SEM), and scanning tunnelling (STM) electron microscopes. Electron microscopy provides visually stunning examples of how engineers are able to use the wave nature of electrons.

Figure 5.1 In this electron micrograph the flea's eye (in red) and mandibles used to suck the host's blood (long tubes) are clearly visible.

ELECTRONICS: ELECTRON WAVES The transistor is at the heart of every electronic device. A typical computer chip holds 200 million transistors. Engineers use a wave model of electrons when they design and build transistors. Every time you use a cell phone, MP3 player, computer, or anything electronic you are taking advantage of the quantum nature of electrons. Quantum computers that will exploit nature's fundamental quantum properties offer untold promise for the future. The transistor, which was once the size of an apple and confined to fundamental research, spawned the Information Age and is now woven into the very fabric of society. We can only imagine what quantum-based innovations will bring.

PHOTONS: PARTICLES OF LIGHT A particle of light, known as a photon, is at the heart of the light detectors needed for remote control systems, digital cameras, and solar cells. Running a solar cell process in reverse yields light emitting diodes (LEDs).

Positron Emission Tomography (PET) is a powerful medical imaging system. The patient swallows a small amount of positron emitting material, and then whenever a positron and electron collide, they annihilate and emit two photons. Detectors capture these photons to produce detailed and dynamic images of biochemical processes within our body.

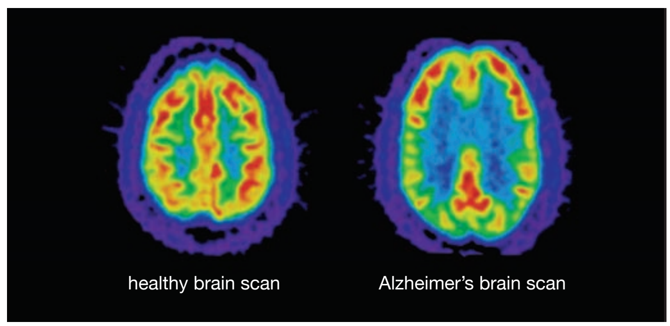


Figure 5.2 This Positron Emission Tomography (PET) scan shows maximum, healthy blood flow in red and limited blood flow in blue.

FUTURE APPLICATIONS

Individual photon detection is also essential for quantum cryptography, which ensures secure data transmission using fundamental principles of quantum physics. If someone tries to listen in, they necessarily disturb the system, just as electron detection at the slits destroys the double-slit interference pattern.

Today's supercomputers are number crunching behemoths, but may fade to insignificance if the promise of quantum computers comes true. Quantum computing and all of its related endeavours are currently exciting and active areas of research around the globe.

Appendix C:
Equations and Constants

Description	Equation		SI Unit
Path Difference	$\lvert \overline{P_nA} - \overline{P_nB} \rvert = (n - \frac{1}{2})\lambda$	$\overline{P_nA}$ = the distance from source A to a point on the nth nodal line $\overline{P_nB}$ = the distance from source B to a point on the nth nodal line λ = wavelength n = integer assigned to the nodal line	m m m
de Broglie Wavelength	$\lambda = \frac{h}{p}$	λ = wavelength h = Planck's constant p = momentum	m J·s kg·m/s
Momentum	$p = mv$	p = momentum m = mass v = velocity	kg·m/s kg m/s
Photon Energy	$E = hf$	E = energy of a photon h = Planck's constant f = frequency of the photon	J J_s S^{-1}
Young's Double Slit	$\lambda = \frac{\Delta x \cdot d}{L}$	Δx = separation of adjacent fringes λ = wavelength L = distance from slits to screen d = separation of slit centres	m m m m
Electric Potential Energy (point charge)	$E_Q = \frac{kq_1q_2}{r}$	E_Q = electric potential energy k = Coulomb's constant q_1 = electric charge on object 1 q_2 = electric charge on object 2 r = distance between object centres	J N·m^2/C^2 C C m
Electric Potential	$V = \frac{E_Q}{q}$	V = electric potential E_Q = electric potential energy q = electric charge on object	V J C
Electric Field Intensity	$\varepsilon = \frac{F_Q}{q}$	F_Q = electric field intensity q = force exerted by field ε = electric charge on object in field	N/C N C
Electric Potential (parallel plates)	$V = \varepsilon d$	V = potential difference between parallel plates ε = electric field intensity d = distance between plates	V N/C m
Kinetic Energy	$E_K = \frac{1}{2}mv^2$	E_K = kinetic energy m = mass v = speed	J kg m/s
Franck-Hertz	$E_K = \frac{qV\Delta x}{L}$	E_K = kinetic energy of electron q = charge on electron V = potential difference applied across the tube Δx = distance between successive bands L = distance from anode to cathode	J C V m m
Thermal Drift (simplified)	$E_k = \frac{1}{2}k_BT_{drift}$	E_K = kinetic energy attributed to thermal interactions k_B = Boltzmann's constant T_{drift} = drift temperature	J J/K K

Name	Symbol	Value	SI Unit
Planck's constant	h	6.626×10^{-34}	J·s
speed of light	c	3.00×10^{8}	m/s
Coulomb's constant	k	8.99×10^{9}	N·m^2/C^2
Boltzmann's constant	k_B	1.38×10^{-23}	J/K

Name	Symbol	Value	SI Unit
mass of electron	m_e	9.11×10^{-31}	kg
atomic mass unit	amu	1.6605×10^{-27}	kg
charge on electron	q_e	1.602×10^{-19}	C