Part IV

WHAT CAN WE KNOW WITH CERTAINTY?

This section examines the current scientific thought about quantum physics in relation to the Christian doctrines of the Incarnation and the Trinity. Quantum physics raises the question of certainty and objective reality for both science and religion.

Beginning with Newton's laws of motion, a mechanistic view of nature developed. Newtonianism stated that given the position and velocity of an object, one could calculate its past travel as well as its future travel. This certainty ended when scientists began to probe the inside of the atom. Scientists discovered that the act of measuring changed properties of an object. Certainty is replaced with probabilities.

The idea of creation includes more than the idea of origins. It also includes the idea that God sustains and governs the universe and all of its substructures. As a result of this situation, Christians can speak of "objective reality." Monotheistic and Eastern religious views of reality differ dramatically at this point.

How does God relate to the world of sensory perception? The idea of God intervening in the world in a fashion that might be seen as a violation of the laws of nature offends many modern people. To what extent are the arguments against intervention actually emotional and philosophical arguments rather than conclusions of scientific inquiry?

CHAPTER TEN

THE QUANTUM WORLD

THIS CHAPTER DEALS WITH THE SCIENCE OF THE SUBATOMIC WORLD. In a chemistry class, a student learns that atoms are the basic building blocks of matter. The physical and chemical properties of everyday objects result from the interactions of their atoms. For example, the interactions of the atoms of wood make it combustible; the interactions of the atoms of gold make it shiny, malleable, and ductile; the interactions of the atoms of grass make it green; the interactions of the atoms of a particle of food with the atoms on the tongue begin the sensation of taste. In the twentieth century, it was discovered that atoms are made of even tinier parts: *electrons, protons, neutrons*. Later it was realized that there are many additional subatomic particles. We identified a few of these subatomic particles in chapter 4.

The challenge to science was how to model and understand these invisible atoms and subatomic particles. Were subatomic particles and their interactions like ordinary particles and their interactions? For example, were atoms like billiard balls colliding with one another? Were subatomic particles just small balls within larger balls? This subatomic world is called the *quantum* world. As we shall see in this chapter, the quantum world is not a miniaturized version of our *macroscopic* world. In this chapter, we will also examine how our understanding of the quantum world affected our philosophical understanding of the macroscopic world.

We live in a macroscopic world of golf balls, cars, trees, and stars. Our understanding of the motion of objects in this world is due to the work of English scientist Isaac Newton (1642–1727). Newton determined a key concept that helps us organize all the varied information about motion. For centuries before Newton, it was believed that one set of rules governed motion on earth; another set governed motion in the heavens. On earth objects seemed to move a while and then come to rest, while in the heavens the stars seemed to move forever. Newton's key concept was that one set of laws governed all motion. What is today called Newton's three *Laws of Motion* along with the *Law of Universal Gravitation* explains the fall of the apple and the orbit of the moon. Using Newton's key concept, modern scientists can calculate the position and speed of a planet thousands of years into the future or the path of a rocket sent from earth to explore that planet. To carry out these calculations, the scientist needs to know the current position and momentum (*mass* and *velocity*) of the object plus this information about any other objects interacting with the original object.

The success of explaining motion by Newton's laws led to development of the philosophy of *determinism*. Determinism is the theory that all action, including human, is caused entirely by preceding events. The French astronomer and mathematician Pierre Simon de Laplace (1749–1829) believed that an omniscient Intelligence could use Newton's laws to calculate all future events based on the position and motions of all particles in the universe. If Laplace was correct, then there can be no *free will* (which would present challenges to Christian doctrines). Until the development of quantum theory (mechanics) in the twentieth century, many thought that science left no room for *indeterminacy*. With the development of quantum mechanics, indeterminacy would again enter into the scientists' models of the universe.

Why do we need quantum mechanics? Quantum mechanics makes it possible to describe the interaction of light and matter at the subatomic level. Quantum mechanics arose at a time (the end of the nineteenth century) when physicists thought they had answered all the problems in physics. Yet in this utopia there were a few clouds. The best minds could not explain the following phenomena that arose in experimentation: black body radiation in 1859, photoelectric effect in 1887, solar model of the atom in 1911, and wave-particle duality of light in 1704. As scientists examined these problems, a new view of nature would emerge.

Black Body Radiation

One source of light is *incandescence* in which an object is heated to a temperature high enough to cause its excited electrons to emit light. In an incandescent light source, heat causes atoms to vibrate more and collide with one another. During these collisions energy is transferred to electrons. When the electrons release this energy, they emit light. Burning candles emit light from the excited electrons in the hot atoms of the soot in the candle flame. An incandescent lightbulb emits light from the excited atoms in the thin wire (filament) that is heated when an electric current passes through it. A metal pan in the kitchen oven or an iron poker in a fireplace emits light from the vibration of its atoms. Scientists model real incandescent light sources by studying an idealized incandescent light source called the *black body*. Unlike a real incandescent light source, a black body's light emission only depends upon its temperature, not on the material of the source.

As you may have observed, when an iron pan or iron poker is heated, we gradually notice a change in the appearance of the object and the emission of heat from the object. While the object is at a relatively low temperature, its appearance has not changed but we can feel it radiate heat. As the temperature continues to increase, we begin to notice a change in the object's appearance. The object becomes dull red, then bright red, and finally blue-white. Note that the radiation output is moving from infrared (heat) to the visible spectrum (red to blue). Note also that, as the temperature is increased, the amount of radiation emitted also increases; the object feels hotter and looks brighter. The next part of the spectrum is ultraviolet. If we continue to increase the temperature, does the radiation output move into the ultraviolet and does the amount of radiation emitted continue to increase? Classical physics, using the black body model, indicated that the output would move into the ultraviolet and the radiation output would go to infinity. Fortunately, this does not occur in our ovens, fireplaces, or incandescent lightbulbs or we would all acquire skin cancer from the ultraviolet flux. This failure of the classical physics prediction is known as the "ultraviolet catastrophe." It may be a catastrophe, but at first no one could explain why it was not observed.

In 1900 the German physicist Max Planck (1858–1947) proposed a solution for the theoretical problem for the ultraviolet catastrophe. He discovered a formula whose output reproduced the black body radiation output exactly. Planck's formula was *empirical,* which means it had been modified to fit the experimental data and that it had no theoretical basis. Planck found that he could theoretically explain the black body radiation output if he made two radical assumptions. First, he assumed that vibrating atoms can vibrate only at certain energies or that the energies are *quantized*. Previously, classical physics had no limit on the energies of the vibrating atoms; their energies could be any of an infinity of values. Planck's second assumption was that the atoms only radiated energy when they moved from one energy state to another. This means that the energy is radiated in discrete bundles that Planck called *quanta*.

At the time Planck was studying black bodies, the current scientific theory of light stated that light was emitted as a wave. A wave is a series of crests and troughs that is *continuous;* it is uninterrupted as it extends through space. Consider a wave traveling across a surface of water; the wave is a continuous series of crests and troughs. Waves are characterized by their wavelength and frequency. The *wavelength* is the distance between two consecutive wave crests. The *frequency* is the number of crests that pass a point in a given time. In contrast to a wave, Planck was proposing that black body radiation could be understood if light were a particle. A particle is *discrete,* not continuous. A particle is located by a position in space, not by a wavelength and frequency. Particles and waves are mutually exclusive. The second finding of Planck was that the energy of the emitted light depended upon the frequency of the light rather than the intensity of the radiation. The energy is related to the frequency by a universal constant, now called Planck's constant. The numerical value of Planck's constant is very small, 6.63×10^{-34} joule-seconds. Planck received the Nobel Prize in physics in 1918 for his work.

Planck's relating energy of the quanta to the frequency raises a quantum paradox: Frequency is associated with wave, a continuous phenomenon, while the quanta are discrete particles! Could nature be this strange at the subatomic level? Or was Planck's observation just a mathematical calculation that worked? Or did the epistemology reflect the ontology? Planck, himself, was concerned by all of this. As he wrote, "My futile attempts to fit the elementary quantum of action [Planck's constant] somehow into the classical theory continued for a number of years, and they cost me a great deal of effort."[1] Scientists would not have to wait long before the quantum was used to explain another phenomenon (the photoelectric effect).

Photoelectric Effect

Certain metals will liberate electrons when light is shined upon the metal's surface. This phenomenon is called the *photoelectric effect*. This effect is the basis of the photoelectric cell or phototube or electric eye used in burglar alarms, door openers, and traffic-light controls. The wave theory of light could not explain certain features of the photoelectric effect. Wave theory predicted that the energy of the emitted electrons should increase as the intensity of the light beam is increased; but the energy of the photoemitted electrons are independent of the light intensity. Wave theory predicted that the photoelectric effect should occur at any light frequency; but for each metal surface, there was a frequency below which no photoelectric effect is observed, no matter how intense the illumination. Wave theory implied that there should be a time delay as the wave is "soaked up" by the metal surface; no such time delay is observed.

In 1905 Albert Einstein (1879–1955) used Planck's insights to explain the photoelectric effect. Einstein proposed that light is propagated through space in discrete particles called *photons* and that the energy of the photon depends upon the frequency of the light. Photons are different from other particles, such as a baseball or a train. Photons are massless and always travel at the speed of light.

Einstein's photon hypothesis successfully addressed the features of the photoelectric effect that wave theory could not explain. The first problem was that the energy of the emitted electron is independent of the light intensity. The energy of the emitted electron depends only on the energy with which the photon strikes the electron. The photon's energy depends on the light's frequency, not the light's intensity. The intensity only measures the number of photons striking the metal. The second problem was that a minimum frequency was required for electrons to be emitted. The electron is held in the metal by an electrostatic attraction. A certain energy is required to break this attraction. Since the energy of the photon is dependent on the frequency of light, only photons above a certain frequency will have enough energy to dislodge an electron. The third problem was no time delay. The photon is a concentrated bundle. A photon is not spread over a large area like a wave would be. Thus, as soon as the photon hits the metal's surface, an electron can be emitted.

Like Planck, Einstein had again created a quantum paradox of relating the continuous property (frequency) with a discrete property (photon). Einstein received the Nobel Prize in physics in 1921 for his work. We can ask the same question about Einstein's work that we asked about Planck's. Does the epistemology reflect the ontology? Confirmation of the concept that the photon is a bundle of energy came in 1923 from the work of the American physicist Arthur Holly Compton (1892–1962). Compton allowed a beam of X-rays of a sharply defined wavelength to fall on a block of graphite. The X-rays are scattered by the electrons in the surface of the block. Compton observed that the scattering causes a change in the wavelengths of the X-rays. Wave theory cannot explain this change, while the photon postulate can. Compton won the Noble Prize in physics in 1927.

Solar System Model of the Atom

In 1911 Ernest Rutherford (1871–1937) proposed that an atom consists of a very small, positively charged nucleus surrounded by negatively charged electrons that revolve around the nucleus. Classical physics stated that these moving electrons should emit energy and eventually fall into the nucleus. Thus, Rutherford's atom should be unstable. In 1913 Niels Bohr applied the quantum concept to the Rutherford atom. He proposed that the electrons' orbits around the nucleus were quantized or that only orbits of certain diameters were allowed; the allowed orbital diameters were related to Planck's constant. In classical physics, any orbital diameter is allowed. Bohr could not explain why the orbits were quantized; he only knew that this proposal resulted in a stable atom.

Bohr also postulated that electromagnetic radiation is emitted from an atom if an electron moves from a higher energy orbit (farther from nucleus) to a lower energy orbit (closer to nucleus). Absorption of radiation occurs, Bohr proposed, when the electron moves from a lower energy orbit to a higher energy orbit (see Fig. 10.1). These electron movements are called *quantum jumps*. These quantum leaps are easy to observe. When one burns the Sunday comics or special fire logs in the fireplace, the colored flames that result come from the emission of quanta of radiation as electrons move from higher Bohr orbits to orbits closer to the nucleus. Bohr won the Nobel Prize in physics in 1922 for his work.

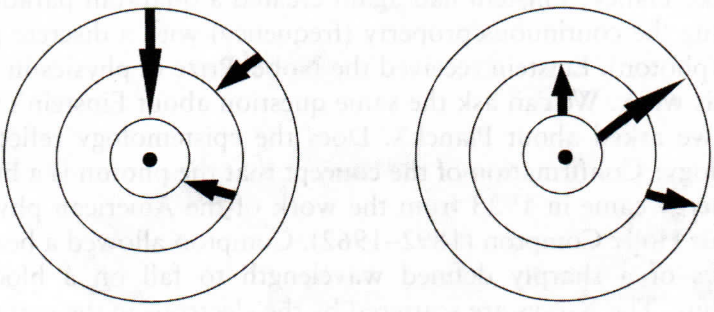


Fig. 10.1. Bohr Model of the Atom, Explaining the Emission and Absorption of Radiation by an Atom.

Wave-Particle Duality of Light

Since the time of Newton, scientists have been debating whether light is a wave (continuous) or a particle (discrete). Visible light is a small part of the *electromagnetic spectrum* which ranges from low-energy radio waves, to microwaves, to infrared light, to visible light, to ultraviolet light, to X-rays, to gamma rays. So the question should be stated: Is electromagnetic radiation a particle or a wave? Certain experiments imply a wave: interference, diffraction, polarization. Other experiments imply a particle: photoelectric effect (Einstein), X-ray scattering (Compton). As we shall see, we may be asking the wrong question when we ask if light is a wave or a particle.

Wave-Particle Duality of Matter

In 1924 Louis de Broglie (1892–1987) turned the question on its head by asking if particles of matter behave like waves! Or does the electron (a particle) have a wavelength? Assuming that the electron does, de Broglie discovered that he could explain why certain distances from the nucleus of the Bohr atom were stable for an orbit while others were unstable. He explained the stability of the orbits in terms of interference of waves. *Interference* occurs when two waves overlap. If the crest of one wave overlaps with the crest of another wave, a new wave is produced that has crests that are the sum of two overlapping crests. This is called *constructive inter-*

ference. If the crest of one wave overlaps with the trough of another wave, the two waves cancel each other, producing no wave at all. This is called *destructive interference*. An example of these types of interference is a concert hall that has areas with enhanced sound (constructive interference) and no sound (destructive interference). De Broglie observed that stable orbits had circumferences that allowed for constructive interference of the electron wave (see Fig. 10.2). The electron wave will be reinforced and stable. Unstable orbits had circumferences that produced destructive inferences of the electron wave. The electron wave would be unstable. De Broglie won the Nobel Prize in physics in 1929.

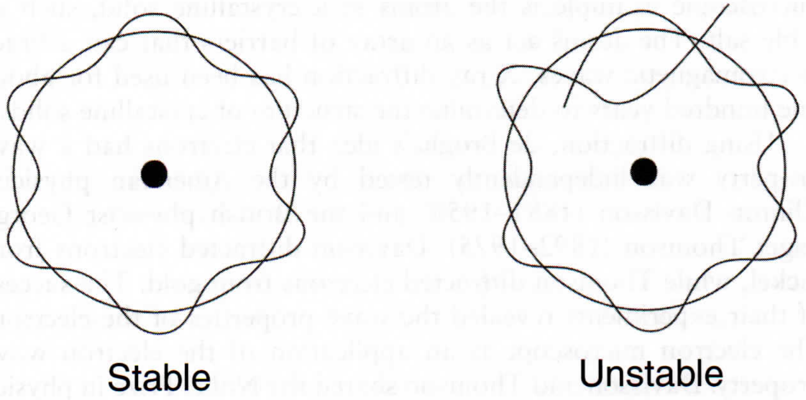


Fig. 10.2. De Broglie's Wavelength for Electrons.
A whole number of crests would be stable, while
a non-integer number of crests would be unstable.

The epistemology and ontology question was bad enough when quantum results implied wavy light was a particle. Now quantum results are implying that particles have waves. Can this be correct? Think about it. For centuries physicists had observed that energy was carried by either waves or particles. Waves carried energy over water and a particle like a stone carried energy from the top of a mountain to the bottom. Physicists extended these models into the invisible realm of nature. Sound was explained as a wave while subatomic particles were particles. Protons, neutrons, and electrons have mass. Thus, in a beginning chemistry course, one learns that the atom is made of three particles: proton, neutron, and electron—not that an atom is made of a proton, a neutron, and a wave!

However, experimental confirmation of de Broglie's idea came quickly. Two independent groups used diffraction of electrons to test de Broglie's idea. *Diffraction* is a wave property where waves spread as they pass through a small opening or around a barrier. One example of diffraction is a person's ability to hear a radio in a room adjacent to the room where the radio is located. Sound waves diffract through the doorway into the adjacent room. Another example is the behavior of water waves as they pass a boat dock. The waves that pass the dock's supports diffract into the area behind the dock's supports which is directly blocking the waves. A microscopic example is the atoms in a crystalline solid, such as table salt. The atoms act as an array of barriers that can diffract electromagnetic waves. X-ray diffraction has been used for about one hundred years to determine the structure of crystalline solids.

Using diffraction, de Broglie's idea that electrons had a wave property was independently tested by the American physicist Clinton Davisson (1881–1958) and the British physicist George Paget Thomson (1892–1975). Davisson diffracted electrons from nickel, while Thomson diffracted electrons from gold. The success of their experiments revealed the wave properties of the electron. The electron microscope is an application of the electron wave property. Davisson and Thomson shared the Nobel Prize in physics in 1937. There is an irony in Thomson's winning the Nobel Prize for showing that the electron is "a wave." In 1906 his father, J. J. Thomson (1856–1940), won the Nobel Prize for experimentally establishing that the electron is "a particle." If it was not upsetting enough that the electron was wavy, scientists soon were observing diffraction for protons, neutrons, hydrogen atoms, helium atoms, and hydrogen molecules, revealing that all these particles had wave properties. Recently, the research group of Anton Zeilinger[2] in Vienna performed the double slit experiment on a fullerene molecule containing sixty carbon atoms. Even this large molecule was shown to exhibit wave as well as particle properties. The fullerene experiment is an important extension of the wave/particle duality toward a genuinely macroscopic region.

Quantum Wave Mechanics

The work of de Broglie led the Austrian/English physicist Erwin Schrödinger (1887–1961) to develop quantum *wave equations* to describe the behavior of electrons in atoms. The quantum wave equations were similar to classical physics equations used in optics to describe the waves of light or used in music to describe the standing waves in a violin string. The Schrödinger wave equation is a mathematical expression consisting of an operator and a wave function. The *operator* is a mathematical expression that tells one what to do with whatever follows it. For example, in the expression "1/3," the "1/" is an operator telling one to take the inverse of what follows, in this case 3. The *wave function,* usually represented by the Greek letter psi, ψ, is a mathematical expression describing the physical system, in this case the nucleus of an atom and its electrons. Operation on the wave function yields *eigenvalues,* or characteristic values for the system. Different mathematical expressions are used as operators on the same wave function to yield eigenvalues for the electron's characteristics, such as energy or momentum. Another way of saying this is that the observed properties of an atom can be calculated by the appropriate operator and wave function.

Solving the Schrödinger wave equation for the hydrogen atom yielded the same energy levels for the electrons as found in the Bohr model. What information did the wave equations give about the trajectories (paths or orbits) of the electrons? In 1926 the German-English physicist Max Born (1882–1970) suggested that the mathematical squaring of the wave function (ψ^2) gives a representation of the probability of finding an electron at a certain distance from the nucleus. Rather than a sharp line for the trajectory of the electron, the quantum mechanical treatment yields probabilistic predictions of the electron's position. Figure 10.3 shows these probability distributions. The maxima of the curves labeled 1s, 2p, and 3d correspond to the radius of the orbits predicted by the Bohr model. Figure 10.4 shows the three-dimensional shapes of these probability distributions. In quantum wave mechanics, the Bohr orbits are replaced by probability distribution *orbitals*. One of these orbitals has a spherical shape and is labeled the "s" orbital; orbitals of a dumbbell shape are labeled a "p" orbital; and those of a four-leaf clover shape are labeled a "d" orbital. The electron can no longer be located with precision. One now speaks of a certain probability that the electron is at a particular location. Schrödinger won the Nobel Prize in physics in 1933 for his work, while Born won the Nobel Prize in physics in 1954.

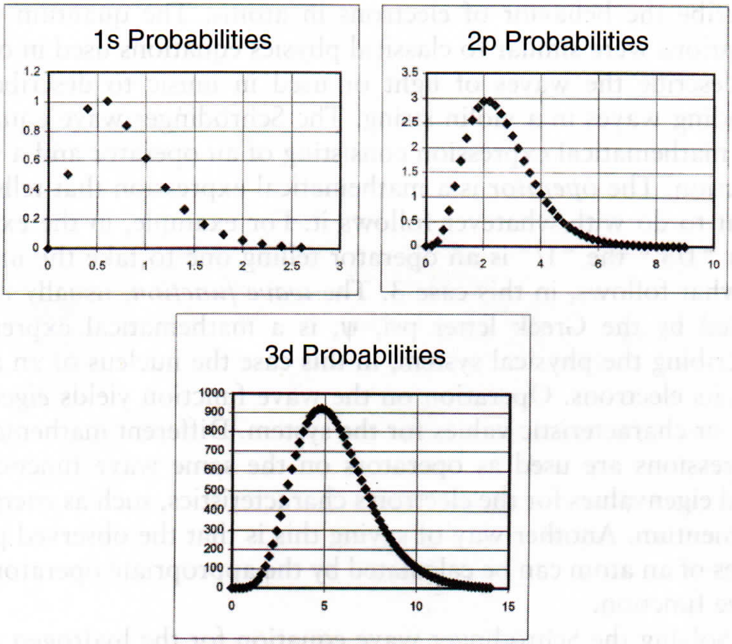


Fig. 10.3. Probability Densities for Electron Positions around the Nucleus.

Heisenberg's Uncertainty Principle

Max Born further interpreted the work of de Broglie and Schrödinger to say that photons and electrons are particles associated with probabilities that interfere as waves. The German physicist Werner Heisenberg (1901–1976) extended the indeterminacy

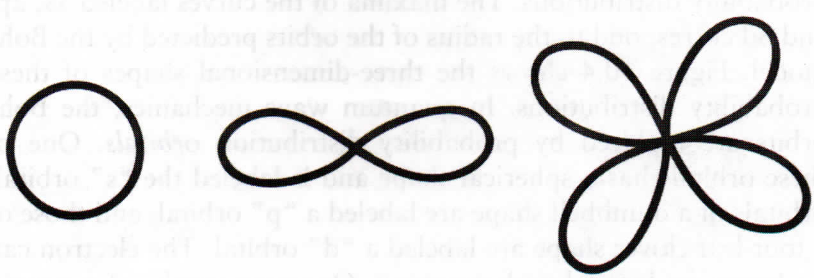


Fig. 10.4. Shapes of Atomic Orbitals.

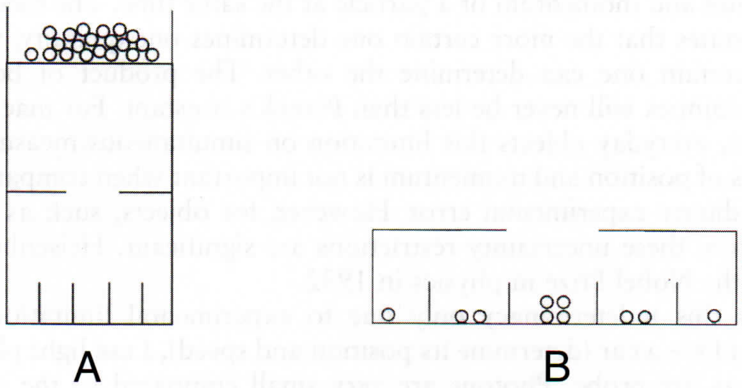
further by stating that it is impossible to know exactly both the position and momentum of a particle at the same time. The theory also states that the more certain one determines one quantity, the less certain one can determine the other. The product of both uncertainties will never be less than Planck's constant. For macroscopic, everyday objects this limitation on simultaneous measurements of position and momentum is not important when compared to ordinary experimental error. However, for objects, such as an electron, these uncertainty restrictions are significant. Heisenberg won the Nobel Prize in physics in 1932.

Is this indeterminacy only due to experimental limitations? When I see a car (determine its position and speed), I use light photons as my probe. Photons are very small compared to the car. Thus, bouncing the photons off the car has no measurable effect on the car's position and momentum. When I try to "see" an electron (determine its position and speed), I use electrons as the probe. But now the probe and the object are the same size. The probe electrons can cause the object electron to move. An example from the macroworld would be to use rockets tipped with explosives to determine where airplanes are over an airport; this probe would no doubt affect the speed and position of the airplanes!

Heisenberg's insight goes beyond experimental limitations. Suppose we could find a new smaller probe to discover the position and momentum of electrons. We would still not be able to obtain simultaneous exact position and momentum values for the electron because of the electron's wave probabilities. Thus, the Heisenberg Uncertainty Principle has raised uncertainty to a universal principle. Even if there were no errors in a measurement, it would still be impossible to obtain a precise value for both the momentum and position at the same time. The more precisely we can determine one variable, the less precise would be our simultaneous measurement of the other. Before Heisenberg's statement, it had been assumed that one could, in theory, do these measurements without any uncertainty.

The Strange Quantum World

I am not sure that the reader has grasped how strange the quantum world really is. Two experiments, the double slit experiment and the particle twins experiment, will be used to give us a "glimpse" of this strangeness.



A. Apparatus that allows marbles to roll down an inclined plane and pass through a single slit.
B. Distribution of the marbles after passing through the slit.

Fig. 10.5. Marbles Passing Through a Single Slit.

Double Slit Experiment

Before examining the double slit, consider what happens when particles and waves pass though a single small opening, the *slit*. As shown in Figure 10.5, marbles are allowed to roll down an incline and pass through a slit. Once the marbles pass through the slit, they are collected in boxes. After the marbles pass though the slit, most

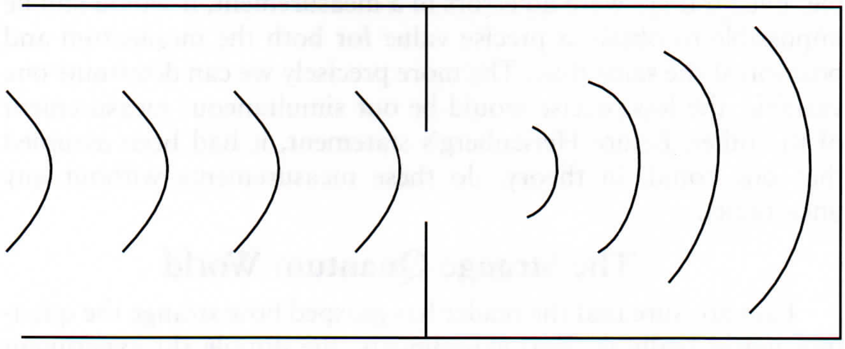
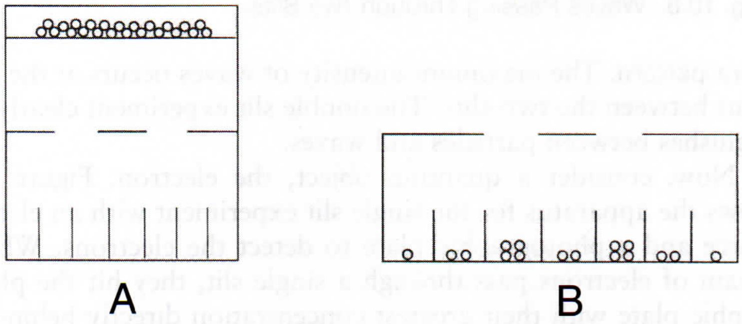


Fig. 10.6. Wave Passing Through a Single Slit.

of the marbles collect in the center boxes with fewer marbles toward the sides.

What happens when a water wave passes through a slit? In Figure 10.6, water waves approach a slit. The waves spread out behind the barrier. Using detectors for wave intensity, one discovers that the greatest wave intensity is right behind the slit as seen for the marbles. Although the maximum intensity is the same for both the particle and the wave, the particles strike localized spots on the detector while the wave covers the whole detector.

What happens when we send particles through two parallel slits, the double slit experiment? In Figure 10.7, marbles are allowed to roll down an incline and pass through two slits. Once again the marbles are collected in boxes. As with the single slit, the largest concentration of marbles is directly behind each slit.

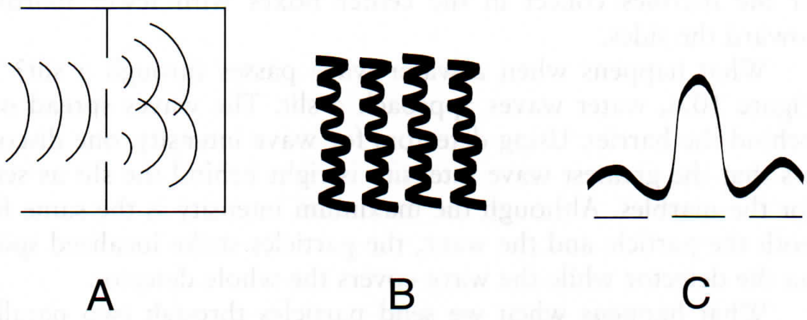


A. Apparatus that allows marbles to roll down an inclined plane and pass through a single slit.

B. Distribution of the marbles.

Fig. 10.7. Marbles Passing Through Two Slits.

Will the wave behavior in the double slit experiment parallel the particle behavior? The answer is no because of wave interference. In Figure 10.8, one observes that waves emerging from each of the slits interfere with each other, creating regions of constructive and destructive interference. The interference creates a pattern of alternating regions of wave, no wave, wave, no wave, wave or a



A Interference pattern as waves exit from two slits.
B. Light/Dark/Light (zebra) pattern that results from interference.
C. Wave intensity distribution.

Fig. 10.8. Waves Passing Through Two Slits.

zebra pattern. The maximum intensity of waves occurs at the midpoint between the two slits. The double slit experiment clearly distinguishes between particles and waves.

Now, consider a quantum object, the electron. Figure 10.9 shows the apparatus for the single slit experiment with an electron source and a photographic plate to detect the electrons. When a stream of electrons pass through a single slit, they hit the photographic plate with their greatest concentration directly behind the slit, as we saw for the experiment with the marbles and water.

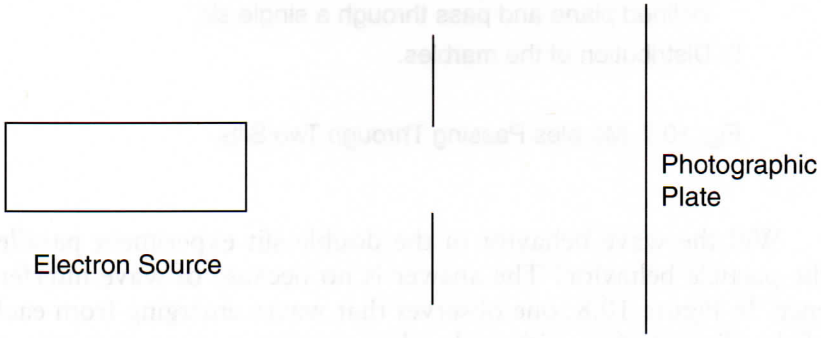


Fig. 10.9. Electron Single-Slit Experiment.

What would you expect if a beam of electrons were sent through the double slit apparatus? Would the electrons behave like the marbles (particle) or water (wave)? The electrons behave like the water waves, creating both the interference pattern of zebra stripes and the greatest intensity midpoint of the two slits. Maybe this interference is occurring because we are sending electrons through both slits simultaneously? De Broglie did "show" that electrons had a wave property and it is not too farfetched to imagine the wave of one electron interfering with the wave of another. Let's modify the experiment and send only one electron through the apparatus at a time. We will also wait until this electron has passed through a slit and hit the photographic plate before sending the next electron through the apparatus. Under these conditions, will the behavior be like the marbles (particle) or water (wave)?

As we watch the individual electrons arrive at the photographic plate, they seem to be random at first. But as more and more individual electrons arrive at the photographic plate, the wave interference pattern results. Even though only one electron at a time is sent through the apparatus and only one electron is detected on the plate, the electrons are interfering with one another as waves. How can the electrons interfere with one another when they pass through the apparatus one at a time? It may not make sense, but it is how nature works in the strange quantum world.

But wait, there is more. If during the double slit experiment, we close one of the slits, the individual electrons now hit the photographic plate as particles. How does the electron "know" when the second slit is closed? Reopen the second slit and the interference pattern begins again. Somehow the electron "knows" if two slits are open and "acts" as a wave or if one slit is open and "acts" as a particle. De Broglie called the electron a matter wave, which is a holistic system that always contains information from the particle side as well as the wave side. A very strange world indeed.

Particle Twins Experiment or the EPR Paradox

Further insight into the idea of a holistic system resulted from an experiment proposed in 1935 by Einstein, Boris Podolsdy (1896–1966), and Nathan Rosen (1901–1995).[3] Einstein believed that the results of the proposed experiment would reveal that quantum mechanics was incomplete and that there are yet undiscovered hidden variables that remove the uncertainty of quantum mechanics. In 1962 the physicist John Bell developed a theorem, called

Bell's Theorem, which showed that the predictions of the hidden-variable theory would be different from the predictions of quantum mechanics.

The experiment proposed by Einstein is called the EPR Paradox. In this narrative, the experiment is also called the particle twins because two particles are formed simultaneously. The EPR Paradox involves the following ideas. Subatomic particles, such as electrons and protons, contain a rotational property called *spin*. A model of spin would be the rotation of the earth on its axis. The particle spin orientations are quantized; this is, they are restricted to only two values, called spin up and spin down. If two particles are formed simultaneously (like twins), then the system of the two particles will have a total spin of zero with the two particles having opposite spins. If we experimentally cause the spin of one particle to change, say from up to down, then the spin of the other particle will immediately change from down to up. These changes maintain the zero value for the total spin of the system.

Scientists wondered if there was a limit on how far apart the two particles could be and still maintain the coupling between their spins. If, once the particles are formed, the two particles are sent in opposite directions, will the left particle always change spin when the spin of the right particle is changed? Also as the particles get farther and farther apart, how do they "know" what is happening to each other? If they "communicate" with each other, would the theory of relativity's limit that nothing can move faster than the speed of light apply? This experiment was performed in 1972 by the physicists John Clauser and Stuart Freedman and later in a more sophisticated version in 1982 by the physicist Alain Aspect.[4] Aspect designed his experiment so that he was able to change the orientation (change or do not change) of his right detector while the particles were in flight and with the particles too far apart to signal each other. Yet the particles behaved as if they were communicating. Even under these extreme conditions, when one particle changed spin, the other "knew" and changed its spin. Guided by Bell's Theorem, scientists observed that the results of the particle twins experiment followed the predictions of quantum mechanics rather than the hidden-variable theory.

How did one particle "know" what the other particle was doing? Some say the problem is viewing our example as two separate particles. Rather, this example should be viewed as a whole, a single system. The quantum wave function of the example is not two separate wave functions for two particles but a single wave function including both particles. The physicist Paul Davies said, "The system of interest cannot be regarded as a collection of things, but as an indivisible, unified whole."[5] Again as in the case of the double slit experiment, the matter waves are providing "information" about the whole. A very strange world indeed.

Responses to Quantum Mechanics

Quantum theory has been very successful in helping scientists explain atomic structure, chemical bonding, and radioactivity. It led to the development of the electron microscope, transistor, and laser. Yet the uncertainties and probabilities of quantum mechanics raise many philosophical questions and concerns. The following are some of the more common responses to quantum mechanics.

We Have Not Seen the Big Picture: Hidden-Variable Theory

Although Planck, Einstein, and de Broglie were instrumental in developing quantum mechanics, they believed that there was an underlying determinacy to nature. De Broglie wrote, "It is possible that looking into the future to a deeper level of physical reality we will be able to interpret the laws of probability and quantum physics as being the statistical results of the development of completely determined values of variables which are at present hidden from us."[6] This view is sometimes called the "hidden variables interpretation." They believed that once the hidden variables were found, all the quantum uncertainty would vanish. Einstein said, "Quantum mechanics is very impressive. But an inner voice tells me that it is not yet the real thing. The theory produces a good deal but hardly brings us closer to the secret of the Old One. I am at all events convinced that He does not play dice."[7] At first Einstein tried to show that quantum mechanics was inconsistent; after all his challenges were met, Einstein admitted that quantum mechanics was consistent. Einstein then changed his attack to say quantum mechanics was incomplete, that hidden variables would remove the quantum uncertainties. Many believe the results of the EPR Paradox show that quantum mechanics is complete and there are no hidden variables.

Noncausal and Nonlocal: The Copenhagen Interpretation

This interpretation is the most common interpretation of quantum mechanics and was developed under the leadership of Bohr with input from Heisenberg, Born, and Wolfgang Pauli (1900–1958). Bohr held that the wave functions do not represent the reality of nature but rather what we can know about nature. Or we do not know the quantum reality, only our observations on the quantum reality. As Bohr wrote, "We meet here in a new light the old truth that in our description of nature the purpose is not to disclose the real essence of the phenomena but only to track down, so far as possible, relations between the manifold aspects of our experience."[8] The observation (the collapse of the wave function) changes our knowledge of the world, not the reality itself.

Some postulates of the Copenhagen Interpretation are complementarity, indeterminism, no event-by-event causality, and nonlocality. *Complementarity* says that quantum objects have contradictory properties: wave/particle duality. Our choice of experiment determines what we observe with loss of information about the complementary property. The Copenhagen Interpretation says that the quantum world is truly indeterminate. The Heisenberg Uncertainty Principle represents a new universal principle. The Copenhagen Interpretation says that we cannot know anything about the trajectory of the electron. There is no causality. The electron is in one energy level and then in another energy level; the collapse of the wave function gives us no information on the path the electron took or even if there is a path. It is as if the electron disappears from one energy level and reappears in another energy level. *Locality* is the assumption that an event in one part of space cannot immediately affect another event separate from the first. The Copenhagen Interpretation says that a change in one part of the system causes the wave function to change immediately everywhere.

Causal but Nonlocal: The Pilot-Wave Interpretation

Building upon the proposal of de Broglie, the physicist David Bohm developed the Pilot-Wave Interpretation. Bohm assumed that the electron is a particle accompanied by a wave. Thus, one can know the path the electron takes, which is causality. The wave directs the path that the particle takes. If there is one slit, the wave directs the electron on a path like a particle. If there are two slits, the wave directs the electron on a path that involves wave interference. The paths the electrons take depend upon knowing precise initial conditions. Since these initial conditions cannot be precisely known, the best one can do is to obtain a statistical prediction of the path. The Heisenberg Uncertainty limitation sets the lower limit on the accuracy of knowing the path of the electron. Although this interpretation has causality, this interpretation contains the concept of nonlocality, like the Copenhagen Interpretation. Thus, Bohm has causality with nonlocality. Since there is no way to distinguish mathematically between the Copenhagen Interpretation and Bohm's interpretation, most scientists have followed the earlier Copenhagen Interpretation.

What We Choose to Observe Is What We See

The idea that what we choose to observe is what we see is a radical interpretation of the Copenhagen Interpretation. Not only does the choice of instrument result in what we observe (wave/particle), but the act of observing creates the reality. As physicist John Wheeler says, "No elementary phenomenon is a real phenomenon until it is an observed phenomenon."[9] What makes something observed: the click of a Geiger counter, the image in a photograph, or the mind of a human? The mathematician John von Neumann argues that since all instruments contain atoms (quantum events), only the human mind can do the observing. Thus, the most extreme view would be that the universe was in an indeterminate state until a human mind observes it.

A Seamless Whole

Experiments such as the double slit and the particle twins led to the view that the universe is a unified, seamless whole. The observer and observed are not separate. They are part of the same experiment. As physicist David Bohm says, "One is led to a new notion of unbroken wholeness which denies the classical analyzability of the world into separately and independently existing parts."[10] Physicists who blend physics and Eastern religions have adopted this interpretation.[11]

Many Universes

Hugh Everett first proposed the "many universes" interpretation of quantum theory while a Princeton graduate student. He suggested that when the wave function collapses, it collapses to all possible outcomes. When one runs the particle twins experiment, in one universe the spin of the right particle is changed, in the other universe the spin of the right particle is unchanged. Thus, the universe is forever splitting into universes on top of universes.

Apparently there is no way to communicate between the universes. This idea was the basis of Frederik Pohl's science fiction work, *The Coming of the Quantum Cats,*[12] which is an appropriate place to treat this view.

Summary

Once scientists began exploring the subatomic world, they discovered that the causal determinism of their Newtonian worldview could not explain the subatomic world. Quantum mechanics stated that subatomic particles are associated with probabilities that interfere as waves. This led to the realization that uncertainty was a universal principle. Responses to the implications of quantum mechanics have ranged from a denial of quantum uncertainty, to fundamental concept of uncertainty, to mysticism. If at the end of this chapter you still feel that you do not understand quantum theory, you are in good company. As Richard Feynman, one of the leading physicists of the twentieth century and Nobel Prize winner (1965) said, "We have always had a great deal of difficulty understanding the worldview that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me."[13]