Also by Amit Goswami

The Concepts of Physics
Quantum Mechanics

With Maggie Goswami

The Cosmic Dancers

THE SELF-AWARE UNIVERSE

HOW CONSCIOUSNESS CREATES THE MATERIAL WORLD

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Chapter 3

QUANTUM PHYSICS AND THE DEMISE OF MATERIAL REALISM

ALMOST A CENTURY AGO, a series of experimental discoveries was made in physics that called for a change in our worldview. What started showing up were, in the words of philosopher Thomas Kuhn, anomalies that could not be explained by classical physics.[1] These anomalies opened the door to a revolution in scientific thought.

Imagine that you are a physicist at the turn of the century. One of the anomalies you and your colleagues are interested in understanding is how hot bodies emit radiation. As a physicist of Newtonian vintage, you believe that the universe is a classical machine consisting of parts that behave according to Newtonian laws that are almost all completely known. You believe that once you have all the information about the parts and have figured out the few remaining glitches about the laws, you will be able to predict the future of the universe forever. Still, those few glitches are troubling. You are not prepared to answer such questions as, What is the law of emission of radiation from hot bodies?

Imagine, as you puzzle over the question, that your loved one is comfortably seated beside you in front of a glowing fire.

YOU (*muttering*): I just can't figure this out.
LOVED ONE: Pass the nuts.

YOU (*while passing the nuts*): I just can't figure out why we are not getting a good tan right now.
LO (*laughing*): Well, that would be nice. We could even justify using the fireplace in the summertime.
YOU: You see, theory says that the radiation from the fireplace should be as rich in high-frequency ultraviolet as sunlight is. But what makes sunlight and not fireplace light rich in these high frequencies? Why aren't we tanning in an ultraviolet bath right now?
LO: Wait a minute, please. If I am going to listen to this seriously, you'll have to slow down a little and explain. What's frequency? What's ultraviolet?
YOU: Sorry. Frequency is the number of cycles per second. It's the measure of how fast a wave wiggles. For light, that means color. White light is made up of light of various frequencies, or colors. Red is low-frequency light, and violet is high-frequency light. If the frequency is even higher, it's invisible black light, what we call ultraviolet.
LO: Okay, so light from both burning wood and the sun should give out plenty of ultraviolet. Unfortunately, the sun follows your theory, but burning wood doesn't. Maybe there's something special about burning wood. . . .
YOU: Actually, it's even worse than that. All light sources, not just the sun or burning wood, should give off copious amounts of ultraviolet.
LO: Ah, the plot thickens. The inflation of the ultraviolet is ubiquitous. But isn't all inflation followed by a recession? Isn't there a song, what goes up must come down? (*Your loved one starts humming.*)
YOU (*exasperated*): But how?
LO (*holding out the bowl of nuts*): Nuts, dear?

(The conversation ends.)

PLANCK TAKES THE FIRST QUANTUM JUMP

Many physicists in the late nineteenth century were frustrated until, finally, one of them broke rank: Max Planck, of Germany. In 1900, Planck took a bold conceptual leap and said that what the old theory needed was a quantum jump. (He borrowed the word *quantum*, meaning "amount," from Latin.) What emitted the light from an incandescent body—burning wood, for example, or the Sun—were tiny jiggling charges, the electrons. These electrons absorb energy from a hot environment, such as a fireplace, and then emit it back as radiation. This part of the old physics was correct, but then classical physics predicts that the emitted radiation should be rich in ultraviolet, which is contradicted by our observations. Planck declared (very bravely) that if the electrons are assumed to emit or absorb energy only in certain specific, discontinuously discrete amounts—which he called "quanta" of energy—the problem of the emission of varying degrees of ultraviolet could be solved.

To explore the meaning of the quantum of energy, consider an analogy. Compare the case of a ball on a staircase with one on a ramp (fig. 1). The ball on the ramp can assume any position, and its position can change by any amount. It is, therefore, a model of continuity and represents how we think in classical physics. In contrast, the ball on the staircase can sit only on this step or that; its position (and its energy, which is related to position) is "quantized."

You may object. What happens when the ball falls from one step to another? Is it not taking on an intermediate position during the descent? This is where the strangeness of quantum theory enters: For a ball on a set of stairs, the answer is obviously yes, but for a quantum ball (an atom or an electron), Planck's theory answers no. A quantum ball will never be found in any place intermediate between two steps; it is either on this one or on that one. This is a quantum discontinuity.

So why can you not get a tan from a wood-burning fireplace? Imagine a pendulum in the wind. Ordinarily a pendulum will swing in such a situation, even when there is not a high wind. Suppose, however, that the pendulum is allowed to absorb energy only in discrete steps of high denominations. In other words, it is a quantum pendulum. What then? Clearly, unless the wind is able to impart the required high increment of energy in one step, the pendulum will not move. Accepting energy in small denominations will not enable it to build up enough energy to cross a threshold. So it is with the jiggling electrons in a fireplace. Low-frequency radiation arises from small quantum jumps, but high-frequency radiation requires large quantum jumps. A large quantum jump must be fueled by a large amount of energy in the electron's environment; the energy in a wood-burning fireplace simply is not strong enough

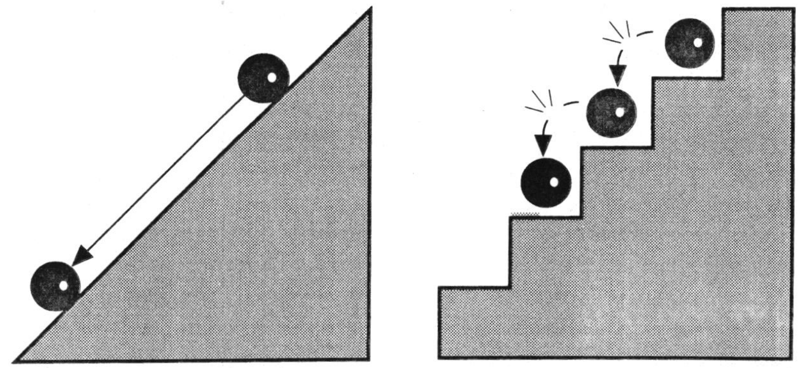

Figure 1. The quantum jump. On the ramp, the classical motion of the ball is continuous; on the staircase, quantum motion acts in discontinuous steps (quantum jumps).

to create the conditions even for much blue light, let alone ultraviolet. That is the reason you cannot get a tan from a fireplace.

By all accounts, Planck was a rather traditional sort of guy and declared his ideas about quanta of energy reluctantly. He even used to work on his mathematics standing up, as was at that time customary in Germany. He did not particularly like the implications of his breakthrough idea; that it pointed to a whole new way of understanding our physical reality was becoming clear, however, to scientists who would carry the revolution much further.

EINSTEIN'S PHOTONS AND BOHR'S ATOM

One of these revolutionaries was Einstein. He was working as a clerk at the patent office in Zurich at the time he published his first research paper on the quantum theory (1905). Challenging the then-popular belief that light is a wave phenomenon, Einstein suggested that light exists as a quantum—a discrete bundle of energy—that we now call a photon. The higher the frequency of the light, the more energy in each bundle.

Even more revolutionary was Danish physicist Niels Bohr, who in 1913 applied the idea of light quanta to suggest that the whole world of the atom is full of quantum jumps. We all have been taught that the atom resembles a tiny solar system, that electrons rotate around a nucleus much as the planets rotate around the sun. It may come as a surprise to learn that this model, originated by the British physicist Ernest Rutherford in 1911, has a crucial flaw that Bohr's work resolved.

Consider the swarm of orbiting satellites that are launched quite regularly by our space shuttles. These satellites do not last forever. Due to collisions with Earth's atmosphere, they lose energy and slow down. Their orbits shrink, and eventually they crash (fig. 2). According to classical physics, the electrons that swarm around the atomic nucleus would also lose energy, by radiating light continuously, and would eventually crash into the nucleus. So the solar-system atom is not stable. Bohr (who supposedly saw the solar-system atom in a dream), however, created a stable model of the atom by applying the concept of the quantum jump.

Suppose, said Bohr, that the orbits that electrons describe are discrete, like the quanta of energy suggested by Planck. The orbits

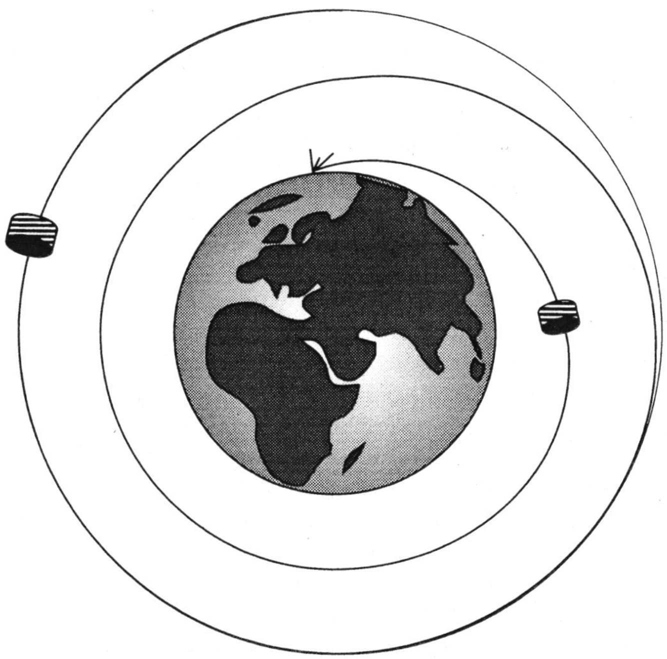

Figure 2. The orbits of satellites around the earth are unstable. The orbits of the electrons in the Rutherford atom behave in the same way.

can then be looked upon as making up an energy staircase (fig. 3). They are stationary—nonchanging in their energy value. The electrons, while in these quantized stationary orbits, do not radiate light. Only when an electron jumps from a higher-energy orbit to one of lower energy (from a higher level of the energy staircase to a lower level) does it emit light as a quantum. Thus, if an electron is in its lowest-energy orbit, it has no lower level to which it can jump. This ground-level configuration is stable, and there is no chance of an electron crashing into the nucleus. Physicists everywhere greeted Bohr's model of the atom with a sigh of relief.

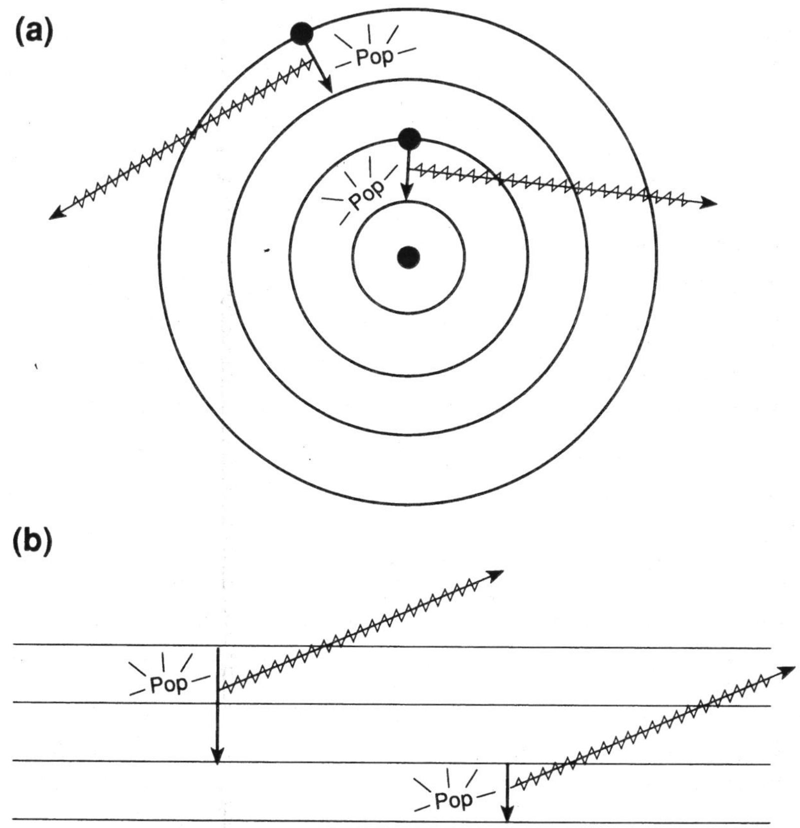

Figure 3. Bohr orbit and the quantum jump. (a) Bohr's quantized orbits. Atoms emit light when electrons jump orbits. (b) To quantum jump the energy ladder, you do not have to go through the intervening space between rungs.

Bohr had cut off the Hydra's head of instability, but another grew in its place. The electron, according to Bohr, can never occupy any position between orbits; thus when it jumps, it must somehow transfer directly to another orbit. This is not an ordinary jump through space but something radically new. Although you might be tempted to picture the electron's jump as a jump from one rung of a ladder to another, the electron makes the jump without ever passing through the space between the rungs. Instead, it seems to disappear at one rung and to reappear at the other—quite discontinuously. There is more: We cannot tell when a particular electron is going to jump nor where it is going to jump if it has more than one lower rung from which to choose. We can only give probabilities.

THE WAVE-PARTICLE DUALITY

Perhaps you have noticed something strange about the quantum conception of light. To say that light exists as quanta, as photons, is to say that light is made of particles—like grains of sand. Such a statement, however, contradicts many ordinary experiences that we have with light.

Imagine, for example, looking at a distant streetlight through the fabric of a cloth umbrella. You will not see a continuous, uninterrupted stream of light pouring through, which is what you would expect if light were made of tiny particles. (Pour sand through a sieve and you will see what I mean.) Instead, what you will see is a pattern of alternating bright and dark fringes, technically called a diffraction pattern. Light bends in and around the threads of the fabric and creates patterns that only waves make. So even our ordinary experience shows that light behaves like a wave.

Quantum theory nevertheless insists that light also behaves like a bunch of particles, or photons. Our eyes are such wonderful instruments that we can observe the quantum, grainy nature of light for ourselves. Next time you leave your loved one in the twilight, watch the person walk away from you. Notice how the image of the receding body appears fragmentary. If the light energy reflected off the body and onto the optical receptors of your retina had a wavelike continuity, at least some light from every part of the body would always be exciting your optical receptors: You would always see a complete image. (Granted, in dim light the contrast between light and dark would not be very clear, but this would not affect the sharpness of the outline.) What you see instead, however, is not a sharp outline because the receptors of your eyes respond to individual photons. Dim light has fewer photons than does bright light; so in this hypothetical twilight scenario only a few of your receptors will be stimulated at any given time, too few to define the outline or shape of a dimly lit body. Consequently, the image that you see will be fragmentary.

One more question may be nagging you. Why can the receptors not store their data indefinitely until the brain has enough information to collect all the fragmentary pictures into one whole? Fortunately for the quantum physicist, who is always desperately in need of everyday examples of quantum phenomena, the optical receptors can store information for only a tiny fraction of a second. In dim light not enough receptors in your eyes will fire at any given time to create a complete image. When next you wave adieu to the misty, departing figure of your loved one in the twilight, don't forget to ponder the quantum nature of light; it will surely lessen the pain of your separation.

When light is seen as a wave, it seems capable of being in two (or more) places at the same time, as when it passes through the slits of an umbrella and produces a diffraction pattern; when we catch it on a photographic film, however, it shows up discretely, spot by spot, like a beam of particles. So light must be both a wave and a particle. Paradoxical, isn't it? At stake is one of the bulwarks of the old physics: unambiguous description in language. Also at stake is the idea of objectivity: Does the nature of light—what light is—depend on how we observe it?

As if these paradoxes regarding light were not provocative enough, another question inevitably arises: Can a material object, such as an electron, be both a wave and a particle? Can it have a duality like that of light? The physicist who first asked this question and doggedly suggested a profession-shaking answer in the affirmative was a prince in the French aristocracy, Louis-Victor de Broglie.

MATTER WAVES

When de Broglie was writing his Ph.D. thesis around the year 1924, he made an association between the discreteness of the stationary orbits of the Bohr atom and that of sound waves produced by a guitar. The connection is a fruitful one.

Imagine a wave of sound traveling through a medium (fig. 4). The vertical displacement of the particles of the medium fluctuates from zero to a maximum (crest), back to zero, to a negative maximum (trough), and back to zero, over and over again, as the distance increases. The maximum vertical displacement in one direction (crest, or trough, to zero) is called the amplitude. The individual particles of the medium move back and forth about their undisturbed position. The wave going through the medium, however, propagates: A wave is a propagating disturbance. The number of crests passing a given point in a second is called the frequency of the wave. The crest-to-crest distance is the wavelength.

Plucking a guitar string sets it in motion, but the resulting vibrations are called stationary because they do not travel beyond the string. At any given place on the string, the displacement of the particles of the string changes with time: There is waviness, but the waves do not propagate in space (fig. 5). The propagating waves that we hear are those that have been set in motion by the stationary waves of the vibrating strings.

A musical note from a guitar consists of a whole series of sounds—a spectrum of frequencies. The interesting thing for de Broglie was that the stationary waves along the guitar string make up a discrete frequency spectrum called the harmonics. The lowest-frequency sound is called the first harmonic, which determines the pitch we hear. The higher harmonics—the musical sounds in the note that give it a distinctive quality—have frequencies that are represented as integer multiples of that of the first harmonic.

Being stationary is a property of waves in confinement. Such

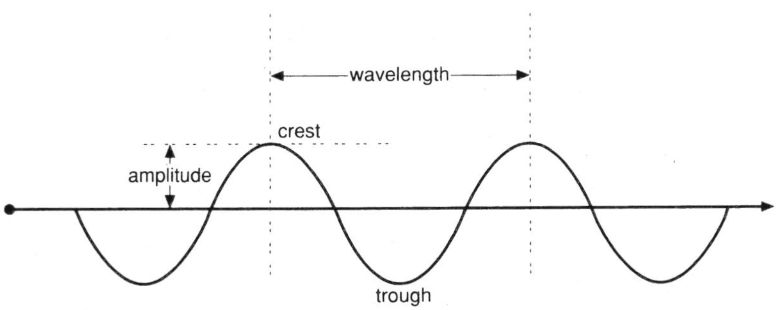

Figure 4. Graphic representation of a wave.

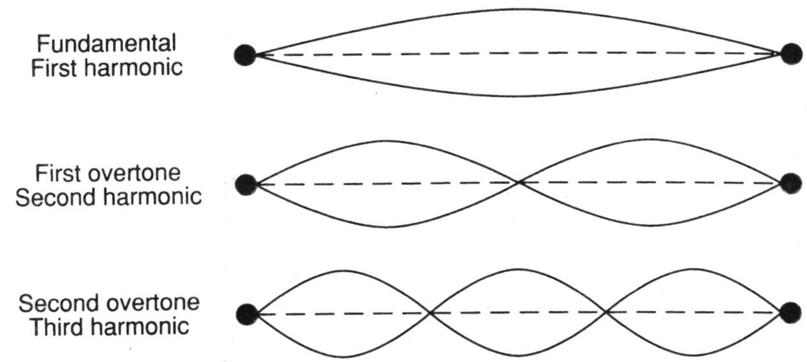

Figure 5. The first few harmonics of a standing or stationary wave on a guitar string.

waves are easily set up in a cup of tea. De Broglie asked, Are atomic electrons confined waves? If so, do they produce discrete stationary wave patterns? For example, maybe the lowest atomic orbit is one in which one electron makes a stationary wave of the smallest frequency—the first harmonic—and the higher orbits correspond to stationary electron waves of higher harmonics (fig. 6).

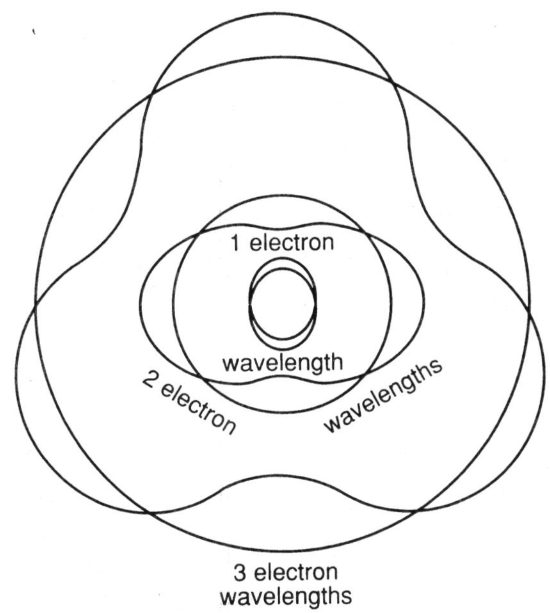

Figure 6. de Broglie's vision: Could electrons be stationary waves in the confinement of the atom?

Of course, de Broglie backed up his thesis with arguments much more sophisticated than the above, but even so, he had a hard time getting his thesis approved. It was eventually sent to Einstein for his opinion. Einstein, the first to perceive the duality of light, had no difficulty in seeing that de Broglie could very well be right: Matter might well be as dual as is light. De Broglie was given his degree when Einstein wrote back about his thesis: "It may look crazy, but it really is sound."

In science, experimentation is the final arbiter. De Broglie's idea of the electron's wave nature was demonstrated brilliantly when a beam of electrons was passed through a crystal (a three-dimensional "umbrella" suitable for diffracting electrons) and photographed. The result was a diffraction pattern (fig. 7).

If matter is a wave, quipped one physicist to another at the end of a seminar in 1926 on de Broglie's waves, there should be a wave equation to describe a matter wave. The physicist who said this promptly forgot about it, but the one who heard it, Erwin Schrö-

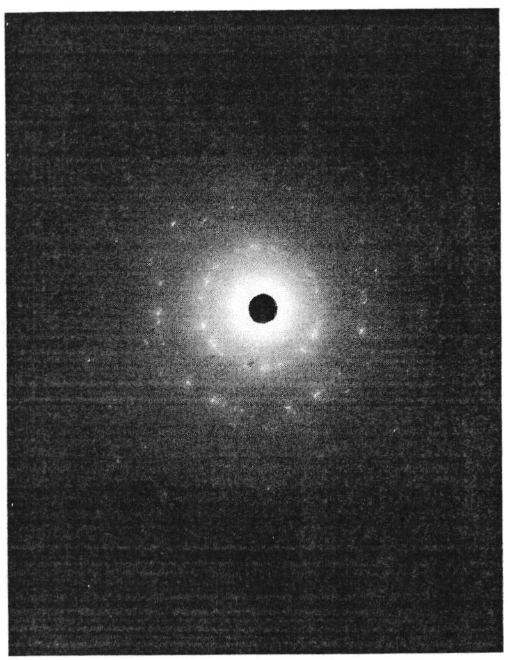

Figure 7. The concentric diffraction rings signify the wave nature of electrons. (Courtesy: Stan Miklavzina.)

dinger, proceeded to discover the wave equation for matter, now known as the Schrödinger equation. It is the cornerstone of the mathematics that replaced Newton's laws in the new physics. The Schrödinger equation is used to predict all the wonderful properties of submicroscopic objects that our laboratory experiments reveal. Werner Heisenberg had discovered the same equation even earlier but in a more obscure mathematical form. The mathematical formalism that grew out of the work of Schrödinger and Heisenberg is called quantum mechanics.

De Broglie's and Schrödinger's idea of the matter wave generates a remarkable picture of the atom. It explains in simple terms the three most important properties of atoms: their stability, their identity with one another, and their ability to regenerate themselves. I have already explained how stability arises—that was the great contribution of Bohr. The identity of atoms of a particular species is simply a consequence of the identity of wave patterns in confinement; the structure of the stationary patterns is determined by the manner in which the electrons are confined, not by their environment. The music of the atom, its wave pattern, is the same wherever you find it—on Earth or Andromeda. Furthermore, the stationary pattern, depending only on the conditions of its confinement, has no trace of past history, no memory; it regenerates itself, repeating the same performance over and over.

PROBABILITY WAVES

Electron waves are no ordinary waves. Even in a diffraction experiment, the individual electrons show up at the photographic plate as localized individual events; only when we observe the pattern created by a whole bunch of electrons do we find evidence of their wave nature—the diffraction pattern. Electron waves are probability waves, said the physicist Max Born. They tell us probabilities: For example, where we are most likely to find the particle is where the wave disturbances (or the amplitudes) are strong. If the probability of finding the particle is small, the wave amplitude will be weak.

Imagine that you are watching traffic from a helicopter above the streets of Los Angeles. If the cars were described by Schrödinger's waves, we would say that the wave is strong at the location of traffic jams and that between jams the wave is weak.

Furthermore, electron waves are conceived of as *wave packets.* By employing the notion of packets we can make the wave amplitude large in specific regions of space and small everywhere else (fig. 8). This is important because the wave has to represent a localized particle. The wave packet is a packet of probability, and Born said that for electron waves, the square of the wave amplitude—technically called the wave function—at a point of space gives us the probability of finding the electron at that point. This probability can be represented as a bell-shaped curve (fig. 9).

THE HEISENBERG UNCERTAINTY PRINCIPLE

Probability begets uncertainty. For an electron or any other quantum object, we can speak only of the probability of finding the object at such and such a position or of its momentum (mass times velocity) being so and so, but these probabilities form a distribution such as that represented by the bell-shaped curve. The probability will be maximum for some value of the position, and this will be the most likely place to find the electron. But there will be an entire region of places where there will be a considerable chance of locating the electron. The width of this region represents the degree of uncertainty of the electron's position. The same argument enables us to talk about the uncertainty of the electron's momentum.

From such considerations, Heisenberg mathematically proved that the product of the uncertainties of the position and the momentum is greater than or equal to a certain small number called Planck's constant. This number, originally discovered by Planck, sets the quantitative scale at which quantum effects become appreciably large. If Planck's constant were not small, the effects of the quantum uncertainty would invade even our ordinary macro reality.

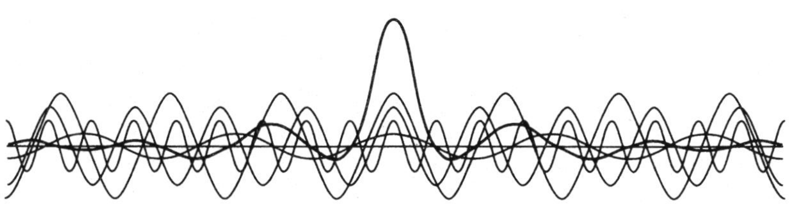

Figure 8. Superposition of many simple waves produces a typical localized wave packet. (Adapted with permission from P. W. Atkins, *Quanta: A Handbook of Concepts*. Oxford: Clarendon Press, 1974.)

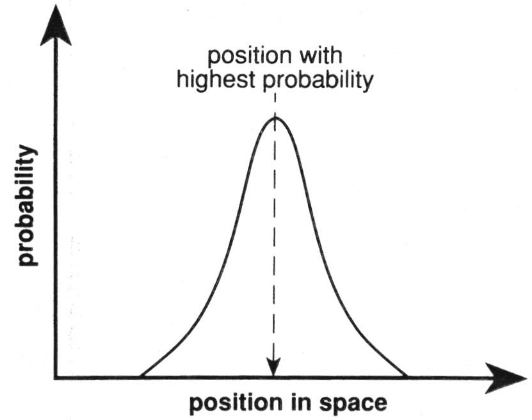

Figure 9. A typical probability distribution.

In classical physics, all motion is determined by the forces that govern it. Once we know the initial conditions (the position and the velocity of an object at some initial instant of time), we can calculate its precise trajectory using Newton's equations of motion. Thus classical physics leads to the philosophy of determinism, the idea that it is possible to predict completely the motion of all material objects.

The uncertainty principle throws a Molotov cocktail into the philosophy of determinism. According to the uncertainty principle, we cannot simultaneously determine with certainty both the position and the velocity (or momentum) of an electron; any effort to measure one accurately blurs our knowledge of the other. Thus the initial conditions for the calculation of a particle's trajectory can never be determined with accuracy, and the concept of a sharply defined trajectory of a particle is untenable.

By the same token, the Bohr orbits do not provide a strict description for the whereabouts of the electron: The position of the actual orbits is fuzzy. We really cannot say that the electron is such and such distance away from the nucleus when it is at this or that energy level.

UNCERTAIN FANTASIES

Consider a few fantasy scenarios in which the writers were unaware of or forgot the importance of the uncertainty principle.

In *Fantastic Voyage*, a science fiction book and movie, objects were miniaturized by squeezing. Have you ever wondered whether it is possible to squeeze atoms? After all, they are mostly empty space. Is such a thing possible? Decide for yourself by considering the uncertainty relation. The size of an atom gives a rough estimate of the degree of uncertainty regarding position of its electrons. Squeezing the atom will localize its electrons within a smaller volume of space, thus reducing the uncertainty about their position; but then the uncertainty regarding momentum must increase. An increase in the uncertainty of the electron's momentum means an increase in its velocity. Thus, as a result of squeezing, the electrons' velocity increases, and they are better able to run away from the atom.

In another example of science fiction, Captain Kirk (of the classic television series "Star Trek") says, Energize. A lever is then pulled down on an instrument panel; voilà, people standing on a platform disappear and reappear at a destination that is supposed to be an unexplored planet but that looks a lot like a Hollywood sound stage. In one of his novels based on "Star Trek," James Blish tried to characterize this process of reappearing as a quantum jump. Just as an electron jumps from one atomic orbit to another without ever passing through the intermediate space, so would the crew of the spaceship *Enterprise*. You can see a problem with this. When the electron will take the jump and to where are acausal and unpredictable because probability and uncertainty rule the quantum jump. Such quantum transport would force the *Enterprise* heroes, at least occasionally, to wait a long time to get somewhere.

Quantum fantasies can be fun, but the ultimate purpose of this new science, and of this book, is serious. It is to help us deal more effectively with our everyday reality.

WAVE-PARTICLE DUALITY AND QUANTUM MEASUREMENT

The preceding background information helps explain a couple of puzzling questions. Does the quantum picture of the electron moving in waves around the atomic nucleus imply that the electron's charge and mass are smeared all through the atom? Or does the fact that a free electron spreads out, as a wave must according to the theory of Schrödinger, mean that the electron is everywhere, with its charge now smeared all through space? In other words, how do we reconcile the wave picture of the electron with the fact that it has particlelike, localized properties? The answers are subtle.

It may seem that, with wave packets at least, we should be able to confine the electron in a small place. Alas, things do not stay that simple. A wave packet that satisfies the Schrödinger equation at a given moment in time must spread with the passage of time.

At some initial time, we may localize an electron to a tiny dot, but the electron's wave packet will spread all over town in a matter of seconds. Although initially the probability of finding the electron localized as a tiny dot is overwhelmingly high, it takes only seconds before the probability becomes considerable that the electron might appear anywhere in town. And if we wait long enough, the electron may show up anywhere in the entire country, even in the entire galaxy.

It is this spreading of the wave packet that promotes incessant jokes about quantum weirdness among the connoisseurs. For example, the quantum mechanical way of materializing a Thanksgiving turkey is as follows: Prepare your oven and wait; there is a nonzero probability that the turkey from a nearby grocery store will materialize in your oven.

Unfortunately for the turkey lover, with such massive objects as turkeys, the spreading is ever so slow. You might wait the entire lifetime of the universe to materialize even a little morsel of Thanksgiving turkey in this way.

What about the electron? How do we reconcile the spreading of the electron's wave packet all over town with the picture of a localized particle? The answer is that we must include the act of observation in our reckoning.

If we want to measure the electron's charge, we must intercept it with something like a cloud of vapor, as in a cloud chamber. As a result of this measurement, we must assume that the electron's wave collapses, so now we are able to see the electron's track through the cloud of vapor (fig. 10). According to Heisenberg: "The path of the electron comes into existence only when we observe it." When we measure it, we always find the electron localized as a particle. We may say that our measurement reduces the electron wave to the particle state.

When Schrödinger introduced his wave equation, he and others thought that perhaps they had purged physics of quantum jumps—of discontinuity—since wave motion is continuous. The particle nature of quantum objects, however, had to be reconciled with their wave nature. Thus, wave packets were introduced. Finally, with the recognition of the spreading of the wave packet and

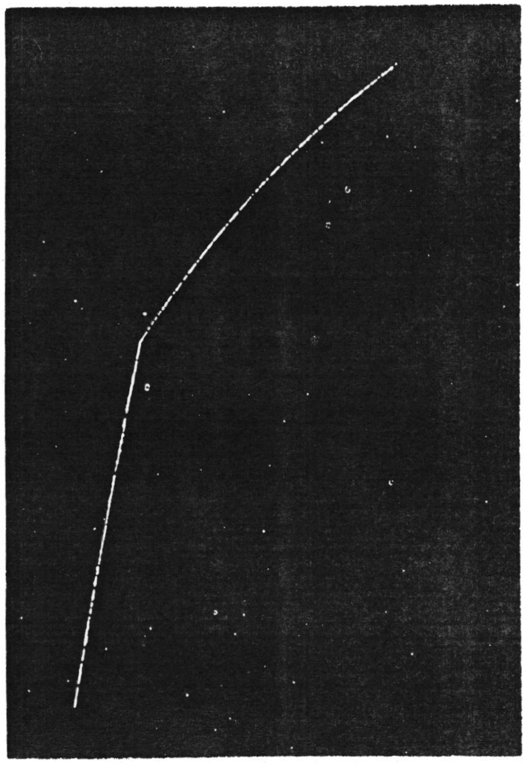

Figure 10. An electron's track through a cloud of vapor.

with the realization that it is our observation that must instantly collapse the size of the packet, we see that the collapse has to be discontinuous (continuous collapse would take time).

It seems as though we cannot have quantum mechanics without quantum jumps. Schrödinger once visited Bohr in Copenhagen, where he protested for days against quantum jumps. Ultimately, he purportedly conceded the point with this emotional outburst: "If I had known that one has to accept this damned quantum jump, I'd never have gotten involved with quantum mechanics."

Coming back to the atom, if we measure the position of the electron while it is in an atomic stationary state, we will again collapse its probability cloud to find it in a particular position, not smeared everywhere. If we make a large number of measurements to look for the electron, we will find it more often at those places where the probability of finding it is high as predicted by the

Schrödinger equation. Indeed, after a large number of measurements, if we plot the distribution of the measured positions, it will look quite like the fuzzy orbit distribution given by the solution of the Schrödinger equation (fig. 11).

How does an electron in flight appear from this perspective? When we make an initial observation of any submicroscopic projectile, we find it localized in a tiny wave packet, as a particle. After the observation, however, the packet spreads, and the spread of the packet is the cloud of our uncertainty about the packet. If we

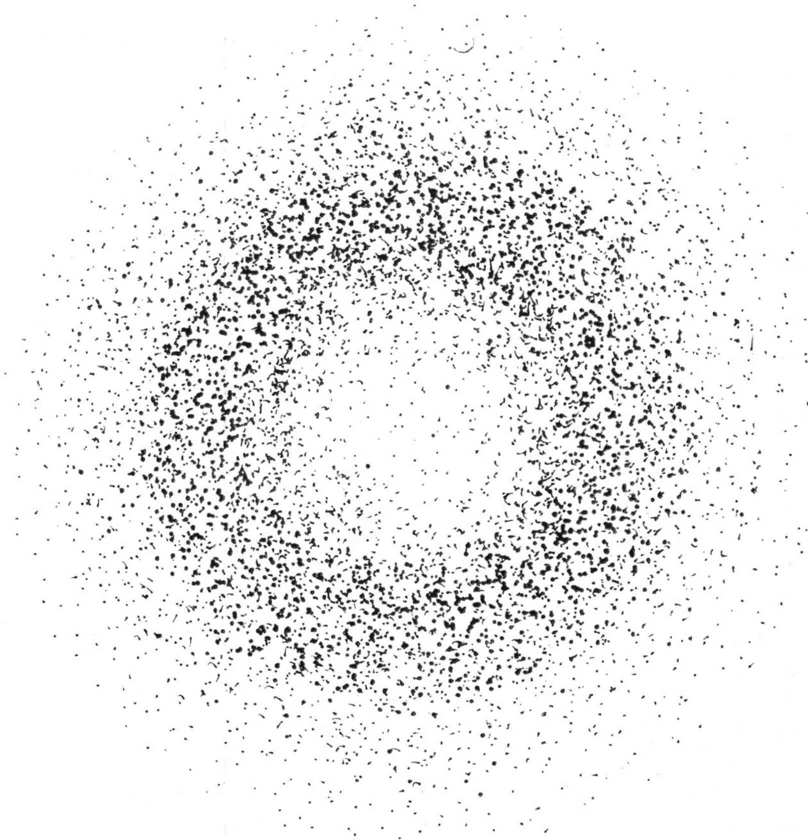

Figure 11. The results of repeated measurements of the position of a hydrogen electron in the lowest orbit. Obviously, the electron's wave usually collapses where the probability for finding it is predicted to be high, giving the fuzzy orbit.

observe again, the packet localizes once more but always spreads between our observations.

Watching electrons, said the physicist-philosopher Henry Margenau, is like watching fireflies on a summer evening. You can see a flash here and another twinkle of light there, but you have no idea where the firefly is between your observations. You cannot define a trajectory for it with any confidence. Even for a macroscopic object, such as the moon, quantum mechanics predicts essentially the same picture—the only difference being that the spreading of the wave packet is imperceptibly small (but nonzero) between observations.

Now we are getting to the crux of the matter. Whenever we measure it, a quantum object appears at some single place, as a particle. The probability distribution simply identifies that place (or those places) where it is likely to be found when we do measure it—no more than that. When we are not measuring it, the quantum object spreads and exists in more than one place at the same time, in the same way that a wave or cloud does—no less than that.

Quantum physics presents a new and exciting worldview that challenges old concepts, such as deterministic trajectories of motion and causal continuity. If initial conditions do not forever determine an object's motion, if instead, every time we observe, there is a new beginning, then the world is creative at the base level.

There was once a Cossack who saw a rabbi walking through the town square nearly every day at about the same time. One day he asked curiously: "Where are you going, rabbi?"

The rabbi answered: "I am not sure."

"You pass this way every day at this time. Surely, you know where you're going."

When the rabbi insisted that he did not know, the Cossack became irritated, then suspicious, and finally took the rabbi to jail. Just as he was locking the cell, the rabbi faced him and said gently: "You see, I didn't know."

Before the Cossack interrupted him, the rabbi knew where he was going, but afterward, he no longer knew. The interruption (we can call it a measurement) offered new possibilities. This is the message of quantum mechanics. The world is not determined by initial conditions, once and for all. Every event of measurement is potentially creative and may open new possibilities.

THE COMPLEMENTARITY PRINCIPLE

A novel way of looking at the paradox of wave-particle duality was described by Bohr. The wave and the particle natures of the electron are not dualistic, not simply opposite polarities, said Bohr. They are complementary properties revealed to us in complementary experiments. When we take a diffraction picture of an electron, we are revealing its wave nature; when we are tracking it in a cloud chamber, we are seeing its particle nature. Electrons are neither waves nor particles. We might call them "wavicles," for their true nature transcends both descriptions. This is the complementarity principle.

Since contemplating the fact that the same quantum object has such seemingly contradictory attributes as waveness and particleness can be hazardous to one's mental health, nature has provided a buffer. Bohr's complementarity principle assures us that although quantum objects have both particle and wave attributes, we can measure only one aspect of the wavicle with any given experimental arrangement at any given time. By the same token, we choose the particular aspect of the wavicle we want to see by choosing the appropriate experimental arrangement.

THE CORRESPONDENCE PRINCIPLE

Once one has grasped the revolutionary ideas of the new physics, it would be grossly inaccurate to think that Newtonian physics is all wrong. The old physics lives on in the realm of most (but not all) bulk matter as a special case of the new physics. An important characteristic of science is that when a new order replaces an older one, it usually extends the arena to which the order applies. In the old arena, the mathematical equations of the old science still hold (having been verified by experimental data). Thus, in the domain of classical physics, the deductions of quantum mechanics for the motion of objects correspond clearly to those that are made using Newtonian mathematics, as if the bodies we were dealing with were classical. This is called the correspondence principle and was formulated by Bohr.

The relationship between classical and quantum physics in some sense resembles the optical illusion "My wife and my mother-in-law" (fig. 12). What do you see in this drawing? Initially, you see either the wife or the mother-in-law. I always see the wife first. It may actually take you a while to discover the other image in the drawing. Suddenly, if you keep at it, the other image emerges. The wife's chin transforms into the nose of the mother-in-law, her neckline into the chin of the older woman, and so on. What is going on? you may wonder. The lines are the same, but suddenly a new way of perceiving the picture has become possible for you. Very soon you find that you can easily go back and forth between the two pictures, the old and the new. You still see only one of the two images at any given time, but your consciousness has enlarged so that you are aware of the duality. In such an extended awareness, the strangeness of quantum physics begins to make sense. It even becomes exciting. Paraphrasing Hamlet's comment to Horatio, there are more things in heaven and Earth than were dreamt of in classical physics.

Figure 12. My Wife and My Mother-in-Law. (After W. E. Hill.)

Quantum mechanics gives us a wider perspective, a new context that extends our perception into a new domain. We can see nature as separate forms—either waves or particles—or we can discover complementarity: the idea that waves and particles both are inherent in the same thing.

THE COPENHAGEN INTERPRETATION

According to the so-called Copenhagen interpretation of quantum mechanics, developed by Born, Heisenberg, and Bohr, we calculate quantum objects as waves and interpret the waves probabilistically. We determine their attributes, such as position and momentum, somewhat uncertainly and understand them complementarily. In addition, discontinuity and quantum jumps—for example, the collapse of a sprawling wave packet upon observation—are regarded as fundamental aspects of the behavior of a quantum object. Another aspect of quantum mechanics is inseparability. Talking about a quantum object without talking about how we observe it is ambiguous because the two are inseparable. Finally, for massive macro objects, quantum mechanical predictions match those of classical physics. This introduces a suppression of such quantum effects as probability and discontinuity in the macro domain of nature that we perceive directly with our senses. Classical correspondence camouflages the quantum reality.

CUTTING THROUGH MATERIAL REALISM

The principles of quantum theory make it possible to discard the unwarranted assumptions of material realism.

Assumption 1: Strong objectivity. A basic assumption that the materialist makes is that there is an objective material universe out there, one that is independent of us. This assumption has some obvious operational validity, and it is often assumed to be necessary to conduct science meaningfully. Is this assumption really valid? The lesson of quantum physics is that we choose which aspect—wave or particle—a quantum object is going to reveal in a given situation. Moreover, our observation collapses the quantum wave packet to a localized particle. Subjects and objects are inextricably blended together. If subjects and objects mesh in this way, how can we uphold the assumption of strong objectivity?

Assumption 2: Causal determinism. Another assumption of the classical scientist that lends credence to material realism is that the world is fundamentally deterministic—all we have to know are the forces acting on each object and the initial conditions (the initial velocity and position of the object). The quantum uncertainty principle, however, says that we can never determine both an object's velocity and its position simultaneously with absolute accuracy. There will always be error in our knowledge of the initial conditions, and strict determinism does not prevail. The idea of causality itself is even suspect. Since the behavior of quantum objects is probabilistic, a strict cause-effect description of the behavior of a single object is impossible. Instead, we have statistical cause and statistical effect when talking about a large group of particles.

Assumption 3: Locality. The assumption of locality—that all interactions between material objects are mediated via local signals—is crucial to the materialistic view that objects exist essentially independent and separate from one another. If, however, waves spread over vast distances and then instantly collapse when we take measurements, then the influence of our measurement is not traveling locally. Thus locality is ruled out. This is another fatal blow to material realism.

Assumptions 4 and 5: Materialism and epiphenomenalism. The materialist maintains that subjective mental phenomena are but epiphenomena of matter. They can be reduced to material brain stuff alone. In order to understand the behavior of quantum objects, however, we seem to need to inject consciousness—our ability to choose—according to the complementarity principle and the idea of subject-object mixing. Moreover, it seems absurd that an epiphenomenon of matter can affect matter: If consciousness is an epiphenomenon, how can it collapse the spread-out wave of a quantum object to a localized particle when it takes a quantum measurement?

The correspondence principle notwithstanding, the new paradigm of physics—quantum physics—contradicts the dicta of material realism. There is no way around this conclusion. We cannot say,

citing correspondence, that classical physics holds for macro objects for all practical purposes and that since we live in the macro world, we will assume that the quantum strangeness confines itself to the submicroscopic domain of nature. On the contrary, the strangeness haunts us all the way to the macro level. There are unresolvable quantum paradoxes if we divide the world into domains of classical and quantum physics.

In India, people ingeniously catch monkeys with a jar of chickpeas. The monkey reaches into the jar to grab a fistful of chickpeas. Alas, with its fist closed on the food, it can no longer remove its hand. The mouth of the jar is too small for its fist. The trap works because the monkey's greed prohibits him from letting go of the chickpeas. The axioms of material realism—materialism, determinism, locality, and so forth—served us well in the past when our knowledge was more limited than it is today, but now they have become our trap. We may have to let go of the chickpeas of certainty in order to embrace the freedom that lies outside the material arena.

If material realism is not an adequate philosophy for physics, what philosophy can deal with all the strangeness of quantum behavior? It is the philosophy of monistic idealism, which has been the basis of all religions worldwide.

Traditionally, only religions and the humanistic disciplines have given value to human life beyond physical survival—value through our love of aesthetics; our creativity in art, music, and thought; and our spirituality in the intuition of unity. The sciences, locked into classical physics and its philosophical baggage of material realism, have been the Pied Piper of skepticism. Now the new physics is crying out for a new, liberating philosophy—one befitting our current level of knowledge. If monistic idealism fits the need, for the first time since Descartes, science, the humanities, and the religions can walk arm-in-arm in the search for the whole human truth.