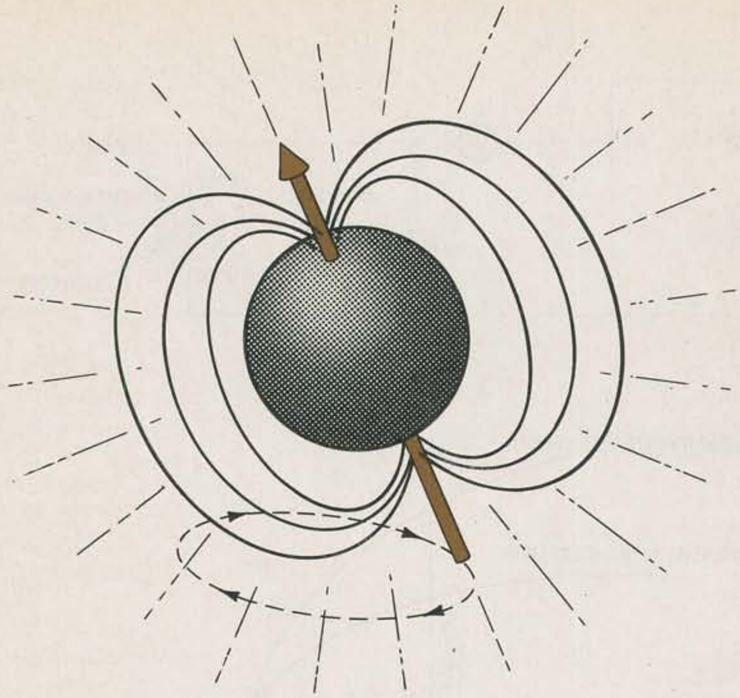

What are Electrons Made of?

We trace the trail of discoveries that lead to our modern understanding of the electron.

BY DAN BECKER

Many of the appliances and devices that make our lives easier, more enjoyable, entertaining, and informed, depend upon our ability to control and manipulate electrons. Electrical current is a flow of electrons, and it is the driving impetus behind many of today's technological advancements and those of the near future. Although we have countless uses for electricity, and power plants are a prominent part of our culture, do we know what electrons are made of?

The Electron is Found. As early as about 800 B.C., the Greeks recorded observing the electric phenomenon produced by rubbing amber. In fact, our word "electron" comes from the Greek word for amber: *elktron.*

In 1600, William Gilbert (1540–1603) recorded that electrification was not limited to amber, but was a more generalized phenomenon. Toward the end of the 1700's, induction-type generators were available. These were capable of producing high voltage, but very little amperage (*i.e.*, they produced static electricity).

About the year 1785 Charles Coulomb (1736–1806) discovered the inverse-square law of electrostatic attraction, who's mathematical relationship is similar to that of the force of gravity. As shown in Fig. 1, we can use this law to depict an electron's force field as directional arrows emanating from an electron's center.

Another important breakthrough occurred in 1772 when a physicist named Alessandro Volta (1745–1827) (after whom the volt is named) discovered a difference in potential between two dissimilar metals in contact with an electrolyte. By 1800 he had a working battery!

With the proliferation of batteries, scientists were now more curious than ever about the source and nature of electric charge. It was during the 1820's that Michael Faraday (1791–1867) discovered the relationship between magnetism and electricity. He discovered that a moving electric charge (an electric current) produces a magnetic field.

In 1864 James Clerk Maxwell (1831–1879) formulated equations that combined Coulomb's equations for electrostatic force with Faraday's work on moving electric charge. Without any additional information, Maxwell's equations made two important revelations. Firstly, that an accelerating electric charge radiates an electromagnetic wave. Secondly, that the resulting electromagnetic wave propagates at 300,000-meters-per-second. From that point forward, research into the nature of electric charge has depended heavily on our understanding of electromagnetic waves and their experimental use.

As technology expanded, new instruments and techniques for investigating the smallest parts of matter became available. By April 1897 it was understood that electrically charged particles are emitted when a metal wire is heated in a vacuum (the ancestor of our cathode-ray tube). In 1891, the particle was named the "electron."

Quanta are Noted. During the late 1800's, numerous attempts to explain blackbody radiation were unsuccessful. Ideally, a blackbody is an object that absorbs all wavelengths of electromagnetic radiation. Conversely, as an ideal blackbody is heated, it begins to radiate all wavelengths of radiation. However the radiated power is not equal at all wavelengths, but peaks at a certain wavelength (depending upon the blackbody's temperature).

In 1900 Max Planck (1858–1947) discovered a mathematical formula that completely agreed with the experimental results. His formula marked the beginning of a entirely new way of defining how matter and energy interact. Basically, he assumed that a blackbody consists of countless little electromagnetic transmitters (not an entirely new idea). The new part of Planck's concept was to say that these tiny electromagnetic transmitters could only emit or absorb energy in

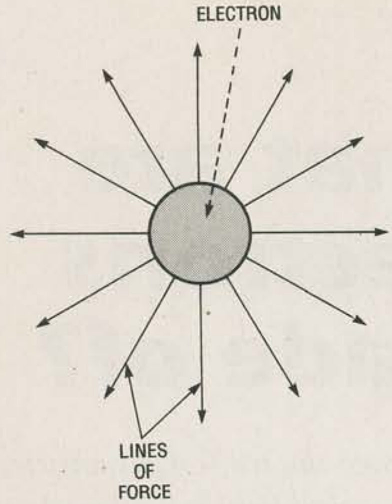

Fig. 1. Coulomb's electron may be visualized as a tiny sphere with electric lines of force radiating out in all directions.

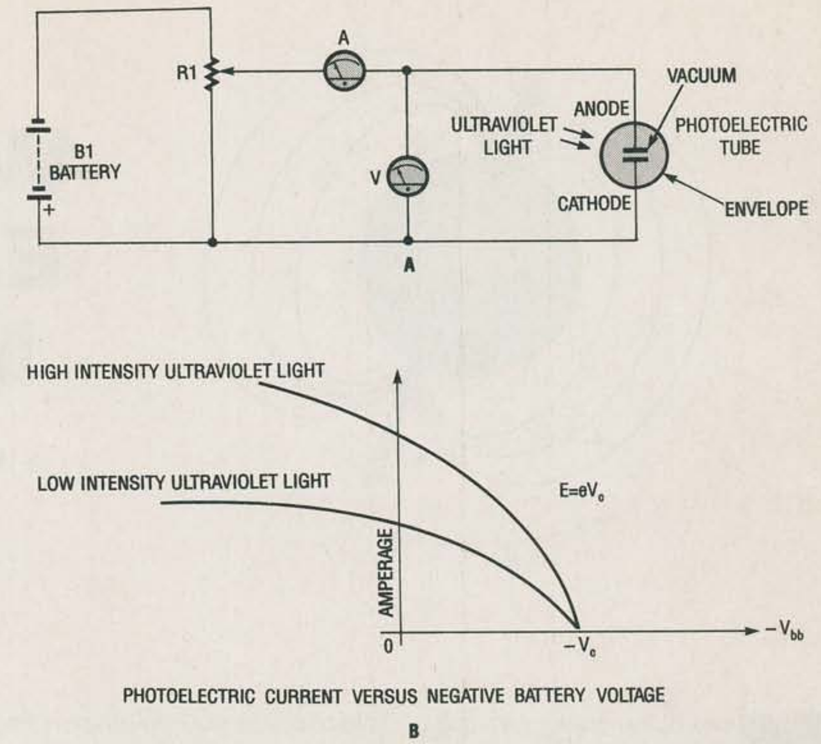

Fig. 2. The circuit in A is typical of those used to measure an electrons kinetic energy. The test procedure used results in a graph such as that shown in B.

little packages called "quanta." Planck's law:

$$E = nhf$$

defines this relationship. There, E is the total energy (in joules); n is a positive whole number (integer) accounting for a given number of energy units (quanta); h is Planck's constant: (6.626×10^{-34} joule-seconds); and f is the frequency (in hertz) of the electromagnetic wave. As you can see, this formula restricts electromagnetic waves to whole-number multiples of the fundamental unit of energy, h. In addition, this formula tells us that high-frequency electromagnetic radiation packs more energy than low-frequency radiation. This quantitative approach to energy marked the birth of quantum theory.

A few years earlier, in 1887, Heinrich Hertz (1857–1894) had been experimenting with a spark gap. His apparatus consisted of a metallic cathode (electron emitter) and anode (electron absorber) suspended in a vacuum bottle. When he connected a battery across the electrodes, Hertz found that an electric current would flow through the vacuum, but only while the spark gap was exposed to light; in total darkness no current would flow.

In 1902 this phenomena was further investigated using a circuit similar to the one shown in Fig. 2A. It was found that high-frequency light (ultraviolet) is much better at liberating electrons

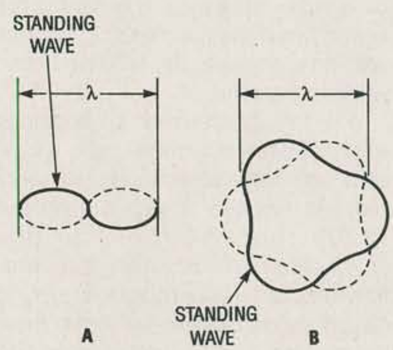

Fig. 3. Like an oscillating string fastened at both ends (A), an integral number of de Broglie wavelengths must fit into Bohr's electron orbits (B).

from the cathode's surface. In addition, no electrons are ejected if the frequency is decreased below a certain value, regardless of the light's intensity.

When illuminated by ultraviolet light at different intensities, a negative voltage must be applied to the spark-gap's anode (as shown in Fig. 2A) to completely stop all current flow. In other words, ultraviolet light ejects electrons from the cathode with enough kinetic energy so that they

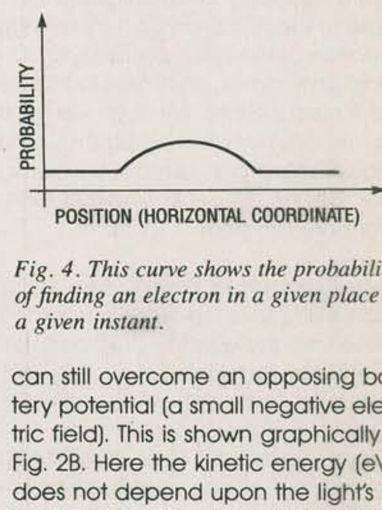

Fig. 4. This curve shows the probability of finding an electron in a given place at a given instant.

can still overcome an opposing battery potential (a small negative electric field). This is shown graphically in Fig. 2B. Here the kinetic energy (eV_c) does not depend upon the light's intensity, since all values of intensity intersect the cutoff point at the same negative voltage $-V_c$! This phenomenon was named the photoelectric effect, and Hertz is credited with its discovery.

A Partial Explanation. At this time, most scientists believed that light was a wave phenomena, not a particle. In fact, as far back as 1801 Thomas Young's (1773–1829) double-slit experiment (more about that later) clearly demonstrated that light ex-

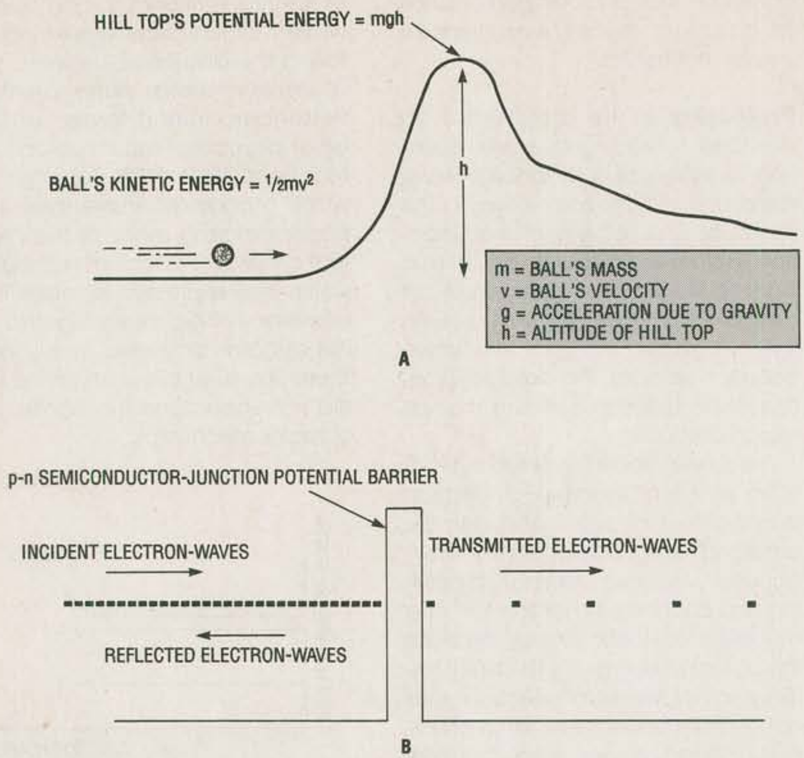

Fig. 5. The bowling ball's kinetic energy must exceed the hill's potential-energy barrier if it is to make it to the other side (A). However, electrons can "tunnel" through a potential barrier when they cannot overcome it (B).

hibits the interference behavior characteristic of waves. However, waves cannot account for the photoelectric effect, otherwise the electron's kinetic energy would increase as the light becomes brighter.

In 1905 Albert Einstein introduced his Special Theory of Relativity. Due to the results of that theory, Einstein became convinced that Planck's concept of light quanta was real. In addition, he was able to write a mathematical expression explaining the photoelectric effect. In 1916, Robert Millikan (1868–1953) confirmed Einstein's theory. Thus, when an electron absorbs a quanta (named a "photon" in 1926 by Gilbert Lewis) of energy, the electron's kinetic energy increases by a fixed amount. However, since there were many experiments that clearly demonstrated the wave nature of light, most scientists still believed that light was a wave.

Up to that point in history, the concept of an atom as we know it today was not proposed. In addition, a lot of the work in quantum theory was based on experiments with emission spectra. That is, trying to explain how and why certain elements like hydrogen would only emit or absorb narrow segments of the electromagnetic spectrum. However, it was becoming clear that light energy and electrons worked together to generate this phenomena.

In 1911 another important development occurred. After experimenting with radioactive substances, Ernest Rutherford (1871–1937) proposed the now-famous planetary model of a hydrogen atom. His model placed a negatively charged electron in orbit around a positively charged nucleus (proton). According to Rutherford's model, as an electron moves closer to the nucleus, its energy level decreases and the excess energy is radiated out into space in the form of electromagnetic waves. Unfortunately however, this simple model allows an atomic electron to emit a continuous spectrum of wavelengths (energy levels), which does not agree with experimental findings.

In 1913 Neils Bohr (1885–1962) used Planck's energy quanta along with Einstein's explanation of the photoelectric effect to improve Rutherford's model of a hydrogen atom. Bohr's model is based on two assumptions: 1) an electron's orbit is restricted to discrete values; 2) if an electron absorbs a quantum of energy it jumps to a higher orbit; if it emits a quantum of energy it jumps to a lower orbit. The energy in the quantum absorbed or emitted must equal the difference in the energy levels of the two orbits.

Since Bohr's atomic electrons are restricted to specific orbits, they can only absorb or emit specific wavelengths of energy (a good example is the orange glow of a neon lamp). Although this model was in better agreement with experimental findings, Bohr did not know why electrons are restricted to certain orbits.

Electron Size? In 1923 an American physicist named Arthur Compton (1892 1962) showed that X-rays can bounce off of an electron. The effects are similar to two colliding billiard balls (the difference is that when an X-ray gives up some of its momentum to an electron, instead of changing velocity as a billiard ball would, the X-ray changes frequency). Thus, by 1923 it was demonstrated that an electromagnetic wave (in this case, an X-ray) can also behave like a particle.

At this point in history it was possible (but erroneous) to ascribe physical dimensions to an electron. One could imagine it to be a tiny sphere. Using the information known at that time, Hendrik Antoon Lorentz (1853–1928) introduced a classical model in which the electron is a tiny sphere. In his model, the energy in the electric field surrounding the electron and outside a radius (r), is given by the formula:

$$E = e^2/r$$

Assuming that all of an electrons energy is contained in its electric field (which is erroneous), then this energy must equal mc^2 (as given by Einstein's formula, $E = mc^2$, for an electron at rest). We know an electron's charge ($e = 4.803 \times 10^{-10}$ electrostatic units or 16.021×10^{-20} coulombs); and mass ($m = 9.109 \times 10^{-28}$ grams). Therefore, since $E = mc^2 = e^2/r$:

$$r = e^2/mc^2 = 2.8 \times 10^{-13} \text{ cm}$$

In the old way of thinking (classical mechanics), this is an electron's minimum radius.

Wave Mechanics. During the 1920's quantum theory progressed to a much more mature level. Many new ideas and theories were presented in rapid succession. The emphasis was on trying to explain and characterize the behavior of atomic electrons. In general, this amounted to examining the emission spectra of hydrogen and other elements and then finding a mathematical expression to define all of the possible energy states or levels.

Beginning as early as 1922, physicist Louis de Broglie (1892–1987) had a new idea. He thought that if light waves can act like particles, why can't particles act like waves? De Broglie's theory determined a particle's wavelength to be:

$$h/mv$$

where h is Planck's constant, m is the particle's mass, and v is its velocity.

In addition to assigning a wavelength to an electron, de Broglie used his particle/wave idea to explain why electron orbits are limited to specific radii. Although a single electron may occupy one orbital ring, an integral number of wavelengths must be used to determine the orbital ring's circumference. As shown in Fig. 3, one can envision standing waves encircling a nucleus. De Broglie found that his wavelengths fit precisely into Bohr's orbital radii! Initially this concept was not accepted. However, in 1927 two American scientists, C.J. Davisson and L.H. Germer, conducted additional experiments that completely verified the wave nature of electrons. They did this by scattering a beam of electrons off of a crystalline lattice of atoms. A diffraction pattern was obtained and its wavelength corresponded to de Broglie's wavelength for electrons.

In 1925 Erwin Schrodinger (1887–1961) heard about de Broglie's matter/wave concept. This appealed to Schrodinger because he was looking for a physical explanation for the restricted electron orbits. Using this and Bohr's model of the atom, Schrodinger developed a very sophisticated wave equation. Initially, Schrodinger assumed that electrons were actually physical waves just like water or sound waves—an assumption that, again we now know is incorrect. However, it made his wave equations very appealing. In addition, it brought about wide acceptance of the idea that all matter and energy have both wave and particle characteristics. Schrodinger's solution to quantum theory was dubbed "wave mechanics."

Probability. In the late 1920's, Borh modified Schrodinger's wave equation to represent a probability wave rather than a physical wave. In this sense, instead of thinking of an electron as a wave, you can think of it as a particle having only a probability of being in any given place at a given time. As shown in Fig. 4, the wave equation spreads the possible location of an electron out over a small region of space.

The tunnel diode (invented in 1958) is an excellent example of electron probabilities at work, and can be analyzed using Schrodinger's wave equation. As shown in Fig. 5A, a bowling ball cannot roll over the top of a hill unless its kinetic energy exceeds the potential energy it will have at the hill's peak. However, an electron does not operate under these same principles. Instead, a very small, but real probability exists that an electron can appear on the other side of the energy barrier (hill top).

Even though (in classical terms) an electron may not have enough kinetic energy to transverse an energy barrier, if it gets close enough, and the barrier is thin enough, there will be a small probability that it will suddenly appear on the other side! As shown in Fig. 5B, most of the electron-waves traveling toward the diode's PN junction (energy barrier) are reflected back. However, the wave equation says that a small number of these electron-waves have a chance of being found on the other side of the junction (energy barrier or hill top). Moreover, those that do appear on the other side of the p-n junction have the same energy they started with! It is as though they tunneled right through the barrier unimpeded!

Another physicist working in Europe in the mid 1920's was Werner Heisenberg (1901–1976). Heisenberg's approach was very different than Schrodinger's. To begin with, he discarded analogies that were not based on experimental findings. These included the idea that electrons orbit an atom's nucleus. There was no experimental evidence supporting this idea. Instead, Heisenberg concerned himself with the evidence of spectral emissions. In particular, he wrote mathematical expressions detailing the difference between pairs of electron energy states. Eventually, Heisenberg joined forces with two other physicists, Pascual Jordan and Max Born (1882–1970). Together they wrote a comprehensive three-man paper detailing many of the important aspects of quantum mechanics, which they expressed in matrix form. However, in 1925 matrix algebra was not as commonly used as it is today. Therefore, most physicists at the time did not understand the significance of matrix mechanics.

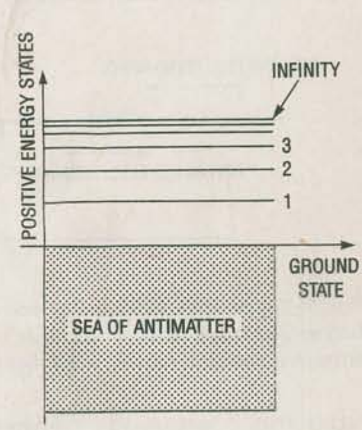

Fig. 6. Dirac's atomic model predicts a sea of antimatter energy states filled with electrons below the ground state of normal electrons.

Fortunately however, Paul Dirac (1902–1984) was given a copy of the three-man paper (as it was called). Dirac quickly saw the connection between their work and that of William Hamilton. During the late 1820's, William Hamilton (1805–1865) developed a very useful set of matrix equations. Hamilton's equations can be used to describe wave motion or particle motion.

In light of Hamilton's equations, Dirac reworked the matrix mechanics of the three-man-paper. In addition, he invented his own mathematics that he called quantum algebra. Dirac's first paper on quantum mechanics was published in 1925. Over the next few years Dirac added to his original work. Dirac's equations are more general and complete in that they include Schrodinger's wave mechanics and the three-man team's matrix mechanics as special cases. In addition, Dirac's quantum mechanics automatically included the more subtle aspects of atomic-electron behavior, as well as satisfying the requirements of Einstein's special relativity. Dirac's equations were so effective that they could actually determine the recoil motion of an atom that occurs when an electron emits a photon.

Antimatter However, Dirac's relativistic wave equations had a curious twist. In addition to all of the possible positive energy states that an electron may occupy, Dirac's equations implied that there are negative energy states as well!

Figure 6 is a simplified illustration of Dirac's explanation of this finding. There a horizontal line represents the ground state, or an electron's lowest energy state. Moving vertically up the y-axis represents moving to higher energy states. Electrons filling positive energy states are allowed to exist only at those levels (states) indicated by horizontal lines. It requires a photon of energy (equivalent to the difference in the initial and final states) to boost an electron up vertically on the scale (into a more energetic energy state). Moreover, all electrons will spontaneously eject excess energy and drop into a lower energy state if such a position is available.

In addition to all possible positive energy states, there is a large well of negative energy states existing below the ground state. All electrons would fall into this huge reservoir and vanish forever except, as Dirac proposed, it is already filled up with electrons! Lucky us!

Interestingly enough, Dirac calculated just how much energy would be required to kick one of those negative-energy electrons up into a positive energy state—where it could be seen! However, that is not all: doing so would leave behind a hole, or a vacancy on the negative-energy side. The hole can be interpreted as a particle with the same mass, but an electric charge *opposite* to that of the electron. This particle was discovered in 1932 by C.D. Anderson (and others) and was named the "positron."

A positron is the exact opposite of an electron and is therefore referred to as an "antimatter" particle. Positrons are readily produced in particle accelerators and even in nature. When an electron and positron collide, both vanish leaving behind high-energy gamma rays (photons). Conversely, the transmutation of a high-energy gamma ray into an electron-positron pair is also possible! The study of the interaction of particles with the sea of negative-energy electrons is an important branch of physics that has led to many new ideas and theories.

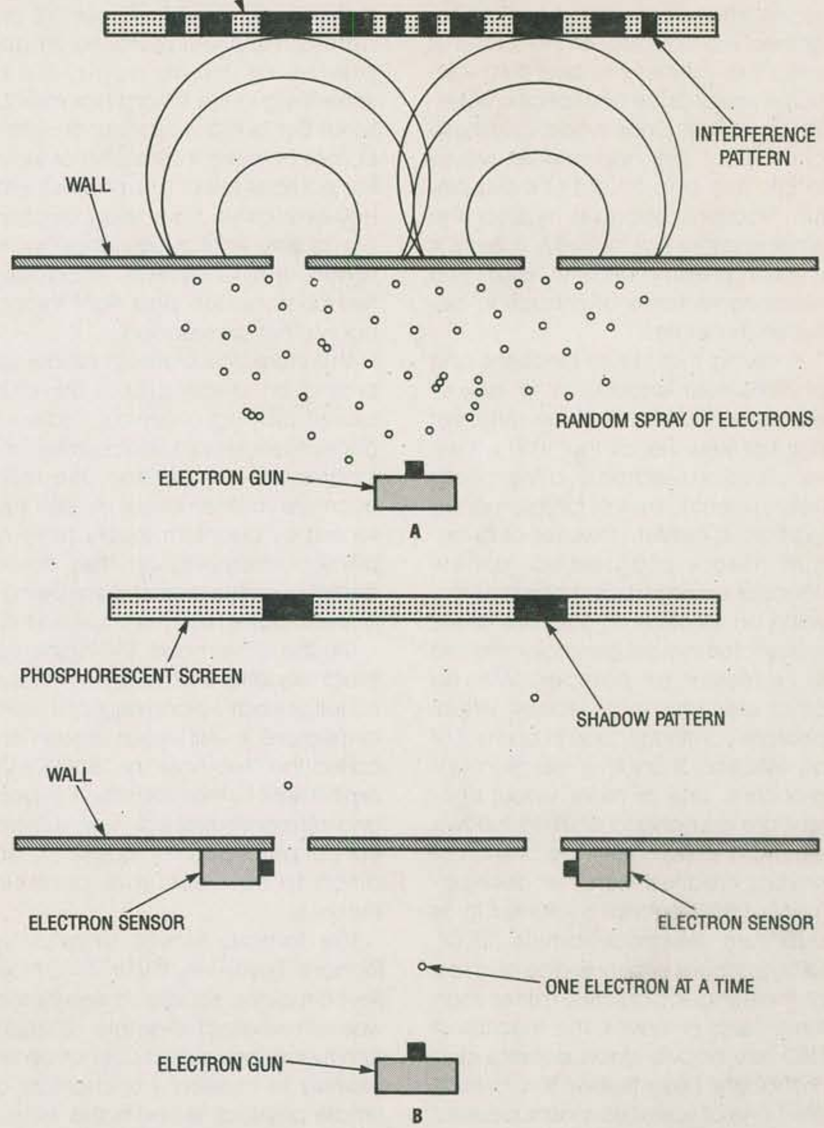

Fig. 7. The interference pattern resulting from electrons randomly sprayed through two slits in a wall can be viewed on a phosphor-coated screen (A), even if you only emit electrons one at a time; that is until you try to detect their position (B).

To Be, or Not to Be Negative-energy electrons are just like positive-energy electrons, except that they do not have enough energy to become a visible part of our physical world. However, according to Heisenberg, uncertainty is an inherent part of the microscopic world of atoms. Using Heisenberg's Uncertainty Principle, it is possible to imagine that any particle, including electrons and photons, can appear out of nowhere and then just as quickly disappear into the quantum vacuum. Provided the particle does not stay around more that a very brief instant the probability of such an event is very real. Physicists refer to these mysterious entities as virtual particles. In fact, empty space is a sea of all types of virtual particles.

A variety of experiments have been successfully performed in the laboratory that measure the effects of virtual particles. For example, the Casimir effect (named after its inventor

Hendrik Casimir) uses two reflective plates (mirrors) placed very close together. The spacing of the plates is critical as it tunes the quantum vacuum to resonance at a specific wavelength of light. Once tuned, only those photons of the appropriate wavelength can pop up out of the quantum vacuum. Because most of the other photons are locked out, there is a loss in pressure and this results in a measurable force of attraction between the plates.

Knowing that virtual electrons and photons exist enables us to look at electrons from a entirely different point of view. Recall that in Fig. 1 we visualized an electron as a tiny sphere having electric lines of force emanating from its center. However, as quantum theory progressed, a new concept emerged. One can now envision an electron as a source of virtual photons (more generally referred to as messenger particles). With no other electrons in its vicinity, virtual photons continually pop in and out of an electron. If another electron approaches, one or more virtual photons are exchanged causing the two electrons to separate. The branch of physics credited with the development of this concept is referred to as quantum electrodynamics (QED). QED describes empty space as a sea of messenger particles, rather than force fields or waves. The theories of QED rely heavily upon statistics and probability, nevertheless it is considered one of science's most successful propositions.

Going Further. Using particle accelerators, physicists are able to analyze the interior structure of many of the subatomic particles known today. With the particle accelerators presently available, details as small as 10^{-16} cm are discernible. However, even at that resolution, no internal structure can be detected in an electron! That is, they appear to be a point source of charge with no geometric extension and no internal parts.

With all of the forgoing in mind, we can now speculate about the nature of electrons, photons, and our perception of the world in general. Let's use a billiard ball as an example. Your first impression is that the billiard ball is a solid object. Even if you visualize it as a collection of smaller pieces (molecules, atoms, electrons, etc.) bound together by invisible forces, it's only natural to visualize these smaller pieces as being solid. Surely *something* in the billiard ball must be solid! But our perception of solidity comes from the interaction of wave-like particles (electrons, photons, etc.). However, as we have seen, electrons can absorb photons, and they are not spherical solid objects. In addition, two photons can pass right through each other unimpeded.

Therefore, the classical model depicting an electron as a miniature planet orbiting a central nucleus is deceptively simple, inaccurate, and incomplete. In addition, the more accurate mathematical models presented by quantum theory have no physical interpretation: they do not depict or define a electron as being a physical object such as a billiard ball.

On the other hand, the highly abstract equations of quantum theory *do* tell us what we can expect to "see" or measure. A well known experiment, called the "two-hole" or "double-slit" experiment further illustrates this point and demonstrates just how vulnerable our perception of reality is, in addition to how accurate quantum theory is.

The famous American physicist Richard Feynman (1918–1988) believed that the double-slit experiment was an excellent example of quantum theory because it cannot be explained in classical (mechanical or simple physical) terms. In this experiment (which can be done with electrons or photons), two holes are cut into a wall that separates a source of electrons from a phosphorescent (electron-detection) screen. Wherever an electron hits the screen, a bright spot appears. Assuming that electrons behave like waves, it is not difficult to imagine how two electron waves could mix together to generate a pattern of interference fringes on the detector screen. This is shown graphically in Fig. 7A. Using quantum theory, the probability of an electron hitting any given place on the detector screen is given by the square of the sum of the two individual wave functions. Thus, when you superimpose the two wave functions together they form an interference pattern.

If we cover up one of the holes, then as you would expect, a large spot without interference fringes is produced. In this case, the probability of an electron hitting any given place on the detector screen is given by the square of a single wave function.

Now the strange part: let's say we open both holes, but adjust our electron source so that it emits just one electron at a time. Since only one electron passes through one hole at any given time, we should not expect to see the interference pattern characteristic of a two-hole experiment. Instead, we would expect each hole to allow a single large spot to form on the detector screen. Nevertheless, the interference pattern appears! It is as though each electron knows that there are two holes in the wall! The quantum wave function predicts this unreasonable result.

But wait, there is more! As shown in Fig. 7B, we can repeat the two-hole version of the experiment, but this time monitoring each hole with a sensitive detector. Whenever an electron passes through a hole, one of the detectors will beep to alert us. Oddly enough, the interference pattern is no longer produced. You might say that the electron knows we are watching! By observing the particle characteristic of each electron, we have in a sense "destroyed" its wave characteristics! The wave probability of each electron was collapsed the instant our detector pointed out the location of the electron particle.

The deceptiveness of our world is similar to watching a baseball game on television. If you stop to think about it, you'll realize that the picture is merely a facsimile of a real event occurring somewhere else. After all, you are just starring at a screen that generates a complicated pattern of light, but you do not consciously think of it in that way. Instead you become involved in the game, not on how its television image is being generated. In a similar, but much more subtle way, wave-like particles play an essential role in generating our physical world (or physical reality); but they are not made of anything solid!

The postulates of Einstein's Special Relativity also make this deception apparent, but from a slightly different perspective. They state that the laws of physics must be the same everywhere in the universe, regardless of an

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observer's relative velocity. In fact, our universe works this way for an important reason: to keep physical reality constant. In other words, everything works the same, no matter how fast you may be traveling relative to someone else. Consequently, you cannot travel faster than light because light always appears to be going the same speed even if you're moving!

The electron is just one component of our universe. However, the efforts of scientists to define and characterize the electron's behavior have led to countless advancements in technology. Moreover, these advancements have changed our perception of the universe, transforming it into a quantum vacuum where virtual particles randomly appear and vanish. A universe where electrons and photons generate the illusion that objects are solid. Furthermore, although an electron's behavior is well defined, its structure—what it is made of, and how it works—remains a mystery. ■