



One Hundred Years of Quantum Physics

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PATHWAYS OF DISCOVERY

One Hundred Years of Quantum Physics

Daniel Kleppner and Roman Jackiw

An informed list of the most profound scientific developments of the 20th century is likely to include general relativity, quantum mechanics, big bang cosmology, the unraveling of the genetic code, evolutionary biology, and perhaps a few other topics of the reader's choice. Among these, quantum mechanics is unique because of its profoundly radical quality. Quantum mechanics forced physicists to reshape their ideas of reality, to rethink the nature of things at the deepest level, and to revise their concepts of position and speed, as well as their notions of cause and effect.

Although quantum mechanics was created to describe an abstract atomic world far removed from daily experience, its impact on our daily lives could hardly be greater. The spectacular advances in chemistry, biology, and medicine—and in essentially every other science—could not have occurred without the tools that quantum mechanics made possible. Without quantum mechanics there would be no global economy to speak of, because the electronics revolution that brought us the computer age is a child of quantum mechanics. So is the photonics revolution that brought us the Information Age. The creation of quantum physics has transformed our world, bringing with it all the benefits—and the risks—of a scientific revolution.

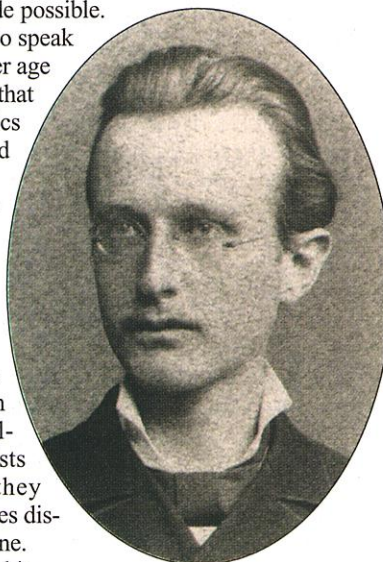
Unlike general relativity, which grew out of a brilliant insight into the connection between gravity and geometry, or the deciphering of DNA, which unveiled a new world of biology, quantum mechanics did not spring from a single step. Rather, it was created in one of those rare concentrations of genius that occur from time to time in history. For 20 years after their introduction, quantum ideas were so confused that there was little basis for progress; then a small group of physicists created quantum

mechanics in three tumultuous years. These scientists were troubled by what they were doing and in some cases distressed by what they had done.

The unique situation of this crucial yet elusive theory is perhaps best summarized by the following observation: Quantum theory is the most precisely tested and most successful theory in the history of science. Nevertheless, not only was quantum mechanics deeply disturbing to its founders, today—75 years after the theory was essentially cast in its current form—some of the luminaries of science remain dissatisfied with its foundations and its interpretation, even as they acknowledge its stunning power.

This year marks the 100th anniversary of Max Planck's creation of the quantum concept. In his seminal paper on thermal radiation, Planck hypothesized that the total energy of a vibrating system cannot be changed continuously. Instead, the energy must jump from one value to another in discrete steps, or quanta, of energy. The idea of energy quanta was so radical that Planck let it lay fallow. Then, Einstein, in his wonder year of 1905, recognized the implications of quantization for light. Even then the concept was so bizarre that there was little basis for progress. Twenty more years and a fresh generation of physicists were required to create modern quantum theory.

To understand the revolutionary impact of quantum physics one need only look at prequantum physics. From 1890 to 1900, physics journals were filled with papers on atomic spectra and essen-



Papa Quanta. In 1900, Max Planck started the quantum-mechanical snowball.

JANUARY
"Science Wars"

FEBRUARY
Planetary
Sciences

MARCH
Genomics

APRIL
Infectious
Diseases

MAY
Materials
Science

JUNE
Cloning and
Stem Cells

JULY
Communications
and Science

AUGUST
Quantum
Physics

SEPTEMBER
The Cell Cycle

OCTOBER
Atmospheric
Sciences

NOVEMBER
Neuroscience

DECEMBER
Astrophysics and
Cosmology

"Quantum theory is the most precisely tested and most successful theory in the history of science."

A Timeline of Quantum Physics

1897

Pieter Zeeman shows that light is radiated by the motion of charged particles in an atom, and Joseph John (J. J.) Thomson discovers the electron.

1900

Max Planck explains blackbody radiation in the context of quantized energy emission: Quantum theory is born.

1905

Albert Einstein proposes that light, which has wavelike properties, also consists of discrete, quantized bundles of energy, which are later called photons.

1911

Ernest Rutherford proposes the nuclear model of the atom.

1913

Niels Bohr proposes his planetary model of the atom, along with the concept of stationary energy states, and accounts for the spectrum of hydrogen.

1914

James Franck and Gustav Hertz confirm the existence of stationary states through an electron scattering experiment.

1923

Arthur Compton observes that x-rays behave like miniature billiard balls in their interactions with electrons, thereby providing further evidence for the particle nature of light.

tially every other measurable property of matter, such as viscosity, elasticity, electrical and thermal conductivity, coefficients of expansion, indices of refraction, and thermoelastic coefficients. Spurred by the energy of the Victorian work ethic and the development of ever more ingenious experimental methods, knowledge accumulated at a prodigious rate.

What is most striking to the contemporary eye, however, is that the compendious descriptions of the properties of matter were essentially empirical. Thousands of pages of spectral data listed precise values for the wavelengths of the elements, but nobody knew why spectral lines occurred, much less what information they conveyed. Thermal and electrical conductivities were interpreted by suggestive models that fitted roughly half of the facts. There were numerous empirical laws, but they were not satisfying. For instance, the Dulong-Petit law established a simple relation between specific heat and the atomic weight of a material. Much of the time it worked; sometimes it didn't. The masses of equal volumes of gas were in the ratios of integers—mostly. The Periodic Table, which provided a key organizing principle for the flourishing science of chemistry, had absolutely no theoretical basis.

Among the greatest achievements of the revolution is this: Quantum mechanics has provided a quantitative theory of matter. We now understand essentially every detail of atomic structure; the Periodic Table has a simple and natural explanation; and the vast arrays of spectral data fit into an elegant theoretical framework. Quantum theory permits the quantitative understanding of molecules, of solids and liquids, and of conductors and semiconductors. It explains bizarre phenomena such as superconductivity and superfluidity, and exotic forms of matter such as the stuff of neutron stars and Bose-Einstein condensates, in which all the atoms in a gas behave like a single superatom. Quantum mechanics provides essential tools for all of the sciences and for every advanced technology.

Quantum physics actually encompasses two entities. The first is the theory of matter at the atomic level: quantum mechanics. It is quantum mechanics that allows us to understand and manipulate the material world. The second is the quantum theory of fields. Quantum field theory plays a totally different role in science, to which we shall return later.

Quantum Mechanics

The clue that triggered the quantum revolution came not from studies of matter but from a problem in radiation. The specific challenge was to understand the spectrum of light emitted by hot bodies: blackbody radiation. The phenomenon is familiar to anyone who has stared at a fire. Hot matter glows, and the hotter it becomes the brighter it glows. The spectrum of the light is broad, with a peak that shifts from red to yellow and finally to blue (although we cannot see that) as the temperature is raised.

It should have been possible to understand the shape of the spectrum by combining concepts from thermodynamics and electromagnetic theory, but all attempts failed. However, by assuming that the energies of the vibrating electrons that radiate the light are quantized, Planck obtained an expres-

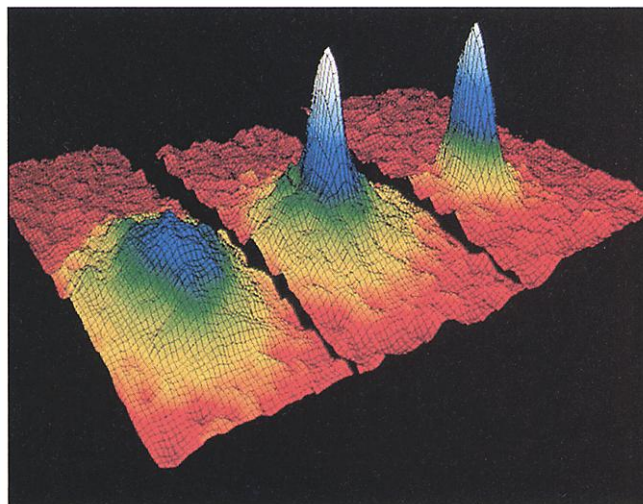
sion that agreed beautifully with experiment. But as he recognized all too well, the theory was physically absurd, "an act of desperation," as he later described it.

Planck applied his quantum hypothesis to the energy of the vibrators in the walls of a radiating body. Quantum physics might have ended there if in 1905 a novice—Albert Einstein—had not reluctantly concluded that if a vibrator's energy is quantized, then the energy of the electromagnetic field that it radiates—light—must also be quantized. Einstein thus imbued light with particlelike behavior,

notwithstanding that James Clerk Maxwell's theory, and over a century of definitive experiments, testified to light's wave nature. Experiments on the photoelectric effect in the following decade revealed that when light is absorbed its energy actually arrives in discrete bundles, as if carried by a particle. The dual nature of light—particlelike or wavelike depending on what one looks for—was the first example of a vexing theme that would recur throughout quantum physics. The duality constituted a theoretical conundrum for the next 20 years.

The first step toward quantum theory had been precipitated by a dilemma about radiation. The second step was precipitated by a dilemma about matter. It was known that atoms contain positively and negatively charged particles. But oppositely charged particles attract. According to electromagnetic theory, therefore, they should spiral into each other, radiating light in a broad spectrum until they collapse.

Once again, the door to progress was opened by a novice: Niels Bohr. In 1913, Bohr proposed a radical hypothesis: Electrons in an atom exist only in certain stationary states, including a ground state. Electrons change their energy by "jumping" between the stationary states, emitting light whose wavelength depends on the energy difference. By combining known laws with bizarre assumptions about quantum behavior, Bohr swept away the problem of atomic stability. Bohr's theory was full of contradictions, but it provided a quantitative description of the spectrum of the hydrogen atom. He recognized both the suc-



Superatom. These colorful data, from NIST in 1995, emerged from measurements of rubidium atoms coalescing into the first documented Bose-Einstein condensate.



Atoms go quantum. In 1913, Niels Bohr ushered quantum physics into world of atoms.

problem of atomic stability. Bohr's theory was full of contradictions, but it provided a quantitative description of the spectrum of the hydrogen atom. He recognized both the suc-

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PATHWAYS OF DISCOVERY

cess and the shortcomings of his model. With uncanny foresight, he rallied physicists to create a new physics. His vision was eventually fulfilled, although it took 12 years and a new generation of young physicists.

At first, attempts to advance Bohr's quantum ideas—the so-called old quantum theory—suffered one defeat after another. Then a series of developments totally changed the course of thinking.

In 1923 Louis de Broglie, in his Ph.D. thesis, proposed that the particle behavior of light should have its counterpart in the wave behavior of particles. He associated a wavelength with the momentum of a particle: The higher the momentum the shorter the wavelength. The idea was intriguing, but no one knew what a particle's wave nature might signify or how it related to atomic structure. Nevertheless, de Broglie's hypothesis was an important precursor for events soon to take place.

In the summer of 1924, there was yet another precursor. Satyendra N. Bose proposed a totally new way to explain the Planck radiation law. He treated light as if it were a gas of massless particles (now called photons) that do not obey the classical laws of Boltzmann statistics but behave according to a new type of statistics based on particles' indistinguishable nature. Einstein immediately applied Bose's reasoning to a real gas of massive particles and obtained a new law—to become known as the Bose-Einstein distribution—for how energy is shared by the particles in a gas. Under normal circumstances, however, the new and old theories predicted the same behavior for atoms in a gas. Einstein took no further interest, and the result lay undeveloped for more than a decade. Still, its key idea, the indistinguishability of particles, was about to become critically important.

Suddenly, a tumultuous series of events occurred, culminating in a scientific revolution. In the 3-year period from January 1925 to January 1928:

- Wolfgang Pauli proposed the exclusion principle, providing a theoretical basis for the Periodic Table.

- Werner Heisenberg, with Max Born and Pascual Jordan, discovered matrix mechanics, the first version of quantum mechanics. The historical goal of understanding electron motion within atoms was abandoned in favor of a systematic method for organizing observable spectral lines.

- Erwin Schrödinger invented wave mechanics, a second form of quantum mechanics in which the state of a system is described by a wave function, the solution to Schrödinger's equation. Matrix mechanics and wave mechanics, apparently incompatible, were shown to be equivalent.

- Electrons were shown to obey a new type of statistical law, Fermi-Dirac statistics. It was recognized that all particles obey either Fermi-Dirac statistics or Bose-Einstein statistics, and that the two classes have fundamentally different properties.

- Heisenberg enunciated the Uncertainty Principle.

- Paul A. M. Dirac developed a relativistic wave equation for the electron that explained electron spin and predicted antimatter.

- Dirac laid the foundations of quantum field theory by providing a quantum description of the electromagnetic field.

- Bohr announced the complementarity principle, a philosophical principle that helped to resolve apparent paradoxes of quantum theory, particularly wave-particle duality.

The principal players in the creation of quantum theory were young. In 1925, Pauli was 25 years old, Heisenberg and Enrico Fermi were 24, and Dirac and Jordan were 23. Schrödinger, at age 36, was a late bloomer. Born and Bohr

were older still, and it is significant that their contributions were largely interpretative. The profoundly radical nature of the intellectual achievement is revealed by Einstein's reaction. Having invented some of the key concepts that led to quantum theory, Einstein rejected it. His paper on Bose-Einstein statistics was his last contribution to quantum physics and his last significant contribution to physics.

That a new generation of physicists was needed to create quantum mechanics is hardly surprising. Lord Kelvin described why in a letter to Bohr congratulating him on his 1913 paper on hydrogen. He said that there was much truth in Bohr's paper, but he would never understand it himself. Kelvin recognized that radically new physics would need to come from unfettered minds.

In 1928, the revolution was finished and the foundations of quantum mechanics were essentially complete. The frenetic pace with

which it occurred is revealed by an anecdote recounted by the late Abraham Pais in *Inward Bound*. In 1925, the concept of electron spin had been proposed by Samuel Goudsmit and George Uhlenbeck. Bohr was deeply skeptical. In December, he traveled to Leiden, the Netherlands, to

attend the jubilee of Hendrik A. Lorentz's doctorate. Pauli met the train at Hamburg, Germany, to find out Bohr's opinion about the possibility of electron spin. Bohr said the proposal was "very, very interesting," his well-known put-down phrase. Later at Leiden, Einstein and Paul Ehrenfest met Bohr's train, also to discuss spin. There, Bohr explained his objection, but Einstein showed a way around it and converted Bohr into a supporter. On his return journey, Bohr met with yet more discussants.

When the train passed through Göttingen, Germany, Heisenberg and Jordan were waiting at the station to ask his opinion. And at the Berlin station, Pauli was waiting, having traveled especially from Hamburg. Bohr told them all that the discovery of electron spin was a great advance.



Getting weirder. Louis de Broglie said that if wavelike light can behave like particles, then particles can behave like waves.



Unknowable reality. Werner Heisenberg articulated one of the most societally absorbed ideas of quantum physics: the Uncertainty Principle.

1923

Louis de Broglie generalizes wave-particle duality by suggesting that particles of matter are also wavelike.

1924

Satyendra Nath Bose and Albert Einstein find a new way to count quantum particles, later called Bose-Einstein statistics, and they predict that extremely cold atoms should condense into a single quantum state, later known as a Bose-Einstein condensate.

1925

Wolfgang Pauli enunciates the exclusion principle.

Werner Heisenberg, Max Born, and Pascual Jordan develop matrix mechanics, the first version of quantum mechanics, and make an initial step toward quantum field theory.

1926

Erwin Schrödinger develops a second description of quantum physics, called wave mechanics. It includes what becomes one of the most famous formulae of science, which is later known as the Schrödinger equation.

Enrico Fermi and Paul A. M. Dirac find that quantum mechanics requires a second way to count particles, Fermi-Dirac statistics, opening the way to solid state physics.

Dirac publishes a seminal paper on the quantum theory of light.

1927
Heisenberg states his Uncertainty Principle, that it is impossible to exactly measure the position and momentum of a particle at the same time.

1928
Dirac presents a relativistic theory of the electron that includes the prediction of antimatter.

1932
Carl David Anderson discovers antimatter, an anti-electron called the positron.

1934
Hideki Yukawa proposes that nuclear forces are mediated by massive particles called mesons, which are analogous to the photon in mediating electromagnetic forces.

1946–48
Experiments by Isidor I. Rabi, Willis Lamb, and Polykarp Kusch reveal discrepancies in the Dirac theory.

1948
Richard Feynman, Julian Schwinger, and Sin-Itiro Tomonaga develop the first complete theory of the interaction of photons and electrons, quantum electrodynamics, which accounts for the discrepancies in the Dirac theory.

1957
John Bardeen, Leon Cooper, and J. Robert Schrieffer show that electrons can form pairs whose quantum properties allow them to travel without resistance, providing an explanation for the zero electrical resistance of superconductors.

The creation of quantum mechanics triggered a scientific gold rush. Among the early achievements were these: Heisenberg laid the foundations for atomic structure theory by obtaining an approximate solution to Schrödinger's equation for the helium atom in 1927, and general techniques for calculating the structures of atoms were created soon after by John Slater, Douglas Rayner Hartree, and Vladimir Fock. The structure of the hydrogen molecule was solved by Fritz London and Walter Heitler; Linus Pauling built on their results to found theoretical chemistry. Arnold Sommerfeld and Pauli laid the foundations of the theory of electrons in metals, and Felix Bloch created band structure theory. Heisenberg explained the origin of ferromagnetism. The enigma of the random nature of radioactive decay by alpha particle emission was explained in 1928 by George Gamow, who showed that it occurs by quantum-mechanical tunneling. In the following years Hans Bethe laid the foundations for nuclear physics and explained the energy source of stars. With these developments atomic, molecular, solid state, and nuclear physics entered the modern age.

Controversy and Confusion

Alongside these advances, however, fierce debates were taking place on the interpretation and validity of quantum mechanics. Foremost among the protagonists were Bohr and Heisenberg, who embraced the new theory, and Einstein and Schrödinger, who were dissatisfied. To appreciate the reasons for such turmoil, one needs to understand some of the key features of quantum theory, which we summarize here. (For simplicity, we describe the Schrödinger version of quantum mechanics, sometimes called wave mechanics.)

Fundamental description: the wave function. The behavior of a system is described by Schrödinger's equation. The solutions to Schrödinger's equation are known as wave functions. The complete knowledge of a system is described by its wave function, and from the wave function one can calculate the possible values of every observable quantity. The probability of finding an electron in a given volume of space is proportional to the square of the magnitude of the wave function. Consequently, the location of the particle is "spread out" over the volume of the wave function. The momentum of a particle depends on the slope of the wave function: The greater the slope, the higher the momentum. Because the slope varies from place to place, momentum is also "spread out." The need to abandon a classical picture in which position and velocity can be determined with arbitrary accuracy in favor of a blurred picture of probabilities is at the heart of quantum mechanics.

Measurements made on identical systems that are identically prepared will not yield identical results. Rather, the results will be scattered over a range described by the wave

function. Consequently, the concept of an electron having a particular location and a particular momentum loses its foundation. The Uncertainty Principle quantifies this: To locate a particle precisely, the wave function must be sharply peaked (that is, not spread out). However, a sharp peak requires a steep slope, and so the spread in momentum will be great. Conversely, if the momentum has a small spread, the slope of the wave function must be small, which means that it must spread out over a large volume, thereby portraying the particle's location less exactly.

Waves can interfere. Their heights add or subtract depending on their relative phase. Where the amplitudes are in phase, they add; where they are out of phase, they subtract. If a wave can follow several paths from source to receiver, as a light wave undergoing two-slit interference, then the illumination will generally display interference fringes. Particles obeying a wave equation will do likewise, as in electron diffraction. The analogy seems reasonable until one inquires about the nature of the wave. A wave is generally thought of as a disturbance in a medium. In quantum mechanics there is no medium, and in a sense there is no wave, as the wave function is fundamentally a statement of our knowledge of a system.

Symmetry and identity. A helium atom consists of a nucleus surrounded by two electrons. The wave function of helium describes the position of each electron. However, there is no way of distinguishing which electron is which. Consequently, if the electrons are switched the system must look the same, which is to say the probability of finding the electrons in given positions is unchanged. Because the

Omniscient math. It's tough to solve, but Erwin Schrödinger's famous equation (shown in one of its many forms) describes every observable state of a physical system.

probability depends on the *square* of the magnitude of the wave function, the wave function for the system with the interchanged particles must be related to the original wave function in one of two ways: Either it is identical to the original wave function, or its sign is sim-

ply reversed, i.e., it is multiplied by a factor of -1 . Which one is it?

One of the astonishing discoveries in quantum mechanics is that for electrons the wave function always changes sign. The consequences are dramatic, for if two electrons are in the same quantum state, then the wave function has to be its negative opposite. Consequently, the wave function must vanish. Thus, the probability of finding two electrons in the same state is zero. This is the Pauli exclusion principle. All particles with half-integer spin, including electrons, behave this way and are called fermions. For particles with integer spin, including photons, the wave function does not change sign. Such particles are called bosons. Electrons in an atom arrange themselves in shells because they are fermions, but light from a laser emerges in a single superintense beam—essentially a single quantum state—because light is composed of bosons. Recently, atoms in a gas have been cooled to the quantum regime where they form a Bose-Einstein condensate, in which the system can emit a superintense matter beam—forming an atom laser.

These ideas apply only to identical particles, because if different particles are interchanged the wave function will



$$i\hbar \frac{\partial}{\partial t} \psi(\vec{x}, t) = -\frac{\hbar^2}{2m} \nabla^2 \psi(\vec{x}, t) + V(\vec{x}, t) \psi(\vec{x}, t)$$

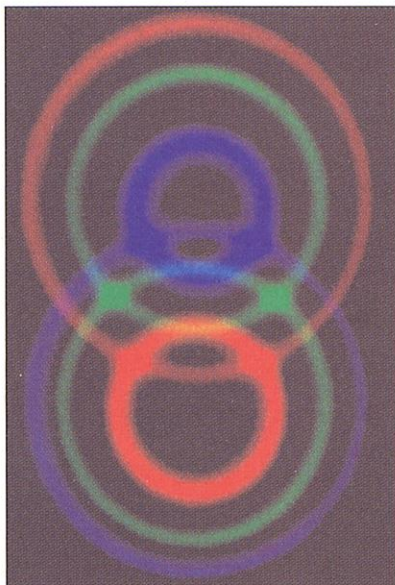
certainly be different. Consequently, particles behave like fermions or like bosons only if they are *totally* identical. The absolute identity of like particles is among the most mysterious aspects of quantum mechanics. Among the achievements of quantum field theory is that it can explain this mystery.

What does it mean? Questions such as what a wave function “really is” and what is meant by “making a measurement” were intensely debated in the early years. By 1930, however, a more or less standard interpretation of quantum mechanics had been developed by Bohr and his colleagues, the so-called Copenhagen interpretation. The key elements are the probabilistic description of matter and events, and reconciliation of the wavelike and particle-like natures of things through Bohr’s principle of complementarity. Einstein never accepted quantum theory. He and Bohr debated its principles until Einstein’s death in 1955.

A central issue in the debates on quantum mechanics was whether the wave function contains all possible information about a system or if there might be underlying factors—hidden variables—that determine the outcome of a particular measurement. In the mid-1960s John S. Bell showed that if hidden variables existed, experimentally observed probabilities would have to fall below certain limits, dubbed “Bell’s inequalities.” Experiments were carried out by a number of groups, which found that the inequalities were violated. Their collective data came down decisively against the possibility of hidden variables. For most scientists, this resolved any doubt about the validity of quantum mechanics.

Nevertheless, the nature of quantum theory continues to attract attention because of the fascination with what is sometimes described as “quantum weirdness.” The weird properties of quantum systems arise from what is known as entanglement. Briefly, a quantum system, such as an atom, can exist in any one of a number of stationary states but also in a superposition—or sum—of such states. If one measures some property such as the energy of an atom in a superposition state, in general the result is sometimes one value, sometimes another. So far, nothing is weird.

It is also possible, however, to construct a two-atom system in an entangled state in which the properties of both atoms are shared with each other. If the atoms are separated, information about one is shared, or entangled, in the state of the other. The behavior is unexplainable except in the language of quantum mechanics. The effects are so surprising that they are the focus of study by a small but active theoretical and experimental community. The issues are not limited to questions of principle, as entanglement can be useful. Entangled states have already been employed in quantum communication systems, and entanglement underlies all proposals for quantum computation.



Quantum webs. By creating particles that share quantum states, such as these “entangled” photons at the intersections of these laser-generated rings, researchers are developing new quantum encryption schemes and quantum computers.

The Second Revolution

During the frenetic years in the mid-1920s when quantum mechanics was being invented, another revolution was under way. The foundations were being laid for the second branch of quantum physics—quantum field theory. Unlike quantum mechanics, which was created in a short flurry of activity and emerged essentially complete, quantum field theory has a tortuous history that continues today. In spite of the difficulties, the predictions of quantum field theory are the most precise in all of physics, and quantum field theory constitutes a paradigm for some of the most crucial areas of theoretical inquiry.

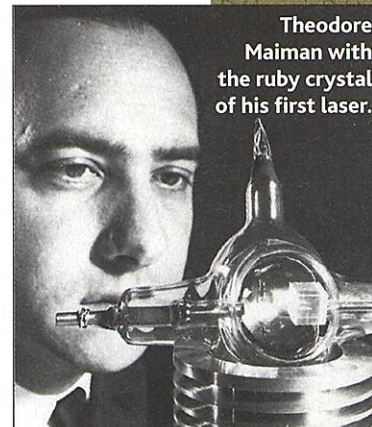
The problem that motivated quantum field theory was the question of how an atom radiates light as its electrons “jump” from excited states to the ground state. Einstein proposed such a process, called spontaneous emission, in 1916, but he had no way to calculate its rate. Solving the problem required developing a fully relativistic quantum theory of electromagnetic fields, a quantum theory of light. Quantum mechanics is the theory of matter. Quantum field theory, as its name suggests, is the theory of fields, not only electromagnetic fields but other fields that were subsequently discovered.

In 1925 Born, Heisenberg, and Jordan published some initial ideas for a theory of light, but the seminal steps were taken by Dirac—a young and essentially unknown physicist working in isolation—who presented his field theory in 1926. The theory was full of pitfalls: formidable calculational complexity, predictions of infinite quantities, and apparent violations of the correspondence principle.

In the late 1940s a new approach to the quantum theory of fields, QED (for quantum electrodynamics), was developed by Richard Feynman, Julian Schwinger, and Sin-Itiro Tomonaga. They sidestepped the infinities by a procedure, called renormalization, which essentially subtracts infinite quantities so as to leave finite results. Because there is no exact solution to the complicated equations of the theory, an approximate answer is presented as a series of terms that become more and more difficult to calculate. Although the terms become successively smaller, at some point they should start to grow, indicating the breakdown of



Fields go quantum. Paul Dirac spearheaded work leading to quantum field theory as well as discoveries such as antimatter.



Theodore Maiman with the ruby crystal of his first laser.

1959

Yakir Aharonov and David Bohm predict that a magnetic field affects the quantum properties of an electron in a way that is forbidden by classical physics. The Aharonov-Bohm effect is observed in 1960 and hints at a wealth of unexpected macroscopic effects.

1960

Building on work by Charles Townes, Arthur Schawlow, and others, Theodore Maiman builds the first practical laser.

1964

John S. Bell proposes an experimental test, “Bell’s inequalities,” of whether quantum mechanics provides the most complete possible description of a system.

1970s

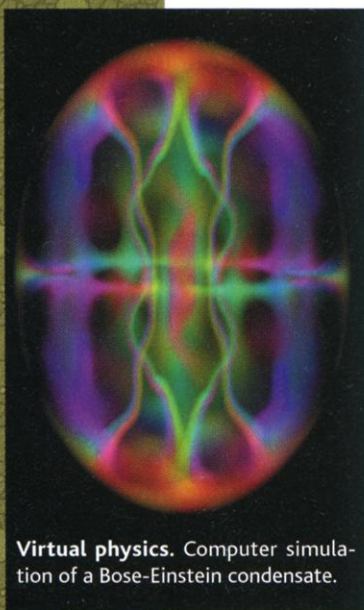
Foundations are laid for the Standard Model of Particle Physics, in which matter is said to be built of quarks and leptons that interact via the four physical forces.

1982

Alain Aspect carries out an experimental test of Bell’s inequalities and confirms the completeness of quantum mechanics.

1995

Eric Cornell, Carl Wieman, and Wolfgang Ketterle trap clouds of metallic atoms cooled to less than a millionth of a degree above absolute zero, producing Bose-Einstein condensates, which were first predicted 70 years earlier. This accomplishment leads to the creation of the atom laser and superfluid gases.



Virtual physics. Computer simulation of a Bose-Einstein condensate.

For more extensive timelines of quantum physics, see two of Abraham Pais's books: *Inward Bound: Of Matter and Forces in the Physical World* and *Niels Bohr's Times: In Physics, Philosophy, and Polity*.

Also see timeline.aps.org/APS/index.html

the approximation. In spite of these perils, QED ranks among the most brilliant successes in the history of physics. Its prediction of the interaction strength between an electron and a magnetic field has been experimentally confirmed to a precision of two parts in 1,000,000,000,000.

Notwithstanding its fantastic successes, QED harbors enigmas. The view of empty space—the vacuum—that the theory provides initially seems preposterous. It turns out that empty space is not really empty. Rather, it is filled with small, fluctuating electromagnetic fields. These vacuum fluctuations are essential for explaining spontaneous emission. Furthermore, they produce small but measurable shifts in the energies of atoms and certain properties of particles such as the electron. Strange as they seem, these effects have been confirmed by some of the most precise experiments ever carried out.

At the low energies of the world around us, quantum mechanics is fantastically accurate. But at high energies where relativistic effects come into play, a more general approach is needed. Quantum field theory was invented to reconcile quantum mechanics with special relativity.

The towering role that quantum field theory plays in physics arises from the answers it provides to some of the most profound questions about the nature of matter. Quantum field theory explains why there are two fundamental classes of particles—fermions and bosons—and how their properties are related to their intrinsic spin. It describes how particles—not only photons, but electrons and positrons (antielectrons)—are created and annihilated. It explains the mysterious nature of identity in quantum mechanics—how identical particles are absolutely identical because they are created by the same underlying field. QED describes not only

the electron but the class of particles called leptons that includes the muon, the tau meson, and their antiparticles.

Because QED is a theory for leptons, however, it cannot describe more complex particles called hadrons. These include protons, neutrons, and a wealth of mesons. For hadrons, a new theory had to be invented, a generalization of QED called quantum chromodynamics, or QCD. Analogies abound between QED and QCD. Electrons are the constituents of atoms; quarks are the constituents of hadrons. In QED the force between charged particles is mediated by the photon; in QCD the force between quarks is mediated by the gluon. In spite of the parallels, there is a crucial difference between QED and QCD. Unlike leptons and photons, quarks and gluons are forever confined within the hadron. They cannot be liberated and studied in isolation.

QED and QCD are the cornerstones for a grand synthesis known as the Standard Model. The Standard Model has successfully accounted for every particle experiment carried out to date. However, for many physicists the Standard Model is inadequate, because data on the masses, charges, and other properties of the fundamental particles need to be found from experiments. An ideal theory would predict all of these.

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Today, the quest to understand the ultimate nature of matter is the focus of an intense scientific study that is reminiscent of the frenzied and miraculous days in which quantum mechanics was created, and whose outcome may be even more far-reaching. The effort is in-

extricably bound to the quest for a quantum description of gravity. The procedure for quantizing the electromagnetic field that worked so brilliantly in QED has failed to work for gravity, in spite of a half-century of effort. The problem is critical, for if general relativity and quantum mechanics are both correct, then they must ultimately provide a consistent description for the same events. There is no contradiction in the normal world around us, because gravity is so fantastically weak compared to the electrical forces in atoms that quantum effects are negligible and a classical description works beautifully. But for a system such as a black hole where gravity is incredibly strong, we have no reliable way to predict quantum behavior.

One century ago our understanding of the physical world was empirical. Quantum physics gave us a theory of matter and fields, and that knowledge transformed our world. Looking to the next century, quantum mechanics will continue to provide fundamental concepts and essential tools for all of the sciences. We can make such a prediction confidently because for the world around us quantum physics provides an exact and complete theory. However, physics today has this in common with physics in 1900: It remains ultimately empirical—we cannot fully predict the properties of the elementary constituents of matter, we must measure them.

Perhaps string theory—a generalization of quantum field theory that eliminates all infinities by replacing pointlike objects such as the electron with extended objects—or some theory only now being conceived, will solve the riddle. Whatever the outcome, the dream of ultimate understanding will continue to be a driving force for new knowledge, as it has been since the dawn of science. One century from now, the consequences of pursuing that dream will belie our imagination.

Further Reading

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