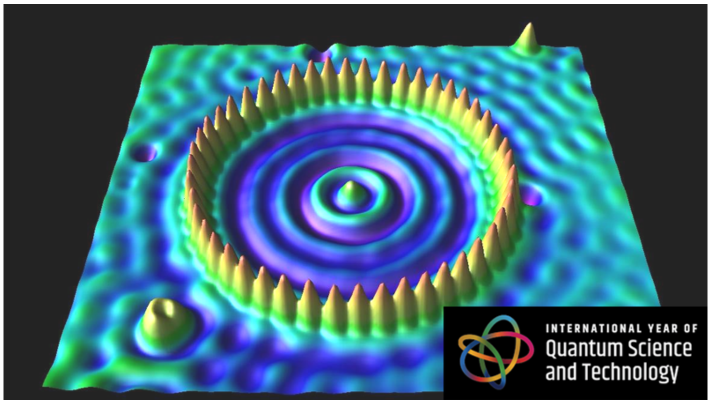
The Tumultuous Birth of Quantum Mechanics

The creation of modern quantum mechanics was a messy business in which many of the participants did not grasp the significance of their own discoveries.

By **Phillip Ball**

The UN-designated International Year of Quantum Science and Technology recognizes the centenary of the birth of quantum mechanics as a complete theory. In 1925 German physicist Werner Heisenberg developed the first formal mathematical framework for the new physics. His "matrix mechanics" enabled the prediction of the quantum behavior of atoms, such as emission spectra [**1**]. At the end of the year, Austrian physicist Erwin Schrödinger devised an alternative and ultimately more popular scheme called wave mechanics (published in 1926).

But, in fact, quantum mechanics wasn't created all at once. It took several decades and was a messy, confused process, during most of which the true nature of this revolution was obscure. In some ways it still is. Looking back at the development of quantum theory reveals that the motivations for such a dramatic shift in how we think about the physical world were initially rather flimsy. So it is scarcely surprising that the new ideas—and what they meant—were hotly contested not only within a conservative "old guard" but even among those who proposed them. These ideas only emerged because of the readiness of some of the key players to take bold imaginative leaps beyond what the empirical evidence or rigorous logic seemed strictly to demand.

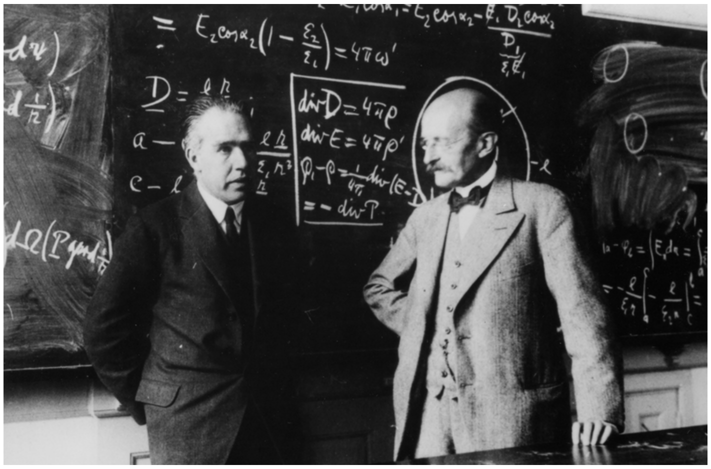


The wave nature of electrons is revealed in this 1993 image of ripples on a copper surface. The electrons are confined within a "quantum corral" made from a ring of iron atoms (peaks). The image was recorded using a scanning tunneling microscope. **Credit: M. F. Crommie, C. P. Lutz, and D. M. Eigler/IBM**

The first intimation of the quantum nature of the physical world could scarcely have been less auspicious. In 1900 German physicist Max Planck, working at the University of Berlin, proposed that the energies of the vibrating atoms in a warm object are quantized, the vibrations being restricted to discrete frequencies like the notes of a musical scale [**2**].

Even this is not quite what Planck said, and his contribution is often misunderstood. He was initially interested in the origins of irreversibility in chemical reactions, being unsatisfied with the answer proposed by Austrian physicist Ludwig Boltzmann. Boltzmann suggested that the observed direction of a chemical reaction was merely a result of the most probable outcome of many molecular events. (There's some irony in Planck being drawn to the quantum hypothesis in an attempt to avoid probabilistic arguments.) The quest led Planck to a problem in electrodynamics: how a perfectly absorbing object, called a blackbody, emitted electromagnetic radiation (heat and light).

The spectrum of blackbody emission has a maximum at a



Niels Bohr (left) and Max Planck lecturing, possibly in Copenhagen in 1930.
Credit: AIP Emilio Segrè Visual Archives, Margrethe Bohr Collection

particular wavelength (λ_m), a peak that moves to shorter wavelengths with increasing temperature T—when an object is heated, it glows red at first and then becomes white as the emission includes more colors toward the bluer end of the spectrum. German physicist Wilhelm Wien had shown empirically that the product $\lambda_m T$ is a constant [**3**]. Planck set out to derive Wien's result from first principles, on the assumption that the emission comes from the vibration of vaguely defined "oscillators." These oscillators might be interpreted as the constituent atoms, although Planck was at that stage not wholly convinced that atoms even existed.

In December 1900 Planck reported that he could obtain good agreement with the empirical data on the assumption that the total energy E_t emitted at a particular wavelength—or frequency ν—is quantized, determined by the integer number of oscillators n that oscillate at this frequency. That's to say, $E_t = nh\nu$, where h is a constant, later known as Planck's constant [**2**].

Planck attributed no physical significance to this quantization—it was just an *ad hoc* "trick," as he put it, to get a result that fit the data. He certainly did not consider that his theory broke with classical physics and neither did almost anyone else. Dutch physicist Hendrik Lorentz merely pointed out later that, while Planck's formula fit the data, the theory lacked a sound theoretical basis.

The exception was Albert Einstein, who in 1905 proposed that Planck's formula for the energy of a vibrational mode $E = h\nu$ be applied to light [**4**]. There had been no suggestion of that in Planck's work on blackbody radiation, and Einstein's reasoning now looks remarkably casual for so radical a proposal.

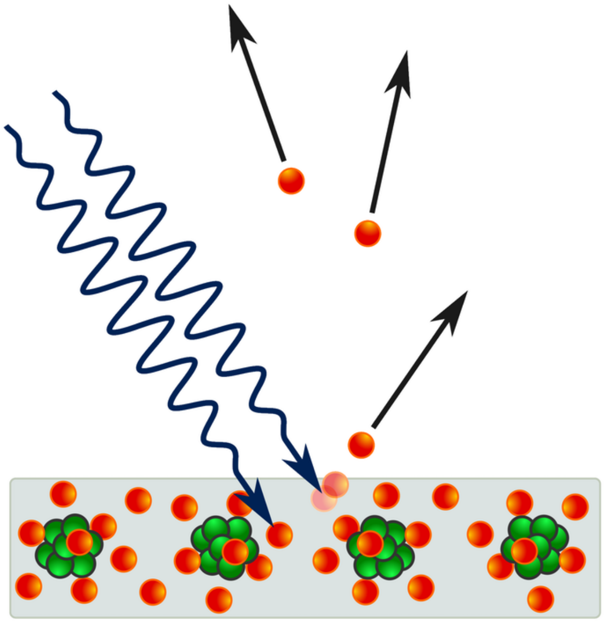
It seems odd, Einstein argued, that we model matter as discrete—coming in atom-sized lumps—whereas electromagnetic radiation is described in the accepted theory of electrodynamics as continuous. Would it not be more consistent to also treat light as discrete, made of energy packets with energies corresponding to Planck's formula?

Einstein's hypothesis led to some experimental predictions. Shining light on a metal was known to expel electrons, a phenomenon called the photoelectric effect. Einstein showed that, if these light packets exist, one would expect that the energies of the emitted electrons should depend only on the frequency (and thus the energy) of the light quanta and not on the light's intensity.

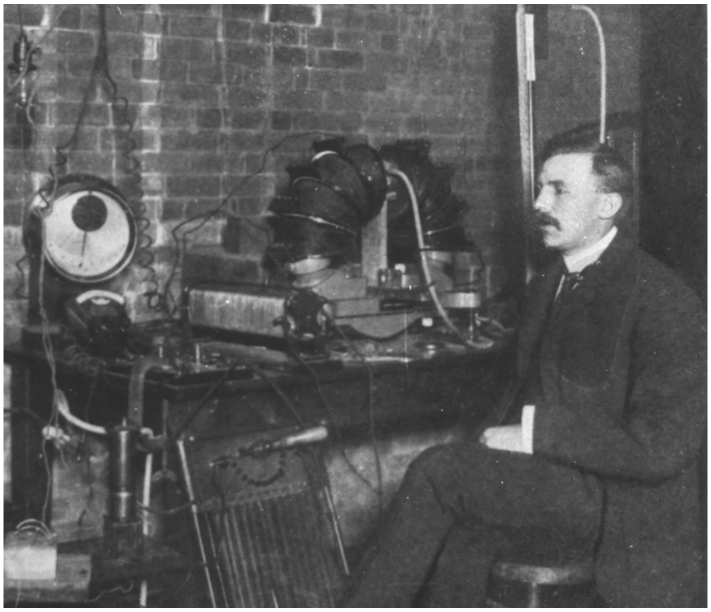
All this seemed a rather thin basis for such an astonishing proposal: that light was not fundamentally wavy, as all experiments to date had seemed unequivocally to demonstrate. After all, no one recognized any urgent problem with the photoelectric effect that needed resolving. And even when Einstein's predictions were verified in 1916 by American physicist Robert Millikan [**5**], it was with only grudging acceptance—Millikan had anticipated disproving an idea he considered "bold, not to say reckless" (see **Special Feature: Quantum Milestones, 1916: Millikan's Measurement of Planck's Constant**). Even then it was not obvious that alternative, classical theories could not equally account for Millikan's results.

Initially, then, Einstein was out on a limb with his quantized light. He understood how radical it was: Looking back on his four groundbreaking papers of 1905, including his first two on relativity, he considered only the light-quanta paper to be truly revolutionary.

Einstein went on to apply the quantum hypothesis to the heat



In the photoelectric effect, ultraviolet light ejects electrons from a solid material.
Credit: Ponor/Wikimedia Commons/CC BY-SA 4.0



Ernest Rutherford in his laboratory in 1905.
Credit: McGill University, Rutherford Museum

capacity of solids [**6**], consolidating it as a fundamental aspect of the description of matter and energy. But many physicists still saw no reason to doubt the completeness of classical physics. Even at the first Solvay Conference in Brussels in 1911, a meeting of top European physicists on “Radiation and the Quanta,” the quantum hypothesis received a mixed reception, particularly from some of the senior scientists. Planck, however, became a reluctant convert, telling the German Chemical Society that same year that “with this [quantum] hypothesis, the foundation is laid for the construction of a theory that is someday destined to permeate the swift and delicate events of the molecular world with a new light.”

A big shift came in 1913, when Danish physicist Niels Bohr, working in the lab of Ernest Rutherford at the University of Manchester in the UK, showed how the quantum hypothesis could rationalize Rutherford’s new model of the atom as a sort of miniature solar system. According to classical physics, this atom would be unstable, as the circulating, charged electrons would be predicted to radiate away energy and spiral into the nucleus. Bohr’s theory avoided this instability by quantum fiat, suggesting that the energies of the electrons were confined to quantized values and, therefore, could not change by arbitrary amounts [**7**]. Only when they absorbed or emitted photons of an energy $h\nu$ equal to the energy difference between two quantized orbits could electrons move between them, doing so in instantaneous “quantum jumps.”

Bohr’s hypothesis could account for the pattern of discrete emission lines, known as the Balmer series, in the spectrum of the hydrogen atom—a mathematical regularity that had puzzled physicists for years. (Spectroscopy was arguably the major focus of physics at that time.) And when Bohr showed that his theory could also explain the spectrum of the helium ion He^+ with great accuracy, many were persuaded that there was something to it. Hearing of the helium results, Einstein called it “an enormous achievement.”

All the same, Bohr’s quantum atom typifies this nascent phase of quantum theory in being an ungainly and *ad hoc* mixture of quantum and classical notions, structured around ideas such as quantum numbers that were largely empirically motivated. Discrepancies and difficulties with this “old quantum theory” began to accumulate. By 1923 these problems were so acute

One of the islands of Helgoland, in the North Sea, where Heisenberg developed matrix mechanics.
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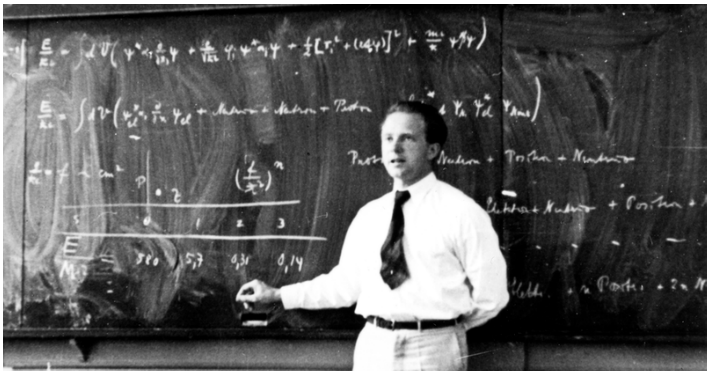
that Max Born of the University of Göttingen in Germany felt compelled to say that “the whole system of concepts of physics must be reconstructed from the ground up.” But how?

In the fall of 1924, Heisenberg, a brilliant and ambitious student of Born’s, visited Bohr at the Institute for Theoretical Physics in Denmark to work on formulating a better quantum theory. They labored away until the following spring with much frustration but little success. After returning to Göttingen, Heisenberg took a summer vacation on the archipelago of Helgoland, Germany, in the North Sea. There, while clambering over the rocks, he worked out a “crazy” theory (in his words to Born) for calculating the electron energy levels of atoms [**1**]. (**A conference in June** will celebrate Helgoland as the birthplace of quantum mechanics a century ago.)

Heisenberg decided that it was necessary not just to accept a break with classical physics but to relinquish any hope of having a quantum theory that could be visualized in conventional terms, with particles moving in space. Rather than describing, say, the unobservable positions and velocities of electrons, he sought “a basis for theoretical quantum mechanics founded exclusively upon relationships between quantities that in principle are observable.” Observable quantities included the frequencies of light emitted as electrons make transitions. He tabulated those frequencies in matrices that completely described the motions of the electrons and could be mathematically manipulated to make predictions about other observables.



Werner Heisenberg at the Niels Bohr institute, Copenhagen, 1936.
Credit: AIP Emilio Segrè Visual Archives

This “matrix mechanics” was hard to understand and to use, which was why many researchers welcomed the alternative, wave-based quantum mechanics presented by Schrödinger in 1926 [**8**, **9**]. Schrödinger was inspired by the (hitherto largely ignored) suggestion made by French physicist Louis de Broglie in 1924 that, just as wavy light could be reimagined as discrete particles, so, too, might particulate matter have a wave-like description [**10**].

Many physicists recognized the practical advantages of Schrödinger’s wave mechanics for making calculations. But although Schrödinger showed that matrix and wave mechanics were mathematically equivalent, the hypercompetitive Heisenberg found Schrödinger’s physical interpretation of his wave equation “disgusting.” Heisenberg was convinced that any attempt to visualize the subatomic world in this way was doomed. Nevertheless, Schrödinger’s wave picture eventually became the standard conceptual framework for quantum mechanics.

Three further developments helped to complete the quantum revolution. First came Born’s recognition in July 1926 that the amplitude of the electron wave function in Schrödinger’s equation did not predict the spatial distribution of charge density but rather the probability of finding an electron in a particular place—quantum mechanics seemed to be inherently probabilistic [**11**]. Then, in 1927 Heisenberg unveiled his uncertainty principle: the impossibility of knowing exactly and simultaneously certain combinations of properties, such as the position and momentum of an electron or another quantum entity [**12**].

Finally, in 1935 Einstein, along with younger colleagues, Russian American Boris Podolsky and American Israeli Nathan Rosen, showed that the theory seemed to imply the existence of nonclassical and nonlocal correlations between quantum particles [**13**] (see **Focus: What's Wrong with Quantum Mechanics?**). This interparticle connection, which Schrödinger called entanglement, would mean that a quantum particle may not be wholly described by properties localized on the particle itself. Einstein, Podolsky, and Rosen intended their paper as a demonstration of the incompleteness of quantum mechanics, since they assumed such interdependence of particle properties was absurd—but experiments have verified it.

The quantum revolution is often cited as a paradigm shift—a notion put forth by science historian Thomas Kuhn to characterize a scientific crisis that can only be resolved by some radical break with existing ideas [**14**]. After the break, Kuhn said, the new paradigm becomes so natural that scientists cannot really imagine returning to the old way of thinking. Whether science really advances this way in general has been contested. But while Kuhn paints a picture of scientists clinging conservatively to old ideas for as long as they can, history suggests that radical new ideas are often not so much resisted as simply ignored or overlooked—sometimes even by those who conceive of them.

What's more, at least in the case of quantum mechanics, it was not apparent from the outset quite where the real radicalism lay—which is to say, not in quantization but in the fundamentally probabilistic, apparently acausal, and nonlocal nature of quantum phenomena. Those characteristics are still the source of arguments a century later.

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