Max Planck founded quantum physics in 1900 — accidentally. In the years following 1920, many physicists developed modern quantum mechanics — through labyrinthine paths and amid intense disputes. This complex history is being studied by a group of historians working with Jürgen Renn, Director at the Max Planck Institute for the History of Science, his colleague Christoph Lehner, and a group of physicists working with Matthias Scheffler, Director at the Fritz Haber Institute.

On December 14, 1900, Max Planck, who was born 150 years ago, gave a lecture before the Physical Society of Berlin that is now considered to be the birth of quantum theory. Planck had solved a problem that had long perplexed many theoretical physicists. He had found the right formula for the electromagnetic radiation spectrum that a perfect black body radiates. This experiment played a key role at the time: the black body is an idealized test object for the question of how matter emits – and conversely, absorbs – electromagnetic radiation as a function of its temperature. Without this intervention of light and matter, our world would be pretty dark because the Sun, for instance, wouldn’t shine.

Planck found the right formula for the temperature-dependent spectral behavior of black-body radiation because he was extremely well versed in thermodynamics. Prior to this, he had significantly modernized the theory of heat. However, to obtain his solution, the Berlin-based physics professor had to postulate a completely new physical variable, which he by no means considers as detracting from Planck’s outstanding achievement. Only the second great pioneer of quantum physics, Albert Einstein (1879–1955), suspected early on that black-body radiation harbored a revolution in physics. In his publication on the light hypothesis of 1905, his annus mirabilis, Einstein clearly demonstrated the break with classical physics that was hidden in Planck’s work.

The young research field experienced turbulent development until the early 1920s. Today, it is frequently referred to as the old quantum theory. After Planck’s initial spark, some of the important milestones include Einstein’s pioneering publications in 1905 and 1907. In these, the young physicist showed that Planck’s constant has a truly fundamental significance. A further milestone was the 1913 Bohr model of the atom, with which Danish physicist Niels Bohr (1885–1962) solved a pressing problem of earlier atomic models. According to them, the electrons should orbit a positively charged nucleus, much like planets around the Sun. But the laws of electrodynamics dictate that, by doing so, they would have had to radiate their kinetic energy like small antennas and crash into the nucleus. If the world worked like that, atoms would have no chance of survival. Bohr saved matter as we know it by introducing quantized paths on which electrons can move without losing energy.

Bohr’s atomic model fit the experimental findings well. However, it could not explain why the electron paths are quantized. That is typical for the key weakness of the old quantum theory. They were dealing purely phenomenologically with quantum properties without being able to explain what caused them. “These quantum conditions were postulated,” explains Christoph Lehner, a historian at the Max Planck Institute for the History of Science, “but it remained unclear why certain physical variables, such as energy, are quantized.”

The brightest minds in physics were becoming more and more dissatisfied with this situation. In the early 1920s, they committed themselves to creating a new, more basic quantum theory. After many missteps, their collective efforts led to success. Near the end of the 1920s, modern quantum mechanics had nearly taken on the form in which it is still valid today, and which also explains the quantization of energy. Some of its findings are now more precisely substantiated by experiment than any other fundamental theory of physics. At the time, however, a heated debate raged among physicists as to their interpretation – that is, as to the statements that could be derived from them with respect to the nature of our world – and it still continues today.

Surprisingly, the creation story of modern quantum mechanics is far less researched than one would expect, given its importance for our culture. After all, we have long since evolved into “quantum manipulators,” putting semiconductor electronics and lasers to work for us with the touch of a button. However, this research subject is no walk in the park for historians. Even just the tangled web of relationships among the many players back then is very complex. “There

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are so incredibly many sources," says Lehner, "and these sources are not particularly well analyzed." Furthermore, the research subject itself – quantum physics with all of its philosophical implications – is very difficult to digest. It is thus no wonder that science historian Lehner, like many of his colleagues, studied physics.

Two years ago, Jørgen Renn, Director at the Max Planck Institute for the History of Science, and Matthias Schelleff, Director at the Berlin-based Fritz Haber Institute of the Max Planck Society, launched an initiative that is being financed by the Innovation Fund of the President of the Max Planck Society. The project aims to thoroughly research the genesis of modern quantum mechanics from today's perspective.

Working visit in Copenhagen: Max Planck traveled to see Niels Bohr (left) in 1930. Bohr played a key role in developing Planck's discovery that energy is quantized into modern quantum mechanics.

There are now ten historians working on it at the institute in Berlin alone, says Lehner, who coordinates the project. "For our profession, that's huge." In addition, there are partnerships around the world with other historians – and, as a special treat, also with physicists who have a natural tendency to present the research subject itself – quantum physics with all of its philosophical implications – is very difficult to digest. It is thus no wonder that science historian Lehner, like many of his colleagues, studied physics.

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De Broglie's relation (1924)

\[ \psi = \frac{1}{\sqrt{\frac{m_0 c^3}{\hbar^2}}} \]

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This behavior contradicted the classical theory. Planck conjectured that a quantum effect was playing a role, and tried to use a trick to reach a new statistical theory of gases. He was the first to account for the fact that, in the quantum world, individual particles – such as gas molecules – have no individual properties. Consequently, particles of the same kind in the same physical state are indistinguishable; they can be exchanged around like shells in a shell game and the overall physical system will not change at all. A statistical theory must take this into account.

Planck tried to do this, but his approach was too simple. The quantum pioneer had the right instinct, but it was a young Indian physicist who found the solution. Satyendra Nath Bose (1894–1974) developed a statistics that systematically counted indistinguishable quantum particles in the same quantum state as a single state. Bose's theory allowed him to describe the behavior of photons, Schrödinger light quanta, correctly. The Indian published this work in 1921 and sparked Einstein's interest. Einstein recognized that Bose's statistical approach could be successfully applied to other matter particles in, for example, the gaseous state.

Erwin Schrödinger studied the new Bose-Einstein statistics. He tested it by see what statistical gas theory would result if he described the gas molecules as waves instead of as particles. "He counted the wave states and, in doing

\[ u dv = \frac{u}{c} \left( \frac{u}{c} - 1 \right) \]

Planck's distribution law (1900)
so, elegantly obtained the Bose-Einstein gas theory," explains Lehner. Inspired by this success, Schrödinger came up with his wave equation in 1926. This Schrödinger equation is one of the most famous formulas in physics today. A further reason why Schrödinger had a keen eye for wave phenomena was because he was familiar with the work of another outsider. The French theoretician Louis de Broglie (1892–1987) had boldly extended the concept of quanta since Einstein’s publications in 1905 to all matter. De Broglie, in his 1924 dissertation, was the first to derive a wave formula for electrons. It was clear that photons were not a special case: it appeared that, in the quantum world, all particles also possessed wave properties. Schrödinger delved into this.

However, there is a speed limit for Schrödinger’s wave equation. It becomes imprecise as soon as the electrons become so fast that they enter the domain of relativistic effects. That does indeed happen in atoms. “For Schrödinger, this equation was thus merely a stopgap solution,” says Lehner. As he noticed when studying the notebooks, the Viennese physicist was desperately searching for a generally applicable, relativistic formulation and viewed his now famous equation as an unloved byproduct.

But someone else was to crack this difficult nut: English physicist Paul Dirac (1902–1984) in 1928, with his Dirac equation. The young genius from Cambridge University was one of the main actors in the drama of the emerging quantum mechanics. Two years prior, Dirac had already had a major breakthrough that led to the currently valid mathematical formulation of modern quantum mechanics. “Before that, wave mechanics and matrix mechanics essentially constituted two half theories,” says Lehner. In 1926, Dirac combined the two halves into a whole in his transformation theory. Then 1927 became what was possibly the most exciting year in the development of quantum mechanics. Werner Heisenberg formulated his uncertainty relation in Göttingen, and the fifth Solvay Conference took place in October. “This conference, especially, was fantastic,” raves Lehner. “Everyone who was anyone at the time was there, and all of the various opinions collided.” At this legendary physicists conference, which Belgian industrialist Ernest Solvay had brought into being in 1911, the foundations would be laid for the now dominant interpretation of quantum mechanics. After the conference, Niels Bohr and Werner Heisenberg battled it out and came to an agreement about the interpretation that

Bohr then successfully propagated in the physics community. That is why, decades later, the name “Copenhagen interpretation” came to be widely accepted. Bohr’s adversary was Albert Einstein, who was becoming more and more suspicious of the ghosts that he himself had summoned. Particularly Heisenberg’s new uncertainty relation became a point of contention between Bohr and Einstein. It states that the location and the momentum – that is, the speed – of a particle cannot both be precisely determined at the same time. Heisenberg, Bohr and other physicists accepted this uncertainty as a natural, fundamental limit of measuring precision. Einstein was not willing to accept that. He saw uncertainty as an indication that quantum mechanics was not a fundamental theory, but rather merely a statistical approach. To prove this, Einstein devised more and more thought experiments that Bohr, in return, rebutted. Eyewitness Paul Ehrenfest (1880–1933) wrote the following about the debate between the two titans: “[...] like a game of chess. Einstein all the time with new examples [...] to break the uncertainty relation. Bohr from out of philosophical smoke clouds constantly searching for the tools to crush one example after the other. Einstein like a jack-in-the-box; jumping out fresh every morning. Oh, that was priceless. But I am almost without reservation pro Bohr contra Einstein. Despite a few attacks and counterproposals, the Copenhagen interpretation comprises, for example, Max Born’s finding that God – contrary to Einstein’s famous witticism – evidently does play dice: physical events occur only with a certain probability, and quantum mechanics can precisely predict only this probability. A further ingredient is Niels Bohr’s complementarity principle. It states that an experiment can demonstrate either the particle properties of the object of interest or its wave properties, but never both at once. However, the most recent experiments contradict Bohr’s strict verdict.

Einstein would never let go of his criticism that quantum mechanics is incomplete. In 1935, he published, together with Boris Podolsky (1898–1966) and Nathan Rosen (1909–1995), a thought experiment that was intended to highlight this problem of incompleteness. It is famous today as the Einstein-Podolsky-Rosen paradox. If two or more particles are in a joint quantum state, then all other particles must immediately sense when one of the particles is measured. In quantum mechanics, this applies without restriction, even if the “entangled” particles are far apart from one another. Einstein called this effect “spooky action at a distance,” and it told him that there was a fundamental flaw in quantum mechanics.

But nature does indeed have this strange property, as has since become clear. Viennese physicist Anton Zeilinger, who is also involved in the research project with the team in Berlin, and his group recently completed a particularly spectacular experiment in which photons remained entangled across a distance of 144 kilometers. Such technological developments as quantum cryptography are already taking advantage of this phenomenon. It is always possible to tell when a message encoded in entangled photons has been intercepted by comparing the properties of both light particles. It is thus relatively easy to expose a spy. But Erwin Schrödinger did not yet suspect any of this when he first wrote the wave equation in his notebook. Christoph Lehner enthusiastically points to a copy of this page. A legal dispute is currently raging over the ownership of the original, between the University of Vienna, where it is housed, and Schrödinger’s daughter and sole heir. The manuscripts of the pioneers of quantum mechanics have long since become coveted items.