Einstein's Unfinished Revolution

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Second part - two: 5 & 6 chaps.

(J. Giraldo 14/05/2019.)
CPTPT

FIVE

What Quantum Mechanics Doesn't Explain

Quantum mechanics doesn't answer every question we can ask about the atomic world, but it gets a lot right. This is a good time to sum up what we've learned about what quantum mechanics does and does not explain.

Roughly speaking, quantum mechanics predicts and explains two kinds of properties: properties of individual systems, and averages taken over many individual systems. These are very different.

When we can attribute a definite value to a quantity—as we can when we make a measurement—this is a property of the individual system that has been measured. But often the uncertainty principle forbids us from discussing anything other than averages.

To what do these averages refer? Because of the uncertainty principle it can happen that two atoms, prepared identically in the same initial state, give different values when measured later. For example, atoms prepared in the same starting position will tend to spread out, and be found in different places later. When the final answers vary we can still measure their average value. Quantum mechanics tells us these averages are taken over many runs of an experiment. An experiment requires us to prepare many copies of a system, wait and then measure each copy, and then take the average of the results.

A collection of atoms which are similar in some way but different in others is called an *ensemble*. Quantum mechanics deals with ensembles. These may be defined by fixing one quantity, such as energy, to have some definite value, while other parameters vary over a range of values, as required by the uncertainty principle. When we speak of averages or probability in quantum mechanics, we are usually referring to something that can be measured by taking an average over the members of an ensemble consisting of many copies of the atom in question.

That is often easy to do because many experiments deal with a collection of atoms, such as a gas. These are real ensembles, because the atoms in the collection are real. Sometimes, though, the ensemble exists only in the theorist's imagination.

It is normal to explain the results of averaging over many copies of an individual system in terms of the properties of those individual systems. However, in quantum mechanics it is often the other way around, and a property of an individual atom will be explained in terms of averages over many atoms. But how can the collective determine the individual? These kinds of cases are at the heart of what is most mysterious about the quantum world.

One of the individual properties that quantum mechanics can discuss is the energy of an atom or molecule. It turns out that in quantum mechanics the energies of many systems come in certain discrete values, called the spectrum. The spectrum is a property of individual atoms, as it can be observed in experiments involving just one atom. Atoms, molecules, and various materials all have spectra, and in all these cases they are correctly predicted by quantum mechanics. More than that, quantum mechanics *explains* why these systems can have only these energies. It accomplishes this by making use of the wave-particle duality. This is one place where averages over many systems are used to explain what happens in an individual system.

The explanation involves two steps. The first is to use the relation between energy and frequency, which is the foundation of the wave-particle duality. A spectrum of discrete values of energy corresponds to a spectrum of discrete frequencies. The second step exploits the picture of a quantum state as a wave. A wave ringing at a definite frequency is like a bell or a guitar string producing sound. The string resonates when plucked, as does the bell when struck, ringing at a definite frequency.

We then use the equation for quantum states changing in time to predict the resonant frequencies of the system. The equation takes as input the masses of the particles involved in the system and the forces between them, and gives as output the spectrum of resonant frequencies. These are then translated into resonant energies.

This works well. For example, if we input that the system is made of an electron and a proton, bound together by their electrical attraction, the equation outputs the spectrum of the hydrogen atom.

In most cases, there is a state of lowest energy, which is called the ground state. States of higher energy are called excited states. You excite the ground state by adding the energy needed to bring it up to the level of one of these excited states. This causes the state to transition from the ground state to the excited state. The added energy is often delivered by photons. Excited states tend to be unstable, because they can drop back down to the ground state by radiating away the excess energy in the form of a photon. The ground state has no state below it to decay to, and so it is stable. Most systems spend most of the time in their ground states.

This method has been tested on a great many systems, including atoms, molecules, nuclei, and solids. In all cases the predicted spectra are observed. In addition to getting the spectrum of possible energies right, quantum mechanics makes predictions for averaged quantities, such as average values of the positions of the particles making up the system.

For each resonant frequency, the equation that defines quantum mechanics can be solved to yield the corresponding wave. We then use Born's rule (that the square of the wave is proportional to the probability of finding the particle) to predict probabilities for the particle to be found different places.

The states of definite energy have indefinite positions. Suppose we prepare a million different hydrogen atoms, all in the ground state. In each of these, we measure the position of the electron (relative to the proton, which is held fixed in the center of the atom). Each individual measurement results in a different position. Measuring a million different atoms gives us a million different positions. Some will be far from the proton, but most will be clustered around the proton in the center. The array of possible positions makes up a statistical distribution and it is this distribution, rather than a definite position, that quantum mechanics predicts.

According to the uncertainty principle, the position of any one of the electrons cannot be predicted. But the statistical distribution of positions, which results from measuring a great many cases, can be found. These statistical distributions are computed by squaring the wave.

To summarize, quantum mechanics makes two kinds of predictions. It makes predictions for the discrete spectra of energies, or other quantities, a system can have. And it also makes predictions for statistical distributions of quantities such as positions of particles.

In every case I know of, these two kinds of predictions have been confirmed by experiment. This is exceedingly impressive.

But does quantum mechanics explain how individual atoms work? Is a successful prediction always the same as an explanation?

IT IS EQUALLY IMPRESSIVE what quantum mechanics does not do. It does not describe or predict where a particular individual electron will be found. Because it deals in averages, quantum mechanics has little to tell us about what goes on in individual systems.

There are lots of cases where we deal with averages. We have no problem measuring the average height of Canadians. This is because each Canadian is some definite number of centimeters tall. We add all those centimeters up, divide by the number of Canadians we measured, and we get the average.

In cases like this, the average is made up of individual heights, which are properties of individuals. We could choose to work with the whole list of heights, but for many purposes, such as designing furniture or cars, the averaged value is all we need. If we need anything else, it is likely to be the *standard deviation*, which tells us the typical range of variations of height. Using the average and standard deviation, an airline could (if it wanted to) build airplane seats in which 95 percent of Canadians would be comfortable.

In these cases, the information which we ignore when we use averages is really present in the world, but we choose to suppress it in favor of the averages. The uncertainties which arise from our use of probabilities are purely due to our ignorance.

But suppose that each time we measured someone's height, we got a different result. There is then an element of genuine randomness, because there is no way for us to know how tall someone might be the next time they are measured. That is closer to the case we deal with in quantum theory. What does the average signify, and what does it explain, when there is no story about individual cases?

Quantum mechanics makes correct predictions for averages, in spite of having nothing definite to say about individual cases. We seem to lack the kind of explanation we usually expect in cases like height, where the basis of an average is found in the fact that the average is composed of individual cases.

One of the most unexpected aspects of quantum mechanics is that a system can change over time in two ways. I described these in chapter 3. Most of the time the quantum state evolves deterministically under Rule 1. But when we make a measurement of the system it evolves in a very different way under Rule 2. The measurement will produce one number out of a range of possible values. Just after the measurement, the quantum state jumps into a state corresponding to the definite value which was measured in the experiment.

Rule 1 is continuous and deterministic; Rule 2 by contrast is abrupt and probabilistic. The state jumps abruptly just after the measurement, but quantum mechanics predicts only probabilities for the different outcomes, and hence for which state the system jumps to.

Most people are perplexed when they learn about these two rules. As we discussed before, the situation is genuinely puzzling. The first thing that puzzles them is the measurement problem:

What's so special about a measurement? Aren't measuring devices and the people who use them made of atoms, to which Rule 1 applies?

Rule 1, by dictating how a quantum system changes in time, plays the same essential role in the theory that Newton's laws of motion played in pre-quantum physics. Like Newton's laws, Rule 1 is deterministic. It takes an input state and evolves it to a definite output state at a later time. This means it takes input states which are constructed as superpositions to output states which are similarly constructed from superpositions. Probability plays no role.

But measurements, as described by Rule 2, do not evolve superpositions to other superpositions. When you measure some quantity, like pet preference or position, you get a definite value. And afterward the state is the one corresponding to that definite value. So even if the input state is a superposition of states with definite values of some observable quantity, the output state is not, as it corresponds to just one value.

Rule 2 does not tell you what the definite value is; it only predicts probabilities for the different possible outcomes to occur. But these probabilities are not spurious; they are part of what quantum mechanics predicts. Rule 2 is essential, because that is how probabilities enter quantum mechanics. And probabilities are essential in many cases; they are what experimentalists measure.

However, quantum mechanics requires that Rule 1 and Rule 2 never be applied to the same process, because the two rules contradict each other. This means we must always distinguish measurements from other processes in nature.

Yet if we are realists, then measurements are just physical processes, and there is nothing special that should distinguish them fundamentally from anything else that happens in nature. Thus, it is very hard to justify giving a special role to measurements within realism. Hence, it is hard to square quantum mechanics with realism.

AT THE END OF THE DAY, the question will be this: Can we live with these contradictions and puzzles, or do we want and expect more from science?

SIX

The Triumph of Anti-Realism

Quantum theory does not describe physical reality.
What it does is provide an algorithm for computing
probabilities for the macroscopic events ("detector clicks")
that are the consequences of our experimental interventions.
This strict definition of the scope of quantum theory
is the only interpretation ever needed, whether
by experimenters or theorists.

—CHRIS FUCHS AND ASHER PERES

The person who first understood that quantum physics would require a radically new theory based on a duality of waves and particles was Albert Einstein. Einstein was a realist to the core. Yet the quantum revolution he sparked culminated twenty years later in a theory that requires that measurements be singled out and treated differently than all other processes—a distinction that, as I discussed in the last chapter, is foreign to realism. The resolution, according to most of the pioneers of the quantum world, was to give up realism. How did this abandonment of realism come to happen?

The idea of a duality of wave and particle first appeared in Einstein's studies of the nature of light in the early years of the twentieth century. By that time physicists had considered theories in which light is a particle and theories in which light is a wave, but always one or the other. Newton considered the wave theory and rejected it in favor of a theory in which light is conveyed by a stream of particles traveling from objects to the eye. (Some ancient thinkers had them going the other way, which led to trouble explaining why we don't see in the dark.) Newton's reason for this choice was interesting: he thought that particles did a better job of explaining why light travels in straight lines. Waves, he knew, could bend as they diffract around obstacles, and he didn't think light could do that. Newton's particle theory of light reigned until an English scientist named Thomas Young showed in the early years of the nineteenth century that light did indeed bend and diffract at the edges of obstacles and as it passed through slits. Young was a medical doctor who contributed to several areas of science and medicine as well as Egyptology. He was an expert in a broad range of fields, something that the rapid expansion of the sciences was shortly to make impossible. He was sometimes called "the last person to know everything," but his greatest accomplishment was his wave theory of light, which, together with the experimental evidence he provided for diffraction, led to the overthrow of Newton's particle theory.

One of the examples Young considered was the double slit experiment, which is illustrated in figure 5. Water waves originating from the left pass a breakwall broken by two slits, on the way to a beach on the right. The waves from the two slits interfere with each other: the height of the water at each point to the right of the wall is a combination of waves propagating from the two slits. When the peaks of the two waves coincide, you see reinforcement—the combined wave is at its highest; but when the peak of one wave arrives in coincidence with the trough of the other, they cancel each other out. The result is the pattern graphed at the right, which is called an *interference pattern*. The key thing to understand and remember is that the interference pattern is the result of waves arriving from the two slits.

Thomas Young was able to construct the analogue of a double slit apparatus for light, and he saw an interference pattern. This made a strong case for light being a wave.

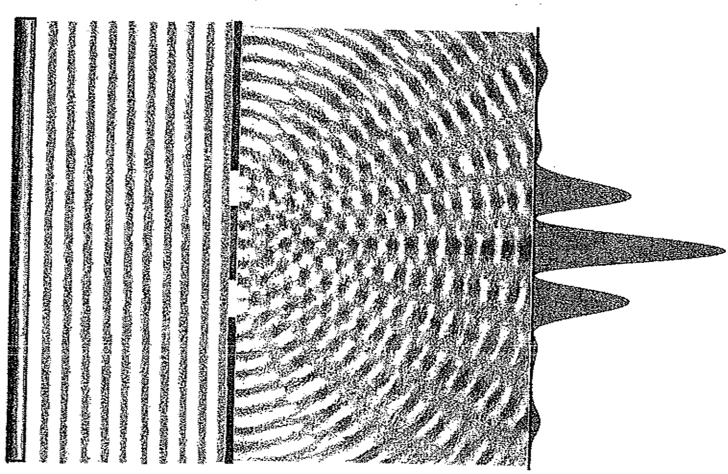

FIGURE 5. The double slit experiment, which shows that light behaves as a wave.

Further support for the idea that light is a wave came from the Scottish physicist James Clerk Maxwell, who showed around 1860 that light is a wave shimmying through the electric and magnetic fields that fill space as they convey forces between charges and magnets.

Einstein accepted Maxwell's hypothesis but added one of his own, which was that the energy carried by light waves comes in discrete packets, which he called photons. Thus was born the idea that light has a dual nature—it travels like a wave but conveys energy in discrete units like a particle. Einstein tied together the waves and particles by a simple hypothesis, according to which the energy a photon carries is proportional to the frequency of the light wave.

Visible light spans a range of frequencies, within which red light has the lowest frequency. Blue light is almost the highest frequency we can see, vibrating roughly twice as fast as red. Thus, a blue photon carries roughly twice the energy of a red photon.

What led Einstein to make such a radical proposal? He knew of experiments which could distinguish the effect of increasing the intensity of a beam of light from the effects of changing its color or frequency. This was done by shining light on metal, which caused some of the electrons in the metal to jump out, making an electric current that could be detected by a simple instrument an electrician might use.

The experiments measured how much energy the jumping electrons acquired from the light shining on the metal. The results showed that if you want to increase the energy each electron gets, you have to turn up the light's frequency. Dialing up the intensity has little or no effect; this merely raises the number of photons falling on the metal, without changing the energy the electron acquires from individual photons. This accords with Einstein's hypothesis that the electrons take energy from light by absorbing photons, whose energy is each proportional to the light's frequency.

Electrons are normally imprisoned in a metal. The energy a photon gives to an electron is like atomic bail: it liberates the electron, allowing it to travel free of the metal. But that bail is set at a certain amount. Photons which carry too little energy have no effect. If the electron is to escape, it has to get its energy from a single photon; it cannot collect up a lot of small increments. Hence, red light doesn't suffice to get a current started, but even a few photons of blue light will liberate some electrons, because each photon carries enough to bail out an electron.

The fact that no amount of red light, no matter how intense, will suffice to liberate an electron, while even a tiny amount of blue light succeeds, was to Einstein a big hint that the energy of light is carried in discrete packets, each unit proportional to the frequency. An even more direct hint came from measurements carried out in 1902 that showed that, once the threshold for bail was met, the liberated electron flew away with an energy proportional to how far the frequency was over the threshold. This was called the photoelectric effect, and Einstein was the only one who correctly interpreted it as signaling a revolution in science. This was one of four papers he wrote in his miracle year of 1905, when he was twenty-six and working in a patent office.

At that time the reigning theory of light was Maxwell's, namely that light is a wave moving through the electric and magnetic fields. Einstein knew Maxwell's theory intimately, having carried Maxwell's book in his pack for a year he spent hiking the mountains as a teenage dropout. No one understood better than Einstein that, great as it was, Maxwell's wave theory of light could not explain the photoelectric effect. For if Maxwell were right, the energy a wave conveys to an electron would increase with intensity, which is exactly what the experiments were not seeing.

The photoelectric effect was not the only clue. The generation of Einstein's teachers had developed the study of light given off by hot bodies, such as the glow of red-hot charcoal. There were beautiful experimental results, which the theorists hoped to explain, which showed that the colors of the emitted light change as the charcoal is heated up. In 1900, theoretical physicist Max Planck explained the result through a derivation that featured one of the most creative misunderstandings in the history of science. To get a glimpse into this comedy, you need to know that even at the turn of the twentieth century, the scientific consensus among physicists, which Planck shared, was that there are no atoms—rather, matter is completely continuous. There were a few prominent theorists who believed in atoms, among them Ludwig Boltzmann of Vienna. Boltzmann developed a method for deriving the properties of gases by treating them as collections of atoms.

Planck, even though he was a skeptic of the atomic hypothesis, borrowed the methods Boltzmann used to study gases and applied them to the properties of light.* Without meaning to do so, he effectively described light as a gas made up of photons, rather than atoms. Navigating in deep waters unfamiliar to him, he found he could get an answer that agreed with experiments if he took the energy of each photon to be proportional to the frequency of the light.

Planck didn't believe in atoms of light any more than he believed in atoms of matter. So he didn't understand that he had made the revolutionary discovery that light is made of particles. But Einstein believed in both, and, almost single-handedly, he understood that the success of Planck's theory rested on treating light as a gas of photons. When he learned about the photoelectric effect, he immediately thought of applying to it the proportionality between the energy of a photon and the frequency of light that had

* For more on how Planck misappropriated Boltzmann's methods, see Thomas Kuhn's *Black-Body Theory and the Quantum Discontinuity, 1894–1912*, or a wonderful biography of Paul Ehrenfest by Martin Klein, both listed in the Further Reading section.

appeared in Planck's work. So it was he, and not Planck, who was given the good fortune of making one of the great discoveries in the history of science: that light has a dual nature, part particle and part wave.

At first Einstein's proposal was greeted with a high degree of skepticism. After all, there was still the double slit experiment to contend with, which clearly showed light traveled through both slits, like a wave. Somehow, light is both wavelike and particle-like. Einstein was to wrestle with this apparent contradiction for the rest of his life. But by 1921 some detailed predictions he'd made in his 1905 paper had been confirmed, and Einstein was awarded the Nobel Prize for the photoelectric effect.

As a footnote to this story, we can mention that another of the four papers Einstein wrote that year gave the final, convincing proof that matter is made of atoms. Atoms were too small to see even with the best microscopes at that time. So Einstein focused his attention on objects just big enough to see through a microscope: pollen grains. These were known to dance unceasingly when suspended in water, which was at the time a great mystery. Einstein explained that the dance was due to the grains colliding with the water molecules, which are themselves constantly moving.*

The other two papers Einstein wrote in that momentous year presented his theory of relativity and the iconic relation between mass and energy: $E=mc^2$.

If we want to find an analogue of what Einstein achieved in that single year, we can only look at Newton. Einstein launched two revolutions—relativity and the quantum. Of the latter he had wrested from nature two precious insights: the dual nature of light,

* Unfortunately, this came too late for Boltzmann, who, depressed at his failure to convince his colleagues of the reality of atoms, committed suicide the next year. And as a footnote to a footnote: a young Viennese physics student called Ludwig Wittgenstein was so dismayed by news of Boltzmann's suicide that he switched to philosophy.

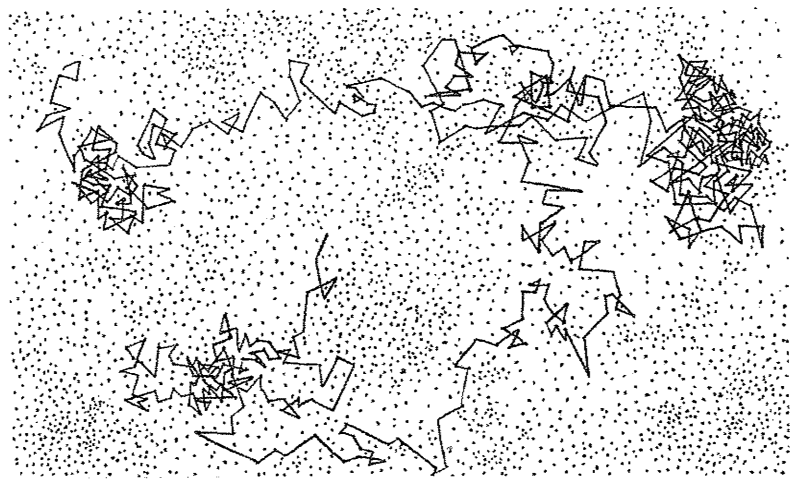

FIGURE 6. BROWNIAN MOTION Brownian motion is the random motion of molecules and other small particles found in nature. Einstein explained that the motion results from the frequent collisions of molecules making up the air or water, and was able to predict how the magnitude of the effects depends on the density of the atoms.

and the relation between the energy of the particle and the frequency of the wave, which ties together the two sides of the duality.

Einstein's fourth paper, which proved the existence of atoms, said nothing about the quantum nature of light. But it contained two mysteries, which it would take the quantum theory to resolve. How could atoms be stable? And why do atoms of the same chemical element behave identically?

While the theorists had been squabbling over whether atoms existed, experimentalists had been busy separating their constituents. First to be identified was the electron, which was revealed to carry a negative charge and to have a tiny mass, about one two-thousandth of that of a hydrogen atom. The chemical elements were understood to be classified by how many electrons they contained. Carbon has 6 electrons, uranium 92, for example. Atoms are electrically neutral, so if an atom contains, say, 6 electrons, that means if you remove those electrons you get a structure with 6 positive charges. Since electrons are so light, this structure, which we can call the nucleus, has most of the mass.

In 1911 Ernest Rutherford determined that the nucleus of an atom is tiny, compared to the whole atom. If the atom is a small city, the nucleus is a marble. Shrunk into that tiny volume are all the positive charges and almost all the mass of an atom. The electrons orbit the nucleus in the vast empty space that is most of the atom.

The analogy to the solar system is inevitable. The electrons and the nucleus are oppositely charged, and opposite charges attract through the electrical force. This holds the electrons in orbit around the nucleus. This much is similar to planets being held in orbit around a star due to their mutual gravitational attraction. But the analogy is misleading because it hides the two puzzles I mentioned. Each provides a reason why Newtonian physics, which explains the solar system, cannot explain atoms.

Electrons are charged particles, and Maxwell's great theory of electromagnetism tells us that a charged particle moving in a circle should give off light continuously. According to Maxwell's theory, which is to say prior to quantum physics, the light given off should have had the frequency of the orbit. But light carries energy away, so the electron should drop closer to the nucleus as its energy decreases. The result should be a quick spiral into the nucleus, accompanied by a flash of light. If Maxwell's theory is right, there can be no picture of electrons circling in gentle, stable orbits around the nucleus. This can be called the crisis of the stability of electron orbits.

You might ask why the same problem doesn't afflict planetary orbits. Planets are electrically neutral, so they don't give off light in the same way. But, according to general relativity, planets in orbit do radiate energy in gravitational waves and spiral into the sun. It is just that gravity is extremely weak, so this process is extraordinarily slow. The effect has been observed in systems consisting of pairs of neutron stars in close orbits. And, very dramatically, gravitational wave antennas have detected the radiation given off by pairs of massive black holes spiraling into each other and merging.

The second problem is why all atoms with a certain number of electrons appear to have identical properties. Two solar systems with six planets each are, beyond that, not generally very similar. The planets will have different orbits and masses and so on. But chemistry works because any two carbon atoms interact with other atoms in exactly the same way. This differs from how oxygen atoms interact, any two of which are also identical to each other. This is the puzzle of the stability of chemical properties. The analogy to the solar system fails because Newtonian physics, which works just fine to explain the solar system, cannot explain why all atoms with six electrons have the same chemical properties.

The answer to both these questions about atoms required applying to atoms the radical new ideas Einstein was developing about the nature of light. This was a bold step of the kind that Einstein was capable of, but even he missed it. The physicist who had the insight was the young Dane Niels Bohr. This insight meant it was Bohr, not Einstein, who would assume the leadership of the revolutionaries who invented quantum mechanics. Throughout his life, Bohr was a radical anti-realist, and it was he, more than anyone else, who was responsible for making the quantum revolution a triumph of anti-realism. Over his career, Bohr fashioned a series of arguments that the behavior of atoms and light could not be understood from a realist perspective.

Bohr grew up in an academic family, the son of a professor of physiology, the brother of a mathematician. He was that fortunate sort who got to live his whole life in the city of his birth, in more or less the same setting as his parents. But in his case, a simple and conservative life was an incubator of radical thought.

In this comfortable, intellectual milieu, he and his wife brought up six sons, several of whom also became professors. One even followed his father to a Nobel Prize in physics. Another son, the oldest, drowned while sailing with his father. Still another son represented Denmark at the Olympics, as did an uncle.

Denmark is a small country that values science, and Bohr's leadership of the quantum revolution was facilitated by the creation of a new institute to support his activities, sponsored by the Danish government and the Carlsberg beer company. This gave Bohr the perfect setting in which to extend his influence, by surrounding himself with the best young theorists from around the world. They were stimulated by a steady stream of visitors who came to collaborate with Bohr or to argue with him about quantum theory. The institute provided him with a comfortable house, where Bohr and his family hosted many of the visitors.

Niels Bohr's sons had to share him with many of these young quantum revolutionaries, who looked up to him as a mentor. His wife looked after them and played matchmaker, introducing several of them to the women who would become their wives. (There were few women who were scientists in Bohr's circle.)

Bohr clearly fascinated those who worked with him. He saw science as a dialogue with nature and his method of working was also based on dialogue—although of a kind that often lapsed into monologue. He used collaborators as scribes, who had the job of taking down Bohr's thoughts, uttered in whispered riddles, corrected and corrected again, as Bohr paced in circles around the room.

Bohr began to work on quantum physics shortly after receiving his PhD. He went right to the heart of the problem by proposing a simple but radical quantum model of the atom. He built on Einstein's nascent quantum theory, particularly the idea that energy is carried by photons. To address the problem of the stability of the electron orbits, Bohr simply postulated that Maxwell's theory is wrong on the atomic scale. He hypothesized, instead, that there are a small number of orbits of the electron, which are stable. To distinguish these good orbits, he made use of Planck's constant, which is the conversion factor between frequency and energy. This conversion factor has units of a quantity called angular momentum. This works just like momentum, but for circular motion. A spinning body has an inertia to continue rotating. This is because spinning or orbiting bodies carry angular momentum, which, like energy and regular momentum, cannot be created or destroyed. It is this conservation of angular momentum that keeps a bicycle wheel spinning; it is also what causes a figure skater to spin more rapidly when she pulls her arms in.

Let's think about a hydrogen atom, which has only a single electron. Bohr postulated that the good orbits are those in which the electron has certain special values of angular momentum. These special values are integer multiples of the unit of angular momentum, given by Planck's constant. Bohr called these *stationary states*. There is an orbit with zero angular momentum which also has the lowest possible value of energy for an electron in orbit around the nucleus. This state is stable; it is the ground state. At higher energies above the ground state are a discrete series of energies which are the excited states.

Atoms can absorb light, gaining energy, and they can also radiate energy away by giving off light. Bohr next postulated that these processes happen when the electron jumps between the stationary states. To describe these jumps, Bohr made use of Einstein's photon hypothesis. When an electron jumps down from an excited state to the ground state, it gives off a photon. That photon has an energy equal to the difference in energies of the two states, so that the total energy is unchanged. It has a specific frequency, given by Planck and Einstein's relation between frequency and energy.

If you reverse this process you can cause an electron to jump from the ground state up to an excited state, by giving it a photon with an energy equal to the difference of the two states.

A given atom can then give up or absorb light only at the special frequencies that correspond to these energy differences between states of its electrons. These special frequencies are called the spectrum of the atom.

By the time Bohr worked this all out, in 1912, chemists had measured the spectrum of hydrogen. Using the ideas I've just described, Bohr was able to calculate the spectrum, and his simple theory reproduced what the experimentalists had seen.

This was a huge step, but it was only a first step toward an understanding of the quantum. There remained many open questions and problems. What is an electron such that it can travel freely outside the atom, but can exist only in one of the stationary states when in an atom? And, most urgently, can the theory be applied to atoms besides hydrogen?

The next decade was taken up by numerous clever attempts to apply Bohr's theory to different atoms and other systems. We can generously say the results were mixed, even as we admire the ingenuity of the attempts. This was the situation by the time a young French aristocrat named Louis de Broglie started graduate school in Paris around 1920.

Louis Victor Pierre Raymond, duc de Broglie, was born of a noble family in the last years of the nineteenth century and studied history before switching to physics. He served in the army during the First World War in the wireless telegraphy section; he was stationed at the Eiffel Tower.

The small world of theoretical physics was then, as it is now, intensely social. During the crucial period when quantum mechanics was being developed, the proponents were continually in touch by letter and postcard, and they made frequent train trips to visit and consult. The aristocrat de Broglie was an outsider to this world by dint of his personality and position, and because Paris was at the time a backwater in theoretical physics. Louis de Broglie spoke regularly about his work with only one person, his brother, Maurice de Broglie, an experimental physicist who worked on X-rays.

Isolation is usually an obstacle for scientists, but sometimes it can lead to someone stumbling on an insight that everyone in the crowd has missed. De Broglie was still a doctoral student when he shook physics to the core by putting forth an audacious hypothesis: that the wave-particle duality is not just a feature of light—it is universal. In particular, electrons, like light, are waves as well as particles.

As he remarked, "When in 1920 I resumed my studies . . . what attracted me . . . to theoretical physics was . . . the mystery in which the structure of matter and of radiation was becoming more and more enveloped as the strange concept of the quantum, introduced by Planck in 1900 in his researches into black-body radiation, daily penetrated further into the whole of physics."[1]

The power of a fresh mind taking a fresh look at a problem is one of the wonders of the world. The young de Broglie had the obvious idea, which had somehow eluded even Einstein and Bohr. They sought to avoid the embarrassment of the wave-particle duality. De Broglie doubled down on it. If light was both a wave and a particle, why couldn't the same be true of electrons? Why not hypothesize that the wave-particle duality applies universally to all matter and radiation?

As de Broglie later recounted it, "As in my conversations with my brother we always arrived at the conclusion that in the case of X-rays one had both waves and corpuscles, thus suddenly . . . I got the idea that one had to extend this duality to material particles, especially to electrons."[2]

What motivated de Broglie to come up with an idea which many more experienced physicists had missed? De Broglie was engaged in an ambitious project to reinvent physics from the ground up to incorporate the wave-particle duality. He started with light, where there was already good evidence for a duality of waves and particles, and asked a simple question few had asked before: How do the light quanta move?

Recall that Newton had favored a particle theory of light because he believed that particles travel in straight lines. The same assumption had led Thomas Young to abandon the particle picture and embrace the idea that light is a wave when he understood that light could bend when diffracted by an obstacle or refracted by passing between two media. It makes sense that if light doesn't travel in straight lines, it is not made of particles. What then of photons? Didn't they have to travel in straight lines? De Broglie's idea was that they don't because they are guided by the waves, which do diffract and refract.

This is stunningly revolutionary. The idea that particles travel in straight lines is a consequence of the most basic principle in all of physics, which is Newton's first law of motion. Also called the principle of inertia, it states that a particle with no forces on it moves at a constant speed in a straight line. One consequence is that momentum is conserved. It is also closely related to the principle of relativity, for another consequence is that velocity is a purely relative quantity.

De Broglie understood that light quanta were going to have to bend around obstacles, violating all these fundamental principles. The goal of his thesis was to formulate a revolutionary new theory of motion, which would apply to the particles contemplated by the wave-particle duality. In this context, it was a small and necessary step to extend the wave-particle duality from light to all forms of matter and energy.

In 1924 he wrote this up as his PhD thesis. The thesis was short and uncompromising. The legend is told that had he not been from the aristocracy, it is possible de Broglie would simply have been failed. Not knowing what else to do, his committee sent the thesis to Einstein to evaluate. Einstein saw de Broglie's point and recommended approval. At the same time, he sent de Broglie's thesis to a few people he knew would be very interested in it.

One of these was his friend Max Born, then a young professor in Germany. An experimentalist colleague of his, Walter Elsasser, heard of it and suggested that de Broglie's prediction that electrons could be diffracted might be tested by scattering a beam of electrons off a crystal. Max Born passed the suggestion to experimentalists in England. None succeeded, but meanwhile two American experimentalists working at Bell Labs, Clinton Davisson and Lester Germer, were, for other reasons, studying how electrons scatter off the surfaces of metals. They accidentally discovered the diffraction of electrons when, in 1925, they tried a new procedure which had the unintended consequence of developing a layer of atoms organized in the regular arrays of a crystal on the surface of their sample. When they measured where the electrons went that scattered off the metal with the crystal surface, they saw interference patterns. Davisson was unaware of the significance of this until he attended a conference in Oxford in the summer of 1926, and happened to listen to a talk by Max Born, who showed a figure from one of Davisson's own papers as evidence for de Broglie's revolutionary hypothesis of matter waves. When Davisson returned, he and Germer went back to the lab and were able to definitively confirm that electrons diffract, just as de Broglie had predicted.

Erwin Schrödinger was a brilliant mathematical physicist, originally from Vienna, who had become a professor at the University of Zurich. Schrödinger was closing in on forty and did not belong to the young generation of de Broglie and the other physicists who were revolutionizing their field. On November 23, 1925, he attended a colloquium by Peter Debye, who gave an enthusiastic presentation of de Broglie's matter wave hypothesis. Debye ended by saying there was one thing missing from de Broglie's beautiful picture: an equation to describe how the electron waves travel in space. Leaving his wife behind in Zurich, Schrödinger took de Broglie's papers with him to a Christmas holiday in the mountains with his girlfriend. (His wife was spending the Christmas holidays with her lover, the great mathematician Hermann Weyl, who was also Schrödinger's best friend.) The first day, he excused himself from skiing, stayed in their chalet room, and read de Broglie's papers. He challenged himself to invent the equation that would govern de Broglie's electron wave. He succeeded the next day, and by the time he returned from the mountains, he had captured the equation that bears his name, the fundamental equation of quantum theory.

Not only that, but, shortly after returning, with the help of Weyl, Schrödinger solved his equation for the case of a single electron in orbit around a nucleus, and reproduced Bohr's theory of stationary states and his prediction of the spectrum of hydrogen. The key idea is that the electron waves have to fit around an orbit, as we see in figure 7. The thoughts of the girlfriend—and, indeed, her name—are lost to history. But legend tells us that when Schrödinger went to Stockholm to receive his Nobel Prize he showed up with his wife and their girlfriend.

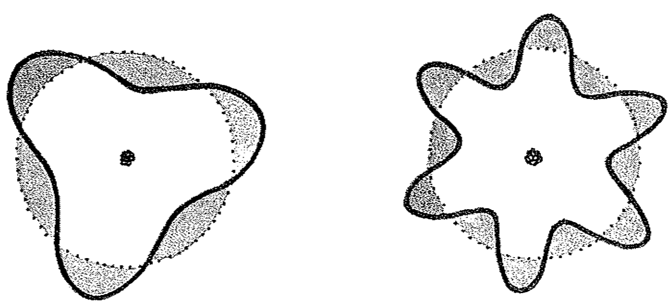

FIGURE 7. Electron waves in the atom. The wave on the left fits around the nucleus in three steps, so the wavelength is the diameter of the atom divided by three. The right figure has half the wavelength and so fits around in six steps.

Thus quantum mechanics was born. The question everyone then faced was how to think of the electron wave that de Broglie had invented and Schrödinger had tamed. Schrödinger at first thought that the electron simply is a wave. This didn't hold up because it was easy to show that the wave tended to spread out in space as it traveled, whereas one could always find a localized particle. Max Born then proposed his rule that the wave is related to the probability of finding the particle.

For Einstein, the wave-particle duality, while a profound challenge, had been limited to speculation about the constitution of light. Confined to that domain, it did limited damage, perhaps because particle and wave theories of light each had long histories and recognized virtues. But the idea of matter waves came as a complete shock. De Broglie and Schrödinger transformed physics by bringing the wave-particle duality into the core of physics, where it sat enshrined as the central mystery of the revolutionary new quantum physics.

The question was no longer "How can light be both a particle and a wave?" but rather, "How can *everything* be both a particle and a wave?"

Einstein, who had been the first to formulate the wave-particle duality, was stumped. Despite, by his own admission, spending far more time on quantum physics than he ever did on relativity, he was unable to make a convincing move. His peerless intuition failed him, and it is worth wondering why. Perhaps his realism, his demand for complete conceptual clarity, held him back.

Schrödinger also was, for a time, at a loss. As were most others.

Of the great pioneers, only Bohr knew what to do. It was his moment and he seized it, announcing the birth not just of a new physics but of a new philosophy. The moment for radical antirealism had come, and Bohr was ready for it.

Bohr called the new philosophy *complementarity.* Here is how he talked about it: Neither particles nor waves are attributes of nature. They are no more than ideas in our minds, which we impose on the natural world. They are useful as intuitive pictures that we construct from observing large-scale objects such as marbles and water waves. Electrons are neither. Electrons are microscopic entities that we cannot observe directly, and so we have no intuition about them. To study electrons we must construct big experimental devices to interact with them. What we observe is never the electron itself; it is only the responses of our big experimental devices to the tiny, invisible electrons.

To describe how the experimental devices respond to electrons, we may find it useful to employ intuitive pictures such as the wave picture or the particle picture. But we cannot take these pictures too seriously because different experiments require different pictures. The different pictures would contradict each other if we forgot the context and applied them to the electrons themselves. But there is no actual contradiction so long as we remember two things. The pictures are useful only as a description of an electron in a specific context, which is in a particular experimental device. And there is no experimental device that forces us to apply both contradictory pictures simultaneously.

Bohr's position is anti-realist in the extreme, in that he denies it is even possible to talk about or describe an electron as it is in itself, outside the context of an experiment we construct. Science according to this picture is not about electrons; it is about how we talk about our interactions with them.

For Niels Bohr, complementarity was more than a principle; it was a proposal for a whole philosophy of science. And what a radical proposal it was. Bohr championed the philosophy of complementarity throughout his life, as did other founders of quantum mechanics, including, to some extent, Heisenberg.

For Bohr, science is not about nature. It does not and cannot give us an objective picture of what nature is like. That would be impossible, because we never interact with nature directly. We gain knowledge about the natural world only through intermediaries, which are experimental devices we invent and construct.

Thus, we must give up the idea that science gives us an objective description of nature, or has anything at all to say about what nature is like, absent our existence and our interventions. Science is rather an extension of a common language we use to describe to each other the results of our interventions into nature.

In essays and books, Niels Bohr argued that his philosophy of complementarity had wide applicability. It has been claimed he got the idea of complementarity from the Kabbalah, the Jewish mystical writings, which speak of the complementarity between God's love and God's justice. Bohr talked about the complementarity between life and physics, between energy and causation, and, indeed, between knowledge and wisdom. For Bohr the lesson of quantum mechanics was a revolution that extended beyond physics, beyond science.

One reason quantum mechanics captured the interest of the younger generation of physicists was that it could be approached from several points of view. I have so far told the story of one way the quantum theory was invented, centering on the wave-particle duality, but there was another route, which had been discovered shortly before Schrödinger took his Christmas holiday. This was pioneered by Werner Heisenberg, a young and very confident German theorist, who completed his education in Max Born's group in Göttingen and then in 1925 went on a research fellowship to work in Copenhagen with Bohr. He spent the next several years bouncing between Göttingen and Copenhagen, which is to say he was in close touch with the two most dynamic scientific personalities of that moment, Born and Bohr. Max Born and several of his students and assistants also played important roles in the story; indeed, the full story of how quantum mechanics was invented involves at least half a dozen theorists, in frequent communication.

Heisenberg worked from a particular idea about physics, an idea that was anti-realist to begin with. He asserted that physics does not give a description of what exists, as realists suppose, but is only a way to keep track of what is observable. For large-scale objects, we have gotten used to confusing the two. But if we want to make sense of atomic physics, we must adhere strictly to the dictum that science can only refer to what can be observed.

Hence, Heisenberg asserts that it is meaningless to talk about how the electron moves in the atom, unless that motion has consequences which can affect large-scale measuring devices. According to Bohr's model, an atomic electron spends most of its time in stationary states, during which it has no interaction with anything outside the atom. It is then meaningless to ask how the electron moves while it is in a stationary state. It is only when it jumps between stationary states that the atom can interact with the world outside, because the jump is accompanied by the absorption or creation of a photon, and that photon's energy can be measured by a spectrograph.

Heisenberg's admonition not to try to model the trajectories of electrons in stationary states must have come as a breath of fresh air to others of his generation who were spending much of their time in frustrating and ultimately fruitless attempts to do just that.

Heisenberg was inspired by this thinking to invent a new way of representing the energy of the electron. Not by a single number, because to do so would be to claim that the energy is a property of the atom alone. What is relevant for physics is only what aspect of energy affects a measuring device. These are the energies carried by the photons that the atoms absorb or emit when the electrons jump between energy levels. These are the differences between the energies in the different stationary states.

Heisenberg arranged these energy differences as a table of numbers. He then imagined that such tables could represent observable aspects of other quantities, such as the electron's position and momentum. To make a theory he had to do more, which was to find a way to write equations involving these tables of numbers. In the equations of physics we often find ourselves adding or multiplying numbers. He needed to do the same with tables of numbers. So he had to invent rules for how to do this.

As a member of both Bohr's institute and Max Born's research group, Heisenberg was under the influence of two masters with very different styles of work, and the contrast between them undoubtedly stimulated his thinking. But to realize his ideas in detail, he needed isolation, no less than Einstein, de Broglie, and Schrödinger had. Like Schrödinger, he took off on a holiday, in his case to a small island called Helgoland.

Once there, it took him only a few days to take himself on the journey I've just sketched, and to invent ways to write and solve equations with his tables of observable quantities.

He tested his ideas on a simple toy model of an atom, in which the electron is bound by a constantly increasing force, as if on a spring. This was not meant to be realistic, but it was a simple test, because the answer was known, and his method passed. There was only one hitch: he discovered that the order in which he multiplied two tables together matters. In the language I proposed earlier, Heisenberg's tables of numbers don't commute. This is of course not the case for ordinary numbers, and at first this discovery dismayed Heisenberg.

Nonetheless, he wrote up his findings in a paper published at the end of 1925. It was in the introduction to that paper that he announced his program of constructing laws of physics that dispensed with mechanical models describing the trajectories of the electrons and involved only relationships between observable quantities, namely the spectra of light the atoms emit and absorb.

This was a big step, but it was not yet the complete theory. He then returned to Göttingen and worked with Max Born and a brilliant student of his, Pascual Jordan. Born and Jordan were already partway to a new theory, and explained to Heisenberg that his tables of numbers were known to mathematicians as matrices; and they were able to reassure him that the failure to commute was a feature and not a bug. Heisenberg then understood that since the tables/matrices represent a process of measurement, the order does matter—because it matters in which order we make measurements. Together the three theorists then worked out the rest of the new theory, which they named quantum mechanics. A joint paper by the three of them was the first complete statement of the new theory.

Austrian wunderkind Wolfgang Pauli quickly followed up and applied the new theory to find the spectrum of the hydrogen atom, and it came out exactly right. Thus was quantum mechanics born by a second route, and in a way that was directly inspired by the anti-realist principles Heisenberg had expressed in his 1925 paper. The new theory of Born, Heisenberg, and Jordan is expressed in terms of quantities that describe how an atom responds to being probed by an external measurement device; there are no quantities that describe the exact trajectories of the electrons, independent of our interactions with them.

One quantum theory of the atom is great, but two are a problem, especially since they both reproduced the right spectrum of hydrogen. The two theories could not have differed more, as reflects the philosophies of their discoverers. Einstein, de Broglie, and Schrödinger were realists. Even if there were mysteries, they believed an electron was real and somehow existed as both wave and particle. Bohr and Heisenberg were enthusiastic anti-realists who believed we have no access to reality, only to tables of numbers which represent the interactions with the atom, but not the atom directly.

The tension lasted a few months, and then had an unexpected resolution when Schrödinger showed that the two forms of quantum mechanics are completely equivalent. Like two languages, you could speak in terms of waves or talk the language of matrices, but the math problems you had to solve turned out to be just different expressions of the same logic.

Heisenberg and Bohr, together in Copenhagen, shared an anti-realist perspective. They sought a way to speak consistently about properties that could not be realized simultaneously, such as waves versus particles or position versus momentum. Bohr's resolution of the apparent paradoxes was his principle of complementarity. Heisenberg's was his great uncertainty principle, which we talked about in chapter 2.

The uncertainty principle is a very general principle, as it says that we cannot know exactly both where a particle is and with what momentum it is moving. It has, as Heisenberg and his mentor Bohr realized immediately, stunning consequences. One is that the determinism of Newtonian physics cannot survive in the quantum world, because to predict the future motion of a particle you must know both its present position and how fast and in what direction it is moving, and hence its momentum. If you cannot know both precisely, you cannot predict where the particle will be at later times. As a result, the best that quantum theory can do is to make probabilistic predictions about the future.

The consistency of complementarity depends on there never being a case where we are forced to use both the particle picture and the wave picture in the description of a single experiment. The impossibility of doing so is safeguarded by Heisenberg's uncertainty principle, which he proposed in 1927, after he had moved back to Copenhagen and was in close contact with Bohr.

Historians tell us that luck plays a big role in science. Heisenberg was doubly fortunate for, as the protégé of both Max Born and Niels Bohr, he was not just in the right place at the right time, but doubly so! From his mentor Bohr he was inspired to abandon realism and model the atom only in terms of the energies it exchanges with our measuring devices, and from his mentor Born he got the mathematical tools needed to give these ideas a precise expression.

Of course, Heisenberg knew his good fortune and was the one who pushed to frame the new theory precisely. There were perhaps half a dozen young theorists who were also in the orbits of Bohr and Born, who contributed pieces, like Pauli, or got partway there, like Jordan, or were a few months late and so got to elegantly frame the new theory, like the English theorist Paul Dirac. The full story of the invention of the matrix form of quantum mechanics is far more complex than I can tell here, as it reveals a very dynamic, collective effort of a diverse community of theorists, in close interaction.

Still, diverse as they were, the matrix mechanicians were by 1927 all framing the new theory in terms of the radically anti-realist philosophy that Bohr preached. The only holdouts were those who had come to quantum mechanics through the wave-particle duality, Einstein, de Broglie, and Schrödinger, who stubbornly remained realists. But once it was proved that Schrödinger's wave mechanics was equivalent to Heisenberg's matrix mechanics, the realists could be dismissed as stubbornly grasping on to old metaphysical fantasies, and ignored.

The essence of Bohr's philosophy is the necessity of basing science on incompatible pictures and languages. Heisenberg preached a view which differed in emphasis from Bohr's while being loosely compatible with it. Heisenberg emphasized that science concerns only measurable quantities and can't give an intuitive picture of what is happening at atomic scales. The observable quantities relevant for interacting with an atom include the energies and lifetimes of the stationary states, but do not include the positions or motions of electrons in their orbits around the nucleus. So quantum physics only has to yield an answer to a question of where an electron is if you force it into a context where that position is measured. According to Heisenberg, observable quantities are brought into existence only by the act of measuring them. When an atom is free of a measuring apparatus, no quantity describes it.

This may be called an *operationalist perspective.* It is certainly anti-realist, in that Heisenberg stressed that this view is mandatory. There was, according to him, no possibility of seeing deeper into the atom to perceive how the electrons move in their orbits. His uncertainty principle precluded it.

Heisenberg explained that uncertainty and complementarity were closely connected.

> We can no longer speak of the behavior of the particle independently of the process of observation. As a final consequence, the natural laws formulated mathematically in quantum theory no longer deal with the elementary particles themselves but with our knowledge of them. Nor is it any longer possible to ask whether or not these particles exist in space and time objectively. . . .
>
> When we speak of the picture of nature in the exact science of our age, we do not mean a picture of nature so much as a *picture of our relationships with nature.* . . . Science no longer confronts nature as an objective observer, but sees itself as an actor in this interplay between man and nature. The scientific method of analyzing, explaining and classifying has become conscious of its limitations, which arise out of the fact that by its intervention science alters and refashions the object of

investigation. In other words, method and object can no longer be separated. . . .

[T]he different intuitive pictures which we use to describe atomic systems, although fully adequate for given experiments, are nevertheless mutually exclusive. Thus, for instance, the Bohr atom can be described as a small-scale planetary system, having a central atomic nucleus about which the external electrons revolve. For other experiments, however, it might be more convenient to imagine that the atomic nucleus is surrounded by a system of stationary waves whose frequency is characteristic of the radiation emanating from the atom. Finally, we can consider the atom chemically. . . . Each picture is legitimate when used in the right place, but the different pictures are contradictory and therefore we call them mutually complementary.[3]

Bohr's point was even more radical. For him,

An independent reality in the ordinary physical sense can . . . neither be ascribed to the phenomena nor to the agencies of observation. . . .

A complete elucidation of one and the same object may require diverse points of view which defy a unique description. Indeed, strictly speaking, the conscious analysis of any concept stands in a relation of exclusion to its immediate application.[4]

Other quantum luminaries, such as Wolfgang Pauli, a wunderkind who published a textbook on general relativity when he was twenty-one, and John von Neumann, a Hungarian mathematician who is famous for his inventions in a broad range of fields, from the architecture of computers to the mathematics of quantum theory, taught variants of these anti-realist philosophies. Their views differed in emphasis, but anything written by them was classified as part of the "Copenhagen interpretation" of quantum mechanics. This name recognized Bohr's dominance as the oldest of the group and mentor to most, as well as the originator of nothing less than a new way of talking about science. The name also recognized Bohr's institute as the central node in the network of quantum physicists, where they all studied, worked, or visited.

One of the hardest lessons to learn in academic life—and for me one of the most disconcerting—is the speed with which a radical insurgency can become orthodoxy. In just a few years a generation of students championing a dangerous new idea are elevated by an initial success into professorships. From these positions of influence they form a powerful network of academic power brokers, which they use to ensure the continuation of the revolution. Such was the case with the generation of quantum revolutionaries. In 1920 Heisenberg was a student, as were Dirac, Pauli, and Jordan; 1925 found them young researchers fully engaged in the invention of quantum theory; by 1930 they were senior professors, and the revolution was over. The fact that there remained a handful of defectors—Einstein and Schrödinger from the older generation, and de Broglie among their contemporaries—did nothing to diminish their triumph, for students knew which way the wind blew and followed the ascendant orthodoxy. For the next half century, the anti-realism of the Copenhagenists would be the only version of quantum theory taught.