First Steps of Quantum Theory Developments

The Bohr Atom:

Niels Bohr's early work concerned the application of Lorentzian electron theory to metals and conductance. While completing his dissertation on the subject in 1911, he became convinced that existing theories were insufficient and that a new model, probably based in the new quantum hypothesis, was needed. He travelled to England in order to work with J. J. Thomson, the established authority on electrons and atomic theory. Disappointed with Thomson's lack of interest in his ideas, Bohr was instead inspired by Ernest Rutherford, recently returned from the Solvay Conference. Returning to Copenhagen, Bohr abandoned his earlier work and set out to improve Rutherford's atomic model by using quantum theory to stabilize electron orbits. While working on this problem, a colleague casually asked him how it related to the Balmer formula for hydrogen spectra. Unexpectedly, Bohr realized he could explain both atomic stability and hydrogen's spectral lines through the same model. His key insight was that the orbital frequency of the election (ω) was not equal to the frequency of the emitted spectral lines (f), as was commonly assumed.

Bohr's model of 1913 was criticized for its strange theoretical assumptions (how does the electron "know" which energy levels are stationary states?), but its incredible agreement with observations made it difficult to argue against, and most critics chose to accept the model. Further progress was slowed by World War I, but important contributions were made, especially by Arnold Sommerfeld. Sommerfeld explored the possibility of elliptical electron orbits (which seemed to be allowed by the theory), introduced special relativity into the Bohr model, and used these to explain fine structure splitting. While Bohr understood his model as a preliminary step before a fuller understanding of quantum mechanics could be achieved, he and Sommerfeld were incredibly successful at explaining various phenomena under a single framework.

Physics and International Politics:

The 1920s were a difficult time for Germany. After its defeat in 1918 and transition from a German Empire to the new Weimar Republic, Germany faced an economic slump, food shortages, political unrest, and massive inflation that did not stabilize for several years. Despite many challenges, these years were incredibly productive for German physicists and saw some of the most important advances of modern physics.

The international situation made cooperation with non-German physicists difficult. International organizations such as the new International Research Council (IRC) restricted membership to Allied countries, only accepting neutral countries (such as Denmark) in 1922 and Germany in 1925. German physicists were largely excluded from international conferences until the late 1920s and German-language publications often went untranslated. On top of this, Germany's economic situation further impeded cooperation: with rampant inflation, it was difficult for Germans to import the latest foreign publications or travel abroad in order to keep up to date with current research elsewhere.

This divide between German and Allied physicists was never total (Einstein was accepted by both communities, and Bohr, as a neutral Dane, was more respected in the West than his German colleagues), but it harmed physics as a whole. German and Danish physicists formed a mostly self-contained community where important ideas from the English- and French-speaking world (such as de Broglie's matter waves) had little impact until the international situation improved toward the middle of the 1920s. The rest of this week will cover these self-contained advancements in the German community, which focused on energy transitions in the hydrogen atom and produced the first version of quantum mechanics in 1925. Next week will follow advancements outside of this community, which tended to give more emphasis to the wave-particle duality and led to Schrodinger's version of quantum mechanics in 1926.

Physics and Weimar Culture:

German culture in the 1920s was hostile to the physics community. During the war, scientists had enjoyed public status and prestige as an important component of the militarized society. After the defeat, much of the German public saw science as the cause of the disastrous war and subsequent crisis. There was a general feeling that German culture had lost its soul as rational science had replaced the music and poetry of the past. Interest in artistic icons such as Goethe and Mozart increased at the expense of interest in physics. This zeitgeist was expressed in Oswald Spengler's best-selling book *The Decline of the West*, which claimed that science only had value relative to its particular culture and that physics needed to abandon "outdated" concepts like strict causality and determinism in order to keep up with the times. These anti-rational streams of thought had long been a feature of German culture (for example, in the 19th century Romantic Movement), but they resurged dramatically in the atmosphere of crisis after World War I.

While a few physicists (most notably Planck and Einstein) responded to this hostile environment by reasserting the value of classical physics and defending the discipline from criticism, many German scientists seemed to capitulate to these views in their public addresses. Physicists tended to highlight connections between physics and philosophy while downplaying their association with technology. They admitted that physics' power to describe abstract ideas like the human spirit was limited and portrayed physics research as being for its own sake, rather than utilitarian usage. Most significantly, physicists began arguing that concepts like strict determinism and cause and effect might have to be abandoned, in line with Spengler's analysis.

Exactly why German physicists acted this way is not entirely settled. In 1971, the historian of science Paul Forman made the controversial argument that physicists basically capitulated to the 1920s culture and accepted the need for acausality; thus, when the probabilistic nature of quantum mechanics was discovered, German physicists were generally willing to accept it quickly. In other words, forces outside of science shaped the direction that quantum physics took in a direct cause-and-effect relationship. Other historians have challenged this view as focusing too much on external rather than internal motivations away from causality. For example, John Hendry has argued that physicists were already considering abandoning concepts like determinism and strict conservation of energy before the cultural backlash; in this view, internal rather than external forces pushed physicists toward acausality.

Heisenberg's Quantum Mechanics:

Regardless of the degree to which Forman was correct, by the mid-1920s there was an atmosphere of crisis both in the physics community and German culture at large. While the Bohr model was very useful through the 1910s, its deficiencies could no longer be ignored: it offered no explanation for the intensity or polarization of light emitted in transitions and could not be used at all in describing atoms larger than hydrogen or chemical bonds. The most pressing issue was fine structure splitting due to the anomalous Zeeman effect, which would not be fully explained until the discovery of electron spin.

In early 1924, Bohr, his assistant Hans Kramers, and the American John Slater published a paper outlining what has become known as BKS theory. Although Compton scattering had been discovered in 1923, demonstrating that photons behave like particles, Bohr was committed to the wave theory, and formulated BKS theory as a final effort to explain energy transitions without light particles. The theory attributes the frequencies of light emitted during a transition to virtual charges oscillating with the required frequency and intensity. However, without photons to induce transitions, the theory abandoned strict cause and effect and energy conservation in order to preserve the wave theory. BKS theory enjoyed popularity for a few months, until experimental evidence demonstrated that transitions strictly obey energy conservation.

At this point, when all existing theories had been shown to be imperfect, Heisenberg arrived at the key breakthrough which led to the resolution of quantum theory. Everything discussed so far in this history is often called the “old quantum theory,” while Heisenberg’s advances of 1925 truly began “quantum mechanics.” Inspired by BKS theory, Heisenberg chose to do away with any description of electron orbits or positions and instead focus solely on observable quantities. His work, along with additions from Max Born and Pascual Jordan, is usually called matrix mechanics to distinguish it from Schrodinger’s wave-based quantum mechanics. The final theory expressed the probabilities of transitions between stationary states in a matrix consisting of the amplitudes of the terms of a Fourier series that describes an electron’s periodic motion. This formulation was highly abstract and relied on obscure matrix calculus, but it described hydrogen satisfactorily. With the addition of electron spin, discovered the same year, matrix mechanics provided the most powerful description of quantum phenomena yet. While Schrodinger’s version of quantum mechanics is the more widely-used formulation, Heisenberg’s work is one of the key turning points in the history of quantum theory.

Key Ideas:

- The controversy around the Forman thesis demonstrates the difference between internalist and externalist histories of science. Forman’s argument was radically externalist, in the sense that the entire course of quantum theory was determined by factors outside the physics community. Hendry’s position is more moderate: while he accepts that factors from society at large may have influenced physicists, he argues that the primary reason physicists moved away from causality was that physical evidence pointed in that direction. Resolving this tension between external and internal explanations is one of the key tasks of historians of science.
- Another example of an externalist explanation comes in the influence that international relations had on physics. The fact that German and French physics were largely cut off during the early 1920s meant that de Broglie’s hypothesis had a delayed reception in the mainstream physics community. Had external social conditions been different, Bohr and Heisenberg may have realized the importance of wave-particle duality earlier and developed their ideas differently. The aftermath of WWI was not the only factor that shaped the course of quantum mechanics, but I would argue that evidence indicates that it is one of several important factors.
- Relativity, as we have seen, was almost entirely the work of a single individual, whereas quantum mechanics was formed through the interactions of many physicists. The advances discussed this week were facilitated by personal correspondences and visits to other universities. The primary centers of research were Copenhagen, where Bohr and

Kramers worked, Munich, where Sommerfeld was chair of the physics department, and Göttingen, where Born served as a mentor for Heisenberg, Pauli, and Jordan. These physicists frequently travelled between these universities and collaborated on papers. The dynamics of how relativity and quantum theory spread and developed followed distinct patterns of social interaction, with quantum developments being helped by the existing university structure.

- Beginning in the 1920s, many of the most important advances in quantum theory were made by very young physicists: Heisenberg, Pauli, Dirac, and Jordan were all in their 20s during this period. Older physicists continued to play an important role, often as facilitators of cooperation in addition to researchers. Famous theorists of the previous generation, such as Bohr and Born, helped their students by spreading awareness of their theories and arguing for their importance. Their existing prestige and credibility helped establish Heisenberg and Pauli in the physics community. Others, such as Planck, moved farther away from involvement in research, acting as elder statesmen facilitating university research at a higher level.

Waves and Particles:

Although Einstein had certainly established his reputation as a leading physicists by the 1920s, his particle theory of light outlined in 1905 took many years to be taken seriously. The wave description of light had been a central feature of classical physics since the early 1800s and could be demonstrated using a simple double-slit setup. Even when Einstein's photoelectric predictions were confirmed with reasonable accuracy, most experimentalists were unwilling to accept the underlying explanation of wave-particle duality: Millikan, who performed the decisive experiments confirming the photoelectric equation in the mid-1910s, claimed that the mathematical relationship had been inarguably confirmed but argued just as strongly that the underlying explanation of light quanta could not be accepted.

The early 1920s saw renewed interest in light quanta. First, Einstein received the 1921 Nobel Prize specifically for his work on the photoelectric effect, lending some extra prestige to the wave-particle theory. Also important was Arthur Compton's 1923 discovery of Compton scattering, attributing definite momentum to light. Even with this demonstration of particle behavior, some theorists held out for several years. The German community discussed previously was especially hostile to any wave-particle model of light, leading to the BKS theory's sacrifice of strict energy conservation in favor of wavelike light. By 1924, the community as a whole had yet to reach agreement on the wave-particle problem.

De Broglie's Thesis:

Louis de Broglie began his research career by assisting his older brother Maurice with data analysis. In 1921, the older de Broglie presented his work on X-ray diffusion and concluded that radiation must be absorbed or emitted from atoms in finite quanta. Although this did not resolve the issue to the community as a whole, it convinced Louis of the importance of the wave-particle model. Revisiting Einstein's 1905 paper, de Broglie's early publications claimed that light quanta have mass and thus travel at slightly less than c. He theorized "light molecules" or agglomerations whose interactions would explain interference. However, his most important step, made in his dissertation in late 1924, was an attempt to link special relativity with quantum theory and produced the equation $mc^2=hf_0$. This suggests that all massive particles (including light, in this model) have a characteristic frequency f_0 in their rest frame. Although he was vague as to the specific meaning of this frequency, he was confident that matter waves had physical significance: they could explain the energy levels of the Bohr atom and predicted electron interference as a falsifiable test. The dissertation extended wave-particle duality beyond disagreements on the nature of light and first suggested a more fundamental unity between light and matter.

Einstein was the first to argue for de Broglie's significance. In 1924, Einstein was collaborating with the equally-unknown Satyendra Nath Bose on quantum gas theory and establishing Bose-Einstein statistics. Working out the specifics of Bose's new method of counting particles, Einstein found that the number of particles within a partial volume would fluctuate according to similar laws of radiation fluctuation. This suggested interference between particles and thus a wave-particle duality. At this point, Einstein received an advance copy of de Broglie's thesis from Paul Langevin, one of the thesis' judges. Einstein realized its importance to his statistical methods and began arguing its significance to his colleagues. Schrödinger, Born, and most other physicists heard about de Broglie through Einstein.

However, even with Einstein's help, matter waves had little influence in Copenhagen and Göttingen. This was partly due to continuing poor relations between France and Germany and the difficulty of translating discoveries in physics across the gap. Also important was the influential Bohr's aversion to any theory on wave-particle duality. De Broglie's poor understanding of spectroscopy (the most significant problem for German physicists) and some condescending remarks about Sommerfeld and Heisenberg certainly did not help his reputation. Although Heisenberg was likely at least aware of de Broglie's thesis when he first formulated quantum mechanics, it is unlikely that he was influenced by the idea.

Schrödinger's Equation:

Schrödinger, however, was an outsider to the mainstream German physics community. An Austrian working in Switzerland, he was known as a loner and did not align himself with any school of thought within quantum theory, working on a variety of problems over time. Like Einstein, he was working on gas theory in 1925 and thus came to appreciate de Broglie's significance. In particular, de Broglie's use of matter waves to model hydrogen's energy levels shared a mathematical similarity to an earlier theory of Schrödinger's from 1922: using Hermann Weyl's work on general relativity, Schrödinger concluded that, if an electron carries an associated four-vector (derived from Weyl's theory) as it orbits an atom, the value of this vector will be multiplied by an integer value every time it completes a revolution. With some modifications, this bears similarity to de Broglie's condition of electrons as standing waves. By 1925, Schrödinger had abandoned this work on atomic modeling; after Einstein introduced him to de Broglie's ideas, he returned to the hydrogen atom to describe it using matter waves.

After failing to construct a working relativistic wave equation (now known as the Klein-Gordon equation), Schrödinger published his work in several papers that appeared early in 1926. These provided several derivations of his equation (the most famous being an extension of Hamilton's analogy between mechanical and optical motion to quantum theory) and demonstrated its power at solving existing quantum problems. In his original interpretation, Schrödinger considered the square of the wave function to be a measure of charge density distributed over space. At this point, there was nothing probabilistic about the Schrödinger equation.

Almost as important as the equation itself was Schrödinger's rigorous proof that his and Heisenberg's versions of quantum mechanics are mathematically equivalent (Schrödinger later claimed that he had been aware of Heisenberg's work while developing his equation but was unaffected by it). Immediately after Schrödinger's publication, the physics community was split over whether to accept matrix or wave mechanics—both gave the correct answers, but their forms were so different that establishing a connection between them was difficult. With the demonstration that both were equally legitimate, the community was free to choose the version it preferred. Schrödinger's equation quickly became the more popular: it relied on a well-known mathematical basis (rather than the obscure matrix calculus), making calculations simpler, and it was easier to visualize electrons as waves rather than as abstract matrices. Despite some animosity between Schrödinger and the Copenhagen/Göttingen physicists, the community as a whole accepted wave-particle duality and moved on. With a mathematical basis established, the next step in developing quantum mechanics was interpreting exactly what the wavefunction meant and what it implied. This led to the construction of the Copenhagen interpretation beginning around 1927.

Key Ideas:

- As was the case with matrix mechanics (see last week's summary), Schrödinger's wave mechanics was the product of communication and collaboration between physicists. However, collaboration took a different form in the two theories: in the matrix mechanics case, cooperation took place within the existing structure of the universities and was facilitated by formal research groups and semesters abroad. The key physicists who developed wave mechanics were more spread out (as far as India, in Bose's case), and communicated through unofficial channels such as private letters. In both cases, sharing ideas was necessary to the development of quantum mechanics.
- Between these two communities developing quantum mechanics, we can see both hostility and cooperation. Heisenberg was initially upset that Schrödinger's method had become the standard despite being published later. Both thought that other was emphasizing the wrong fundamental principle in their derivation (Heisenberg focused on observable quantities; Schrödinger focused on created a visualizable model). However, both groups made important contributions to the fully realized quantum mechanics. While Schrödinger's mathematical notation became accepted, the former developers of matrix mechanics provided the theoretical interpretations used today (Born's probability density, Heisenberg's uncertainty principle, and Bohr's complementarity). In this sense, quantum mechanics was the product of a single, unified community of physicists.
- De Broglie was an exception among physicists in many ways: he was French at a time when Germany (and to a lesser extent England) dominated the sciences, he was originally trained as a historian, and he was an aristocrat. Louis and several of his siblings expressed interest in science in their youth: Maurice, as mentioned, worked on x-ray experimentation, while their sister Pauline became interested in geology and archaeology. This went against the wishes of their relatives, who wanted the youths to take more traditional aristocratic professions such as diplomacy or banking. This unusual status between social classes meant that Louis' place within the scientific community was uncertain; when he, like Einstein, objected to the Copenhagen interpretation and indeterminism, de Broglie's criticisms carried less weight and were easier to ignore.
- Since its publication, de Broglie's 1924 thesis has been celebrated to the point of developing a mythology around it. Calling it "the most important thesis of the 20th century" is certainly appropriate, but the anecdotes surrounding it can be questioned. I have found no evidence that it really was the shortest physics thesis ever written; at roughly 70 pages, it does not seem likely. The story of Langevin giving the thesis to Einstein for judgment is probably true, but many sources leave it out entirely as if it never

happened. These anecdotes surrounding the thesis should at least be taken with a grain of salt.

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