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 electron ($\omega$) 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
Bohr and the German Physics Community

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 Schrödinger’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 resurfaced 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 Schrödinger’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 Schrödinger’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.

Bibliography: