Quantum Theory before World War I

Fin de Siècle Physics:

It is sometimes casually claimed that physicists at the end of the 19th century believed they were approaching the end of their discipline and that there was nothing left for them to discover. While there may be a few who believed this (as a student, Max Planck was discouraged from pursuing physics because its basic structure was already in place), the 1890s in particular were an important period of discovery that foreshadowed the advances of 20th century physics.

The most famous event of the decade was Wilhelm Röntgen's discovery of x-rays in 1895. Both physicists and the general public were fascinated by the unexplained rays, which seemed to behave differently from both visible light and cathode rays. Röntgen himself suggested that they might be longitudinal ether vibrations (as opposed to the transverse vibrations of regular electromagnetic waves). The matter was not settled until the early 1910s, when evidence such as crystal diffraction showed that x-rays are simply high frequency EM waves. Inspired by Röntgen, Henri Becquerel began investigating other sources of rays and discovered what he called "uranium rays." Later, Marie Curie showed that these rays emit from compounds other than uranium and renamed the phenomenon "radioactivity." These discoveries inspired others to seek out new varieties of rays, most of which do not actually exist. Black light, N-rays, and magnetic rays were all considered as possibilities. The existence of cosmic rays was also doubted until they were observed in the 1910s.

The 1890s also saw important progress in knowledge of the electron. Early electron theories, such as proposed by Hendrik Lorentz and Joseph, thought of the electron as the physical manifestation of the ether and the fundamental constituent of matter. Such a worldview would unite all known areas of physics under the common basis of electromagnetism and the ether. Pieter Zeeman's 1896 discovery of the influence of a magnetic field on light (the Zeeman Effect) established more definite physical characteristics of the theoretical electron, such as its negative charge and high ratio of charge to mass. The next year, J. J. Thomson demonstrated that cathode rays are composed of negatively charged particles with a constant charge/mass ratio. These two lines of research, theoretical and experimental, were pursued separately, but by 1900 they established the electron as a negative particle of small mass that was either the sole fundamental particle or one of several.

Planck and Quantum Theory:

During the 19th century, Max Planck's main interest was in thermodynamics. In particular, he saw the second law of thermodynamics as a fundamental feature of nature rather than a statistical trend. In contrast to Ludwig Boltzmann, whose statistical mechanics predicted that the entropy of a system could occasionally decrease, Planck took as a first principle the fact that entropy increase was a strictly unidirectional process. In 1899, he derived Wilhelm Wien's blackbody radiation distribution from this assumption, which seemed to agree with experiment. When it was discovered that the Wien distribution was incorrect for long wavelengths, Planck slightly modified his derivation and came up with the famous Planck distribution in 1900. While the new results matched observations very closely, he saw this derivation as unsatisfactory, as it was more mathematical guessing to fit the facts rather than an explanatory theory. Later that year, he announced that his distribution only made sense if the total energy of the blackbody was divided into several finite portions of energy $\varepsilon = hf$.

Historians have debated exactly what Planck thought of his work in 1900. Some have argued that he did not think his equation had any definite physical meaning and that it was only a temporary mathematical construction. Others believe that he recognized that his work implied energy discontinuity but was unwilling to accept this result fully. In any case, it is clear that Planck took a conservative, cautious approach to physics and that he did not see his distribution as particularly revolutionary. He did not move forward exploring the implications of energy discontinuity or the new constant h; instead, he spent much of the next decade fleshing out the dynamics of special relativity.

It is also worth noting that the so-called “ultraviolet catastrophe” played little role in Planck’s theorizing. Using the classical equipartition theorem (which states that the energy of a system will spread evenly across all degrees of freedom) results in the Rayleigh-Jeans distribution of blackbody radiation. Unlike the Wien distribution, this law broke down at short (ultraviolet) wavelengths, where it gave infinite energy. Eventually, Lorentz proved that his ether-based electromagnetic theory necessarily led to the incorrect Rayleigh-Jeans distribution. This was the context of the ultraviolet catastrophe: there was no way to explain the blackbody distribution if physical reality reduced to a fundamentally electromagnetic basis. For Planck, with his worldview instead based in thermodynamics, the Rayleigh-Jeans distribution was less important.

Einstein and Quantum Theory:

The first of Einstein’s 1905 papers is usually referred to as “the photoelectric effect paper,” but this does not convey its extent or how thoroughly it departed from contemporary ideas. Einstein began his paper by noticing the inelegant contrast between discrete matter and the continuous electromagnetic field, and aimed to resolve it by suggesting that light is composed of corpuscles rather than waves. This contradicted years of evidence in favor of wavelike light, but Einstein pointed out that the wave theory inevitably led to incorrect results for the blackbody problem. He derived an expression for the entropy of blackbody radiation and noted that it had the same mathematical form as the entropy of an ideal gas. By analogy, Einstein reasoned that, as gases are composed of discrete molecules, blackbody radiation is quantized in packets of energy $E = hf$. He then suggested using the photoelectric effect to test the implications of this new model of light, predicting the effects of varying the light’s frequency. These predictions were confirmed by Robert Millikan in 1914 (although Millikan refused to accept the theoretical basis of Einstein’s work).

Although Einstein mentioned Planck’s distribution formula, he made few direct references to Planck in the 1905 paper. In fact, Einstein probably believed in 1905 that he and Planck were working from different theoretical bases that contradicted each other. In a 1906 paper, Einstein reconsidered his and Planck’s ideas and concluded that Planck’s assumptions in creating his distribution also imply the existence of light quanta.

Early Growth of the Quantum Theory:

In the early 1900s, blackbody radiation was a specialized branch of physics that concerned few physicists. Because of this, quantum theory made little impact until it was applied to other subjects. In 1907, Einstein extended his ideas into solid-state physics by using quantized energy to explain irregularities in the specific heats of different elements. This was a much more mainstream field and introduced new physicists to quanta, while also suggesting quantum theory's eventual use in atomic structure and chemistry. Another important step came in 1908, when a lecture by Lorentz demonstrated that classical electromagnetism would only lead to the incorrect Rayleigh-Jeans distribution (as mentioned above), convincing his followers that Planck's distribution was the only way forward.

The specific heat problem introduced quantum theory to German physicist Walther Nernst, who became convinced of its importance and played an important part in its general acceptance. Nernst convinced the philanthropist Ernest Solvay to hold a conference on the new quantum theory summing up its relationship to radiation and gas theory. The Solvay Conference, held in November 1911 in Brussels, brought together Lorentz, Planck, Curie, Einstein, Rutherford, and other leading physicists in a discussion on quantum theory's progress thus far. The meeting did not lead to any new breakthroughs or insights (a fact which annoyed Einstein), but helped focus attention on the breadth of problems related to quantum theory. It also transformed quantum theory into a community project recognized by the mainstream of physics and gave the sense that it was a revolutionary departure from older physics. Many historians have argued that the concept of "modern physics" was created at the Solvay Conference.

Key Ideas:

- A large portion of this week's historical narrative is focused on misconceptions and confusions about the early history of quantum theory: late 19th century physics was not stagnant, Planck did not begin a scientific revolution, and exactly what he and Einstein thought at given times is not entirely clear. This is understandable, as a lot of the work done before 1920 became obsolete after fuller quantum mechanical theories took shape. It feels less pressing to understand exactly how these theorists understood their physics. Also, many of the exciting aspects of quantum theory (the uncertainty principle, the Bohr-Einstein debates, nuclear fission) came later; compared to them, blackbody radiation is less glamorous. Because of this, historical research in this area is less robust than that of relativity or later quantum theory.
- One of the key ideas made obsolete by quantum theory was the electromagnetic worldview (or "electron theory," in Lorentz's terms), which appears occasionally in the history above. As mentioned on the first week, the late 19th century saw physicists trying to unify the entirety of nature under a single physical framework. The electromagnetic worldview, usually associated with Hendrik Lorentz and Joseph Larmor, aimed to explain all the different areas of mechanics using electromagnetic waves and the ether. In this view, electrons were discrete manifestations of the continuous ether; thus, if electrons were the only fundamental particle, there would be no physical reality except for the electromagnetic ether. This simple, elegant formulation of nature is tempting; it might be compared to more recent unified theories that attempt to unite the four fundamental interactions. As time went on, however, it became clear that natural phenomena required quantum as well as electromagnetic explanations.
- It is easy to pinpoint 1905 as the beginning of relativity, but finding the exact beginning of quantum theory is not as simple. Although 1900 is the most common date given, physicists did not realize that Planck's work constituted a definite break with classical theories until several years later. The shift from classical to modern physics did not happen all at once, but was a more gradual process as different physicists added individual components to quantum theory and realized that their work was a complete departure from 19th century traditions. This is one reason why the Solvay Conference is

important: despite not seeing any new scientific breakthroughs, it helps convince its participants that significant historical changes were happening.

- A wide range of phenomena require quantum theory to understand fully, including radioactivity, the blackbody distribution, the photoelectric effect, specific heats, and atomic structure. Part of the difficulty in constructing a unified quantum theory was recognizing that all these problems share underlying features. Thus, many of the important steps in early quantum theory involved physicists crossing between different problems and drawing connections between them. This is most apparent in Einstein’s work with photons and in the Solvay Conference. After this event, progress towards quantum mechanics moved much more smoothly as physicists recognized the need for a unified approach to quantum phenomena.
- A few weeks ago, I argued that the 1919 confirmation of general relativity saw unprecedented media attention to a discovery in physics. This is not entirely true, as Röntgen’s discovery of x-rays also began a media frenzy that was unusual for the time. That said, the scale of relativity’s impact was much greater than that of x-rays. In addition, Einstein became a worldwide celebrity along with his theory, while Röntgen remained relatively unknown outside the world of physics.

Bibliography:

Heilbron, John L. *The Dilemmas of an Upright Man: Max Planck as Spokesman for German Science*. Berkeley: University of California Press, 1986.

Klein, Martin J. “Einstein’s First Paper on Quanta.” *The Natural Philosopher* 2 (1963): 57-86.

Kragh, Helge. *Quantum Generations*. Princeton: Princeton University Press, 1999.

Kuhn, Thomas S. “Revisiting Planck.” *Historical Studies in the Physical Sciences* 14 (1982): 231-252.

McCormmach, Russell. “H. A. Lorentz and the Electromagnetic View of Nature.” *Isis* 61 (1970): 459-497.

Seth, Suman. “Quantum Physics.” In *The Oxford Handbook of the History of Physics*, edited by Jed Z. Buchwald and Robert Fox, 814-859. Oxford: Oxford University Press, 2013.

Seth, Suman. “Quantum Theory and the Electromagnetic World-view.” *Historical Studies in the Physical and Biological Sciences* 35 (2004): 67-93.