Hans Bethe and Quantum Electrodynamics

In 1947 no one knew how to calculate the fine structure of spectroscopic levels of a real electron making transitions in a real hydrogen atom—except Hans Bethe.

Freeman Dyson

From 2 to 4 June 1947, a carefully selected group of distinguished physicists assembled at Shelter Island, a small and secluded spot near the eastern tip of Long Island, to discuss the outstanding problems of physics. This was the first serious meeting of physicists who had played leading roles in World War II and then returned to the pursuit of peaceful science. The Shelter Island Conference succeeded in its purpose: It set the direction for physics for the next 30 years.

The main subject of discussion was the experiment of Willis Lamb and Robert Retherford, who used the tools of microwave spectroscopy, developed during the war for military purposes, to measure the fine structure of the energy levels of the hydrogen atom. The results showed a clear deviation of the observed levels from the predictions of the Dirac theory of the hydrogen atom. Lamb and Retherford measured a quantity that became known as the Lamb shift—the frequency of a microwave field that induced transitions between the lowest two excited states of the hydrogen atom. According to the Dirac theory, the two states should have had equal energy and the Lamb shift should have been zero. Lamb measured it to be 1000 megahertz, with an uncertainty of a few percent. The discrepancy was far outside the limits of possible experimental error.

Many people at the conference, including Victor Weisskopf and Robert Oppenheimer, suggested that the deviation resulted from quantum fluctuations of the electromagnetic field acting on the electron in the atom. Such fluctuations would give the electron an additional energy, called the self-energy. It was well known that the existing theory of quantum electrodynamics (QED) gave an infinite value for the self-energy and was therefore useless. Physics had reached an impasse. On the one hand, the Lamb experiment gave clear evidence that the effects of electromagnetic quantum fluctuations were real and finite. On the other hand, the existing theory of QED gave infinite and absurd results. It was obvious to everyone at the meeting that breaking the impasse would require a new idea.

Hendrik Kramers, one of the few non-US attendees, provided the new idea, which was named "renormalization." That name was already familiar to physicists in 1947; it had been used in a similar context by Robert Serber in 1936. Kramers had come from the Netherlands to spend a term as a visiting scientist at the Institute for Advanced Study in Princeton, New Jersey. He remarked that the observed energy of an electron according to QED is the sum of two unobservable quantities: a bare energy, which is the energy that an electron is supposed to have when it is uncoupled from electromagnetic fields, and the self-energy, which results from the electromagnetic coupling. The bare energy appears in the equations of the theory but is physically meaningless, since the electromagnetic coupling cannot really be switched off. Only the observed energy is physically meaningful. The point of renormalization was to get rid of bare energies and replace them with observed energies.

Kramers proposed that the results of the Lamb experiment should be calculated in terms of observed energies, with all mention of bare energies removed. He conjectured that when the bare energies were eliminated from the calculation, the infinite self-energies would cancel out and the calculated value of the energy difference that Lamb and Retherford measured would become finite. Kramers sketched a simple model of an electron for which the calculation could be done and the result was finite. But he did not know how to carry through the calculation for a real electron in a real hydrogen atom. Nobody at the meeting knew how to do a realistic calculation following Kramers's idea. Except Hans Bethe.

After the meeting, Bethe traveled by train from New York to Schenectady, a distance of 75 miles. On the train he finished a calculation of the Lamb shift for a real electron. The value that he found was 1040 megahertz, a result agreeing pretty well with Lamb's experiment. On 9 June he wrote a paper summarizing his calculation,[1] and sent it to the other participants of the Shelter Island meeting. The paper, two pages long with only 12 equations, was received by the *Physical Review* on 27 June and published on 15 August. It was a turning point in the history of physics. Before it appeared, the prevailing view of such experts as Niels Bohr and Oppenheimer was that existing theories of particle physics were fundamentally flawed and that progress could come only from revolutionary new concepts. After the paper appeared, the experts began to think that the existing theory of QED was physically correct and needed only some new technical tricks to make it mathematically consistent and practically useful.

How did it happen that Hans Bethe was the one who broke the impasse? There were two reasons. First, Bethe understood that the reaction of the electron to electromagnetic quantum fluctuations was mainly a nonrelativistic process and could be calculated using ordinary nonrelativistic quantum mechanics. Everyone else at the meeting assumed that a calculation of the Lamb shift had to use the notoriously difficult and complicated theoretical apparatus of relativistic QED. Only Bethe had the courage to plunge ahead with a calculation using old-fashioned nonrelativistic quantum mechanics to describe the hydrogen atom. Ignoring relativity made the calculation enormously simpler.

Second, Bethe was uniquely prepared by his previous training and experience to do the calculation and get the

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Richard Feynman explains a point during the 1947 Shelter Island Conference. Standing (from left to right) are Willis Lamb, Karl Darrow, Victor Weisskopf, George Uhlenbeck, Robert Marshak, Julian Schwinger, and David Bohm. Seated are Robert Oppenheimer, Abraham Pais, Feynman, and Herman Feshbach. (Courtesy of National Academy of Sciences.)

right answer. By a happy combination of circumstances, he had unrivaled knowledge of QED, of atomic physics, and of the art of calculating physical processes in which QED and atomic physics came together. It was his habit, when confronted with any physical problem, to sit down and calculate the answer. So, when the problem of the Lamb shift arose, it was natural for him to be the one who sat down and calculated the answer. To explain how Bethe acquired the knowledge and skills that enabled him to calculate the answer, I go back 20 years.

Mastering QED

The history of QED began at the end of the 1920s with three independent lines of development. First, in 1927 Paul Dirac developed a version of QED in which both electrons and photons are treated as particles. Second, in 1929 Werner Heisenberg and Wolfgang Pauli used the complicated mathematics of quantum field theory to develop a version in which both electrons and photons are treated as fields. Third, in 1930 Enrico Fermi developed a version in which the electrons are treated as particles and the photons as fields. Fermi's version was typical of his work—mathematically simple and physically transparent. Fermi intended it for use, not for ornament. Of the three versions of QED, Fermi's was the most practical and the best suited for solving real problems. Bethe had the good sense to go to Rome in 1931 and learn QED from Fermi. The two men published a paper[2] using Fermi's version of QED to calculate the retarded interaction between two electrons caused by the emission and absorption of photons. This collaboration gave Bethe his first experience of using QED for practical purposes and provided the foundation for his later mastery of QED.

After Bethe returned to Germany from Rome in 1932, he wrote a monumental review article for the *Handbuch der Physik* on the quantum theory of one-electron and two-electron systems.[3] That review, concerned mainly with hydrogen and helium atoms, provided an outstanding display of Bethe's thoroughness and attention to details. All the wavefunctions of states of the hydrogen atom are precisely calculated in several different representations, using spherical, cylindrical, or parabolic coordinates as required for the interpretation of various experimental observations. After writing the review, Bethe probably had a deeper understanding of the hydrogen atom than anyone else on Earth. He knew under which conditions a relativistic theory of the atom was necessary and under which conditions a nonrelativistic theory was sufficient.

After leaving Germany in 1933 and finding temporary refuge in Manchester, England, Bethe collaborated with his fellow refugee Walter Heitler, who was also expert in QED. Together they carried out the first precise relativistic calculation of the two dominant processes of high-energy electrodynamics—the production of photons by high-energy electrons and the production of electron–positron pairs by high-energy photons passing through matter.[4] The Bethe–Heitler calculation of photon production (called by its German name, "bremsstrahlung") and pair production was the most important achievement of QED in the 1930s. The calculation was a tour de force of analytical

Colleagues gather to discuss high-energy nuclear and particle physics at a 1955 conference in Rochester, New York. In front (from left to right) are Pierre Noyes, Freeman Dyson, Jack Steinberger, Richard Feynman, and Hans Bethe. (Courtesy of AIP Emilio Segrè Visual Archives, Marshak collection.)

skill, and it explained quantitatively the observations of cosmic-ray showers, in which high-energy electrons passing through the atmosphere generated a multitude of lower-energy electrons, positrons, and photons traveling together in the same direction. Bethe and Heitler called attention to the fact that not all high-energy cosmic rays generated showers.

The theory of QED appeared to apply well to some cosmic rays and not to others. Bethe and Heitler thought that the absence of showers accompanying some of the fast particles indicated a breakdown of QED at high energies. Some years later the particles that did not produce showers were identified as mesons, and the evidence for a breakdown of QED disappeared. The Bethe–Heitler calculation remained the gold standard for careful and accurate work in high-energy physics.

In 1935 Bethe found his permanent home at Cornell University. For the rest of the 1930s, he was mainly occupied with nuclear physics and with understanding the nuclear reactions that keep the Sun and the stars shining (see the article by John Bahcall and Ed Salpeter on page 44). He received a richly deserved and long overdue Nobel Prize for this work in 1967. And still, in my opinion, Bethe's calculation of the Lamb shift was a more profound and, in the long run, a more important contribution to science. It broke through a thicket of skepticism and opened the way to the modern era of particle physics. It showed us all how to connect QED with the real world.

After the Lamb shift calculation, Bethe continued to work out the consequences of QED. The most original of his later discoveries was the Bethe–Salpeter equation, a relativistic wave equation for bound states of two particles.[5] With his student Leonard Maximon he worked out a new version of the Bethe–Heitler calculation of bremsstrahlung and pair production; they used more modern methods and gave results that are more accurate when the atoms causing those processes are heavy.[6] With Ed Salpeter he published a greatly revised and expanded version of the *Handbuch der Physik* article on quantum mechanics of one-electron and two-electron systems.[7]

Hans Bethe never ceased to give help and encouragement to Toichiro Kinoshita and other colleagues at Cornell, who continued to push the calculation of QED processes to fourth, sixth, and eighth order of perturbation theory and thus keep pace as experiments in atomic physics became more and more accurate. Theory and experiment are now both accurate to 12 significant figures, and QED still stands confirmed. The confirmation of QED as the most precisely tested of all the laws of nature is one of the great triumphs of 20th-century science. We owe that triumph chiefly to the vision of two men, Willis Lamb and Hans Bethe.

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