MILESTONE 6

QED

Much of the groundwork for what would become one of the most successful theories ever devised was laid in the 1920s, particularly in the work of Paul Dirac and the other, usual suspects — Pascual Jordan, Werner Heisenberg and Wolfgang Pauli. As quantum mechanics took shape, Dirac commented, in a 1927 paper, that "hardly anything has been done up to the present on quantum electrodynamics": for instance on how to describe the production of an electromagnetic field by a moving electron and the reaction of that field on the electron; and what happens when force propagates at the speed of light rather than instantaneously.

Willis Lamb, Abraham Pais, John Wheeler, Richard Feynman, Herman Feshbach and Julian Schwinger (left to right) at Shelter Island in 1947. Courtesy of AIP Emilio Segrè Visual Archives

Dirac devised a workable, non-relativistic theory using a Hamiltonian to describe the dynamical system of an atom amidst "light-quanta". But the devil was in the details: it soon became apparent that attempts at accurate calculation using quantum electrodynamics were beset by divergences. If proper account were taken of all terms in calculating the mass or charge of an electron under the effect of an electromagnetic field, the answer for each was infinite.

Not until 1947 was the solution found. On the opening day of the Shelter Island conference, in June of that year, Willis Lamb presented his data showing the splitting of the $2S_{1/2}$ and $2P_{1/2}$ electron energy levels of the hydrogen atom, predicted by Dirac to be degenerate. On the train home from Shelter Island, Hans Bethe realized the significance of this 'Lamb shift' — that the electron mass calculated in quantum electrodynamics was not the electron mass measured in experiment, and that a procedure of 'renormalization' was necessary to link the two.

By the time of the Pocono conference in March 1948, others had worked out exactly how to accommodate renormalization in a relativistically invariant theory. Julian Schwinger presented, as was his wont, a thorough mathematical formulation that was subsequently found to have been matched, independently in Japan, by Sin-Itiro Tomonaga. Richard Feynman, too, had his own formulation to offer, although he later grumbled that "renormalization theory is simply a way to sweep the difficulties of the divergences of electrodynamics under the rug."

Freeman Dyson soon proved the equivalence of all three approaches, and Schwinger, Tomonaga and Feynman shared the Nobel Prize in Physics in 1965 "for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles". Accurate calculation was at last possible, and was aided greatly by the illustrative tool that Feynman had presented at Pocono: the Feynman diagram. One of the first ever published Feynman diagrams appeared in his 1949 paper, showing the now-familiar spacetime representation, as straight and wavy lines, of electrons exchanging a photon.

Quantum electrodynamics is now recognized as an Abelian gauge theory with the symmetry group U(1). Its calculations, using renormalization, have been shown to match experiment to the level, so far, of 1 in 10^{12}. What began with Maxwell's equations for the electromagnetic field (MILESTONE 2) has become the most stringently tested, most successful theory in all of physics. QED.

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