Old *and* New Fashions *in* Field Theory

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By Freeman J. Dyson

Sixteen years ago I gave my first invited talk to the American Physical Society, and spoke about the exciting work that was then just coming to an end in quantum electrodynamics. Now I am here again, and it seems that everything looks very much the same as it did in 1949. Only two things have changed. I am not as nervous as I was then, and the audience looks a great deal younger.

I am here to review the history of quantum electrodynamics in these sixteen years, so far as it can be done in three quarters of an hour. I will take as my theme the notion that in some sense the history of quantum electrodynamics in this period has repeated the history of gravitation thirty years earlier.

Einstein's theory of gravitation took the world by storm in 1919 for two reasons. In the first place, there was the dramatic prediction of the displacement of star-images by the sun's gravitational field, the organization of eclipse expeditions to Brazil and Africa to make the very difficult observations that could test the theory, and the clearly positive outcome of the test. In the second place, there was the appealing philosophical character of the Einstein theory, the statement that God created a space-time continuum without any special framework of coordinates to label points of space-time with numbers, so that all the laws of physics should be statements which are true in any possible coordinate system.

To Einstein himself and to many other physicists of the 1920's, including Herman Weyl and the youthful Pauli, it appeared that this beautiful and successful gravitation theory must be the model for the future development of physics. They expected that further extension of the two principles of Einstein, firstly the representation of physical reality as geometrical in nature, and secondly the insistence on general coordinate invariance, would lead to understanding of electromagnetism and of matter, the chief phenomena that remained outside Einstein's original theory. As is well known, these expectations proved false. The theory of matter and electromagnetism took a totally different direction with the advent of quantum mechanics in 1925. Everybody involved in the development of quantum mechanics forgot rather

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quickly about gravitation and assumed special coordinate systems without apology. Meanwhile the study of gravitation itself lost interest for physicists because nobody could think of any new observations or experiments. So the theory of gravitation gradually became detached from the rest of physics and was studied only by specialists. Only recently have some efforts been made by a few theorists, notably Feynman, Weinberg, and Thirring, to bring gravitation back into contact with the fashionable parts of physics. These efforts are interesting but cannot yet be said to have been successful. It still remains a mystery that the geometrical analysis which led to such a deep understanding of gravitation has no success elsewhere in physics. At the root of this mystery there is the fact that no experimental study of the overlap of gravitation with atomic physics seems to be feasible. Gravitational effects on the atomic scale are just too miserably weak to be observed.

I think one can now see a certain similarity between this history of gravitation and the later history of quantum electrodynamics. Quantum electrodynamics was invented by Heisenberg, Pauli, Fermi, and Dirac in the years 1928-1930, by putting together the newly established principles of quantum mechanics with the classical electrodynamics of Maxwell. It succeeded magnificently in describing all the standard radiation processes which occur in atomic physics, the emission and absorption of light by atoms, the Raman effect, the Compton effect, the photoelectric effect, the production of electron-positron pairs, and the existence of photons as particles obeying Bose-Einstein statistics. It began to run into trouble in the later thirties with the so-called "divergence difficulties". When one tried to calculate fine details of atomic spectra produced by the reaction of radiation on the motion of electrons in the atom, the theory gave infinite and therefore meaningless results. These difficulties stopped further progress from about 1936 until 1946.

I had the good fortune to come into physics during the years 1946-49 when the dramatic events occurred which led to a satisfactory theory of quantum electrodynamics. Leading this development were new experiments made possible by microwave spectroscopy and magnetic resonance techniques. The small effects of radiation reaction on atomic structure were for the first time accurately measured in brilliant experiments by Rabi, by Kusch and Foley, and by Lamb and Retherford, all working in the dark recesses of the Pupin physics building at Columbia University. Spurred on by these experiments, theorists discovered how to eliminate the divergence difficulties from quantum electrodynamics. The roads which they followed had been pointed out years before by Stueckelberg and by Kramers, and the quantitative comparison of theory with experiment was begun by Bethe. The programs of Stueckelberg, Kramers, and Bethe were carried to completion in 1948 by three men working independently, Feynman at Cornell, Tomonaga in Tokyo, and Schwinger at Harvard. The three were able to calculate the radiation reaction effects in a consistent way, and their results were confirmed in detail by the experiments. At the same time as these accurate experimental checks were coming in, the theory of quantum electrodynamics itself became elegant and philosophically appealing. It was no wonder that we were dazzled by these successes, just as the physicists of 1919 were dazzled by general relativity.

So when I spoke here in 1949 I proclaimed my faith that the style of field theory into which quantum electrodynamics had then grown would prove equally successful in describing the two other main categories of physical phenomena, namely the weak interactions (beta decay and mu mesons) and the strong interactions (nuclear forces and pi mesons). In fact, I made the same mistake which led Pauli (as he claimed) to miss helping to invent quantum mechanics in 1925 because he was busy constructing five-dimensional extensions of Einstein's gravitation theory. The later progress that has been made in understanding both weak and strong interactions has been through exploiting new features, parity violation and internal symmetry-groups, respectively, which have no place in quantum electrodynamics. Thus the elegant and beautiful formalism of quantum electrodynamics has been left high and dry, like Einstein's general relativity, having less and less connection with the rest of physics.

There are two respects in which the isolation of quantum electrodynamics has been less complete than that of gravitation theory, one theoretical and one experimental. I will discuss the theoretical situation first, the experiments afterwards.

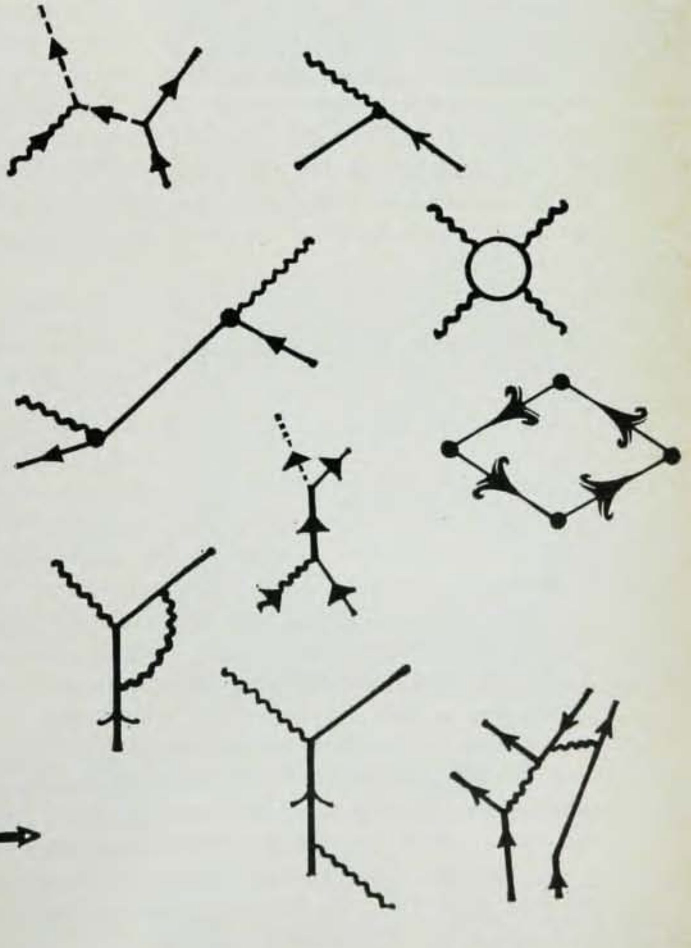
Theoretically speaking, there were two opposed points of view in quantum electrodynamics as it emerged in 1946-49. Tomonaga and Schwinger developed the theory strictly as a field theory. They believed in electric and magnetic fields as physically meaningful quantities, and their theory is based on the idea of a field as an object distributed in space and time and susceptible to local measurement. They were conservatives, maintaining the idea of measurability of fields by classically constructed apparatus as originally propounded by Bohr and Rosenfeld in the thirties. On the other hand, Feynman was (and still is) a radical. He did not believe that fields exist except as some kind of classical limit. His version of quantum electrodynamics was the prototype of what is now called *S*-matrix theory. He considered that the only physically measurable quantities were elements of the scattering or *S*-matrix, and his theory gave directly the rules for calculating *S*-matrix elements by means of Feynman diagrams and Feynman integrals. The Feynman diagram describes any physical process naively as a propagation of particles from place to place. The Feynman theory was a pure particle theory, just as the theories of Tomonaga and Schwinger were field theories. For a long time Feynman, like Stueckelberg who had proposed similar ideas some years earlier, had difficulty getting people to listen to him. At the Pocono meeting in 1948 at which the competing theories were first presented, Niels Bohr was the most distinguished person present; he listened most attentively to Schwinger, but interrupted Feynman so frequently that Feynman was never able to make himself understood.

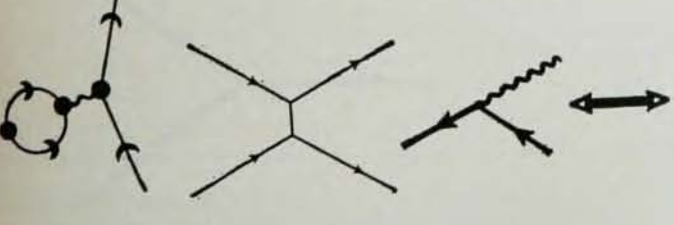
In those days, the field-theory fashion was very strong. It was really hard for any other point of view to gain a hearing. I remember my own first meeting with Pauli which occurred during this period. Pauli was talking in German to a group of his friends, and he was saying, "Yes, we had Schwinger to give us a seminar this week, and he made everything beautifully clear, not at all like the nonsense which Dyson has been writing." At that moment Fierz, who was standing by Pauli and saw me in the group, said with a happy smile on his face, "Professor Pauli, allow me to introduce to you Mr. Dyson." And Pauli replied without any hesitation, "Oh, that's all right, he doesn't understand German."

I had been a student of Feynman at Cornell, and so what I wrote was automatically nonsense. What I had in fact been trying to do was to make Feynman respectable by proving that his theory was mathematically equivalent to those of Schwinger and Tomonaga. This was my main contribution to the development of quantum electrodynamics; I allowed people like Pauli who believed in field theory to draw Feynman diagrams without abandoning their principles. It was for this that I was invited to give my talk here sixteen years ago, and it is for this that I am honored by standing here and talking to you now.

What makes the situation ironic is that now, sixteen years later, Feynman needs no defender. Of all the work that was done in the years 1946-49, it is the Feynman diagrams that have best survived the ravages of time. Many people are now profoundly skeptical about the relevance of field-theory to strong-interaction physics. Field theory is on the defensive against the now fashionable *S*-matrix. Those of us who still pursue field theories are gradually becoming an isolated band of specialists similar to the specialists in general relativity. It is easy to imagine that in a few years the concepts of field theory will drop totally out of the vocabulary of day-to-day work in high-energy physics. It is impossible to imagine the bulk of theoretical work in modern high-energy physics being done without Feynman diagrams.

So I spent my youth in defending Feynman's *S*-matrix heresy against Pauli's field-theoretical





orthodoxy, and I shall spend my declining years in defending the field-theory heresy against Geoffrey Chew's *S*-matrix orthodoxy.

To return to the subject of quantum electrodynamics. This field has not become quite so isolated as gravitation-theory from the rest of physics, for two main reasons. The first reason is the theoretical one that I have just described. Quantum electrodynamics has a dual character, it is both a field theory and an *S*-matrix theory. Thus, although I was totally wrong in saying in 1949 that the field-theoretical aspects of quantum electrodynamics would open the door to understanding of mesons and nucleons, it turned out that the *S*-matrix aspects of quantum electrodynamics were useful and suggestive in strong-interaction physics. So we have been left with the present peculiar situation, in which the electromagnetic field appears from one point of view as something very special and unique in the universe, while from another point of view the photon is just a particle like the others in the physicist's menagerie.

The second and more important reason for the continued relevance of quantum electrodynamics to particle physics is that, in contrast to the situation in gravitation theory, experiments on the border-line between electrodynamics and strong-interaction physics are feasible. We have a point of attack for exploring directly the way in which electromagnetic interactions fit into high-energy physics. I would like just to mention two pieces of work done in the last two years which seem to me of outstanding importance in keeping alive the communications between electrodynamics and the rest of physics.

The first of these two achievements is the explanation of the mass difference between neutron and proton by Roger Dashen, working at the time as a graduate student under the supervision of Steve Frautschi. The neutron-proton mass difference has for thirty years been believed to be electromagnetic in origin, and it offers a splendid experimental test of any theory which tries to cover the border-line between electromagnetic and strong interactions. However, no convincing theory of the mass-difference had appeared before 1964. In this connection I exclude as unconvincing all theories, like the early theory of Feynman and Speisman, which use one arbitrary cut-off parameter to fit one experimental number. Dashen for the first time made an honest calculation without arbitrary parameters and got the right answer. His method is a beautiful marriage between old-fashioned electrodynamics and modern bootstrap techniques. He writes down the equations expressing the fact that the neutron can be considered to be a bound state of a proton with a negative pi meson, and the proton a bound state of a neutron with a positive pi meson, according to the bootstrap method. Then into these equations he puts electromagnetic perturbations, the interaction of a photon with both nucleon and pi meson, according to the Feynman rules. The calculation of the resulting mass-difference is neither long nor hard to understand, and in my opinion it will become a classic in the history of physics.

The last development I wish to mention in this survey of quantum electrodynamics is the experiment on wide-angle pair-production which was recently carried out at the Harvard-MIT accelerator and reported at this meeting. The experiment is reported under seven names: Blumenthal, Ehn, Faissler, Joseph, Lanzerotti, Pipkin, and Stairs, and it was suggested in a theoretical analysis by Drell, Bjorken, and Frautschi. One measures electron-positron pairs produced by high-energy gamma rays in a carbon target, looking only at wide-angle pairs for which the momentum transfers are so large as to come into the range of strong-interaction physics. Experiments on elastic electron scattering at the same momentum transfer enable the nuclear electromagnetic form factors to be determined independently. Thus the pair-production experiment is supposed to test the behavior of strictly electromagnetic processes in a higher momentum range than other similar experiments. The result appears to show a definite departure from the predictions of pure quantum electrodynamics. If this result is confirmed, it will for the first time give us direct evidence concerning the way in which quantum electrodynamics at high energies should be made to merge into the rest of high-energy physics. The possibility of such experiments is full of promise for a future growth of physics in which quantum electrodynamics will no longer be an isolated museum-piece. I have hopes that ultimately some new experimental technique will reclaim the gravitation theory for physics in a similar way.