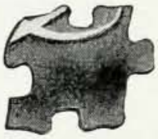
"Recent advances in quantum electrodynamics are essentially an advance in understanding and formalism," writes Dr. Stern, "rather than an advance in the region of applicability of quantum electrodynamics."

TREND IN CONTEMPORARY PHYSICS



by Alexander W. Stern

The introduction by Bohr of Planck's quantum of action h in atomic theory to explain the stability of atoms and their fixed properties culminated in the discovery of the Uncertainty Principle, or the Principle of Indeterminancy, as it is sometimes called. This principle necessitates a redefinition and generalization of the concept of causality, and in the early days of its discovery caused much confusion and misunderstanding among physicists.

This confusion was for the most part due to the fact that the principle was explained by resorting to illustrations of ideal experiments. These ideal experiments were designed to illustrate the maximum precision with which dynamically conjugate quantities such as position and momentum can be measured. In these illustrations the observer played a fundamental role, and not a few physicists believed that the indeterminism in nature, as expressed by the uncertainty relations, was the fault of the observer. It was believed that the laws of nature were simple and exact, and that the indeterminism in quantum mechanics has nothing to do with causation. According to a typical opinion, indeterminism really signifies "not determined," and "not determined" means "not ascertained," implying that there were exact laws in nature but that we could not ascertain them.

What these physicists did not realize was that the indeterminism as expressed by the uncertainty relations is imbedded in the structure of quantum mechanics. The uncertainty relations are a consequence of the existence of Planck's constant h which is the very heart of quantum mechanics. The general laws of quantum mechanics, which are fundamental laws of nature, reveal that this indeterminism exists in nature and is made manifest when we attempt to observe, say, the exact position and velocity of a particle at a given time. It is interesting to note here that in non-relativistic quantum mechanics the *observer,* and not the *mathematics,* was blamed for those consequences of the theory which shocked the common prejudices of the time and upset some cherished beliefs. Later, in relativistic quantum mechanics, the mathematics and not the inevitable interfer-

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ence of the observer was accused of being responsible for the fantastic results of that theory.

As an example, the mathematics of Dirac's electron theory yields infinite field and charge fluctuations in an infinitely small, well-defined region of space. Such a region of space is not realized in practice, and an observer therefore cannot be blamed for creating the necessary experimental conditions. The discovery by Dirac of the relativistic wave equation which bears his name was a great and fundamental advance. Nevertheless some of the difficulties of this equation at once became apparent. One of these difficulties was the prediction of negative energy states. Negative energy states are obviously unphysical. Electrons with negative energy behaved in a way that violated the fundamental physical principle of action and reaction. Many physicists could not become reconciled to accepting negative energy states, and their natural reaction was that the mathematics was wrong.

There were several attempts to eliminate negative energy states from the theory. Prominent among these were a paper by Schroedinger and one by Majorama, but all such attempts were, of course, unsuccessful. Negative energy states are an integral part of the theory, and their use as intermediate states is what makes possible the excellent agreement between theory and experiment, as evinced, for instance, in Compton scattering.

Now negative energy states are generally accepted. It is remarkable as well as significant that quantum mechanics which was initiated with the object of allowing only observable concepts to enter the theory finds it is necessary to deal with such unphysical concepts as negative energy states and infinite energy. Bohr has stated, in writing about the development of quantum mechanics, that, "In this theory the attempt is made to transcend every use of mechanical concepts in a way suited to the nature of the quantum theory *and such that in every stage of the computation only directly observable quantities enter.*" (Italics mine.)

In fact, what was once a difficulty is now used to explain other difficulties. Schoenberg in his article on The Quantum Theory of the Point Electron in the October, 1948 Physical Review applies the concept of negative energy to the classical unquantized radiation field. The classical radiation field in Schoenberg's theory has negative as well as positive energy density. Here the concept of negative energy is accepted wholeheartedly and is dissociated from its original and legitimate region of application and given a broad classical basis.

Infinite Energies

We come now to the second great difficulty of relativistic quantum mechanics—the divergences of the field theories. These infinite energies which were considered as a plague to the field theories shocked our physical sense even more than the negative energy states.

There were heroic attempts to cut out the troublesome infinite terms from the theory, principally by Heitler, Heisenberg, and Dirac. There followed an era of what I call the Omission Theories, which started about 1942 and has just ended. At first glance, the more that was cut out of the theories, the better they looked. But not long after the operation the patient, that is, quantum mechanics, began to show the effects of surgery. It was soon realized that the patient was much better off before, than after, the surgery, for like some surgeons, the physicists who had assumed that role had cut out too much. In particular, the infrared catastrophe reappeared in the theories of Heitler and Dirac, which is to say that the theories failed in the low and moderate energy region where we should expect any acceptable theory to have validity. The Heisenberg attempt is admittedly incomplete, and requires rules of computation before it can be applied to specific problems. His formulation also had difficulty with the elementary time sequence of events demanded by causality.

In Heitler's attempt a method was discovered for cutting out all infinite terms beyond the lowest nonzero terms from the equation describing the interaction of the particle with the quantized field. This Heitler succeeded in doing in a relativistically invariant way, but it was found that finite terms which may be physically important were also cut out in this process.

Heisenberg adopted a completely positivistic attitude toward the situation and omitted all terms in his formulation which were not directly observable. He thought it sufficient merely to have a mathematical scheme for calculating the results of experiments. The important paradox ensued that one must go beyond a mere calculating scheme in order to calculate. The calculating scheme of Heisenberg is so completely devoid of all elements that are necessary for a theory, of all content necessary for an understanding of physical processes, that it does not yield means for calculating the very foundation of his formulation—the unitary S matrix. Besides, it is evident that in his approach as well as in Heitler's, static problems such as computing the magnetic moment of the proton may present an insurmountable difficulty.

But if Heitler's and Heisenberg's formulations excluded a great deal which is physically important, Dirac's heroic attempt excluded the entire physical world. His theory, which appeared the most successful of the three, applies to a hypothetical world. By doing this he avoids the infinities associated with the real world. In order to avoid the infinite number of negative energy electrons involved in the self energy divergences, Dirac assumed that practically all but a few of the negative energy states are unoccupied.

Remembering that an unoccupied negative energy state is equivalent to a positron, we have a world almost completely saturated with positrons. The calculations are thus greatly simplified, involving but one or two electrons. This idea coupled with a classical procedure of eliminating divergences due to Wentzel and Dirac, and known as the lambda limiting process, appeared to eliminate all the divergences. But there arise difficulties concerning the physical interpretation of the Dirac formalism due to the fact that it applies to a hypothetical world. Besides, it appears from calculations by Pauli and Jauch that the Dirac theory encountered the old difficulty of the infrared catastrophe when applied to the emission of low energy photons.

In summarizing the results of the Dirac theory one may say that the application of the lambda limiting process tends to eliminate field inertia effects and causes the electron's electromagnetic mass to become zero, while the abandonment of the electron-positron or hole theory cut out the divergent self energy expressions of the electron.

Electromagnetic Mass

One can now see how black things looked for quantum field theory when at the time of these difficulties important experimental evidence was brought forward by Lamb and Retherford concerning a minute displacement of the 2 S energy level of the hydrogen atom from the position predicted by the Dirac theory. Furthermore a precise measurement of the magnetic moment of the electron during the same year revealed yet another disagreement with current theoretical prediction and a deviation from Dirac's theory.

It was in this atmosphere that new progress in quantum electrodynamics was achieved by the theorists. Many names are connected with this development, which was started in this country and in Japan independently. I shall discuss here mainly the fundamental and exhaustive paper by Schwinger, in the November 15, 1948 Physical Review in which he brought forward his well-ordered and completely relativistically co-variant and consistent formulation of quantum electrodynamics. Many physicists at one time or another doubted that quantum and relativity theory could be reconciled. It is interesting and instructive to note that a successful quantum electrodynamics was not forthcoming until a complete union between relativity and quantum theory was achieved.

To begin with, Schwinger cut out nothing. His work suggests that theoretical physicists nowadays should have more faith in the mathematics of quantum field physics and not quite so much in their own common sense. The very infinities which physicists spend so much time, labor, and ingenuity cutting out contained terms which were of fundamental importance and which were necessary to insure a completely relativistic co-variant theory. Besides, the infinite terms were to shed light on the very structure and stability of the electron by redefining and reinterpreting its mass and charge.

In order to get some idea of Schwinger's achievement let us first consider a free, isolated electron (an electron abstracted from the rest of the world) and its electromagnetic field. There is no surrounding matter. A remarkable phenomenon now ensues. When this electromagnetic field is quantized, the average value of its field strengths will no longer be zero but will fluctuate. It is these electromagnetic field fluctuations in empty space that cause an isolated electron, although not interacting with matter, continuously to emit and absorb radiation. This interaction involves the virtual emission and absorption of electromagnetic quanta, or photons, with unlimited energy. These virtual quanta are parts of the field which the electron carries around with it. Therefore this virtual emission and absorption of light quanta produces an infinite electromagnetic self energy.

This was looked upon as one of the defects of the Dirac theory, and in practical problems involving more complicated interactions of the electron, attempts were made to cut out these infinite self-energy-like terms. But in these more complicated interactions there are finite terms of fundamental

importance, which are contained in the infinite terms, and by cutting out the infinite terms these finite terms are also eliminated.

Schwinger was wise; instead of cutting out these infinite terms he subjected them to mathematical analysis. He succeeded in isolating the infinite electromagnetic self energy terms from the finite terms and identified the finite terms as yielding the radiative correction effects due to the interaction of an electron with an external field. When applied to the problem of the electron in a Coulomb field, these finite terms predict the correct level displacement of the hydrogen lines, as found by Lamb. When applied to the problem of an electron in an external magnetic field it results in giving to the electron an additional magnetic moment which was nicely confirmed by recent experimental data.

The infinite electromagnetic self energy term in the interaction energy which was isolated from the finite terms is due, as I mentioned before, to the interaction of an electron with the electromagnetic field vacuum fluctuations. This strange fluctuation phenomenon, which is represented by the infinite term, results in giving to the electron an additional mass of electromagnetic origin if one considers those energies in this term up to the order mc^2. And so is born the electromagnetic mass of the electron. The actual electron mass observed, the mass that is measured, is the sum of this electromagnetic mass and the mechanical mass. The self energy term has the same form as the mass term in the Dirac equation and can be incorporated with this mass term to give the total experimental electron mass. The Dirac equation heretofore contained the wrong mass term of the electron—the mechanical mass instead of the total mass—which fact was revealed by an analysis of the electromagnetic self energy infinities.

The current quantum electrodynamics which was vindicated by the recent impressive developments is based on the assumption of a small interaction between matter and radiation, of the magnitude e^2/hc. We have seen that in the divergent electromagnetic self energy term there is no limit to the frequency of the emitted light quanta. In order to retain the weak coupling between the electron and the electromagnetic field one includes the effect of the virtual emission and absorption of quanta only up to energies mc^2 into the mass of the electrons, whose value we know. The efforts of the low and moderate energy region are well described by the theory, such as the Lamb shift and the shift of the magnetic moment of the electron which a successful theory must predict. Those aspects of the theory which are still divergent are due to high energy effects, and are successfully separated and isolated without in the least destroying the relativistic covariance of the theory.

The electromagnetic field also interacts with the electron-positron matter field in a vacuum. The matter field, like the electromagnetic field, can exist in empty space. But this seemingly contradictory statement necessitates redefining a vacuum. A vacuum is defined by Heitler, for example, as a region where all states of positive energy are unoccupied and all states of negative energy are occupied. Since the negative energy electrons are assumed to produce no external field, the above definition defines the zero point for charge and energy measurement.

The interaction of the electromagnetic field, in the form of a current distribution, with the electron-positron matter field in empty space causes an infinite charge. This interaction consists of a continuous transition of electrons from negative energy states to positive energy states and vice versa. This results in an infinite charge due to the possibility of creating electron-positron pairs with unlimited energy, in the same way as the continuous absorption and emission of radiation (light quanta) with unlimited energy gave an infinite electromagnetic mass.

It has been shown long ago (1934) by Heisenberg, Dirac, and Weisskopf that these charge fluctuations in empty space are equivalent to an alteration to the electron charge as classically defined in accordance with electromagnetic theory. Here again we have a divergent factor which, when properly resolved and exhibited, reinterprets and redefines a fundamental constant, in this case the electron charge. An electromagnetic field in a vacuum is no longer a valid abstraction. The electron-positron field and the electromagnetic field are always coupled. An electron can interact only with the electron pair field when it is actually radiating, and conversely, an electron interacting with the electromagnetic field is also interacting with the electron-positron field. Here again those aspects of the theory which are due to high energy effects and are still divergent are separated under the assumption that the present quantum electrodynamics is valid only to a first approximation.

Advance in Understanding

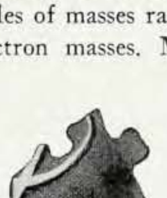
One can now see the great objectivity that marks the science of contemporary physics. Physicists were dissatisfied with the field and charge fluctuations in empty space as yielded by theory. They were unphysical, unobservable, and yet one could not eliminate them from the theory. We see now that these effects are necessary and fundamental for the physical interpretation of quantum electrodynamics.

In my opinion it is not correct to say with some physicists that the remaining infinities of the theory, which were isolated as belonging to the high energy region, would turn out to be zero. The recent advances are essentially an advance in understanding and formalism rather than an advance in the region of applicability of the quantum electrodynamics. The theory still has a validity only up to approximately nuclear dimensions or energies, say $137\ mc^2$. Schwinger's work is a vindication of the present quantum electrodynamics and a justification of perturbation theory in the energy region of applicability of quantum electrodynamics.

For high energies the complexities, paradoxes, and self energy difficulties still remain. There may be a limit to the complexity of physics as we go to higher and higher energies. This may be so if there exists a fundamental natural constant of length which would limit the smallness of the region of interaction between particle and field and which would allow an unambiguous distinction to be made between particle and field. It is just these charge and field fluctuations which, when confined to an infinitesimal region of space, produce an infinite number of electron pairs and an infinite field. In physics, as particle and field get closer and closer together, instead of shutting out the external world, so to speak, the interaction produces an entire universe. The infinite is contained in the infinitesimal.

What does this mean for high energy phenomena? There is a term in the electromagnetic self energy expression which diverges logarithmically with increasing frequency. Some physicists hope that there may be a natural cutoff to this term by some natural limitation to the energy of the emitted quanta. On the other hand, it may be an indication of the possible explosive production in one elementary act of a great number of different particles—electrons, mesotrons, and protons. For in the second and higher approximations not only can one not make an unambiguous distinction between particle and field, signifying the failure of the present quantum electrodynamics, but the different particles get mixed up—lose their individuality. In such a situation, one would be forced to treat all the different kinds of fundamental particles together. This production of a great many particles of different masses would, roughly speaking, tend to "dissolve" the infinities in the higher approximations.

Some evidence for phenomena of this type exists in cosmic rays. And so the infinities in the higher approximations may be tied up with the existence of explosion phenomena and the existence of a family of unstable particles with masses intermediate between that of electron and proton. We now have evidence ranging from excellent to fair for the existence of particles of masses ranging from ten to one thousand electron masses. Mesons of masses



two hundred and three hundred are well established, and there is good experimental evidence for a meson mass of nine hundred. In the November 12, 1948 issue of Science there was published a photograph which could be interpreted as showing an elastic collision between a particle of mass ten and an electron. The only sure thing one can expect in physics is the unexpected. We can console ourselves by the thought that the miraculous complexity of physics will prove it to be an exciting and open field for research for many, many years to come.

Physics and Biology

If there is a fundamental complexity in nature as revealed in the biological sciences, there is no a priori reason why this complexity should not invade physics. In fact we have seen that physics is not the obvious, commonsense, naive science that it was once thought to be. The simple, static billiard ball like conception of the electron is far from the truth.

The elemental units of life involve a large number of atoms. Their great complexity is a matter of organization. On the other hand, the difficulty in formulating a theory of the electron and the other elementary particles, lies in their ultimate simplicity. In the study of the elementary particles our space-time concepts, our physical intuitions, our familiar thought patterns, fail us. The methods and devices which are so useful as aids to our understanding of macroscopic matter are no longer applicable. This wavering, vibrating, and trembling happening which is the electron has not the properties of matter as we know or experience it. The failure to project the electron on the space-time curtain of physics, on which events of the physical world are assumed to be portrayed, makes the attempt to understand its existence so difficult. One can now see that in order to understand the origin of matter one needs go beyond matter.

It is interesting to note that at a time when there is a trend in physics toward greater and greater abstraction, there is a tendency in the opposite direction in the biological sciences. We are finding mechanisms for biological phenomena at a time when we are discarding them for physical phenomena. Activities which are associated with living matter, in fact, with the highest form of living matter—man—and which are of teleological nature can now be mirrored by appropriate mechanical systems. The investigations of Weiner and his school in cybernetics have revealed a striking analogy between the behavior of modern calculating machines which exhibit properties akin to memory, association, and choice, and the human brain, when it is functioning. Our nervous systems have also been found to behave like a mechanism with negative feedback properties. Surely it would seem that the mystery of matter is just as legitimate a connotation as the mystery of life.

NOTES from ABROAD

The Netherlands

In a previous letter I described the slow birth of the Netherlands Foundation for Pure Research. I mentioned that, in spite of the fact that the bill about the foundation has not yet passed Parliament, the provisional council of the foundation has not delayed its activities. The Sub-Foundation for Research on Matter has been at work for three years.

The Foundation for Research on Matter found its first task after the liberation in promoting nuclear physics. During the war the nations occupied by Germany lagged seriously behind in nuclear physics in comparison with their more fortunate allies. It was realized in Holland that it would put a very high strain on the nation's hampered resources and scientific manpower if an attempt should be made to catch up within a few years; so after long discussions the foundation decided to concentrate upon promoting modest nuclear research programs at the different universities and upon establishing a new cyclotron laboratory in cooperation with the Municipal University of Amsterdam and with the Philips Works. The researches thus promoted by the foundation consisted largely in perfecting and developing instruments and accessories for nuclear research, including counters of various types, counter circuits, ionisation vessels, Wilson chambers, and beta-ray and mass spectrographs. Rather small scale research with radioactive substances and with neutrons is carried out in Groningen, Amsterdam and Utrecht, while in Leyden, nuclear magnetic resonance and nuclear relaxation are investigated.

In the new Amsterdam Laboratory for Nuclear Research, the cyclotron secretly built during the war at the Philips Works has been mounted. The eighty kilowatt magnet has a pole diameter of seventy-two inches. With a pole gap of thirteen inches it gives a central field of thirteen and a half kilo-oersted. The apparatus is being adjusted as a syncho-cyclotron for accelerating deuterons and alpha particles to thirty and sixty electron volts respectively. A department of radiochemistry is attached to the laboratory.

In principle the Foundation for Research on Matter does not wish to confine itself to the promotion of nuclear research. The University of Leyden and the Institute of Technology of Delft have developed a research program concerned with the physics of metals (crystal growth, electric, elastic and mechanic properties of metals).

C. J. Gorter