THE UNIFIED FIELD THEORY

Werner Heisenberg Among the many ideas which Einstein has pursued in connection with his theory of general relativity, his proposal of a unified theory has aroused the widest interest on account of its philosophical implication. Einstein has suggested that such different phenomena as gravitation, electromagnetism and material bodies could ultimately be described by one fundamental field or system of fields; that all the different empirical laws of nature could be expressed by one universal system of non-linear equations for the components of this field. From a philosophical point of view this possibility looks very attractive. Different groups of phenomena, like gravitation and electricity, can scarcely be separated completely. They may influence each other, and therefore the laws of nature responsible for them cannot be completely independent. The unified field theory would contain the different laws as special cases and would at the same time establish the connection and thereby state the structure of nature.

Einstein was not able to carry this program very far. His starting point was the field of gravitation for which the field equations were given by the theory of general relativity. He then intended to find a field structure which would be a natural generalization of the symmetrical (metrical) tensor, representing gravitation, as well as a system of field equations for this structure which would represent a natural generalization of the equations of pure gravitation. In a first attempt he tried to include the electromagnetic laws; with regard to the material bodies, he hoped that at a later stage of the theory the elementary particles could be understood as singularities in space of the universal field. This hope was motivated by the non-linear character of the field equations which might lead to such singularities. But at this point he ignored — one may almost say, by intention — the quantum theoretical nature of the elementary particles and therefore he could not possibly find a correct mathematical description of their behavior.

Before going into the details of this question we have to mention another important problem, the connection between the system of field equations and the cosmological model of the world. Einstein saw this connection in the light of the ideas proposed by Mach. The rotation of a single body in empty space has, according to Mach, no meaning. Therefore a centrifugal force can occur only if space is not empty, if distant masses produce this force. Hence the reaction of a single body on its motion depends on the distribution of matter in the universe. This distribution and the corresponding structure of space-time is not uniquely determined by the field equations. But it is not completely arbitrary; it is limited by the field equations and should correspond to one of the many solutions of the field equations. The behavior of a single particle under the influence of local fields may then to some extent depend on the structure of the universe. It is true that Mach's principle is not so intimately connected with Einstein's field equations as Einstein had believed. But the relation between the cosmological model of the world and the field equations, the relevance of this cosmological structure for the behavior even of small bodies remains an essential feature of any unified field theory.

Coming back to the quantum theoretical nature of elementary particles, we first notice that singularities in space produced by a classical non-linear field equation would behave quite differently from real elementary particles in a given field of force. All those features, which in quantum theory are connected with the apparent dualism between the pictures presented by waves and particles and which are expressed by the mathematical scheme of quantum or wave mechanics, would not be seen in the behavior of the singularities. Therefore in our time it would be a quite unrealistic approach to try to connect different groups of phenomena in nature without taking quantum theory into account from the very beginning.

Besides that, the many experiments carried out with the help of the big accelerators during recent years have given us a great wealth of information about elementary particles, not accessible for Einstein in his time. We have learned that besides electromagnetic forces and the corresponding photons, besides gravitation and the corresponding gravitons, there exist very many different fields of force, each characterized by the corresponding elementary particle, for example: those forces which bind an atomic nucleus together. A unified field theory would have to comprise all those different fields. When two elementary particles collide at very high energy, many new particles emerge from the collision; we speak of multiple production of particles. But such phenomena would not be well described by saying that the particles have been broken into many smaller pieces. It is much more correct to state that the big kinetic energy of the colliding particles has been transmuted into matter — following Einstein's law — by the creation of many new elementary particles. Actually, whatever the special nature of the colliding particles may have been, the emerging particles always belong to the same well-known spectrum of elementary particles. Energy becomes matter by assuming the form of an elementary particle. The spectrum of elementary particles reproduces itself in the high-energy collision processes.

A number of very important conclusions can be drawn from these results. One can see at once that any attempt to construct a separate theory for each of the hundred different fields of force would be absurd. The unified theory may have been an object of speculation for Einstein; in our time it is an absolute necessity in theoretical physics if we want to understand the elementary particles.

One may perhaps doubt whether the future theory will be a unified field theory, or whether other mathematical tools than fields could be more adequate for the description of the experiments. But it must be a unified theory comprising all the different empirical fields.

Einstein had believed that the particles were singularities of the field in space. In quantum field theory we have learned in the meantime that the particles are singularities — namely poles — in momentum space, not in ordinary space. For Einstein the field was real, it was in fact the ultimate reality and determined both the geometry of the world and the structure of the material bodies. In quantum theory the field distinguishes, as in classical physics, between something and nothing; but its essential function is to change the state of the world, which is characterized by a probability amplitude, by a statement concerning potentialities. In this way experimental situations in elementary particle physics can be described by applying operators constructed from products of field operators on the groundstate "world". But one can scarcely consider the fields as real and objective in the same sense as Einstein did in his field theory.

Both in Einstein's theory and in modern quantum field theory, the final formulation of the underlying natural law is given by the field equation. Therefore the central problem of the unified field theory is the correct choice of the field equation and the comparison of the results with the experimental observations. In this respect any attempt at a unified quantum field theory is in a much better position than Einstein's older theory. So many details are known nowadays about the spectrum of elementary particles, their interactions, selection rules in transitions etc., that it should be comparatively easy, in spite of the great mathematical difficulties, to see whether a special field equation suggested as fundamental law has a chance to give results in agreement with the many observations.

If one tries to find the fundamental field equation as a result of an analysis of the experiments, the most important information is obtained from the laws of conservation, selection rules and empirical quantum numbers. Already forty years ago the physicists had learned from the mathematicians that these relations are due to symmetries, to "group properties" in the underlying natural law. Therefore the empirical information will reveal the group structure of the fundamental field equation, and it may well be that the group structure — perhaps together with a few other plausible postulates — determines this equation uniquely.

The analysis of the spectrum and of the selection rules would be a straightforward method for determining the group structure of the underlying natural law, if all observed symmetries were exact symmetries. This, however, is not true: there are approximate symmetries like the isospin group, and higher groups like SU_3, SU_6, SU_{12} etc., which hold only in a very rough approximation. In this case one has no choice but between two possibilities. One may either assume that the underlying law is strictly symmetrical under the group concerned, but that the symmetry is broken later on by an asymmetrical groundstate. Or one may assume that the symmetry is not contained in the underlying law, but that the approximate symmetry is produced indirectly by the dynamics of the system. The two possibilities can be distinguished by an experimental criterion. In the first case one should, according to a theorem of Goldstone, observe bosons (particles obeying Bose statistics) of rest mass zero, responsible for breaking the symmetry. In the second case such particles should not exist. For the isospin group, one actually observes the electromagnetic field and the photons of rest mass zero which are responsible for the violation of the symmetry. For the higher groups, SU_3, SU_6 etc., such particles have not been seen. If one takes this as the final result of the analysis, one arrives at the conclusion that the underlying natural law should be invariant under the Lorentz group, the isospin group and a few gauge groups (the latter for baryonic, leptonic number, strangeness and electric charge). There is just one simple nonlinear differential equation containing these symmetries, and it is therefore natural as a trial to take this equation as a basis for the unified field theory. The differential character of the equation emphasizes the relation between cause and effect which is sometimes called relativistic causality. Relativistic causality is compatible with the statistical character of quantum theory, and its consequences seem to agree well with the observations of collision processes.

Starting from this non-linear spinor equation one, arrives at a number of encouraging results which in my mind make it probable that this equation is already the correct basis of elementary particle physics. But I cannot go into any details. Instead of discussing special consequences of this unified quantum field theory, I will try to compare its general structure and its results with Einstein's earlier program. The center of the new theory is formed by the strong interactions in which most elementary particles, baryons and mesons, participate and which have the full symmetry of the equation. The strongly interacting particles and the corresponding fields had not been considered by Einstein in his attempts at a unified theory, partly because he could not accept the quantum theoretical relation between fields and particles, and partly because very few of those particles and fields were known in his time. Therefore in this respect the two theories are very different.

The electromagnetic field however was included in Einstein's attempt; it appears in the unified quantum field theory as a rather special kind of field resulting from the asymmetry of the world under the isospin transformations. At this point the new theory has revealed a most interesting relation between the macroscopic structure, the cosmological model of the world and the properties of the elementary particles. This relation has been expressed in a somewhat mathematical form as a theorem by Goldstone. If the underlying natural law is invariant under certain transformations (in this case, the transformations are isospace), and if this symmetry is broken by an asymmetry of the groundstate "world", the theorem states that necessarily bosons of rest mass zero must appear, or — changing over from particles to fields — long-range forces. These forces make it understandable that the properties of the particles cannot be completely independent of the macroscopic structure of the world. Actually, the number of protons in the world is very different from the number of neutrons; therefore the real world is not invariant under rotations in isospace. At the same time, we know that the electromagnetic forces have long range; the corresponding particles, the photons, have rest mass zero. Therefore, it looks very natural to assume that the electromagnetic field, or parts of it, represent a Goldstone field and that its existence is due to the asymmetry of the world in isospace.

This result emphasizes the close similarity between the forces of inertia (for example: centrifugal force) and their cosmological origin in Einstein's theory, on the one hand, and the electromagnetic forces with their cosmological origin in the unified quantum field theory, on the other hand. In both cases, a qualitative assumption about a fundamental asymmetry in the cosmological model is sufficient to determine the forces uniquely and quantitatively. In general relativity the value of the centrifugal force follows when one knows that, at large distances, the metric approaches the Euclidean metric. In quantum field theory, the strength of the electromagnetic field or the elementary charge are determined when one knows that the macroscopic world is asymmetric under rotations in isospace. It is encouraging to see that the value of the electric charge — or, what is equivalent to it, the value of Sommerfeld's fine structure constant — comes out in satisfactory agreement with the observed value, as could be demonstrated in a paper by Duer, Yamamoto and Yamasaki. This result is perhaps the strongost argument in favor of the assumed non-linear field equation.

The field of gravitation was at the center of Einstein's unified field theory. In the unified quantum field theory, gravitation has not yet been considered, and it certainly plays only a very minor role for the spectrum of elementary particles. Still, the general way to the incorporation of the gravitational field seems to be rather clear. It would not be convenient to start, as Einstein had done, with a general Riemannian geometry. Thirring has been able to show in a very important paper, that one may very well start from a field equation invariant under Lorentz transformations, like the non-linear spinor equation. If the fundamental equation leads — among many other asymptotic fields — to a tensor field of long range, then this asymptotic field could have all the properties of the gravitational field. Such a long-range force could again appear in connection with an asymmetry of the groundstate "world", according to Goldstone's theorem. Gravitation would in this way again be a consequence of the macroscopic structure of the world, as in Einstein's theory.

Furthermore, Thirring has pointed out that the behavior of measuring rods and clocks would be influenced by the presence of such a gravitational field. If the four-dimensional geometry in space-time could be measured by real rods and clocks, the result would be a Riemannian geometry of just the type considered by Einstein. Therefore, this geometry is a natural but indirect consequence of the postulate, that the measuring rods and clocks should obey the same universal law expressed by the field equation; that the unified field theory should, as von Weiszäcker has put it, have its inner "semantic", its own consistent scheme of interpretation.

In the present state of physics, we are still very far from a complete solution to all these problems. There are many phenomena in elementary particle physics, and possibly elsewhere, which have not yet been properly understood within the framework of the unified field theory. Still, the program formulated by Einstein's fundamental idea has kept its philosophical force, in spite of, or rather because of, all the new experimental information about elementary particles, and defines in our time perhaps the most fascinating field of research.

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SPRINGER-VERLAG BERLIN · HEIDELBERG · NEW YORK 1971

Translated from the French by Barbara M. Crook, with the exception of the papers by J. R. Oppenheimer, W. Heisenberg, Sir Julian Huxley, G. Holton and B. M. Kedrov, also certain contributions to the debates, which were originally delivered in English.

Original publication in French by Gallimard.

Softcover reprint of the hardcover 1st edition 1967
Library of Congress Catalog Card Number 77-143044

ISBN-13: 978-3-642-95208-1 e-ISBN-13: 978-3-642-95206-7
DOI: 10.1007/ 978-3-642-95206-7