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Summary of the Chapel Hill Conference*

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This conference may be summarized under two main headings, classical theory of gravitation and quantization of general-relativistic theories; a third topic, the theory of measurement, forms a link between these two topics. I shall not attempt to summarize the discussion of cosmological problems by Dr. T. Gold and Dr. A. Lilley, because cosmology is a field of its own and, at least at present, not intimately connected with the other aspects of general relativity to which this conference has been devoted.

I. NONQUANTUM THEORY OF GRAVITATION

FOLLOWING roughly the outline of the conference itself, I shall begin with experimental work, past, current, and proposed. Professor J. A. Wheeler has given us a summary of the present status of the so-called "critical tests," that is the precession of planetary orbits, the deflection of light passing close to the sun, and the gravitational red shift. I think as nonspecialists we may consider the situation in this respect quite satisfactory, but additional work, leading to higher precision, is highly desirable. A very different type of experimental test of general relativity forms the first topic of Professor Dicke's talk. Whereas at least the two first of the critical tests are designed to provide confirmation of the detailed quantitative predictions of Einstein's 1916 theory of gravitation, the experiment by Eötvös tests the principle of equivalence, the root of *any* general-relativistic theory. I think that we shall all await with anticipation the outcome of these experiments by Dicke.

The remaining experiments suggested by Professor Dicke, which are not yet in the stage of actual planning, are mostly designed to see whether there is some minute variability in the universal parameters of elementary particles, which we used to consider as constants. I do not believe that the theories sponsored for instance by P. Jordan have as yet been clarified conceptually to the extent that they merit experimental testing. In this connection I call attention to a recent paper by M. Fierz in *Helvetica Physica Acta*. Of course, it might be interesting to test for variability of atomic constants irrespective of any detailed theory. Clearly a positive result of such experiments or observations would have most serious implications both for cosmology and for the theory of elementary particles.

Let me take up as the next topic the mathematical investigation of general-relativistic theories that have been reported principally by the members of the French group. I believe that the techniques pioneered by A. Lichnérowicz are applicable not only to the general theory of relativity and to the asymmetric theory, but to general-relativistic theories in general. The law of propagation for infinitesimal disturbances of the field will define the light cone in a physically convincing manner. I am very gratified to learn that there exists a method for formulating the Cauchy problem, but I take it that we do not as yet possess a method for constructing the variables whose values at time t are determined uniquely by the initial conditions set at the time t_0. If we had such a construction, these variables would presumably be identical with the "true observables," about which I shall have more to say later.

None of us can fail to be impressed with the availability of at least a few global theorems in general relativity, though one might wish that more, and more powerful ones, may be discovered in the years to come.

I shall now turn to the investigations that have been concerned with specific physical models that can be, or ought to be, constructed with the help of Einstein's field equations. It appears to me that the geons, which have been invented by J. A. Wheeler and which have been discussed here by him and by members of his group, cannot yet be considered to be actual solutions of the field equations, with or without electromagnetic terms. Geons are obtained in a manner that might be called a self-consistent approach: a collection of particles or waves, which is described in terms of statistical assemblies, with random phasing, serves as the source of a static gravitational field; the latter in turn confines the constituent particles to a limited region in space. Though these models undoubtedly have considerable heuristic value, I believe we all would be happier if it could be established that there exist at least some rigorous solutions of the field equations with properties similar to the geons.

In my opinion the most important nonquantum problem that has been discussed at this conference is the existence of gravitational waves. Actually there is a whole series of questions to which we should like to have answers. Many years ago A. Einstein and N. Rosen constructed rigorous waves radiated off the axis of a cylinder. According to N. Rosen and according to J.

* Work by the author in this field is currently being supported by the National Science Foundation and by the Air Force Office of Scientific Research. In this paper I have consolidated the introduction to the sessions on the quantum theory of gravitation with my summary talk. Of course I have been influenced by the talks and discussions of the conference; but I must accept personal responsibility for the selection of material and for all opinions voiced.

Weber these waves do not carry energy in any physical sense. It may well be that because of the line singularity extending into spatial infinity any attempt to balance energy, in the sense of an equation of continuity, is foredoomed to failure. In that case we should want to focus our attention on spherical waves. At present we do not know whether there exist any rigorous solutions of the field equations that may be interpreted as spherical waves, nor do we know whether such solutions carry energy from a center of radiation toward infinity.

Another unsolved question is whether a first approximation of a double-star system gives rise to gravitational waves and whether these waves carry energy proportional to the square of the amplitude. From the point of view of the astronomer, all these questions may appear highly academic, because gravitational waves, if generated by astronomical systems, undoubtedly play a negligible role in the energy budget of stars, compared to electromagnetic radiation and compared to the exchange of particles with the surrounding space. But in view of our interest in the role that gravitation, and particularly its quantum properties, may play in microphysics, the existence and the properties of gravitational waves represent an issue of preeminent physical significance.

Only in passing I should like to remind you of the investigations by the Princeton group of the stability of model universes, and of the pair of accelerated mass dipoles constructed by H. Bondi. The latter is one of the very few rigorous solutions of the field equations that are not static; as a model it may well prove of great value in future investigations.

I shall comment on the wormhole picture presented by Professor J. A. Wheeler in my final remarks on elementary particle problems.

We have had some discussions concerning the prospects of unified field theories and a number of different views have been presented. Wheeler considers that it may well be that all the physical fields known to us at present will turn out to be manifestations of but one field, the original gravitational field of Einstein's theory of 1916. Others are following up the possibilities inherent in asymmetric field theories. A third approach, unfortunately not represented at this conference, is being followed by Professor O. Klein; he has been interested in five-dimensional manifolds with periodicity properties such that there exists a sort of isotopic spin transformation. Personally, I am convinced of the long-range desirability of some unified field theory; but I have the impression that right now we are obtaining so much information about new fields and new types of particles that it may be advisable to wait for a few years before making a new determined attempt at unification.

II. THEORY OF MEASUREMENT

In recent years several different workers have asked which physical aspects of general-relativistic fields are susceptible to observation and measurement. This problem differs from the corresponding problem in Lorentz-covariant theories in that in the latter type of theory a world point is identifiable by means of its coordinates, and irrespective of the physical fields present. Accordingly we may, at least classically, speak of the value of a field, or a field component, at such a world point unambiguously. But in general relativity the identification of a world point in terms of its coordinate values lacks any invariant meaning unless the coordinate system is fixed in its immediate vicinity by means of physically real instrument components, such as rods and clocks. Naturally the presence of such instruments will in turn affect the field to be measured at that world point.

Classically we may make the instruments negligibly small and light and thus minimize the reaction. Even so I think it represents real progress that Dr. Pirani has shown us how to measure (classically) the individual components of the Riemann-Christoffel curvature tensor.

As for the quantum theory of measurement we have the contributions by Dr. H. Salecker and the remarks by Professor L. Rosenfeld. I believe that in conceptual experiments it is dangerous to introduce for the purpose of observations instruments that are not made an integral part of the physical system itself. The experiment with a diffraction grating suggested by Dr. Salecker can however be freed of this objection. Suppose we consider a small planetary system with gravitational attraction in a low quantum state. Even if the central body is assumed to possess a very large mass, the DeBroglie wavelength of the small particle depends on its mass. Hence the quantum orbits will depend on the planetary mass as well, and we find that such a model is not subject to an equivalence principle. This result is not to be construed as a violation of the usual principle of equivalence in quantum theory: properly speaking the principle of equivalence refers to local conditions, whereas the phase integral rule applies to a global model.

If I understand Professor Rosenfeld's remarks rightly, he suggests that the safest procedure is to have the observability of a physical quantity decided on the basis of formal quantum theory. Subsequently the edicts of the theory can be buttressed by conceptual experiments.

III. QUANTUM THEORY OF GRAVITATION

Basically we feel the need for a quantum theory of the gravitational field, because we cannot reconcile ourselves to the idea that classical and quantum fields can exist side by side. More particularly it appears unlikely that a mass point that gives rise to a classical Schwarzschild field is itself subject to Heisenberg's uncertainty relations. This, I believe, is the principal argument in favor of quantization. On the positive side, we may perhaps hope with Pauli that quantizing the metric tensor may ameliorate the infinities of the other field propagators along the light cone and that it may make a contribution to the theory of elementary particles.

The task of quantizing the metric field is not yet really close to its solution. If I am to describe its present status, I would divide all approaches known to me into those that take their point of departure from some canonical or Lagrangian formulation of the theory and those that attempt a path-integral quantization. There appears little doubt that for all approaches belonging to the first class the construction of so-called *true observables* is an unavoidable preliminary.

For those who are not familiar with the terminology let me repeat that a true observable is a physical variable whose value is independent of the choice of coordinate system, gauge frame, and the like. Incidentally, true observables are also the appropriate variables for the formulation of the Cauchy problem. Analytically they may be described as variables whose Poisson brackets with all the constraints of the theory vanish.

J. Géhéniau, and independently A. Komar, have proposed to construct true observables with the help of methods of differential geometry. Unfortunately we have been unable to learn of this work directly from them at this conference. E. Newman and I have worked out a method by which we obtain true observables in the course of a systematic approximation procedure; our work may be suspect because we have no assurance that our approximation converges toward the correct quantities. Finally one might hope that the method used so successfully by Fermi in electromagnetic theory will lead toward the true observables in the theory of gravitation; A. Janis and I have looked into this question and have reluctantly concluded that this hope is probably unjustified.

I come now to the proposals involving quantization by means of path integrals. Within this classification there appear two schools of thought, those who believe that true observables are a prerequisite for this method of quantization as well, and those who propose to go ahead and calculate formal expressions in terms of the original $g_{\mu\nu}$, in the hope that these expressions will automatically be useful propagators. Feynman has given this latter group encouragement. Perhaps just to balance any effect that his words may have I should like to voice my opinion to the effect that in the theory of gravitation any calculation that you may attempt will involve such enormous amounts of labor, and will lead to results of such complexity, that generally a look at the final expressions will not enlighten us much.

In conclusion I should like to comment, briefly at least, on the word pictures of elementary particle theory presented to us by Professor J. A. Wheeler and Dr. S. Deser. If we permit the components of the metric tensor to fluctuate widely and without regard to each other, there will be many regions in which the signature of the metric changes and which no longer correspond to a singly connected Riemannian manifold. Thus Wheeler arrives at a figure of 10^{60} wormholes in the volume of space filled by a single electron. According to this picture, elementary particles are by no means simple structures but some sort of collective modes of the froth of the vacuum. Deser proposes a different approach. He wants to carry out a path-integral calculation with a Lagrangian combining the gravitational, electromagnetic, and other fields. He proposes to proceed first with a fixed metric tensor, so that he may quantize the other fields in a given c-number Riemannian manifold; the quantization of the metric field itself is to be left for the final stage of the calculation. Feynman has attacked Deser's proposal on the grounds that it fails to resolve the divergences of the self-energy diagrams, but I cannot accept Feynman's argument as conclusive. At any rate both Wheeler's and Deser's proposals promise a fresh attack on the structure of elementary particles. It will be very interesting to see whether either of the proposals can be made to yield results.

In summary then, I believe that in the time between this conference and the next relativity conference (planned in Europe for the summer of 1958) we have a good chance to make significant progress in the two classical problems concerning gravitational waves and true observables, and that thereby we may also contribute to the task of quantizing general-relativistic fields.