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Invited paper presented at the Symposium on the Foundations of Modern Physics, 50 Years of the Einstein-Podolsky-Rosen Gedanken Experiment, Joensuu, Finland, June 16-20, 1985

ON THE UNIFICATION OF QUANTUM THEORY AND CLASSICAL PHYSICS

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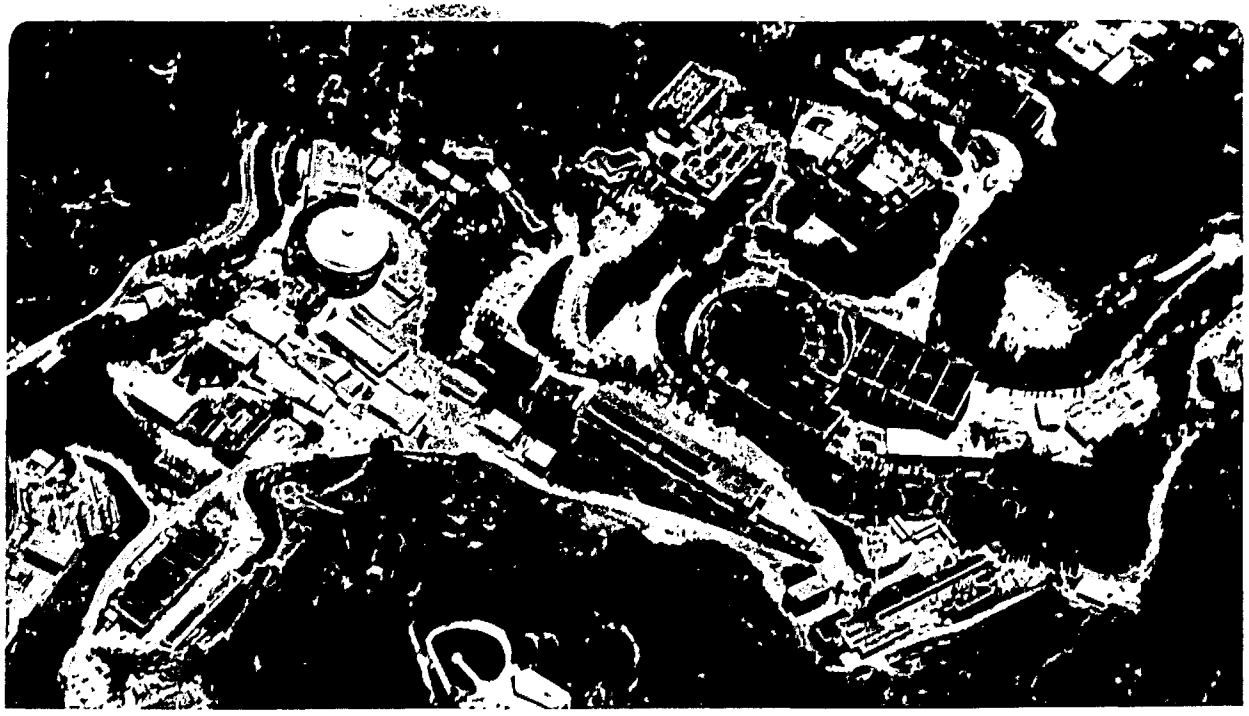

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ON THE UNIFICATION OF QUANTUM THEORY AND CLASSICAL PHYSICS

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ABSTRACT

A program is described for unifying quantum theory and classical physics on the basis of the Copenhagen-interpretation idea of external reality and a recently discovered classical part of the electromagnetic field. The program effects an integration of the intuitions of Heisenberg, Bohr, and Einstein.

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1. LIMITATION IN SCOPE OF CONTEMPORARY QUANTUM THEORY

Quantum theory in its present form can be applied only to situations in which the unified physical world can be considered divided into two parts, such that one part, the object, can be described in terms of quantum states, and the other part, the measuring systems, can be described in terms of the concepts of classical physics. In the words of Niels Bohr:

> *This necessity of discriminating in each experimental arrangement between those parts of the physical system considered which are to be treated as measuring instruments and those which constitute the object under investigation may indeed be said to form a <u>principal distinction between classical and quantum-mechanical description of physical phenomena</u>. ...*
> *While ... in classical physics the distinction between object and measuring agencies does not entail any difference in the character of the description of the phenomena concerned, its fundamental importance in quantum theory ... has its roots in the indispensible use of classical concepts in the interpretation of all proper measuremeants ...* [1]

Bohr has also stressed that "the definition of a state of a system, as ordinarily understood, claims the elimination of all external disturbance"[2]
Indeed, the separation described above can be made only if the quantum object during the period between its preparation and detection by measuring instruments has no significant influence upon its classically described environment. Otherwise, quantum-mechanical phase information will be transferred to the environment, and the Schroedinger equation for the object will fail, as it in fact does when the object interacts with the measuring instruments. These instruments, on the other hand, are large enough to significantly influence their environment. The resulting disruption of phase relationships renders a quantum-mechanical description of these devices impossible, and opens the possibility that a description in terms of the concepts of classical physics might be adequate.

In the domain of atomic physics this division of the world into these separate parts, can be achieved. But, as both Bohr[3] and Heisenberg[4] have emphasized, it is not clear how far the required idealizations can be extended into other domains of science. Indeed, as the object is increased in size a point must eventually be reached where it is neither small enough to have only negligible influence upon its environment, nor large enough to be described classically. At this point a limit in the scope of contemporary quantum theory is reached.

2. COPENHAGEN-INTERPRETATION IDEA OF EXTERNAL REALITY

A basic element of the orthodox Copenhagen interpretation of quantum theory is the precept that the quantum-theoretical formalism should be regarded not as a description of "external reality itself", in the normal sense of these words, but merely as a tool for making predictions about observations. In the words of Bohr:

> *... the appropriate physical interpretation of the symbolic quantum mechanical formalism amounts only to predictions, of determinate or statistical character, pertaining to individual phenomena appearing under conditions defined by classical physical concepts.*[5]

or

> *Strictly speaking, the mathematical formalism of quantum mechanics and electrodynamics merely offers rules of calculation for the deduction of expectations pertaining to observations obtained under well-defined experimental conditions specified by classical physical concepts.*[6]

Although the Copenhagen interpretation is able, by virtue of this pragmatic stance,[7] to avoid all commitment regarding the nature of "external reality", there is nevertheless an underlying, but unarticulated, acceptance in the writings of Bohr of the idea that our observations are not the only things in Nature; that our observations are observations of realities that are not dependent upon their being observed by somebody.

Heisenberg, in the chapter on the Copenhagen interpretation in his 1958 book "Physics and Philosophy", goes beyond the more cautious wordings of Bohr. He offers a description of external reality itself:

> *If we want to describe what happens in an atomic event, we have to realize that the word "happens" can apply only to the observations, not to the state of affairs between two observations. It applies to the physical, not the psychical act of observation, and we may say that the transition from the "possible" to the "actual" takes place as soon as the interaction of the object with the measuring device, and thereby with the rest of the world, has taken place; it is not connected with the act of registration of the result in the mind of the observer. The discontinuous change in the probability function, however, takes place with the act of registration, because it is the discontinuous change in our knowledge in the instant of recognition that has its image in the discontinuous change of the probability function.*[8]

This description of external reality is gratuitous: it does not enter into either the formalism or our use of the formalism.

Heisenberg's idea of external reality is different from the one brought to mind by classical physics. Instead of a deterministic continuous evolution that eventually fills the entire spacetime continuum with a continuous microscopic picture of the history of the world, one has discrete happenings. These events are transitions from the "possible" to the "actual", and they occur only under special macroscopic conditions.

von Weizsäcker has emphasized to me that this picture of external reality described by Heisenberg is in general accord with the ideas of Bohr. I shall therefore call it the Copenhagen-interpretation idea of external reality.

3. COPENHAGEN-INTERPRETATION IDEA OF EXTERNAL REALITY AS BASIS FOR EXTENSION OF QUANTUM THEORY

If quantum theory is to be extended into domains of science where the idealized division of the physical world into object and agencies of measurement is no longer possible then it is likely that a representation of external reality will need to be introduced into the formalism. Among the possible conceptions of external reality a prime candidate is the one of Bohr and Heisenberg. This conception is in general accord with the ideas of orthodox quantum theorists, and, as we shall see, it can be brought into conformity with the principal demands of Einstein.

4. ORIGIN OF THE CLASSICAL CHARACTER OF MACROSCOPIC PHENOMENA

According to Bohr, the measurements we make can be described in terms of classical physical concepts. To bring the contemplated extension of quantum theory into ideal alignment with the ideas of Bohr and Heisenberg the transition from the "possible" to the "actual" should create realities that can be described in terms of the concepts of classical physics. This would resolve the basic puzzle of quantum theory, which is: why can the observable phenomena be described in terms of the concepts of classical physics.

Bohr argues for the indispensible use of classical concepts as follows:

... we must recognize above all that, even when the phenomena transcends the scope of classical physical theories, the account of the experimental arrangement must be given in plain language, suitably supplemented by technical physical terminology. This is a clear logical demand, since the very word "experiment" refers to situations where we can tell others what we have done and what we have learned.[9]

This argument might explain why we must use classical physical concepts. But it does not explain why we can use classical physical concepts: it does not explain why the classical physical concepts work so well in the vast domain of classical physics. Of course, certain classical relationships do emerge from quantum theory from certain averaging procedures. But quantum theory gives predictions "pertaining to individual situations", not averaged-out situations. Consequently, the adequacy of classical physical concepts for the description of phenomena is not actually entailed either by the quantum theoretical dynamical laws or by general logical requirements. It is simply put in by hand, as a matter of empirical fact.

In situations where we can cleanly separate the quantum object from its classically described environment we can simply assert that one theory applies to one system and the incompatible theory applies to the other system, and connect the two parts only statistically. But in the more general situation where no such clean separation is possible the unified theory must cope with the interpenetration of the aspects of nature represented by the classical and quantum concepts.

5. CLASSICAL PART OF ELECTROMAGNETIC FIELD

Attempts to unify classical physics and quantum theory have been frustrated by fundamental differences in their structures. For example, the classical electromagnetic field is represented by a single function of one spacetime variable, whereas its quantum theoretical analog is either an operator, or an infinite, interconnected set of functions of $3n + 1$ degrees of freedom, where n ranges from zero to infinity. The classical description seems to arise from the quantum description only through certain averaging or limiting procedures. A more subtle difficulty had been that in quantum electrodynamics, due to the infrared divergence problem, the classical spacetime structure did not even seem to emerge in appropriate macroscopic limits.

A recent resolution[10] of this second problem has altered the situation also in regard to the first. For this solution has revealed that there is in quantum electrodynamics a precisely

defined classical part of the electromagnetic field. This classical part arises from neither averaging nor limiting procedures.

The classical part of the electromagnetic quantum field arises from a separation of the usual electromagnetic current into its "classical" and "quantum" parts: the classical part of the electromagnetic field is the part that arises from the classical part of the current. This classical part of the electromagnetic quantum field has various classical features,[13] and it may provide a basis for integrating classical physics and quantum theory.

The separation between the classical and quantum parts of the electromagnetic current has a simple form only in the spacetime representation. It is based on the introduction of classical vertices, located at spacetime points. The classical part of the current is defined in conjunction with these classical vertices. Each charged particle (electron or positron) is represented by a Feynman spacetime trajectory containing vertices at which photons are emitted or absorbed. Exactly one photon is emitted or absorbed at each quantum vertex, but an arbitrary number can be emitted or absorbed at each classical vertex.

One can introduce a classical current trajectory that passes from one classical vertex to the next, skipping the quantum vertices. The photons emitted and absorbed at a classical vertex depend only upon the location of that vertex, the directions of the spacetime lines to the two neighboring classical vertices, and the momentum of the associated photon. For a given classical current trajectory, with fixed spacetime vertices, each photon emitted or absorbed at a classical vertex is emitted or absorbed independently of every other one, and of everything else. Consequently, for closed charged-particle loops, one can sum the contributions from all numbers of photons emitted and absorbed at all the classical vertices. The result can be represented in closed form as an operator in the space of initial and final photons. In the physical sector this operator is unitary. Acting upon the photon vacuum it creates a quantum state that is precisely that coherent state which corresponds to the unique classical field radiated by a charge e moving along the classical current trajectory. This state, and also the operator that creates it, is completely specified by this classical field, which is a single function over the spacetime continuum of classical physics. Thus for each classical current trajectory the associated quantum field can be represented in terms of the concepts of classical physics.

The numerical coefficient of this classically described field is essentially the amplitude for the quantum-mechanical particle represented by the original trajectory to pass through the fixed set of classical vertices. Thus the classical current acts, in effect, like a classically described probe of the distribution of the charged quantum-mechanical particles.

6. THE CLASSICAL PART OF THE ELECTROMAGNETIC FIELD AS THE EXTERNAL REALITY

To account for the detailed success of the concepts of classical physics in the domain of classical physics, within the framework of the Copenhagen-interpretation idea of external reality, it would seem that the transition from the "possible" to the "actual" should bring into being some ingredient of the classical description of nature. The foregoing section suggests that this ingredient should be some aspect or component of the classical electromagnetic field. The happening, or macroevent, would then be analogous to what occurs in a measurement situation, where some classically describable result appears. However the pertinence of the concepts of classical physics would now not be tied to human observers, but would arise from the presence in external reality, as represented in our theory, of the appropriate classical quantities.

The history of classical physics suggests that the concepts of classical physics correspond to aspects of nature that do not depend upon their being observed by somebody. An ideal physical theory should reflect this fact by allowing the classical features to be independent of observers. The present proposal conforms to this ideal. However, it is based upon the Copenhagen-interpretation idea of external reality. It also conforms to Einstein's demands that basic physical theory represent the real external situation,[11] and that this reality be represented by functions defined on the spacetime continuum.[12]

Technical details pertaining to the elaboration of the general program outlined above can be found elsewhere.[13], [14]

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