Microphysical Reality and Quantum Formalism

Volume 2

Fundamental Theories of Physics

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Fundamental Theories of Physics

A New International Book Series on The Fundamental Theories of Physics: Their Clarification, Development and Application

PREFACE

Quantum mechanics has reached maturity as an awesome scientific theory, and undeniably no experiment has so far produced any result conflicting with its predictions. Nevertheless, an increasing number of scholars are seriously questioning the limits of this discipline's validity, a fact that is eloquently attested to by the four international conferences devoted to the foundations of quantum theory which were held in 1987 alone - in Joensuu, Vienna, Gdansk, and Delphi, respectively. There is an increasing awareness that the founding fathers of quantum mechanics have left behind a theory which, though spectacularly successful in its applications, severely limits our intuitive understanding of the microworld, and that their reasons for doing so were at least partly arbitrary and open to question.

The problem of the relationship between the existing quantum theory and objective reality at the atomic and subatomic levels can be tackled in essentially two ways:

(i) One may focus attention on the *formalism* of the theory and attempt to deduce from it a coherent description of our measuring processes and a deeper understanding of the microworld.

(ii) Alternatively, one may start from the experimental evidence and/or from models of the objective reality compatible with it and go on to investigate whether or not formalization of this knowledge can be accomodated within the broad confines of existing quantum theory.

The thirty-eight papers collected in the present book, the second of a two-volume set, approach the forementioned problem mostly from the second point of view. The large majority of them was presented at the International Conference on Microphysical Reality and Quantum Formalism which was held in Urbino (Italy) from September 25 through October 3 of 1985. In more than one way, this meeting was a unique event - because of the large number of participants (about two hundred physicists and philosophers of science from all corners of the world), because of the feeling of liberation and achievement that prevailed among them, and because of the exceptionally high quality of many of the papers that were read.

Remarkable trends and exciting results are reported in the present volume; some of the highlights involved are:

1. More than half of the thirteen papers dealing with the wave-particle duality problem discuss either proposed experiments or experiments that have already been performed.
2. New experimental data are also presented in papers examining the EPR paradox.
3. The analysis of earlier experimental investigations into the EPR paradox has led to the conclusion of their full compatibility with local realism and to an important distinction between inhomogeneous ("Bell-like") inequalities and homogeneous ("CHSH-like") inequalities.

4. The objection to "counterfactuality" in previous proofs of the EPR paradox can be overcome.
5. An increasing number of quantum phenomena have found a natural interpretation in terms of a causal model that utilizes particle trajectories along with a "quantum potential" representing the physical action of the quantum wave on the particle.

The unifying idea behind researches such as these is the realization that new and important discoveries lie within the reach of scholars working on the foundations of modern physics. On the other hand, it becomes clear on inspection that very significant differences in perspective, programs, and priorities exist between the workers involved. But such a diversity of approaches was of course to be expected in a field of activity that has started to flourish only in recent years and that seeks to fathom the full extent of revolutionary ideas originated by profound thinkers who, in addition to a successful formalism, also left us in possession of a badly divided set of conceptions concerning the relationship of this formalism to microphysical reality.

The editors wish to thank the organizers of the Urbino conference and everyone else who contributed to the success of this impressive meeting. Particularly deserving of our appreciation are the members of the International Advisory Committee: David Bohm (London), Max Jammer (Ramat-Gan), Trevor Marshall (Manchester), Oreste Piccioni (La Jolla), Karl Popper (London), Ilya Prigogine (Brussels), Emilio Santos (Santander), Roman Sexl (Vienna), John Wheeler (Austin), and Eugene Wigner (Princeton). We also owe a debt of gratitude for financial support to the Italian Consiglio Nazionale delle Ricerche, to the Istituto Nazionale di Fisica Nucleare, and to the Provincia di Pesaro e Urbino.

Franco Selleri
Gino Tarozzi
Alwyn van der Merwe

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A REALIST VIEW OF QUANTUM THEORY

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ABSTRACT

In this paper[1] a realist view that is consistent with the quantum theory is systematically developed. The starting point is the causal interpretation of quantum theory, which assumes that the electron is a particle always accompanied by a wave satisfying Schrödinger's equation. This wave determines a quantum potential, which has several qualitatively new features, that account for the difference between classical theory and quantum theory.

Firstly, the quantum potential depends only on the form of the wave function and not on its amplitude, so that its effect does not necessarily fall off with the distance. From this, it follows that a system may not be separable from distant features of its environment and may be nonlocally connected to other systems that are quite far away from it.

Secondly, in a many-body system, the quantum potential depends on the overall quantum state in a way that cannot be expressed as a preassigned interaction among the particles. These two features of the quantum potential together imply a certain new quality of quantum wholeness which is brought out in some detail in this article.

Thirdly, the quantum potential can develop unstable bifurcation points, which separate classes of particle trajectories according to the "channels" into which they eventually enter and within which they stay. This explains how measurement is possible without "collapse" of the wave function and without the need for a human observer. The fact that the observer does not play a fundamental role in the theory means that the causal interpretation is more appropriate especially for cosmology than are the usual approaches.

1. INTRODUCTION

Quantum theory has been presented almost universally as a theory giving nothing but statistical predictions of the results of measurements. It therefore imparts a fundamental significance both to

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epistemology and to probability. In 1952, a causal interpretation of the quantum theory was presented. This approach was expressed directly in terms of the motions of individual systems, and there was no need to attribute a basic role either to measurement or to probabilities. The measurement process itself was indeed later analyzed in some detail.(2) It was shown in this analysis that the objective reality of the individual measurement process can be maintained consistently without the need to appeal either to the "collapse of the wave function," or to the consciousness of an observer.

However, insofar as in this treatment there remains a rather strong emphasis on the role of the measuring apparatus, it might seem at first sight that epistemology is still being given a significant basic role, at least tacitly. In the present paper, we shall meet the problem by showing in some detail how the whole theory can be put solely in terms of what Bell(3,4) has called "beables," i.e., things that are assumed to exist whether they are observed or not. "Observables" are then seen to be nothing but special cases of what is happening among the beables (involving, for example, the interaction of the individual system of interest with a measuring apparatus, in an actual process in which the objective existence of both is taken to be *essentially* on the same footing). Thus in this approach there is a single notion of reality that is valid at all levels, and the classical behaviour results when a certain typically quantum mechanical contribution to this reality (the quantum potential) can be neglected.

2. NEW ONTOLOGICAL IMPLICATIONS OF THE CAUSAL INTERPRETATION

We shall now develop in some detail the main new implications of the causal interpretation of quantum theory. Firstly, we suppose that the electron, for example, actually *is* a certain kind of particle following a continuous and causally determined trajectory. This particle, however, is never separated from a new type of quantum wave field that belongs to it and that fundamentally affects it. This quantum field, $\psi(x,t)$, satisfies Schrödinger's equation, just as the electromagnetic field satisfies Maxwell's equations. It, too, is therefore causally determined.

In classical physics, a particle moves according to Newton's laws of motion, and, as is well known, the forces that enter into these laws can be derived from the classical potential V. The basic proposal in the causal interpretation is that the quantum theory can be understood in a relatively simple way by assuming that the particle is also acted on by an additional quantum potential Q, given by

$$Q = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}, \quad \text{where } R = |\psi|^2 \tag{1}$$

and h is Planck's constant, while m is the mass of the particle. Evidently, the quantum potential is determined by the quantum wave field ψ.

To justify this proposal, we begin by considering Schrödinger's equation for a single particle,

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + V\psi \tag{2}$$

We write

$$\psi = Re^{iS/\hbar}$$

and obtain

$$\frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{2m} + V + Q = 0 \tag{3}$$

where Q is given in eq. (1) and

$$\frac{\partial P}{\partial t} + \frac{\nabla.(P\nabla S)}{m} = 0, \quad \text{with } P = R^2. \tag{4}$$

Clearly eq. (3) resembles the Hamilton-Jacobi equation except for additional term Q. This suggests that we may regard the electron as a particle with momentum $\underline{p} = \underline{\nabla}S$ subject not only to the classical potential V but also to the quantum potential Q. Indeed the action of the quantum potential will then be the major source of the difference between classical and quantum theories. This quantum potential depends on the Schrödinger field ψ and is determined by the actual solution of the Schrödinger equation in any particular case.

Given that the electron is always accompanied by its Schrödinger field, we may then say that the whole system is causally determined; hence the name "causal interpretation."

Equation (4) can evidently be regarded as a continuity equation with $P = R^2$ being a probability density, as Born suggested. The function P has, however, two interpretations, one through the quantum potential and the other through the probability density. It is our proposal that the fundamental meaning of R (and therefore indirectly of P) is that it determines the quantum potential. A secondary meaning is that it gives the probability density for the particle to *be* at a certain position. Here we differ from Born who supposed that it was the probability of *finding* the particle there in a suitable measurement. Indeed, as has been pointed out in the introduction, in the causal interpretation the measurement process itself has to be interpreted as a particular application of the theory, which is formulated basically in terms of "beables" rather than of "observables"(2) (while the observables are treated as statistical functions of the beables).

Equation (4) implies that it is consistent to interpret P as a probability density in a statistical ensemble of well-defined trajectories, each following the causal laws described above. For, if the density holds initially, then this equation guarantees that it will hold for all time. We shall discuss the question of why there is such a statistical ensemble further on, as well as why its probability density will approach $|\psi|^2$, no matter what the initial form of this density may have been.

As the theory develops, we shall find that the electron is by no means a structureless particle. Rather, what is suggested by its behavior is that it is a highly complex entity that is deeply affected by its quantum field in an extremely subtle and dynamic way. Moreover, this entity is not to be regarded (as is done in the usual interpretations) as somehow directly possessing both particle-like and wave-like properties. Rather, the observed wave-like properties will follow, as we shall see, from the general effect of the quantum wave field on the complex structure of the particle.

At first sight, it may seem that to consider the electron as some kind of particle that is affected by the quantum field ψ is a return to older classical ideas. Such a notion is generally felt to have long since been proved to be inadequate for the understanding of quantum processes. However, closer inspection shows that this is not actually a return to ideas of this sort. For, the quantum potential has a number of strikingly novel features, which do not cohere with what is generally accepted as the essential structure of classical physics. As we shall see, these are just such as to imply the qualitatively new properties of matter that are revealed by the quantum theory.

The first of these new properties can be seen by noting that the quantum potential is not changed when we multiply the field intensity ψ by an arbitrary constant. (This is because ψ appears both in the numerator and the denominator of Q.) This means that the effect of the quantum potential is independent of the strength (i.e., the intensity) of the quantum field but depends only on its *form*. By contrast, classical waves, which act mechanically (i.e., to transfer energy and momentum, for example, to push a floating object), always produce effects that are more or less proportional to the strength of the wave.

To give an analogy, we may consider a ship on automatic pilot being guided by radio waves. Here too, the effect of the radio waves is independent of their intensity and depends only on their form. The essential point is that the ship is moving with its own energy, and that the *information* in the radio waves is taken up to direct the much greater energy of the ship. We may therefore propose that an electron too moves under its own energy, and that the information in the *form* of the quantum wave directs the energy of the electron.

This introduces several new features into the movement. First of all, it means that particles moving in empty space under the action of no classical forces still need not travel uniformly in straight lines. This is a radical departure from classical Newtonian theory. Moreover, since the effect of the wave does not necessarily fall off with the intensity, even distant features of the environment can profoundly affect the movement. As an example, let us consider the interference experiment. This involves a system of two slits. A particle is incident on this system, along with its quantum wave. While the particle can only go through one slit or the other, the wave goes through both. On the outgoing side of the slit system, the waves interfere to produce a complex quantum potential which does not in general fall off with the distance from the slits. This potential is shown in Fig. 1.

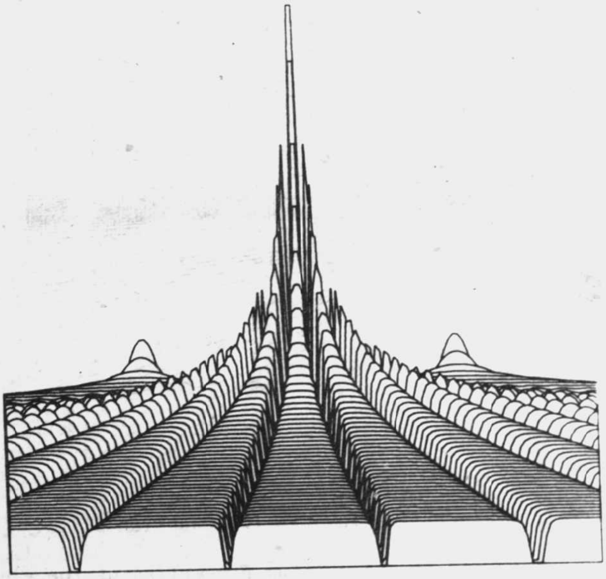

Fig. 1. The quantum potential for two Gaussian slits viewed from screen.

Note the deep "valleys" and broad "plateau." In the regions where the quantum potential changes rapidly there is a strong force on the particle. The particle is thus deflected, even though no ordinary type of force is acting. The movement of the particle is therefore modified as shown in Fig. 2 (which contains an ensemble of possible trajectories).