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Unbroken Quantum Realism, from Microscopic to Macroscopic Levels

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By means of the quantum-potential interpretation we show that there is no need for a break or "cut" in the way we regard reality between quantum and classical levels.

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Because of the possible appearance of macroscopic quantum tunnelling in superconducting quantum interference devices, Leggett and Garg[1] have questioned the commonly accepted view concerning the role of macroscopic and microscopic realism in quantum theory, i.e., that while quantum mechanics presupposes macroscopic realism, it is not compatible with microscopic realism (or else, if there is an underlying microscopic reality, it is, as brought out in some detail by d'Espagnat,[2] assumed to be "veiled" and thus not capable of being discussed in physics). Such a view, however, raises the further question of how the classical limit is approached. Where, for example, does the nonrealistic or veiled realistic quantum level turn into the evidently realistic level? If there is no such point, then it should definitely be possible to have macroscopic quantum phenomena. Would these then be realistic, nonrealistic, or veiled realistic? What is involved here is, of course, not the predictions of the theory but the question of the ontological status of the microscopic level and the relationship of this level with the classical level.

There is, however, another approach to these problems, i.e., the quantum-potential interpretation, in which microreality, in the usual sense of the word, is assumed from the outset. This interpretation has been applied successfully in a variety of cases, including electron interference,[3] single-crystal neutron interferometry,[4] and the delayed-choice experiment of Wheeler.[5] In this approach, individual quantum systems are taken to be real, independent of all discussion of measuring apparatus and of preparation of the quantum state. Moreover, because all levels are thus assumed to be real, there is an unbroken approach to the classical limit, which arises in a very simple and direct way wherever this quantum potential can be neglected. We feel that this interpretation may provide insight into the questions that are being raised in this context because it avoids making the distinction between realism in the classical level and some kind of nonrealism in the quantum level that produces the difficulty in the first place.

In order to understand how the quantum-potential interpretation makes possible universal realism we have first to bring out some of the main features of our point of view. These include the following:

(1) The electron is assumed to be a particle which is always accompanied by a quantum field, ψ, that satisfies Schrödinger's equation. Both are assumed to be objectively real. This means that we no longer regard the wave function as the most complete possible description of the state of the system.

(2) By expressing the quantum field in polar form as $\psi = R^{iS/\hbar}$, we obtain for Schrödinger's equation

$$\frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{2m} + V + Q = 0, \quad Q = \frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}, \quad (1)$$

$$\partial R^2/\partial t + \mathrm{div}(R^2 \nabla S/m) = 0. \quad (2)$$

The first of these equations reduces to the classical Hamilton-Jacobi equation, if Q can be neglected. If Q is not negligible, it constitutes, in effect, an additional potential which we call the quantum potential. This equation describes trajectories of a particle, with momentum $p = \nabla S$. Such trajectories can be calculated for this case too, and this has indeed been done for the two-slit interference experiment.[3] The second equation then expresses conservation of probability, with density $P = R^2$.

(3) We propose that the quantum potential is basically what is responsible for the new features of the quantum theory. We have indeed already illustrated this with the aid of many examples, but ultimately these depended for their meaning on the assumption of a measuring apparatus. However, we can now show that this is not necessary. To illustrate how this works, we consider an atom containing an electron with coordinate $\mathbf{x}$, having an initial wave function $\psi_i(\mathbf{x}) \times \exp(-iE_0t/\hbar)$, corresponding to a stationary state with energy E_0. This atom is to "jump" to a new state with wave function $\psi_f(\mathbf{x})\exp(-iE_ft/\hbar)$, and energy E_f. In order to make this possible, we assume an additional particle with coordinates $\mathbf{y}$, which will take up the energy $E_0 - E_f$, released in the transition in an Auger-type effect. If $\phi_0(\mathbf{y},t)$ is the initial wave function of this additional particle, which we assume to be a wave packet, the combined system will have an initial wave function

$$\Psi_0(\mathbf{x},\mathbf{y},t) = \psi_0(\mathbf{x}) e^{-iE_0t/\hbar} \phi_0(\mathbf{y},t). \tag{3}$$

Through the interaction between the two particles, the combined wave function $\Psi(\mathbf{x},\mathbf{y},t)$ will begin to include other stationary states. To simplify the discussion, we assume that only one of these, $\psi_f(x) \times \exp(-iE_ft/\hbar)$, contributes significantly. The wave function of the combined system will then be

$$\Psi = \psi_0(\mathbf{x}) e^{-iE_0t/\hbar} \phi_0(\mathbf{y},t) + \int_0^t \alpha(t',t) \psi_f(x) e^{-iE_ft/\hbar} \phi_f(y,t-t')\, dt', \tag{4}$$

where $\alpha(t',t)$ can be calculated using time-dependent perturbation theory.

What the above formula means is that during a small interval of time dt', a contribution to the wave function will be produced which is given by the integrand. This corresponds to a $\mathbf{y}$ particle that during the time interval $t - t'$ moves away from the atom very rapidly (because it has absorbed the energy difference, $E_f - E_0$, which is very large). As a result, this part of the wave function will have a negligible overlap with $\phi_0(\mathbf{y},t)$. The integral then represents the sum of a set of contributions, each of which has moved a different distance from the atom, and ultimately from each other.

Up to this point, the treatment is essentially the same as in the usual approach to the quantum theory. But now we bring in the basically new feature of our approach; i.e., that the reality includes particles following well-defined trajectories, as well as the wave function. From the point of view of these particles, each of the nonoverlapping parts of the wave function described above establishes a separate "channel." It can be shown that the particle enters one of these channels and stays in it thereafter. If the particle is in such a channel, the quantum potential is determined by that channel alone, and the other channels do not contribute. Thus, the quantum potential, and therefore the behavior of the particle, is the same as if all the other channels had vanished, or equivalently, as if the wave function had "collapsed" to this channel under consideration (although in fact no collapse of any kind has actually taken place).

Moreover, a closer study shows that the totality of possible trajectories has many bifurcation points. On one side of each point, the system enters into a particular channel, and on the other side, it does not. One can thus see why an actual transition takes place in a time very much shorter than the mean lifetime of a quantum state, and in a more detailed treatment one can show why a watched state cannot undergo transition. Neither of these questions is adequately treated in other interpretations, but in the quantum-potential approach this can be done because the wave function does not exhaust the whole of reality. There is also the particle, which enables us to give meaning to the time of transition, and to the physical state of a system, whether it is being observed or not.

(4) There remains the problem of the ontological status of the part of the wave function corresponding to the possible results of this process which do not actually take place (i.e., the channels not occupied by particles). In a paper which will be published shortly[6] we develop an objective ontological basis of quantum mechanics in a detailed and systematic way and in doing so we propose a solution to the problem described above, along lines which we shall only briefly indicate here. The wave function, which is in a multidimensional configuration space, cannot be interpreted as a field producing a force or pressure that would transfer energy to the particles. Rather, our suggestion is that the particles move under their own energies but that the form of this motion is fundamentally affected by a multidimensionally ordered kind of information that is represented by the wave function. Because of the ultimate irreversibility of the various processes under discussion, the information represented by the wave packets corresponding to channels that are not occupied by particles is "lost" through dissipative activity, e.g., as in diffusion. Therefore, this information will cease to act, as for example would happen analogously to information printed on a page that was shredded and then dispersed (though, of course, the actual process that we have in mind[5] is much more subtle and dynamic than is this analogy).

(5) Since we have provided a completely objective ontology it follows that the quantum level is treated in a realistic way even if it should turn out that macro-

scopic states of low quantum number are possible, e.g., as in superconducting quantum interference devices. The distinction between the quantum and classical levels has thus nothing to do with the question of realism or nonrealism.

It has commonly been assumed that the classical level arises when $\hbar \to 0$ or else in the limit of high quantum numbers. But evidently, since $\hbar$ is fixed, it cannot go to zero. Moreover, though high quantum numbers generally imply classical behavior, they do not always do so. For example, a particular case where they do not is that of motion of a particle in a box with perfectly reflecting walls. Even when the quantum number is high, the wave function has a distribution of nodes, where there is zero probability of finding the particle. Classically such nodes are impossible, as the particle would have to move back and forth uniformly, and would therefore be able to be present everywhere with finite probability. To be sure, if the probe that measures position were "blunt" within a few de Broglie wavelengths, this effect would not show up. But in principle technical refinements would always be possible that would reveal the predicted nodes.

In this connection there is a common and very natural tendency to form the notion of some kind of further averaging process that would wipe out these nodes. This would, in fact, be appropriate for most large scale systems. For example, there might be averaging over random thermal disturbances due to the environment or, in a simpler case of the isolated system, one can take a linear combination of solution with a small range of energies to form a local wave packet. In this latter situation the amplitude of the wave function would change slowly so that the quantum potential would be negligible and the classical limit would therefore be approached for high quantum numbers.

However, if the system is isolated and its energy is well defined so that only one quantum state is present, then the nodes predicted inescapably by the quantum mechanics will have to be present. And because the amplitude of the wave function changes very rapidly so that the quantum potential will be very large, the dynamics will differ radically from what would be the case of the classical limit. Of course, such a state of well-defined energy requires a very special kind of experimental situation to bring it about and maintain it because it is (as a more detailed treatment shows) highly unstable to small perturbations.

Einstein[7] used the above example of the particle in a box to object to the quantum-potential interpretation, which, because the wave function for this case is real, implies that the momentum $p = \nabla S = 0$. Einstein felt that this violated physical intuition, which, for him, required that the particle move back and forth. Nevertheless, if there is a particle in the system at all, $p = 0$ is clearly a possibility that is consistent with nodes. Certainly, equiprobability of opposing velocities is not.

What was behind Einstein's feeling, however, was the assumption that high quantum numbers must always imply classical behavior. But if we reflect on this point further, we can see that Einstein's objection implied that quantum mechanics itself must be incorrect for this example, in the sense that its production of nodes in states of high quantum number for the probability density would have to be wrong if the particle moved in both directions with equal probabilities, as is required classically. However, if we replaced the impenetrable walls with high but penetrable barriers, this experiment would shade into an interference experiment. Indeed, it would be just the equivalent for electrons or neutrons of the Fabry-Perot interferometer. In fact, with neutron mirrors, it is actually possible[8] to set up such a quantum state experimentally. These states can be studied by observing the resonance behavior in a transmission through samples consisting of a sequence of three thin films, and indeed the results confirm the quantum theory. To be sure, these experiments were done with low quantum numbers. Yet it seems arbitrary to suppose that for reasons not known thus far, the quantum theory will fail beyond certain quantum numbers. Indeed, considering further the many kinds of macroscopic-scale quantum interference experiments for electrons and neutrons, some of them involving thousands of nodes, we can see no reason at all to doubt that the quantum theory is correct in this regard for indefinitely high quantum numbers. And so the prediction of nonclassical properties for such cases seems quite acceptable and, indeed, unavoidable. It is clear, therefore, that high quantum numbers are not a universally valid criterion for the classical limit. (Other authors have come to similar conclusions but through different approaches,[9–11] i.e., that a careful selection of quantum states yields nonclassical results not only at high quantum numbers but also on the large-scale level more generally.)

It is an advantage of our interpretation that it gives a simple and correct criterion for the classical limit; i.e., that the quantum potential be negligible. Our modified Hamilton-Jacobi equation (1), which includes both classical and quantum potentials, covers all cases. When the quantum potential is sufficiently small it is clear that the classical behavior follows in a very simple way. We are thus treating reality on all levels in the same way without the kind of break or "cut" between the quantum and classical levels that seems to be required in other interpretations. It would seem that in any investigation of macroscopic quantum phenomena, clarity would be enhanced if we do not need to introduce arbitrary dichotomies such as the one referred to at the beginning of this article, i.e., between evident macroscopic (classical) realism and microscopic (quantum) nonrealism or veiled realism.

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