Realism or Locality: Which Should We Abandon?

Raymond Y. Chiao* and John C. Garrison
Department of Physics, University of California, Berkeley, California 94720-7300
Tel: (510) 642-4965, (510) 642-5620, Fax: (510) 643-8497, E-mail:
chiao@physics.berkeley.edu, garrison@physics.berkeley.edu
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Abstract

We reconsider the consequences of the observed violations of Bell's inequalities. Two common responses to these violations are: (i) the rejection of realism and the retention of locality, and (ii) the rejection of locality and the retention of realism. Here we critique response (i). We argue that locality contains an implicit form of realism, since in a world view that embraces locality, spacetime, with its usual, fixed topology, has properties independent of measurement. Hence we argue that response (i) is incomplete, in that its rejection of realism is only partial.

^{*}On appointment as a Miller Research Professor in the Miller Institute for Basic Research in Science

I. INTRODUCTION

It is a great pleasure to dedicate this paper to Prof. Daniel Greenberger on the occasion of this Festschrift in his honor.

The proof of Bell's theorem [1] is based on the two main assumptions of realism and locality. Theories which satisfy these two assumptions are commonly called "local realistic theories."

Realism, roughly speaking, is the belief that there exists an objective world "out there" independent of our observations. This is the world view of classical physics. In an extension to quantum physics, this world view was expressed in the classic paper of Einstein, Podolsky and Rosen (EPR), when they made the following statement [2]:

"If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

In this formulation the authors have identified a class of situations for which, in their view, it would be absurd to deny independent physical reality [3] to a property of the system. This is not to say that there are no other "elements of physical reality" with definite (but possibly unknown and unpredictable) values which do not depend on measurement. We shall use the term elements of physical reality in this more general sense, reserving the term EPR elements of physical reality for the specific features described in the quotation. Thus in a realist's world view, there exist physical quantities with objective properties, which are independent of any acts of observation or measurement. For example, consider the case of two spin 1/2 particles emitted in opposite directions from a common spin zero source prepared in the Bohm singlet state [4],

$$|S_{total} = 0\rangle = \frac{1}{\sqrt{2}} \{ |S_{z1} = +1/2\rangle |S_{z2} = -1/2\rangle - |S_{z1} = -1/2\rangle |S_{z2} = +1/2\rangle \}.$$
 (1)

When a measurement of one particle, by a detector located at the end of one arm of the experimental apparatus, yields a definite result of spin $S_z = +1/2$, then conservation of the total spin angular momentum of the system necessarily requires that immediately upon this measurement, the other particle must definitely possess a spin $S_z = -1/2$, and that this result must be independent of whether or not any measurement is actually made on the other particle. According to EPR, this implies that the other particle must actually possess spin $S_z = -1/2$ as an EPR element of physical reality.

Locality is the other main assumption which goes into the proof of Bell's theorem. the The idea here is that what happens in a finite spacetime region A cannot be affected by what is done (e.g., by the choice of settings of measuring devices) in a spatially well-separated spacetime region B. In the context of special relativity, "spatially well-separated" means that all points of A have spacelike separations from all points of B. Thus the locality principle is usually assumed to be equivalent to relativistic causality, i.e., the nonexistence of controllable superluminal signals. Combining the idea of realism with the locality principle leads to a strong separability condition, i.e., the factorizability of joint probabilities of spacelike separated coincidence detections. This factorizability is the most important technical ingredient in the proof of Bell's theorem.

Many experiments have shown that the Bell's inequalities, which follow from Bell's theorem, are violated (apart from technical caveats concerning detection loopholes, etc.), and that the predictions of quantum theory, which also violate these inequalities, are confirmed. These observations imply that some or all of the assumptions used in the proof of Bell's theorem are inconsistent with experiment. In addition to realism and locality, there are auxiliary (but not necessarily independent) assumptions, which include absence of advanced actions, contrafactual definiteness, etc. In accord with the usual practice in this discussion, we shall accept the auxiliary assumptions and concentrate on realism and locality. With this understanding the following alternatives exist:

- (i) Reject realism and retain locality (the *localist* position).
- (ii) Reject locality and retain realism (the *realist* position).
- (iii) Reject both realism and locality (the *nihilist* position).

The nihilist position is the most difficult to analyze, since it contains no positive statement of what is to be retained. Thus an application of Occam's razor suggests that the localist and realist options should be examined first.

II. THE LOCALIST POSITION

Here we would like to critique the localist position, which consists of two components. The first is a denial of the existence of EPR elements of reality, and hence by implication, of realism in general. The second is an affirmation of relativistic causality, as embodied in special relativity and the standard notions of causality, and hence of the locality principle. Einstein foresaw this position in his 1948 letter to Born as follows [5]:

"There seems to me no doubt that those physicists who regard the descriptive methods of quantum mechanics as definitive in principle would react to this [EPR] line of thought in the following way: they would drop the requirement for the independent existence of the physical reality present in different parts of space; they would be justified in pointing out that the quantum theory nowhere makes explicit use of this requirement."

In this quote, Einstein predicted that those physicists who believe that quantum theory is fundamental would abandon ("drop") realism ("the independent existence of the physical reality present in different parts of space"). However, these same physicists would of course not abandon special relativity, which has been so amply validated by experiment. Thus Einstein presciently described the localist response to Bell's theorem.

In his review article [6], "Is the moon there when nobody looks? Reality and the quantum theory," written after Bell's discovery, Mermin described the situation as follows:

"Using a *gedanken* experiment invented by David Bohm, in which 'properties one cannot know anything about' (the simultaneous values of the spin of a particle along several distinct directions) are required to exist by the EPR line of reasoning, Bell showed ('Bell's theorem') that the *nonexistence* [emphasis added] of these properties is a direct consequence of the quantitative numerical predictions of quantum theory."

This rejection of the kinds of realistic elements required by the EPR line of reasoning emphasizes, at least on the surface, the apparent impossibility of a realistic account of microscopic phenomena. The combination of this anti-realistic line of reasoning with the evident importance of relativistic causality explains the strong attraction that the localist position holds for many physicists.

We argue here that this position is incomplete in its rejection of realism, since the concept of locality, as applied to EPR experiments, must implicitly carry within it a realist's view of space and time.

III. SPACETIME AS AN ELEMENT OF PHYSICAL REALITY

Implicitly in the localist's world view, the spacetime manifold itself is an important element of physical reality in the EPR experiments. In all currently successful physical theories, e.g., the Standard Model of particle physics, spacetime is treated as if all its properties are independent of observation or measurement; hence it is indeed an element of physical reality in the general sense used here. In particular, the position of a photon detector in an EPR experiment is treated as if it were a classical quantity whose value does not depend on observations. Also, the time when a "click" goes off at this detector is a definite, realistic quantity. Thus an event defined by a particle detector firing at a given position and at a given time is assumed to be immune from any quantum back-actions, and is therefore viewed as constituting an element of physical reality. (Here the small back-actions of the detector on the particle [8] are neglected).

In special relativity, the metric of the spacetime through which a photon propagates is strictly Minkowskian. Thus the Minkowskian (or flat) spacetime metric is also an element of physical reality which is immune from quantum back-actions arising from any acts of measurement. In particular, the causal light-cone structure of spacetime is a realistic concept which is implicitly assumed in the proof of Bell's theorem, in order to enforce the factorizability of the joint probability distribution of coincidence detections of EPR particles. This factorizability expresses the strong separability of spacelike-separated measurements. Also assumed is the absence of backwards-in-time causation (in other words, "advanced actions"), i.e., the current values of the realistic variables do not depend on the values to be found in any future measurement. Thus in the proof of Bell's theorem, it is assumed from the start that spacetime, as embodied in special relativity and the standard notions of causality, is an element of physical reality.

The localist position, in which realism is abandoned for material systems, but implicitly retained for the properties of spacetime, is not logically inconsistent. Indeed it may be viewed as a weaker version of the traditional Copenhagen interpretation in that spacetime is required to be described by a classical realistic theory, but all physical objects, including the measuring apparatus, would be described entirely by quantum theory. The real difficulty with this view is physical. We already know from classical general relativity that the spacetime manifold is itself dynamical. The question naturally arises: Should the spacetime manifold itself be treated by the quantum theory? This question is usually discussed in the context of quantizing the gravitational field, so that one would expect the EPR effects to occur only on Planck length scales rather than on the macroscopic length scales involved in EPR experiments. However, the correct answer may involve more radical, global alterations

in the topology of spacetime (e.g., wormholes, strings, etc.) [7], which have manifestations on macroscopic length scales. Thus the assumption of the standard fixed topology for spacetime used in both special and general relativity may no longer apply. Since quantum theory is believed to be universally applicable, the position we take here is that if one quantizes one part of system (matter), one should also in principle quantize the other part of system (spacetime), even if this is very difficult to accomplish in practice.

The above approximations concerning the realistic nature of detector events and of the flat spacetime inside which they occur, are of course extremely good ones, and therefore are usually not explicitly stated. However, it is important to state them explicitly here, since these approximations carry with them a realist's world view of a very important part of the entire physical system, namely, the spacetime inside which the apparatus resides. To sum up: the localist position, in which realism is rejected for one part of the system, but retained for another part, represents in principle an incomplete point of view.

IV. THE SUPERPOSITION PRINCIPLE IMPLIES SUPERLUMINAL PHENOMENA

Quantum theory predicts, and experiments demonstrate, that certain counterintuitive superluminal effects exist. These effects arise from the tension between the *local* nature of all physical phenomena required by special relativity, and the *global* nature of superposed states required by quantum theory. However, these superluminal effects do not in fact violate relativistic causality due to the acausal nature of the correlations imposed by the superposition principle. The result is what Shimony has called "peaceful coexistence" between relativity and the quantum theory [9].

There exists evidence for quantum superluminal effects other than EPR, namely, in tunneling. Experiments have shown that individual photons penetrate a tunnel barrier with an effective group velocity which is considerably greater than c [10]. The experiments were conducted with a two-photon parametric down-conversion light source, which produced correlated, but random, emissions of photon pairs. The two photons of a given pair were emitted in slightly different directions so that one passed through a tunnel barrier, while the other passed through vacuum. The time delay for the tunneling photon relative to its twin was measured by adjusting the path length difference between the two photons in order to achieve coincidence detection. The photon transit time through the barrier was found to be smaller than the light transit time through an equal distance in the vacuum. However, according to standard theory there is no violation of relativistic causality, since the front velocity of the tunneling photon wave packet, which represents the speed at which an effect is connected to its cause, is still exactly c [11].

Both the EPR and the tunnel effects represent examples of quantum superluminalities, but of different kinds. Tunneling involves one-particle states, while the EPR correlations involve many-particle states, so that the many-particle configuration space becomes important. The superposition principle of quantum theory is at the heart of both of these superluminal phenomena. In the case of the EPR effect, the superposition in Eq. (1) leads to an "entangled state," i.e., a superposition of product states, which results in nonfactorizable, i.e., nonseparable, joint probabilities, and thus superluminal correlations in coincidence detection. This quantum nonseparability is in direct contradiction to the strong separability,

i.e., factorizability, assumption of Bell's theorem. In the case of the tunnel effect, superposition gives rise to exponential decay and spatial independence of the phase of the wave function inside the barrier. This leads to the superluminal behavior of the tunneling photon wave packet [10,11].

V. WHAT IS TO BE DONE?

We have argued above that the rejection of realism in the localist position does not go far enough, since general relativity implies that spacetime itself must be treated as a dynamical quantum system. This argument seems to lead to a curious impasse, since denial of reality for spacetime makes it difficult to formulate the notion of locality which is such an important part of the localist position. Furthermore this approach seems to be perilously close to the nihilist position. If the localist position is to be maintained, it would seem to be necessary to formulate a notion of locality which does not require a realistic spacetime. Thus we may have to abandon the usual, fixed topology of spacetime.

The realist position might offer an alternative in the form of an explicitly nonlocal theory which ascribes objective properties to material systems and spacetime alike. This approach has the obvious advantage that the existing notions of locality can still be formulated, but it poses the equally obvious difficulty of constructing a nonlocal theory which does not violate relativistic causality, at least in the approximation that spacetime fluctuations can be neglected. In particular this theory should satisfy the principle of "peaceful coexistence" with relativity, i.e., the explicitly superluminal (nonlocal) features of the theory should not permit the sending of controllable superluminal signals. It is difficult to see how this condition could be satisfied without taking the unpleasant step of postulating elements of physical reality which are in principle unobservable. It is an open question whether further development of the nonlocal, realistic quantum theory proposed by Bohm et al. [12] could lead to a model satisfying these constraints.

At the present time there does not seem to be any decisive argument for choosing between these alternatives.

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