LBL--20094

DE86 005217

October 1985

LBL-20094

EINSTEIN LOCALITY, EPR LOCALITY, AND THE SIGNIFICANCE FOR SCIENCE OF THE NONLOCAL CHARACTER OF QUANTUM THEORY*

Henry P. Stapp
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720, U.S.A.

ABSTRACT

The immense difference between Einstein locality and EPR locality is discussed. The latter provides a basis for establishing the nonlocal character of quantum theory, whereas the former does not. A model representing Heisenberg's idea of physical reality is introduced. It is nondeterministic and holistic: the objects, measuring devices, and their environment are treated as an inseparable entity, with, however, macroscopically localizable attributes. The EPR principle that no disturbance can propagate faster than light is imposed without assuming any structure incompatible with orthodox quantum thinking. This locality requirement renders the model incompatible with rudimentary predictions of quantum theory. A more general proof not depending on any model is also given. A recent argument that purports to show that quantum theory is compatible with EPR locality is examined. It illustrates the importance of the crucial one-world assumption. The significance for science of the failure of EPR locality is discussed.

*A contribution to the conference *Microphysical Reality and Quantum Formalism - Prospectives on the Einstein-Bohr Debate Fifty Years After the EPR Argument*, held at the University of Urbino, Urbino, Italy, Sept. 26 - Oct. 3, 1985. This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U. S. Department of Energy under Contract DE-AC03-76SF00098.

1. Introduction

"Einstein locality" has come to mean the Clauser–Horne factorization property described in Eq. (1) below. Thus the locality principle used by Einstein, Podolsky, and Rosen needs another name. Let it be called "EPR locality".

The immense difference between these two conceptions of locality becomes apparent if we review the argument of EPR. This argument has two parts. The first is based on the EPR criterion of physical reality: "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability unity) the value of a physical quantity, then there is an element of physical reality corresponding to this physical quantity".

The details of the EPR-Bohm experimental arrangement need not be reviewed here, but it involves two spatially separated spacetime regions R_1 and R_2. The EPR criterion then allows one to conclude that: 1) if A_1 is measured in R_1 then the value of A_2 in R_2 will be an element of physical reality, and, alternatively, 2) if B_1 is measured in R_1 then the value of B_2 in R_2 will be an element of physical reality. Thus the first part of the EPR argument yields the <u>disjunctive</u> conclusion that the value of either A_2 or B_2 in R_2 is an element of physical reality, according to whether A_1 or B_1 is measured in R_1.

The second part of the argument yields the <u>conjunctive</u> conclusion that the values of A_2 and B_2 in R_2 are simultaneous elements of reality. The transition is effected by the assertion that the reality or nonreality of quantities pertaining to R_2 cannot depend on what we do in R_1, because the system in R_2 is, by assumption, not disturbed in any way by our actions in R_1, which is spatially separated from R_2.

But if the values of A_2 and B_2 are simultaneous elements of physical reality then quantum–mechanical description of physical reality is incomplete, because it cannot describe these two values simultaneously, in the case at hand where A_2 and B_2 are incompatible physical quantities.

This quick review of the argument of EPR brings out two essential features:

1. The locality assumption is expressed not by a local model of reality, but rather by a general principle of nondisturbance suggested by the theory of relativity.

2. The principles used by EPR are prima facie compatible with the principles of *orthodox quantum thinking. They are formulated in terms of the quantum* theoretical idea of what can be predicted with certainty. To the quantum principles

is added only a principle of nondisturbance suggested by the theory of relativity.

The prima facie compatibility of the EPR assumptions with the principles of orthodox quantum thinking is an essential feature of the EPR argument. For this argument was intended to have weight in the community of scientists who had accepted the orthodox quantum principles. Any apparent incompatibility of the EPR assumptions with orthodox quantum principles would be grounds for an immediate rejection of the EPR argument.

The Clauser-Horne factorization assumption is that there exists a set $\{\lambda\}$ of hidden variables such that the probability for obtaining results r_1 and r_2 in regions R_1 and R_2, respectively, under conditions a_1 and a_2 in R_1 and R_2, respectively, takes the form

$$P(r_1, r_2; a_1, a_2) = \int d\lambda \rho(\lambda) P(r_1; a_1, \lambda) P(r_2; a_2, \lambda) \tag{1}$$

where $\rho(\lambda)$ is a positive weight factor, and $P(r_1; a_1, \lambda)$ and $P(r_2; a_2, \lambda)$ are the probabilities for obtaining results r_1 and r_2, respectively, under conditions (a_1, λ) and (a_2, λ), respectively.

This Clauser-Horne factorization property expresses conditions arising from a local model of microscopic reality, rather than merely expressing a general locality principle suggest by the theory of relativity. This model contradicts the principles of orthodox quantum thinking in two ways: it assumes at the outset the existence of local micro- realities; and it assumes the existence of a set of hidden variables that is sufficiently complete to effect a decomposition of the probability function into a sum of factorized terms.

The existence of a faster-than-light connection cannot be deduced directly from a failure of Clauser-Horne factorization. For any failure of Clauser-Horne factorization can more reasonably be attributed to a failure of features of the Clauser-Horne model that directly contradict quantum thinking. It must be stressed that a failure of the idea of microscopic realism that underlies the Clauser-Horne property does not entail a failure of the general idea of physical realism that underlies the scientific world view: no retreat to idealism or subjectivism is required. This is made clear by the model considered in the following section.

The failure, then, of "Einstein locality" does not entail the existence of a faster-than-light connection. As we are interested primarily in basic assumptions, and the conclusions that may properly be drawn from them, we shall refrain from using

"Einstein locality" even as an intermediate construct.

The purpose of the EPR argument was to say something about "physical reality". Consequently, the EPR assumptions necessarily had to involve "physical reality". Locality was, for EPR, not the focal point: it merely provided access to "physical reality".

This involvement with "physical reality" provided the flaw that was the basis of Bohr's criticism. Bohr noted, in effect, that the potential physical realities introduced by EPR, on the basis of their criterion of physical reality, namely the quantities measurable in R_2 that could be predicted with certainty from results of experiments performed in R_1, are in fact disturbed by the choice of experiment made in R_1: what can be predicted with certainty certainly depends on what one decides to do in R_1. Thus even though the "system" in R_2 is not disturbed by what is done in R_1, nevertheless the "physical realities" defined by the EPR criterion are disturbed.

In order to confront to locality issue, without being derailed by the extraneous issue of "physical reality", we shall separate the EPR principle of nondisturbance first from all reality assumptions alien to orthodox quantum thinking, and eventually from all reality assumptions except a crucial one–world assumption and an assumption of effectively free choice of experiments.

The initial development is based on a formalization of Heisenberg's conception of physical reality. In this connection it is useful to distinguish the strict Copenhagen interpretations from the informal Copenhagen interpretation. In both interpretations the quantum formalism is interpreted merely as a tool for making prediction pertaining to observations obtained under conditions described in terms of the concepts of classical physics. But in the strict interpretation nothing of all is said about any reality other than our observations, whereas in the informal interpretation one accepts the common sense idea that the commonality in the observations of the community of communicating observers corresponds to a macroscopic reality that exists independently of these observations and can be described, at least approximately, in terms of the concepts of classical physics.

This informal idea was discussed by Heisenberg, and the concrete model introduced below is a formalization of Heisenberg's ideas. Bohr used more cautious phrasings, but von Weizsäcker informs me that Heisenberg's ideas are in general concordance with those of Bohr.

2. Heisenberg-type Model of Reality

Heisenberg[1], in his 1958 book "Physics and Philosophy", in the chapter on the Copenhagen interpretation, speaks of a transition from the "possible" to the "actual". He says 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 come into play; it is not connected with the act of registration of the result in the mind of the observer. The discontinuous change of the probability function, however, takes place with the act of registration, because it is the discontinuous change in our knowledge in the instant recognition that has its image in the discontinuous change in the probability function.

Heisenberg's explication of the Copenhagen interpretation distinguishes sharply between what happens physically during the act of measurement, namely the occurrence of a macroevent that represents a transition of "possible" to "actual", and what happens in the quantum theoretical description, which, according to the Copenhagen interpretation, must be regarded merely as a tool that scientists use to make predictions pertaining to phenomena appearing under conditions described in terms of classical concepts. As regards what happens physically, the essential point is that the act of measurement involves a *choice*. This choice picks the actual from among what had previously been mere possibilities: the choice renders fixed and settled something that had prior to the choice been undetermined.

If r_1 and r_2 represent the results or values appearing in R_1 and R_2, respectively, then the macroevent can be represented schematically as

$$\text{Indefinite}(r_1, r_2) \rightarrow (r_1(c, d), r_2(c, d)),$$

where c represents a choice that determines which experiments are performed, and d represents a value that either is determined, or can be considered to be determined, independently of the choice c. One can write $d = (d', d'')$, where d' is strictly predetermined, and d'' is any stochastic choice that can be separated from the choice of c.

The choice c represents the choice of experiment. Two preliminary assumptions are first that c has the form $c = (c_1, c_2)$, where c_1 and c_2 represent the choices of experiment in R_1 and R_2, respectively, and second that these two choices can be regarded as independent free variables. They are regarded as localised causes.

The variable d can thus be assumed to represent the deterministic and stochastic quantities that characterize the entire unified and holistic universe, apart from two tiny stochastic disturbances, c_1 and c_2, localizable in R_1 and R_2, respectively, that eventually become amplified in ways that fix the experiments performed in R_1 and R_2, respectively.

There are at least a continuum of ways of choosing an experiment that measures a given observable. Thus the number N_j of elements in the range of c_j is assumed to be infinite. Let $O_j(c_j)$, $j = 1$ or 2, be the observable corresponding to the choice c_j. It is assumed that c_j cannot be written in the form $c_j = (O_j, c_j')$.

If, contrary to the above assumptions, N_1 and N_2 were both equal to two, and $c_j = O_j$ for $j = 1$ and 2, and if d'' were absent, then our model would be a deterministic hidden variable theory: for any fixed $d = d'$ the values (r_1, r_2) for all four alternative possible choices of the pair of observables (O_1, O_2) would be predetermined by the pair of functions $r_1(c, d)$ and $r_2(c, d)$. If $c_j = O_j$, and d'' were present, then the results (r_1, r_2) for all four cases would not be predetermined, but they would be *codetermined*: the values of (r_1, r_2) for all four alternative possible choices of observables would be fixed by the fixing of d'', and hence counterfactual definiteness would hold. (i.e., definite values would be associated with all four observables, only one of which can be measured). However, in our case $N_j = \infty$ the fixing of d alone does not fix the value of (r_1, r_2) for any of the four alternatives possible cases. And the fixing of both c and d fixes the value only of the observable that is measured: the values of the other three observables remain indefinite. Thus the model does not entail counterfactual definiteness.

The model described above goes beyond orthodox quantum theory because it tries to represent what happens physically during the act of measurement, rather than merely providing a tool for making predictions pertaining to observations appearing under classically described conditions. Nevertheless, the model is not incompatible with orthodox quantum thinking. It entails neither predeterminism, nor counterfactual definiteness, nor any concept of reality that contradicts quantum ideas. Rather, it formalizes Heisenberg's idea of what happens physically during the act of measurement.

3. EPR Locality

The EPR idea of locality [2] is that a mere change in the choice of the experiment performed in one region cannot disturb events in the spatially separated region. For any such disturbance would represent a faster-than-light influence. This locality condition is represented by the conditions $r_1(c, d) = r_1(c_1, d)$ and $r_2(c, d) = r_2(c_1, d)$: the result produced in R_1 is independent of the choice of experiment made in R_2, and vice versa.

To fill out the model let a probability measure μ_j be assigned to c_j, for $j = 1$ and 2. Suppose that for each region R_j either choice of observable is equally likely. That is, for $j = 1$ and 2, let

$$\mu_j\{c_j;\ O_j(c_j) = O'_j\} = \mu_j\{c_j;\ O_j(c_j) = O''_j\} = 1/2,$$

where O'_j and O''_j are the two possible choices of observable in region R_j.

This model, prior to adding the locality conditions, is compatible with both orthodox quantum thinking and all the predictions of quantum theory. But the addition of the locality condition renders it incompatible with rudimentary predictions of quantum theory. To show this one may first note that if $c(r_1, r_2)$ is the usual correlation function [3]

$$c(r_1, r_2) = \frac{1}{n}\sum_{i=1}^{n} r_{1i} r_{2i}$$

(where $r_{ji} = \pm 1$, and n is the number of pairs of particles in the run), and $\bar{c}(O_1, O_2)$ is the quantum theoretical expectation value of $c(r_1, r_2)$ in experiments that measure (O_1, O_2), and $\rho(d)$ is the weight function for d, then the quantity

$$\Delta(r_1, r_2, O_1, O_2) \equiv \frac{(c(r_1, r_2) - \bar{c}(O_1, O_2))^2}{n^{-1/2}}$$

has expectation value

$$
\begin{aligned}
<\Delta> &= \sum_{c_1,c_2,d} \Delta(r_1(c_1,\, d),\, r_2(c_2,\, d),\, O_1(c_1),\, O_2(c_2)) \times \mu_1(c_1)\mu_2(c_2)\rho(d) \\
&= \sum_{\{O_1,O_2,r_1,r_2,d\}} \Delta(r_1,\, r_2,\, O_1,\, O_2) \times \sum_{\{c_1; r_1(c_1,d)=r_1, O_1(c_1)=O_1\}} \mu_1(c_1) \\
&\quad \times \sum_{\{c_2; r_2(c_2,d)=r_2, O_2(c_2)=O_2\}} \mu_2(c_2) \times \rho(d) \\
&= \sum_{(r_1,\, r_2)} \sum_{(O_1,O_2),d} \Delta(r_1,\, r_2,\, O_1,\, O_2) w_1(r_1, O_1, d) w_2(r_2, O_2, d)\rho(d) \qquad (2) \\
&= \sum_{r_1',\, r_1'', r_2', r_2'', d} (\Delta(r_1', r_2', O_1', O_2') + \Delta(r_1', r_2'', O_1', O_2'') \\
&\quad + \Delta(r_1'',\, r_2',\, O_1'',\, O_2') + \Delta(r_1'',\, r_2'',\, O_1'', O_2'')) \times \rho(d) \\
&\quad \times 4 w_1(r_1', O_1', d) w_1(r_1'', O_1'', d) w_2(r_2', O_2', d) w_2(r_2'',\, O_2'',\, d) \\
&= \sum_{Q,d} (\Delta(Q_1) + \Delta(Q_2) + \Delta(Q_3) + \Delta(Q_4)) w(Q,\, d)\rho(d),
\end{aligned}
$$

where

$$
\begin{aligned}
Q &\equiv [Q_1,\, Q_2,\, Q_3,\, Q_4] \\
&\equiv [(r_1'(Q),\, r_2'(Q),\, O_1',\, O_2'),\, (r_1'(Q),\, r_2''(Q),\, O_1',\, O_2''), \\
&\quad (r_1''(Q),\, r_2'(Q),\, O_1'',\, O_2'),\, (r_1''(Q), r_2''(Q),\, O_1'',\, O_2'')]
\end{aligned}
$$

is a local quartet, and $\sum_Q w(Q,\, d) = 1/4$, $w(Q,\, d) \geq 0$.

The essential point here is that in the last line of the expression (2) for $<\Delta>$ *there is a sum over every possible local quartet* Q, and for each local quartet Q there is a sum over the contribution to Δ from each of the four members of this local quartet. In this second sum all four terms have equal weight.

These local quartets are the same combinations that occur in a local deterministic hidden variable theory. And the final line of Eq. (2) is the same expression that would appear in that case. In that case the grouping together, with equal weight, of the four members of each local quartet is a consequence of the assumption of equal weights for each of the four possible choices of $(O_1,\, O_2)$ coupled with the property (entailed by "determinism") of counter factual definiteness: i.e., for each d (there called λ) the results of all four possible experiments are simultaneously specified. In the present model there is no counterfactual definiteness, or any singling out of preferred quartets. But the EPR nondisturbance condition has, by itself, allowed us to reduce the expression for $< \Delta >$ to the form that occurs in the deterministic case.

The incompatibility of Eq. (2) with the statistical predictions of quantum theory is easy to show. The observables O_1', O_1'', O_2', and O_2'' are chosen to be a very "bad" set (large violation of Bell inequalities). Then it can be shown [3] that every local quartet Q has at least one member Q_i such that $\Delta(Q_i) \geq 10^{-4} \times n^{1/2}$. But then Eq. (2) shows that $< \Delta >$ must tend to infinity as n tends to infinity. On the other hand, quantum theory predicts that $< \Delta >$ tends to a number that is of the order of unity.

The above proof differs from all previous proofs of nonlocality based on hidden variables by the fact that it does not introduce the assumption that the degrees of freedom of the object plus devices plus environment can be represented in the form $\lambda = (\lambda', O_1, O_2)$. This usual form, in which the observables O_1 and O_2 are isolated as separate variables, is unrealistic because in practice many degrees of freedom differ in the two different experimental situations, for any practical choice of variables. Moreover, the independent and localizable free choices are more reasonably ascribable to tiny systems that stand apart from the devices, so that the combined system of objects plus devices plus environment, minus these two tiny disturbing systems, can be regarded as a single unified organic entity that produces macroscopic events in the two regions, subject only to the demand that the effects of the two disturbances propagate no faster than light. Finally, if one includes in λ also the random variables whose eventual fixing fixes the result that eventually appears, then the assumption $\lambda = (\lambda', O_1, O_2)$ would allow one to imagine that λ' could be held fixed as O_1 and O_2 are changed. This would permit one to specify simultaneously the results that *would occur* under each of the four alternative possible choices of (O_1, O_2), contrary to the orthodox ideas of quantum theory.

The proof given above shows that neither determinism, nor counterfactual definiteness, nor any idea of reality incompatible with orthodox quantum thinking need be assumed in order to prove the incompatibility of rudimentary predictions of quantum theory with the EPR idea that no influence can propagate faster than light.

The model used above is a formalization of Heisenberg's ideas about physical reality. However, no assumption of any external physical reality is actually required.

For the results r_1 and r_2 can be reinterpreted as representations of certain common features of "our observations".

The model is expressed it terms of certain "hidden variables". But the hidden variables d represent simply all of the deterministic and stochastic quantitites that characterize the unified organic world. They are not used to provide the basis for a special factorization structure that reflects ideas of separation, division, or microscopic structure.

An important role of the hidden variables in this model is to enforce, in a concrete form, a crucial uniqueness assumption. This uniqueness (or one–world) assumption demands that for each of the four alternative possible sets of observables (O_1, O_2) some unique, though possibly nonpredetermined, result (r_1, r_2) will be produced if that set of observables is chosen. (No results are initially specified for the observables that are not chosen.) This one–world assumption is necessary because many–worlds theories are known to be compatible with EPR locality [4].

4. Elimination of Hidden Variables

An important role of hidden variables in the model described above is to enforce the crucial uniqueness requirement. But this requirement can be enforced, instead, by limiting the set of conceivable possibilities. Then hidden variables are not needed. This alternative approach [3] is briefly described in this section.

There are four alternative possible choices of observables: (O_1', O_2'), (O_1', O_2''), (O_1'', O_2'), and (O_1'', O_2''). Our interest is in theories that reproduce the (rudimentary) predictions of quantum theory. Quantum theory gives (rudimentary) predictions for all of the four alternative possible cases listed above. Thus the requirement of agreement with predictions of quantum theory imposes one condition on the theory for each of the four alternative possible cases, even though only one of these four alternative possibilities can be realized physically.

The EPR argument [2] is based essentially upon an assumption that applied to our case becomes: if O_1' were chosen in R_1 then some unique result would be produced in R_1, and that result, whatever it turns out to be, cannot be in any way disturbed by the choice between O_2' and O_2'' made in R_2; and if, alternatively, O_1'' were chosen in R_1 then some unique result would be produced in R_1, and that result, whatever it turns out to be, cannot be in any way disturbed by the choice between O_2' and O_2'' made in R_2.

If the theory under consideration is deterministic, or entails counterfactual definiteness, then the phrase "cannot be in any way disturbed by" can be replaced by "must be independent of". However, if the theory is nondeterministic and does not entail counterfactual definiteness, and , moreover, unlike the model considered in earlier sections, does not explicitly exhibit the random variables whose fixing fixes the results produced under the various conditions, then the theory itself lacks sufficient structure to enforce the requirement that the result produced in R_1, under either of the conditions that might be set up there, must be independent of the choice of O_2 in R_2. However, in these more general cases one can inquire whether the conditions imposed on the theory at least allow the possibility that the result produced in each region could be independent of the choice made in the other region.

The first condition imposed on the theory is that it reproduce the statistical predictions of quantum theory for each of the four alternative possible choices of (O_1, O_2). The second condition is the uniqueness (or one-world) assumption, which limits the conceivable possible results under any condition (O_1, O_2) to some unique one of the $(2^n)^2$ possible values of (r_1, r_2). The locality condition links the possibilities for what can be produced under the alternative possible conditions. When all four alternative possibilities for (O_1, O_2) are considered the uniqueness condition limits the conceivable possible results to the $(2^n)^{2\times 4}$ conceivable possible quartets of values. This set of quartets includes every conceivable combination of possible results for the four alternative possible choices of (O_1, O_2).

Quantum theory predicts that if the observable (O_1, O_2) were to be measured then the probability that the correlation function $c(r_1, r_2)$ defined earlier would satisfy $|c(r_1, r_2) - \bar{c}(O_1, O_2)| > 10^{-2}$ tends to zero as n, the number of pairs, tends to infinity. Each of the four members Q_i of each of the 2^{8n} conceivable quartets Q represents a conceivable possible result that the experiment could have if the corresponding observable (O_1, O_2) were to be measured. Thus the requirement of compatibility with the predictions of quantum theory, in the large n limit, restricts the set of allowed quartets Q to the set QM defined by imposing $|c(r_1, r_2) - \bar{c}(O_1, O_2)| < 10^{-2}$ on each of the four element Q_i of Q. On the other hand, the condition that the conceivable possibilities be restricted to those in which the results in each region are independent of the choice of observable measured in the other region restricts the full set of 2^{8n} quartets Q to the set LOC consisting of the local quartets described earlier. However, a slight generalization of the argument of [3] shows that

$$LOC \bigcap QM = EMPTY\,SET:$$

the intersection of LOC and QM is void. That is, the constraints imposed by the requirement of compatibility with quantum theory exclude the possibility that the results in each region could be independent of the choice of experiment made in the other region.

5. Discussion of a Counter–Claim

It has recently been claimed [5,6] that there is in fact no conflict between quantum theory and EPR locality. In the argument leading to this claim one is first asked to imagine that one of the choices of (O_1, O_2), say (O_1', O_2'), has been made and that some definite result, say (r_1', r_2'), has been produced. One is then asked to invent possible results corresponding to the three other values (O_1, O_2). These invented results are supposed to represent possibilities for what might have occurred if the other choices has been made, and they are required to conform to the locality conditions.

These locality conditions are applied in various prescribed orders. The "order" involved in this construction is the order in which one imagines making changes from the assumed actual situation (O_1', O_2'). Thus the sequence $(O_1', O_2') \rightarrow (O_1'', O_2') \rightarrow (O_1'', O_2'')$ corresponds to first making the change $O_1' \rightarrow O_1''$ in R_1, and then making the change $O_2' \rightarrow O_2''$ in R_2. But the sequence $(O_1', O_2) \rightarrow (O_1', O_2'') \rightarrow (O_1'', O_2'')$ corresponds to first making the change $O_2' \rightarrow O_2''$ in R_2, and then making the change $O_1' \rightarrow O_1''$ in R_1.

These two changes are made in spatially separated regions. According to the ideas of relativity theory the order in which one imagines changes to be made in spatially separated regions has no physical signifcance. But the argument in the cited references depends on making the invented results corresponding to $(O_1'' O_2'')$ depend upon the order in which these changes in spatially separated regions are imagined to occur.

The essential feature of this argument is that it leads to a doubling of the results produced under conditions (O_1'', O_2''): one violates the uniqueness requirement that for any one of the four possible choices of (O_1, O_2) some unique result (r_1, r_2) would be produced if that choice were to be made. Instead, one requires that at least two results, $(r_1, r_2)_a$ and $(r_1, r_2)_b$, be produced under conditions (O_1'', O_2'').

It is easy to show that with a two–sheeted covering of the base space

$$((O_1', O_2'), (O_1', O_2''), (O_1'', O_2'), (O_1'', O_2'')),$$

and a corresponding special interpretation of what one will then mean by the EPR locality condition, one can indeed reconcile (this extended idea of) EPR locality with the statistical predictions of quantum theory, for the system under consideration here. This way of evading the conflict between quantum theory and (the modified version of) EPR locality emphasizes the importance of the uniqueness (or one-world) assumption. The importance of this assumption was strongly stressed in [3], and every previous work of this author on the subject.

The logical distinction between this crucial uniqueness assumption and the assumptions of determinism or counterfactual definiteness is illustrated by the model discussed in the earlier sections.

6. Significance of the Nonlocal Character of Quantum Theory.

The significance of the incompatibility of "Einstein locality" with the predictions of quantum theory is evident: the quantum predictions cannot be reproduced by any microlocal model of reality that entails the Clauser–Horne factorization property. This conclusion is completely in line with orthodox quantum thinking, which enjoins us to reject the idea of a microlocal reality. In its place orthodox thinking, at least at the informal level, suggests that objective reality is built upon myriads of macroevents which, rising from a sea of micro-level potentialities, create or actualize attributes that weave together to form the fabric of a macroscopic spacetime reality that is describable in terms of the concepts of classical physics.

Bohr's insistence on the holistic aspect of quantum phenomena contains perhaps already the suggestion that the dynamics of the generations of macroevents cannot be regarded to be as a strictly local process. This general suggestion is given specific form by the appropriately generalized work of Bell, which shows, as exhibited by the concrete demonstration given above, that even the rejection of microscopic reality and adherence to quantum precepts is not sufficient to reconcile the dynamics of macroevent generation with the EPR principle of nondisturbance suggested by the theory of relativity.

It must be strongly emphasized that EPR locality is not an actual consequence of the theory of relativity. The basic demand of the theory of relativity is covariance, which pertains, strictly speaking, to deterministic systems that are well defined over all of spacetime. The failure of EPR locality does not jeopardize covariance. Nor does it jeopardize relativistic quantum field theory, which is constructed to ensure that its predictions do not depend either on the frame of reference, or upon the order in which one imagines performing measurements in spacelike separated regions. Moreover, in spite of the failure of EPR locality, no signal can be sent faster than light by any system adequately described by quantum theory.

This last-mentioned property arises from the fact that the quantum-theoretical probabilities in one region are independent of the choice of experiment made in a spatially separated region. This nondependence of the quantum probabilities in one region upon the choice made in a spatially separated region suggests that quantum theory should also at least allow the possibility that the individual macroscopic events in one region could be independent of the choice of experiment made in the spatially separated region. But this conceivable possibility is precisely what is not allowed by quantum theory, or by any theory that makes the same predictions as quantum theory in the correlation experiments under consideration here [3].

To assess the significance of this result one must recognize that one is considering here the logical possibility of a theoretical nondependence of the generation of macroevents in one region upon a choice, made in the other region, between two experiments only one of which can actually be performed. Indeed, the entire EPR discussion was based squarely on the consideration of choices between alternative possibilities. This means, however, that the analysis and its conclusions pertains to hypothetical situations. In the words of Wheeler they refer to a "never-never land".

This "never-never-land" quality entitles most physicists to be relatively complacent about Bell-type nonlocality properties. The failure of "Einstein locality" can be reasonably attributed to the failure of an overly-classical concept of microscopic reality. This failure of microrealism does not jeopardizes the general idea of scientific realism, for one can fall back to the position that ordinary ideas about reality apply only at the macroscopic level. On the other hand, EPR locality involves no assumptions about microscopic realities. But it pertains to "never-never land".

To go beyond this serene point of view one must consider the purpose of the whole enterprise of examining the EPR-Bell arguments. The purpose, in my view, to give guidance in the search for theories that subsume contemporary quantum theory but have greater scope. The scope of contemporary quantum theory is limited in various ways. It deals with situations that can be idealised by considering the world to be separated into two parts one of which can be described quantum mechanically, and the other of which can be described classically. It deals with phenomena that are closed by an "irreversible" act of amplification. And it deals with phenomena in which the possible results are characterised by answers to a denumerable set of questions defined by well-separated responses of measuring devices. However, most processes occurring in nature do not conform to these special conditions. So a basic question for science is whether a more general theoretical structure can be found that reduces to quantum theory under appropriate special circumstances, but provides also some understanding of more general processes. To be scientific this understanding must be testable, but the tests might not be of the kind that are possible in atomic physics.

In the search for such theories we are concerned with theoretical structures that include or reduce in appropriate limits to quantum theory. Quantum theory, considered as a theoretical structure, is a conjunction of predictions for the alternative possible cases. Thus if x_1, x_2, x_3, and x_4 are the four alternative possible cases, and y_1, y_2, y_3, and y_4 are the corresponding predictions, then quantum theory, restricted to this situation, is "If x_1 then y_1" and "If x_2 then y_2" and "If x_3 then y_3" and "If x_4 then y_4". In the analysis of theoretical structure this whole structure is relevant: we seek theoretical structures that contain this entire conjunctive structure, i.e., that contain the predictions of quantum theory for each of the four alternative possible cases. But the structure of the whole set of predictions is such that it does not allow the possibility that the results in each region could be independent of the choice made in the other region. This means that in the construction of the more general theory one cannot allow the processes of macroevent generation in various spacetime regions to be completely independent of choices of experiments made in spatially separated regions. Consequently, the search for more comprehensive physical theories can be, and must be, restricted to theories that violate a simple locality condition. This locality condition is expressible strictly in terms of macroscopic quantities, and is based on no assumptions at all concerning microscopic substructure. It expresses the idea, suggested by the theory of relativity, that no disturbance can propagate faster than light.

Acknowledgment

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of HighEnergy Physics of the U. S. Department of Energy under Contract DE-AC03-76SF00098.

References

1. W. Heisenberg, *Physics and Philosophy*, (Harper Rowe, New York, 1958) Ch. III.

2. A. Einstein, B. Podolsky, N.Rosen, Phys. Rev. 35, 777 (1935).

3. H. P. Stapp, Amer. J. Phys. 15, 306 (1985).

4. H. P. Stapp, Found. of Physics, 10, 767(1980).

5. K. Kraus, *Open Questions in Quantum Physics* G. Tarozzi and A. van der Merwe (eds), Reidel, Dordrecht (1985).

6. K. Kraus, *Quantum Theory, Causality, and EPR Experiments*, Preprint, Center for Particle Theory, University of Texas at Austin.