Title
Nonlocal Character of Quantum Theory

Author
Stapp, H.P.

Publication Date
1996-05-01

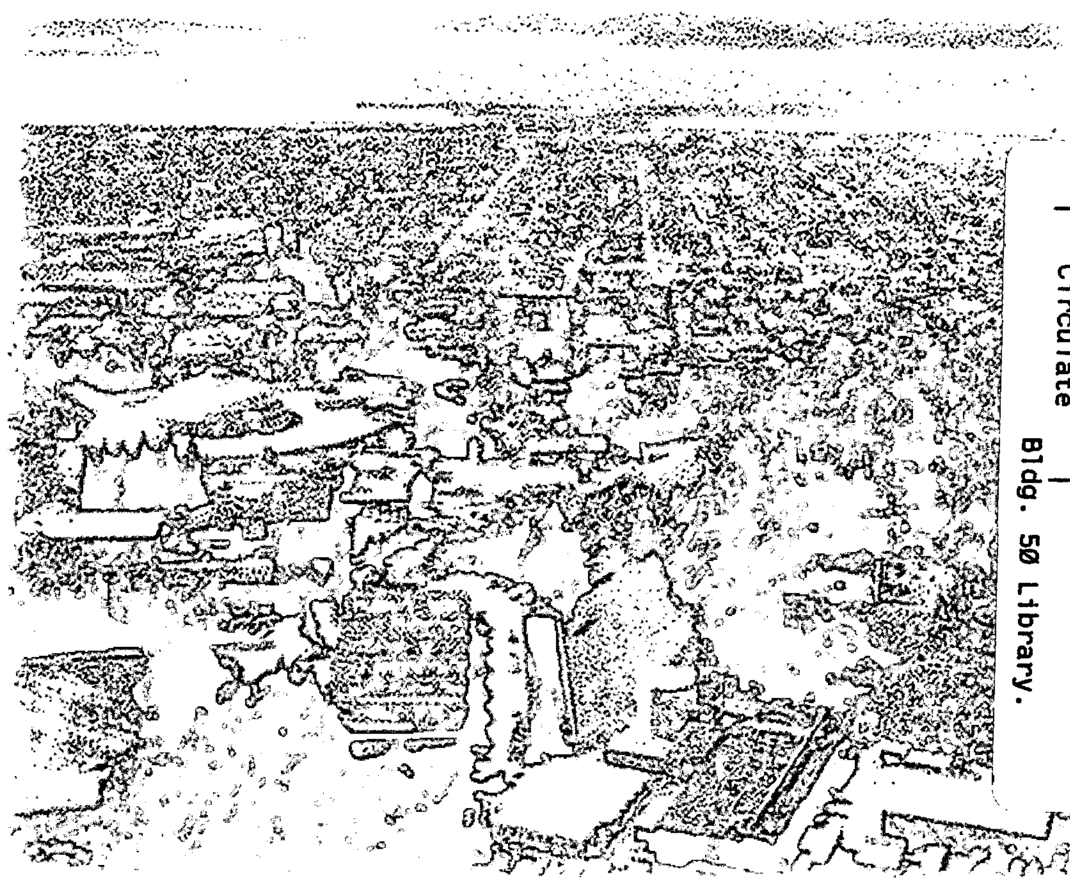
LBNL-38803
UC-414
Preprint

Ernest Orlando Lawrence Berkeley National Laboratory

Nonlocal Character of Quantum Theory

H.P. Stapp
Physics Division

May 1996
Submitted to *American Journal of Physics*



DISCLAIMER

May 28, 1996 LBNL-38803

Nonlocal Character of Quantum Theory *

Henry P. Stapp
Theoretical Physics Group
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

According to the usual conception of causality, the truth of a statement that refers only to events occurring at a given time cannot depend upon an unconstrained choice to be made by an experimenter at a later time. According to the usual concept of relativistic causality this causality condition can be applied in all Lorentz frames. It is shown here that this concept of relativistic causality is incompatible with certain simple predictions of quantum theory.

*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.

Recycled Paper

1. Introduction

Certain generalizations [1] of the works of Einstein, Rosen, and Podolsky [2] and John Bell [3] show that the predictions of quantum theory are incompatible with a property called "local realism". The word "local" refers here to a putative causality condition that claims that, in any Lorentz frame, the truth of a statement pertaining only to outcomes of experiments localized in one region at a given time cannot depend upon which experiment is freely chosen and performed in a spatially separated region at a later time. The word "realism" signifies that those demonstrations depend on the validity of an Einstein-type conception of physical reality, or perhaps on an assumption of determinism or of hidden variables. But if any of these three reality concepts is used then locality is not placed in jeopardy, for orthodox quantum philosophy claims the failure of all three reality concepts in the realm of quantum phenomena. I intend to show here, in a way perhaps simpler than before [4,5], that the locality property itself is incompatible with certain predictions of quantum theory, without assuming determinism, hidden variables, or Einstein reality.

2. Hardy-type Experiment

Use of a Hardy-type experiment [6,7,8] allows it to be shown that the putative locality condition itself is incompatible with the predictions of quantum theory. The essential features of the Hardy-type experimental set up are first that it involves two regions that are spatially separated from each other. Here they are called **R** and **L**. In **R** there are two alternative possible experiments, called $R1$ and $R2$, and in **L** there are two alternative possible experiments, called $L1$ and $L2$. In some Lorentz frame the experimenter's choice in **R** occurs *later* than the appearance and recording of the observable outcomes of the experiments in **L**. According to the usual causality concept it is reasonable to entertain the notion that observable properties in **L** at an earlier time cannot depend upon which measurement will be chosen and performed in **R** at a later time. According to the relativistic causality concept there is an analogous condition with **R** and **L** interchanged. But in this second case "earlier" and "later" are specified by using a different Lorentz frame.

What is under consideration here, then, is a set of just four possible experimental set ups that are specified to be identical except for the unconstrained bivalent choices of each of the two experimenters, and the various differences that can arise from differences in these two choices. If the defining conditions of two of these possibilities differ only by the choice to be made in one region at a later time then our putative locality condition claims that outcomes in the spatially separated region at the earlier time must be *the same* in these two cases: what happens *before* this free choice occurs must be common.

The logical structure of the Hardy experiment is shown in Figure 1, along with the four pertinent predictions of quantum theory.

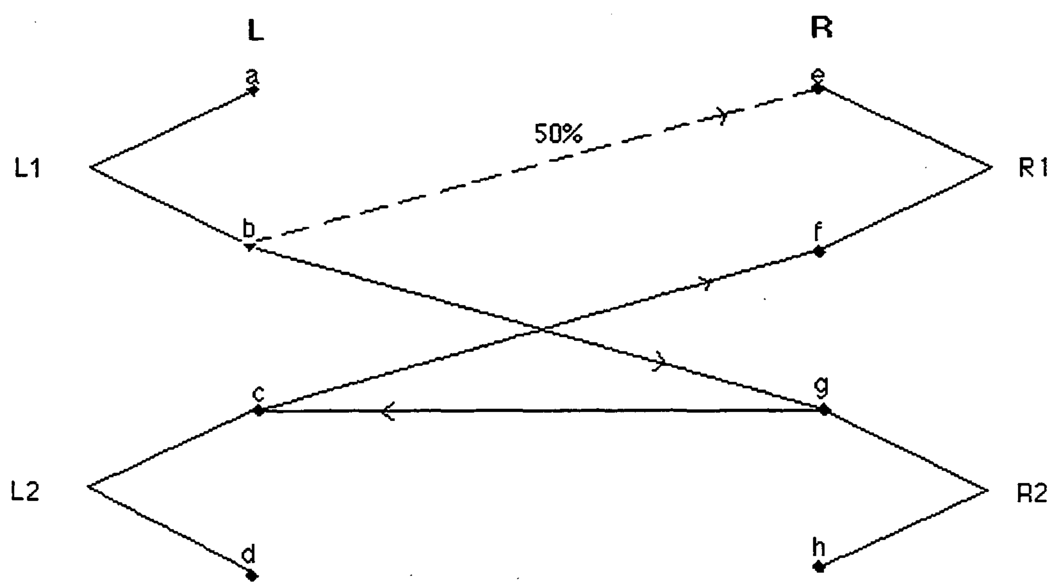


Figure 1: The logical structure of the Hardy experiment is represented, together with the four pertinent predictions of quantum theory. The three solid paths between pairs of labelled points represent predictions that have conditional probability equal to unity. The dotted line represents a connection that has conditional probabilty equal to 50%.

For example, the solid line from b to g represents the prediction that: if $L1$ is performed in **L** and the outcome there is b, then if $R2$ is performed in **R** the outcome there will be g.

This prediction can be written symbolically as:

$$(L1 \wedge b) \Longrightarrow (R2 \Longrightarrow g),$$

where $\Longrightarrow$ stands for *implies*, the strict conditional, and $\wedge$ stands for conjunction. Equivalently, this prediction can be written in the form of line 9 below. **3.**

The Proof

I state the steps of the proof in logical symbols, and also in words for the first few steps in order to make clear the meanings of the symbols. Later, I justify each step on the basis of the predictions of quantum mechanics (QM) or the locality condition described above (LOC), or simple logic (LOGIC).

In the proof I shall use the symbol $R1\Box\rightarrow$. It is taken from modal logic, and is to be read: "If $R1$ is performed, instead of $R2$, then...". In modal logic the truth of a statement containing this symbol is generally supposed to be justified by appeal to the notion of "closeness of worlds", which is not part of physics. Here it is justified by appeal to our physics-based causality condition LOC.

1. LOC: "If $L2$ is chosen and performed (at some earlier time) and the outcome of $L2$ is c and $R2$ is chosen and performed (at a later time), then under the alternative possible condition that $R1$ is chosen and performed (at the later time), instead of $R2$, the outcome of $L2$ (at the earlier time) would still be c":
$(L2 \wedge c \wedge R2) \Longrightarrow [R1\Box \rightarrow c]$.

2. LOGIC: "If $L2$ and $R2$ are chosen and performed and the outcome of $L2$ is c then under the alternative possible condition that $R1$ is chosen and performed (at the later time), instead of $R2$, then $L2$ and $R1$ would be performed and the outcome of $L2$ would be c":
$(L2 \wedge R2 \wedge c) \Longrightarrow [R1\Box \rightarrow (L2 \wedge R1 \wedge c)]$.

3. QM: "If $L2$ is chosen and performed (at the earlier time) and $R2$ is chosen and performed (at the later time) and the outcome of $R2$ is g, then $L2$ and $R2$ are performed and the outcome of $L2$ is c":
$(L2 \wedge R2 \wedge g) \Longrightarrow (L2 \wedge R2 \wedge c)$.

4. QM: "If $L2$ and $R1$ are performed and the outcome of $L2$ is c then $L2$ and $R1$ are performed and the outcome of $R1$ is f":
$(L2 \wedge R1 \wedge c) \Longrightarrow (L2 \wedge R1 \wedge f)$.

5. LOGIC: $(L2 \wedge R2 \wedge g) \Longrightarrow [R1\Box \rightarrow (L2 \wedge R1 \wedge f)]$.

6. LOGIC: $(L2) \Longrightarrow [(R2 \wedge g) \Longrightarrow (R1\Box \rightarrow f)]$.

7. LOC: $(L1) \Longrightarrow [(R2 \wedge g) \Longrightarrow (R1\Box \rightarrow f)]$.

8. LOGIC: $(L1 \wedge R2) \Longrightarrow [g \Longrightarrow (R1\Box \rightarrow f)]$.

9. QM: $(L1 \wedge R2) \Longrightarrow [b \Longrightarrow g]$.

10. LOGIC: $(L1 \wedge R2) \Longrightarrow [b \Longrightarrow (R1\Box \rightarrow f)]$.

11. LOC: $(L1 \wedge R2) \Longrightarrow [R1\Box \rightarrow (b \Longrightarrow f)]$.

12. LOGIC: $R2 \Longrightarrow [L1 \Longrightarrow [R1\Box \rightarrow (b \Longrightarrow f)]]$.

13. QM: $L1 \Longrightarrow [R1 \Longrightarrow \neg(b \Longrightarrow f)]$.

14. LOGIC: $L1 \Longrightarrow [R1\Box \rightarrow \neg(b \Longrightarrow f)]$.

15. LOGIC: $R2 \Longrightarrow [L1 \Longrightarrow [R1\Box \rightarrow \neg(b \Longrightarrow f)]]$.

The symbol $\neg$ is negates the proposition that follows it. Thus 15 contradicts 12, and the incompatibility of LOC and QM is established.

4. Justification of each step

1. The statement $(R2 \wedge X) \Longrightarrow [R1\Box \rightarrow Y]$ asserts: "If $R2$ is performed and X is true then [if $R1$ is performed, instead of $R2$, then Y is true.]" The validity of line 1 thus follows from LOC, which claims that the truth of statements referring only to measurements performed and outcomes appearing in **L** at the earlier time cannot be affected by changing in **R**, at the later time, the freely chosen $R2$ to the freely chosen $R1$.

2. This line is just a rewriting of line 2.

3. This is the prediction of QM corresponding to the path from g to c in Fig. 1.

4. This is the prediction of QM corresponding to the path from c to f in Fig. 1.

5. This follows from lines 2, 3, and 4 by two syllogisms.

6. This line follows from line 5 by elementary logic.

7. This follows from line 6 and the LOC claim that (also in the second Lorentz frame, in which the experiments in **L** occur later) a true statement referring only to experiments and observables that can appear only at an earlier time in **R** cannot be made false by changing the free choice made at a later time

in **L** from $L2$ to $L1$.

8. This is just a restatement of line 7.

9. This is the prediction of QM corresponding to the path from b to g in Fig. 1.

10. This follows from lines 8 and 9 by syllogism.

11. Note that in line 10 the statement b is made under the condition that $R2$ is performed whereas in line 11 statement b is made under the condition that $R1$ instead of $R2$ is performed. But then line 11 follows from line 10 and LOC, for LOC implies that the truth of b, which is fixed in **L** at the earlier time, cannot be altered by changing the choice in **R** at the later time from $R2$ or $R1$. It follows from this that if 10 is true then so is 11.

12. This is just a re-writing of 11.

13. This line is entailed by the dotted line from b to e in Fig. 1. Under the condition that $L1$ and $R1$ are performed it is not true that that if b appears in **L** then f must appear in **R**: 50% of the time the outcome e appears instead of f.

14. If something is true under a condition $R1$ then it is true if $R1$ is performed instead if the alternative.

15. This is implied by 14.

As mentioned previously, I have used a symbol, $\Box\!\!\rightarrow$, that is similar to one used in modal logic, and which has a verbal translation identical to the one used in modal logic. But the meaning of this symbol in modal logic is usually tied to a notion of "closeness of possible worlds" that is not part of physical theory, and for which various definitions can be given. Consequently, there are many modal logics, and appeal to "modal logic" is, by itself, not sufficient to determine the correctness of arguments [5].

The present proof, although structurally more complex than the proof given in [4] is logically simpler in that all of the steps that follow from LOGIC are true in the *general* theory of counterfactuals [9], without appeal to the special rules that define closeness of worlds.

The present proof, although dealing with "instead of" conditionals, is self contained and uses, in addition to the general logical principles, only ordinary ideas from quantum physics. These include the idea that the choices made by experimenters can be considered to be free, and the idea that an outcome that appears "now", although not completely fixed by past events, does become fixed when the experiment is actually performed, and hence cannot depend upon what an experimenter will choose to do at a later time. This idea leads to line 6.

But then in line 7 a switch is made: the assertion in line 6, made under the condition that $L2$ is performed earlier, is claimed to be true even if $L2$ is not actually performed. This is justified by saying that in some frame the choice between $L1$ and $L2$ has not even been made when all the components of the statement on the right are in place. The statement on the right is that "If under condition $R2$ outcome g occurs then if $R1$ were to be be performed, instead of $R2$, the outcome would be f." The truth of this statement is derived from QM, LOC, and the condition that $L2$ be performed earlier. But if we now imagine $L2$ to be performed later, then the LOC condition would say that the truth of the statement on the right cannot be altered by what will be chosen only later. This application of causality in the second Lorentz frame leads to the contradiction.

Of course, one can simply deny that it makes any sense at all to contemplate this relativistic idea that causal independence of the past on the future holds in all Lorentz frames. Indeed, that seems to be the message. But there is no problem with the idea that this causality condition holds in one preferred frame alone.

Acknowledgement

I thank Philippe Eberhard for useful comments and suggestions.

References

1. J.F. Clauser and A. Shimony, Bell's theorem: experimental tests and implications, *Reports on Progress in Physics 41*, 1881-1927 (1978); D.M. Greenberger, M.A. Horne, A. Shimony, and A. Zeilinger, Bell's theorem without inequalities *American Journal of Physics 58*, 1131-1143 (1990); Lucien Hardy, Quantum mechanics, local realistic theories, and Lorentz-invariant realistic theories, *Physical*

Review Letters 68, 2986-2984 (1992); Lucien Hardy, Nonlocality for two particles without inequalities for almost all entangled states, *Physical Review Letters 71*, 1665-1668 (1993); P.H. Eberhard and P. Rosselet, Bell's theorem based on a generalized EPR criterion of reality, *Foundations of Physics 25*, 91-111 (1995).

2. A. Einstein, B. Podolsky, and N. Rosen, "Can Quantum Mechanical Description of Physical Reality be Complete?" *Physical Review 47*, 777-780 (1935).

3. J.S. Bell, "On the Einstein-Podoksky-Rosen Paradox", *Physics 1*, 195-200 (1964).

4. H.P. Stapp, "Noise-induced reduction of wave packets and faster-than-light influences", *Physical Review 46 A*, 6860-6868 (1992).

5. H.P. Stapp, Reply to 'Stapp's algebraic argument for nonlocality', *Physical Review A49*, 4257-4260 (1994).

6. Lucien Hardy, "Quantum mechanics, local realistic theories, and Lorentz-invariant realistic theories", *Physical Review Letters 68*, 2981-2984 (1992); "A quantum optical experiment to test local realism", *Physics Letters A 167*, 17-23 (1992).

7. P.H. Eberhard and P. Rosselet, Bell's theorem based on a generalized EPR criterion of reality, *Foundations of Physics 25*, 91-111 (1995)

8. N. David Mermin, "Quantum mysteries revisited", *American Journal of Physics 58*, 880-887 (1994).

9. David Lewis, *Counterfactuals,* Blackwell Press, Oxford; *Philosophical Papers Vol II*, Oxford University Press, Oxford; D. Bedford and H.P. Stapp, "Bell's Theorem in an Indeterministic Universe", *Synthese 102*, 139-164, 1995.

Ernest Orlando Lawrence Berkeley National Laboratory
One Cyclotron Road | Berkeley, California 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098