Comment on "Quantum Mechanics, Local Realistic Theories, and Lorentz-Invariant Realistic Theories"

In a recent very interesting Letter, Hardy [1] claims that "if we retain realism, ... we are forced to accept that quantum mechanics implies ... violation of Lorentz invariance" (*). Hardy takes "realism" to imply a "reality condition," which he applies to the analysis of a particular experiment viewed from three different Lorentz frames. The reality condition allows him to conclude that, whenever the measurements of certain observables D^+ and D^- yield the value 1 for both, there exist "elements of physical reality" (epr's) corresponding to unmeasured observables U^+ (in the absolute past of D^+) and U^- (in the absolute past of D^-) [2], the values of which (again both 1) are impossible as the outcome of an actual joint measurement of U^+ and U^-. Since the very notion of epr as used by Hardy is such that when a measurement is performed it reveals the value of the corresponding epr, Hardy concludes (*). The purpose of this Comment is to point out that this proof is inadequate.

The reality condition on which the argument rests asserts that "If we can predict with certainty the result of measuring a physical quantity, then there exists an element of reality corresponding to this physical quantity and having a value equal to the predicted measurement result." We claim that this condition is by no means an inevitable consequence of "realism." Moreover, it is fatally ambiguous. 1) The EPR-Bell-Aspect analysis has shown that nonlocal effects exist in nature. Therefore, particularly in a relativistic framework which lacks an absolute present, our ability to predict the result of measuring a physical quantity can be explained by our being nonlocally affected by the measurement *result* and thus does not demand a preexisting element of reality. 2) How are we to understand Hardy's reference to a "physical quantity"? We already know from the no-hidden-variables theorems, i.e., from Gleason, from Kochen and Specker, or, best, from Bell—indeed, from the first part of Hardy's paper!—that if we demand that "physical quantities" be associated with elements of reality, with predetermined values which are merely discovered by measurement, then this phrase must refer to the complete globally (nonlocally!) defined experimental setup (the "context"), and not just to the operator that the quantum formalism associates with it [3]. Taking this into account, Hardy's contradiction is resolved—indeed, the argument does not get off the ground: Hardy's epr's $[U^{\pm}]$ refer to the context of *not measuring* $U^{\mp}$; therefore they are not appropriate to the context of "joint measurement of U^+ and U^-." In fact, nothing precludes the existence of (different) epr's $\{U^{\pm}\}$ referring to the latter context. (Related points have been made by several authors [4].)

To further support our refutation of Hardy's argument for (*), we would like to draw attention to Bell's multi-time version of the GRW-theory [5]. This is a *realistic* theory which yields (pretty much) the same predictions as orthodox quantum theory, and which is "Lorentz invariant enough" [6] to be a counterexample to Hardy's argument.

Moreover, even "realistic interpretations which assume that the particles have real trajectories" are not excluded: What Hardy's additional argument for this statement really shows is that the joint distribution of the positions of particles cannot in general agree with $|\psi|^2$ in all Lorentz frames. (The field-theoretic analogue of) this important conclusion has already been conjectured in [7]. We are preparing a detailed exposition of this statement and its significance, including how it might be compatible with Lorentz invariance on the microscopic as well as on the macroscopic level.

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[1] L. Hardy, Phys. Rev. Lett. **68**, 2981 (1992)
[2] We shall here grant Hardy's assumption that "the 'elements of reality' corresponding to Lorentz-invariant observables are themselves Lorentz-invariant."
[3] In this regard it would perhaps be well to recall Bohr's criticism of the original EPR reality criterion—that it "contains an essential ambiguity" related to the fact "that the procedure of measurements has an essential influence on the conditions on which the very definition of the physical quantities in question rests" (N. Bohr, Nature **136**, 65 (1935)).
[4] R. Clifton and P. Niemann, Phys. Lett. A **166**, 177 (1992); L. Vaidman, Phys. Rev. Lett. **70**, 3369 (1993)
[5] J. S. Bell, *Speakable and unspeakable in quantum mechanics* (Cambridge University Press, Cambridge 1987), p. 201
[6] The effect of a Lorentz transformation in Hardy's experiment, which involves measurements in a system composed of well-separated subsystems (after preparation of the entangled state, which is Hardy's (9)), is that of a relative time translation. The Bell-GRW theory is invariant under such transformations [5]. Therefore it is a suitable *realistic account* for quantum phenomena of the kind discussed by Hardy.
[7] D. Dürr, S. Goldstein, and N. Zanghí, in *Stochastic Processes, Physics and Geometry*, edited by S. Albeverio, G. Casati, U. Cattaneo, D. Merlini, and R. Moresi (World Scientific, Singapore 1990)