Spatial Locality: A hidden variable unexplored in entanglement experiments

Abstract

In a recent *Nature* article Hensen *et al*. reported that they have accomplished a "loophole-free" test of Bell's theorem. The authors speculated that further improvements in their experimental design could settle an 80 year debate in favor of quantum theory's stance that entanglement is "action at a distance". We direct attention to a *spatial* aspect of locality, not considered by Bell's Theorem or by any of its experimental tests. We refer to the possibility that two distanced particles could remain spatially disconnected, even when distanced enough to ensure that information between them was transmitted faster than the velocity of light. We show that any local-deterministic relativity theory which violates Lorentz's contraction for distancing bodies can maintain spatial locality at any distance. We conclude that until the loophole of spatial locality is closed by future experiments, the news about the death of locality will remain greatly exaggerated.

Keywords: Entanglement; Nonlocality; Bell's Theorem; Quantum Theory; EPR; Lorentz contraction.

Hensen et al.[1] reported a test of Bell's Theorem [2,3] in which two electrons' spins were entangled while at distance which ensured that the interaction between the electrons was faster than light. Hensen et al. speculated that further improvements in the implemented event-ready scheme [4], with higher entangling rates, could settle the 80 year debate between the stance of quantum theory, positing that quantum entanglement is nonlocal, and the stance of Albert Einstein, who strongly objected the possibility of action at a distance [5], calling it "spooky" [6].

We direct attention to a *spatial* aspect of locality, not considered by Bell's Theorem or by any of its experimental tests, 7-10, including the recent test by Hensen et al [1, 7-10]. We refer to the possibility that two distanced particles could remain spatially disconnected, even when distanced enough to ensure that information between them was transmitted faster than the velocity of light. We ascribe the neglect of a probable spatial locality between distanced particles to its counter-intuitive nature and to the fact that it contradicts the Lorentz contraction predicted by Special Relativity. However, our intuitions are largely gained by observations of large and slow objects, and thus cannot be extrapolated automatically to the behavior of small particles moving and spinning with high velocities. Moreover, the contradiction between the possibility of particles maintaining spatial locality and Lorentz contraction should not be a source of worry, especially since Lorentz contraction is in contradiction with Quantum Theory itself [11,12].

We interpret Hensen et al. findings as strong evidence against the *temporal* aspect of locality, but not against the *spatial* aspect. We argue that any realistic relativity theory which predicts *length extension* between distanced particles cannot be dismissed by theory as candidate for explaining entanglement and that until the possibility of spatial locality is eliminated experimentally the fate of local realism stays unsettled.

To substantiate our argument, consider a system in which two particles A and B distance from each other along the $+x$ axis with normalized constant velocity β. Denote the radius of particle B in its rest-frame by Δx^0.

For an inertial system, as the one described above, the relativistic distance transformation is given by:

$$\Delta x = \Lambda_x(\beta)\,\Delta x^0 \qquad \dots (1)$$

Where Δx is the length of particle B along the x-axis in the reference-frame of particle A, and $\Lambda_x(\beta)$ is the distance's transformation factor.

Now consider the set of all continuous and well behaved local and deterministic relativity theories, in which $\Lambda_x(\beta)$ satisfies the following conditions:

$$\Lambda_x(0) = 1 \qquad \dots. (2)$$

$$\frac{\partial \Lambda_x(\beta)}{\partial \beta} \geq 0, \text{ for } \beta \geq 0, \text{ and } \frac{\partial \Lambda_x(\beta)}{\partial \beta} < 0, \text{ for } \beta < 0 \qquad \dots. (3)$$

$$\Lambda_x(1) = \infty \qquad \dots. (4)$$

The condition in (2) ensures the invariance of Δx^0 if the two particles are stationary with respect to each other. The conditions in (3) and (4), contrary to the Lorentz contraction, prescribe that the spatial dimension Δx^0 of particle B, along its movement relative to particle A, will continually "stretch" with β, approaching ∞ as β approaches 1.

In a theory satisfying the aforementioned conditions, local entanglement becomes feasible even when temporal-locality has been eliminated. It is easily noticed that for any distance *d* between A and B, conditions (1)-(4) guarantee the existence of a critical velocity $\beta^*(d)$, above which the *relativistic stretch* of particle B in A's frame is larger than *d*.

In conclusion, we argued that while Bell's theorem disqualifies temporally-local theories from being candidates for reproducing the results of quantum theory, it cannot equally forbid spatially-local theories. We demonstrated that any realistic relativity theory which predicts length extension between distanced particles cannot be dismissed by theory as candidate for explaining entanglement. Obviously there is no guarantee that a theory that surpasses Bell's inequality can reproduce quantum theoretic results, but until the spatial-locality loophole is satisfactorily closed, the fate of such theories should be decided by future entanglement experiments.

References

1. References 1. Hensen et al. Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometers, *Nature* (2015) doi:10.1038/nature157592.

2. Bell, J., 1964, *Physics* 1, 195.

3. Bell, J. S. *Speakable and Unspeakable in Quantum Mechanics*: Collected Papers on Quantum Philosophy 2nd ed. (Cambridge Univ. Press, 2004).

4. Zukowski, M., Zeilinger, A., Horne, M. A. & Ekert, A. K. Event-ready-detectors-Bell experiment via entanglement swapping. *Phys. Rev. Lett*. 71, 4287-4290 (1993).

5. Einstein, A., Podolsky, B. & Rosen, N. Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev*. 47, 777–780 (1935).

6. Letter from Einstein to Max Born, 3 March 1947; The Born-Einstein Letters; Correspondence between Albert Einstein and Max and Hedwig Born from 1916 to 1955, Walker, New York, 1971.

7. Aspect, A., Dalibard, J. & Roger, G. Experimental test of Bell's Inequalities using time-varying analyzers. *Phys. Rev. Lett*. 49, 1804-1807 (1982).

8. Weihs, G., Jennewein, T., Simon, C., Weinfurter, H. & Zeilinger, A. Violation of Bell's Inequality under strict Einstein locality conditions. *Phys. Rev. Lett*. 81, 5039-5043 (1998).

9. Matsukevich, D. N., Maunz, P., Moehring, D. L., Olmschenk, S. & Monroe, C. Bell Inequality Violation with Two Remote Atomic Qubits. *Phys. Rev. Lett*. 100, 150404 (2008).

10. Giustina, M. et al. Bell violation using entangled photons without the fair-sampling assumption. *Nature* 497, 227-230 (2013).

11. Hardy, L. Quantum mechanics, local realistic theories, and Lorentz-invariant realistic theories. *Phys. Rev. Lett*. 68, 2981(1992).

12. Berndl, K., Dürr, D., Goldstein, S., and Zanghì, N. Nonlocality, Lorentz Invariance, and Bohmian Quantum Theory. *Phys. Rev. A* 53, 2062–2073 (1996).