What could Bell's theorem be telling us?

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Abstract

We point out that there is no obvious contradiction between the results of quantum mechanics and consequences of general relativity conceived in its most general form.

1 Where can one look for a real contradiction?

Recently, claims that a final Bell experiment has been performed excluding (local) realism are put into perspective. What I intend to do in this short note is to offer a small counterweight to the myth surrounding Bell's theorem as if realism or indeed local realism would be refuted if a Bell inequality would be surpassed be the raw data. Moreover, I offer some evidence that there is no obvious contradiction behind the *ideas* of quantum mechanics and general relativity; certainly such clash is not to be found in the EPR paradox. So, I ask to the reader, what is Bell's theorem [1] [2] telling us? The only thing it reveals is that the notion of locality of Bell cannot be maintained for the microscopic world. While it works perfectly well for macroscopic objects (since they are not entangled in a way we would notice), something else seems to be going on for elementary particles. Nowadays, many people seem to think that at short distance scales our notions of spacetime must break down either because of the infinities arising in quantum field theory or for reasons inherently present in general relativity (that probing spacetime at such distances would cause the formation of microscopic black holes). Often, the point of view of a spacetime foam has been put forward where, possibly, virtual wormholes are created and annihilated. Another idea, inspired by the holistic nature of quantum mechanics and results concerning black hole thermodynamics is that the universe is like a hologram; obviously, if both are on the right track, they ought to be isomorphic to one and another. None of these considerations are in contradiction to general relativity which leaves entirely open what the correct spacetime structure really is and nevertheless both have something to say about quantum non-locality. For suppose that two entangled particles are connected by a traversable Einstein Rosen bridge (better known as a wormhole) then it is possible for them to communicate at *effective* spacelike separated locations without exceeding the local velocity of light. Now, the Copenhagen interpretation of quantum mechanics does not require the wormhole to be destroyed after both particles were measured, it only tells that both individual particles are put

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into a definite state (and that both particles together do not form a state of zero spin anymore) which is good news since otherwise we would need a new dynamics for spacetime given that general relativity does not know how to deal with topology change (without creating singularities). The only conclusion we must draw here is that elementary particles are not such simple objects as most people believe, they do not only carry internal "quantum" numbers but also hidden variables relating them to other particles in the universe. Effectively, such theory is of course nonlocal but there is no need to look for theories with signals exceeding the *local* velocity of light; one only needs to recognize that for elementary particles the assumed notions of spacetime do not uphold! In my view, this is where Bell's definition of local realism fails; his theorem has no grand implications upon the whole philosophy of science as Bohr would have wished, but it shows us that the observed macroscopic simplicity of spacetime is either an illusion or breaks down at the microscopic scales.

What about wave-particle duality, I hear you say? My views here are somewhat unorthodox, but suffice it to say that we only observe particles, we never see the wave. Clearly, something akin to the wave, no matter if it satisfies a linear Schrodinger equation or not, must be present but perhaps not at the most fundamental level. We humans also show wavelike behaviour in some circumstances even at an individual level (and certainly in a collective way, for example in traffic situations) and nobody would dare to utter that we are fundamentally wavelike. People would say that our brain makes such computations unconsciously so why would nature, or even the fundamental particle, not do that either? Bohm-de Broglie theory already partially recognizes that there is a particle and a wave, but I would go even further and say that particle and wave are both different manifestations of an entirely new thing. This "thing" must be nonlocal, not as to say entirely holistic in nature; in this way the two opposites (particle and wave) may find a higher synthesis. This is the philosophy of Hegel in opposition to that of Kierkegaard. Locality may get an entirely new definition in such framework and it could very well be possible that the theory in terms of the "holistic" variables is a local one in some natural topology (such as is the case with the traversable wormholes); as such, Einstein's insights may be translated into this new language.

More conventionally, if one considers Einstein's thought that geometry and matter are influencing one and another then one must come to the conclusion that the collapse of the wavefunction has a physical significance unlike when geometry is frosen. Now, the reason why we don't see such effects is because G as well as the mass of elementary particles are small. So there is a dynamically preffered frame in nature (call this the reinstatement of the arrow of time in general relativity) [3] just as is the case for causal set theory when one deals with finite posets (there however, this frame does not influence the physics!). There is still a notion of causality in such framework (just as there is a notion of causality in Newtonian physics) but as mentioned before this does not need to be the effective notion of causality which is valid in the macroscopic world! The latter must dynamically arise when one considers interaction of macroscopic objects, so macroscopic Lorentzian geometry should have a dynamical origin. As far as I know, this idea has not been explored yet by causal set proponents but it is certainly a way to potentially avoid a lot of trouble with "quantization".

In other words, for physics of elementary particles the *effective* Lorentzian geometry should break down (which does not of course imply that Lorentzian geometry breaks down).

Alternative ways to introduce non-locality, such as a traditional non-local signalling in a conventional spacetime between two particles are all unplausible avenues since one can consider the Bell experiments to take place in isolated subsystems from such point of view.

2 What are we looking for precisely?

I might have called this section, akin to Bell, "against measurement" [1] but have chosen not to do so. A fairly conventional, but illuminating discussion of what measurement "does" can be found in the PhD thesis of Feynman [5]. Feynman fails to grasp the occasion, as he himself admits, to define what measurement really is but contents himself with writing the Copenhagen doctrine in a more direct way (he avoids operators, wave functions and all that). More specifically, let P_{ab} denote the probability that if first quantity A is measured to be a on a system then quantity B is measured to be b and generalize this to more "quantities" $P_{abc\ldots d}$. Then classically, we have that

$$P_{abc} = P_{ab}P_{bc}$$

and

$$P_{ac} = \sum_b P_{abc}$$

both of which are also true quantum mechanically if we actually measure B. If B is not measured then the last equality is replaced by

$$\psi_{ac} = \sum_b \psi_{ab}\psi_{bc}$$

where $P_{ab} = |\psi_{ab}|^2$. Therefore, if one wants to dispose of "measurement" one needs to explain why these two different rules hold proviso an experiment has been made or not. Clearly, there is nothing in the quantum formalism which can realize this so one needs to add hidden variables. This is precisely what happens in the Bohm-de Broglie theory or the Everett interpretation, but let us proceed somewhat more formally since our analysis should transcend those "pictures" too. The problem with setting up such analysis is that up to this date we don't have a mathematically sound relativistic quantum theory yet so that we cannot refer to that theory as being the necessary approximation to the more fundamental one; for an attempt in that direction, see [3]. Hence, we need to refer directly to the non-relativistic limit, which is Schrodinger's multi-particle theory where we are free from issues such as particle creation and annihilation. So, suppose our theory has been constructed from "variables" λ_i where $i \in I$ and I is some index set; ultimately spacetime itself is a function of the λ_j where the j constitute some subset of I. We can define worldlines of particles $\gamma^k(\lambda_j)$, a complex valued wave function $\Phi(\lambda_j)$ and a *Cartesian* coordinate system $x^\mu(\lambda_j)$ such that in *some* limit Φ reduces to a function which depends upon the positions of the particles at a given time, its internal quantum numbers, of time itself and of some variables which should take into account measurement. Moreover, we would demand that the worldlines of particles coincide with the Bohm-de Broglie currents, generalized to Φ satisfying for example a GRW type of "Schrodinger" equation. This is precisely what we mean with looking for a theory behind quantum mechanics; first we look for suitable "non-local" variables obeying possibly local and deterministic laws (in a suitable topology) and then *define* particles and a wave function from those such that we get ordinary non-relativistic physics out.

It is remarkable to notice that general relativity appears to imply a similar worldview since here space and time "evaporate" from the *physics* albeit not from its mathematical formulation which is why the symmetry group of relativity is that large. Indeed, for vacuum gravity in the canonical formulation on $\mathcal{M} = \Sigma \times \mathbb{R}$, one has that there is no dynamics at all in the sense that the Hamiltonian is pure constraint and if one were to isolate the true dynamical degrees of freedom, then one should conclude these are frosen indeed. These fundamental degrees of freedom constitute a space smaller than the space of diffeomorphism classes of Riemannian metrics on Σ which is non-local; including classical matter in the picture makes the space of diffeomorphism equivalence classes much larger than this, but it remains a non-local configuration space with a Hamiltonian which is pure constraint. This implies that quantum mechanics as it is formulated now cannot be a fundamental theory as it is irreducibly based upon the notions of space and time. All this of course results from the assumption that the Lorentzian geometry is fundamental: if that were to be false, then the whole rationale behind relativistic quantum field theory would fade away since the notion of causality is not a fundamental one then, something which we have offered as a way out before. It would make relativity an emergent theory though, just as its associated Lorentz invariance. Both conclusions, one which assumes relativity to be fundamental and another which implies it to be emergent, strengthen the hypothesis of realism and weaken the locality assumption. I wish I could be more specific and present such theory in detail; however, I anticipate progress in this direction to be slow as we still need to further deepen our understanding of the theories of quantum mechanics and general relativity. Perhaps, experiment will guide us in some unforseen way in the future.

References

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