Quantum Entanglement and Time

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Abstract

In this paper, we argue about temporal Bell Inequalities in order to introduce the notion of entanglement in Time.

1 Temporal Bell Inequalities

Brukner et.al (Brukner et al, 2004) derive the temporal Bell inequalities from simple principles. These temporal Bell inequalities are derived from the assumptions of realism and locality in time. The authors shown that QM violates these inequalities and thus is in conflict with the two assumptions. This can be used for performing certain tasks that are not possible classically. Their results open up a possibility for introducing the notion of entanglement in time in quantum physics.

Conceptually, as well as mathematically, space and time are differently described in QM. While time enters as an external parameter in the dynamical evolution of a system, spatial coordinates are regarded as quantum-mechanical observables. Moreover, spatially separated quantum systems are associated with the tensor product structure of the Hilbert state-space of the composite system. This allows a composite QS to be in a state that is not separable regardless of the spatial separation of its components. We speak about *entanglement in space*. On the other hand, time in QM is normally regarded as lacking such a structure.

Entanglement in space displays one of the most interesting features of QM (called nonlocality). As we know, *Locality in space* and *realism* impose constraints, Bell's inequalities, on certain combinations of correlations for measurements of spatially separated systems, which are violated by QM. Furthermore, entanglement in space

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is considered as a resource that allows powerful new communication and computational tasks that are not possible classically. Because of different roles time and space play in quantum theory one could be tempted to assume that the notion of *"entanglement in time"* cannot be introduced in quantum physics.
The authors will explicitly derive *temporal Bell's inequalities*. (the notion of temporal Bell's inequalities was first introduced by Leggett and Garg (Leggett et al. 1985) in a different context) in analogy to the spatial ones. There are constraints on certain combinations of temporal correlations for measurements of a *single* QS, which are performed at *different* times. Brukner explicitly shows that QM violates these inequalities.
The temporal Bell's inequalities are derived from the following two assumptions:

(a) *Realism:* The measurement results are determined by "hidden" properties the particles carry prior to and independent of observation, and
(b) *Locality in time:* The results of measurement performed at time are t_2 independent of any measurement performed at some earlier or later time t_1

It should be noted that in contrast to spatial correlations, where the special theory of relativity can be invoked to ensure locality in space, no such principle exists to ensure locality in time for temporal correlations. Nevertheless, it is meaningful to ask whether or not the quantum-mechanical predictions are compatible with the assumptions (a) and (b). Ultimately we expect to learn more about the relation between the structure of space and time and the abstract formalism of quantum theory.
In conclusion, the difference between the spatial and temporal structure may ultimately be fundamental, or it may be an indication that we need a deeper theory in which the two need to be treated on a more equal footing (quantum field theory does not suffice in this sense). Either way, it appears that the next step should lie in exploring the consequences of combining entanglement in space and time in order to study how they relate to each other.

2 Entanglement as Nonlocal Determinism

As we have seen quantum correlations in space-like separated, according Einstein, imply particles carrying hidden variables, which determine the particle's behavior. In this way Einstein concluded that the quantum mechanical description of the physical reality cannot be considered complete. Bell (1964) showed that if one only admits relativistic local causality the correlations occurring in two-particle experiments should fulfill clear locality conditions ("Bell's inequalities"). Bell experiments conducted in the past two decades (in spite of their loopholes), suggest a violation of local causality: statistical correlations are found in space-like separated detections; violation of Bell's inequalities ensure that these correlations are not predetermined by local hidden variables. Nature seems to behave nonlocally, and QM predicts well the observed distributions. So, the QM predicts correlated outcomes in space-like separated regions for experiments using two-particle entangled states. Bell experiments demonstrate nonlocal correlations[1] between space-like separated events, which cannot be explained by means of relativistic influences bounded by the velocity of light. According Suarez, giving up the concept of locality is not sufficient to be consistent with quantum experiments. One has to give up also nonlocal determinism (i.e. the view that one event occurring before in time can be considered the cause, and the other occurring later in time the effect.). In other words, this means that one has to give up the view that the outcomes at each part of the setup result from properties preexisting in the particles before measurement: outcomes in Alice's (respectively Bob's) cannot be explained by the properties the photon carries when leaving the source and the settings of Alice's (respectively Bob's) measuring devices. According the before-before or Suarez-Scarani[2]. The time-notion makes sense only in the domain of the relativistic local phenomena. The nonlocal correlations cannot be explained by any history in spacetime, they come from outside spacetime. Putting together the results of these experiments types one can conclude that in entanglement experiments local random events experience influences from outside spacetime to produce nonlocal order. Quantum correlations unite in the same phenomena full local randomness and nonlocal timeless order. According, Suarez the before-before experiment demonstrates that quantum randomness can be controlled by influences from outside spacetime, and therefore by immaterial free will. Rather than looking at quantum physics as the model for explaining free will, one should look at free will as a primitive principle for explaining why the laws of Nature are quantum. QM actually means that in nature this ordering activity comes about without flow of time.

1 According Suarez-Scarani (Suarez-Scarani, 1997), the experiments demonstrates that these nonlocal correlations cannot be explained in terms of "before" and "after".

2 They argued that recent experiments with moving beam-splitters demonstrate that there is no real time ordering behind the nonlocal correlations: In Bell's world there is no "before" and "after"

BIBLIOGRAPHY

-(Brukner et.al,2004) Quantum Entanglement in Time in arXiv:quant-ph/0402127v1

-(Leggett et al. 1985) Quantum Mechanics versus macroscopic realism: is the flux there when nobody looks? Phys. Rev. Lett. 54, 857 (1985)

-(Suarez-Scarani, 1997) Does entanglement depend on the timing of the impacts at the beam-splitters? Phys.Lett. A, 232, 9-14 390

-(Suarez, 2003) Entanglement and Time in quant-ph/0311004

-(Suarez et al. 2007)Is There a Time Ordering Behind Nonlocal Correlations?"Quantum Philosophy Theories (2007)