When GHZ meet Wigner's Friend: Does unitary single-world quantum mechanics necessarily violate Lorentz symmetry?

Since the work of Einstein and Minkowski at the beginning of the 20th century, the symmetries of spacetime present in relativity theory are generally considered to be fundamental symmetries of Nature. However, the nonlocal nature of quantum mechanics, as made explicit by Bell and followers from the 1960's, has caused many to doubt the fundamentality of these symmetries. An explicit example of this is given by Bohmian mechanics, which introduces a preferred reference frame, violating Lorentz symmetry. Bohmian mechanics can be seen as an attempt to combine unitary quantum mechanics, where the evolution of the wavefunction of any closed system is always unitary, with the demand that every measurement only has a single outcome. While a measurement may result in the unitarily evolving wavefunction containing many 'branches', each corresponding to a different outcome of the measurement, the Bohmian particle positions effectively select one of these branches, thereby securing the fact the the measurement only has a single outcome.

For many, introducing a preferred reference frame is a price too high to pay. However, unitary quantum mechanics has the advantage that measurement interactions are treated as any other interaction. Therefore, physicists and philosophers have been searching for a version of unitary quantum mechanics that does not sacrifice Lorentz symmetry, while still holding on to a single-worlds view, see e.g. Kent (2015). It might however be the case that the violation of Lorentz symmetry is a general feature of any possible variant of unitary single-world quantum mechanics. In this paper we show that in unitary single-world quantum mechanics, the Born rule cannot be satisfied in all inertial reference frames, which suggests a violation of Lorentz symmetry. More specifically, this happens when the Greenberger-Horne-Zeilinger (GHZ) state (Greenberger et al., 1990) enters the 'Wigner's Friend' gedanken experiment (Wigner, 1967). We stress that the result applies not only to existing approaches such as Bohmian mechanics, but to any possible (future) approach that is unitary and single-world.

First, we discuss the Wigner's friend thought experiment. Our presentation of the experiment is similar to that of Barrett (1999). We consider a laboratory, containing Wigner's Friend who is measuring the z-spin of a spin–1/2 particle. Wigner himself is outside of the laboratory. It is assumed that the composite system, consisting of the laboratory (including the friend) and the particle, is a closed system during the measurement performed by the friend. The particle is prepared in the x-spin up state. According to unitary quantum mechanics, the measurement of the friend corresponds to some unitary transformation of the laboratory and the particle. If Wigner would know what this unitary transformation is, he could in principle check unitary quantum mechanics by performing a measurement of an observable A which has the unitarily transformed state of the laboratory-plus-particle system as an eigenstate; the measurement would then with certainty yield the corresponding eigenvalue as the outcome. Barrett calls such a measurements 'A-measurements'.

We now consider three copies of the above thought experiment. The 'Friends', inside the laboratories, are called Alice, Bob and Charlie, while the 'Wigners', outside the laboratories, are called Anna, Barbara and Chloe, respectively. The single spin–1/2 particle is also replaced by three particles, prepared in a GHZ state. Alice, Bob and Charlie measure the spin of the particles in the y-direction, while Anna, Barbara and Chloe perform A-measurements. Furthermore, measurements pertaining to any laboratory are spacelike separated from the measurements at the other laboratories. Assuming Lorentz symmetry, we can describe the six measurements in various inertial reference frames. Applying the Born rule in various frames results in predictions about correlations between measurement outcomes (which are all +1 or –1). Specifically, the product of the three outcomes of the 'Wigners' Anna, Barbara and Chloe is predicted to be –1, while the product of an outcome of a 'Wigner' with the two outcomes of the friends at the other laboratories is predicted to be +1. However, the combination of these correlations leads to a contradiction, much like a contradiction is reached for deterministic hidden variable theories by Greenberger et al. (1990). Therefore, if we want to maintain the assumption of single outcomes, at least one of the predicted correlations must fail to hold, and therefore the Born rule must fail in some inertial reference frame.

While one might think that the failure of the Born rule can simply be established by the 'Wigners' and the 'Friends' by comparing the six outcomes, this is actually not the case. The measurements by the 'Wigners' can be shown to erase the measurement outcomes of the 'Friends', rendering such a comparison impossible.

For example, in Bohmian Mechanics, the correlations in the preferred reference frame can be shown to hold, while they necessarily fail to hold in some of the other frames. However, the preferred reference frame cannot be detected because of erasure of the outcomes of the friends.

Because not all correlations can in fact be checked by the 'Wigners' and the friends, a solution might be that not all combinations of outcomes satisfy the Born rule. Bohmian mechanics also takes this route, but there a preferred reference frame becomes manifest at the level of measurement outcomes, because in that frame the Born rule is always satisfied. We will discuss the prospect of a relativistic solution, that does not introduce a preferred frame.

References

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