Quantum correlations, measurement and the origin of uncertainty

Daniele Tommasini

Departamento de Física Aplicada, Área de Física Teórica,
Universidad de Vigo, 32004 Ourense, Spain

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Abstract

I argue that the correlations that are predicted by Quantum Field Theory should not be interpreted as a real sign of non locality.

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In 1935 Einstein, Podolsky and Rosen (EPR) [1] pointed out that Quantum Mechanics apparently implied some mysterious, instantaneous action at a distance. This was considered a paradox, since it made the Quantum Theory incompatible with Special Relativity, suggesting the need for a more fundamental description of Nature.

Recently, I have shown that this EPR paradox is removed in Quantum Field Theory (QFT) due to an uncertainty on the number of soft photons that can appear in any process [2, 3]. For instance, let me consider a typical EPR experiment, involving two spin 1/2 particles A and B that are produced in coincidence in a rotation-invariant process with zero initial angular momentum. In my previous works, I have shown that when the spin component is measured on particle A, no certain conclusion can be obtained for the result of the measurement on B, since the angular momentum conservation involves also an unknown number of soft photons [2, 3]. This fact is sufficient to remove the paradox at least in practice, since it makes it impossible to use the supposed quantum nonlocality, e.g. to teleport a state to distant particles.

In Ref. [2], I have also argued that the QFT correlations turn out to be smaller than those obtained by ignoring the soft photons, but still can allow for the observed violation of the “Bell’s inequalities” [4, 5]. However, such correlations are commonly thought to be a sign of quantum nonlocality by themselves. Then, even if the hardest part of the EPR paradox is removed by the soft photons argument, we are left with the residual mystery of explaining how comes that in the correlations the angular momentum is exactly conserved after the measurement due to an apparent cancellation amongst distant particles (A, B and the soft photons).

In Ref. [3], I have noticed that in QFT the angular momentum is conserved locally. Therefore, if one interprets the measurement as the result of scattering processes, only the particles that come in causal contact with A during the measurement can change their state as a consequence of the measurement. No effect can be induced on the distant particles (B and the possible soft photons), and the correlations should be causal. This is also a sound prediction of QFT [3], however it seems to be contradicted by the fact that in the actual correlations [2] the angular momentum is conserved for the system of particles A, B and the soft photons, independently of the measuring apparatus. How comes that some quantities that are obtained by a causal theory apparently imply an instantaneous action at a distance (whatever unobservable it would be)?
Even if this can be considered a philosophical problem, I think that it is relevant. One could hope that it would disappear in a more fundamental theory, such as a String Theory. Of course, such an attitude is legitimate, and is justified by the fact that QFTs themselves are not thought to be the ultimate Theory of Everything, since e.g. they do not describe gravity. However, I think that we should already get a solution to this apparent contradiction without leaving QFT. In fact, it has been shown that QFT is the form that any Relativistic Quantum Theory should get at “low” enough energies [1]. Since our problem has to do with “large” distances, i.e. with low energies, it can be expected that it should be solved without waiting for the ultimate Theory of Everything. In this brief note, I will show that this is actually the case: when QFT is interpreted correctly, the contradiction between the causality of the theory and the apparent nonlocality of the correlations that it predicts will disappear.

To see this, let me first notice that the field equations are deterministic. If we consider the Universe as a whole, instead of dividing it in an examined system, a measurement apparatus and the rest, QFT would just describe a smooth, deterministic evolution. We can consider as the dynamical variables the fields themselves, or equivalently the Complete Set of Commuting Observables (CSCO) made with the number operators \( N_i(\vec{p}, \lambda) \) that count the (density) number of particles of the type (i) (e.g., electrons, or positrons, or photons, etc.) having momentum \( \vec{p} \) and spin/helicity \( \lambda \). In any case, in the Heisenberg picture, all these dynamical variables have a well determined, smooth evolution (equivalently, in the Schrödinger picture the vector state evolves continuously in a deterministic way). Then, where comes the quantum uncertainty from? It is obvious that the determinism of the theory is not destroyed by the apparatus of measurement itself, that is included in the system of the whole Universe. The uncertainty only appears when we split the world in a measuring apparatus and a measured system (and the rest). Of course, this division is necessary if we want to do physics, i.e. to describe the phenomena that occur in a given subsystem of the Universe. But it is important to understand that this is the unique origin of the uncertainty: the separation between the object and the observer, and the limited point of view of the latter, that has to renounce even to take into account the effect of the measurement on the measuring apparatus itself.

This artificial division implies a lack of information which is the ultimate reason for the probabilistic character of the predictions of the QFT. This is also evident in scattering theory:
the scattering matrix (giving the correlations) is obtained by considering the amplitudes of the state at $t \to \infty$ (using the Schrödinger picture) into the out states, that are just the possible eigenstates of the CSCO $\{N^i(\vec{p}, \lambda)\}$. Any such a scalar product is usually thought to correspond to a “collapse” process, but the latter is actually a result of smooth scattering processes. In other words, the state vector of the Universe evolves continuously, and the correlations are just made out of its components, integrating out the variables that do not correspond to the observed (sub)system \[\text{[3]}. Therefore, the collapse does not happen at a fundamental level. According to the discussion of Ref. \[\text{[3]}, this is sufficient to remove also the last piece of the EPR paradox, i.e. the contradiction between the causality of QFT and its apparently nonlocal correlation functions. It is now obvious that the correlations are actually the reminder of the common origin of our two particles A and B, as we also expected from the causality of the theory. This also reconciles us with the relativistic intuition.

In my previous paper \[\text{[3]}, I concluded that Einstein was right in thinking that local realism was a fundamental characteristic of any reasonable theory of physics. Moreover, we see now that, in some sense, his intuition that the solution to the EPR paradox should be a deterministic theory was also correct. QFT is amazing, since it is at the same time extremely probabilistic and fully deterministic, without being a Hidden Variable theory \[\text{[8]. The Universe evolves in a deterministic way, while the act of measuring on an object subsystem, using another subsystem called measuring apparatus, implies a restricted knowledge, allowing only for probabilistic predictions. Einstein would probably say that God does not play dice; but we actually do.

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[7] Actually, there is also a theoretical impossibility to define unambiguously the system, due e.g. to the uncertainty on the soft photons.

[8] Actually, it could be said that the number of soft photons plays a role similar to that of an Hidden Variable.