Quantum Theory finally reconciled with Special Relativity

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Abstract

In 1935 Einstein, Podolsky and Rosen (EPR) pointed out that Quantum Mechanics apparently implied some mysterious, instantaneous action at a distance. This paradox is supposed to be related to the probabilistic nature of the theory, but since deterministic alternatives involving “Hidden Variables” hardly agree with the experiments, the scientific community is now accepting this “quantum nonlocality” as if it were a reality. However, I have argued recently that Quantum Electrodynamics is free from the EPR paradox, due to an indetermination on the number of the unobserved “soft photons” that can be present in any step of any experiment. Here, I will provide a more general proof, based on an approach to the “problem of measurement” that implies the full reconciliation of Quantum Field Theory with Special Relativity. I will then conclude with some considerations on the interpretation of the Quantum Theory itself.

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ment
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. For a long time, many physicists have tried to build a causal local, deterministic theory, in the belief that the probabilistic behavior of the microscopic world was only due to the non-observation of some Hidden Variables. Apart from the difficulty in elaborating a satisfactory model, such a project is now considered to be undermined by the results of several experiments that have been performed in the last 20 years [2, 3]. This has lead a large part of the scientific community to accept the Quantum Theory, including its supposed nonlocality, that is even used as the base for Teleportation and the current theories for Quantum Information and Quantum Computers. However, in the last few decades a very beautiful and successful description of the fundamental interactions has been achieved in terms of Quantum Field Theories (QFTs) [4, 5]. Recently, I have argued that the most popular of these theories, Quantum Electrodynamics (QED), is free from the EPR paradox, due to an indeterminacy on the number of the unobserved “soft photons” (i.e. photons that carry a very low energy) that can be present in any step of any experiment [6]. Here, I will provide a more general proof, based on an approach to the “problem of measurement” that implies the full reconciliation of QFT with Special Relativity. I will then conclude with some considerations on the interpretation of the Quantum Theory itself.

Let me first briefly describe a typical, ideal EPR experiment, following Chap. 17 of Ref. [7]. Two particles A and B, say two electrons [9], are emitted in coincidence by a source and travel in opposite directions. Far from the production point, some conserved observable, say the $z$-component of the angular momentum (spin), is measured on both of them. To fix the ideas, suppose that we know that the total angular momentum is zero, and that each of the two particles is created without a definite value for the spin component $S_z$. According to ordinary Quantum Mechanics, the measurement of the spin $S_z(A)$ of the electron A that is produced in a given single event will yield either the value $+\hbar/2$, or the value $-\hbar/2$. If the experiment is repeated a great number of times, each of these two results will appear with a frequency that will be an approximation for the corresponding probability. For instance, if the initial state were completely “unpolarized”, these two probabilities would be equal to 1/2. Now, let me consider again a single event, and measure the spin $S_z(A)$
of particle A far from the source, obtaining -say- the value $+\hbar/2$. According to the usual interpretation \[7\], the conservation of the total angular momentum would then force particle B to get the definite value $-\hbar/2$ of $S_z(B)$. In other words, particle B would immediately change its state, “collapsing” in the eigenstate $| -\hbar/2 \rangle$ of $S_z(B)$, as a mere consequence of the measurement performed on the distant particle A! Such a situation is called a violation of “local realism”, and shows an evident contradiction with Relativity, that forbids any action to propagate faster than light. This is the Einstein-Podolsky-Rosen paradox.

In practice, what can be done to test locality according to the previous ideas? It is clear that it is not sufficient to measure the spins of the two electrons in a single event and check that the spin of B takes a value which is opposite to that of A. In a single event, this could just be due to a casuality. For the test to be significant, in our simple example it seems that we have to check two things: 1) each of the two electrons should not be prepared in a $S_z$ eigenstate before the measurement (this condition can be guaranteed a priori by the experimental settings, and can be controlled a posteriori by verifying that different single measurements do not always give the same result for the individual spins); 2) the two spins should always give opposite values, whatever event is considered. In other words, we have to check that the two spins are “maximally correlated” \[10\]. In fact, this seems to be a consequence of Quantum Mechanics. For a long time, the experimental study of the correlations amongst the components of the spins of A and B along two arbitrary (in general different) directions in space, was also (erroneously) believed to allow to prove (or to discard) “quantum nonlocality” \[11\].

Let me now come back to the paradox, and make some historical remarks. Since the authors of Ref. \[1\] considered that local realism was a necessary ingredient of any reasonable physical description of Nature, they judged that a new theory was needed. Einstein also thought that the problem was due to the intrinsically probabilistic description of Quantum Mechanics, and hoped that a solution would eventually be found in Hidden Variable Theories, that would also allow for a deterministic description of Nature (“God does not play dice”, he used to say). Was he right?

In the last few decades, there has been increasing agreement within the scientific community that he was wrong. This conclusion seemed to be justified by the actual realization of a series of experiments measuring the statistical correlations between the spin/polarizations of the two (or more) particles A, B, that were produced in coincidence in an EPR experiment.
The data were considered to be incompatible with Hidden Variables Theories, while they agreed with the prediction of Quantum Mechanics. Since Einstein himself used to relate locality with determinism, it is perhaps not surprising that these results were also interpreted (erroneously!) as an experimental evidence of “quantum nonlocality”. This conclusion was then transformed in the so-called “Bell theorem”. As a consequence, instead of being concerned with that implicit violation of Special Relativity that was apparently implied by Quantum Mechanics, several physicists have decided to accept the EPR paradox, i.e. that mysterious “quantum nonlocality”, as if it were a real characteristic of Nature itself. It is then generally believed that some mysterious action at a distance continues to link the fate of distant particles that have been produced in coincidence in the past. Such a supposed “phenomenon” is also called entanglement, and it is also believed to allow for the teleportation of the state of a particle A to another distant particle B. Enormous efforts in using the EPR paradox to build Quantum Information Theories and models for Quantum Computers have then been performed. To justify the strong violation of intuition and, what is a more serious problem, of Relativity, that is implied by such applications, it is common to cite some old sentences of authorities such as Richard P. Feynman (“I think I can safely say that nobody today understands Quantum Physics”) or Roger Penrose (Quantum Theory “makes absolutely no sense”). Ironically, Feynman himself is also one of the main contributors to the construction of the QFTs that allow for the solution of the paradox and the recovery of local realism and of a good deal of intuition.

In fact, the above argument leading to the EPR paradox is based on ordinary Quantum Mechanics, with two hidden assumptions: i) before the measurement is done, only the particles A and B are supposed to exist, i.e. no additional particle is allowed to appear in coincidence with them (this implies that, when the spin of A is measured and fixed to a definite value, it can only be compensated by an opposite value of the spin of B in order to conserve the zero total angular momentum); ii) the measurement process is supposed to modify the state of particle A, forcing it to ‘collapse’ into an eigenstate of the observed magnitude (e.g. angular momentum), and the actual modifications induced in the measuring apparatus are not considered to be relevant.

However, the old Quantum Mechanics approach is not correct in QFT, and these two assumptions turn out to be wrong.

In Ref. [6], I have already disproved assumption i). That argument was related to a basic
characteristic of QFTs: they predict a non vanishing probability for any process that does not violate any fundamental symmetry. It is important to point out that this corresponds perfectly to the behavior observed in the High Energy Physics experiments: for instance, it is well known that an electron-positron collision can produce any result (each with its own probability) that is allowed by the available energy and the conservation of momentum, angular momentum, electric and color charge, etc. It is so rare to find an “accidental cancellation” for the rate of an allowed process, that such a case would be considered as a hint for some new symmetry forbidding that channel \[12\]. In other words, all the new particles that can be created without violating the universal conservation laws can actually be produced, and any definite process involving the creation of a particular set of particles has his corresponding amplitude of probability, that can eventually be computed approximately by drawing the relevant Feynman diagrams (when perturbation theory is applicable). In particular, since photons have zero rest mass, their energy can be arbitrarily low. Since they also have zero charge and color, we can conclude that an arbitrary number of “soft” photons, with low enough total energy, can always be created in coincidence with any physical process! It is important to point out that these soft photons can exist even if they are not observed: not only are they not looked for, but they would also easily escape detection anyway, due to their very low energy.

Incidentally, this result by itself will imply very important consequences for the Theory of Measurement. For instance, according to the usual postulates, the measurement of an observable in a system that is previously in one of its eigenstates will leave the system unaltered. But we see that such a situation is not realizable as a matter of principle, since we can never exclude the possible creation of unobserved soft photons (actually, we cannot know the soft photon content of the initial state either). In other words, the ideal measurement that is used to build ordinary Quantum Mechanics is excluded due to the relativistic effects that are described by QFT. It also seems that QFT is even less deterministic than Nonrelativistic Quantum Mechanics, due to this underlying sort of Indetermination Principle on the Number of Particles. In fact, the only predictions that it allows are on probabilities and average values. I will come back later to this important point.

In Ref. \[6\], I argued that this greater indetermination allows the EPR paradox to be removed. The argument went as follows. First, I noticed that there are two sources of indetermination on the number of real particles in an EPR experiment: at the production
process, or at the measuring apparatus. In Ref. [6], I have explicitly drawn some Feynman diagrams that predict these effects. Here, just knowing that they exist is sufficient. In our example, after the spin \( S_z(A) \) is measured to be, say, \( +\hbar/2 \) on particle A, there is now way of knowing how many soft photons there are around. At most, we could say that the rest of the world, including particle B and an undetermined number of unobserved soft photons, should get a definite value of the angular momentum, \( -\hbar/2 \), to compensate the result obtained on A. This means that the measurement on A does not allow for any prediction of the value of the spin (or any other conserved quantity) on B with certainty. One could even look for single events showing an apparent symmetry violation (which could be important in the case of angular momentum), due to the fact that we observe just A and B, i.e. a part of the particles involved in the process [6]. In any case, no mysterious action at a distance can be observed.

Here, one could raise a subtle question: is any non locality implied by the fact that the rest of the world (including the soft photons) apparently “collapses” into a \( -\hbar/2 \) eigenstate of the angular momentum, after the measurement is made on particle A [13]? Even though such a non locality would not be observable, the question is relevant as a matter of principle. The complete answer requires a deep understanding of the process of measurement in QFT, to be interpreted as the result of a succession of elementary scattering processes. This will allow me to correct the wrong assumption (ii) (see several paragraphs above), that is usually made in the treatment of the EPR paradox. As we shall see, this will also provide a more general and complete argument against quantum nonlocality, that could even work in the absence of the soft photons (but, of course, they exist!).

First of all, let me recall that in QFT the scattering matrix respects causality, and that all the conservation laws hold locally [1, 3]. (In perturbation theory, this means that the conservation laws are ensured by each vertex of any Feynman graph.) Therefore, when particle A interacts with the measuring apparatus in an EPR experiment, the angular momentum is conserved locally: only the particles of the apparatus that come in interaction with A (including the ones that might be created) can change their angular momenta when the spin of A is measured! This is a prediction of QFT.

In other words, we find that assumption (ii) was wrong, and the measurement on A is not compensated by a collapse on B, but merely by a change of the angular momentum state of the measuring apparatus! After the measurement, the state of the composite system, A +
measuring apparatus (including the possible soft photons that might appear there), has the same angular momentum properties than before the measurement. No instantaneous effect is implied on B or on any distant particle. Special Relativity is saved!

Therefore, when the process of measurement is interpreted correctly in QFT, no quantum nonlocality exists! Incidentally, by considering the measurement as made out of scattering processes, we are also avoiding giving the observer the magic role that he/she had in the old formulation of Quantum Mechanics.

This also implies that we will have to renounce to the direct applications of the EPR paradox, such as entanglement and teleportation. However, I hope that the views that I am presenting here might stimulate further research on the applications of QFT, and could provide a new base for the construction of Quantum Information Theory and Quantum Computers, that will eventually continue to be a theoretical and practical necessity.

As a result of the previous discussion, I can safely assume that the EPR paradox is removed in QFT. But then one could wonder: what does the known QFT of Particle Physics actually predict for the correlations that have been measured by now in EPR experiments? Is there any risk of the agreement of the old Quantum Mechanics with the data being affected? In Ref. [6], I have given a rough computation that shows that the correlations are generally smaller than those obtained by the usual, old “entanglement” theory, which were “maximal” in our simple example. The difference was roughly proportional to the total probability for the appearance of an odd number of soft photons. If in the considered experimental settings that probability is small enough, the correlations predicted by QFT are expected to be close to the ones that were obtained by the old, soft photons-less, entanglement theory, and that showed an agreement with the actual data. In other words, not only are QFTs locally realistic (as we have seen); they can still predict correlations that can violate Bell inequalities. Incidentally, this shows that the Bell theorem cannot be applied to QFT.

It is worth noting that such correlations are just a reminder of the common origin in the past of the particles, and are not due to any mysterious action at a distance. This is a general result in QFT, where the correlation are proven to be causal, i.e. they respect Special Relativity [4, 5]. This is considered to be necessary for the consistency of the theory itself, which turns out to be more intuitive (or at least less absurd) than it was thought.

At last, Einstein, Podolsky and Rosen were right at least on one basic principle: nonlocality is impossible. However, the solution to their paradox does not reside in Hidden Variable
Theories and determinism, but in the Quantum Field Theories that have been introduced to describe Particle Physics [4, 5], and that represent one of the most beautiful and successful achievements in the History of Physics. What Einstein did not expect was the fact that it was not necessary to renounce to the indetermination to solve the paradox. In fact, QFT seems to be even less deterministic than the old Quantum Mechanics!

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[9] The following discussion can be generalized, e.g. to include the case, that has been studied in actual experiments [4, 5], where the particles under measurement are two (or more) photons [6].
[10] For simplicity, I will consider only such a case, that corresponds to our two electron system. Any complication of such a scheme is not relevant for the present discussion.
[11] Actually, a more elaborated test was invented by Bell [8] that allowed to evaluate just some combinations of the correlations. A set of inequalities made out of them was then argued to be satisfied by Hidden Variable Theories and violated by Quantum Mechanics.
[12] This is the case e.g. of Baryon and Lepton Numbers conservations, that are often thought to be due to some Grand Unification.
[13] I thank Esther Pérez for asking me this question.