Quantum Electrodynamics is free from the Einstein-Podolsky-Rosen paradox

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Abstract

I show that Quantum Electrodynamics (QED) predicts a sort of uncertainty principle on the number of the “soft photons” that can be produced in coincidence with the particles that are observed in any EPR experiment. This result is argued to be sufficient to remove the original EPR paradox. A signature of this soft-photons solution of the EPR paradox would be the observation of apparent symmetry violation in single events. On the other hand, in the case of the EPR experiments that have actually been realized, the QED correlations are argued to be very close to those calculated by the previous, incomplete treatment, which showed a good agreement with the data. Finally, the usual interpretation of the correlations themselves as a real sign of nonlocality is also criticized.

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I. INTRODUCTION

In their famous 1935 paper [1], Einstein, Podolsky and Rosen (EPR) pointed out that the Quantum Mechanics probabilistic description of Nature apparently leads to some mysterious action at a distance. They eventually deduced that the Quantum Theory itself was necessarily incomplete. This suggested the need for some Hidden Variables, allowing for a causal local, deterministic description, but such an hypothesis can hardly agree with the results of a series of experiments carried out in the last several years [2, 3].

It is now commonly believed that local realism is violated by quantum effects even in the relativistic case [4]. This is so paradoxical, that some authors still suggest the need for a “more consistent” theory beyond the present day Relativistic Quantum Mechanics, and argue that a conclusive experimental proof against Hidden Variables is lacking [5].

Actually, it turns out that no new physics is needed. In fact, there is already a very elegant theory, which describes with extreme accuracy all the known phenomena involving the electromagnetic interaction [10]. It is Quantum Electrodynamics (QED) [6, 7]. Since it is by construction relativistic, and based on the local U(1) gauge principle, it is not surprising that it is protected against the EPR paradox, as I show in the present paper.

II. THE EPR PARADOX

Let me consider an ideal EPR experiment [1, 8]. Two particles, e.g. two photons as in the actual experiments [3], are emitted by a source and travel in opposite directions [11]. Far apart, some conserved observable, such as energy, momentum, or a component of the angular momentum (spin, helicity or polarization), is measured on both of them.

According to the usual interpretation, the measurement carried on one of the two subsystems (call it A) reduces it to an eigenstate of the measured observable, whose conservation immediately forces also the second particle (call it B) to “collapse” into the corresponding “entangled” eigenstate. Since before the experiments the two particles are not prepared in an eigenstate of the measured quantity (see also point 2 few lines below), it seems that the observation on A implies an instantaneous change of the state of the distant particle B. The observed quantity would then get “an element of physical reality”, according to the original definition: “If, without in any way disturbing a system we can predict with certainty (i.e.
with probability equal to unity) the value of a physical quantity, then there is an element of physical reality corresponding to this physical quantity” [1] (the italics and the parenthesis also belong to the original paper).

According to Einstein and collaborators, the problem of Quantum Mechanics is that: 1) the considered observable gets a definite value on B, after a measurement on the distant particle A, and this occurs with certainty, so that the observable gets a “physical reality” on B; 2) such a physical reality depends on the actual measurement that is done on A (for instance, if instead of measuring the component $J_z$ of the angular momentum we decided to measure an observable incompatible with it, such as $J_x$, then the state of the distant particle B would correspond to a different physical reality) [1]. Such a situation is also called a violation of “local realism”.

This is the original EPR paradox of Quantum Mechanics. Only much later, mainly due to the work of Bell [2], it was reformulated in terms of the correlations (see also sections IV and V), in order to work out predictions that could be tested experimentally. Up to now, the two formulations were thought to be equivalent, but in section IV we shall see that this is not the case. For the moment, let us notice that, according to Einstein and collaborators, the existence of an action at a distance working with perfect efficiency would imply a much harder incompatibility with Special Relativity, as compared with a possible statistical nonlocality as shown in the correlations. I will come back later to the problem of the correlations, and concentrate for the moment on the original EPR paradox.

It is worth mentioning that Einstein and collaborators concluded that the solution to the paradox should necessarily imply that “the wave function does not provide a complete description of the physical reality” [1]. For the wave function, they meant that associated to the two particle system, describing A and B and nothing else. We shall see that they were right, even though they would perhaps not expect that the solution was to be found in the modern version of the Quantum Theory itself. In fact, the complete description in QED is not limited to the “entangled” state of A and B, since it allows also for the presence of an arbitrary number of “soft photons”.
III. THE UNCERTAINTY IN THE NUMBER OF SOFT PHOTONS

The EPR paradox, as described above, is originated by the assumption of a two particle state, which is incorrect in Relativistic Quantum Mechanics. As we shall see, states involving two or more particles are not “stable” in QED. There are no entangled “stationary” states! In other (more correct) words, *additional real particles can be created in coincidence with A and B*. Which additional species can appear depends on the available energy. Since massless particles can have arbitrarily low energy, the possible presence of real “soft photons” (i.e. very low energy photons) should always be taken into account in the theoretical treatment. In any case, since soft photons usually escape detection (or they are not looked for), no event can be guaranteed with absolute certainty to involve only the two observed “hard” particles.

Moreover, soft photons can also be created due to the interaction of both A and B with the measuring apparatus. Even though the latter effect will not be used in the rest of the present work, in this section I will mention it since it can be interesting for the Theory of Measurement (for instance, due to possible creation of soft photons during the measurement, the ideal measurement that is used to define the eigenstates of the observables should be considered as a mere approximation). According to the previous discussion, 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. I will prove this statement using QED perturbation theory (i.e. Feynman diagrams). For simplicity, I will only discuss two kinds of EPR experiments: i) those involving two charged spin 1/2 particles; and ii) those involving two photons. In both cases, I will give explicit examples predicting the creation of an arbitrary number of soft photons.

i) In Fig. 1, I have drawn a tree-level diagram where the blob represents the particular elementary process that produces particles A and B. Even without specifying that part of the diagram (involving some “initial” particles), we see that an arbitrary number of real soft photons (three in the particular case of the figure) can be attached to each of the external fermion legs. This is a well known effect in QED [7]. Fig. 2 shows a diagram describing the interaction of any one of our two particles with a charged particle belonging to the measuring apparatus, through the exchange of a virtual photon. Here, an arbitrary number of *real* soft photon lines can be attached to both the electron under measurement and the
FIG. 1: Feynman diagram describing the production of an EPR pair of charged spin 1/2 particles, A and B, in coincidence with three soft photons. The dashed blob represents the part depending on the particular basic process and the initial particles that are considered.

charged particle belonging to the experimental device.

ii) The two photon case, which corresponds e.g. to Aspect et al. experiment [3], seems to be a bit more complicated from a theoretical point of view. Since no three photon vertex exist, we have to look for one loop effects. In Fig. 3, I show a “box” diagram for the production of two real soft photons [12]. The virtual particle in the loop can be any charged fermion (electron, muon, tau, quarks). On the other hand, the interaction with the measuring apparatus can proceed through diagrams such as the tree level one of Fig. 4. Here, soft photons can be attached in an arbitrary number to the line of the electron or nucleon belonging to the experimental detector [13].

It is clear that these considerations can be generalized: an arbitrary and unknown number of soft photons can always be created in any experiment, in any step that involves an interaction.

In the following discussion, we will be interested in particular in the soft photons that are created in coincidence with the two (or more) particles observed in an EPR experiment, as described by diagrams such as those in Figs. 1 and 3. We are now able to understand how QED is protected from the EPR paradox.
FIG. 2: Feynman diagram describing the creation of four soft photons due to the interaction of any one of the EPR spin 1/2 particles A,B, with an electron e or a nucleus N of the measuring apparatus.

IV. THE QED SOLUTION TO THE EPR PARADOX

After the measurement of the conserved observable, say a component of the angular momentum, is performed on particle A, we cannot have any idea about how many soft photons are there around. QED predicts that the conservation law holds for the set including particles A and B together with all the soft photons that are created with them, through diagrams such as those in Figs. 1 or 3. Therefore, we could only say that the subsystem consisting of particle B and all the soft photons that have been produced in coincidence with them will get a definite value of the angular momentum, determined by the result obtained on A. This means that the measurement on A does not allow for a certain prediction of the value of the considered conserved quantity on B. Therefore, the (component of the) angular
FIG. 3: Feynman diagram describing the production of an EPR pair of photons, A and B, in coincidence with two soft photons. The dashed blob represents the part depending on the particular basic process and the initial particles that are considered.

momentum *will not be given a “physical reality”* on B after the measurement on A. According to the discussion of section II, this is sufficient to save the theory from the original EPR paradox.

It is important to recall that there is no possibility to control completely the uncertainty on the number of soft photons in a single event. In other words, QED is even less deterministic than Nonrelativistic Quantum Mechanics, due to this underlying sort of Uncertainty Principle on the Number of Particles. In fact, the only predictions that it allows are on probabilities and average values. This greater indetermination protects the theory from the EPR paradox. In other words, it seems that, to remove the paradox, one has to choose between the most extreme possibilities: determinism (hidden variables, the favorite option for Einstein and collaborators), or complete lack of determinism for the single processes (QED, the dice of God) [14].

Let me come back to our EPR experiments, and notice that the conservation laws, including energy and momentum, are not expected to hold strictly for the two particle (sub)system, A and B. A general single event will show apparent symmetry violations, except when by chance no soft photon is created. In particular, any violation of a discrete variable such as
angular momentum is important, since it is a multiple of $\hbar$. These considerations suggest that a possible signature of the theoretical explanation I am proposing would be the observation of an apparent symmetry violation event in an EPR experiment. This would confirm the presence of unobserved soft photons, resulting in a further triumph of QED.

Notice that in the actual EPR experiments the correlations between the polarizations of the “hard” photons (A and B) are evaluated. Such correlations are statistical averages over the results for the different single events. The data agree with the prediction of a Quantum Mechanics that did not take into account the soft photons, and are incompatible with the predictions of Hidden Variables theories, that were also considered to be the only possible locally realistic theories. This fact was interpreted as a proof that Nature is EPR paradoxical. However, such a conclusion is not correct. As we will see in the next section, in
the case of the EPR experiments that have been performed up to now the QED prediction for the correlations is very close to that obtained in Quantum Mechanics by ignoring the soft photons, so that it can still agree with the data within the experimental errors. However, even a very small probability for soft photons creation is sufficient to forbid any certain prediction for the measurement on B as a consequence of the measurement on A, and this is enough to remove the original EPR paradox, as we have seen. This implies that the experimental study of the correlations cannot be used to decide about the original EPR paradox; it can be used only to disprove the Hidden Variable solution. In other words, the equivalence between the original EPR paradox and its version in terms of the correlations, as worked out by Bell, would hold only if the theoretical correlations were strictly maximal (i.e. if the soft photons did not exist). On the other hand, the observation of a single event showing an apparent violation of the considered conservation law would be an evidence in favor of the present solution for the EPR paradox, since it would confirm that no certain prediction can be made on the state of B after measuring on A.

Notice also that this solution to the EPR paradox is based on two points: the existence of massless particles, the photons; and of the fermion-photon vertex, that allows photons to be created in any external line of the relevant Feynman diagrams. But it is well known that both the electromagnetic vertex and the masslessness of the photon are the direct consequences of the local gauge symmetry. Not only the local symmetry defines the theory, but it also protects against the EPR paradox and the violation of local realism.

V. THE QED PREDICTION FOR THE CORRELATIONS

Even though we have found that the study of the correlations is not relevant for the original EPR paradox, we have to check that the QED predictions still agree with the experiments. The calculation can be done by using the methods discussed in Ref. [7], and the result depends on the actual selectivity in energy and momentum of the experimental setting. Here, I will just provide a rough argument to show that the correlations are usually not expected to be seriously modified by the soft photons creation.

For simplicity, I will consider an ideal EPR experiment involving two charged spin 1/2 particles created after the decay of a zero spin system (let us forget here the difficulty in the measurement of the spin of the charged particles). In this case, the relevant correlation
functions are the average values of the products of the components $S_\vec{u}(A)$ and $S_\vec{v}(B)$ of the spins of the two particles along arbitrary axes $\vec{u}$ and $\vec{v}$ [8]. For instance, let $\vec{u} = \vec{v}$, chosen to be the z axis. If we do not take into account the soft photons, according to Quantum Mechanics the two particles must have opposite spins in order to conserve the total angular momentum. Then we get

$$< S_z(A)S_z(B) > = -\frac{\hbar^2}{4}. \quad (1)$$

Notice that this is the maximal correlation (in absolute value) that can be achieved for two observables whose eigenvalues are $\pm \hbar/2$. (If the spins were completely independent, $< S_z(A)S_z(B) >= < S_z(A) >< S_z(B) >= 0$.)

In general, allowing for the soft photons creation through diagrams similar to that of Fig. 1, the correlation will be smaller than maximal. Now, as shown in Chapter 13 of Ref. [7], in the limit where the energy of the soft photons is neglected the helicities of the two fermion will remain opposite. Therefore, the correction to Eq. (1) due to diagrams such as that of Fig. 1 is suppressed by powers of $\left(\frac{E_{\text{soft}}}{E}\right)^2$, where $E$ is the “hard” fermions energy and $E_{\text{soft}}$ is the typical soft photons energy (essentially, it is the “infrared cutoff” introduced in Ref. [7]). This parameter depends on the experimental settings, but it can be made small by increasing the energy selectivity in the observation of particles A and B. Moreover, in a “selective enough” experimental setting, the two particles will be detected in opposite directions with small angular indetermination, then the total transversal momenta of the soft photons will have a limited phase space available, and this will result in a further suppression of the corresponding diagrams. Diagrams involving an increasing number of soft photons will also be suppressed by the corresponding powers of the fine structure constant $\alpha \simeq 1/137$.

For all these reasons, in the usual EPR experiments we expect that the correlation will be close to that computed using the “entanglement” theory, and the agreement with the data will not be spoiled within the experimental errors.

However, as we have discussed, even a very small probability for soft photons creation is sufficient to save the theory from the original EPR paradox, since it prevents the possibility of a certain prediction on the single event. For instance, in event involving a single photon travelling close to the direction of the two particles A and B, the two fermion helicities will most probably be found parallel rather than antiparallel, in order to cancel the $\pm \hbar$ helicity of the photon.

A similar result can be found in the case of the actual EPR photons experiments. In fact,
the probability due to the relevant diagram (Fig. 3) is suppressed by four powers of the fine structure constant, by the reduced phase space and by the electron propagators in the loop (the mass of the electron is large as compared with the typical energy of the “hard” photons involved in the experiment, which are typically in the eV range). Therefore, the prediction obtained in QED, taking into account the soft photons, is expected to be very close to that of the previous approach, and will still agree with the present experimental results.

VI. THE PROBLEM OF THE APPARENT NONLOCALITY OF THE QED CORRELATIONS

In the QED correlations that we have discussed above, the conservation laws hold for the set of particles A and B and all the possible soft photons. Everything goes as though there were a secret agreement amongst all the distant particles that can appear in a single event (including those that are not observed). This fact is often interpreted as a sign of some “quantum nonlocality”. Before discussing this point, I would like to remember that this problem of the EPR correlations is not the EPR paradox, that is removed by taking into account the uncertainty on the soft photons (see sections II and IV above). On the other hand, the correlations do not imply any direct violation of Special Relativity, since they are merely a statistical property (at least, this was the point of view of Einstein and collaborators, see also few lines below).

In principle, it could be hoped that such an apparent nonlocality of the correlations could be used to save some supposed applications of the EPR paradox, such as teleportation [9], that might thus be interpreted as intrinsically statistical processes. For instance, if teleportation is realized using (“hard”) photons in the eV range, the probability for soft photons creation is very small, as we have discussed above, and the existing theory could be thought to be a good approximation. However, I think that a deep study of the measurement problem is needed to prove whether such an interpretation can be correct. This point is of extreme importance and urgency, since teleportation is presently used as a base for Quantum Information Theory and Quantum Computing.

Here, I will provide a possible qualitative argument against the nonlocality interpretation of the correlations, without pretending it to be definitive, in order to stimulate a debate on such an urgent problem. In fact, in QED the correlations are obtained from a covariant
Lagrangian density that only involves local interactions; they are causal and the prediction for them is deterministic \cite{4}. The fact that the Feynman diagrams of the kind of Figs. 1 and 3 imply a conservation of energy, momentum, angular momentum, etc., amongst the external legs, is a causal, deterministic consequence of the initial “in” state and the local interaction that occurs at the production point. Therefore, I think that it is not correct to interpret the global conservation law as a result of an “instantaneous agreement” occurring at the moment of the measurement, since the correlations showing such a global conservation are calculated as a deterministic result of the evolution from the common origin of the particles A, B and the soft photons. In other words, the global conservation is merely a causal consequence of the local conservation law. No mysterious action at a distance is then working. The real “quantum mystery” is the wave-particle duality, with the localization of the particles in the single events. But the amplitude of probability is a wave, whose evolution respects causality and locality. I think that for this reason Einstein and collaborators in Ref. \cite{1} were not concerned with the (nonmaximal) probabilities or correlations, and they were so careful in defining the paradox as a problem occurring if A and B were perfectly “entangled” (“with certainty, i.e. with probability equal to one”, as they say explicitly). Therefore, since we have found that this original paradox (i.e. the “perfect entanglement”) is removed by the soft photons mechanism (even with a very small probability for them to be created), I think that also the nonlocality interpretation of the correlations is undermined. At least, such a “sort of nonlocality”, that (roughly speaking) originates from the causal and local propagation of a “wave” from the production point, does not correspond to any mysterious action at a distance, and cannot be used e.g. as a base for teleportation.

VII. CONCLUSIONS

To conclude, I have shown that QED is protected from the original EPR paradox by the local gauge symmetry. This corresponds to the fact that it allows for the creation of an arbitrary number of soft photons in coincidence with the observed particles in an EPR experiment. This mechanism would be confirmed by the experimental observation of an apparent symmetry violation in a single event. On the other hand, the correlations are expected to be smaller than those calculated by ignoring the soft photons, but in the case of the actual EPR experiments that have been realized up to now the correction is
expected to be very small, so that the agreement of the Quantum Theory with the present
data is not spoiled. Such correlations are usually thought to be by themselves a sign of a
“quantum nonlocality”. Although here I have already presented an argument against such
an interpretation, this problem deserves further research, which is particularly urgent in
order to decide about the actual viability of several supposed applications of the Quantum
Theory that were based on the EPR paradox.

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70, 1895 (1993).
[10] Moreover, it is a part of the Glashow-Weinberg-Salam Standard Model, that describes all
known interactions except gravity.
It is easy to generalize the present discussion to the case of three or more particles.

This box diagram has been studied in different contexts, e.g. in the theory of two photon scattering.

Actually, in the common experimental situation the “hard” photon energy is comparable with the electron binding energies in matter, and QED perturbation theory breaks down. But even if it will be hard to compute its rate, soft photon emission during the measurement will still be possible.

However, QED is also a deterministic theory, since the field equations are deterministic. The correlation functions themselves are determined by the initial conditions and the interaction lagrangian. This is an important point, whose possible consequences will be discussed below.