CIENCIA 10(4), 353-359, 2002
Maracaibo, Venezuela

Bell-EPR Experiments

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Recibicdo. 09-06-99 Aceptado: 30-04-02

Abstract

On the grounds of recent developments of the two particle interferometry, it is shown that the conditional state and the corresponding real pilot wave can provide a semiclassical account of Bell-EPR experiments in perfect agreement with the extended Feynman's rule.

Key words: Bell-EPR experiments; conditional state; Feyman; quantum mechanics; wave function.

Experimentos de Bell-EPR

Resumen

Sobre los fundamentos de los desarrollos recientes de la interferometría de dos partículas, se demuestra que el estado condicional y la correspondientes onda piloto puede proveer un enfoque semiclásico de los experimentos de Bell-EPR, que están en perfecta concordancia con las reglas de Feyman.

Palabras clave: Estado condicional; experimentos de Bell-EPR; Feyman; función de onda; mecánica cuántica.

1. Introduction

The aim of the present note is to show on experimental basis (1-13) that the conditional state and the corresponding conditional pilot wave (14-16) can give a semiclassical account of the coincidence multiparticle oscillations leading to the Bell's inequality violation. We shall consider both, the polarization and the phase entanglement, and stress the complementarity relations involving the different types of interference patterns and which-path information which constitute the extended Feynman rule (15,17). We shall pay a special attention to the incompatibility between the one-particle and the coincidence patterns in relation with the lack or presence of the potential freedom at the emission (14).

2. Entangled polarization

The notion of conditional state does not collide with the orthodox quantum theory; however, if only one-particle systems were considered, the introduction of this device would not bring a very fundamental contribution to the quantum description. But it is a different story if one considers the one-particle systems as a part of an entangled multiparticle system. In fact, let

$$|\psi\rangle := \frac{1}{\sqrt{2}}\left[|++\rangle + |--\rangle\right] \qquad [1]$$

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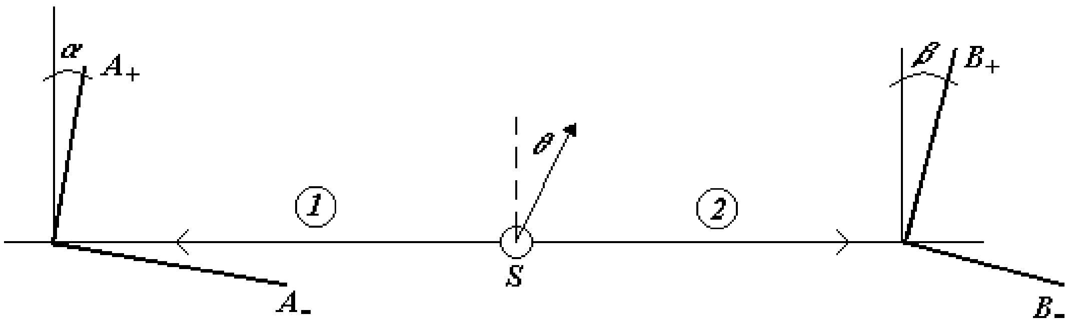


Fígura 1. $A_{\pm}$, as well as $B\pm$, are orthogonal linear polarizers. Photon ***1*** and ***2*** are emitted from the source S with the same linear polarization but the potentially free orientation θ. The conditional state arises thanks to this freedom either for particle *1* with $\theta=\alpha$ or $\theta=\alpha+\pi/2$ or for particle ***2*** with $\theta=\beta$ or $\theta=\beta+\pi/2$.

be the two-photon entangle state of the Aspect et al experiment (1) depicted in Figure 1, which corresponds to the perfect correlation condition when $\alpha=\beta$. The two photons, simultaneously emitted at the source S in opposite directions, are correlated in polarization. If the photon 1 endowed with the necessary potential freedom is going to be found in the channel A_+ *at* t_0, its conditional state at $t<t_0$ *is* $|1_+\rangle_\alpha$. Then, the photon 2 is described by the correlated state $|2_+\rangle_\alpha$ and its classical-like probabilities of crossing the orthogonal polarizers B_+ amd B_- are

$$P_{++}=\frac{1}{2}\cos^2(\alpha-\beta) \quad [2a]$$

$$P_{+-}=\frac{1}{2}\sin^2(\alpha-\beta) \quad [2b]$$

respectively, where the normalization factor 1/2 takes into account the similar probabilities $P_{--}=P_{++}$ and $P_{+-}=P_{-+}$. This coincides exactly with the quantum prediction capable of violating Bell's inequality, which follows from the wave packet reduction of the state (1). We see that the conditional state accounts for this reduction. We remark that the probabilities [2ab] are semiclassical. In fact, they comply the classical Malus law under the quantum-like condition that the initial polarization of one photon be determined by the polarizer in which it is going to be detected in accordance with the conditionality hypothesis and the conditional probability (14). We underline that the conditional state is realized by only one of the two photons emitted simultaneously, which is regarded as the first photon. Indeed, the conditional pilot wave arises in fulfillment of the principle of stationarity of the wave function under the influence of the actual behaviour of the first photon, being conditioned by the presence of the corresponding orthogonal polarizers in the role of boundaries which must be present at least during the creation process of this photon and part of its fly time. Such a conditional pilot wave of the first photon is correlated to the pilot wave of the second photon, which, as an ordinary pilot wave, determines the probabilistic behaviour of that second photon in crossing the corresponding two-channel polarizer which is merely playing the role of an analyzer. It is clear that the potential freedom is being used in getting the conditional pilot wave of the first photon, so that it is no longer at disposal of the correlated second photon.

3. Entangled phase

An astonishing manifestation of the quantum correlation and the involved Bell's inequality violation can occur with the two-particle double slit interferometer. The first experiment of this kind was performed by Rarita and Tapster (3). Schematically, in Figure 2, two photons correlated in phase are emitted from the source *S* in either the opposite directions *A* and B or *A*' and *B*', the slits separation being of the order of their distances from the source. At the 50 - 50 beam splitters *M* and *N* the unprimed and primed amplitudes superpose into $a_{\pm}$ and $b_{\pm}$, respectively. The phase shifts α and β can be chosen to be such that $\alpha-\beta$ fulfills the perfect correlation condition, so that the entangle state

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left[|a_+ b_+\rangle + |a_- b_-\rangle\right] \quad [3]$$

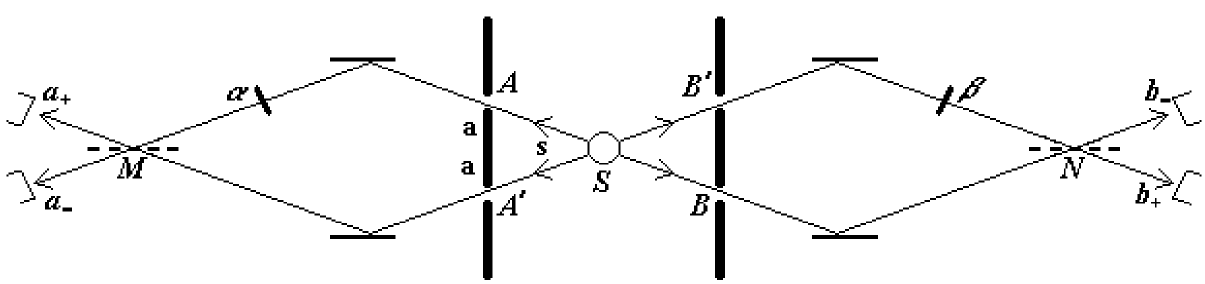
similar to [3], may be expressed in terms of the final paths $a_{\pm}$ and $b_{\pm}$. Now then, in accordance with the principle of stationarity of the wave function (1), and supposing for example but not necessaritly that the 50 - 50 beam splitters be spatially symmetric (19), it can easily be seen that if the first photon happens to end in the path a_+, it is because the amplitude of its conditional pilot wave exhibits the adequate phase difference between *A* and *A´*, such that the resulting superposition at a_+ and a_- be entirely constructive and destructive respectively. Therefore, assuming the perfect correlation, the corresponding phase difference between *B* and *B´* is such that the superpositions at b_+ and b_- are constructive and destructive respectively, in agreement with [3]. Clearly, considering an experimental arrangement such that the perfect correlation be achieved with $\alpha = \beta = 0$, and taking into account that only one photon falls into the conditional state, it can be esasily seen that the probabilities that any photon be detected in either the path b_+ or b_- almost simultaneously to the detection of its partner in the path a_+, are

$$P_{++} = \frac{1}{2}\cos^2\frac{\alpha-\beta}{2} \quad [4a]$$

$$P_{+-} = \frac{1}{2}\sin^2\frac{\alpha-\beta}{2} \quad [4b]$$

respectively, what is equivalent to [2ab]. In fact, in [4ab] the switching between + and - corresponds to the phase difference $\alpha-\beta=\pi$; whereas in [2ab] corresponds to the difference $\alpha-\beta=\pi/2$ of the polarization orientation.

Again, the conditional state is called to explain the wave packet reduction. We emphasize that the existence of such a state requires the potential freedom of the correlated phase difference between the primed



Fígura 2. The source *S* emits a pair of photons correlated in phase, one of which reaches the beam splitter *M* through either *A* or *A'* and the other reaches ***N*** through either *B* or *B*'. The potential freedom of the position of *S* allows the conditional state to arise as a maximum constructive interference in one of the four outputs $a_{\pm}$ and $b_{\pm}$, no matter the phase shifts and .

and the unprimed paths, similar to the freedom of the correlated polarization orientation in the Aspect et al experiment discussed in the previous section. For this freedom, it is essential that the separation of the slits be comparable to their distances from the source; what, on the basis of the uncertainty of the source position, destroys the one-particle interference implying that the one-particle and the coincidence pattern be mutually exclusive, as shown in (15).

4. Induced coherence

Let us consider a fundamental setup which involves not only the splitting of the pilot wave, but also its down-conversion without necessarily the corresponding particle emission. This experiment is not necessarily concerned with coincident detections; but it shows very clearly the crucial role of the which-path information in the form of the phase freedom which destroys the one-particle interference, opening the possibility for the conditional state, then also pointing out the relevance of the conditional pilot wave to the behaviour of a single particle. The arrangement, due to Zoo, Wang and Mandel (4), is depicted schematically in Figure 3. A single photon, "splitted" at M into a and a' is down-converted into two photons either at *D* or *D´*. The corresponding pilot wave, splitted and down-converted, ends up into b, c, b´ and c´. The paths c and c´ are recombined at the splitter *N* into d_+ and d_-; whereas b either merges with b´ through *D´* or is deflected at the point P into b´. In the former case the emissions at *D* and *D´* are induced coherently, what makes impossible to distinguish between c and c´; so one gets a one-particle interference patterns at d_+ and d_- dependent upon the phase shift However, if b is deflected at P into b´´, the potential freedom of the relative phase between c and c´ reappears. Accordingly, the detection of one down-conversion photon in b´´ or b´ determines that the other photon was going through c or c´ respectively. In this case, in agreement with the extented Feynman rule (15-17), the one-particle interference at $d_\pm$

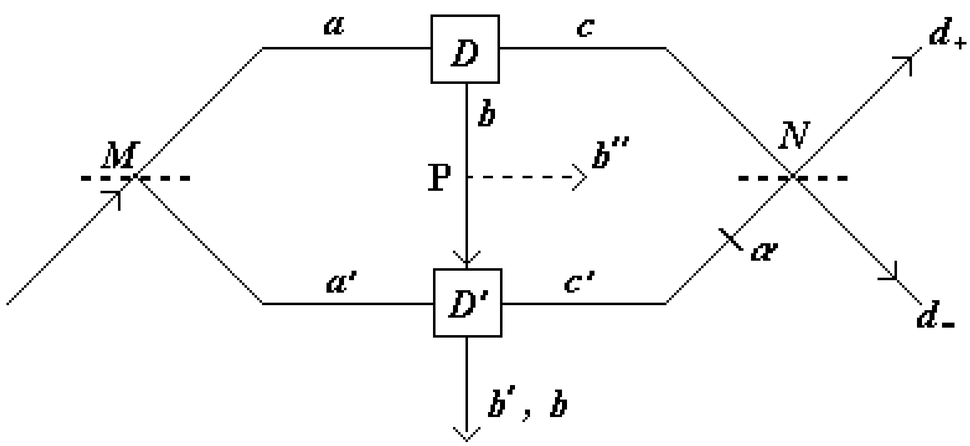


Figura 3. The incident photon is splitted at ***M*** into ***a*** and ***a'*** and down-converted at *D* and *D'* into *b* and *c* and into *b'* and *c'* respectively, all with the same linear polarization. The waves ***c*** and ***c'*** are recombined at the splitter ***N*** into $d_\pm$. The one-particle fringes appear in d_+ and d_- because the induced coherence obtained by letting *b* superpose to *b'* through *D'* restricts the fluctuation of the relative phase freedom of ***c*** and *c'*. In fact, by deflecting *b* into *b'* at P, this potential freedom yields the conditional state with a maximum at d_+ and a minimum at d_- or viceversa, with the same probability; whereas by superposing *b* into *b'* this potential freedom is being used to get the conditional state of *b' b*.

disappears. Clearly, in none of these cases there can be simultaneous detections at d_+ and d_-; because only one photon is down-converted either at *D* or *D´*.

In terms of the conditional pilot wave, it is seen that if the path information concerning c and c´ is potentially present due to the deflection at P, this wave arises either in d_+ or d_-. Indeed, every time a photon ends up in d_+ or d_- the relative phase of the branches c and c´ of the conditional wave, no matter the phase shift, , is such that the superposition at d_+ or d_- is constructive; whereas as in section 3, with any 50 - 50 beam splitter it is destructive at d_- or d_+ respectively. Of course, the two cases have the same chance of occurring; so that, both one-particle counting rates are flat. In contrast, if the path information about c and c´ is destroyed by merging b into b´, the conditional pilot wave at $d_\pm$ being replaced by an ordinary pilot wave, the opposite behaviour at d_+ and d_- does not occur; being possible that a photon be captured in any channel without corresponding to a maximum amplitude. As a matter of fact, the one-particle interference patterns observed statistically at $d_\pm$ are conformed by such an ordinary pilot wave. This shows that the conditional pilot wave is not only relevant to the multiparticle coincident events; but, though less important, also to the behaviour of a single particle.

We underline the great relevance of the experiment described above in showing that the which-path information which destroys only the one-particle fringes is what brings about the conditional freedom needed for the conditional state, in agreement with the complementarity of the one-particle and the coincidence fringes. W remark, however, that this complementarity is destroyed by means of the very same induced coherence. Indeed, with the help of references (16), it can be realized that the conditional state arises in the channel bb´, which preserves the necessary potential phase freedom under the effect of the induced coherence, while under this effect and precisely because of the conditional state in bb´, the superposition of the channels c and c´ produces one-particle oscillations. The corresponding entanglement between bb´ and cc´ which yields coincidence oscillations is observable without modifying the arrangement of Figure 3. Consistently, by detecting a photon in c or c´ one knows if the other photon was going into b or b´ which are then distinguishable in principle in spite of their superposition and therefore suitable for the conditional state.

5. Quantum eraser

The relation between the conditional pilot wave and the which-path information can be stressed by having recourse to the quantum eraser suggested by Scully and Drühl, firstly realized by Kwiat, Steinberg and Chiao, and then by Herzog, Kwiat, Winfurter and Zeilinger among others (6). The latter setup is based on the interferometer introduced by Herzog, Rarita, Weinfurter and Zeilinger (10), which is largely discussed in (16) in connection with a detailed analysis of the induced coherence. Here we are interested in the elementary version of the quantum eraser which uses the Hong-Ou-Mandel in terferometer (11), depicted in Figure 4. A single photon is down-converted at D into two photons with the same linear polarization. The pilot wave of each photon goes through the unprimed and primed paths which can differ in phase with respect to each other, the phase difference between a and a' being the same as that between b´ and b. A polarization rotator R can be inserted so as to rotate the polarization of b and a´ by 90°; what, being observable at $c_\pm$, constitutes a which-path information additional to that of the phase freedom between the primed and unprimed paths which allows the entanglement of the two down-conversion photons. However, by also inserting the linear polarizers $P_\pm$ oriented 45° with respect to the original polarization axis, the path information provided by the rotator R is erased. Then, if the splitter S is spatially symmetric, for example, the reflected beam is shifted 90° in phase with respect to the transmitted beam, and considering either the absence or the presence of the rotator and both the polarizers, it is seen that in order that c_+ be a maximum of interference, a and a´ must differ in phase by 90° and the same goes for b´ and b, so that c_- must be a minimum. On the basis of the conditional pilot waves, it is thus inferred that the two photons cannot be detected simultaneously one at c_+ and the other at c_-; unless of course the rotator is used without the polarizers to provide the additional which-path information, which makes impossible any kind of interference. Here, the conditional state controls the coincidence events in the most drastic way, by forbidding them; hence, this experiment may be regarded as a direct test of the very existence of this state.

We underline, in Figure 4, the crucial role of the conditional pilot wave. In fact, not considering this wave, the photons could be detected without corresponding to maxima of interference, and therefore, coincident events at c_+ and c_-, though not predicted by the quantum algorithm (11), would be observed even in absence of the rotator and of the polarizers. On the other hand, let us remark that, because of the lack of induced coherence in the process of down-conversion. what constitutes a distinguishability condition analogous to that considered in (15) in the case of the double slit, both the one-particle interference patterns are absent with or without rotators and polarizers.

6. Conclusion

The concept of the conditional state based on the principle of stationarity of the wave function and the corresponding conditional probability fits the considered experimental results. It allows to see that the potential freedom in the form of the conditionality hypothesis is in the heart of the entanglement of the quantum systems, stressing the necessity that the features of the particle emission be corresponding to the outcome of the measurement. All that brings support to the feasibility of a semiclassical explanation of the nonlocal quantum behaviour in

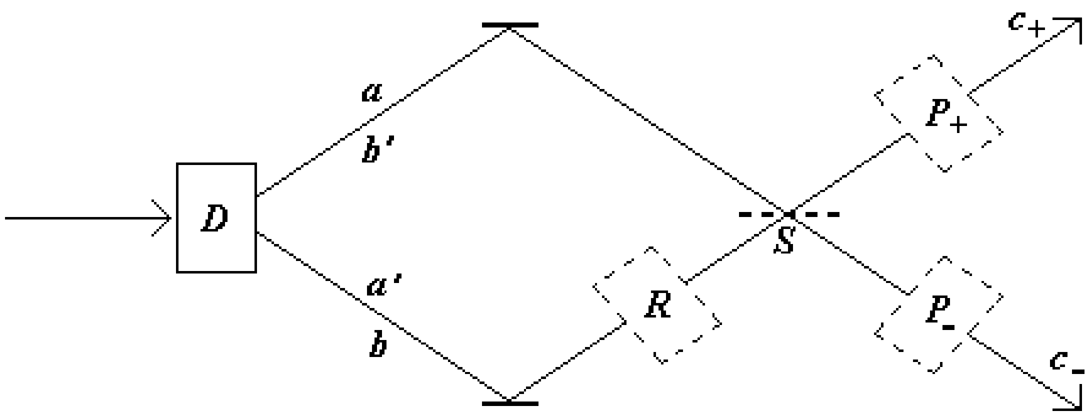


Figura 4. The incident photon is down-converted at *D* into two photons with the same linear polarization, one of which reaches the beam splitter *S* either through the paths *a* or *a'*, the other either through *b* or *b'*. In absence of the rotator *R* and the polarizers $P_\pm$, or in presence of all of them, the conditional state arises as a maximum of interference at c_+ and a minimum at c_- or viceversa , with both photons in the same channel. Of course this is due to the potential freedom of the relative phase between the primed and the unprimed paths characteristic of the down-conversion process.

terms of a classical-like real wave. This wave, endowed with global properties, capable of being influenced by and of influencing the behaviour of the quantum particle taking into account the effect of the boundary conditions, needs to be a real entity so as to fulfill causality. But it is not locally observable. It cannot be used for monitoring coincident events, and less for carrying information from one detector to another, what can only be made by interchanging at least one quanta of energy which never travels faster than light.

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