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COEXISTENCE OF QUANTUM THEORY AND SPECIAL RELATIVITY IN SIGNALING SCENARIOS

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Abstract

The coexistence between Quantum Mechanics and Special Relativity is usually formulated in terms of the no-signaling condition. Several authors have even suggested that this condition should be included between the basic postulates of Quantum Theory. However, there are several scenarios where signaling is, in principle, possible: based on previous results and the analysis of the relation between unitarity and signaling we present an example of a two-particle interferometric arrangement for which the dynamics is, in principle, compatible with superluminal transmission of information. This type of nonlocality is not in the line of Bell's theorem, but closer in spirit to the one-particle acausality studied by Hegerfeldt and others. We analyze in this paper the meaning of this non-locality and how to preserve the coexistence of the two fundamental theories in this signaling scenario.

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1 Introduction

According to most theorists the conflict between Quantum Mechanics and Special Relativity due to the existence of nonlocal correlations does not represent a fundamental difficulty for the coexistence of both theories because of the no-signaling condition [1, 2, 3]. This condition prevents the transmission of superluminal signals.

Recently it has been discussed by several authors the possibility of including the no-signaling condition or some related axiom between the basic postulates of Quantum Theory [4, 5]. In particular, it has been explored the possibility of deriving the linearity of the theory from a set of assumptions which includes the prohibition of superluminal communication [4]. An example of a system which, at least in principle, could signal would drastically restrict the scope of these programmes and, more important, would undoubtedly indicate the existence of physical mechanisms beyond the quantum dynamics of the system responsible for the coexistence of Quantum Mechanics and Special Relavity.

We present in this paper an example of this type. As we shall see the possibility of dynamic signaling (the signaling when only the dynamic evolution ruled by Schrödinger's equation is taken into account without including considerations about emission, detection or other types of processes) easily follows from the existence of one- particle interferences in completely entangled two-particle systems. In previous work it has been found that for some types of interferometric arrangements of completely entangled particles in momentum we can have one-particle interferences [6, 7, 8]. These interferences are not excluded by the results of Ref. [9], where it was demonstrated the absence of one-particle interferences for a large class of completely entangled systems.

Of course, we do not want to say that these effects are experimentally accessible. Probably their magnitude is exceedingly small to be experimentally measured. A simple estimation based on the results of Refs. [7, 8] shows the extremely thin magnitude of the interferences. Moreover, as we shall discuss later, other conditions of a non-dynamic type should be fulfilled in order to observe these effects. However, although they are surely inaccessible to the experiment their conceptual impact can be important. For instance, they say to us that the dynamics is compatible with signaling. These considerations are very close in spirit to the analysis by Hegerfeldt and others of the acausal spread of one-particle wavefunctions with initial localization [10]. It was shown that systems which are approximately localized at a given time, spread at later times in a way that violates Einstein's causality. In words of the author,

> this possible acausality is seen more as a problem of the underlying theory than as an experimentally verifiable prediction

In a related context other authors have discussed the possible effects associated with the non-vanishing of the Feynman propagator in space-like regions [11, 12]. In particular, it has been suggested that this property could be used to generate entanglement in a superluminal way (although it cannot be used to transmit information faster than the speed of light) [13]. Finally, we must refer to the paper [14], where some non-local aspects no conflicting with the non-signaling condition are discussed.

In order to go deeply into the physical meaning of this new type of non-locality, which is not within the usual framework provided by Bell's theorem, we shall emphasize the relation between unitarity and locality. We shall show that the non-locality associated with interferometric arrangements is closely linked to an effective (not from a fundamental type)non-unitarity that emerges when we restrict our considerations to only the detected particles disregarding those absorbed by the screen. We shall demonstrate this property in the path integration formalism.

Assuming the impossibility of superluminal communication as a fundamental constrain on any physical system, we must explore the physical mechanisms that prevent in our arrangement the well- known causal paradoxes associated with the violation of that postulate of Special Relativity. We shall show that in addition to the dynamic condition for the transmission of superluminal signals another conditions (not from a dynamic type) must be fulfilled. In this paper, as an example, we shall consider a condition associated with the rate of emission of entangled particles by the source. Other conditions of non- dynamic type have been considered in the literature. In particular, in Ref. [15] it has been shown that the detection process preserves the cause-effect order for fast light (pulses with superluminal group velocity).

The plan of the paper is as follows. In Sect. 2 we present the dynamic no-signaling condition in terms of the reduced density matrix of the system. We show that this condition is not fulfilled by some interferometric arrangements as those discussed in Refs. [6, 7, 8]. The relation between unitarity and locality is discussed in Sect. 3, where we also demonstrate that the evolution in some interferometric arrangements is non-unitary in an effective way. Section 4 deals with a constrain on the ratio of emission of entangled pairs by the source necessary to preserve the no-signaling. Finally, in the discussion we consider the results obtained in the paper.

2 Signaling and one-particle interferences in two-particle systems

We show in this section that the existence of one-particle interferences in completely entangled two-particle systems would provide (in the absence of other inhibiting mechanisms) a simple way, at least in principle, for signaling.

We consider the following ideal experiment. A source emits pairs of particles that fall upon two diffraction gratings with two slits each. Slits A and B are in one grating and C and D in the other. Slit C is just placed in front of A and D of B. The particles are prepared in the maximally entangled state (we only consider the stationary problem):

$$\psi(\mathbf{x_1},\mathbf{x_2}) = \frac{1}{\sqrt{2}}\psi_{1A}(\mathbf{x_1})\psi_{2D}(\mathbf{x_2}) + \frac{1}{\sqrt{2}}\psi_{1B}(\mathbf{x_1})\psi_{2C}(\mathbf{x_2}). \quad (1)$$

For instance, we can have a source that emits pairs of particles completely correlated in momentum,

$$\mathbf{p_1} + \mathbf{p_2} = 0 \quad (2)$$

with $\mathbf{p_1}$ and $\mathbf{p_2}$ the momenta of the two particles. Obviously, in quantum theory the pairs cannot be prepared in this state because of the uncertainty relations, that would imply a complete delocalization of the (center of mass of the) source. However, reaching an adequate compromise between the localization of the (center of mass of the) source and the deviations with respect to the exact relation (2) we can have states of the type (1) to a good approximation (see, for instance, Ref. [8] for a source of finite size). We shall return to this point later in the Section.

The discussions about one-particle interferences in entangled systems are usually carried out in terms of the reduced density matrix, which for particle 1 is defined by

$$\rho_1(\mathbf{x_1},\mathbf{x'_1}) = \int d^3\mathbf{x_2}\psi(\mathbf{x_1},\mathbf{x_2})\psi^*(\mathbf{x'_1},\mathbf{x_2}) = \frac{1}{2}\psi_{1A}(\mathbf{x_1})\psi^*_{1A}(\mathbf{x'_1}) +$$
$$+\frac{1}{2}\psi_{1B}(\mathbf{x_1})\psi^*_{1B}(\mathbf{x'_1}) + \frac{1}{2}I\psi_{1A}(\mathbf{x_1})\psi^*_{1B}(\mathbf{x'_1}) + \frac{1}{2}I^*\psi_{1B}(\mathbf{x_1})\psi^*_{1A}(\mathbf{x'_1}), \quad (3)$$

where

$$I = \int d^3\mathbf{x_2}\psi_{2D}(\mathbf{x_2})\psi^*_{2C}(\mathbf{x_2}) \quad (4)$$

is the scalar product of the two wave functions ψ_{2C} and ψ_{2D} (we assume both to be normalized to unity).

Taking $\mathbf{x'_1} = \mathbf{x_1}$ in the reduced density matrix we see that the condition for the existence of one-particle interferences is the scalar product to be different from zero.

The existence of one-particle interferences in the two-slit experiment has been demonstrated in a number of ways: semiclassical approximation [6], Fresnel's functions and Gaussian-slit approximation [7] and Gaussian-slit approximation with extended incoherent sources [8]. These results are in marked contrast with the demonstration of the absence of one-particle interferences for a large class of completely entangled states [9]. As discussed at length in [6], the difference between both behaviors lies in the impossibility in the first case of distinguishing between the available alternatives for the particle using measurements in the companion particle. In particular, the extended Feynman rule (following the nomenclature of Ref. [6]) valid for the types of arrangements considered in [9] does not hold for those considered here.

We note by completeness that the results of [6, 7] could be criticized because the particles stopped at the diffraction grating were not taken into account. However, in [8] these stopped particles were included in the calculations without destroying the one-particle interferences. The results of [6, 7, 8] could also be criticized because of the use of exactly opposite paths for both particles (a consequence in the path integration formalism of the use of relations of the type $\mathbf{p_1} + \mathbf{p_2} = 0$). As discussed before that exact match between the momenta is incompatible with the total momenta-source position uncertainty relations. However, the existence of paths that are not exactly opposite gives rise to terms in Eq. (1) of the type $\psi_{1A}\psi_{2D}$ and $\psi_{1B}\psi_{2C}$ or paths stopped by the screen (as those discussed in Ref. [8]). These new terms would reduce the visibility of the fringes associated with the terms present in Eq. (1), but without eliminating their effects. Therefore, we can continue our reasoning using only Eq. (1) (although taking into account that this approach gives a visibility larger than the real one).

Let us consider now the question of signaling. We introduce, for instance in slit C, some physical element producing a phase shift ϕ in the particles passing through that slit. Therefore, after the slit the wave function is modified as

$$\psi_{2C} \rightarrow e^{i\phi}\psi_{2C}. \tag{5}$$

Introducing the polar decomposition of the wave functions, $\psi_\alpha = R_\alpha e^{i\varphi_\alpha}$, we obtain for the detection probability of particle 1

$$\rho_1 = \frac{1}{2}R_{1A}^2 + \frac{1}{2}R_{1B}^2 + R_I R_{1A} R_{1B} cos(\varphi_I + \varphi_{1A} - \varphi_{1B} - \phi). \tag{6}$$

This expression clearly shows a displacement ϕ of the one- particle interference pattern in the opposite side.

This is an explicit example of nonlocality going beyond the nonlocal correlations obtained in Bell-type experiments (see the Discussion). We shall refer to it as a "dynamic signaling" because it is only related to the dynamics or evolution of the particles without taking into account other processes such as emission or detection. We shall demonstrate in Sect. 4 that the dynamic signaling is only a necessary condition for superluminal communication, which only becomes a sufficient one when some additional conditions are imposed on the emission and detection properties of the system.

3 Unitarity and locality

In this section we shall analyze in detail the relation between unitarity and locality and to show that the the evolution in interferometric experiments where we restrict our considerations to the detected particles is non-unitary in an effective way.

3.1 An example

In order to simplify the analysis as much as possible we shall carry out it in a simple state. Initially, at time t_o, the two particles 1 and 2 are prepared in the state

$$|t_o>=\frac{1}{\sqrt{2}}|1_+(t_o)>|2_-(t_o)>+\frac{1}{\sqrt{2}}|1_-(t_o)>|2_+(t_o)>, \quad (7)$$

where the $\pm$ subscripts refer to the possible values of a binary observable, for instance the third component of a spin-1/2 particle.

The evolution of the state between times t_o and t is ruled by the evolution operators $\hat{U}_1(t,t_o)$ and $\hat{U}_2(t,t_o)$. We assume no interaction between both particles after the initial preparation and, consequently, the total evolution operator factorizes into the product of $\hat{U}_1$ and $\hat{U}_2$. Then $|t_o>$ evolves into $|t>$, given by:

$$|t>=\frac{1}{\sqrt{2}}|1_+(t)>|2_-(t)>+\frac{1}{\sqrt{2}}|1_-(t)>|2_+(t)>, \quad (8)$$

where $|1_+(t)>=\hat{U}_1(t,t_o)|1_+(t_o)>,...$

The probability of detecting the particle 1 in state "$+$" at time t is

$$P(1_+(t))=|<1_+(t)|<2_+(t)|t>|^2+|<1_+(t)|<2_-(t)|t>|^2. \quad (9)$$

We rewrite this expression in terms of the evolution operators and the initial states (which we assume to be orthonormal, $<1_\pm(t_o)|1_\pm(t_o)>=1=<2_\pm(t_o)|2_\pm(t_o)>$ and $<1_+(t_o)|1_-(t_o)>=0=<2_+(t_o)|2_-(t_o)>$). Assuming, moreover, that $\hat{U}_1$ is unitary we obtain

$$P(1_+(t))=\frac{1}{2}|<2_+(t_o)|\hat{U}_2^+(t,t_o)\hat{U}_2(t,t_o)|2_-(t_o)>|^2+ \\ +\frac{1}{2}|<2_-(t_o)|\hat{U}_2^+(t,t_o)\hat{U}_2(t,t_o)|2_-(t_o)>|^2. \quad (10)$$

Similarly, for 1_- we have

$$P(1_-(t))=\frac{1}{2}|<2_+(t_o)|\hat{U}_2^+(t,t_o)\hat{U}_2(t,t_o)|2_+(t_o)>|^2+ \\ +\frac{1}{2}|<2_-(t_o)|\hat{U}_2^+(t,t_o)\hat{U}_2(t,t_o)|2_+(t_o)>|^2. \quad (11)$$

When $\hat{U}_2$ is also unitary these probabilities become $P(1_+(t)) = 1/2$ and $P(1_-(t)) = 1/2$. The probabilities on side 1 are independent of the operations done on side 2. It is impossible to signaling using this arrangement.

On the other hand, when $\hat{U}_2$ is not unitary, $\hat{U}_2^+ \hat{U}_2 \neq \hat{1}$, the signaling becomes possible. For instance, if we take

$$\hat{U}_2^+ \hat{U}_2 = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \neq \hat{1}$$

the probabilities become

$$P(1_+(t)) = \frac{1}{2}(|\beta|^2 + |\delta|^2) \tag{12}$$

and

$$P(1_-(t)) = \frac{1}{2}(|\alpha|^2 + |\gamma|^2). \tag{13}$$

Except in the cases $|\beta|^2 + |\delta|^2 = 1$ and $|\alpha|^2 + |\gamma|^2 = 1$ the information encoded by an observer on side 2 (using adequate interactions) as $|\beta|^2 + |\delta|^2$ and $|\alpha|^2 + |\gamma|^2$ can be transmitted to side 1. If, moreover, we take $\alpha = 1 + \alpha_o \theta(T), \beta = \beta_o \theta(T), ..$ with $\theta(T)$ the Heaviside function ($\theta(T) = 0$ for $t < T$ and $\theta(T) = 1$ for $t \geq T$) and T is chosen large enough that information can be transmitted in a superluminal way.

This result can sound strange because we are accustomed to demand quantum evolutions to be unitary in order to preserve probabilities. However, as we shall show in the next subsection, the non-unitarity is an "effective" characteristic of the interferometric experiments when we disregard the particles absorbed by the screen.

3.2 Effective non-unitarity

We show in this subsection that the dynamics of a particle passing through a slit is non-unitary in an effective way because of the particles absorbed by the screen surrounding the slit. The situation is similar to that found in nuclear physics in scattering problems when some of the incident particles are captured by the target. In a phenomenological way the problem is described by a complex potential, for instance the optical potential [16]. The non-unitarity associated with this complex potential leads to the non conservation of probability, representing the capture of particles.

Let us consider now the problem of the diffraction of a particle by a slit. The mathematical description of interferometry and diffraction is particularly simple in the path integration formalism [17]. As the probability is conserved if and only if the evolution is unitary, to demonstrate the non- unitarity it suffices to show that the probability is not conserved. The condition for the conservation of probability in the path integral approach is

$$\int K^*(\mathbf{x_f}, t_f; \mathbf{x_i}', t_i) K(\mathbf{x_f}, t_f; \mathbf{x_i}, t_i) d^3\mathbf{x_f} = \delta^3(\mathbf{x_i}' - \mathbf{x_i}), \qquad (14)$$

where $K(\mathbf{x_f}, t_f; \mathbf{x_i}, t_i)$ is the kernel for a particle going from $(\mathbf{x_f}, t_f)$ to $(\mathbf{x_i}, t_i)$ (Eq. (4-37) of Ref. [17]).

The arrangement we consider in this subsection consists of a source which emits particles that impinge on a screen with a slit. Some particles are stopped or absorbed by the screen and the rest go through the slit being scattered and resulting in the usual diffraction pattern after the screen. The problem is essentially bidimensional with x and y representing the coordinates parallel and perpendicular to the screen in the plane of source and screen. The source is at the point $x = y = 0$ and the width of the slit is $2b$. The condition for the conservation of probability becomes

$$\int_{-\infty}^{\infty} d^2\mathbf{x_f} \int_{-\infty}^{\infty} d^2\mathbf{y_f} K^*(\mathbf{x_f}, \mathbf{y_f}, t_f; \mathbf{x_i}', \mathbf{y_i}' t_i) \times$$
$$\times K(\mathbf{x_f}, \mathbf{y_f}, t_f; \mathbf{x_i}, \mathbf{y_i}, t_i) = \delta^2(\mathbf{x_i}' - \mathbf{x_i}) \delta^2(\mathbf{y_i}' - \mathbf{y_i}). \qquad (15)$$

In the path integral formalism the problem of diffraction of a particle through a slit, which constrains its motion, is approached by breaking the path into two successive free particle motions, scattering the slit the particle from one to the other free particle evolution [17]. The kernel of a free particle is:

$$K(a', a) = \frac{m}{2\pi i\hbar(t_{a'} - t_a)} exp\left(\frac{im((x_{a'} - x_a)^2 + (y_{a'} - y_a)^2)}{2\hbar(t_{a'} - t_a)}\right). \qquad (16)$$

It is simple to check by direct substitution that (16) fulfills Eq. (15).

When the slit is present we have $K = K_x K_y$ with

$$K_x(\mathbf{x_f}, t_f; \mathbf{x_i}, t_i) = \int_{-b}^{b} dx_c exp\left(\frac{im(x_c - x_i)^2}{2\hbar(t_c - t_i)}\right) exp\left(\frac{im(x_f - x_c)^2}{2\hbar(t_f - t_c)}\right), \tag{17}$$

where x_c is the coordinate of the slit.

On the other hand K_y is the kernel of a free particle since in the y-direction the particle is not constrained. Consequently, the integral on y of K_y in (15) gives $\delta(y_i' - y_i)$.

Note that we have removed the factors before the exponential because they are unessential for the final result. Introducing Eq. (17) into Eq. (15) we have

$$\int_{-\infty}^{\infty} dx_f \int_{-b}^{b} dx_c \int_{-b}^{b} dx_c' exp\left(\frac{im}{2\hbar}\left(\frac{x_c^2 - (x_c')^2 - 2x_f(x_c - x_c')}{t_f - t_c}\right)\right) \times$$
$$\times exp\left(\frac{im}{2\hbar}\left(\frac{x_c^2 + x_i^2 - (x_c')^2 - 2x_i x_c + 2x_c' x_i'}{t_c - t_i}\right)\right). \tag{18}$$

First, we evaluate the integral on x_f

$$\int_{-\infty}^{\infty} dx_f exp\left(\frac{-im(x_c - x_c')x_f}{t_c - t_i}\right) = \delta\left(\frac{m(x_c' - x_c)}{t_f - t_c}\right). \tag{19}$$

Using this result we can evaluate Eq. (18):

$$\int_{-b}^{b} dx_c exp\left(\frac{im}{2\hbar}\left(\frac{x_i^2 - (x_i')^2 - 2x_c(x_i - x_i')}{t_c - t_i}\right)\right) = \tag{20}$$
$$= exp\left(\frac{im}{2\hbar}\left(\frac{x_i^2 - (x_i')^2}{t_c - t_i}\right)\right) \int_{-b}^{b} dx_c exp\left(\frac{-im}{\hbar}\left(\frac{(x_i - x_i')x_c}{t_c - t_i}\right)\right) \neq$$
$$\neq \delta(x_i - x_i')$$

We can only obtain the result $\delta(x_i - x_i')$ in the limit $|b| \rightarrow \infty$.

We conclude that the probability is not conserved and the evolution is not unitary. Clearly, the loss of probability is associated with the absorption of particles (paths) by the screen. These particles cannot be detected after the screen, and the number of particles arriving to the detectors is smaller than the number of emitted particles at the source. Thus the dynamics is non-unitary in this restricted sense. If we would include in the calculations the stopped particles we would recover the unitarity.

4 Mechanisms preserving the coexistence

We show in this Section that in addition to the dynamic condition discussed in Sect. 2 other types of conditions must be taken into account in order to decide if signaling is possible.

Let us imagine that we try to use the arrangement of Sect. 2 to transmit superluminal signals. In order to obtain a detection pattern sufficiently clear from which to read the information"ϕ" we need a minimum number of detected particles N, which must be determined in every possible experiment (depending on the type of detector, incident particle...). We denote by L the separation between the slit C (where the element producing the phase change ϕ is placed) and the detector of particle 1. Finally, T is the time delay between the arrival to the detector of the first and the last of the N particles. Obviously, the condition for the existence of superluminal communication is $T < L/c$ with c the light speed. This condition can be rewritten in function of the mean time between the emission of two entangled pairs by the source, τ, becoming the above expression:

$$\tau < \frac{L}{Nc}. \tag{21}$$

When the source can emit pairs of particles fulfilling this condition we can transmit the information "ϕ" in a superluminal way.

We can estimate the order of magnitude of τ by comparison with standard one-particle interferometry. Typical values are $N = 7.000$ and $L = 50cm$, that would correspond to $L/Nc \approx 10^{-13} seconds$. This value is extremely short when compared to the typical emission ratio of the usual sources of single particles, around $10^{-3} seconds$.

In conclusion, the dynamic signaling plus the condition (21) leads to the possibility of signaling. On the other hand, when we have $\tau \geq L/Nc$ the no-signaling condition is recovered.

The above considerations provide an example of a condition preventing the possibility of signaling. They are an example of a physical mechanism preserving the coexistence of Quantum Mechanics and Special Relativity. It is not the only possible mechanism. For instance, in the above analysis we have used the crude approximation of an instantaneous response of the detector after the arrival of the particles. It is by now well-known that this response time of the detector is finite. In particular, in Ref. [15] it has been experimentally demonstrated that in optical mediums where the group velocity exceeds the speed of light the detection of the information encoded in the pulse takes a longer time, being recovered in this way the relativistic limit for information transmission. Probably, a complete non-dynamic condition for no-signaling must include simultaneously considerations about the emission and detection processes. See also Ref. [11] for related considerations in the context of superluminal behavior associated with non-local propagators.

We conclude that there are physical mechanisms of a non-dynamic type that could avoid the signaling, although from the dynamic point of view it is in principle possible.

5 Discussion

We have analyzed in this paper a new type of non-locality differing from the usual one based on Bell-type correlations. The system considered is a gedanken two-particle two-slit interference arrangement with completely entangled states. Based on previous results [6, 7, 8], it is simple to show that, in principle, a phase change in one of the particles can modify the distant one-particle detection pattern of the companion particle. This non-local effect could, in principle, be observed (in the absence of other inhibiting mechanisms) detecting only the particles in one side of the arrangement without having any information of the results of the detection process on the other side, or even without detecting at all that particles. This differentiates the arrangement from the usual one in Bell-type experiments, where the nonlocal effects are determined comparing the results of detections at both sides of the arrangement (avoiding in this well-known way the possibility of signaling).

The effects associated with this non-locality are extremely small and, probably, unobservable. However, their importance can be large from the foundational point of view. For instance, they show interesting resemblances with the analysis of Hegerfeldt of the acausal behavior of particles initially localized.

We have also introduced the distinction between signaling and dynamic signaling. The second one refers to the possibility of superluminal information transmission when only the dynamic processes (evolution of the wave function) are taken into account. It is a necessary condition. However, the possibility of experimentally detecting signaling in a given arrangement also requires from additional conditions related to the emission and detection processes. Then signaling refers to the complete evolution of the system, including the emission, subsequent dynamical evolution and, finally, the detection.

In our example, where the dynamic signaling is in principle possible, the no-signaling condition can be preserved by the constrains on the ratio of emission of entangled pairs. As shown experimentally in Ref. [15] the general no-signaling condition must also take into account the detection process.

The above results show that the dynamic no-signaling (the only usually considered) is not a fundamental characteristic of quantum dynamics and cannot be included between the basic postulates of Quantum Theory. On the other hand, the possibility of including the more general condition of no-signaling remains an open question. However, it becomes clear from our analysis that this possibility would require from a more general framework, including emission and detection processes, than the one usually considered.

Another interesting question, closely related with the above one, is the possibility of deducing the constrains on the emission ratio or the detection properties from a purely quantum basis. This would require from the quantum study of the behavior of very general types of sources of entangled particles and detectors.

Finally, we remark that the constrain on the ratio of emission of entangled particles strongly remembers the thermodynamic formalism, where some general principles stating the impossibility of some processes (perpetual motion of first and second kind) play a fundamental role in the foundations of the theory.

In conclusion, we have shown the existence of dynamic signaling scenarios. However, we have remarked the existence of non-dynamic mechanisms that could prevent the superluminal transmission of information in these scenarios preserving the coexistence of Quantum Mechanics and Special Relativity.

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Comment on COEXISTENCE OF QUANTUM THEORY AND SPECIAL RELATIVITY IN SIGNALING SCENARIOS

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Sancho studies one-particle interferences in particular entangled two-particle systems and their connection with signaling. He states that he considers only the stationary problem. Since for a pair of particles which are completely correlated in momentum by $\mathbf{p}_1 + \mathbf{p}_2 = 0$ the uncertainty relations would imply a complete delocalization of the center of mass of the source he tries to reach an adequate compromise between the localization of the center of mass of the source and the deviations with respect to the exact momentum relation.

He considers two spatially separated double slits by which the particles are diffracted. In one of the slits he introduces some physical element which produces a phase shift ϕ to the particles passing through the slit. In this way he endeavors to obtain an explicit example of nonlocality going beyond the nonlocal correlations obtained in Bell-type experiments. He calls this type of nonlocality "dynamic signaling". Later he then shows that this, together with a *non-unitary* time-development operator, may perhaps lead to superluminal communication.

The non-unitarity Sancho considers is of an effective type, i.e. the particles absorbed by the screen surrounding the slits are missing in the two-particles description and thus the total probability is not conserved. Often this is described phenomenologically by a complex potential and he exhibits it here by using Feynman path integrals.

Now, this "effective" non-unitarity and its connection to possible superluminal communication raises interesting questions. It is believed that such an effective non-unitarity is due to the restriction to a two-particle system and that the time-development becomes unitary in a bigger, infinite particle, Hilbert space which includes the absorbing material. This complete description will necessarily become a field theory. The question then is whether the claimed superluminal communication persists also in this unitary case and, if so, whether one can find a way to avoid this by field theoretical means. In this context the discussion in [1, 2] may be illuminating.

References

[1] G. C. Hegerfeldt, Causality, Particle Localization and Positivity of the Energy in Quantum Theory, in: *Irreversibility and Causality*. Edited by A. Bohm, H.-D. Doebner, and P. Kielanowski. Springer Lecture Notes in Physics 504, p. 238-245 (1998)

[2] G. C. Hegerfeldt, Localization of Particles, Spreading and the Notion of Einstein Causality, in: *New developments in fundamental interaction theories* : 37th Karpacz Winter School of Theoretical Physics, Karpacz, Poland, 2001. Edited by J. Lukierski and J. Rembielinski. Melville, N.Y.: American Institute of Physics, 2001. p. 357