Quantum spatial superpositions and the possibility of superluminal signaling

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Mari *et al.* [Sci. Rep. 6, 22777 (2016)] and Belenchia *et al.* [Phys. Rev. D 98, 126009 (2018)] explore a gedankenexperiment in which the (gravitational or electromagnetic) interaction between two objects, one placed in a state of quantum superposition of two locations, seems to allow for faster-than-light communication. Building on the analysis carried out in Mari *et al.* [Sci. Rep. 6, 22777 (2016).], Belenchia *et al.* [Phys. Rev. D 98, 126009 (2018)] argue that, by considering the quantization of radiation and the existence of "vacuum quantum fluctuations" of the fields, the apparent possibility of superluminal signaling is completely avoided. Moreover, in the gravitational case, such a conclusion is taken as providing support for the view that gravity must necessarily have a quantum nature. In this work, we reconsider the situation and find several limitations of these assessments.

1 Introduction

Search for a theoretical framework incorporating general relativity and quantum theory has proven to be one of the most difficult undertakings in physics. A common assumption behind such a pursuit is that gravity itself must have a quantum nature. In fact, the possibility of schemes in which matter fields are treated in quantum terms, but gravity is treated classically, has been argued against on several grounds [1, 2]. However, those arguments have been found to be less convincing than intended [3, 4, 5].

Quite independently of whether gravity ought to have a quantum nature at the fundamental level, questions concerning the viability of semiclassical gravity as an approximated description, and its precise regime of applicability, are of clear practical and conceptual interest. It is clear that general relativity works exquisitely well in a large set of regimes, including the solar system, binary pulsars, black hole collisions, the generation of gravity waves and sectors of cosmology. All these applications rely on a classical treatment of matter, but we know that matter is better described via a quantum treatment. Therefore, there must be a regime for which semiclassical gravity is an excellent approximation. Moreover, there are scenarios in which semiclassical gravity is employed (mostly) without raising objections, such as in the Hawking evaporation of black holes (at least in the relatively early stages).

At any rate, as with all physical questions, the final verdict regarding the fundamental nature of gravity must depend on experimental evidence arising from situations where both quantum theory and gravitation play a relevant role. The standard expectation is that such situations only emerge in phenomena involving extremely high energies or when curvature values approach the Planck scale (i.e., $R \sim 1/m_p^2$), both of which are currently well beyond our empirical reach. However, there have been recent proposals to look for a possible quantum behaviour of gravity directly in a tabletop experiment, [6, 7]. In the meantime, there have also been proposals suggesting that useful hints might be acquired by exploring gedankenexperiments, together with well-established physical principles. The general idea is to obtain clues regarding the nature of gravity, by thinking about gravitational fields associated with matter sources in states that require a quantum mechanical treatment, [8, 9].

A concrete instance of such an approach has been explored in some detail in [10, 11, 12]. The gedankenexperiment considered involves two observers, one in control of an object placed in a quantum superposition of two spatial locations, and the other deciding whether a second object is allowed to react to its (electromagnetic or gravitational) interaction with the first. The setup in such that an interaction between the objects would prevent the observability of an interference pattern for the first object. And since the decision to allow the objects to interact or not can be taken with spacelike separation from the first object, that would seem to allow for superluminal signaling.

In [10, 11, 12], however, it is argued that, if one attributes quantum properties to the mediating fields, then the possibility for superluminal signaling is fully avoided. In particular, the claim is that taking into account the quantization of radiation of the fields, and the existence of their vacuum quantum fluctuations, allows for the undesired conclusion to be evaded. Moreover, in the gravitational case, this conclusion is used to argue for the view that the gravitational field must be given a quantum description. It is worth noting that this last claim is very strong indeed, as it goes well beyond the "mere" notion that "everything is quantum at the fundamental level". In particular, it seems to immediately discard the possibility, as proposed in [13], for the gravitational field to be an emergent entity, unsuitable for a quantum description.[1]

Considerations like this motivate us to reexamine the seemingly dramatic conclusions reached in [10, 11, 12]. It is not that we necessarily disagree on there being a high likelihood for everything ultimately having a fundamental quantum nature. However, we find it quite surprising that, at this stage in the history of physics, and via a simple gedankenexperiment, such robust conclusions could be reached. With this in mind, we explore what we perceive as weak points in the arguments that have been put forward in the works mentioned above.

In particular, we first point out that, in order for the signaling protocol to get off the ground, one needs to *presuppose* the quantum nature of the fields. Otherwise, the two objects would not get entangled and the interaction between them would not destroy the interference pattern. Therefore, the fact that considering the quantum nature of the fields might eliminate the possibility of signaling cannot be used to argue that gravity must be quantized. Second, we note that the discussions in [10, 11, 12] do not consider certain decoherence effects, inherent in the experimental design, that could prevent the protocol from actually working. In particular, taking into account the trap

[1] We do seem to frequently admit the existence of objects of that nature, such as an ecological system, a nation's economy or even something as simple as the heat flow in an ordinary material, described by a "field" which one would not attempt to quantize.

used to determine whether the objects are allowed to react to the interaction or not could prevent control of the signal. Finally, by explicitly constructing a version of the gedankenexperiment in which the second observer controls many particles, instead of one, and where the quantization of the fields and vacuum fluctuations do not avoid signaling, we show that the solution for the apparent superluminal communication presented in [11, 12] is defective (or at least incomplete).

Our manuscript is organized as follows. In section 2 we describe the gedankenexperiment, as discussed in [11, 12] and review their proposal for avoiding the (apparent) superluminal signaling. Then, in section 3, we present our evaluation of such a proposal, pointing out what we take to be important limitations. Finally, in section 4 we offer our conclusion.

2 The gedankenexperiment and the solution proposed by Belenchia *et al.*

In [10], Mari *et al.* proposed and analyzed a gedankenexperiment in which the (electromagnetic or gravitational) interaction between two objects, one placed in a quantum superposition of two locations, apparently allows for superluminal communication. The experiment was later reanalyzed by Belenchia *et al.* in [11] (see also [12]). Although the settings considered are slightly different, the basic idea, as well as the conclusions reached, have the same spirit: if one takes into account the quantization of the radiation emitted by the fields, as well as the existence of their vacuum fluctuations, then the apparent possibility of superluminal signaling is completely avoided. Here, we focus on the analysis developed in [11, 12]. In what follows we review the gedankenexperiment considered in such works, as well as the details of the solution advocated by them.

2.1 The gedankenexperiment

The gedankenexperiment considered in [11, 12] has two versions, one electromagnetic and one gravitational. Both contain two observers, Alice and Bob, separated by a distance D. Alice has control over a particle with spin, charge q_A and mass m_A and Bob over a particle with charge q_B and mass m_B. In the electromagnetic case, all gravitational effects are ignored; in the gravitational one, the charges is set to zero. We work in units with $\hbar = c = 1$.

The experiment starts by assuming that, in the distant past, Alice's particle was sent through a Stern-Gerlach apparatus, leaving its state in the superposition $\frac{1}{\sqrt{2}}(|L\rangle_A |{\downarrow}\rangle_A + |R\rangle_A |{\uparrow}\rangle_A)$ with distance d between $|L\rangle_A$ and $|R\rangle_A$. This step is assumed adiabatic, with negligible radiation emitted. Bob's particle, on the other hand, is initially assumed to be held on a strong trap, so its interaction with Alice's particle is negligible. The experiment then proceeds as follows. At time $t = 0$, Bob decides whether to release his particle from the trap or leave it there; we call T_B the time at which Bob completes his experiment. Also at $t = 0$, Alice starts an interference experiment with her particle, which ends at time T_A (see Figure 1).

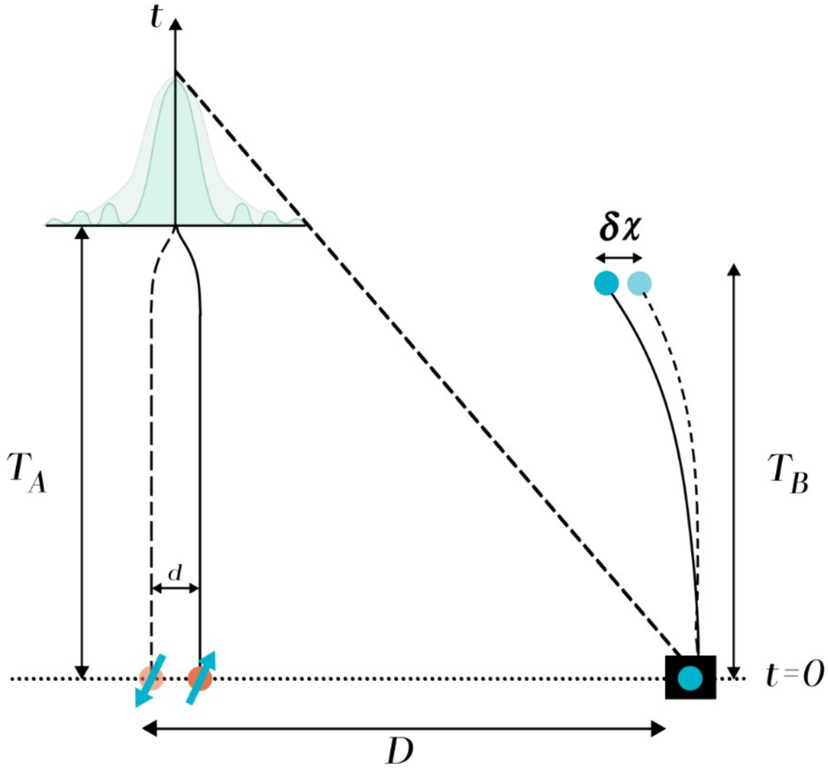

Figure 1: Spacetime diagram of the gedankenexperiment.

Now, if Bob decides to release his particle, it will get entangled with the fields produced by the components $|R\rangle_A$ and $|L\rangle_A$ of Alice's particle, which would put Bob's particle in a spatial superposition with separation δx. If δx is large enough, the states of that superposition would be nearly orthogonal, so Bob's particle would be nearly maximally entangled with Alice's, which would prevent her from observing interference. If, on the other hand, Bob does not release his particle, nothing would prevent Alice from observing interference. Then, Bob's decision to release or not the particle determines whether Alice observes interference or not. Therefore, if $T_A, T_B < D$, in which case the experiments of Alice and Bob would be spacelike separated, Alice and Bob would have access to a superluminal channel.[2]

[2]In [11], this result is presented as a tension between complementarity and causality: if complementarity is the case, superluminal signaling would be possible.

2.2 The solution proposed by Belenchia *et al.*

Below we review the solution proposed in [11, 12], first for the electromagnetic case and then for the gravitational one.

2.2.1 The electromagnetic case

For the electromagnetic case, [11, 12] treat the particles with non-relativistic quantum mechanics and the electromagnetic field as a relativistic quantum field. Then, at $t = 0$, they take the state of the whole system to be given by

$$|\Psi\rangle = \frac{1}{\sqrt{2}} \left[|L\rangle_A |\downarrow\rangle_A |\alpha_L\rangle_F + |R\rangle_A |\uparrow\rangle_A |\alpha_R\rangle_F \right] |\psi_0\rangle_B \,, \tag{1}$$

with $|\psi_0\rangle$ the state of Bob's particle inside the trap and $|\alpha_L\rangle_F$ and $|\alpha_R\rangle_F$ the states of the electromagnetic field associated with each term of the spatial superposition of Alice's particle. They point out that, typically, it will be the case that $|\langle\alpha_L|\alpha_R\rangle_F| \ll 1$. Therefore, in this sense, Alice's particle will have decohered, even before Bob could make a decision. However, [11, 12] argues that this would be a case of what [14] calls "false decoherence": if Alice recombines her particle adiabatically, then the fields would "follow" the particle and would allow for a complete recombination.

Now, in order to determine the effects of Bob opening the trap on the decoherence of Alice's particle, [11, 12] claim that there are two properties of the quantum electromagnetic field that play a crucial role: vacuum fluctuations and the quantization of the field. Regarding the former, it is argued that, due to the inevitable vacuum fluctuations of the electromagnetic field, a charged particle cannot be localized to better than its charge-radius q/m. Since this would be true for Bob's particle, in order for him to be able to destroy Alice's coherence, he needs for the displacement of his particle to be larger than its delocalization, i.e.,

$$\delta x > \frac{q_B}{m_B}. \tag{2}$$

In order to estimate δx, it is argued that it will depend on the difference between the resultant electromagnetic fields of Alice's particle, $E \sim \mathcal{D}_A/D^3$, with the corresponding "electric dipole moment" given by $\mathcal{D}_A = q_A d$. Since Bob's particle is released for a time T_B,

$$\delta_x \sim \frac{q_B}{m_B} \frac{\mathcal{D}_A}{D^3} T_B^2, \tag{3}$$

so, in order to ensure Eq. (2), it is necessary that

$$\frac{\mathcal{D}_A}{D^3} T_B^2 > 1. \tag{4}$$

Regarding the existence of quantized electromagnetic radiation, it is argued that for Alice to be able to coherently recombine her particle, she must be able to do the recombination avoiding the emission of even one photon. To estimate the amount of radiation emitted, it is noted that the total radiated energy would be given by $E \sim \mathcal{D}_A^2/T_A$. As this energy is quantized in photons with frequency $\sim 1/T_A$, the number of radiated photons would be of order $(\mathcal{D}_A/T_A)^2$. Thus, it is concluded that, in order for Alice to maintain the coherence of her particle when recombining, it is necessary to have

$$\mathcal{D}_A < T_A. \tag{5}$$

Now, for Bob to be able to influence Alice's interference experiment superluminally, we need $T_A < D$ and $T_B < D$. In that case, there are two options, $\mathcal{D}_A < T_A$ and $\mathcal{D}_A > T_A$. If $\mathcal{D}_A < T_A$, by Eq. (5), Alice can recombine her particle without emitting radiation but, because of Eq. (4), Bob is unable make a difference, so no signaling is possible. If, on the other hand, $\mathcal{D}_A > T_A$, then, by Eq. (5), Alice will not see interference independently of what Bob does, once more avoiding signaling.

2.2.2 The gravitational case

The treatment of the gravitational case in [11, 12] follows closely the electromagnetic one. The main difference being that, because of conservation of stress-energy, and taking into account the entanglement of Alice with her lab, it is argued that the effective mass dipole resulting from the superposition of Alice's particle is zero. Therefore, the gravitational effect on Bob's particle and the radiation emission are taken to be mediated by the quadrupole moment $\mathcal{Q}_A$.

The analysis then proceeds as follows. First it is argued that, due to the inevitable vacuum fluctuations of the gravitational field, Bob's particle cannot be localized to better than the Planck length $l_p \sim 10^{-35}m$, [15]. Consequently, in order for him to be able to destroy Alice's coherence, he needs for the displacement of his particle to be larger than its delocalization, i.e.,

$$\delta x > l_p. \tag{6}$$

Since the separation of Bob's components during time T_B is estimated to be given by

$$\delta_x \sim \frac{\mathcal{Q}_A}{D^4} T_B^2, \tag{7}$$

it is concluded that Bob will be able to cause decoherence only when (setting $l_p = 1$)

$$\frac{\mathcal{Q}_A}{D^4} T_B^2 > 1. \tag{8}$$

On the other hand, as in the electromagnetic case, it is argued that Alice cannot recombine her particle arbitrarily fast. Otherwise, her particle would radiate, which would cause decoherence.

In this gravitational case, the energy radiated is taken to be given by $E \sim (\mathcal{Q}_A/T_A^3)^2 T_A$, with the corresponding number of gravitons of order $(\mathcal{Q}_A/T_A^2)^2$. Therefore, in order to avoid the emission of even one graviton, the time that takes for her to do the experiment must satisfy

$$\mathcal{Q}_A < T_A^2. \tag{9}$$

Finally, in analogy with the electromagnetic case, Eqs. (8) and (9) are argued to prevent superluminal communication between Alice and Bob. For that we would need $T_A < D$ and $T_B < D$ but, if Eq. (9) holds, then $\mathcal{Q}_A < D^2$ so, from Eq. (8), that means that Bob cannot disrupt Alice's interference in time for signaling to occur.

With all this, in [11, 12] it is concluded that, by postulating the quantization and the existence of quantum vacuum fluctuations of the gravitational field, the worry of superluminal signaling is completely avoided. Such a conclusion is then read as providing support for the view that the gravitational field must be given a quantum field description.

3 Our evaluation

In this section, we point out important limitations of the previous assessment. We start by pointing out that, for the signaling protocol to work, one has to *presuppose* that the fields have a quantum nature. Therefore, the use of the protocol to argue that gravity must be quantized is, at best, circular. Next, we argue that there are certain decoherence effects not considered, produced by the presence of the trap and surrounding objects, that could completely derail the protocol. Finally, by considering a version of the gedankenexperiment with N traps, instead of one, we show that, contrary to what is argued in [11, 12], taking into account the quantization of the fields and their vacuum fluctuations does not help in avoiding superluminal signaling.

3.1 Is gravity quantum?

As we saw above, according to [11, 12], consideration of the quantization and the existence of quantum vacuum fluctuations of the gravitational field explains away the alleged possibility of superluminal signaling in the protocol under discussion. Moreover, such a result is promoted as lending support to the idea that the gravitational field must be given a quantum description. There is, however, a difficulty with this logic.

The issue is that, in order for the signaling protocol to function, one needs to *presuppose* that the field in question (gravitational in this case) has a quantum nature. To see this, we note that it is only because one assumes that the field generated by the superposition of Alice's particle is also described by a corresponding quantum superposition of states—that is, that the gravitational field gets entangled with Alice's particle—that Bob's particle also ends up entangled with Alice's particle. Otherwise, Bob's particle would not get entangled with Alice's and Bob would be unable to destroy Alice's coherence.

For instance, in some sort of semiclassical description, in which matter fields are quantum, gravity remains classical, and where the field produced by the superposition of Alice's particle is some sort of *average* of the two terms, Bob's particle would simply respond to that single field and not get entangled with Alice's particle. That is, if the Einstein curvature tensor for the spacetime metric is sourced by the expectation value of the energy-momentum, rather that the individual localized components of the state of matter, no non-trivial entanglement of the sort assumed by the communication protocol will be ever generated.

One could argue that semiclassical frameworks of this sort are already ruled out by works such as [1, 2]. However, as we mentioned above, such arguments are not as conclusive as intended.[3] In any case, this is supposed to be an argument against semiclassical gravity, so it cannot depend upon assuming that semiclassical gravity is not viable.

Now, given that the protocol presupposes a quantum description of the field, it is clear that then using such a quantum nature to avoid signaling should be seen more like a proof of self-consistency, and cannot in any way be used to argue for the quantization of the field in the first place. In other words, in the argument, the conclusion is already contained in the hypotheses, so the argument is, at best, circular.

3.2 Decoherence effects

In the gedankenexperiment under discussion, the influence of any object *external* to the setup itself, is completely neglected. This idealization is assumed in the theoretical treatment of almost all physics experiments. Since it is impossible to completely isolate any experimental setup from the outside, strictly speaking, no theoretical description is completely faithful to the experimental situation it intends to reproduce. However, in most cases, the disregard of external influences is fully justified, either by a comparison of the sizes of the internal and external influences, or by a systematization of external agents.

A crucial component of the proposed gedankenexperiment is the test of coherence of Alice's particle. Such a procedure is extremely sensitive to all sorts of external influences. Even worse, external effects are indistinguishable from internal ones, so it is not clear that the standard practice of neglecting external influences, is valid in this case. In fact, even if complete isolation could be achieved in practice, the analysis disregards the effect that Bob's trap itself could have on the coherence of Alice's particle.

There is, in fact, a direct way in which the trap could play a role. Since Alice's particle is in a superposition of two different locations, each influencing Bob's particle with different forces, the

[3] Even though existing arguments against semiclassical gravity are not conclusive, they do set constraints on semiclassical frameworks (see also [16] for a general assessment of the issue).

trap must also enter into a superposition of two different states. Thus, at $t = 0$ the state of the system must be

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left[|L\rangle_A |\downarrow\rangle |\alpha_L\rangle_F |T_L\rangle_B + |R\rangle_A |\uparrow\rangle |\alpha_R\rangle_F |T_R\rangle_B \right], \tag{10}$$

where $|T_L\rangle_B$ is the state of the trap when Bob's particle interacts with Alice's $|L\rangle_A$ component and $|T_R\rangle_B$ the state when interacts with Alice's $|R\rangle_A$ component. It is possible, then, that even if Bob doesn't release his particle, the trap itself causes decoherence in Alice's system.

One might alternatively reformulate the above consideration in the following terms: the ability of Bob's particle to cause decoherence in Alice's experiment depends on the generation of significant entanglement between them, caused by the action of the field of Alice's particle. Therefore, this decoherence effect could happen with any other object under the influence of Alice's field. In particular, the trap—with its millions of constituent particles—could cause this effect, preventing the establishment of a communication channel, even if Bob doesn't release his particle.

Another issue worth examining is the claim in [11, 12] that, when Alice recombines her particle slowly, the fields undergo so-called "false decoherence". The idea is that, while it is asserted that, when Alice's particle is in a superposition, the fields corresponding to the two components of the superposition are nearly orthogonal, it is also argued that, when Alice's particle is adiabatically recombined, then the fields "follow" the particle, allowing for a perfect recombination. The problem is that the analysis cited to support such a claim, [14], is performed in a non-relativistic setting, with fields propagating instantaneously. It seems far from clear, then, whether such an analysis extends to the relativistic scenario under discussion. In fact, it seems quite possible that, if the two components of the fields were nearly orthogonal at some point in time, then they would continue to be so on any spacial hypersurface containing the recombination of Alice's particle. After all, in regions sufficiently far away from the recombination event, the state of the field would not have had time to change as a result of the recombination, simply because such information is expected to travel causally. Any failure of the previous expectation would seem to offer, by itself, a path for superluminal signaling.

In fact, it seems to us that, the only way in which Alice would ever be able to fully recombine her particle, is when the fields corresponding to the two components of the superposition of her particle are *never* orthogonal. If that is so, it would mean that, if Alice is able to recombine her particle, then Bob's particle would not be able get entangled with it, avoiding from the very beginning the possibility of superluminal signaling.

3.3 Multiple traps

To conclude our analysis, we present a variation of the gedankenexperiment in which we show that the solution offered in [11, 12] must be invalid, or at least incomplete. To do so, we grant all claims in such works, but consider a scenario in which Bob, instead of controlling one particle, controls N particles. What we show is that, if Bob controls a large enough number of particles, then he can cause decoherence on Alice's experiment at time $T_B < D$, even if $\mathcal{D}_A < T_A < D$. If so, he would be able to send a superluminal bit of information to Alice—even if the quantization of the field and its fluctuations are considered.

According to the analysis in [11, 12], the vacuum fluctuations of the fields induce a limit on the localization of a particle in them. Such limits are argued to be given by $\sigma = q/m$, in the electromagnetic case, and by $\sigma = l_P$ in the gravitational one. As a result of this, it is argued that, in order for Bob to be able decohere Alice's particle, the separation in his superposition, δx, must be larger than σ. Finally, it is claimed that, if Alice recombines her particle without emitting radiation, Bob will not be able to obtain a δx large enough, in time to disrupt Alice's recombination.

Suppose, then, that Alice does recombine her particle without emitting radiation. In that case, when Bob releases his particle, he will obtain a δx smaller than σ, so the inner product of the states $|L\rangle_B$ and $|R\rangle_B$ of Bob's superposition will satisfy

$$|\langle L|R\rangle_B| = 1 - \epsilon \tag{11}$$

for some $\epsilon \ll 1$.

Suppose, now, that Bob has not one, but N particles. If he decides to release them, the state of the particles becomes

$$|\Psi_N\rangle = \frac{1}{\sqrt{2}}(|L\rangle_A |L_1\rangle_B |L_2\rangle_B ... |L_N\rangle_B + |R\rangle_A |R_1\rangle_B |R_2\rangle_B ... |R_N\rangle_B). \tag{12}$$

Assuming the same conditions for the N particles than we had for the single particle above, the inner product of the right and left components of Bob's particles then becomes

$$\Pi_i |\langle L_i|R_i\rangle_B| = (1-\epsilon)^N \approx 1 - N\epsilon. \tag{13}$$

Clearly, if N is large enough, this inner product approaches zero, so Bob's particles become able to cause decoherence of Alice's particle. And this is so, even maintaining the experiments of Alice and Bob at a spacelike distance and with Alice avoiding her particle to radiate. That is, if N is large enough, a superluminal communication channel between Alice and Bob would be possible. We conclude that, contrary to what is claimed in [11, 12], consideration of quantization and vacuum fluctuations of the fields in not enough to forbid superluminal signaling.

4 Conclusions

Recent works explore a gedankenexperiment in which the interaction of a particle with the field of a charged or massive object in a quantum superposition, seems to allow for superluminal communication. Building on a previous analysis in [10], [11] and [12] argue that, if one considers the quantization of the radiation of the fields in question, together with the presence of quantum vacuum fluctuations of such fields, then the alleged signaling disappears. Moreover, in the gravitational case, the result that quantization and vacuum fluctuations of the gravitational field are required to avoid signaling is promoted as an argument in favor of the necessity to quantize the gravitational field.

In this work, we have identified a number of limitations of the aforementioned conclusions. First, we point out that, in order for the proposed signaling protocol to function, it is necessary to *presuppose* the quantum nature of the fields. Therefore, the conclusion that the attribution of quantum properties to the fields might remove the possibility of signaling cannot be used as an argument for the quantization of gravity.

Next, we note that the discussions in [11, 12] of the gedankenexperiment fail to take into consideration possible crucial decoherence effects caused by one of the components of the experiment. Moreover, we question some claims regarding the alleged "false decoherence" process, supposedly undergone by the quantum states of the fields involved in the experiment. Finally, by considering a version of the gedankenexperiment in which Bob has control over N particles, instead of just one, we show that the considerations involving the quantization of the fields and vacuum fluctuations do not eliminate the possibility of superluminal signaling. We conclude that the assessment of the gedankenexperiment offered in [11, 12], as well as the proposed solution, are defective, or at least incomplete.

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