Quantum spatial superpositions and the possibility of superluminal signaling

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A recently proposed gedankenexperiment involving 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. However, it has been argued that, if the mediating fields are endowed with quantum properties, then the possibility for superluminal signaling is fully avoided. Moreover, in the gravitational case, this conclusion has been used to argue for the view that the gravitational field must be quantized. In this work, we point out various limitations to this and related assessments and we show that consideration of the way in which entanglement spreads across the system explains how superluminal communication is averted in this and related settings.

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 (see, e.g., [3, 4, 5]).

What is clear is that the final verdict regarding the fundamental nature of gravity must be informed by 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 that look for a possible quantum behavior of gravity in tabletop experiments, [6, 7]. In the meantime, there have also been proposals suggesting that useful hints might be acquired by exploring gedankenexperiments involving gravitational fields associated with matter sources in states that require a quantum mechanical treatment, [8, 9].

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

In [11], 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. More recently, [12] attempts a more precise and rigorous evaluation of the entanglement and decoherence effects occurring in the gedankenexperiment. Such an analysis is said to significantly improve upon the rough estimates provided in [11] and to show that the conclusions reached in such a work are valid in much more general circumstances.

In this work, we note some limitations to the assessments in [11, 12] and offer a more general proof of why superluminal signaling cannot occur in this kind of scenarios. Regarding [11], 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. Therefore, the fact that considering the quantum nature of the fields may eliminate the possibility of signaling cannot be used to argue that gravity must be quantized. Next, by considering a version of the gedankenexperiment in which the second observer controls many particles, instead of one, we show that the solution for the apparent superluminal communication presented in [11], based on quantum nature of the fields, cannot be the whole story.

Regarding the more precise evaluation presented in [12], we find that, although the path of analysis is certainly a very useful one, the precise criterion used to argue against the possibility of superluminal signaling has a couple of shortcomings, one that seems to be readily remedied and one with the potential for generating confusion. In fact, we will argue that the argument presented in [12] can be made more general and transparent by a relatively simple modification. In this regard, we show that, by reconsidering some aspects concerning the fields produced by Alice's particle, and by paying attention to the way in which entanglement spreads across the system, one can explain why the possibility of superluminal signaling is always averted in this type of settings.

Our manuscript is organized as follows. In section 2, we present the gedankenexperiment, as described in [11], we review the proposal in such a work for avoiding the (apparent) superluminal signaling and we describe the more rigorous analysis of the issue in [12]. Then, in section 3, we present our evaluation of these works, pointing out what we take to be important limitations. Next, in section 4, we pay attention to the way in which entanglement gets distributed in the gedankenexperiment and show that the possibility of superluminal signaling is fully avoided. Finally, in 5 we offer our conclusions.

2 The gedankenexperiment and previous assessments

The recent [10] 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 in [11, 12] (see also [13, 14]). Here, we focus on the gedankenexperiment as presented in [11] and on the appraisals of the scenario offered in [11] and [12].

2.1 The gedankenexperiment

The gedankenexperiment considered in [11] 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 are 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).

The experiment is then analyzed as follows. If Bob decides to release his particle, it would 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. It is then concluded that 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,

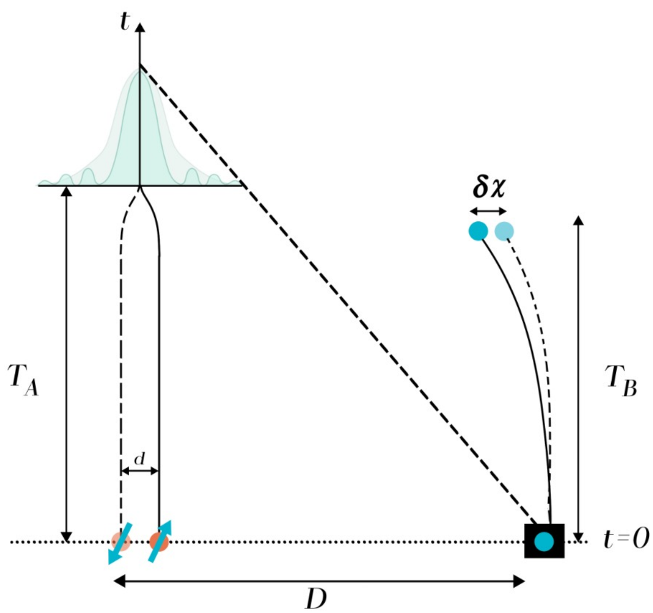

Figure 1: Spacetime diagram of the gedankenexperiment.

Alice and Bob would seem to have access to a superluminal channel.[1]

2.2 A proposed solution via the quantum nature of the fields

According to [11], the apparent possibility of superluminal described above is fully avoided if one takes into account the quantization of radiation of the mediating fields and the existence of their vacuum quantum fluctuations. Moreover, in the gravitational case, such a conclusion is taken as providing support for the idea that the gravitational field must be described in quantum terms.[2] Below we review these arguments, first for the electromagnetic case and then for the gravitational one.

2.2.1 The electromagnetic case

For the electromagnetic case, [11] treats the particles with non-relativistic quantum mechanics and the electromagnetic field as a relativistic quantum field. Then, at $t = 0$, they take

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

[2] Of course, in the case of the electromagnetic field, we already know from several other considerations, involving quite convincing experimental input, that it must be given a quantum treatment.

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 $|\psi_0\rangle_B$ 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. It is pointed 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] argues that this would be a case of what [15] 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] claims 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 "effective 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 $E \sim \mathcal{D}_A^2/T_A$. Moreover, as this energy is argued to be quantized in photons with frequency $\sim 1/T_A$, the number of radiated photons is calculated to 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] 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 $l_p \sim 10^{-35}m$, [16]. 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] 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.

2.3 A more general analysis of the decoherence effects

In [12], a more rigorous analysis of the gedankenexperiment is attempted. The aim, in particular, is to offer a precise description of the entanglement and decoherence effects involved. The new analysis is taken as significantly improving on the rough estimates in [11] and as showing that the conclusions of such a work are valid in much more general scenarios.

In order to better analyze the gedankenexperiment, [12] first explores the decoherence of Alice and Bob, separately. They do so in the electromagnetic version of the experiment, but note that the same discussion applies to the gravitational case. Regarding the decoherence due to Alice, they first note that, formally, as Alice recombines her particle, the state of her particle and its corresponding electromagnetic filed would be given by an expression of the form

$$\frac{1}{\sqrt{2}} \left(|\uparrow; A_1\rangle \otimes |\psi_1\rangle + |\downarrow; A_2\rangle \otimes |\psi_2\rangle \right), \tag{10}$$

with $|\psi_1\rangle$ and $|\psi_2\rangle$ formally corresponding to the field generated by Alice's particle in the respective state. It is noted, however, that such states of the field are not well defined and that, moreover, there is no meaningful way to separate $|\psi_1\rangle$ and $|\psi_2\rangle$ into a "Coulomb part" and a "radiation part".[3]

The situation is said to improve considerably by considering asymptotically late times, where the field naturally decomposes into a radiation field propagating to infinity and a Coulomb field fully determined by the asymptotic state of Alice's particle. Therefore, at

[3]One difficulty in attempting to deal, in a completely rigorous manner, with the problem at hand, is related to the fact that we do not only lack a theory of quantum gravity, but that, even for QED, we do not have a solid mathematically construction of interacting field theory. In fact, Hagg's theorem shows that the so-called interaction picture, which underlies the existent treatments, simply does not exist. We do have empirical successful perturbation schemes but, despite their usefulness, these cannot be thought of as substituting a mathematically rigorous construction.

asymptotically late times, the state would be of the form

$$\frac{1}{\sqrt{2}}\left(|\uparrow;A_1\rangle_{i+}\otimes|\Psi_1\rangle_{\mathscr{I}+}+|\downarrow;A_2\rangle_{i+}\otimes|\Psi_2\rangle_{\mathscr{I}+}\right) \tag{11}$$

with $|\Psi_1\rangle_{\mathscr{I}+}$ and $|\Psi_2\rangle_{\mathscr{I}+}$ the states of the radiation field at null infinity. The decoherence of the asymptotic state of Alice's particle is then written as

$$\mathscr{D}_{\text{Alice}} = 1 - |\langle\Psi_1|\Psi_2\rangle_{\mathscr{I}+}|. \tag{12}$$

Next, [12] considers a situation in which, after the recombination, Alice keeps her particle in inertial motion forever. If so, to the causal future of the recombination event, the field will be the Coulomb field of the recombined particle. Then, they consider an arbitrary Cauchy surface trough the recombination event, Σ, they extend the Coulomb field of the recombined particle to all of $I^+(\Sigma)$ and subtract this Coulomb field from the field in that region. To the resulting field corresponds a well defined state of the source-free electromagnetic field on Σ. Therefore, at "time" Σ, the state of the system would be given by

$$\frac{1}{\sqrt{2}}\left(|\uparrow;A_1\rangle_{\Sigma}\otimes|\Psi_1\rangle_{\Sigma}+|\downarrow;A_2\rangle_{\Sigma}\otimes|\Psi_2\rangle_{\Sigma}\right). \tag{13}$$

Finally, given that $|\Psi_1\rangle_\Sigma$ and $|\Psi_2\rangle_\Sigma$ evolve to $|\Psi_1\rangle_{\mathscr{I}+}$ and $|\Psi_2\rangle_{\mathscr{I}+}$, and that time evolution is unitary, it is noted that Alice's decoherence can be written as

$$\mathscr{D}_{\text{Alice}} = 1 - |\langle\Psi_1|\Psi_2\rangle_{\Sigma}|. \tag{14}$$

Regarding the decoherence due to Bob, it is argued that, after Alice puts her particle through the Stern-Gerlach apparatus, and before Bob makes a measurement to obtain "which path" information about Alice's particle, the state of the whole system would formally be given by

$$\frac{1}{\sqrt{2}}\left(|\uparrow;A_1\rangle\otimes|\psi_1\rangle+|\downarrow;A_2\rangle\otimes|\psi_2\rangle\right)\otimes|B_0\rangle \tag{15}$$

with $|B_0\rangle$ the initial state of Bob's apparatus. Assuming that no radiation is emitted by Alice or Bob, at asymptotically late times, the state of the system would be

$$\frac{1}{\sqrt{2}}\left(|\uparrow;A_1\rangle_{i+}\otimes|B_1\rangle_{i+}+|\downarrow;A_2\rangle_{i+}\otimes|B_2\rangle_{i+}\right) \tag{16}$$

with $|B_1\rangle_{i+}$ and $|B_2\rangle_{i+}$ the final states of Bob's apparatus. If so, the decoherence produced by Bob would be given by

$$\mathscr{D}_{\rm Bob} = 1 - |\langle B_1|B_2\rangle_{i+}|. \tag{17}$$

However, since it is assumed that Bob stops interacting at time T_B, this decoherence would also be given by

$$\mathscr{D}_{\rm Bob} = 1 - |\langle B_1|B_2\rangle_{T_B}|. \tag{18}$$

To employ all this groundwork to re-analyze the gedankenexperiment, [12] first considers a Cauchy surface, Σ_1, containing the recombination event, but to the past of all of Bob's experiment. There, according to Eq. (14), the decoherence of Alice's particle is taken to be given by

$$\mathscr{D}_{\rm Alice} = 1 - |\langle \Psi_1|\Psi_2\rangle_{\Sigma_1}|. \tag{19}$$

Next, they consider another Cauchy surface, Σ_2, for which Alice has not started the recombination, but Bob has completed his measurement. In that case, applying Eq. (18), they conclude that the decoherence of Alice's particle on that hypersurface would be given by

$$\mathscr{D}_{\rm Bob} = 1 - |\langle B_1|B_2\rangle| \tag{20}$$

with $|B_1\rangle$ and $|B_2\rangle$ the states of Bob's apparatus after completing his experiment.

After this, they point out that it is possible for more decoherence to occur as Alice recombines her particle. However, it is argued that, since Bob has completed his experiment, he has stopped interacting after Σ_2, so it is impossible for the decoherence of Alice's particle to be less than the decoherence caused by Bob. That is, it is argued that if

$$|\langle B_1|B_2\rangle| < |\langle \Psi_1|\Psi_2\rangle_{\Sigma_1}|, \tag{21}$$

could be the case, then a paradox would arise. Moreover, it is argued that, if Eq. (21) would hold, then Bob's measurement either would violate causality or it would violate complementarity. In other words, it is argued that Eq. (21) is a precise statement of the potential paradox posed by the gedankenexperiment.

However, according to [12], it is easy to see that such a situation simply cannot arise. To show it, [12] starts by considering the state of the whole system at Σ_1, namely

$$\frac{1}{\sqrt{2}}\left(|\uparrow; A_1\rangle \otimes |\Psi_1\rangle_{\Sigma_1} + |\downarrow; A_2\rangle \otimes |\Psi_2\rangle_{\Sigma_1}\right) \otimes |B_0\rangle\,, \tag{22}$$

and considers its evolution to Σ_3, a hypersurface that lies to the future of, both, Alice's recombination event and Bob's experiment

$$\frac{1}{\sqrt{2}}\left(|\uparrow; A_1\rangle \otimes |\Psi_1'\rangle_{\Sigma_3} \otimes |B_1\rangle + |\downarrow; A_2\rangle \otimes |\Psi_2'\rangle_{\Sigma_3} \otimes |B_2\rangle\right), \tag{23}$$

with $|\Psi_1'\rangle_{\Sigma_3}$ and $|\Psi_1'\rangle_{\Sigma_3}$ the radiation states after interaction with Bob. Next, by pointing out that such an evolution is unitary, so norms of states are preserved, they argue that

$$\begin{aligned} \langle\Psi_1'|\Psi_2'\rangle_{\Sigma_3}\langle B_1|B_2\rangle &= \langle\Psi_1|\Psi_2\rangle_{\Sigma_1}\langle B_0|B_0\rangle \\ &= \langle\Psi_1|\Psi_2\rangle_{\Sigma_1}, \end{aligned} \tag{24}$$

from which it follows that

$$|\langle B_1|B_2\rangle| \geq |\langle\Psi_1|\Psi_2\rangle_{\Sigma_1}|. \tag{25}$$

That is, it is concluded that the inequality of Eq. (21) can never be satisfied, thus avoiding the possibility of using this setup as a faster-than-light signaling protocol.

3 An evaluation of previous assessments

In this section, we point out important limitations to the assessments presented in [11] and [12]; we start with the former.

3.1 The quantum nature of the fields to the rescue?

We start by scrutinizing the claim in [11] that endowing the gravitational field with quantum properties avoids superluminal signaling lends support to the idea that the gravitational field must be given a quantum description. We note, however, that for the signaling protocol of the gedankenexperiment to get off the ground, one has to *presuppose* that the mediating fields have a quantum nature. Therefore, the use of the protocol to argue that gravity must be treated quantum mechanically must be regarded as circular.

It should be emphasized that we are not advocating for a contrary posture, namely, that the gravitational field should *not* be given a quantum treatment. As far as we know (and, in fact, this is something we consider very likely), it might be the case that the gravitational filed should be treated in quantum terms. The point we are objecting is the use of this gedankenexperiment, together with the natural expectation that no superluminal signaling is allowed by nature, as an argument in favor of such a view.

In detail, the issue is that, in order for the signaling protocol to work, one needs to assume that the field in question (gravitational in this case) has quantum properties. 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 particle and would be unable to destroy Alice's interference pattern.

For instance, we should note the possibility of some sort of semiclassical description, in which matter fields are treated quantum mechanically, the treatment of gravity remains classical, and where the geometry associated with the delocalized quantum superposition of Alice's particle corresponds to the geometry associated with a sort of *average* of the two terms of the superposition. In that case, Bob's particle would simply respond to that single "average field" and not get entangled with Alice's particle. That is, if the Einstein curvature tensor for the spacetime metric is being sourced by the expectation value of the energy-momentum tensor, then no entanglement of the sort assumed in the very conceptualization of the communication protocol will ever be 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.[4] In any case, the argument in [11] is supposed to be one against semiclassical gravity, so it cannot depend on assuming that semiclassical gravity is not viable.[5]

In sum, given that the protocol presupposes the fields to be quantum, the fact that their quantum nature may be used to avoid signaling should, at best, be read as a self-consistency proof and cannot be used to argue for the need of quantization of the field in the first place.

The next point we make has to do with the criterion employed in [11] to determine whether superluminal signaling is possible or not. According to [11], for Bob to be able to disrupt Alice's interference experiment, the displacement δx of his particle must be larger than the width of its wave function (see Eqs. (2) and (7)). However, this is *not* a reasonable criterion. To begin with, interference is not an all or nothing affair and all that is required for Bob to be able to send a signal to Alice is for Bob's experiment to noticeably affect Alice's interference experiment. That is, as long as the interference pattern observed by Alice without Bob's experiment is different from that obtained when Bob performs his experiment, a signal could be sent. Therefore, even if the displacement of Bob's particle is not larger

[4] Even though existing arguments against semiclassical gravity are not conclusive, they do set constraints on semiclassical frameworks (see also [17] for a general assessment of the issue).

[5] Our position in this regard is that it might very well be the case that spacetime only allows for a classical description. One extreme possibility is that spacetime is classical at the fundamental level. But there is another reasonable option, which is that, even though the fundamental description is fully quantum, spacetime is emergent and, by the time that it emerges, only a classical description is available. Claims to the contrary are problematic, not only from a mere academic perspective, but could also conceal the potential utility of semi-classical frameworks in regimes where quantum aspects of matter play essential roles.

than the width of its wave function, a signal could be sent.

Moreover, in general, this criterion would not even be successful in maintaining small the decoherence produced by Bob, as the result is largely dependent on the shape of the wave function. For instance, for a Gaussian wave packet, the demand of a displacement no larger than the width of the packet would substantially limit decoherence, as it would mean an overlap of $e^{-1/8} \approx .88$. However, for something approaching a square wave function, it would mean almost complete decoherence. We conclude that the criterion employed in [11] to determine whether superluminal signaling is possible or not is not really adequate.

As we saw above, the main claim in [11] is that, by taking into account the quantization of radiation of the fields and the existence of their vacuum quantum fluctuations, the possibility for superluminal signaling is fully avoided. We close this section by showing that, even granting all criteria and calculations offered in [11], their proposed solution must be invalid, or at least incomplete. To do so, we assume all calculations in [11] are correct and consider a scenario in which Bob, instead of controlling one particle, controls N of them. As we will see, in that case, Bob can cause decoherence on Alice's experiment at time $T_B < D$, even if $\mathcal{D}_A < T_A < D$. That is, he is able to send a superluminal bit of information to Alice—even if the quantization of the field and its fluctuations are fully taken into account.

According to the analysis in [11], 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 to 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

$$|\langle L|R\rangle_B| = 1 - \epsilon \tag{26}$$

for some $\epsilon \ll 1$.

Suppose, now, that Bob has not one, but N particles. If he decides to release them, and assuming no interaction between the N particles, their state becomes

$$|\Psi_N\rangle = \frac{1}{\sqrt{2}}(|L\rangle_A |L_1\rangle_{B_1} |L_2\rangle_{B_2} ... |L_N\rangle_{B_N} + |R\rangle_A |R_1\rangle_{B_1} |R_2\rangle_{B_2} ... |R_N\rangle_{B_N}). \tag{27}$$

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

$$\Pi_i |\langle L_i|R_i\rangle_{B_i}| = (1-\epsilon)^N \approx 1 - N\epsilon. \tag{28}$$

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 the analysis in [11] were correct, for a large enough N, a superluminal communication channel between Alice and Bob would still be possible. We conclude that, contrary to what is claimed in [11], consideration of quantization and vacuum fluctuations of the fields is not enough to forbid superluminal signaling.

The argument presented above assumes Bob's particles to be unentangled, and it could be questioned whether such an assumption is reasonable. To respond, we point out that there are possible arrangements, which maintain all of Bob's particles as far from each other as one likes, making it reasonable for the mutual interactions among them to be neglected. The point is that, for any given desired minimum distance between Bob's particles, r, there are arrangements for Bob's particles with no pair closer than r, which can cause on Alice's particles as much decoherence as desired. To see this, we note that the decoherence caused by a set of particles arranged over a sphere, with a given density of particles per unit area, can be made to be independent of the radius of the sphere. It is clear, then, that by using an appropriate density of particles per unit area and an appropriate number of spheres, the decoherence caused by Bob can be made as large as one would like, with no pair of particles closer than r (see the appendix A for explicit calculations).

We just saw that there are arrangements for Bob's particles that make it reasonable to assume that they are independent. It seems to us, though, that not much would change, even if Bob's particles were allowed to interact. That is, it seems to us that, if the analysis in [11] were correct, then the assumption of independence would not be necessary and, even if Bob's particles were entangled, they would cause decoherence on Alice's particle.

To see this, suppose that Bob has $N \gg 1$ entangled particles in the state

$$|\Psi\rangle = \sum_i a_i |\psi^i\rangle , \tag{29}$$

with the $|\psi^i\rangle$ separable states of the N particles. As the particles interact with the field produced by Alice's particle, their state evolves to

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\Psi_L\rangle + |\Psi_R\rangle\right), \tag{30}$$

with $|\Psi_L\rangle = \sum_i a_i |\psi_L^i\rangle$ and $|\Psi_R\rangle = \sum_i a_i |\psi_R^i\rangle$. That is, the $|\psi_L^i\rangle$ ($|\psi_R^i\rangle$) are the result of the interaction between the i-th separable state of the N particles and the left (right) component of the field produced by Alice's particle.

Consider now $\langle\Psi_L|\Psi_R\rangle = \sum_{ij} a_i a_j \langle\psi_L^i|\psi_R^j\rangle$. Given what we saw above regarding the case of N non-entangled particles, we have that $\langle\psi_L^i|\psi_R^i\rangle \approx (1-\epsilon)^N$. What about the crossed terms $\langle\Psi_L^i|\Psi_R^j\rangle$? We would like to argue that it is reasonable to assume that $\langle\psi_L^i|\psi_R^j\rangle \approx 0$. The point is that, it would be an amazing coincidence for the the state $|\psi^i\rangle$, influenced by the Alice's particle to the left, to have a significant overlap with $|\psi^j\rangle$, influenced by the Alice's particle to the right. Remember that the separable states in question are N-particle states, with $N \gg 1$, so it is enough for one of the particles not to have overlap for the whole inner product to vanish.

Putting everything together,

$$\langle\Psi_L|\Psi_R\rangle \approx \sum_i |a_i|^2 \langle\psi_L^i|\psi_R^i\rangle \approx (1-\epsilon)^N \sum_i |a_i|^2 = (1-\epsilon)^N. \tag{31}$$

We conclude that, if the analysis in [11] were correct, even if Bob's particles are entangled, they could cause decoherence on Alice's particle.

A final argument against the proposed solution in [11] is that, if correct, it would imply a direct clash with Lorentz invariance. The point is that, according to [11], the decoherence that Bob causes on Alice's particle is a function of the separation δx of the components of Bob's superposition. However, such a separation depends on the time T_B at which it is considered (see Eq. (3)). Therefore, given that Alice's and Bob's experiments are stipulated to be spacelike separated, according to the solution proposed in [11], Alice's prediction of Bob's decoherence on her particle would depend on the particular hypersurface she decides to employ to compute her predictions. For instance, if she uses the hypersurface Σ_1, passing through the recombination of Alice's particle, but to the past of Bob's experiment, δx would be zero, so no decoherence would occur. In contrast, if Alice chooses hypersurface Σ_3, passing through the recombination of her particle, but to the future of Bob's experiment, δx would be greater than zero, and decoherence would occur (see Figure 2). If Lorentz invariance is to be valid, the prediction made by Alice regarding the results of her experiment should not depend on the particular hypersurface chosen to perform the calculations.

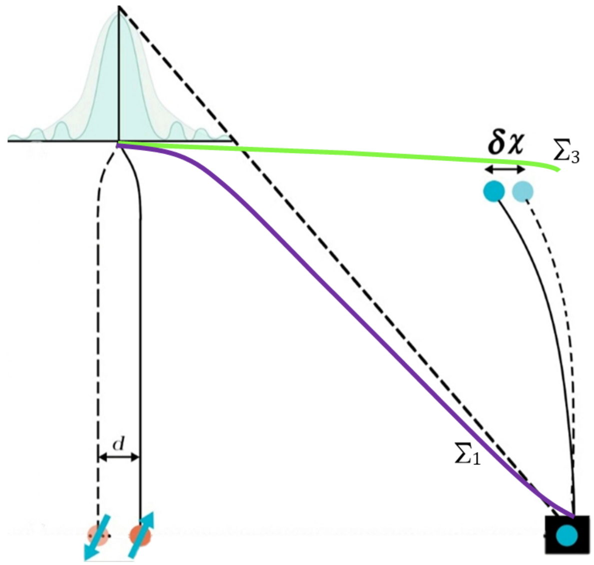

Figure 2: Two different hypersurfaces that could be used to predict Alice's observations.

3.2 Difficulties in the more general analysis

Although it is clear to us that the more general analysis in [12] represents a clear improvement over the one in [11] and that it contains valuable elements that have played a key role in our own considerations, we find that there are aspects in the analysis in [12] that are not completely satisfactory. Our aim here is not simply to be critical of such a stimulating work for the sake of it, but to try to clarify certain issues that, we believe, could lead to confusion.

After analyzing in general terms the decoherence caused by Alice and Bob, [12] compares the decoherence caused by each. To do so, they consider hypersurfaces Σ_1, containing the recombination event, but to the past of all of Bob's experiment, and Σ_2, for which Alice has not started the recombination, but Bob has completed his measurement. Then, they consider the decoherence caused by Bob on Σ_2, and they argue that, since Bob stops interacting after Σ_2, it is impossible for the decoherence of Alice's particle on Σ_1 to be less than the decoherence caused by Bob (see argument leading to Eq. (21) above). In particular, it is argued that if

$$|\langle B_1|B_2\rangle| < |\langle \Psi_1|\Psi_2\rangle_{\Sigma_1}| \tag{32}$$

could be the case, then the possibility for superluminal signaling would arise.

There are, however, several problems with this argument. To begin with, it seems to depend on some sort of "law of increase of decoherence", according to which once created, decoherence cannot disappear. However, such a "law" does not seem to us to be valid. For starters, it seems that it would imply a preferred direction of time—that in which decoherence increases. But it is not at all clear where would such an asymmetry in time arise from, given that the underlying theory is fully symmetric with respect to time inversion.[6] Furthermore, as pointed out in [15], there could be instances of "false decoherence", in which decoherence developed at some stage can completely disappear at a later stage. Therefore, it seems there are no grounds to think that such decoherence-increase "law" should hold in nature in general.

Moreover, it is not even the case that Σ_1 is to the future of Σ_2, as parts of each are to the future of parts of the other, so, even if some sort of decoherence-increase "law" would hold, it would not imply that inequality (32) must be the case. Therefore, its violation would not imply a paradox. There is, though, an apparently simple way to resolve this last issue, which is to consider the decoherence of Bob, not on Σ_2 but on Σ_3, containing the recombination event and to the future of Bob's experiment. This, in fact, is what is actually done in [12] to prove the inequality (see Eq. (4.5)): if one considers hypersurfaces Σ_1 and Σ_3, both passing through the recombination event, then the evolution of Alice's particle is trivial and Eq. (32) follows. All this, however, prompts the question of whether the decoherence of Bob on Σ_2 is equal to that on Σ_3, which takes us to the second problem we find with the above argument.

We saw that, according to [12], since after Σ_2 Bob has completed his experiment, he stops interacting with Alice. The problem, though, is that, even if Bob claims his experiment to be over, the electromagnetic or gravitational interaction between Alice's particle and Bob's experiment remains, so it is not the case that $|B_1\rangle$ and $|B_2\rangle$, the final states of Bob's apparatus, would remain frozen in whatever state they ended up when Bob called the end to his experiment. It is not clear, then, that the decoherence caused by Bob's particle on Σ_2 should be equal to that caused on Σ_3. One perhaps could argue that if Bob actually performs a *measurement*, then, at such point, the experiment would end. This might be so, but the calculations in [12] to derive the inequality depend on all evolution being purely unitary at all times. Therefore, such considerations would not be able to address the issue at hand (in section 4 we will relax this purely unitary requirement).

Finally, according to [12], if Eq. (32) would hold, Bob would be able to send a superluminal signal. However, the decoherence caused by Bob being smaller or larger than that caused by Alice does not seem to have anything to do with Bob being able to send a signal. In other words, even if the decoherence caused by Bob is smaller than that caused by Alice, Bob could be able to send a superluminal signal.

The point is that, as we saw above, interference is not an all-or-nothing issue and all that is needed for Bob to signal Alice is for Bob's experiment to alter Alice's interference

[6] It seems that some kind of account, analogous to that behind the second law of thermodynamics, would be at play, but it is unclear what could it be.

experiment perceivably. That is, even if Alice causes some decoherence, and even if the decoherence caused by Bob is smaller than that caused by Alice, as long as the interference pattern obtained by Alice, in the absence of Bob's experiment, is noticeably different from the pattern obtained when Bob performs his experiment, Bob would be able to communicate with Alice. Note, on the other hand, that satisfaction of Eq. (32) does not guarantee that Bob would be able to signal, at least not in practice, as even if Eq. (32) holds, the decoherence caused by Bob could be so small as to be undetectable.[7] Thus, in our view, Eq. (32) does not reflect the appropriate criterion to address the possibility of superluminal signaling in this setting.

In spite of this, it seems to us that in [12] it is claimed that, if Eq. (32) cannot hold, then Bob would be unable to cause any decoherence on top of the decoherence caused by the field—which is the kind of criterion that would, in fact, serve the desired purpose. We, however, do not see how satisfaction of Eq. (25) shows that Bob cannot contribute further to the decoherence caused by the field on Alice's system. In any case, in the next section we prove in a transparent and general way that it is actually the case that Bob cannot modify in any way, shape or form the decoherence already caused on Alice by the field. In particular, we present a proof that does not rely on the evolution being purely unitary, as is the case with the analysis in [12].

4 Revisiting the experiment

In section 3.1, we saw that, if the analysis in [11] were correct, then the presence of enough Bob's particles, regardless of whether or not they are entangled, would be able to cause decoherence on Alice's particle. And this would be so, even if the experiments of Alice and Bob are spacelike separated and Alice performs the experiment in a way that avoids any radiation. The problem is that all this would imply that almost all interference experiments, and certainly all interference experiments performed so far, would *not* display an interference pattern. The issue is that, surrounding any interference experiment, there are a large amount of objects, composed of an enormous amount of charged, massive particles. Therefore, if the computations and consideration in [11] were correct, the prediction would be that we would never observe interference, at least for interference experiments performed in labs on Earth. Now, we want to point out that the issue is even worse as, according to the computations

[7] This limitation on accuracy could have multiple origins, ranging from quantum mechanical limits related with the uncertainty principle, to more complicated ones involving, say, constraints on concentration of mass, associated with the formation of a black hole. In any case, our point here is not to explore what such limitations could there be, but to argue that the criterion, as expressed in Eq. (32), is not sufficient to prevent the undesirable superluminal signaling.

and consideration in [11], interference experiments would not display interference patterns, even in the absence of external objects—the field generated by the particle would be enough to cause decoherence.

We recall that, according to [11], when Alice recombines her particle slowly, the fields corresponding to the two paths of her particle undergo so-called “false decoherence”. The idea is that, when Alice's particle is in a superposition of two locations, the fields corresponding to the two components of the superposition are nearly orthogonal. However, 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, [15], is performed in a setting with either a spin or an harmonic oscillator coupled to a *massive* scalar field. Moreover, the analysis is carried out in the regime in which the time scale of the behavior of the system is larger that the inverse of the mass of the field. It seems, then, that if one wants to apply the conclusions of such an analysis to the gedankenexperiment in question, in which the fields are *massless*, then one would have to consider the case in which the recombination of Alice's particle takes an infinite time to complete. If, on the other hand, the recombination takes a finite time—as demanded by the gedankenexperiment—then the conclusion in [15] simply does not carry over.

In fact, it seems clear to us that the field would not simply “follow” Alice's particle as she recombines it. 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, precisely 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. Then, it seems 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* nearly orthogonal. That is, in order for Alice to actually produce an interference pattern in her experiment, it must be the case that the fields corresponding to the two components of the superposition of her particle at no moment produce significant decoherence. Otherwise, such decoherence would still be present on any spacial hypersurface containing the recombination of Alice's particle and it would always prevent interference.

Is the above realization enough to explain away the possibility of superluminal signaling? It would seem that it is not, because, even if Alice performs the experiment in such a way that the associated fields only produce negligible decoherence, interaction between the fields and surrounding matter would seem to be able to amplify such decoherence. If so, presence or absence of matter surrounding Alice's experiment would change her observations, opening the door for superluminal signaling. However, as we show below, *interaction between the fields and any other objects is simply unable to increase the amount of decoherence caused* *on Alice's particle*. Therefore, if the fields produce negligible decoherence, which, as we saw, is something required for Alice to obtain an interference pattern, interaction between the fields and anything else would not alter in any way the pattern observed by Alice, shutting the possibility of any sort of superluminal signaling.

To see that interaction between the fields and other elements cannot increase the amount of decoherence caused on Alice's particle, we employ an adaptation of the so-called no-signaling theorem, [18]. In more detail, together with [11], we treat the particles with non-relativistic quantum mechanics and the mediating fields as a relativistic quantum fields. Moreover, as in [12], we assume that, at least formally, there is a Hilbert space for the combined system. Next, we consider hypersurfaces Σ_1, containing the recombination of Alice's particle, but to the past of "Bob's experiment", and Σ_3, also containing the recombination of Alice's particle, but to the future of "Bob's experiment"; we use the quotation marks to denote the fact that we are generalizing the scenario by considering the interaction between the fields and, not only Bob's particles, but any objects interacting with the fields.

Now, regarding the evolution from Σ_1 to Σ_3, we note that, since both hypersurfaces go through the recombination event, the evolution of Alice's particle would be the identity. As for the evolution of the mediating field (F) and surrounding objects (B), we allow for their interaction to be as general as possible, so we model it as a general quantum operation acting on the $F-B$ system—which include among other things, purely unitary evolution and non-selective measurements. Such operations can be written as

$$\mathcal{O}_{FB}(\rho_{FB}) = \sum_i K_i^\dagger \rho_{FB} K_i \tag{33}$$

with the $\{K_i\}$ so-called Kraus operators acting only on the $F-B$ sector, satisfying

$$\sum_i K_i K_i^\dagger = \mathbb{I}_{FB}. \tag{34}$$

Next, we ask: how are the reduced density matrices of Alice's particle on Σ_1 and Σ_3

related? To answer, we compute

$$\begin{aligned}
\rho_A(\Sigma_3) &= Tr_{FB}\left[\sum_i K_i^\dagger \left|\psi(\Sigma_1)\right\rangle_{AFB} \left\langle\psi(\Sigma_1)\right|_{AFB} K_i\right] \\
&= \sum_i Tr_{FB}\left[K_i^\dagger \left|\psi(\Sigma_1)\right\rangle_{AFB} \left\langle\psi(\Sigma_1)\right|_{AFB} K_i\right] \\
&= \sum_i Tr_{FB}\left[\left|\psi(\Sigma_1)\right\rangle_{AFB} \left\langle\psi(\Sigma_1)\right|_{AFB} K_i K_i^\dagger\right] \\
&= Tr_{FB}\left[\left|\psi(\Sigma_1)\right\rangle_{AFB} \left\langle\psi(\Sigma_1)\right|_{AFB} \sum_i K_i K_i^\dagger\right] \\
&= Tr_{FB}\left[\left|\psi(\Sigma_1)\right\rangle_{AFB} \left\langle\psi(\Sigma_1)\right|_{AFB}\right] \\
&= \rho_A(\Sigma_1),
\end{aligned}$$

where we used the cyclic property of the partial trace.

We see that the reduced density matrix of Alice's particle is exactly the same before and after the interaction between the field and any other objects. This, of course, means that interaction between the field and anything else is incapable of modifying any observations Alice could make on her particle, including the presence or absence of interference. We conclude that, if Alice performs her experiment in such a way that interference would be present in the absence of interaction between the field and other objects, the presence of any such objects would not modify the interference pattern in any way, fully closing the possibility of superluminal signaling in this type of experimental setups. We also note that, in stark contrast with the analysis in [11], these calculations are fully compatible with Lorentz invariance:Alice's predictions do not depend on the particular hypersurface chosen to perform the calculations.

Summing up, according to [11], the fields corresponding to the two paths of Alice's particle, initially, are nearly orthogonal, but if Alice recombines her particle slowly, the fields undergo "false decoherence", allowing for a perfect recombination. Above, we argued that this cannot be correct because, if the fields initially cause significant decoherence, then they would continue to do so on any spacial hypersurface containing the recombination of Alice's particle, fully destroying the interference pattern. Therefore, for Alice to observe interference, the fields must never cause significant decoherence. Still, it could seem that interaction between the fields and other objects could cause additional decoherence, opening a potential route for superluminal signaling. However, we have shown that interactions between the field and other objects cannot increase the amount of decoherence on Alice's particle. We conclude that, by analyzing the possible decoherence caused by the fields produced by Alice's particle and by paying attention to the way in which entanglement gets distributed in the gedankenexperiment, one can fully explain how superluminal signaling is averted.

5 Conclusions

Recent works explore a gedankenexperiment in which the interaction of a particle with the field of a charged or massive object in a spatial quantum superposition, seems to allow for superluminal communication. Building on a previous analysis in [10], [11] argues 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.

More recently, [12] offers a more precise analysis, which is argued to improve on the rough estimates in [11] and to show their conclusions to be valid in much more general scenarios.

In this work, we have identified a number of limitations of the aforementioned analyses and have provided what we take to be a complete account of the reasons behind the impossibility for superluminal signaling in these experiments. In particular, we have shown that attention to the way in which entanglement gets distributed in the experiment is enough to explain away the possibility of superluminal signaling.

A Particles on a sphere

In this appendix, we show that, if the analysis in [11] were correct, then the decoherence caused by a set of particles arranged over a sphere, with a given density of particles per unit area, could be made independent of the radius of the sphere. To do so, consider a set of traps arranged over a sphere of radius l, centered on Alice. Assume all traps to contain particles of mass m_B and charge q_B and assume a uniform density ρ of traps per unit area of the sphere. According to [11], the effect of Alice's field on the particles on the traps can be estimated by considering the "effective dipole moment" generated by Alice's superposition, which corresponds to an electric field with magnitude nowhere smaller than $q_A d/l^3$. Therefore, if liberated, the displacements of the particles on the traps would satisfy

$$\delta x \geq \frac{q_B}{m_B}\frac{\mathcal{D}_A}{l^3}T_B^2, \tag{35}$$

with $\mathcal{D}_A = q_A d$. Now, for a superluminal signal to be possible, T_B would need to be smaller than l. Therefore, we take $T_B = \phi l$, with $\phi < 1$, in which case

$$\delta x \geq \frac{q_B}{m_B} \frac{\mathcal{D}_A}{l} \phi^2. \tag{36}$$

Next, for simplicity, we assume the wave functions of the particles to be Gaussians of width q_B/m_B, which, according to [11], corresponds to the smallest possible size for such particles. In that case, the inner product of the left and right components of each particle would satisfy

$$\langle L|R\rangle \leq e^{-\frac{\mathcal{D}_A^2 \phi^4}{8l^2}}. \tag{37}$$

Finally, taking into account that there are $N = 4\pi l^2 \rho$ particles on the sphere, the inner product of the left and right components of all of the particles would obey

$$\langle L|R\rangle^N \leq e^{-\frac{1}{2}\pi \mathcal{D}_A^2 \phi^4 \rho}, \tag{38}$$

which is independent of l. Therefore, if ρ and ϕ are kept constant, according to the analysis in [11], the decoherence caused by a given sphere would be independent of its radius. This means that, by employing enough such spheres, the decoherence caused on Alice's particle could be made as large as desired.

Note that, since we took $T_B = \phi l$, farther particles would be allowed to react to Alice's field for a longer period of time. However, since we also took $\phi < 1$, all such experiments would be spacelike separated from Alice. Note also that, if instead of covering the entire sphere, particles are arranged only over a patch of the sphere corresponding to a given solid angle Ω, it would also be the case that, for constant ρ, ϕ and Ω, the effect of those particles would be independent of the radius of the sphere. Therefore, a decoherence as large as desired could be caused, even if all of the traps were confined to a cone of arbitrarily small solid angle. Finally, note that the decision to release or not the particles from the traps could be coordinated by sending a light signal inwards from the outermost sphere, in such a way that even the last release is spacelike separated from Alice. Another option for coordination would be to distribute among all of the managers of the traps one of a set of spin-$\frac{1}{2}$ particles in the entangled state

$$\frac{1}{\sqrt{2}} \left(|\uparrow\rangle_1 |\uparrow\rangle_2 \ldots + |\downarrow\rangle_1 |\downarrow\rangle_2 \ldots \right) \tag{39}$$

and to link the decision to release or not the particle of a given trap to the result of a spin measurement on the corresponding spin-$\frac{1}{2}$ particle, made by each manager at an appropriate time to ensure all experiments are spacelike separated from Alice.

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References

[1] K. Eppley and E. Hannah, "The necessity of quantizing the gravitational field," *Foundations of Physics*, vol. 7, no. 1, pp. 51–68, 1977.

[2] D. N. Page and C. Geilker, "Indirect evidence for quantum gravity," *Physical Review Letters*, vol. 47, no. 14, p. 979, 1981.

[3] N. Huggett and C. Callender, "Why quantize gravity (or any other field for that matter)?," *Philosophy of Science*, vol. 68, no. S3, pp. S382–S394, 2001.

[4] J. Mattingly, "Why eppley and hannah's thought experiment fails," *Physical Review D*, vol. 73, no. 6, p. 064025, 2006.

[5] S. Carlip, "Is quantum gravity necessary?," *Classical and Quantum Gravity*, vol. 25, no. 15, p. 154010, 2008.

[6] S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. Toroš, M. Paternostro, A. A. Geraci, P. F. Barker, M. Kim, and G. Milburn, "Spin entanglement witness for quantum gravity," *Physical review letters*, vol. 119, no. 24, p. 240401, 2017.

[7] C. Marletto, , and V. Vedral, "Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity," *Phys. Rev. Lett.*, vol. 119, p. 240402, 2017.

[8] C. M. DeWitt and D. Rickles, *The role of gravitation in physics: report from the 1957 Chapel Hill Conference*, vol. 5. epubli, 2011.

[9] H. D. Zeh, "Feynmans interpretation of quantum theory," *The European Physical Journal H*, vol. 36, no. 1, pp. 63–74, 2011.

[10] A. Mari, G. De Palma, and V. Giovannetti, "Experiments testing macroscopic quantum superpositions must be slow," *Scientific reports*, vol. 6, no. 1, pp. 1–9, 2016.

[11] A. Belenchia, R. M. Wald, F. Giacomini, E. Castro-Ruiz, Č. Brukner, and M. Aspelmeyer, "Quantum superposition of massive objects and the quantization of gravity," *Physical Review D*, vol. 98, no. 12, p. 126009, 2018.

[12] D. L. Danielson, G. Satishchandran, and R. M. Wald, "Gravitationally mediated entanglement: Newtonian field versus gravitons," *Physical Review D*, vol. 105, p. 086001, 2022.

[13] A. Belenchia, R. M. Wald, F. Giacomini, E. Castro-Ruiz, Č. Brukner, and M. Aspelmeyer, "Information content of the gravitational field of a quantum superposition," *International Journal of Modern Physics D*, vol. 28, no. 14, p. 1943001, 2019.

[14] R. M. Wald, "Quantum superposition of massive bodies," *International Journal of Modern Physics D*, vol. 29, no. 11, p. 2041003, 2020.

[15] W. G. Unruh, "False loss of coherence," in *Relativistic quantum measurement and decoherence*, pp. 125–140, Springer, 2000.

[16] X. Calmet, M. Graesser, and S. D. Hsu, "Minimum length from quantum mechanics and classical general relativity," *Physical review letters*, vol. 93, no. 21, p. 211101, 2004.

[17] T. Maudlin, E. Okon, and D. Sudarsky, "On the status of conservation laws in physics: Implications for semiclassical gravity," *Studies in History and Philosophy of Modern Physics*, vol. 69, pp. 67–81, 2020.

[18] A. Peres and D. Terno, "Quantum information and relativity theory," *Rev. Mod. Phys.*, vol. 76, pp. 93–123, 2004.