Research Article

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Photonic implementation of quantum gravity simulator

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Abstract. Detecting gravity-mediated entanglement can provide evidence that the gravitational field obeys quantum mechanics. We report the result of a simulation of the phenomenon using a photonic platform. The simulation tests the idea of probing the quantum nature of a variable by using it to mediate entanglement and yields theoretical and experimental insights, clarifying the operational tools needed for future gravitational experiments. We employ three methods to test the presence of entanglement: the Bell test, entanglement witness, and quantum state tomography. We also simulate the alternative scenario predicted by gravitational collapse models or due to imperfections in the experimental setup and use quantum state tomography to certify the absence of entanglement. The simulation reinforces two main lessons: (1) which path information must be first encoded and subsequently coherently erased from the gravitational field and (2) performing a Bell test leads to stronger conclusions, certifying the existence of gravity-mediated nonlocality.

Keywords: quantum information; quantum gravity; quantum optics; quantum simulation; nonlocality.

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1 Introduction

The gravitational field is generally expected to obey quantum mechanics, like any other physical field. But to this day, there is no experimental evidence that this is the case. At the 1957 Chapel Hill conference, Richard Feynman famously emphasized that the gravitational field can be set into quantum superposition by simply setting a source, namely, a mass, into the superposition of two positions.[1] But, given the weakness of the gravitational interaction, how can we find empirical evidence for the superposition of field configurations?

The past few years have seen an intense interest in the possibility of obtaining such evidence on the laboratory bench, by detecting entanglement generated between quantum masses interacting gravitationally.[2–22] The key idea is that if the field mediating an interaction can be in a quantum superposition, this interaction can entangle degrees of freedom. A well-known result in quantum information theory states that quantum entanglement cannot be created between two systems by local operations and classical communication (LOCC).[23–25] Gravity-mediated entanglement (GME) can thus provide evidence that the gravitational field that mediates the interaction is in a quantum superposition.[26] Rapid advances in quantum control of larger masses[27–30] and measuring the gravitational field of smaller masses[31,32] might soon make this momentous experimental test possible.

The effect is predicted by most current tentative quantum gravity theories, such as loop quantum gravity, string theory, as well as low-energy effective field theory. On the contrary, it is not predicted by theories where the gravitational interaction

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is mediated by a local classical field,[33–35] nor by theories where the gravitational field does not display sufficiently long-lasting massive superpositions of macroscopically different configurations or where massive superpositions spontaneously collapse.[6,36–38] Thus, a negative result of the experiment would also be of particular interest, as the absence of GME would falsify common assumptions in quantum gravity research and provide evidence for these unorthodox theories.

The logic of the GME experiments, however, is more subtle: find evidence for a key property of certain collective degrees of freedom by looking at the way these allow other degrees of freedom to get entangled. Unpacking this argument is the subject of a lively debate on the precise epistemological conclusions that can be drawn from the detection of GME. Recent overviews of the debate are given in Refs. 39 and 40.

In this work, we report the photonic implementation of a quantum circuit simulating the experimental proposal of Ref. 3. The simulation sheds light on subtle aspects of the logic behind the claim that detecting GME is tantamount to evidence for the quantum nature of the gravitational interaction. Using an entanglement witness and the violation of a Bell inequality, we study how these different measurement protocols can certify the presence of entanglement, given realistic levels of noise. To study the possibility of a negative experimental outcome, we simulate spontaneous collapse models by introducing decoherence into the simulator and employ quantum state tomography to certify the absence of entanglement. In this way, we clarify the operational and theoretical tools needed to realize the gravitational experiment. We believe that the reported results can help the understanding and analysis of future GME experiments.

2 Experiment and Results

2.1 Gravity-Mediated Entanglement Experiment: Quantum Circuit Simulator

In the GME experiment, two masses are manipulated into a macroscopic center of mass superposition through an inhomogeneous magnetic field that couples to a spin (NV-center) embedded in each mass; see Fig. 1. Once the superposition is accomplished, the state of the full quantum system is

$$|\uparrow\uparrow\rangle|g_{LR}\rangle + |\uparrow\downarrow\rangle|g_{LL}\rangle + |\downarrow\uparrow\rangle|g_{RR}\rangle + |\downarrow\downarrow\rangle|g_{RL}\rangle, \tag{1}$$

where $|\uparrow\rangle$ and $|\downarrow\rangle$ are spin-z eigenstates, and the states $|g_{XY}\rangle$ are coherent states of the gravitational field and center of mass position of the masses.[26,41] These states are approximate energy eigenstates,[13] and they simply accumulate a relative phase during the free fall stage. Once the superposition is undone, the spins disentangle from the geometry. Tracing it out, we get

$$e^{i\phi_{LR}}|\uparrow\uparrow\rangle + e^{i\phi_{LL}}|\uparrow\downarrow\rangle + e^{i\phi_{RR}}|\downarrow\uparrow\rangle + e^{i\phi_{RL}}|\downarrow\downarrow\rangle. \tag{2}$$

For generic values of the phases, this is an entangled state. A detailed covariant derivation of this effect is given in Ref. 41. Note that, although we described the experiment using spin qubits, this represents only a useful choice to describe a particular physical spin-based experimental realization of the GME. The argument is general and different platforms can be employed for the realizations of this kind of experiment, such as nanomechanical oscillators and matter–wave interferometry.

The quantum circuit simulator is shown in Fig. 2(a) (note that the quantum circuit has been also discussed in Ref. 42). It is a straightforward representation of the evolution of the experiment in the regime $\Delta x \gg d$, where only the phase in the branch of the closest approach needs to be considered. This regime simplifies the analysis, without compromising the physics.[3,26]

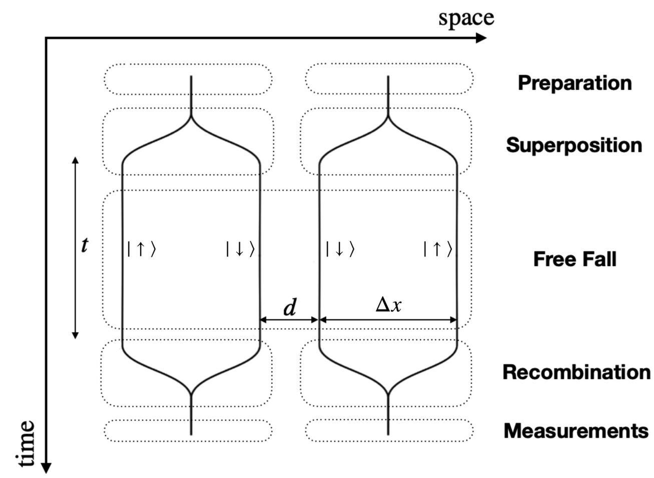

Fig. 1 Two masses in path superposition interacting gravitationally become entangled. Two massive particles with embedded magnetic spins are put into a spin-dependent path superposition. They are then left to free fall, where they interact via the gravitational field only. Then, the path superposition is undone, and measurements are performed on the spins. During the free fall, each branch of the superposition accumulates a different phase, which entangles the two particles.

The circuit represents the two spins and the geometry as a 16-dimensional system. Each embedded spin is simulated with a qubit, while the geometry degrees of freedom with two qubits (a ququart). We write vectors as belonging to the Hilbert space,

$$\mathbb{C}^2 \otimes \mathbb{C}^4 \otimes \mathbb{C}^2 = \mathcal{H}_{\mathrm{spin}_A} \otimes \mathcal{H}_{\mathrm{geometry}} \otimes \mathcal{H}_{\mathrm{spin}_B}. \tag{3}$$

At the end of the free fall stage, the state of the full system is

$$\frac{1}{2}(|0000\rangle + |0011\rangle + |1100\rangle + e^{i\phi}|1111\rangle). \tag{4}$$

After the recombination stage, the state of the geometry ququart factorizes. At the moment of measurement, the spin qubits are in the state

$$\frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + e^{i\phi}|11\rangle). \tag{5}$$

We implemented the quantum circuit simulator on the photonic platform shown in Fig. 2(b). The polarization of the photons carries the qubits representing the spins, while the geometry ququart is encoded in the paths of the photons. The spin and path degrees of freedom are associated with different Hilbert spaces, and therefore the path ququart of the photons can be said to be mediating the interaction between the spin qubits. The mapping from the massive experiment is coarse-grained, lumping the path of the particles and the geometry in the ququart. As we will discuss below, in this framework, the conclusions about the nature of the mediator are drawn from minimal assumptions on the interaction and causal structure and are independent of any specific and possibly unknown dynamics of the massive experiment.

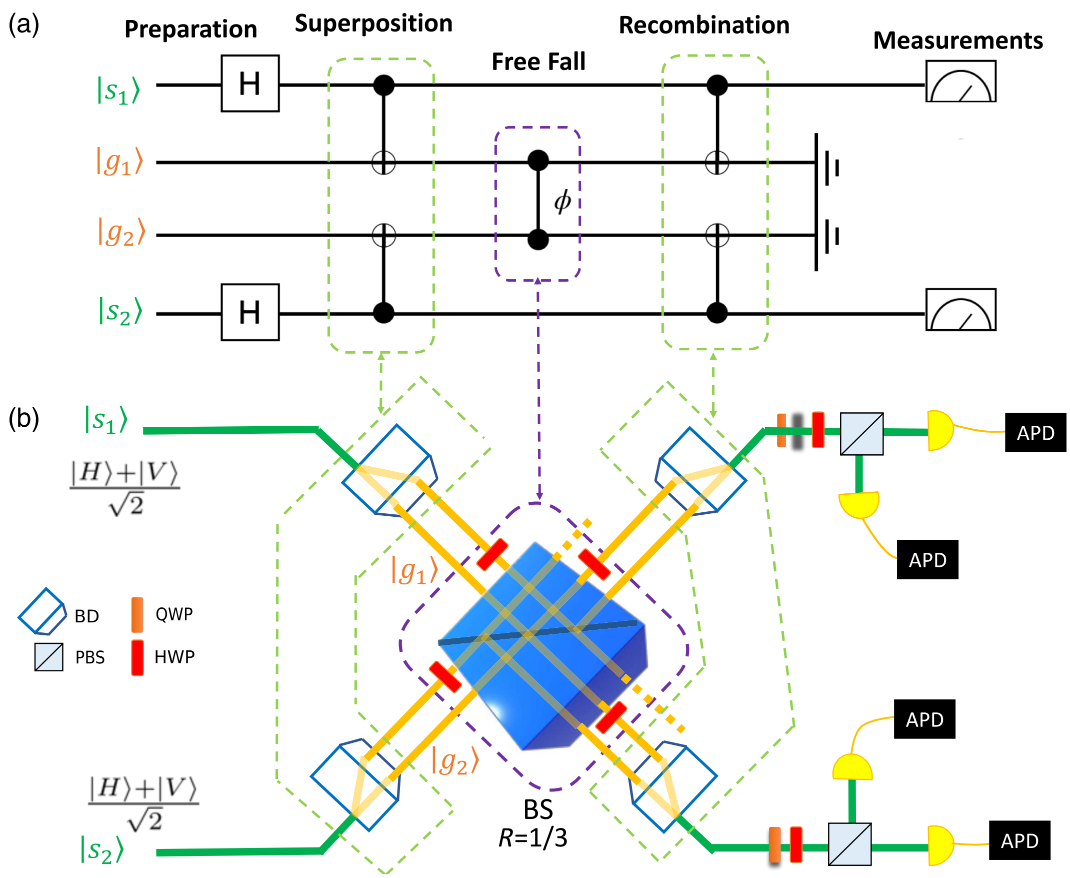

Fig. 2 The quantum circuit simulator and its photonic implementation. (a) Two qubits, $|s_1\rangle$ and $|s_2\rangle$, represent the spin degrees of freedom, while two qubits, $|g_1\rangle$ and $|g_2\rangle$, represent the geometry. Each stage of the experiment is mapped into quantum gates acting on the qubits. (b) The simulator is implemented using the path and polarization degrees of freedom of two photons. The spin qubits of the simulator are encoded in the polarization degree of freedom of the photons, while the geometry degrees of freedom are encoded in the photon paths. The two photons are independently prepared in a superposition of horizontal and vertical polarization, and each one passes through a BD, which completely entangles the path of each photon with its polarization. The control-phase (CZ) gate is implemented due to bosonic interference, which is due to the indistinguishability of the photons at the BS. Two HWPs momentarily make the polarization of all paths equal in order to allow the realization of the CZ gate on this degree of freedom. Finally, the qubit state is restored by two other HWPs and the paths are recombined by final BDs, which disentangles path and polarization. Finally, the polarizations of the photons are measured using quarter- and half-waveplates and polarizing beam splitter followed by single-photon detectors. BD, beam displacer; QWP, quarter-wave plate; PBS, polarization beam splitter; HWP, half-wave plate; BS, beam splitter; APD, avalanche photo diode.

Photons of wavelength ~785 nm are produced by spontaneous parametric downconversion from a nonlinear barium borate crystal pumped by a pulsed laser at 392.5 nm. The CNOT gates of the superposition and recombination stages are deterministically performed on each photon's path-polarization space through calcite beam displacers (BDs). The control-phase gate with a phase equal to π acting on the paths of the photon, which represents the effect of the free fall stage, is realized by a probabilistic scheme exploiting bosonic interference in a beam splitter (BS) with the reflection coefficient $1/3$.[43] Further details on the scheme and the experimental setup are provided in the Supplementary Material.

At the end of the recombination stage, the polarization state of the photons is

$$\frac{1}{2}(|VV\rangle + |HV\rangle + |VH\rangle - |HH\rangle), \tag{6}$$

where horizontal ($|H\rangle$) and vertical ($|V\rangle$) polarizations encode the qubit states $|1\rangle$ and $|0\rangle$ in Eq. (5), respectively.

Before the final measurement, we apply the local unitary operation $(\sigma_z + \sigma_x)/\sqrt{2}$ on the second qubit, by means of a half-wave plate rotated by 22.5 deg with respect to its optical axis. This step allows to recast the state as the maximally entangled singlet state,

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle). \tag{7}$$

This final rotation, which is equivalent to changing the measurement basis, simplifies the analysis without loss of generality.

2.2 Experimental Results

To certify the presence or absence of entanglement at the measurement stage, we implemented three strategies: quantum state tomography, an entanglement witness, and the violation of a Bell inequality. Each comes with its own merits and shortcomings, which we briefly recall.

Quantum state tomography[44] provides the maximum amount of information about a quantum system by measuring enough observables to fully reconstruct the quantum state. Of the three methods considered, this is the only one capable of certifying the absence of entanglement. Quantum state tomography requires the implementation of a large number of measurements that for systems of larger dimensions can be too expensive to perform. Entanglement can be detected with fewer resources by means of entanglement witnesses[45,46] that are observables W such that $\langle W\rangle \geq 0$ for all separable states and $\langle W\rangle < 0$ for at least one entangled state. Therefore, a negative expectation value implies the state is entangled. Alternatively, the violation of a Bell inequality, such as the CHSH inequality,[47] allows one to draw conclusions with strictly weaker assumptions than entanglement witnesses and tomography.[12,48,49] This is because, in contrast to the two previous techniques, Bell inequalities do not rely on assuming the validity of quantum theory nor the correct implementation of the quantum measurements; that is, it provides what is commonly called a device-independent certification of the presence of entanglement, one that relies on minimal assumptions about the experimental setup. Note, however, that not all entangled states can violate a Bell inequality, while an entanglement witness can be designed to detect arbitrary amounts of entanglement.

After the fine alignment of the setup, we performed a CHSH test on the polarization of the photons at the end of the circuit, obtaining a value $S^{\text{exp}} = 2.402 \pm 0.015$. That is, the classical bound of 2 was violated by more than 26 standard deviations. This provides a device-independent certification that entanglement was successfully mediated via the action of the CZ gate on the path degree of freedom of the photons. Then, we measured the following entanglement witness:

$$\mathcal{W} = 1 - |\langle \sigma_x \otimes \sigma_x \rangle + \langle \sigma_y \otimes \sigma_y \rangle|, \tag{8}$$

obtaining a value of $\mathcal{W}^{\text{exp}} = -0.72 \pm 0.02$. This result violates the separable bound of 0 by more than 36 standard deviations, where the statistical uncertainty has been computed assuming

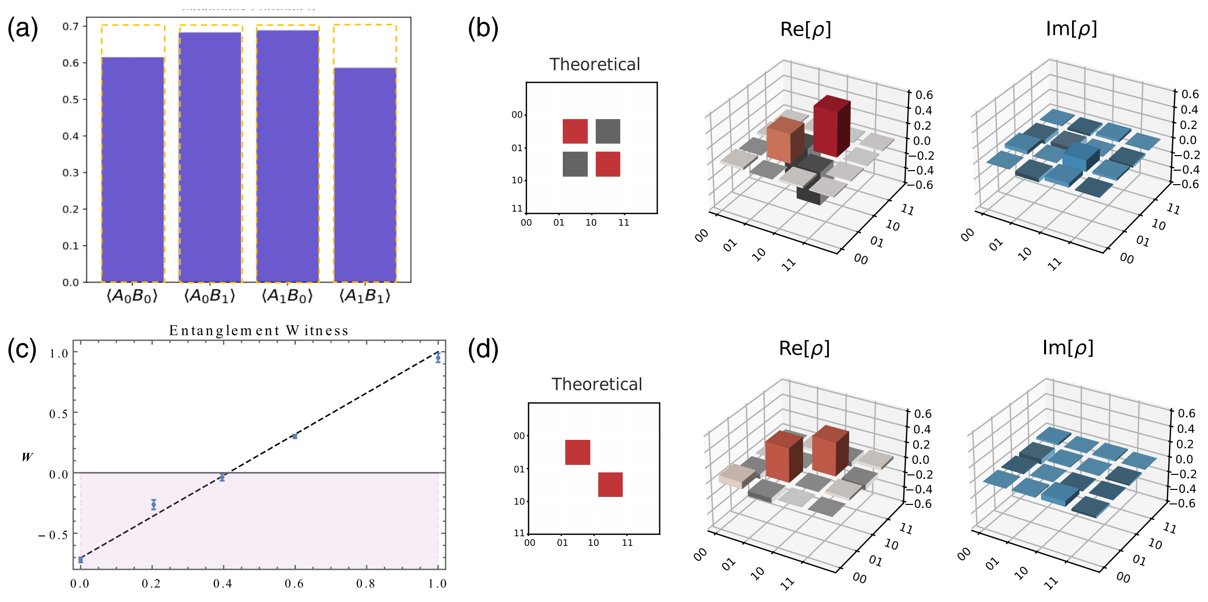

Fig. 3 Results of the simulator without and with decoherence. (a) Expectation values of the operators used for the CHSH test on the spin qubits. The lighter-colored parts in each bar (hardly visible) represent the Poissonian experimental errors associated with each observable. The orange dashed bars are the values expected from an ideal maximally entangled state. (b) Real and imaginary parts of the measured density matrix of the spin qubits. (c) Measured values of the entanglement witness $\mathcal{W}$ as a function of the degree of decoherence η. The latter corresponds to the relative time delay of different polarizations normalized to the coherence time of the photons. The purple-shaded area indicates the region where the witness certifies the entanglement of the state. The dashed black line represents the theoretical curve from the model of the experimental setup. Error bars are due to Poissonian statistics of the measured events. (d) Real and imaginary parts of the measured density matrix of the polarization state of the spin qubits, where the state has experienced maximum decoherence effects ($\eta = 1$) introduced by a delay between linear polarizations greater than the photon coherence time. The off-diagonal terms are completely suppressed and the state is separable.

Poissonian statistics. The entanglement witness (8) is equivalent, up to local unitaries, to the one proposed in Ref. 3. Results from the quantum state tomography of the generated state are given in Fig. 3(b).

To simulate the effects of spontaneous collapse, we induced decoherence by the implementation of time delays across different photon polarizations at the output of the BS. While in some gravity-induced collapse models, the wave function collapses because of stochastic fluctuations of the space–time metric[36,37] and coupling with a classical gravitational field,[33] here, we simulate the result of this effect (not its dynamics) by entangling the polarization of the photons with the temporal degree of freedom. When traced out, the temporal information induces an effective decoherence. As long as the delay is shorter than the coherence time of the photon wave packet, some degree of entanglement can be generated and detected by the witness. However, when the delay is longer than the photon coherence time, no entanglement can be detected in the final state.

If one of the photons passes through a birefringent slice after the BS, the state before measurement becomes

$$|\Psi\rangle_{\mathrm{del}} = \frac{1}{\sqrt{2}}(|H\rangle|V\rangle_{t_V} - |V\rangle|H\rangle_{t_H}). \tag{9}$$

Here, t_H and t_V are the distinguishable delays acquired by the horizontal and vertical polarizations, respectively. When the delay is greater than the coherence time of the photons, tracing out the information regarding the delays results in the completely mixed state,

$$\rho_{\mathrm{mix}}^{\mathrm{pol}} = \frac{1}{2}(|HV\rangle\langle HV| + |VH\rangle\langle VH|). \tag{10}$$

In contrast, when the delay is shorter than the coherence time of the photons, the state is

$$(1-\eta)|\Psi^-\rangle\langle\Psi^-| + \eta\rho_{\mathrm{mix}}^{\mathrm{pol}}, \tag{11}$$

which is partially mixed. The parameter η quantifies the amount of decoherence due to the polarization-dependent delay. Changing the thickness of the birefringent slices allows one to vary η from vanishing to maximum decoherence.

We measured the witness $\mathcal{W}$ and performed state tomography for five values of η. For $\eta > 0.4$, which corresponds to delays greater than around 450 ps, the observed witness does not violate the separable bound; see Fig. 3(c). The state tomography for the completely decohered state ($\eta = 1$) is reported in Fig. 3(d). Results for all values of η are reported in Fig. S2 in the Supplementary Material.

Quantum state tomography allows one to exclude the presence of entanglement in a quantum mechanical framework. Indeed, failure to detect entanglement with the witness is not proof of the absence of entanglement. For example, the entanglement witness did not detect entanglement for $\eta \sim 0.6$, but a positive partial transpose test[45] on the results of state tomography revealed the presence of entanglement. The four eigenvalues were $(0.583, 0.357, 0.230, -0.170) \pm (0.005, 0.007, 0.007, 0.008)$. The error intervals were computed with the Monte Carlo method. Note that, for two-qubit states, the presence of a negative eigenvalue in the partial transpose is a necessary and sufficient condition for entanglement.

We also simulated a conceptually different effect by introducing noise in the state of the geometry ququart. Indeed, while decoherence effects could be caused by the spontaneous collapse of the state of the particles, in a realistic experiment, it may also be the case that the interaction among particles is not strong enough to generate observable effects. For example, this would be the case if the distance between the interferometer paths is too large, or if the particles pass through the interferometers at different times. In both these cases, no gravitational interaction would be present, and the two particles pass along the interferometers in a fully independent way. In our experiment, this independence is provided by the distinguishability of the photons. Therefore, the expected partially distinguishable state $\rho_{\mathrm{part.\,dist.}}$ will be a mixture of the following form:

$$\rho_{\mathrm{part.\,dist.}} = v|\Psi^-\rangle\langle\Psi^-| + (1-v)\rho_{\mathrm{dist}}, \tag{12}$$

where the visibility v depends on the time delay between the photons. The density matrix ρ_{dist} is the expected two-photon state when the delay time is longer than the coherence time of the photons and is given as

$$\rho_{\mathrm{dist}} = \frac{1}{2}(|H+\rangle\langle H+| + |+H\rangle\langle +H|), \tag{13}$$

with $|+\rangle = (|H\rangle + |V\rangle)/\sqrt{2}$. We implemented this by varying the relative time arrival of the photons in the probabilistic control gate. The measured entanglement witnesses $\mathcal{W}$ and quantum state tomographies for different indistinguishability degrees v are reported in Figs. S4 and S3 in the Supplementary Material. The results of the tomography for the two kinds of decoherence models are qualitatively different.

For the sake of completeness, we note another possible effect, relevant in massive experiments but not taken into account in this simulation, that is, the presence of phases $\phi \ll \pi$ in Eq. (5). These smaller phases would be due to the weakness of gravitational interaction and the challenge of tuning the experimental parameters to set $\phi = \pi$. The effect of noise and decoherence would be even more marked in this regime.

3 Materials and Methods

3.1 Experimental Details

To quantify the degree of indistinguishability of the photons imprinting the BS, we measured the visibility of the Hong–Ou–Mandel (HOM) dip of the coincidences with respect to the time delay between the two photons. The experimental value found for the visibility is $V^{\mathrm{exp}} = 0.73 \pm 0.02$ that we compare to the ideal (perfect indistinguishable photons) theoretical one $V^{\mathrm{theo}} = 0.8$, obtaining a ratio equal to $V^{\mathrm{exp}}/V^{\mathrm{theo}} = 0.913 \pm 0.025$.

The calcite BDs act as the entangling gates of the superposition and recombination stages between the path and polarization of the single photons with a fidelity >99.5%.

The measured value of the reflectivities of the BS is $|r_H|^2 = 0.329 \pm 0.001$ for the horizontal polarization and $|r_V|^2 = 0.337 \pm 0.001$ for the vertical polarization of the incoming photons.

The fidelity of the scheme is also affected by the degree of indistinguishability of the interfering photons in all their degrees of freedom. Polarization, frequency, time of arrival, and spatial mode overlap all affect indistinguishability. Time of arrival and spatial mode overlap are crucial: the arrival time on the BS is controlled by suitable delay lines, while spatial modes are recombined by fine alignment through optical mirrors.

4 Conclusions

We detected the creation of mediated entanglement in the photonic simulator using three different methods: Bell inequality violation, entanglement witness, and quantum state tomography. We simulated two kinds of decoherence: those due to noise and due to unknown physics, and noted they may be distinguished with state tomography. The considered noises are indicative, since they represent some of the main challenges of future massive experiments.[6]

The study of the GME experimental proposals is merging the scientific culture of the two research communities of quantum gravity and quantum information. It is shedding light theoretically and experimentally on the possibilities of quantum gravity phenomenology and has sparked a lively debate that reaches the foundations of quantum theory.

A core aspect of the debate is the concept of witnessing the nonclassicality of the gravitational field, and more in general the distinction between "classical" and "nonclassical" behavior. Within quantum mechanics, superposition is a hallmark of nonclassical behavior. Superposition is, however, a theory- and basis-dependent concept. Its operational content can be encapsulated in the existence of noncommuting observables. The existence of noncommuting observables is the defining characteristic of nonclassical systems employed in the recent theory-independent generalizations of the LOCC theorems used to analyze GME.[17,50]

The main goal of this work is to apply known quantum information results and notions to the interpretation of GME experiments.

Our simulation makes explicit the crucial role of the noncommuting variables of the gravitational mediator. The mediating ququart entangles with the spin qubits due to the presence of the $X \otimes I$ and $I \otimes X$ observables in the CNOT gates. The phases are then generated by the ZZ observable. Introducing decoherence in the mediator removes the noncommutativity, since $\mathrm{tr}XYI = \mathrm{tr}YXI$. Once the noncommutativity is removed, no entanglement is generated between the spins.

While high-level abstract tools like the LOCC theorems can be very powerful, in practice, they are only informative insofar as they can be applied to well-developed theories that physicists are interested in testing. Linearized quantum gravity is the effective quantum field theory expected to correctly describe the physics in this regime. Here, different approaches try to define what type of field excitations are responsible for the mediation of entanglement: the Newtonian potential,[51,52] off-shell gravitons,[10,53] or superposition of spacetime geometries.[26,41]

Then, a question is how the mediator carries quantum information and gives rise to GME. In some sense, the entanglement has to be mediated via an interaction that is nonradiative. A hint of what is going on is provided by our simulation. During each run of the simulation, the geometry ququart acquires which-path information about the spin qubits only for a limited amount of time. The initial CNOT gates write the state of the spins in the geometry, while the final CNOT gates erase this information in a coherent way. This is a crucial point: since the geometry ququart is not measured, it would be impossible to detect the entanglement in the spins qubits if they were still entangled with it at the moment of measurement. In the gravitational experiment, the which-path information about the masses should not propagate to infinity. Instead, the which-path information must be coherently erased from the field states by the time of measurement. In the actual experiment, this erasure in the recombination stage is possible due to the fact that the interaction between the gravitational field and the masses is small and can be approximated as "elastic" so that the final state of the field is unentangled with the masses.[5]

A second important lesson of the simulation is that, rather than certifying an entanglement witness, Bell tests would provide more convincing evidence that a quantum gravitational effect has been observed. Similarly, concluding a definitive negative experimental outcome would require state tomography. Much of the literature on possible experimental protocols for detecting GME focuses somewhat misleadingly on employing an entanglement witness to certify, or fail to certify, GME.

Consider first the case of the negative experimental outcome, in which no GME is detected. This measurement would be of extraordinary consequence for fundamental physics, upending convictions held by generations of theoretical physicists. It would immediately falsify all mainstream quantum gravity theories, such as loop quantum gravity and string theory, as well as any other approach that claims linearized quantum gravity as its low energy limit. Such a conclusion would be accepted by the wider competent community only once extraordinary evidence is provided. Even after sources of noise have been excluded, it is likely that scientific consensus would form not with the failure to verify an entanglement witness but when high-precision state tomography has been performed. State tomography yields maximal information of the quantum state of the spins and, unlike a Bell test or an entanglement witness, can certify the complete absence of entanglement. If precise knowledge of the apparatus cannot be assumed, an alternative method to detect entanglement may be provided by automated optimizations for fully black-box approaches.[54]

Consider next the case of the positive outcome. The detection of GME would provide empirical evidence for the existence of quantum gravity, as it would verify a prediction of linearized quantum gravity. A question that remains is whether a theory-independent conclusion may also be drawn by invoking the LOCC-type theorems. The main difficulty in applying these theorems is that they rely on the assumption of the theory possessing a specific tensor decomposition of the state space. In this direction, we suggest that a Bell test would considerably strengthen the case for the importance of detecting GME. The Bell test, being a theory-independent measurement of nonclassical behavior, does not rely on assumptions about the state space of an underlying theory but only makes reference to observed data. The violation of a Bell inequality as a result of the experiment allows for a crisp conclusion: gravitational interactions create Bell nonlocality. Note that, clearly, one would need to make sure that there are no other forms of interactions besides the gravitational ones between the masses during the experiment.

Nonlocality is perhaps the most distinctive of quantum phenomena.[45,48,49,55] It is a resource at the basis of quantum information theory, providing a quantum advantage over classical computers.[56] So, it is fitting that the first glimpse of quantum gravity might come from the detection of gravity-mediated nonlocality.

We finally note that the direction of this work is also aligned with recent research,[57,58] where linear optical platforms are used, with different objectives, to study and simulate loop quantum gravity.

Possible future perspectives could be integrating these studies and extending the GME simulations to new variants of the proposed experiment.[59]

Disclosures

The authors declare no competing interest.

Code and Data Availability

All data needed to evaluate the conclusions are presented in this paper and/or the Supplementary Material.

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