Experimental Study of Nonclassical Teleportation Beyond Average Fidelity

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(Received 20 March 2018; revised manuscript received 30 May 2018; published 1 October 2018)

Quantum teleportation establishes a correspondence between an entangled state shared by two separate parties that can communicate classically and the presence of a quantum channel connecting the two parties. The standard benchmark for quantum teleportation, based on the average fidelity between the input and output states, indicates that some entangled states do not lead to channels which can be certified to be quantum. It was recently shown that if one considers a finer-grained witness, then all entangled states can be certified to produce a nonclassical teleportation channel. Here we experimentally demonstrate a complete characterization of a new family of such witnesses, of the type proposed in Phys. Rev. Lett. **119**, 110501 (2017) under different conditions of noise. We report nonclassical teleportation using quantum states that cannot achieve average fidelity of teleportation above the classical limit. We further use the violation of these witnesses to estimate the negativity of the shared state. Our results have fundamental implications in quantum information protocols and may also lead to new applications and quality certification of quantum technologies.

DOI: 10.1103/PhysRevLett.121.140501

Introduction.—The role of entanglement in quantum information processing is of utmost importance, but it is also subject of debate. Entanglement is today the core of many key discoveries ranging from quantum teleportation [1], to quantum dense coding [2], quantum computation [3–5], and quantum cryptography [6,7]. Quantum communication protocols such as device-independent quantum key distribution [8] are heavily based on entanglement to reach nonlocality-based communication security [9].

The prototype for quantum information transfer using entanglement as a communication channel is the quantum teleportation protocol [1], where a sender and a receiver share a maximally entangled state which they can use to perfectly transfer an unknown quantum state. This protocol represents a milestone in theoretical quantum information science [10–12] and lies at the basis of many technological application such as quantum communication via quantum repeaters [13,14] or gate teleportation [15]. It has been implemented over hundreds of kilometers in free space [16,17] and more recently in a ground-to-satellite experiment [18]. Employed platforms include mainly photonic qubits [19–25], but also nuclear magnetic resonance [26], trapped atoms [27,28], atomic ensembles [29,30], and solid-state systems [31–33].

To fully understand the role of entanglement in quantum teleportation, it is necessary to gauge what is the actual entanglement content (if any) that must be involved in order to upgrade a classical channel to a quantum channel. Indeed, it is known that not all entangled states allow a average fidelity of teleportation [34] to be reached which is higher than the one achievable using only classical communication [35], with the notable example of bound entangled states [36,37]. This mismatch between the nonclassicality of the shared state and nonclassicality of teleportation can be resolved by taking into account the full available information instead of only the average fidelity of teleportation. Very recently it has been theoretically shown [38] that it is possible to use a more informative witness for teleportation scenarios which detects nonclassicality of a teleportation channel whenever any amount of entanglement is present in the shared state. It was also shown that these witnesses allow for the entanglement of the shared state to be estimated [39].

In this Letter, we experimentally test, using pairs of polarization-entangled photons, the properties of a teleportation witness by exploiting a photonic teleportation setup able to generate a family of channel states (shared between the sender and the receiver) characterized by a tunable amount of noise γ. The noise tuning was done by exploiting a calcite interferometer [40,41]. We study the behavior of the teleportation witness for various values of γ and check its agreement with theoretical predictions. We demonstrate experimentally that the teleportation witness is able to detect the presence of a quantum channel even in conditions where the average fidelity of teleportation is below the classical limit. Finally, we use the teleportation witness

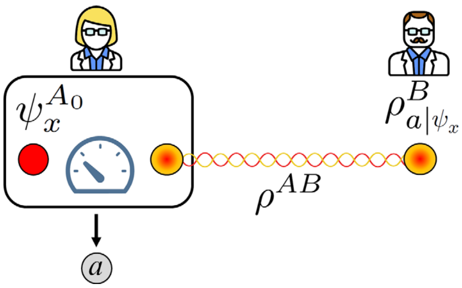

FIG. 1. Teleportation scenario: Alice and Bob use a shared system in a quantum state ρ^{AB}. Alice measures her subsystem together with system A_0 that can be prepared in states $|\psi_x^{A_0}\rangle$. Conditioned on Alice's measurement outcome a Bob's system is left in the state $\rho^B_{a|\psi_x}$.

to estimate the entanglement—in the form of negativity [42]—of the shared state. Our experimental results show that the analyzed teleportation witnesses represent a novel tool which is able to certify the presence of a nonclassical teleportation channel beyond the possibilities of the previously adopted benchmark, and to estimate entanglement.

Teleportation witnesses.—In a teleportation protocol, two parties, Alice and Bob, share a quantum state ρ^{AB}, which they want to use to teleport arbitrary (possibly unknown) states $|\psi_x^{\mathrm{A}_0}\rangle$ (see Fig. 1). Alice applies a measurement M with measurement operators $M_a^{\mathrm{A}_0\mathrm{A}}$ on the systems $\mathrm{A}_0\mathrm{A}$ in her possession, leaving Bob's system in the states

$$\rho^{\mathrm{B}}_{a|\psi_x} = \frac{\mathrm{tr}_{\mathrm{A}_0\mathrm{A}}[(M_a^{\mathrm{A}_0\mathrm{A}} \otimes \mathbb{1}^{\mathrm{B}})(|\psi_x\rangle\langle\psi_x|^{\mathrm{A}_0} \otimes \rho^{\mathrm{AB}})]}{p(a|\psi_x)}, \quad (1)$$

where $p(a|\psi_x) = \mathrm{tr}[(M_a^{\mathrm{A}_0\mathrm{A}} \otimes \mathbb{1}^{\mathrm{B}})(|\psi_x\rangle\langle\psi_x|^{\mathrm{A}_0} \otimes \rho^{\mathrm{AB}})]$ is the probability of the particular outcome a.

As proposed in [38], a particular witness function which exploits the full information obtained from teleportation can be computed in order to certify the presence of entanglement in the channel state ρ^{AB}. In particular, we focus here on the situation where the channel state belongs to the family of quantum states

$$\rho^{\mathrm{AB}}(\gamma) = \gamma|\psi^-\rangle\langle\psi^-| + (1-\gamma)|11\rangle\langle 11|, \quad (2)$$

where $|\psi^-\rangle = (|01\rangle - |10\rangle)/\sqrt{2}$, and as input to the teleportation experiment we consider the six eigenvectors of the Pauli matrices $\{\psi_x^{A_0}\}_{x=0}^5 = \{(|0\rangle + |1\rangle)/\sqrt{2}, (|0\rangle - |1\rangle)/\sqrt{2}, (|0\rangle + i|1\rangle)/\sqrt{2}, (|0\rangle - i|1\rangle)/\sqrt{2}, |0\rangle, |1\rangle\}$. We denote the resulting set of states prepared for Bob $\rho^{\mathrm{B}}_{a|\psi_x}(\gamma)$.

Using the methods discussed in [38], one can obtain operators $F^{\mathrm{B}}_{a|\psi_x}(\theta)$, defining a one-parameter family of teleportation witnesses:

TABLE I. One-parameter family of teleportation witnesses operators $[\theta \in (0, \pi/2)]$ used in Eq. (3) that detects the nonclassicality of the teleportation process using the state in Eq. (2), the input states ψ_x and a partial BSM where the outcome $a = 0$ corresponds to a projection into a singlet state $|\psi^-\rangle = (|01\rangle - |10\rangle)/\sqrt{2}$, and $a = 1$ the orthogonal subspace.[a]

		ψ_x			
	$F^{\mathrm{B}}_{a\|\psi_x}$	$\|0\rangle+\|1\rangle/\sqrt{2}$	$\|0\rangle-\|1\rangle/\sqrt{2}$	$\|0\rangle+i\|1\rangle/\sqrt{2}$	$\|0\rangle-i\|1\rangle/\sqrt{2}$
a	0	$-2\sin\theta\sigma_x$	$2\sin\theta\sigma_x$	$-2\sin\theta\sigma_y$	$2\sin\theta\sigma_y$
	1	0	0	0	0

		ψ_x	
	$F^{\mathrm{B}}_{a\|\psi_x}$	$\|0\rangle$	$\|1\rangle$
a	0	$4(1-\cos\theta)\|1\rangle\langle 1\|$	$4(1+\cos\theta)(\|0\rangle\langle 0\|)$
	1	0	0

[a]The fact that the witness operators are null for $a = 1$ indicates that this outcome does not contribute to the detection of nonclassical teleportation. This is natural since outcome $a = 1$ corresponds to the projection onto the subspace $\mathbb{1} - |\psi^-\rangle\langle\psi^-|$, which is a separable operator.

$$W(\gamma, \theta) = \sum_{a,x} p(a|\psi_x)\mathrm{tr}[F^{\mathrm{B}}_{a|\psi_x}(\theta)\rho^{\mathrm{B}}_{a|\psi_x}(\gamma)], \quad (3)$$

where the operators $F^{\mathrm{B}}_{a|\psi_x}(\theta)$ are given in Table I, and the parameter θ identifies a single witness of the family. By construction, $\sum_{a,x} p(a|\psi_x)\mathrm{tr}[F^{\mathrm{B}}_{a|\psi_x}(\theta)\rho^{\mathrm{B}}_{a|\psi_x}] \geq 0$ for all sets $\{\rho^{\mathrm{B}}_{a|\psi_x}\}$ that come from teleportation processes using only classical communication (or separable states). Thus, $W(\gamma, \theta) < 0$ is a certificate of nonclassical teleportation. It was moreover shown in [39] that the entanglement of the shared state can be estimated based upon the violations of a teleportation witness. In particular, the negativity [42] $\mathcal{N}(\rho^{AB})$ of the shared state can be bounded

$$\mathcal{N}(\rho^{AB}) \geq f(W(\gamma, \theta)), \quad (4)$$

where $f(W(\gamma, \theta))$ is a function that can be computed by semidefinite programming (see the Supplemental Material [43]).

We compare this witness with the average fidelity of teleportation, which is commonly adopted as the benchmark for the quality of quantum teleportation. The average fidelity between the input and output states of the process [12] is given by $\bar{F}_{\mathrm{tel}} = 1/N_x \sum_{a,x} p(a|\psi_x) \times \langle\psi_x|U_a \rho^B_{a|\psi_x} U_a^\dagger|\psi_x\rangle$, where N_x is the number of states to be teleported and U_a are fixed (i.e., independent of the input states) unitary operators conditioned to Alice's result a. In the case of perfect teleportation (using a maximally entangled state), $\bar{F}_{\mathrm{tel}} = 1$, while in experimental situations it is always the case that $\bar{F}_{\mathrm{tel}} < 1$. If one defines $\bar{F}_{\mathrm{cl}}$ as the maximal fidelity that can be obtained given a classical channel (i.e., in the absence of entanglement between Alice and Bob), the observation of $\bar{F}_{\rm tel} > \bar{F}_{\rm cl}$ implies that the teleportation process has no classical counterpart [44]. On the other hand, some entangled states cannot lead to a $\bar{F}_{\rm tel}$ higher than the classical bound. This is the case for some states in the family (2), which lead to an average fidelity lower than the classical bound of $2/3$ when $\gamma \leq 1/2$ (see the Supplemental Material [43]), while the channel state is still entangled. Notably, for these states, the capability to achieve nonclassical teleportation can be still certified through the witness $W(\gamma, \theta)$.

In the following, we experimentally study the behavior of $W(\gamma, \theta)$, characterizing it with respect to the experimental imperfections arising in a photonic setup, and then we finally compare its application with the average fidelity of teleportation for detecting nonclassical teleportation and estimating the negativity of the shared state.

Characterization of the teleportation witness.—We experimentally tested the proposed teleportation witness (3) by implementing a teleportation scenario in which a tunable amount of noise can be introduced in the entangled pair shared between Alice and Bob (see Fig. 2). Two photon pairs (1-2 and 3-4) are generated in two separated nonlinear crystals by means of type-II spontaneous parametric down-conversion (SPDC) process. Photon pair 3-4 will embody the quantum channel $\rho^{\rm AB}$ shared by Alice and Bob. To generate the tunable amount of noise, we send Bob's photon through the interferometer depicted in the yellow rectangle of Fig. 2, which is composed by a first calcite displacer (CD), a half wave plate (HWP) at an angle α, a second CD, and an HWP at 45°. When $\alpha = 45°$ the interferometer implements the identity transformation on Bob's photon, while for $\alpha = 0°$ the state is vertically projected $|V\rangle$. As a result, in the ideal case Alice and Bob will share a state of the form of (2), where the parameter γ can be tuned by acting on the physical angle α. The relationship between α and γ is explicitly derived in the Supplemental Material [43]. This ideal situation, however, cannot be completely reproduced in any actual implementation. As discussed in the Supplemental Material [43], to account for this we develop a model in order to theoretically predict the main imperfections which can arise in a photonic scheme similar to the one in Fig. 2. We address the SPDC generation and the calcite interferometer as the two main sources of imperfection, and we introduce two parameters ($0 \leq v \leq 1$ and $0 \leq \delta \leq 1$, respectively) in order to take them into account. Given our model, we estimate that the state produced in the experiment, to good approximation, has the form

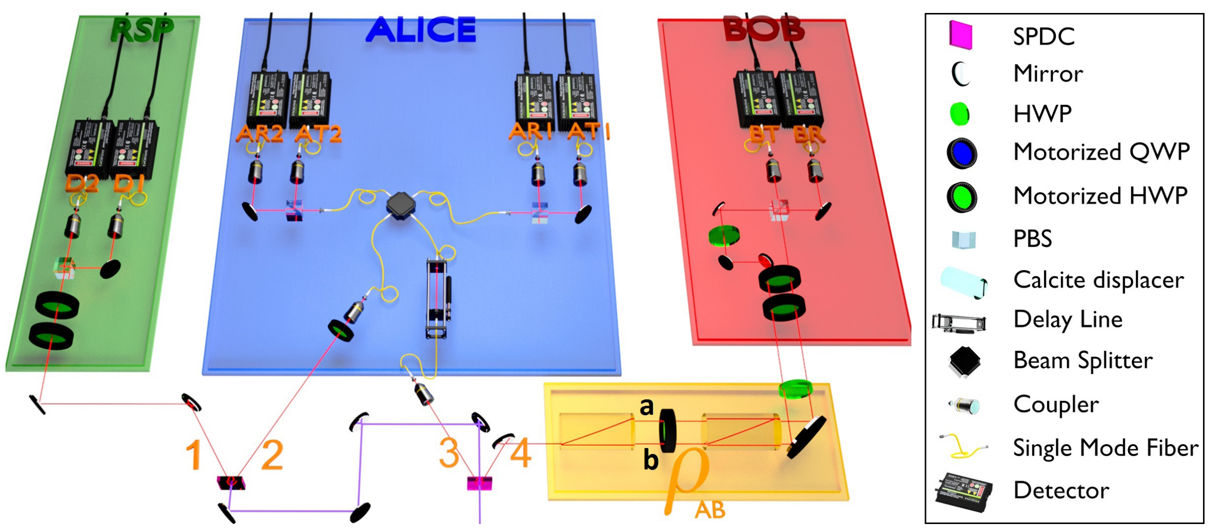

FIG. 2. Experimental apparatus: Two photon pairs (1-2) and (3-4) are generated via parametric down conversion in two separated nonlinear crystals. Remote state preparation of photon 2 is performed by projective measurement on photon 1 via quarter wave plate, half wave plate (HWP), and polarizing beam splitter. Photon 4 is sent through an interferometer composed by a first calcite displacer (CD), an HWP with a tunable angle α, a second CD, and an HWP at 45°. When $\alpha = 45°$, photon 4 comes out in path 4a without modifications of the joint state $\rho^{\rm AB}$. Conversely, when $\alpha = 0°$, photon 4 comes out in path 4b projected onto the vertical polarization $|V\rangle$, and the joint state $\rho^{\rm AB}$ becomes $|VV\rangle$. Intermediate angles between 0° and 45° allow us to tune the two-qubit state $\rho^{\rm AB}$ between $|\psi^-\rangle$ and $|VV\rangle$. The two paths 4a and 4b are incoherently recombined at the polarizing beam splitter (PBS) of Bob's measurement stage by means of an HWP at 45° on path 1b. To carry out a teleportation protocol, Alice performs a Bell state measurement (and transmits the outcome "a" to Bob). To test the nonclassicality of teleportation, Bob measures the operators $F_{a|\psi_x}$ which allows for testing a teleportation witness, and then shares the outcomes with Alice to check a teleportation witness. A motorized delay line ensures temporal indistinguishability in the beam splitter.

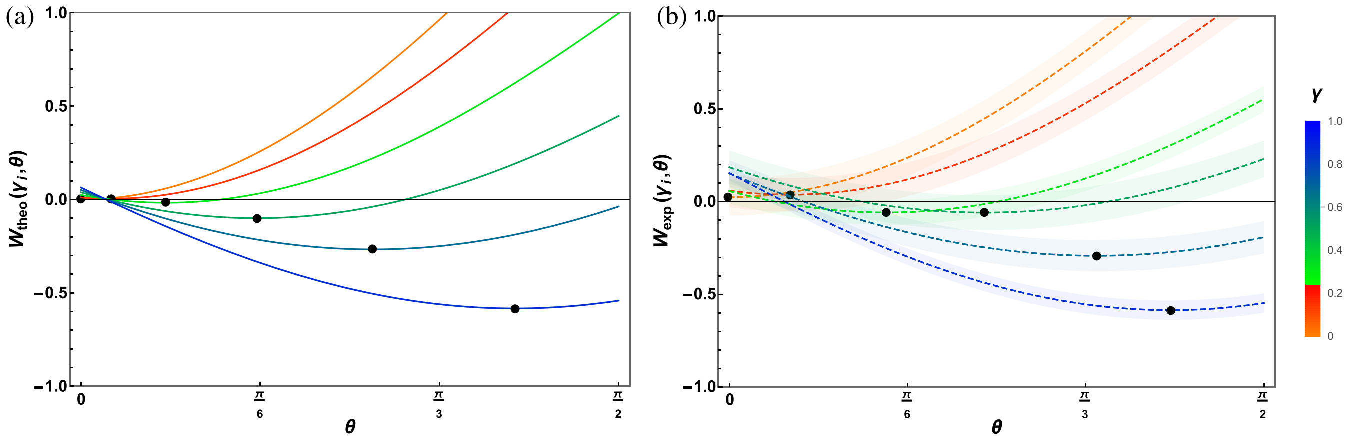

FIG. 3. Experimental test of the non-classical teleportation witness. Theoretical predictions [straight lines in (a)] and estimated witness function [dashed lines in (b)] as a function of the free parameter θ, obtained, respectively, from our noise parameter estimation and our experimental data points. Shaded areas correspond to one standard deviation of uncertainty upper and lower the dashed lines, due to Poissonian statistics. The bar legend on the right explains the color relationship with γ, whereas black points on the curves stand for the minimum theoretical (a) and experimental (b) values obtained for $\gamma = 0$, $\gamma = 0.14$, $\gamma = 0.32$, $\gamma = 0.51$, $\gamma = 0.68$, $\gamma = 0.85$.

$$\rho_{\text{noisy}}^{\text{AB}} = \frac{1}{4}\begin{pmatrix} (1-v^2)\gamma & 0 & 0 & 0 \\ 0 & 2-v^2(2-3\gamma)-\gamma & -2(1-2\delta)^2v^2\gamma & 0 \\ 0 & -2(1-2\delta)^2v^2\gamma & (1+v^2)\gamma & 0 \\ 0 & 0 & 0 & 2+v^2(2-3\gamma)-\gamma \end{pmatrix}. \tag{5}$$

As a result, given the estimated values of v and δ, for some low values of γ the generated quantum states can become separable, differently from the ideal one shown in Eq. (2).

We were able to experimentally test the expected properties of the teleportation witness (3), analyzing its behavior for different values of γ and θ. In our scheme, Alice prepares the state to be teleported in photon 2 by means of

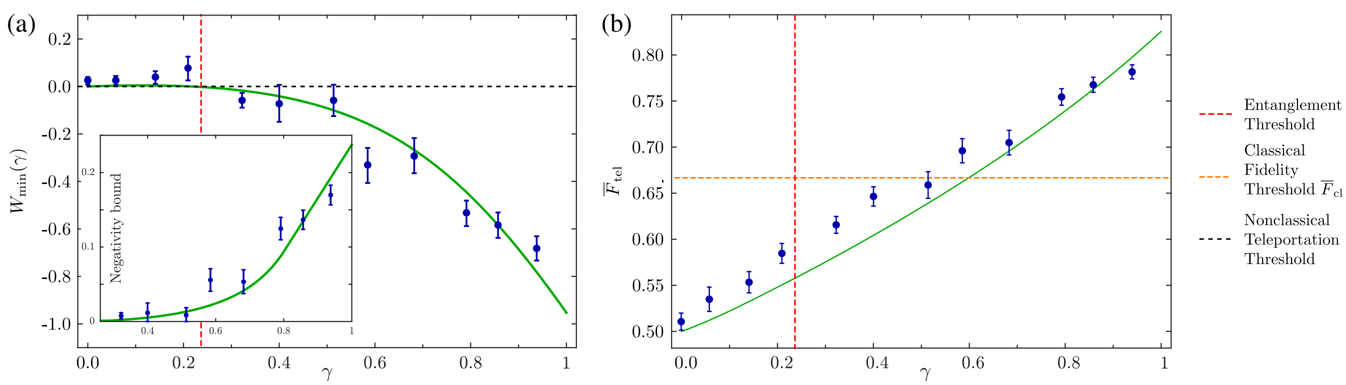

FIG. 4. Experimental application of teleportation witness. (a) Optimized witness as a function of the channel parameter γ, corresponding to the dots in Fig. 3(b). Green line represents the theoretical prediction of $W_{\min}(\gamma)$, accordingly to our noise model (for more information, see the Supplemental Material [43]), whereas blue points show the optimal experimental values of the witness. The black dashed line is the classical teleportation threshold (i.e., the maximal value of $W_{\min}(\gamma)$ necessary to certify nonclassical teleportation), whereas the red dashed line represents the minimal value of γ needed to have an entangled teleportation channel, given our noise model. Inset: The optimal estimated negativity for each value of γ. Green line represents the theoretical prediction, whereas blue points show the experimental value. We stress that for each γ a different θ is used to achieve the best witness violation and the best negativity estimate. (b) Average fidelity of teleportation estimation when considering the outcome $|\psi^-\rangle$. The green line shows the theoretical estimation for the mean value curve $\bar{F}_{\text{tel}}$ (given our noise model), whereas blue points depict the experimental values. The red dashed line represents the minimum value of γ necessary to have entanglement in the teleportation channel, whereas the orange dashed line shows $\bar{F}_{\text{cl}}$, the classical fidelity of teleportation bound. Error bars indicate one standard deviation of uncertainty, due to Poissonian statistics.

remote state preparation (i.e., by performing projective measurement on photon 1) and teleporting it to Bob by performing a partial Bell state measurement (BSM) on photons 2 and 3. BSM is implemented with an in-fiber 50/50 beam splitter followed by polarization analysis on each of the two outputs. Bell states $|\psi^-\rangle$ will be identified by twofold coincidences from different output arms. We address the "robustness" of the witness by considering the six eigenstates of the Pauli matrices $\{\psi_x^{A_0}\}_{x=0}^5$ as the possible states to be teleported. We measured different basis combinations of the teleported states $\rho^{\mathrm{B}}_{a|\psi_x}$ and used this data to experimentally estimate the value of $W(\gamma,\theta)$.

Figure 3(a) shows the theoretical expectations for the same set of states and parameters for comparison. Experimental results (black points) are shown in Fig. 3(b), where the estimated value of $W(\gamma,\theta)$ is plotted as a function of the parameter θ and for different levels of noise γ. The estimated dashed lines of Fig. 3(b) were obtained with our noise model and varying the θ parameter. As expected the witness certifies the nonclassicality of the channel even in those cases when the average fidelity of teleportation is lower than classical fidelity. This is shown in detail in Figs. 4(a) and 4(b).

In Fig. 4(a) are reported the optimal values of W for fixed values of γ. Blue points show the experimental results, obtained evaluating $W(\gamma,\theta)$ for different γ-s and numerically minimizing over the parameter θ. As expected, only those points with γ higher than the estimated entanglement threshold (red dashed line) have $W_{\min}(\gamma) < 0$, and thus show nonclassical teleportation behavior. The data are in good agreement with the theoretical values of $W_{\min}(\gamma)$ (green line) which are expected given our noise model (see the Supplemental Material [43]). To have a direct comparison with the teleportation witness, we plot in Fig. 4(b) the estimated average fidelity of teleportation for the same set of experimental points while in the Supplemental Material [43] can be found the average fidelity considering both outcomes $|\psi^{\pm}\rangle$. Finally, as an inset to Fig. 4(a), we show the optimal lower bound on negativity of the underlying shared state based on the witness violations for different values of γ.

Discussion.—Our work experimentally demonstrates the usefulness of teleportation witnesses, recently introduced in [38], to detect nonclassical teleportation in realistic situations. We started with the generation of a general family of the two-qubit state unable to display a $\bar{F}_{\mathrm{tel}}$ within the quantum regime. We tuned the amount of noise in our states in order to test the properties of the nonclassical witness for different values of γ and θ and establishing in this way a direct and general link between the expected properties and our experimental results. Moreover, we experimentally showed that beyond a certain noise threshold one can enter a region where the standard benchmark of the average fidelity is useless to certify a quantum channel while our witness can, thus, provide an experimental tool with fundamental implications in quantum information protocols, which can also lead to new applications in quantum technologies.

This work was supported by the ERC-Starting Grant 3D-QUEST (3D-Quantum Integrated Optical Simulation; Grant No. 307783), ERC CoG QITBOX, Ramón y Cajal fellowship (Spain), COST project CA16218 NANOCOHYBRI, Spanish MINECO (Grant No. QIBEQI FIS2016-80773-P and Severo Ochoa Grant No. SEV-2015-0522), Fundacio Cellex, AXA chair in Quantum Information Science, Generalitat de Catalunya (Grant No. SGR875 and CERCA Program), and the Royal Society (URF UHQT). G. C. thanks Becas Chile and Conicyt for support from a fellowship.

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