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Quantum vampire: collapse-free action at a distance by the photon annihilation operator

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An absorber placed into a laser beam is expected to cast a shadow. This expectation is confirmed not only by research, but also by our everyday experience. However, the shadow will not be produced if a weak absorber is *known with certainty* to have removed a photon from an optical state. We show this effect by distributing a state of light, via a beam splitter, between two parties. When one of the parties applies the photon annihilation operator to its portion of the state, the photon gets removed from the entire initial state, leaving the spatial and temporal structure of its mode undisturbed. In this way, the local application of the photon annihilation operator has a nonlocal effect, occurring without local state collapse by either party.

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One of the most intriguing and fundamental aspects of quantum mechanics is nonlocality. Discovered about 80 years ago, it became a basis for a lot of fundamental research and practical applications. To date, most studies of quantum action at a distance were based on the local application of the projection measurement of the von Neumann type to an entangled state initially shared between two or more parties. On application of the projection operator, the state collapses, modifying the physical reality at a remote location in a nonlocal fashion. Here we implement action at a distance with a local operation of a different type—the photon annihilation operator, applied by one of the remote parties to its portion of a shared optical state. Unlike von Neumann measurements, the annihilation operator does not collapse a quantum state, but only modifies it. One would intuitively expect this modification to be of local nature, affecting only the optical mode to which it is applied. However, as we find both theoretically and experimentally, the action of the annihilation is sometimes global, removing the photon from the entire state.

Consider state $|\psi\rangle$ prepared in an optical mode defined by the photon annihilation operator $\hat{a}$; we assume all modes orthogonal to $\hat{a}$ to be in the vacuum state. This state is distributed, by means of a beam splitter, between remote parties Alice and Bob in modes $\hat{a}_1$ and $\hat{a}_2$ such that $\hat{a} = \mu\hat{a}_1 + \lambda\hat{a}_2$, with $|\mu|^2$ and $|\lambda|^2$ being the nonvanishing beam splitter reflectivity and transmissivity, respectively [Fig. 1(a)]. Unless $|\psi\rangle$ is a coherent state or a statistical mixture thereof, this operation generates a state that is entangled with respect to the two parties [1].

Now suppose Alice applies the photon annihilation operator to her mode. We have

$$\hat{a}_1|\psi\rangle_{\hat{a}} = (\mu^*\hat{a} + \lambda\hat{a}_\perp)|\psi\rangle_{\hat{a}} = \mu^*\hat{a}|\psi\rangle_{\hat{a}}, \quad (1)$$

where $\hat{a}_\perp = \lambda^*\hat{a}_1 - \mu^*\hat{a}_2$ is the annihilation operator of a mode orthogonal to $\hat{a}$. Because this mode is in the vacuum state, the action of its annihilation operator produces arithmetic zero. We see that the annihilation operator, albeit applied locally, acts upon the entire state $|\psi\rangle$ shared between the two parties.

Suppose, for illustration, that a cloud of weakly absorbing atoms is placed in a wide optical beam in mode $\hat{a}$ as shown in Fig. 1(b) [2]. The mean probability of atoms to absorb a photon is much less than 1. When an absorption event does occur, it is followed by the re-emission of a photon in a random direction, registered by a detector. A "click" of this detector signifies the application of photon annihilation to the mode $\hat{a}_1$ corresponding to the atomic cloud. One would expect the atoms to create a "shadow"—an area of reduced

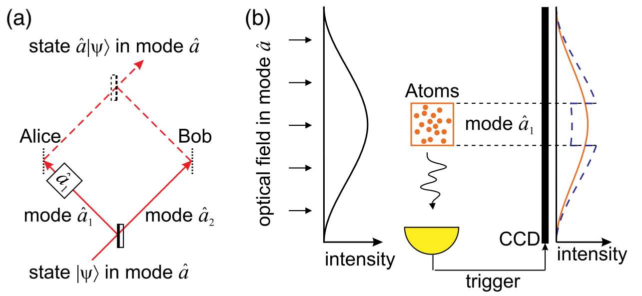

Fig. 1. The quantum vampire effect. (a) When state $|\psi\rangle$ in the mode defined by the annihilation operator $\hat{a}$ is split between two remote parties, the application of the photon annihilation operator $\hat{a}_1$ by one of these parties affects the state $|\psi\rangle$ globally. This can be verified by recombining the modes $\hat{a}_1$ and $\hat{a}_2$ on another beam splitter and analyzing the state in the output. (b) Implementation with a cloud of absorptive atoms. The detection of a re-emitted photon heralds a photon annihilation event and triggers the recording of the image on a CCD camera. Photon subtraction will not cast a shadow on the resulting quantum state, so its intensity distribution (solid orange line) does not change. This contrasts with regular linear absorption, which would cause a local shadow to appear in the intensity distribution (dashed blue line).

intensity—in the laser beam. In fact, this does not happen; the intensity gets reduced uniformly over the entire laser profile, so mode $\hat{a}$ retains its structure. It is impossible to recover the position and shape of the atom cloud by looking at the output state of light. Hence the analogy with the folklore vampire that gave rise to the title of this Letter.

The above argument may appear to contradict our everyday experience of observing shadows. The explanation is that shadows are caused by absorption of light, which is not equivalent to the annihilation operator. Rather, it is described by a Lindbladian $\partial\hat{\rho}/\partial z \propto \hat{a}_1\hat{\rho}\hat{a}_1^\dagger - (\hat{\rho}\hat{a}_1\hat{a}_1^\dagger + \hat{a}_1\hat{a}_1^\dagger\hat{\rho})/2$ (where $\hat{\rho}$ is the density operator of the state being attenuated and z is the direction of propagation), which contains both annihilation and creation operators. The latter, unlike the former, does not possess the nonlocal property described above: $a_1^\dagger|N\rangle_a \not\propto |N+1\rangle_a$ [3].

Importantly, the cloud of atoms in Fig. 1(b) must be weakly absorbing in order to implement the annihilation operator correctly. The cloud is not expected to affect the input state significantly or cast a shadow when it is being monitored without conditioning on the detector's click. However, when a click does occur, the state $|\psi\rangle$ is known to have lost a photon. If it initially contains only a few photons, the relative loss of energy is significant. One would intuitively expect this loss to take the form of a shadow—and yet, it is not the case.

The action-at-a-distance of the photon annihilation operator can be made explicit by observing its effect on the mean number of photons in Bob's mode. If we start with Fock state $|N\rangle$ in mode $\hat{a}$, the photons are distributed between the modes $\hat{a}_1$ and $\hat{a}_2$ in proportion with the beam splitter coefficient, so Bob's channel has $N|\lambda|^2$ photons on average. After Alice's application of $\hat{a}_1$, the state in mode $\hat{a}$ becomes $|N-1\rangle$, so the mean number of photons in Bob's mode changes, becoming $(N-1)|\lambda|^2$.

This observation does not imply superluminal signaling because photon annihilation is not a unitary operation, and as such can be realized only probabilistically. It is typically implemented by tapping a small portion of the target state onto a single-photon detector via a low-reflectivity beam splitter. A "click" of the detector signifies a photon annihilation event [4–10]. One may argue that such a setting involves a measurement of the target mode and the nonlocal properties are thus not surprising. However, a fundamental difference between this implementation of the photon annihilation and regular von Neumann measurement is that in our case no collapse of the target state occurs.

We demonstrate the quantum vampire effect experimentally, with modes $\hat{a}_1$ and $\hat{a}_2$ being, respectively, the horizontal and vertical polarization components of the diagonally polarized mode $\hat{a}$. This corresponds to $\mu = \lambda = 1/\sqrt{2}$.

Mode $\hat{a}$ is initialized in a heralded Fock state. Type-II parametric downconversion takes place in a periodically poled potassium titanyl phosphate crystal pumped at 390 nm with frequency-doubled pulses generated by a Ti:sapphire laser with a repetition rate of 76 MHz and a pulse width of ∼1.8 ps. Clicks of one or two single-photon detectors (silicon-based single-photon counting module by Excelitas, $SPCM_1$ and $SPCM_2$ in Fig. 2) in the idler channel herald the synthesis of the one- or two-photon Fock state, respectively, in the horizontal polarization of the signal channel [11,12]. The heralded state is turned to a 45° polarization using a $\lambda/2$ wave plate.

The annihilation operator is realized using a strongly imbalanced partially polarizing beam splitter (PPBS). It employs a regular dielectric mirror coated for high reflectivity at a 45° angle of incidence. The mirror is positioned to form an angle of incidence of ∼60° with the incoming mode. The S polarization then still exhibits high reflection (>99.8%), whereas in

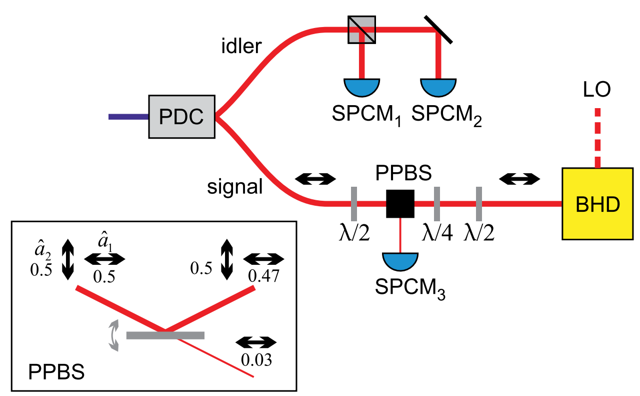

Fig. 2. The experimental setup. Mode $\hat{a}$ is prepared in the signal output of parametric downconversion in either the one- or two-photon Fock state. The wave plates form a Mach–Zehnder interferometer in the polarization basis, with the modes $\hat{a}_1$ and $\hat{a}_2$ being its horizontally and vertically polarized arms, respectively. Photon subtracted from mode $\hat{a}_1$ on the PPBS. Its improvised realization is shown in the inset, with arrows and numbers indicating the polarizations of modes and their normalized intensities. The PPBS transmission, which is a compromise between the count rate and the fidelity of subtraction, can be tuned by tilting the mirror. BHD, balanced homodyne detection [13]; LO, local oscillator; SPCM, single-photon counting module.

the P polarization, about 6% of the incident light is transmitted. The transmitted field is collected and detected using $SPCM_3$, so a click of that detector heralds with a high probability a photon annihilation event. Triple coincidences occur at a relatively low rate of ~10 counts per minute.

The polarization of the reflected light is then adjusted by a combination of a $\lambda/4$ and a $\lambda/2$ plate, thereby returning mode $\hat{a}$ to horizontal polarization and completing the Mach–Zehnder interferometer in Fig. 2. We verify the vampire effect by measuring the state of mode $\hat{a}$ at the output of the interferometer using homodyne tomography [14].

We use the quadrature statistics acquired by the homodyne detector to reconstruct the diagonal elements of the corresponding density matrix. To that end, we apply the maximum-likelihood algorithm [15,16] with loss compensation. The overall efficiency of the reconstruction is ~53%; in addition to the usual loss sources [17,18], an ~3% loss occurs on the PPBS [19]. In the absence of a click from $SPCM_3$, the state transmitted through the interferometer is the one- or two-photon Fock state, as evidenced by the left plots in Fig. 3(a) or 3(b), respectively.

When $SPCM_3$ fires simultaneously with $SPCM_1$ and/or $SPCM_2$, photon subtraction from mode $\hat{a}_1$ occurs. Quadrature histograms acquired in the experiment and reconstructed density matrices are shown in Fig. 3 in the right column. Photon annihilation leaves mode $\hat{a}$ in the almost pure next lower Fock state, detected with the same efficiency. This indicates that the photon has been subtracted from the entire mode $\hat{a}$ without affecting its structure, as predicted theoretically.

In order to generate heralded two-photon Fock states at a reasonable rate, the parametric downconversion setup had to be operated with a relatively high pair production probability per pulse. As a result, counts of $SPCM_3$ sometimes occur even in the absence of clicks in $SPCM_1$ and $SPCM_2$. These background counts are the main reason for the observed imperfection in the photon subtraction. In the case of the two-photon initial state [Fig. 3(b)], we found the probability of a background click of $SPCM_3$ to be $p_{bg} = 6 \times 10^{-4}$ per pulse, whereas conditioned on clicks in $SPCM_1$ and $SPCM_2$, the probability of a click in $SPCM_3$ is $p_{sub} = 1.2 \times 10^{-2}$. Therefore, in the event that $SPCM_1$ and $SPCM_2$ do fire, a fraction $p_{bg}/p_{sub} = 0.05$ of $SPCM_3$ clicks occur due to background emission, in which case no annihilation is present. This brings about a 5% two-photon component in the density matrix. The case of Fig. 3(a) is analogous.

For comparison, we also show in the right column in Fig. 3 a prediction based on the complete absorption of the light in mode $\hat{a}_1$ (horizontally polarized arm of the interferometer), so no nonlocal photon annihilation is taking place. As expected, this prediction is inconsistent with the experimental data.

The nonlocal property of the photon annihilation operator demonstrated here is of generic nature. It is expected to hold for optical modes in any basis (temporal, spatial, spectral, etc.). It also remains valid when multiple annihilation operators are applied to mode $\hat{a}_1$ in series. Importantly, the effect does not require entanglement between the modes $\hat{a}_1$ and $\hat{a}_2$, which is present only when the initial state in mode $\hat{a}$ is nonclassical. For example, if we start with a coherent state $|\alpha\rangle$, the states in modes $\hat{a}_1$ and $\hat{a}_2$ are also coherent, with amplitudes $\mu\alpha$ and $\nu\alpha$, respectively. The coherent state is an eigenstate of the operator $\hat{a}_1$, and hence, applying this operator will not change the output state.

The vampire effect is also expected for bosonic systems other than optical. A related phenomenon, for instance, is known to occur in Bose–Einstein condensates: when a set of atoms is extracted locally from the condensate, the shape of the matter wave does not change.

We expect the quantum vampire effect to find applications in quantum information technology. For example, it enables the nonlocal manipulation of quantum states without precise knowledge of their modes, such as in protocols for the distillation of continuous-variable entanglement by photon annihilation [6,10,20]. The ability to "steal" a photon without casting a shadow may prove useful for eavesdropping in quantum key distribution, as well as for developing quantum cloaking devices. We also believe the effect to be of fundamental interest, as quantum action at a distance that is not associated with a local state collapse has not yet been studied.

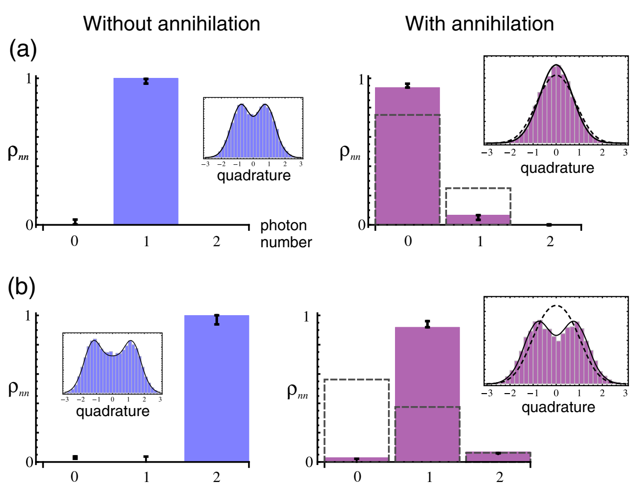

Fig. 3. Experimental results for the initial state of mode $\hat{a}$ being (a) the one-photon and (b) the two-photon Fock state. The left column corresponds to the case without photon annihilation, whereas the right column shows the result of the photon annihilation operator applied to mode $\hat{a}_1$ (i.e., conditioned on $SPCM_3$ events). In each panel, the experimentally observed quadrature distributions and reconstructed diagonal elements of the density matrix are displayed together with those expected theoretically (see Supplement 1 for calculation details). The dashed lines in the right column show, for comparison, the results that would be observed if mode $\hat{a}_1$ were completely absorbed rather than subjected to photon annihilation. The error bars for the experimentally reconstructed density matrices are obtained via bootstrapping.

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See Supplement 1 for supporting content.

REFERENCES AND NOTES

1. Z. Jiang, M. D. Lang, and C. M. Caves, Phys. Rev. A **88**, 044301 (2013).
2. B. Q. Baragiola, R. L. Cook, A. M. Brańczyk, and J. Combes, Phys. Rev. A **86**, 013811 (2012).
3. This can be seen easily from Eq. (1): if $\hat{a}$ is replaced with $\hat{a}^\dagger$, the term $\lambda\hat{a}_\perp^\dagger|\psi\rangle_{\hat{a}}$ no longer vanishes.
4. J. Wenger, R. Tualle-Brouri, and P. Grangier, Phys. Rev. Lett. **92**, 153601 (2004).
5. A. Ourjoumtsev, R. Tualle-Brouri, J. Laurat, and P. Grangier, Science **312**, 83 (2006).
6. A. Ourjoumtsev, A. Dantan, R. Tualle-Brouri, and P. Grangier, Phys. Rev. Lett. **98**, 030502 (2007).
7. H. Takahashi, K. Wakui, S. Suzuki, M. Takeoka, K. Hayasaka, A. Furusawa, and M. Sasaki, Phys. Rev. Lett. **101**, 233605 (2008).
8. A. Ourjoumtsev, F. Ferreyrol, R. Tualle-Brouri, and P. Grangier, Nat. Phys. **5**, 189 (2009).
9. R. Kumar, E. Barrios, C. Kupchak, and A. I. Lvovsky, Phys. Rev. Lett. **110**, 130403 (2013).
10. Y. Kurochkin, A. S. Prasad, and A. I. Lvovsky, Phys. Rev. Lett. **112**, 070402 (2014).
11. A. Ourjoumtsev, R. Tualle-Brouri, and P. Grangier, Phys. Rev. Lett. **96**, 213601 (2006).
12. E. Bimbard, N. Jain, A. MacRae, and A. I. Lvovsky, Nat. Photonics **4**, 243 (2010).
13. R. Kumar, E. Barrios, A. MacRae, E. Cairns, E. H. Huntington, and A. I. Lvovsky, Opt. Commun. **285**, 5259 (2012).
14. A. I. Lvovsky and M. G. Raymer, Rev. Mod. Phys. **81**, 299 (2009).
15. A. I. Lvovsky, J. Opt. B **6**, S556 (2004).
16. J. Řehàček, Z. Hradil, E. Knill, and A. I. Lvovsky, Phys. Rev. A **75**, 042108 (2007).
17. A. I. Lvovsky, H. Hansen, T. Aichele, O. Benson, J. Mlynek, and S. Schiller, Phys. Rev. Lett. **87**, 050402 (2001).
18. S. R. Huisman, N. Jain, S. A. Babichev, F. Vewinger, A. N. Zhang, S. H. Youn, and A. I. Lvovsky, Opt. Lett. **34**, 2739 (2009).
19. Mode $\hat{a}$ is split equally between the horizontal and vertical polarizations; so the 6% transmissivity of the PPBS for the horizontal polarization implies a 3% mean loss for mode $\hat{a}$.
20. H. Takahashi, J. S. Neergaard-Nielsen, M. Takeuchi, M. Takeoka, K. Hayasaka, A. Furusawa, and M. Sasaki, Nat. Photonics **4**, 178 (2010).