Accuracy of a teleported trapped field state inside a single bimodal cavity

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We propose a simplified scheme to teleport a superposition of coherent states from one mode to another of the same bimodal lossy cavity. Based on current experimental capabilities, we present a calculation of the fidelity that can be achieved, demonstrating accurate teleportation if the mean photon number of each mode is at most 1.5. Our scheme applies as well for teleportation of coherent states from one mode of a cavity to another mode of a second cavity, when both cavities are embedded in a common reservoir.

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The teleportation phenomenon [1] has received increasing attention, and a number of protocols have been suggested for its implementation in various contexts, for example running waves [2,3] and cavity QED [4]. Experimentally, teleportation has been demonstrated for discrete variables [5–9], and for a single mode of an electromagnetic field with continuous variables [10,11]. More recently, teleportation between matter and light was announced [12], where matter and light are, respectively, the stationary and flying media.

In the realm of cavity QED, schemes for teleportation of two-particle entangled atomic states [13], multiparticle entangled atomic states, and also entangled field states inside high-Q cavities [14–16] have been proposed. Although these foregoing schemes using high-Q cavities represent advances by simplifying the procedures required to teleport states of cavity modes, all experiments implemented until now have involved only a single high-Q cavity, for reasons related to complex experimental challenges such as decoherence and the difficulty of controlling the interactions. Nonetheless, the cavity is undoubtedly an important scenario for testing fundamentals of quantum mechanics [17] as well as for demonstrating quantum-information processing [18]; hence, experiments involving teleportation—the cornerstone of universal quantum computation [19]—are expected to be reported soon in the context of a high-Q cavity. Aiming at this goal, our group recently proposed a simplified scheme to teleport a superposition of zero- and one-photon states [20], which makes use of only a single bimodal high-Q cavity, the teleportation occurring from one mode to another inside the high-Q cavity. Pursuing this idea, here we propose an oversimplified scheme to teleport a trapped field state with continuous spectra, the mesoscopic superposition on Schrödinger-cat-like state (SCS). The experimental setup is shown in Fig. 1. As in Ref. [20], our scheme uses only one bimodal cavity, supporting mode 1 and mode 2, and two two-level atoms, comprehending the circular states $|g\rangle$ and $|e\rangle$, plus Ramsey zones and selective atomic state detectors. The Hamiltonian including the required dispersive interaction between an atom and the dissipating cavity field is $H=H_0+H_I$, where

$$H_0=\sum_{i=1}^{2}\hbar\omega_i a_i^\dagger a_i+\sum_k \hbar\omega_k b_k^\dagger b_k+\frac{\hbar\omega_0}{2}\sigma_z+\sum_{i=1}^{2}\hbar a_i^\dagger a_i\chi_i\sigma_{ee}, \tag{1}$$

$$H_I=\sum_k \hbar(\lambda_{1k}a_1^\dagger b_k+\lambda_{1k}^* a_1 b_k^\dagger)+\sum_k \hbar(\lambda_{2k}a_2^\dagger b_k+\lambda_{2k}^* a_2 b_k^\dagger). \tag{2}$$

Here $\sigma_{ee}=|e\rangle\langle e|$, $a_i^\dagger$ and a_i are, respectively, the creation and annihilation operators for the ith cavity mode of frequency ω_i, and $b_k^\dagger$ and b_k are the analogous operators for the kth reservoir oscillator mode, whose corresponding frequency and coupling with the mode $i=1,2$ are ω_k and λ_{ik}. The atom-field coupling parameter $\chi_i=g^2/\delta_i$ will always be adjusted to ensure $g^2\tau/\delta_i=\pi$, where g is the Rabi frequency, τ is the atom-field interaction time, and $\delta_i=(\omega_i-\omega_0)$ is the detuning between the field frequency ω_i and the atomic frequency ω_0. The evolution outside the cavity occurs with $\chi_i=0$. It is important to note that the last term in Eq. (1) involving χ_i will be effective only with one mode at a time. Thus, while the interaction of an atom with mode 1 (2) of the cavity field is taking place, the relative phase due to dispersive interaction of this atom with mode 2 (1) of the cavity field will be negligible. This is true provided that the difference Δ be-

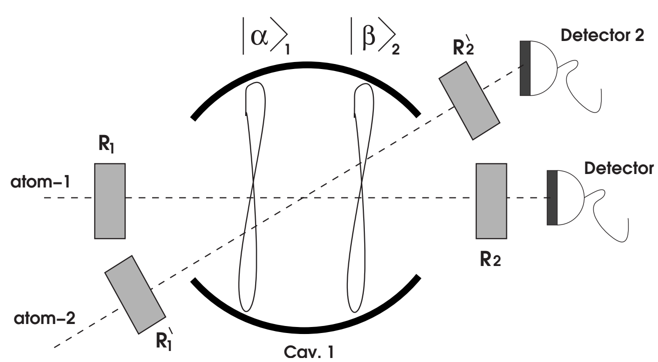

FIG. 1. Experimental setup for engineering and teleporting a Schrödinger cat state inside a bimodal cavity. The Ramsey zones R_1, R_2 (R_1', R_2') and atom 1 (atom 2) are necessary for preparing (teleporting) the SCS.

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tween the two modes is large enough. In addition, to simplify our estimation of the fidelity of the teleported SCS, we will assume that the atom-field coupling is turned on (off) suddenly at the instant the atom enters (leaves) the cavity.

The evolution of coherent states governed by the Heisenberg equations corresponding to Eqs. (1) and (2) are given in detail in Ref. [21]. Here, for brevity, we collect only the main results, assuming a reservoir at absolute zero temperature, which is an excellent approximation [17]. The results of interest for modes $j=1,2$ are

$$a_1(t) = \sum_{j=1}^{2} u_{1j}(t)a_j(0) + \sum_k \vartheta_{1k}(t)b_k(0), \quad (3)$$

$$a_2(t) = \sum_{j=1}^{2} u_{j2}(t)a_j(0) + \sum_k \vartheta_{2k}(t)b_k(0), \quad (4)$$

where

$$u_{11}(t) = \exp\left(-\frac{(A+B)}{2}t\right) \times\left[\frac{(B-A)}{\sqrt{(B-A)^2+4CD}}\sinh\left(\sqrt{\frac{(B-A)^2+4CD}{2}}t\right) + \cosh\left(\sqrt{\frac{(B-A)^2+4CD}{2}}t\right)\right], \quad (5)$$

$$u_{12}(t) = -\exp\left(-\frac{(A+B)}{2}t\right) \times\left[\frac{2C}{\sqrt{(B-A)^2+4CD}}\sinh\left(\sqrt{\frac{(B-A)^2+4CD}{2}}t\right)\right], \quad (6)$$

and

$$A = i(\omega_1 + \chi + \Delta\omega_1) + \gamma_{11}/2, \quad (7)$$

$$B = i(\omega_2 + \chi + \Delta\omega_2) + \gamma_{22}/2, \quad (8)$$

$$C = i\Delta\omega_{12} + \gamma_{12}/2, \quad (9)$$

$$D = i\Delta\omega_{21} + \gamma_{21}/2. \quad (10)$$

The $\gamma_{jj'}$ and $\Delta\omega_{jj'}$, $j,j'=1,2$, as explained in Ref. [21], are the damping rates and the Lamb shifts for the two modes, obtained through the Wigner-Weisskopf approximation [22] $\Sigma_k[\lambda_{kj}^*\lambda_{kj'}/(s+i\omega_k)] \rightarrow i\Delta\omega_{jj'}+\gamma_{jj'}/2$; $\Delta\omega_j \equiv \Delta\omega_{jj}$; $u_{21}(t)$ and $u_{22}(t)$ can be obtained from $u_{12}(t)$ and $u_{11}(t)$, respectively, by simply swapping A and B; and $\vartheta_{jk}(t)$ is an unimportant function when the reservoir is kept at zero temperature. Equations (3)–(10) can be further simplified by assuming the following experimental parameters, in the microwave domain. For the field mode damping times, $\gamma_{11}^{-1}=10^{-3}$ s and $\gamma_{22}^{-1}=0.9\times10^{-3}$ s, corresponding, respectively, to modes 1 and 2, whose frequencies obey the relation $\omega_2=\omega_1+\Delta$, where $\Delta/2\pi$ can be adjusted in the range 100 kHz–2 MHz [24]. The two-level atom must be prepared in such a way that the frequency ω_0 of the atomic transition $|e\rangle \rightarrow |g\rangle$, when the atom enters the cavity, is detuned from mode 1 by $\delta=\omega_1-\omega_0$ and satisfying the condition $g\bar{n} \ll \delta+\kappa$, where κ is the rate of spontaneous emission and $\bar{n}$ is the mean photon number in mode 1. This condition thus implies, for the detuning with mode 2, $g\bar{n} \ll \Delta+\delta+\kappa$. Experimentally, the atomic frequency can be Stark shifted using a time-varying electric field to detune the atomic frequency with each mode [24] by the large amount Δ. As an example, let us consider an experimental setup prepared obeying $\delta \sim 10^5$ Hz, $g \sim 10^4$ Hz, $\Delta \sim 10^7$ Hz. Then, the interaction with mode 2 (which we are assuming as possessing higher frequency), will also be dispersive, and when the atom–mode 1 interaction produces a π pulse, the coherent state in mode 2 will evolve according to $|\beta\rangle \rightarrow |e^{i\phi}\beta\rangle \sim |\beta\rangle$, with $\phi=g^2t/(\Delta+\delta) \sim 0.03$, which we take into account when calculating the fidelity. Further, we can assume the cross-damping rates γ_{12} and γ_{21}, taking as maximum values those of each mode separately, i.e., γ_{12}, $\gamma_{21} \sim 10^3$ s^{-1} [26]. With these assumptions, and taking into account the dispersive interaction in Eq. (1), Eqs. (5) and (6) are simplified as follows: $u_{12}(t)=u_{21}(t)\cong 0$. When the atom is out of or enters the cavity in the ground state, $u_{11}(t)=\exp[(-\bar{\gamma}/2-i\omega_1)t]$ and $u_{22}(t)=\exp[(-\bar{\gamma}/2-i\omega_2)t]$. When the atom is in the cavity in the excited state, $u_{11}(t)=\exp\{[-\bar{\gamma}/2-i(\omega_1+\chi)]t\}$ and $u_{22}(t)=\exp[(-\bar{\gamma}/2-i\omega_2)t]$ when the atom is interacting with mode 1; or $u_{11}(t)=[(-\bar{\gamma}/2-i\omega_1)t]$ and $u_{22}(t)=\exp\{[-\bar{\gamma}/2-i(\omega_2+\chi)]t\}$ when the atom is interacting with mode 2. Here $\bar{\gamma}=(\gamma_{11}+\gamma_{22})/2$, and therefore we have the important result that the damping rate for each of the two modes is simply the mean damping rate of the two modes.

Ideal process. The ideal SCS to be teleported is prepared by injecting a coherent state $|\beta\rangle_2$ into mode 2, assuming $\lambda_{ik}=0$ in Hamiltonian (2). Then a two-level atom 1 is laser excited and rotated in R_1 to an arbitrary superposition $C_+|e\rangle_1+C_-|g\rangle_1$. After that, atom 1 crosses the cavity, having been velocity selected to interact off resonantly with mode 2 such that $\chi\tau=\pi$, where τ is the atom-field interaction time. Atom 1 then crosses R_2, undergoing a $\pi/2$ pulse, and is detected, inducing a collapse of the cavity field to the even (+) or odd (−) SCS, $C_+|\beta\rangle_2 \pm C_-|-\beta\rangle_2$, where C_+ and C_- are unknown coefficients obeying $|C_+|^2+|C_-|^2=1$. The + (−) sign occurs if atom 1 is detected in the state $|g\rangle_1$ ($|e\rangle_1$). From now on let us suppose that the even SCS has been prepared.

The procedure to teleport the SCS is as follows. First, atom 2 crosses the Ramsey zone R_1', undergoing a $\pi/2$ pulse, as shown in Fig. 1, being rotated to the superposition $\sqrt{\frac{1}{2}}(|e\rangle_2+|g\rangle_2)$. Assuming mode 1 has previously been prepared in the coherent state $|\alpha\rangle_1$, the whole state of the system is

$$|\varphi\rangle = \frac{1}{\sqrt{2}}(|e\rangle_2 + |g\rangle_2)|\alpha\rangle_1(C_+|\beta\rangle_2 + C_-|-\beta\rangle_2). \quad (11)$$

Next, atom 2 interacts off resonantly with mode 1, such that $\chi\tau=\pi$, resulting in

$$|\psi\rangle = \frac{1}{\sqrt{2}}(C_+|e\rangle_2|-\alpha\rangle_1|\beta\rangle_2 + C_+|g\rangle_2|\alpha\rangle_1|\beta\rangle_2 + C_-|e\rangle_2|-\alpha\rangle_1|-\beta\rangle_2 + C_-|g\rangle_2|\alpha\rangle_1|-\beta\rangle_2). \quad (12)$$

Soon after the atom 2 and mode 1 interaction, which leads to Eq. (12), the Stark shift is switched to a large detuning $\delta=(\omega_a-\omega_0)$, thus freezing the evolution corresponding to mode 1, and, at the same time, initiating the atom 2 and mode 2 interaction. The result, after this interaction, is

$$|\chi\rangle = \frac{1}{\sqrt{2}}(C_+|e\rangle_2|-\alpha\rangle_1|-\beta\rangle_2 + C_+|g\rangle_2|\alpha\rangle_1|\beta\rangle_2 + C_-|e\rangle_2|-\alpha\rangle_1|\beta\rangle_2 + C_-|g\rangle_2|\alpha\rangle_1|-\beta\rangle_2). \quad (13)$$

After crossing the bimodal cavity, atom 2 crosses the Ramsey zone R_2' undergoing a $\pi/2$ pulse, such that Eq. (13) evolves to

$$|\vartheta\rangle_{2ab} = \frac{1}{2}[|e\rangle_2|-\beta\rangle_2(C_+|-\alpha\rangle_1 - C_-|\alpha\rangle_1) + |e\rangle_2|\beta\rangle_2(-C_+|\alpha\rangle_1 + C_-|-\alpha\rangle_1) + |g\rangle_2|\beta\rangle_2(C_+|\alpha\rangle_1 + C_-|-\alpha\rangle_1) + |g\rangle_2|-\beta\rangle_2(C_+|-\alpha\rangle_1 + C_-|\alpha\rangle_1)]. \quad (14)$$

Therefore, by detecting atom 2 and measuring the phase of the field in mode 2, the field state in mode 1 is projected onto one of the four possibilities allowed by Eq. (14). Assuming atom 2 being detected in its ground state, the phase of the field in mode 2 can be measured by injecting a reference field of known amplitude β into mode 2, which makes the field states $|\beta\rangle_2$ and $|-\beta\rangle_2$ in Eq. (14) evolve, respectively, to the states $|2\beta\rangle_2$ and $|0\rangle_2$. Such states can then easily be distinguished by sending a stream of two-level atoms, all of them in the ground state $|g\rangle_s$, to interact resonantly with mode 2 of the cavity field. Thus, if at least one of these atoms is detected in its excited state $|e\rangle_s$, indicating the result $|g\rangle_2|\beta\rangle_2$ in Eq. (14), then mode 1 is projected exactly on the desired state $|\Psi\rangle_1=C_+|\alpha\rangle_1+C_-|-\alpha\rangle_1$, thus completing successfully the teleportation process. On the other hand, if the measurement result is always $|g\rangle_s$, indicating the result $|g\rangle_2|-\beta\rangle_2$ in Eq. (14), a second atom interacting off-resonantly with mode 1 leads to $C_+|-\alpha\rangle_1+C_-|\alpha\rangle_1 \rightarrow C_+|\alpha\rangle_1+C_-|-\alpha\rangle_1$. For measurements revealing the states $|e\rangle_2|-\beta\rangle_2$ and $|e\rangle_2|\beta\rangle_2$ in Eq. (14), the teleportation process cannot be completed unless additional cavities and/or atoms be introduced, thus overcomplicating the scheme. The teleportation is accomplished provided we let $\alpha=\beta$, and the probability of success for the ideal case is then limited to 50%.

Real process. In real processes, the state $|\Psi\rangle_1$ to be teleported will evolve under the influence of the reservoir, becoming a mixture $\rho(t)$ after tracing out the reservoir. To estimate losses in teleportation, we have to compute (i) the known value of the reference field $\beta(t)$ we have to inject in the cavity in order to obtain $D[\beta(t)]|\beta(t)\rangle_2=|2\beta(t)\rangle_2$, as remarked after Eq. (14), and (ii) the fidelity $\mathcal{F}={}_1\langle\Psi|\rho(t)|\Psi\rangle_1$ of the teleported SCS. To answer question (i), we have to compute the evolution $|\alpha(0)\rangle_1|\beta(0)\rangle_2|\{0\}\rangle_R \rightarrow |\Psi(t)\rangle_{12R}$ and then to trace out mode 1 and the infinite modes of the reservoir, denoted by $\{0\}$, in order to obtain $|\beta(t)\rangle_2$. Again, we quote the result in [21]: starting from the initial state $|\alpha(0)\rangle_1|\beta(0)\rangle_2|\{0\}\rangle_R$ we obtain $|\beta(0)\rangle_2 \rightarrow |\beta(t)\rangle_2$, where $\beta(t)\cong u_{22}(t)\beta(0)$, thus answering question (i). Note that the remarkable result that at zero temperature a coherent state loses excitation coherently remains valid, even when more than one mode is considered. To answer question (ii), we need the evolution of the teleported ideal state $|\Psi\rangle_1$ in the presence of mode 2 and the reservoir, i.e., we have to calculate the evolution of the combined state $|\Psi\rangle_1|\beta(0)\rangle_2|\{0\}\rangle_R = [C_+|\alpha\rangle_1|\beta(0)\rangle_2|\{0\}\rangle_R + C_-|-\alpha\rangle_1|\beta(0)\rangle_2|\{0\}\rangle_R]$, and, after that, to trace out mode 2 and the reservoir. This calculation differs from that in (i) only by the second term. The result is the mixed SCS

$$\rho_1(t) = N\{|u_{11}(t)\alpha_0\rangle_{11}\langle u_{11}(t)\alpha_0| + |-u_{11}(t)\alpha_0\rangle_{11}\langle -u_{11}(t)\alpha_0| + Z(t)[|u_{11}(t)\alpha_0\rangle_{11}\langle -u_{11}(t)\alpha_0| + \text{H.c.}]\}, \quad (15)$$

where H.c. means the Hermitian conjugate, $\alpha_0=\alpha(0)$, and $Z(t)=\exp\{-2|\alpha(0)|^2[1-|u_{11}(t)|^2]\}$ is the term responsible for decoherence. It is important to note that, while t in step (i) is the time spent preparing the SCS in mode 2, in step (ii) t is the time after the SCS is teleported to mode 1. Restricting ourselves to the joint measurement corresponding to $|g\rangle_a|\beta\rangle_2$, which is the only result promptly leading to teleportation without requiring additional unitary operations [see Eq. (14)], in about 25% of the trials the final teleported state will be exactly the original SCS *provided that we let* $\beta(0)=\alpha(0)$. According to [24], the time the atom spends inside the cavity is 40–50 μs, while the total flight time in the experiment is in the 300–400 μs range, which implies an error around 12% when, as is usually done, the time during which the atom interacts with the modes is neglected. Our calculation, however, is more realistic, since it takes into account the time taken by the atom to cross the cavity.

In Fig. 2 we present the fidelity for the teleported SCS, calculated with experimental parameters appropriate for

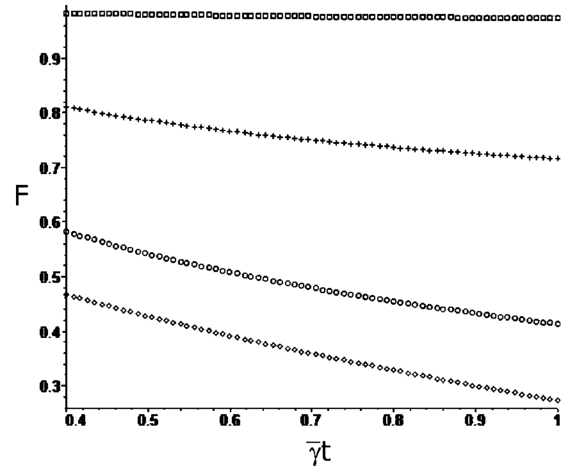

FIG. 2. Fidelity for the teleported SCS for $\alpha=0.5$, 1.0, 1.5, and 2.0. The SCS damping rate for each of the two modes is the mean damping rate value of the two modes. Here we used the experimental values $\gamma_{11}^{-1}=10^{-3}$ s and $\gamma_{22}^{-1}=0.9\times10^{-3}$ s for mode 1 and mode 2, respectively.

present-day technology [18,23,24]. Although these experimental parameters were quoted from experiments involving orthogonally polarized modes, the experimental capabilities such as the time-varying electric field for controllable Stark shifts, two-level Rydberg atoms, the value of the Rabi frequency g, and so on, are expected to work as well for non-orthogonally polarized modes of a same cavity. For orthogonally polarized modes, apart from a relative $\pi/2$ phase, each mode will couple with a different reservoir, and the dynamical fidelity for the prepared and teleported SCS in a given mode will depend solely on the presence of its corresponding reservoir, being independent of the second reservoir as well as of the excitation in the second mode [25]. Also, our scheme applies as well for teleportation of a SCS from one mode of a cavity to another mode of a second cavity, if both cavities are placed in the same reservoir. In this last case, our scheme will work irrespective of the difference $\Delta=\omega_2-\omega_1$.

Note from Fig. 2 that a successful realization of the teleportation process is obtained for α ranging from 0.5 to 1.0. However, while for $\alpha=0.5$ the fidelity remains around unity for all times, for $\alpha=1.0$ the fidelity decays to around 0.85 by the time teleportation is completed, reaching the lowest value 0.7 at long times, still a significantly high value. For $\alpha=1.5$, the fidelity of the SCS by the time the teleportation is concluded is around 0.6, higher than the classical limit 0.5, showing that the teleported SCS has not been substantially degraded. On the other hand, our result shows that teleportation fails for $\alpha\geq 2.0$ given current experimental capabilities. Note that, although we have calculated a conditional fidelity, i.e., the fidelity resulting from 25% of the trials, it would be possible to recover, from any of the measurement results, the original SCS to be teleported, at the expense of introducing additional cavities and/or atoms. However, this procedure would demand considerable effort, in itself decreasing the fidelity of the teleportation process and overcomplicating the present protocol.

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