Exponentially Enhanced Light-Matter Interaction, Cooperativities, and Steady-State Entanglement Using Parametric Amplification

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We propose an experimentally feasible method for enhancing the atom-field coupling as well as the ratio between this coupling and dissipation (i.e., cooperativity) in an optical cavity. It exploits optical parametric amplification to exponentially enhance the atom-cavity interaction and, hence, the cooperativity of the system, with the squeezing-induced noise being completely eliminated. Consequently, the atom-cavity system can be driven from the weak-coupling regime to the strong-coupling regime for modest squeezing parameters, and even can achieve an effective cooperativity much larger than 100. Based on this, we further demonstrate the generation of steady-state nearly maximal quantum entanglement. The resulting entanglement infidelity (which quantifies the deviation of the actual state from a maximally entangled state) is exponentially smaller than the lower bound on the infidelities obtained in other dissipative entanglement preparations without applying squeezing. In principle, we can make an arbitrarily small infidelity. Our generic method for enhancing atom-cavity interaction and cooperativities can be implemented in a wide range of physical systems, and it can provide diverse applications for quantum information processing.

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Cavity [1] and circuit [2,3] quantum electrodynamics (QED) provide promising platforms to implement light-matter interactions at the single-particle level by efficiently coupling single atoms to quantized cavity fields. Exploiting such coupled systems for quantum information processing often requires the strong-coupling regime (SCR), where the atom-cavity coupling g exceeds both atomic spontaneous-emission rate γ and cavity-decay rate κ, such that a single excitation can be coherently exchanged between atom and cavity before their coherence is lost. A typical parameter quantifying this property is the cooperativity defined as $C = g^2/(\kappa\gamma)$. Experimentally, microwave systems (like quantum superconducting circuits) can have very high cooperativities of order up to 10^4 [3–5]. However, for most optical systems (see [6] for a notable exception in photonic band gap cavities), it is currently challenging to achieve the SCR and, in particular, the cooperativity of C larger than 10^2 [7–12]. This directly limits the ability to process quantum information in optical cavities. Here, we propose a novel approach for this problem, and we demonstrate that the light-matter coupling and cooperativity can be exponentially increased with a cavity squeezing parameter. Specifically, we parametrically squeeze the cavity mode to strengthen the coherent coupling g, and at the same time, we apply a broadband squeezed-vacuum field to completely eliminate the noise induced by squeezing. As an intriguing application, we show how to improve exponentially the quality of steady-state entanglement.

Quantum entanglement is not only a striking feature of quantum physics but also a fundamental resource in quantum information technologies. The preparation of an entangled state between atoms in optical cavities can be directly implemented using controlled unitary dynamics [13,14]. However, the presence of an atomic spontaneous emission and cavity loss leads to a poor infidelity scaling $\delta = (1 - \mathcal{F}) \propto 1/\sqrt{C}$ [15], where $\mathcal{F}$ is the fidelity, which characterizes the distance between the ideal and actual states, and δ is the corresponding infidelity. This is owing to the fact that both decays can carry away information about the system and destroy its coherence. For this reason, many approaches, which have been proposed for entanglement preparation, are focused on dissipation engineering, which treats dissipative processes as a resource rather than as a detrimental noise [16–23]. In the resulting entanglement, the infidelity scaling has a quadratic improvement, $\delta \propto 1/C$ [24–30]. Such an infidelity, however, remains lower-bounded by the cooperativity, because only partial dissipation contributes to the entanglement, which still suffers

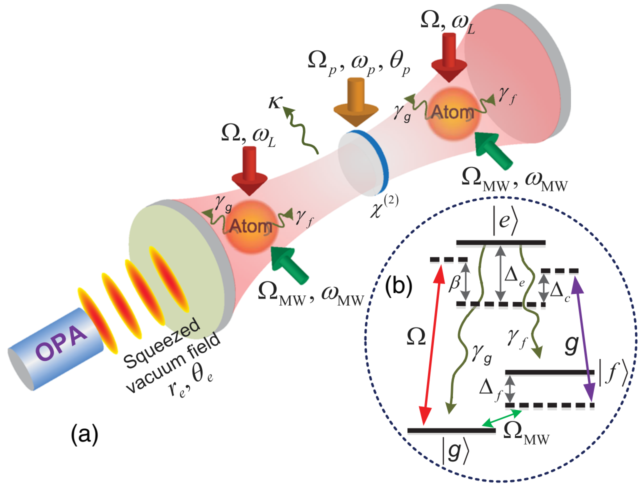

FIG. 1. Schematics of the proposed method for enhancing cooperativity and maximizing steady-state entanglement. (a) Two driven atoms are trapped inside a single-mode cavity, which contains a $\chi^{(2)}$ nonlinear medium strongly pumped at amplitude Ω_p, frequency ω_p, and phase θ_p. The cavity couples to a squeezed-vacuum reservoir, which is generated by optical parametric amplification (OPA) with a squeezing parameter r_e and a reference phase θ_e. As depicted in (b), the three-level atoms (in the Λ configuration) are coupled to the cavity mode with a strength g. In addition, the transition with Rabi frequency Ω ($\Omega_{\rm MW}$) is driven by a laser (microwave) field of frequency ω_L ($\omega_{\rm MW}$). We also assume that, along with a cavity decay rate κ, the excited state $|e\rangle$ of the atoms decays to the ground states $|g\rangle$ and $|f\rangle$ at rates γ_g and γ_f, respectively.

errors from other kinds (or channels) of dissipation. In this Letter, we demonstrate that our approach for the cooperativity enhancement can lead to an exponential suppression of undesired dissipation and, as a consequence, of the entanglement infidelity. Since the discussed model is generic, our proposal can be realized in a wide range of physical systems, in particular, optical cavities.

Basic idea.—As depicted in Fig. 1(a), we consider a quantum system consisting of two Λ atoms and a $\chi^{(2)}$ nonlinear medium. The atoms are confined in a single-mode cavity of frequency ω_c. The ground states of each atom, $|g\rangle$ and $|f\rangle$, are excited to the state $|e\rangle$, respectively, via a laser drive with Rabi frequency Ω and the coupling to the cavity mode with strength g, as shown in Fig. 1(b). If the nonlinear medium is pumped (say, at frequency ω_p, amplitude Ω_p, and phase θ_p), then the cavity mode can be squeezed along the axis rotated at the angle $(\pi-\theta_p)/2$. When Ω_p is close to the detuning $\Delta_c=\omega_c-\omega_p/2$, the atom-cavity coupling can be enhanced exponentially with a controllable squeezing parameter $r_p=(1/4)\ln[(1+\alpha)/(1-\alpha)]$, where $\alpha=\Omega_p/\Delta_c$. Meanwhile, squeezing the cavity mode also induces thermal noise and two-photon correlations in the cavity. In order to suppress them, a possible strategy is to use the squeezed vacuum field to drive the cavity [31–36]. This causes the squeezed-cavity mode to equivalently interact with the thermal vacuum reservoir, and therefore, it yields an effective cooperativity exhibiting an exponential enhancement with $2r_p$.

Furthermore, to generate steady-state entanglement, we tune the squeezed-cavity mode to resonantly drive the transition $|f\rangle\to|e\rangle$, and as a result, the excitation-number-nonconserving processes would be strongly suppressed. Thus, in the limit of $\Omega\ll g_s$, the ground-state subspace, spanned by $\{|\phi_\pm\rangle=(|gg\rangle\pm|ff\rangle)|0\rangle_s/\sqrt{2}, |\psi_\pm\rangle=(|gf\rangle\pm|fg\rangle)|0\rangle_s/\sqrt{2}\}$, is decoupled from all of the excited states except the dark state, $|D\rangle=(|fe\rangle-|ef\rangle)|0\rangle_s/\sqrt{2}$, from the atom-cavity interaction. Here, the number refers to the squeezed-cavity photon number. For entanglement preparation, in order to be independent of an initial state, we apply an off-resonant microwave field of frequency $\omega_{\rm MW}$ to couple $|g\rangle$ and $|f\rangle$ with the Rabi frequency $\Omega_{\rm MW}$, as shown in Fig. 1(b), to drive the transitions $|\phi_-\rangle\to|\phi_+\rangle\to|\psi_+\rangle$. Subsequently, the laser drive Ω excites $|\psi_+\rangle$ to $|D\rangle$, which then decays to $|\psi_-\rangle$ via atomic spontaneous emission. The populations initially in the ground-state subspace are, thus, driven to and trapped in $|\psi_-\rangle$, resulting in a maximally-entangled steady state, the singlet state $|S\rangle=(|gf\rangle-|fg\rangle)/\sqrt{2}$, between the atoms. In contrast to previous proposals of entanglement preparation that relied on the unitary or dissipative dynamics, and where the entanglement infidelities were lower-bounded by the system cooperativities [15,24–28], our approach can, in principle, make the entanglement infidelity arbitrarily small by increasing the squeezing parameter of the cavity mode for a modest value of the cooperativity.

Enhanced light-matter interaction and cooperativity.—Specifically, in a proper observation frame, the Hamiltonian determining the unitary dynamics of the system reads (hereafter, we set $\hbar=1$)

$$H(t)=\sum_k(\Delta_e|e\rangle_k\langle e|+\Delta_f|f\rangle_k\langle f|)+H_{\rm NL}+H_{\rm AC}+\frac{1}{2}\Omega_{\rm MW}\sum_k(|f\rangle_k\langle g|+{\rm H.c.})+V(t). \tag{1}$$

Here, $k=1$, 2 labels the atoms, $H_{\rm NL}=\Delta_c a^\dagger a+\frac{1}{2}\Omega_p(e^{i\theta_p}a^2+{\rm H.c.})$ is the nonlinear Hamiltonian for degenerate parametric amplification, $H_{\rm AC}=g\sum_k(a|e\rangle_k\langle f|+{\rm H.c.})$ is the atom-cavity coupling Hamiltonian, and $V(t)=\frac{1}{2}\Omega e^{i\beta t}\sum_k[(-1)^{k-1}|g\rangle_k\langle e|+{\rm H.c.}]$ describes the interaction of a classical laser drive with the atoms. The detunings are $\Delta_e=\omega_e-\omega_g-\omega_{\rm MW}-\omega_p/2$, $\Delta_f=\omega_f-\omega_g-\omega_{\rm MW}$, and $\beta=\omega_L-\omega_{\rm MW}-\omega_p/2$, where ω_L is the laser frequency of the atom drive and ω_z is the frequency associated with level $|z\rangle$ ($z=g$, f, e). Upon introducing the Bogoliubov squeezing transformation $a_s=\cosh(r_p)a+\exp(-i\theta_p)\sinh(r_p)a^\dagger$ [37], $H_{\rm NL}$ is diagonalized to $H_{\rm NL}=\omega_s a_s^\dagger a_s$, where $\omega_s=\Delta_c\sqrt{1-\alpha^2}$ is the squeezed-cavity frequency. The atom-cavity coupling Hamiltonian likewise becomes $H_{\rm AC} = \sum_k [(g_s a_s - g_s' a_s^\dagger)|e\rangle_k\langle f| + {\rm H.c.}]$, with $g_s = g\cosh(r_p)$ and $g_s' = \exp(-i\theta_p) g \sinh(r_p)$. The excitation-number-nonconserving processes originating from the counter-rotating terms of the form $a_s^\dagger \sum_k |e\rangle_k\langle f|$, and $a_s \sum_k |f\rangle_k\langle e|$ can be neglected under the assumption that $|g_s'|/(\omega_s + \Delta_e - \Delta_f) \ll 1$, corresponding to the rotating-wave approximation, such that $H_{\rm AC}$ is transformed to the Jaynes-Cummings Hamiltonian

$$H_{\rm ASC} = g_s \sum_k (a_s |e\rangle_k\langle f| + {\rm H.c.}), \tag{2}$$

given in terms of the coupling strength g_s between the atoms and the squeezed-cavity mode. Therefore for $r_p \geq 1$, we predict an *exponentially-enhanced atom-cavity coupling*,

$$\frac{g_s}{g} \sim \frac{1}{2}\exp(r_p), \tag{3}$$

as plotted in the inset of Fig. 2. This is because there are $\sim \exp(2r_p)$ photons converted into a single-photon state, $|1\rangle_s$, of the squeezed-cavity mode. Such an exponential enhancement of this light-matter interaction is one of our most important results.

This squeezing also introduces additional noise into the cavity, as mentioned in the description above. To circumvent such undesired noises, a squeezed-vacuum field, with a squeezing parameter r_e and a reference phase θ_e, is used to drive the cavity [see Fig. 1(a)]. We consider the case where such a field has a much larger linewidth than the cavity mode. Indeed, a squeezing bandwidth of up to ~GHz has been experimentally demonstrated via optical parametric amplification [38–40]. Because the linewidth is ~MHz for typical optical cavities, we can think of this cavity drive as a squeezed reservoir. Hence, by ensuring $r_e = r_p$ and $\theta_e + \theta_p = \pm n\pi$ $(n = 1, 3, 5, \cdots)$, this additional noise can be eliminated completely (see the Supplemental Material [41] for details). As a consequence, the squeezed-cavity mode is equivalently coupled to a thermal vacuum reservoir, so that we can use the standard Lindblad operator to describe the cavity decay, yielding $L_{\rm as} = \sqrt{\kappa} a_s$ with κ a decay rate. Similarly, atomic spontaneous emission is also described with the Lindblad operators $L_{g1} = \sqrt{\gamma_g}|g\rangle_1\langle e|$, $L_{f1} = \sqrt{\gamma_f}|f\rangle_1\langle e|$, $L_{g2} = \sqrt{\gamma_g}|g\rangle_2\langle e|$, and $L_{f2} = \sqrt{\gamma_f}|f\rangle_2\langle e|$. Here, we have assumed that in each atom, $|e\rangle$ decays to $|g\rangle$ and $|f\rangle$, respectively, with rates γ_g and γ_f. The dynamics of the atom-cavity system is, thus, governed by the standard master equation in the Lindblad form $\dot\rho(t) = i[\rho(t), H_s(t)] - \frac{1}{2}\sum_n \mathcal{L}(L_n)\rho(t)$, where $\rho(t)$ is the density operator of the system, $H_s(t)$ is given by $H(t)$ but with a $(a^\dagger)$ replaced by a_s $(a_s^\dagger)$, and with $H_{\rm AC}$ replaced by $H_{\rm ASC}$. Moreover, $\mathcal{L}(o)\rho = o^\dagger o\rho - 2o\rho o^\dagger + \rho o^\dagger o$ and

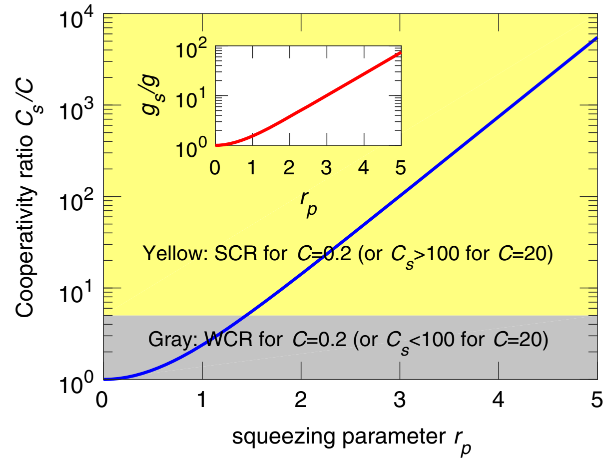

FIG. 2. Cooperativity enhancement C_s/C versus the squeezing parameter r_p. For $C = 0.2$, the gray and yellow shaded areas represent the WCR ($C_s < 1$) and the SCR ($C_s > 1$), respectively. For $C = 20$, the two shaded areas represent the regions, respectively, with $C_s < 100$ and $C_s > 100$. The inset shows the exponentially-enhanced effective coupling, g_s, between atom and cavity.

the sum runs over all dissipative processes mentioned above. We find that the above master equation gives an effective cooperativity $C_s = g_s^2/(\kappa\gamma)$. Consequently, increasing r_p enables an exponential enhancement in the atom-cavity coupling, given in Eq. (3), and thus, the cooperativity enhancement,

$$\frac{C_s}{C} \sim \frac{1}{4}\exp(2r_p), \tag{4}$$

as shown in Fig. 2. Note that our approach can exponentially strengthen the coherent coupling between atom and cavity, but *does not introduce any additional noise* into the system. It is seen in Fig. 2 that the atom-cavity system can be driven from the weak-coupling regime (WCR) to the SCR, e.g., with $C = 0.2$ and $r_p \geq 1.5$. Moreover, an effective cooperativity of $C_s > 10^2$ can also be achieved with modest C and r_p, e.g., $C = 20$ and $r_p \geq 1.5$. As one of many possible applications in quantum information technologies, this enhancement in the cooperativity (or coherent atom-field coupling) can be employed to improve the fidelity of dissipative entanglement preparation.

Maximizing steady-state entanglement.—Let us consider a weak drive Ω, so that the dominant dynamics of the system is restricted to a subspace having, at most, one excitation, and we can treat $V(t)$ as a perturbation to the system [46]. After adiabatically eliminating the excited states, the effective Hamiltonian is given by $H_{\rm eff} = \Delta_f(\mathcal{I}/2 - |\phi_+\rangle\langle\phi_-| + {\rm H.c.}) + \Omega_{\rm MW}(|\psi_+\rangle\langle\phi_+| + {\rm H.c.})$, where $\mathcal{I}$ is an identity operator acting on the ground manifold of the atoms. This implies that the microwave field can drive the population from $|\phi_+\rangle$ (or $|\phi_-\rangle$) to $|\psi_+\rangle$. Upon choosing $\Delta_e = \beta = \omega_s + \Delta_f$, the population in $|\psi_+\rangle$ is transferred to

$|\psi_-\rangle$ via the resonant drive and then the atomic spontaneous emission, which is mediated by the dark state $|D\rangle$. At the same time, the transition from $|\psi_-\rangle$ to the excited state of $|\varphi_e\rangle = (|fe\rangle + |ef\rangle)|0\rangle_s/\sqrt{2}$ is off-resonant, and it is negligible when $\Omega \ll g_s$. In this case, the rates of the effective decays into and out of the desired state $|\psi_-\rangle = |S\rangle|0\rangle_s$ are expressed, respectively, as $\Gamma_{\rm in} = (\Omega/2)^2[4\gamma_g/\gamma^2 + 4/(\gamma C_s) + \gamma_f/(2\gamma^2 C_s^2)]$ and $\Gamma_{\rm out} = (\Omega/2)^2[1/(\gamma C_s) + (\gamma+\gamma_f)/(16\gamma^2 C_s^2)]$ (see the Supplemental Material [41] for a detailed derivation). Here, $\gamma = \gamma_g + \gamma_f$ is the total atomic decay rate. In the steady state, the entanglement infidelity can be expressed as $\delta \sim 1/[1 + \Gamma_{\rm in}/(3\Gamma_{\rm out})]$, which is reduced to $\delta \sim 3\gamma/(4\gamma_g C_s)$ for $C_s \gg 1$. Further, as long as $r_p \geq 1$, we directly obtain

$$\delta \sim \frac{3\gamma}{\gamma_g \exp(2r_p) C}. \tag{5}$$

This explicitly shows an exponential improvement over the infidelity in the case of previous entanglement preparation protocols relying on engineered dissipation. The parametrically-enhanced cooperativity enables the entanglement infidelity to be very close to zero even for a modest value of C, rather than lower-bounded by $1/\sqrt{C}$ and $1/C$ [see Fig. 3(a)]. For the cooperativity values, which are easily accessible in current experiments, an entanglement infidelity of up to $\delta \sim 10^{-3}$ can be generated at a time $t = 200/\gamma$, as shown in Fig. 3(b). Note that, by increasing the driving laser strength Ω, the population transfer into the desired state is faster and, then, the infidelity is smaller for a given preparation time. However, at the same time, a nonadiabatic error increases with Ω, causing an increase in the infidelity. Thus, these are two competing processes. In addition, a larger C can more strongly reduce this nonadiabatic error and, therefore, lead to a smaller optimal driving strength [see Fig. 3(b)]. In a realistic setup based on ultracold ^{87}Rb atoms coupled to a Fabry-Perot resonator as discussed below [11], an atomic linewidth of $\gamma/2\pi = 3$ MHz and the cooperativity of $C = 42$ could result in $\delta \sim 1.2 \times 10^{-3}$, together with $t \sim 11$ μs, which allows us to neglect atomic decoherence.

We now consider the counter-rotating terms. In the limit $|g_s'|/\Delta_e \ll 1$, we find that such terms cause an energy shift of $|g_s'|^2/(2\Delta_e)$ to be imposed on the ground states and a coherent coupling, of strength $|g_s'|^2/(2\Delta_e)$, between the states $|\phi_+\rangle$ and $|\phi_-\rangle$ [47]. To remove these detrimental effects, the detunings need to be modified as $\Delta_e = \beta - |g_s'|^2/(2\Delta_e) = \omega_s + \Delta_f - |g_s'|^2/\Delta_e$ and $\Delta_f = \Omega_{\rm MW}/\sqrt{2} + |g_s'|^2/(2\Delta_e)$, according to the analysis given in the Supplemental Material [41]. In this situation, the full system can be mapped to a simplified system that excludes the counter-rotating terms and has been discussed above. We numerically integrate the full master equation with the modified detunings [48,49], and find that, as in Fig. 3(a), the exact entanglement infidelity is in excellent agreement with the prediction of the effective dynamics during a very long time interval (e.g., $0 \leq t \leq 500/\gamma$).

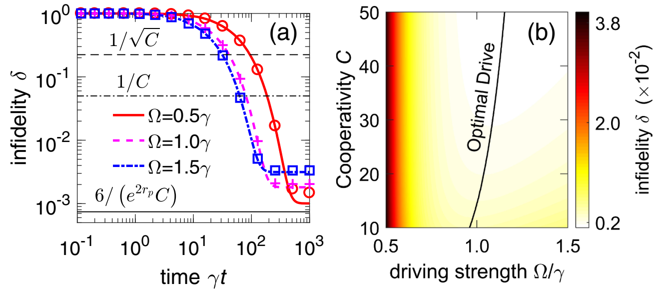

FIG. 3. (a) Evolution of the entanglement infidelity δ for different driving strengths $\Omega = 0.5\gamma$, 1.0γ, and 1.5γ, with the cooperativity $C = 20$. We assumed $\Delta_f = \Omega/2^{7/4}$ and $\Delta_f = \Omega/2^{7/4} + |g_s'|^2/(2\Delta_e)$, $\Delta_e = 200g_s'$ when using the effective (thick curves) and full (symbols) master equations, respectively. This yields an excellent agreement especially for time $t \in [0, 500/\gamma]$. The steady-state error decreases as Ω and becomes closer to $6/(e^{2r_p}C)$ (thin solid line), far below both $1/\sqrt{C}$ (thin dashed line) and $1/C$ (thin dotted-dashed line). (b) Entanglement infidelity at $t = 200/\gamma$ as a function of C and Ω. Here, due to excellent agreement between our predictions based on the full and effective master equations in panel (a), only the latter equation was used in panel (b). The solid line represents the optimal drive resulting in the smallest error for a given cooperativity. In both plots, we have assumed that $\gamma_g = \gamma/2$, $\kappa = 2\gamma/3$, $\Omega_{\rm MW} = \sqrt{2}\Delta_f$, $r_p = 3$, $\theta_p = \pi$, while the initial state of the atoms is $(\mathcal{I} - |\psi_-\rangle\langle\psi_-|)/3$ and the cavity is initially in the vacuum.

Possible implementations.—We consider a possible experimental implementation utilizing ultracold ^{87}Rb atoms trapped in a high-finesse Fabry-Perot resonator [11]. Here, the ^{87}Rb atoms are used for the Λ-configuration atoms, and the Fabry-Perot resonator works as the single-mode cavity. When focusing on electric-dipole transitions of the D_1 line at a wavelength of 795 nm, we choose $|g\rangle \equiv |F = 1, m_F = -1\rangle$, $|f\rangle \equiv |F = 2, m_F = -2\rangle$, and $|e\rangle \equiv |F' = 2, m_F' = -2\rangle$, where $F^{(\prime)}$ and $m_F^{(\prime)}$ are quantum numbers characterizing the Zeeman states in the manifolds $5S_{1/2}$ $(5P_{1/2})$. In this situation, a circularly σ^--polarized control laser and a π-polarized-cavity mode are needed to couple the transitions $|F = 1, m_F = -1\rangle \rightarrow$ and $|F = 2, m_F = -2\rangle \rightarrow |F' = 2, m_F' = -2\rangle$, respectively. For the two ground states, although their electric-dipole transition is forbidden due to their same parity, a microwave field could directly couple these states through the magnetic-dipole interaction. Such a coupling has experimentally reached values of hundreds of kHz [50,51]. Moreover, the cavity mode can be squeezed typically using, e.g., a periodically-poled $KTiOPO_4$ (PPKTP) crystal [52–54]. In order to generate a squeezed-vacuum reservoir, we can also use a PPKTP crystal with a high-bandwidth pump, so the squeezing bandwidth of up to ∼GHz [38,39] is possible.

Solid-state implementations can be considered in the context of nitrogen-vacancy (NV) centers in diamond with a whispering-gallery-mode (WGM) microresonator [7]. In this setup, the electronic spin states of the NV centers are used to form the Λ-configuration structures, such that $|g\rangle \equiv |^3A_2, m_s = -1\rangle$, $|f\rangle \equiv |^3A_2, m_s = +1\rangle$, and $|e\rangle \equiv (|E_-, m_s = +1\rangle + |E_+, m_s = -1\rangle)/\sqrt{2}$. The NV spins have extremely long coherence times at room temperature, while the WGM microresonators made out of nonlinear crystals exhibit strong optical nonlinearities [55,56]. These are the key requirements for the entanglement preparation with a weak atom drive and a squeezed-cavity mode.

As an alternative example of solid-state system, the proposed method of maximizing steady-state entanglement can also be realized in superconducting quantum circuits [57–59], where two flux or transmon qubits and a coplanar waveguide resonator are used [2,60]. A superconducting quantum interference device (SQUID) can be inserted into the resonator, which is able to create the squeezed vacuum in the resonator [31,61–65]. All required parts of such devices have been implemented in superconducting experiments [3].

Conclusions.—We have shown that parametric squeezing enables an exponential enhancement of both coherent coupling between an atom and a cavity, as well as the corresponding cooperativity. As a simple application, the steady-state entanglement preparation, which results in an exponentially better fidelity than previous dissipation-based protocols, has also been demonstrated here. In principle, our method can be extended to other local quantum operations, e.g., many-body entanglement preparation [28,66] and quantum gate implementations [29,67–70]. We suggest to use squeezed light for only performing local intracavity quantum operations and to turn it off for converting stationary qubits into flying qubits. Moreover, due to a controllable squeezed-cavity frequency, the present method should enable reaching the ultra-SCR in optical cavities. Thus, one may observe many interesting phenomena in cavity-QED, similar to those observed in circuit QED [3,71–73]. Indeed, in particular for optical cavities, enhancing the light-matter interaction and cooperativities is of both fundamental and practical importance, so we expect that this technique could find diverse applications in quantum technologies [74,75].

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