

Ground State Electroluminescence

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Electroluminescence, the emission of light in the presence of an electric current, provides information on the allowed electronic transitions of a given system. It is commonly used to investigate the physics of strongly coupled light-matter systems, whose eigenfrequencies are split by the strong coupling with the photonic field of a cavity. Here we show that, together with the usual electroluminescence, systems in the ultrastrong light-matter coupling regime emit a uniquely quantum radiation when a flow of current is driven through them. While standard electroluminescence relies on the population of excited states followed by spontaneous emission, the process we describe herein extracts bound photons from the dressed ground state and it has peculiar features that unequivocally distinguish it from usual electroluminescence.

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The proper dimensionless parameter to study perturbatively the resonant interaction between light and matter in cavity quantum electrodynamics (QED) is the ratio between vacuum Rabi frequency Ω_R and the bare frequency of the excitation ω_C [1,2]. When such a quantity, usually referred to as normalized coupling, $\eta \equiv (\Omega_R/\omega_C)$, becomes non-negligible, higher-order phenomena start to become observable. This is the so-called ultrastrong coupling regime that has been experimentally achieved in a number of solid-state systems [3–16]. The nonperturbative nature of the light-matter coupling in this regime leads to a range of very rich (and as yet not fully understood) phenomenology, including quantum phase transitions [17–19], modification of energy transport [20,21] and light emission properties [22–24], and the appearance of cavity-assisted chemical and thermodynamic effects [25–28]. One of the main consequences of the ultrastrong coupling regime is to modify the ground state of the system, such that it becomes a multimode squeezed state, containing a finite population of bound excitations that can only be observed if the system parameters are nonadiabatically modulated in time [1,29–40]. This quantum vacuum radiation, which has strong similarities with the dynamical Casimir effect [41–47], is a hallmark of the quantum nature of the light-matter interaction, and it can provide insights into the quantum nature of the ground state [48].

Here we investigate a unique quantum electrodynamical effect wherein one can observe the photonic excitations bound in the ground state when an electrical current is driven through the system. We call this effect ground state electroluminescence (GSE), in order to distinguish it from the standard polaritonic electroluminescence observable when a current passes in a strongly coupled light-matter system [12,49–59]. We will see that such a GSE is not only intense enough to be observable in some near-future

solid-state cavity QED experiments, but it also has unique features that clearly distinguish it from the usual polaritonic electroluminescence.

Our aim is to present a novel QED effect, *a priori* relevant for many of the systems in which the ultrastrong coupling regime has been observed. For this reason we will keep the discussion as generic and system independent as possible, investigating the simplest model presenting GSE effects. Possible experimental implementations will be discussed later. We will thus consider a generic model exhibiting GSE: a two-level electronic system ultrastrongly coupled to a single mode of a photonic resonator. When a single electron is present, this is just the Rabi model, one of the simplest models used to investigate the physics of strong light-matter coupling. The important element we add here is that, given that we are interested in electroluminescence, we will consider the system to be electronically open; i.e., we will account for the possibility of electrons to tunnel in and out of the structure. While it is not necessary for our theory, in order to simplify the already rather heavy notation, we will neglect the possibility to have a doubly occupied state. Depending on the specific implementation, this assumption can be physically justified assuming the system to be in a Coulomb-blockade regime. Thus, for this electronic system we consider only a three-dimensional Hilbert space spanned by the empty state $|s\rangle$, and the two singly occupied states $|g\rangle$ and $|e\rangle$, with Hamiltonian

$$H = \hbar\omega_C a^\dagger a + \hbar\omega_e |e\rangle\langle e| - \hbar\omega_s |s\rangle\langle s| + \Omega_R (a + a^\dagger)(|e\rangle\langle g| + |g\rangle\langle e|), \quad (1)$$

where a is the annihilation operator of the photonic mode of energy $\hbar\omega_C$, and $\hbar\omega_e$ and $\hbar\omega_s$ are the energies of the $g \rightarrow e$ and $s \rightarrow g$ transitions. For definiteness, hereafter we

will limit ourselves to the resonant case $\omega_e = \omega_C$. As the Hamiltonian in Eq. (1) conserves the number of electrons, it can be diagonalized separately in the zero and one electron sectors. In the first sector the Hamiltonian is diagonal in the n -photons states $|s, n\rangle$, of energy $n\hbar\omega_C - \hbar\omega_s$, while in the second sector we recover exactly the Hamiltonian of a quantum Rabi model [60]. We will call, respectively, $|G\rangle$ and $|\pm\rangle$ its ground state and first polaritonic doublet, with respective energies $\hbar\omega_G$ and $\hbar\omega_G + \hbar\omega_{\pm}$. For the sake of clarity, we will neglect higher-lying states and temperature effects, as both are inessential to GSE. In order to be able to investigate electroluminescence, we couple such a system to two external electronic reservoirs. Fixing the chemical potential of one of them to $-\hbar\omega_s$, so that it acts only as a sink for electrons, the voltage across the system is described by the effective potential μ of the other reservoir, leading to the effective electronic injection and extraction rates $\Gamma_{\text{in/out}}$. We also couple the cavity itself to a reservoir, describing the extracavity photonic modes in which the luminescence is emitted, leading to a photonic lifetime Γ_{cav} . A diagram of the relevant levels and transition rates for vanishing couplings is in Fig. 1(a). A more extended discussion of the coupling with the reservoirs and of the relative scattering rates can be found in the Supplemental Material [61].

Note that we will consider strongly coupled systems, whose eigenstates are linear superpositions of different electronic and photonic excitations. Therefore, the bare electronic and photonic rates ($\Gamma_{\text{in/out}}, \Gamma_{\text{cav}}$) will give rise to transition rates between pairs of dressed states that can be calculated using the methods that have been developed to deal with strongly coupled open systems [36,62–65]. The levels and transition rates for strong couplings are shown in Fig. 1(b). Limiting ourselves to the low-lying states that we will consider here, we thus define $\Gamma_{\text{in}}^{n \rightarrow j}$ and $\Gamma_{\text{out}}^{j \rightarrow n}$ as the dressed electronic injection and extraction rates to and from the states $|s, n\rangle$ and $|j\rangle$, $j \in \{G, \pm\}$, and $\Gamma_{\text{cav}}^{\pm}$ as the dressed photonic transition rates from $|\pm\rangle$ to $|G\rangle$. Notice that in the zero temperature case we are considering here, electron tunneling can couple two states only if μ is larger than their energy mismatch; that is,

$$\begin{aligned} \Gamma_{\text{in}}^{n \rightarrow G} &\propto \Theta(\mu + n\hbar\omega_C - \hbar\omega_G), \\ \Gamma_{\text{in}}^{n \rightarrow \pm} &\propto \Theta(\mu + n\hbar\omega_C - \hbar\omega_G - \hbar\omega_{\pm}), \end{aligned} \quad (2)$$

where Θ is the Heaviside function.

In order to introduce our discussion of GSE, we will start by reviewing standard electroluminescence in polaritonic systems for $\eta \ll 1$ [58,59]. In this regime, the Rabi Hamiltonian reduces to a Jaynes-Cummings model,

$$|G\rangle \simeq |g, 0\rangle, \quad |\pm\rangle \simeq \frac{|g, 1\rangle \pm |e, 0\rangle}{\sqrt{2}}, \quad (3)$$

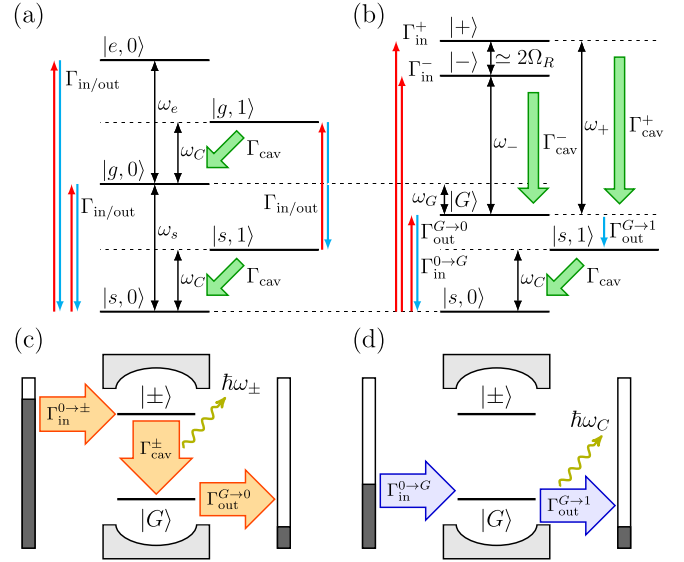


FIG. 1. (a) Energy diagram for the uncoupled system ($\Omega_R = 0$). Photons can leave the cavity at a rate Γ_{cav} and electrons can populate or leave the system at rates $\Gamma_{\text{in/out}}$. (b) Diagram levels for the strongly coupled regime at resonance $\omega_C = \omega_e$. (c) Schematic showing standard electroluminescent emission. (d) Schematic showing the dominant GSE process.

leading to $\hbar\omega_G = 0$ and $\Gamma_{\text{out}}^{G \rightarrow n} = \Gamma_{\text{out}} \delta_{n,0}$, $\Gamma_{\text{in}}^{n \rightarrow G} = \Gamma_{\text{in}} \delta_{n,0}$; as the ground state $|G\rangle$ contains no photons, when we extract the electron we cannot end in a state with a photonic component and vice versa. A current can thus pass through the structure for any $\mu \geq 0$, without any photonic emission, through the path

$$|s, 0\rangle \xrightarrow{\Gamma_{\text{in}}} |G\rangle \xrightarrow{\Gamma_{\text{out}}} |s, 0\rangle. \quad (4)$$

Only for $\mu \geq \hbar\omega_G + \hbar\omega_{\pm}$ can the electrons excite states with a photonic component, corresponding to $\Gamma_{\text{in}}^{0 \rightarrow \pm} > 0$, then decaying to the ground state before being extracted. This leads to the usual polaritonic electroluminescence at energy $\hbar\omega_{\pm}$, through the processes

$$|s, 0\rangle \xrightarrow{\Gamma_{\text{in}}^{0 \rightarrow \pm}} |\pm\rangle \xrightarrow[\hbar\omega_{\pm}]{\Gamma_{\text{cav}}^{\pm}} |G\rangle \xrightarrow{\Gamma_{\text{out}}} |s, 0\rangle, \quad (5)$$

where we highlighted the transition (and its energy) expected to emit light.

The situation radically changes when instead $\eta \simeq 1$. In this case, Eq. (3) is not valid anymore, and the ground state has a non-negligible photonic component, $\langle G|a^\dagger a|G\rangle \neq 0$ [1]. As $|G\rangle$ is now a linear superposition of states with one electron and n photons, when the electron is extracted, it has a finite probability to project the system in the state $|s, n\rangle$, with no electrons and n photons ($\Gamma_{\text{out}}^{G \rightarrow n} > 0$), that will eventually escape out of the cavity. This process is what we term GSE: emission of photons when a current passes through the ground state. The fundamental GSE process, emitting at the cavity frequency $\hbar\omega_C$, has the form

$$|s, 0\rangle \xrightarrow{\Gamma_{\text{in}}^{0 \rightarrow G}} |G\rangle \xrightarrow{\Gamma_{\text{out}}^{G \rightarrow 1}} |s, 1\rangle \xrightarrow[\downarrow \hbar\omega_C]{\Gamma_{\text{cav}}} |s, 0\rangle, \quad (6)$$

where, as in the standard electroluminescence in Eq. (5), the emitted energy is the difference between the incoming and outgoing electron energies. If the photonic lifetime is longer than the electron injection and extraction times, GSE photons can accumulate in the cavity, leading to the occupation of higher-lying states of the Rabi Hamiltonian and luminescence at the respective frequencies. Under the assumption of large enough cavity losses, we will limit ourselves to processes of first order in $\Gamma_{\text{in/out}}/\Gamma_{\text{cav}}$,

$$|s, 0\rangle \xrightarrow{\Gamma_{\text{in}}^{0 \rightarrow G}} |G\rangle \xrightarrow{\Gamma_{\text{out}}^{G \rightarrow 1}} |s, 1\rangle \xrightarrow{\Gamma_{\text{in}}^{1 \rightarrow \pm}} |\pm\rangle \xrightarrow[\downarrow \hbar\omega_{\pm}]{\Gamma_{\text{cav}}^{\pm \rightarrow 0}} |G\rangle \xrightarrow{\Gamma_{\text{out}}^{G \rightarrow 0}} |s, 0\rangle, \quad (7)$$

that clearly emit at the polaritonic energies $\hbar\omega_{\pm}$. We emphasize that the processes in Eqs. (6) and (7) do not depend upon $\Gamma_{\text{in}}^{0 \rightarrow \pm}$, and thus from Eq. (2) they can happen for values of the applied bias $\mu < \hbar\omega_G + \hbar\omega_-$, such that the standard electroluminescence in Eq. (5) is forbidden. In particular, the process in Eq. (6) becomes allowed when $\mu > \hbar\omega_G$, while for Eq. (7) the processes emitting at $\hbar\omega_-$ ($\hbar\omega_+$) become allowed for $\mu > \hbar\omega_G$ ($\mu > \hbar\omega_G + \hbar\omega_+ - \hbar\omega_C$). A more in-depth discussion of the different emission channels as a function of the chemical potential can be found in the Supplemental Material [61]. The GSE emission rate can be calculated by writing a rate equation for the populations P_j of the respective states $|j\rangle$. Limiting ourselves to the first satellite peaks, and to the regime $\mu < \hbar\omega_G + \hbar\omega_-$, in which no standard electroluminescence is possible, we have

$$\begin{aligned} \dot{P}_{s,0} &= -P_{s,0}\Gamma_{\text{in}}^{s,0} + P_G\Gamma_{\text{out}}^{G \rightarrow 0} + P_{\pm}\Gamma_{\text{out}}^{\pm \rightarrow 0} + P_{s,1}\Gamma_{\text{cav}}, \\ \dot{P}_{s,1} &= -P_{s,1}(\Gamma_{\text{cav}} + \Gamma_{\text{in}}^{s,1}) + P_G\Gamma_{\text{out}}^{G \rightarrow 1} + P_{\pm}\Gamma_{\text{out}}^{\pm \rightarrow 1}, \\ \dot{P}_G &= -P_G\Gamma_{\text{out}}^G + P_{s,0}\Gamma_{\text{in}}^{0 \rightarrow G} + P_{s,1}\Gamma_{\text{in}}^{1 \rightarrow G} + P_{\pm}\Gamma_{\text{cav}}^{\pm}, \\ \dot{P}_+ &= -P_+(\Gamma_{\text{cav}}^+ + \Gamma_{\text{out}}^+) + P_{s,1}\Gamma_{\text{in}}^{1 \rightarrow +}, \\ \dot{P}_- &= -P_-(\Gamma_{\text{cav}}^- + \Gamma_{\text{out}}^-) + P_{s,1}\Gamma_{\text{in}}^{1 \rightarrow -}, \end{aligned} \quad (8)$$

where repeated \pm stands for sum over its repeated constituents. In the steady state, this system can be solved for the populations, and, consequently, the emission rates for the fundamental GSE in Eq. (6), f_C , and for the first satellites in Eq. (7), f_{\pm} , can be calculated as

$$f_C = P_{s,1}\Gamma_{\text{cav}}, \quad f_+ = P_+\Gamma_{\text{cav}}^+, \quad f_- = P_-\Gamma_{\text{cav}}^-. \quad (9)$$

Using the perturbative expansion of the coupled eigenstates of the Rabi Hamiltonian $|G\rangle$ and $|\pm\rangle$ over the uncoupled states $|g, n\rangle$ and $|e, n\rangle$, that can be found in the Supplemental Material [61], and considering $\Gamma_{\text{in}} = \Gamma_{\text{out}} \equiv \Gamma$, we can obtain estimates for the radiation

intensity of the main GSE peak in Eq. (6) and for the satellites from Eq. (7). To the lowest nontrivial order in η and to the first order in $\Gamma/\Gamma_{\text{cav}}$, they read

$$f_C = \frac{\eta^2\Gamma}{8} \left(1 - \frac{\Gamma}{\Gamma_{\text{cav}}}\right), \quad f_{\pm} = \frac{\eta^2\Gamma}{16} \frac{\Gamma}{\Gamma_{\text{cav}}}, \quad (10)$$

where, as expected, the emission at $\hbar\omega_{\pm}$, which relies upon a photon buildup in the cavity as from Eq. (7), is weighted down by a factor $(\Gamma/\Gamma_{\text{cav}}) \ll 1$.

For comparison we also calculated, to the same order, the standard electroluminescence intensity for the case $\mu \geq \hbar\omega_G + \hbar\omega_+$, obtaining

$$f'_C = \frac{\Gamma}{6} \left(\frac{2\Gamma}{\Gamma_{\text{cav}}} + \xi^C \eta^2\right), \quad f'_{\pm} = \frac{\Gamma}{6} \left(\xi_0^{\pm} + \xi_1^{\pm} \frac{\eta}{2} + \xi_2^{\pm} \frac{\eta^2}{12}\right), \quad (11)$$

where $\xi^C = 1 - (11/6)(\Gamma/\Gamma_{\text{cav}})$, $\xi_j^{\pm} = 1 - 2^{2j+1}(\Gamma/\Gamma_{\text{cav}})$, and the details of the calculations can be found in the Supplemental Material [61]. To the dominant order in both variables we obtain, as expected, a term not dependent on η emitting at $\hbar\omega_{\pm}$, that is the standard electroluminescence described in Eq. (5). Note that also in this case we recover higher-order processes allowed by the buildup of photonic population in the cavity (and thus of higher order in $\Gamma/\Gamma_{\text{cav}}$); in this case the first one emitting at $\hbar\omega_C$:

$$|s, 0\rangle \xrightarrow{\Gamma_{\text{in}}^{0 \rightarrow \pm}} |\pm\rangle \xrightarrow{\Gamma_{\text{out}}^{\pm \rightarrow 1}} |s, 1\rangle \xrightarrow[\downarrow \hbar\omega_C]{\Gamma_{\text{cav}}} |s, 0\rangle. \quad (12)$$

In order to test such an intuitive understanding of GSE, we studied the system numerically solving [66,67] the master equation

$$\dot{\rho} = -i[H, \rho] + \mathcal{L}_{\text{in}}(\rho) + \mathcal{L}_{\text{out}}(\rho) + \mathcal{L}_{\text{cav}}(\rho), \quad (13)$$

where ρ is the density operator of the system with a converged cutoff over the maximum number of photons and the Lindblad operators $\mathcal{L}_{\text{in/out/cav}}$ are projected over the dressed basis of the system [36,62,65]. Exploiting the input-output formalism compatible with the dressed state analysis developed in Ref. [64], we can write the extracavity emission spectrum as

$$S(\omega) = \frac{\Gamma_{\text{cav}}}{2\pi} \int_{-\infty}^{\infty} d\tau e^{-i\omega\tau} \langle X^+(\tau) X^-(0) \rangle, \quad (14)$$

where $X = (a + a^\dagger)$, $X^- = \sum_{j>i} \langle i|X|j\rangle |i\rangle\langle j|$, and X^+ is its Hermitian conjugate. In Fig. 2 we plot the emitted spectrum from Eq. (14) for $\mu = \hbar\omega_G$ (blue solid line) in which we can clearly see the central GSE peak at $\hbar\omega_C$ and the satellites around $\hbar\omega_{\pm} \approx \hbar\omega_C \pm \Omega$. Figure 2 also shows (yellow solid line) the spectrum for $\mu = \hbar\omega_G + \hbar\omega_+$. In

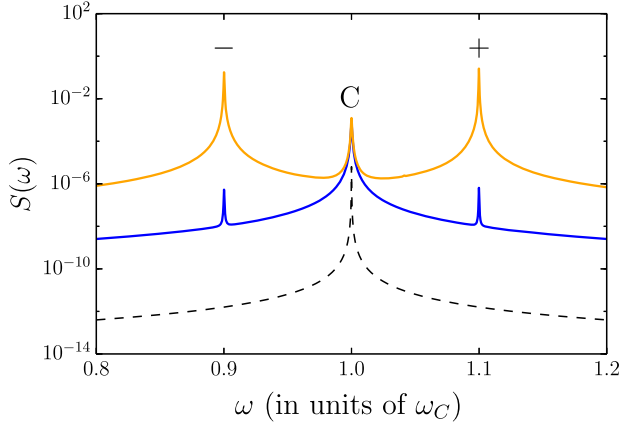


FIG. 2. Emission spectrum $S(\omega)$ for GSE alone (blue solid line, $\mu = \hbar\omega_G$) and GSE plus standard electroluminescence (yellow solid line, $\mu = \hbar\omega_G + \hbar\omega_+$). The peaks corresponding to the processes emitting at the bare cavity frequency $\hbar\omega_C$ and at the polaritonic energies $\hbar\omega_{\pm}$ are explicitly shown. The dashed line represents the blackbody radiation spectrum for $k_B T \sim 0.1\hbar\omega_C$. Parameters are $\eta = 0.1$, $\Gamma = \Gamma_{\text{in}} = \Gamma_{\text{out}} = 0.5 \times 10^{-6}\omega_C$, $\Gamma_{\text{cav}} = 7 \times 10^{-4}\omega_C$.

this case, while the central peak remains substantially unchanged, standard electroluminescence becomes dominant over the satellite frequencies. There we plot, for comparison, the blackbody emission from the cavity for $k_B T = 0.1\hbar\omega_C$. In Fig. 3 we plot (solid lines) the integrated emission of the central peak and of the two satellites, respectively, for $\mu = \hbar\omega_G$ [3(a)] and $\mu = \hbar\omega_G + \hbar\omega_+$ [3(b)], as a function of the perturbative parameter η . The open dots in the same figures are obtained by the analytical estimates from Eqs. (10) and (11), respectively. Their very good quantitative agreement clearly demonstrates the validity of our theoretical analysis. Schematics of the involved processes are shown as insets. Those results prove that GSE has various specific signatures that differentiate it from standard electroluminescence, allowing for direct experimental discrimination. Not only does GSE become active for applied voltages at which standard electroluminescence is forbidden, but its fundamental emission is at the bare cavity energy $\hbar\omega_C$, with emission at polaritonic energies $\hbar\omega_{\pm}$ being of higher order in $\Gamma/\Gamma_{\text{cav}}$, while the opposite is true for standard electroluminescence. Finally, the intensity of the emission at $\hbar\omega_{\pm}$ is, to the leading order, independent of η in standard electroluminescence, while it is of order η^2 in GSE. This difference in dependence could be detected in systems in which the coupling is tunable *in situ* [9,68].

Various developing technological platforms seem possible candidates to experimentally observe GSE, and some of them, like hybrid QED [50,51,69–83] and circuit QED [3,4,49,84–90], in which electronic transitions are coupled to microwave superconducting resonators, seem close to achieving all the needed requirements. In particular, a double quantum dot coupled to a superconducting

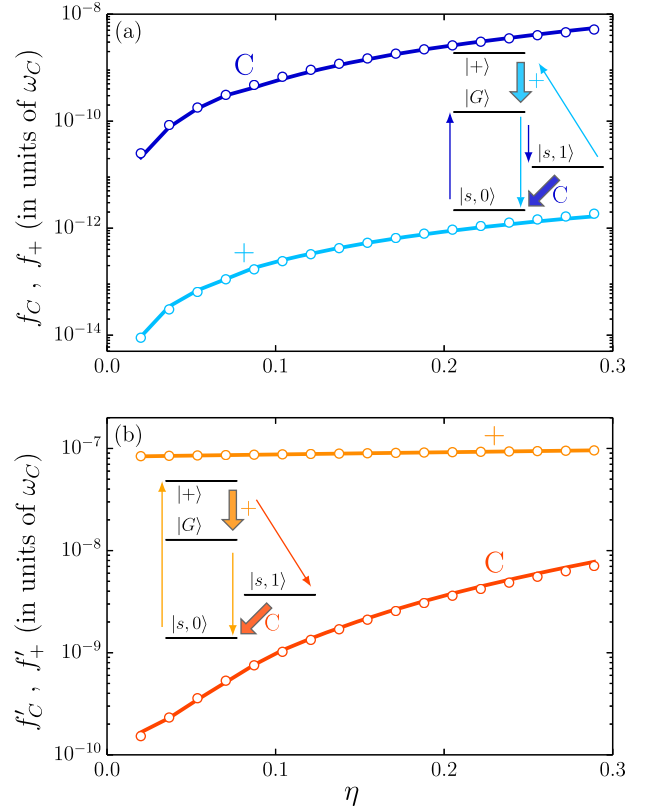


FIG. 3. (a) Integrated emission spectrum $S(\omega)$ (as in Fig. 2) for the central peak and one of the satellite channels for $\mu = \hbar\omega_G$, obtained by integrating the numerical spectrum (solid lines) and from the analytical estimates in Eq. (10) (open dots). In the inset we illustrate the GSE processes from Eqs. (6) and (7). (b) Integrated emissions for $\mu = \hbar\omega_G + \hbar\omega_+$, obtained by integrating the numerical spectrum (solid lines), and from the analytical estimates in Eq. (11) (open dots). Inset: Electroluminescence from Eqs. (5) and (12).

resonator seems to us the system better described by the simple model studied here, where $|s\rangle$ is the empty state, $|g\rangle$ and $|e\rangle$ are the hybridized states of a single excess electron delocalized over the two dots, and where higher electron number occupation states are prevented due to Coulomb blockade. Remarkably, electroluminescence has already been observed in those systems [50,51]. Given that the ratio $\Gamma/\Gamma_{\text{cav}}$ can be engineered in those systems, from Eq. (10) we obtain a rough estimate of the photon population, due to GSE, of $P \approx 0.1\eta^2$. Considering a conservative lower bound to the detectable photon population in microwave resonators of $P_{\text{min}} = 10^{-3}$ [51], $\eta > 0.1$ should thus suffice to observe GSE. This normalized coupling has been achieved in circuit QED [3,4]. In hybrid systems, experiments are moving toward higher couplings and the appropriate regime may become accessible in the near future.

In conclusion, we have highlighted a novel cavity QED phenomenon, leading to the purely quantum emission of photons out of the ground state when an electric current

passes through it. Such a novel form of quantum vacuum emission could be observed in various near-future cavity QED setups. As its characteristics critically depend upon the nature of the coupled ground state, observation of GSE will allow us to test our present understanding of light-matter coupling and take us a step forward in the engineering of the quantum vacuum in the ultrastrong coupling regime.

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