Controllable Switching between Superradiant and Subradiant States in a 10-qubit Superconducting Circuit

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Superradiance and subradiance concerning enhanced and inhibited collective radiation of an ensemble of atoms have been a central topic in quantum optics. However, precise generation and control of these states remain challenging. Here we deterministically generate up to 10-qubit superradiant and 8-qubit subradiant states, each containing a single excitation, in a superconducting quantum circuit with multiple qubits interconnected by a cavity resonator. The $\sqrt{N}$-scaling enhancement of the coupling strength between the superradiant states and the cavity is validated. By applying an appropriate phase gate on each qubit, we are able to switch the single collective excitation between superradiant and subradiant states. While the subradiant states containing a single excitation are forbidden from emitting photons, we demonstrate that they can still absorb photons from the resonator. However, for an even number of qubits, a singlet state with half of the qubits being excited can neither emit nor absorb photons, which is verified with 4 qubits. This study is a step forward in coherent control of collective radiation and has promising applications in quantum information processing.

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Since Dicke's seminal paper in 1954 [1], superradiance featuring the enhanced cooperative radiation of atoms has always been a research focus in quantum optics. Apart from intriguing physics such as the superradiant phase transitions [2,3], superradiance has promising applications in quantum communication [4,5], ultra-narrow-linewidth superradiant lasers [6,7], and sensitive gravimeters [8]. Besides superradiance, the cooperativity between the atoms can also lead to subradiance [9], the inhibited collective radiation closely related to the decoherence-free subspaces [10,11]. By taking advantage of their radiation characteristics, superradiance is perfect for fast writing and reading of quantum information while subradiance can be used in quantum memory [12]. This application in quantum information processing requires a fast switching between superradiance and subradiance, which is also a key ingredient in quantum battery [13–15].

Although superradiance has been demonstrated in many physical systems including hot [16,17] and cold atoms [18–23], trapped ions [24,25], nuclear x-ray radiation [26], and superconducting circuits [27–29], precise control of superradiant states and switching from superradiant to subradiant states remain challenging. For artificial atoms such as superconducting qubits, the maximum number of qubits demonstrated in superradiance is merely four [28,30]. Compared with superradiance, the experimental realization of subradiance is even more difficult due to their weak coupling with photons. In atomic ensembles only partial subradiance with a weak signal has been observed [31]. In trapped ions and superconducting circuits the maximum number of atoms in subradiant states is two [24,25,32]. Despite that the subradiant subspaces were already shown in Dicke's original paper, the transition between states in subradiant subspaces and the radiation properties of subradiant states containing more than one excitations have never been experimentally tested.

Superconducting circuits with advantageous controllability are a flexible platform for synthesizing exotic Hamiltonian [33] and quantum states [34]. In this Letter, we demonstrate the generation of superradiant states with up to 10 qubits and subradiant states with up to 8 qubits in a superconducting quantum circuit, where multiple qubits are directly coupled to a common bus resonator (R). The superradiant states are generated by a cooperative absorption of a photon from the resonator R and is characterized by the simultaneous readout of all qubits and the resonator, which yields Rabi oscillations validating the factor $\sqrt{N}$-enhanced coupling strength between the collective qubits and the resonator. By applying appropriate single-qubit phase gates, we demonstrate a controllable switching between superradiant and subradiant states, and show that the collective coupling can be enhanced or inhibited at will. While the single-excitation subradiant states cannot radiate photons into the resonator, we experimentally show that they can absorb another photon from the resonator. It is well known that the singlet states of an even number of spin excitations can be used in noiseless quantum codes [10,11]. We realize such a singlet subradiant state containing 2 excitations of 4 qubits and verify that it can neither emit nor absorb photons from the resonator.

The qubit-resonator interaction Hamiltonian is described by the Tavis-Cummings model [35] under the rotating-wave approximation,

$$\frac{H}{\hbar} = \omega_R a^\dagger a + \sum_{j=0}^{9} \omega_j \sigma_j^+ \sigma_j^- + \sum_{j=0}^{9} g_j (\sigma_j^+ a + \sigma_j^- a^\dagger), \qquad (1)$$

where $a^\dagger$ (a) is the creation (annihilation) operator of resonator R with a fixed frequency of $\omega_R/2\pi \approx 5.69$ GHz, σ_j^+ (σ_j^-) is the raising (lowering) operator of qubit Q_j with a frequency $\omega_j/2\pi$ tunable in the range from 5 to 6 GHz, and g_j is the Q_j-R coupling strength, which can be approximated as $g \equiv (\sum_{j=0}^{9} g_j^2/10)^{1/2} \approx 13.5$ MHz [36] since all g_j's are measured to be close [see Fig. 1(a) and the Supplemental Material [37] for more details].

We start with preparing the single-excitation superradiant state of N identical qubits $|B_N\rangle = (1/\sqrt{N}) \times \sum_{j=1}^{N} |0_1 0_2 \ldots 1_j \ldots 0_N\rangle$ using the pulse sequence illustrated in Fig. 1(b). After initializing all qubits in the ground state $|0_1 0_2 \ldots 0_N\rangle$ and resonator R in vacuum, we excite Q_0 to $|1\rangle$ using a π pulse and then tune it into resonance with R using a rectangular Z pulse for an iSWAP, which swaps the excitation (i.e., a microwave photon) into R. Next we apply rectangular Z pulses to all N qubits for them to be on resonance with R for an appropriate duration, so that the photon in R is equally distributed among the N qubits and we obtain $|B_N\rangle$. The final states of qubits are directly measured while the resonator photon number is obtained by making a swap with a specific qubit followed by qubit readout [37]. During the state generation, qubits not in use are far detuned and can be ignored.

To generate the subradiant counterpart of $|B_N\rangle$, we apply single-qubit phase gates, i.e., the small rectangular Z pulses in red in Fig. 1(b) to locally modify the phase of each qubit in order to generate a subradiant state denoted as $|D_N\rangle = (1/\sqrt{N}) \sum_{j=1}^{N} e^{-i\phi_j} |0_1 0_2 \ldots 1_j \ldots 0_N\rangle$, where $\phi_j = j(2\pi/N)$ [41]. There are $N-2$ other single-photon subradiant states by replacing ϕ_j with $m\phi_j$ ($m = 2, 3, \ldots, N-1$), which can be generated with the same technique. Here we focus on $|D_N\rangle$ for simplicity. The coupling strength between $|D_N\rangle$ and the N-qubit ground state $|0_1 0_2 \ldots 0_N\rangle$ is zero since they have different exchange symmetries and the interaction Hamiltonian retains this

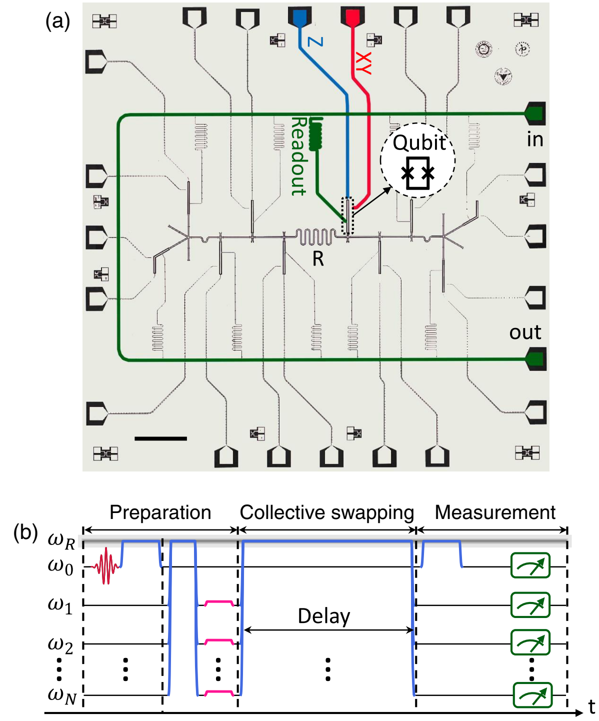

FIG. 1. (a) Image of the device where 10 qubits, shown as line shapes, are capacitively coupled to the central bus resonator. Each qubit has a Z line for frequency biasing, an XY line for microwave excitation, and a readout resonator for qubit state measurement. A ten-tone microwave signal, which targets the resonance frequencies of all readout resonators, is passed through the launch pads "in" and "out" as labeled for the multiqubit readout. The scale bar on the bottom-left corner indicates 1 mm. (b) Pulse sequences used to generate and characterize the single-excitation superradiant or subradiant states, where the horizontal axis is for time and the vertical axis represents frequency. For Q_0 with frequency ω_0, the sinusoid with a Gaussian envelope is a microwave pulse acting as a π-rotational gate. The two rectangular Z pulses with durations of t_{iSWAP} ($\approx\pi/2g$) are iSWAP gates: The first one transfers an excitation quantum from Q_0 to R and the second one is for measurement of the resonator population. For Q_1 to Q_N, the big rectangular Z pulses (blue) simultaneously bring all qubits into resonance with R: The first set has a duration of $\approx\pi/2\sqrt{N}g$ while the second set takes duration values continuously from 0 to 100 ns for observation of the collective swapping dynamics between the N qubits and R. The small rectangular Z pulses (red) are phase gates with durations of 100 ns for switching the superradiant to subradiant states. The switching time is reduced to 10 ns in a later cooldown [37].

symmetry [42]. However, these subradiant states can be excited to states with the same symmetry.

The most striking difference between superradiance and subradiance lies in their radiation properties, which can be witnessed by probing the collective swapping dynamics between the N qubits and R. Rabi oscillations in both the resonator photon number and the $|1\rangle$-state population P_1 of each qubit are well observed for the superradiant states as shown in Fig. 2(a). Based on fittings to the Rabi oscillation

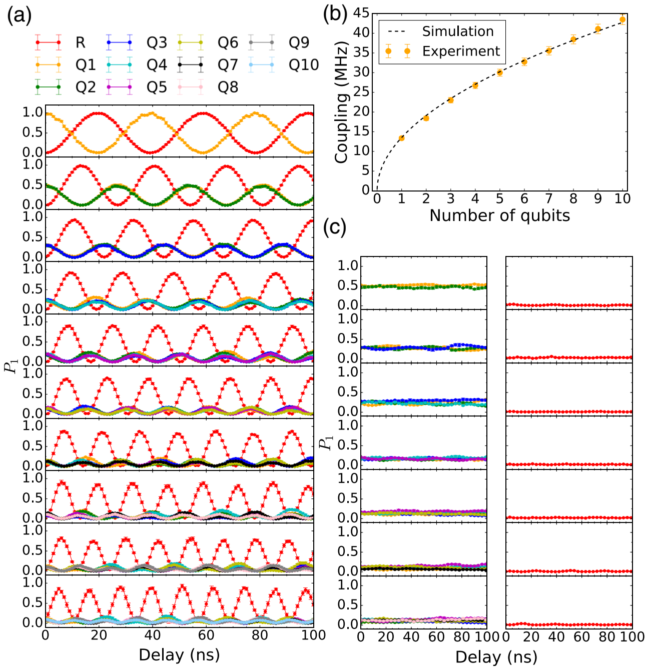

FIG. 2. (a) Collective swapping dynamics after the N qubits in superradiance are tuned into resonance with the resonator in vacuum. Shown are the population for the $|1\rangle$ state, P_1, of each qubit and that for the first excited state of resonator R, measured as functions of the swapping time using the pulse sequence shown in Fig. 1(b). $N = 1$ to 10 from up to down. For $N = 10$, we infer the resonator population by subtracting the P_1 sum of all 10 qubits from unity, instead of directly measuring R using Q_0 and an iSWAP gate. (b) Collective coupling strength (dots) vs N obtained by fitting the oscillation curves in (a) for the Rabi frequency. Line is a fit according to the $\sqrt{N}$ scaling. (c) Collective swapping dynamics between the N qubits ($N = 2$ to 8 from up to down) in subradiance and R. The same data are replotted with logarithmic scale in the Supplemental Material [37]. P_1 of each qubit is measured to be around $1/N$ (left) and that for the first excited state of R remains almost zero (right), where the observable small fluctuations are likely due to the imperfection of the initial state, the slight inhomogeneity in g_j and the qubit-qubit crosstalk couplings (typically less than 0.2 MHz).

curves for the superradiant states with up to 10 qubits, we extract the Rabi frequency as a function of N, which validates the $\sqrt{N}$-scaling enhancement of the collective coupling strength in Fig. 2(b). In contrast, the photon number remains nearly zero and P_1 maintains almost a constant around $1/N$ for the subradiant states as shown in Fig. 2(c). Therefore, the radiation rate of superradiance increases with a factor $\propto \sqrt{N}$ while that of subradiance is always negligible. In a second cooldown of the same device, we use quantum state tomography to characterize and optimize the state preparation process, yielding the state fidelity as high as 0.934 ± 0.008 for 8-qubit superradiant states and 0.911 ± 0.008 for subradiant states [37].

As proposed by Scully [43], the radiation properties of superradiance and subradiance have applications in

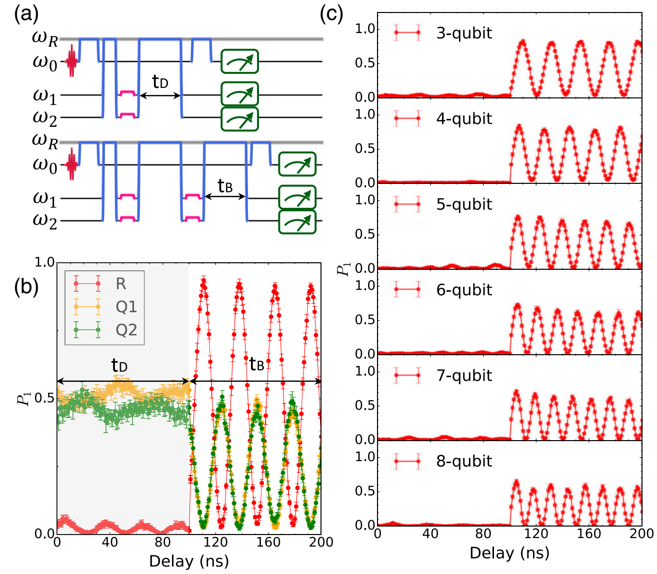

FIG. 3. (a) Pulse sequences used to implement the switching operation from subradiance to superradiance for $N = 2$. The first set of single-qubit phase gates (both the top and bottom panels), small rectangular Z pulses (red), is for generating subradiant states while the second set (the bottom panel) is inserted and configured for switching to superradiance. The collective swapping process is witnessed by tuning the N qubits into resonance with R using a set of big rectangular pulses (blue) followed by simultaneous readout of the N qubits and R. (b) Experimental results using the pulse sequences in (a) as indicated. The appearance of Rabi oscillations at 100 ns signifies the entrance from subradiance to superradiance. The small oscillations during t_D can be suppressed by improving the initial state fidelity [37]. (c) Experimental results of the resonator photon number as a function of the swap time using pulse sequences similar to those in (a), which demonstrate controllable switching operations from subradiance to superradiance with N from 3 to 8.

quantum information processing, where superradiance can be used to speed up reading or writing and subradiance is for storing quantum information. For the proposal to be viable, one needs to be able to switch between superradiant and subradiant states in a controllable manner, which can be accomplished by applying a series of single-qubit phase gates in our experiment. As demonstrated for $N = 2$ in Figs. 3(a) and 3(b), we first prepare a $N = 2$ subradiant state which stores a photon (i.e., the piece of quantum information) for 100 ns. As such, the resonator photon number remains nearly zero and P_1 of the two qubits stays around $1/2$ during the subsequent collective swapping dynamics. At $t = 100$ ns, we pause the swapping process by detuning the two qubits from resonator R, immediately apply single-qubit phase gates to switch the subradiant to superradiant state, and then resume the collective swapping dynamics. As expected from the radiation properties of subradiance or superradiance, the resonator photon number P_1 of the two qubits oscillate again, yielding Rabi oscillations which signify the entrance to superradiance.

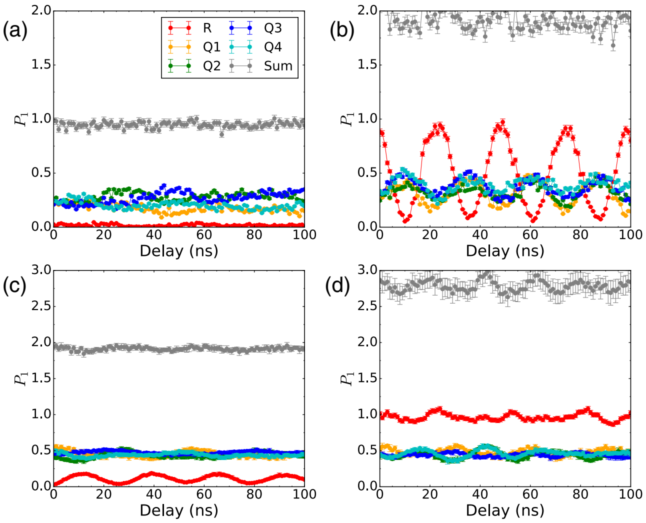

FIG. 4. (a) Collective swapping dynamics for the single-excitation subradiant state after the 4 qubits are tuned into resonance with the resonator in vacuum. Shown are the population for the $|1\rangle$ state, P_1, of each of qubit and that for the first excited state of resonator R, measured as functions of the swapping time using the pulse sequence shown in Fig. 1(b). Variations in P_1 are likely due to the slight inhomogeneity in g_j and the qubit-qubit crosstalk couplings that are not taken into account. Here the data are obtained using a similar experimental sequence as that in Fig. 2(c) for $N = 4$. (b) Collective swapping dynamics showing the well-defined Rabi oscillations for the single-excitation subradiant state after the 4 qubits are tuned into resonance with R that initially hosts a single photon. (c) Collective swapping dynamics for the 4 qubits in $|\psi_S\rangle$ while R is initialized in vacuum. (d) Collective swapping dynamics for the 4 qubits in $|\psi_S\rangle$ while R initially hosts a single photon.

In Fig. 3(c) we perform similar switching operations for N up to 8 qubits. Our switching operation can be of high fidelity. The quantum state tomography data show that the fidelity of the 8-qubit subradiant state right before switching and that of the corresponding superradiant state right after switching differ by less than 2%, which indicates that the switching fidelity is more than 0.98 [37]. It is seen that, as N increases, the Rabi oscillation between the N qubits and R, which can be used for reading or writing, speeds up by a factor of $\sqrt{N}$ although the efficiency, which is related to the oscillation amplitude, actually decreases due to the inhomogeneous crosstalks between the qubits during the subradiant stage. The tiny oscillations of the photon number in the resonator before switching and the reduced Rabi oscillation amplitudes after switching are likely caused by the inhomogeneity in g_j's and imperfection of the subradiant state before switching. We have performed another experiment to illustrate this effect [37].

The flexibility of our device allows us to further investigate the radiation properties of the collective states in subradiant subspaces. Here we show the experimental data of the collective interaction between a group of 4 qubits in the single-excitation subradiant state and R. No Rabi oscillation is observed in Fig. 4(a), which indicates that the subradiant state is decoupled from R in vacuum; i.e., the subradiant state cannot emit a photon to R. However, after injecting an additional photon into R [37], we observe Rabi oscillations as shown in Fig. 4(b); i.e., this second photon can still be collectively absorbed by the qubits in subradiance.

One major challenge in quantum information processing is the unavoidable decoherence due to the interaction between the quantum system and the environment. A possible solution to this problem is the noiseless quantum code in the decoherence-free subspace where the effect of the environmental noise is minimized [10,11]. A particularly interesting candidate for the noiseless quantum code is the singlet state with even number of qubits [10]. These states can neither absorb nor emit photons, although half of the qubits are excited. We generate such a state of 4 qubits by implementing two parallel $\sqrt{\text{iSWAP}}$ gates [44] to obtain two Einstein-Podolsky-Rosen qubit pairs in the form of $(|10\rangle - |01\rangle)/\sqrt{2}$, and the 4-qubit state can be written as $|\psi_S\rangle = (|1100\rangle - |0110\rangle + |0011\rangle - |1001\rangle)/2$. We show the collective swapping dynamics of $|\psi_S\rangle$ for the case of R in vacuum in Fig. 4(c) and that of R hosting a single photon in Fig. 4(d). Despite the small oscillations which are less than 10% of the two excitation quanta hosted in the joint system, no significant exchange of excitations between the 4 qubits in $|\psi_S\rangle$ and R is observed, no matter whether R is in vacuum or not. The remaining exchange of photons between the qubits and R is due to the inhomogeneity of the coupling strengths g_j's, which render $|\psi_S\rangle$ an imperfect subradiant state.

In conclusion, we have deterministically generated multiqubit superradiant or subradiant states and demonstrated controllable processing using phase gates which switch the subradiant states to their superradiant counterparts in a 10-qubit superconducting circuit. Our observation verifies the $\sqrt{N}$-scaling enhancement of the coupling strength between the superradiant states and the resonator, as well as the inhibited interaction between subradiant states and the resonator. We have also generated the singlet state of 4 qubits with 2 excitations, which can be used in the noiseless quantum code and simulating quantum gravity [45]. Therefore, our experiment represents a step forward in coherent control of collective radiation and has promising applications in quantum information processing.

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