Emerging Ultrastrong Coupling Between Light and Matter Observed in Circuit Quantum Electrodynamics

Kouichi Semba

Abstract The strength of the coupling between an atom and a single electromagnetic field mode is defined as the ratio of the vacuum Rabi frequency to the Larmor frequency, and is determined by a small dimensionless physical constant, the fine structure constant $\alpha = Z_{vac}/2R_K$. On the other hand, the quantum circuit including Josephson junctions behaving as artificial atoms and it can be coupled to the electromagnetic field with arbitrary strength (Devoret et al[.](#page-1-0) [2007\)](#page-1-0). Therefore, the circuit quantum electrodynamics (circuit QED) is extremely suitable for studying much stronger light-matter interaction.

We have used a Josephson junction atom, a flux qubit, harmonic oscillator coupled system. This circuit is well described by the Hamiltonian shown in Eq. [\(1\)](#page-0-0).

$$
\mathcal{H}_{\text{total}} = -\frac{\hbar}{2}(\Delta \sigma_x + \varepsilon \sigma_z) + \hbar \omega_0 (\hat{a}^\dagger \hat{a} + \frac{1}{2}) + \hbar g \sigma_z (\hat{a} + \hat{a}^\dagger). \tag{1}
$$

The first, second, and third terms represent the energy of the qubit, the energy of the harmonic oscillator, and the interaction energy, respectively. If the coupling strength g becomes as large as the atomic and cavity frequencies (Δ and ω_o , respectively), the energy eigenstates including the ground state are predicted to be highly entangled (Hepp and Lie[b](#page-1-1) [1973;](#page-1-1) Ashhab and Nor[i](#page-1-2) [2010](#page-1-2)). We have experimentally achieved this deep strong coupling using a superconducting-flux-qubit LC-oscillator system (Yoshihara et al[.](#page-1-3) [2017](#page-1-3)). By carefully designing a superconducting persistent-current qubit interacting with an LC harmonic oscillator that has a large zero-point fluctuation current via a large shared Josephson inductance, we have realized circuits with $\frac{g}{\omega_o}$ ranging from 0.72 to 1.34 and $\frac{g}{\Delta} \gg 1$. From the transmission spectroscopy, we have observed unconventional transition spectra and selection rules which can be interpreted using predicted energy levels which are well described by Schrödingercat-like entangled states between persistent-current states and displaced vacuum or Fock states of the oscillator (Yoshihara et al[.](#page-1-3) [2017](#page-1-3)). By using two-tone spectroscopy, the energies of the six lowest levels of each circuit have been determined. We have

K. Semba (\boxtimes)

National Institute of Information and Communications Technology, 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan e-mail: semba@nict.go.jp

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observed huge light shifts, i.e., Lamb shifts, qubit energy shift due to coupling to vacuum field, that exceed 90% of the bare qubit frequencies and Stark shifts, inversions of the qubits' ground and excited states when there are only a few photons in the oscillator (Yoshihara et al[.](#page-1-4) [2018\)](#page-1-4). We have also observed collective coupling between an engineered 4300 ensemble of flux qubits and a superconducting resonator (Kakuyanagi et al[.](#page-1-5) [2016\)](#page-1-5), and considered the condition for observing generation of superradiant ground state in the presence of parameter fluctuations (Ashhab and Semb[a](#page-1-6) [2017](#page-1-6)).

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