Discovery of a Stable Molecular State Consisting of Photons and an Artificial Atom

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Abstract

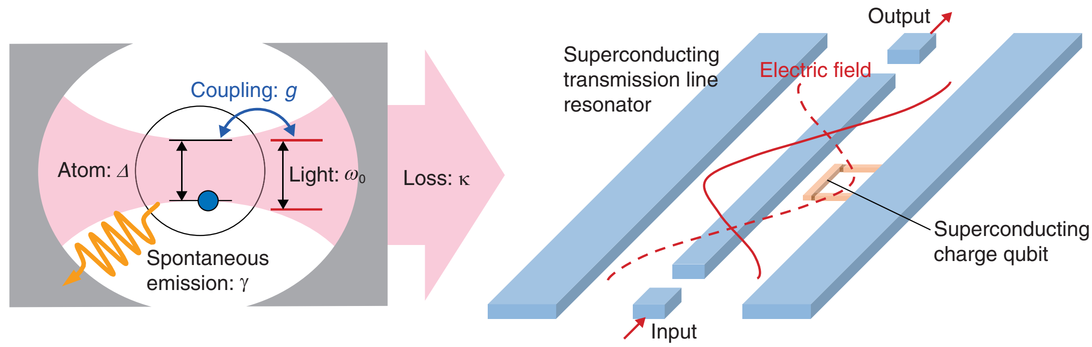
In a joint study with the National Institute of Information and Communications Technology and the Qatar Environment and Energy Research Institute, we have conducted experiments to alter the strength of interactions between a superconducting artificial atom and microwave photons. We have confirmed the existence of a qualitatively new lowest energy ground state where an artificial atom is dressed with virtual photons to form a novel type of molecule. Our research makes it possible to control the interactions between matter and light over a range of energies orders of magnitude higher than has hitherto been possible. This is expected to have applications in quantum technologies including quantum communication, quantum computing, and next-generation ultraprecise atomic clocks.

Keywords: superconducting artificial atom, circuit QED, deep strong coupling regime

1. Introduction

The interaction between atoms and light described by quantum electrodynamics (QED) was first formulated in the early 20th century. By treating light as particles (photons), QED can accurately describe phenomena such as the absorption, emission, and scattering of photons by atoms. At that time, QED treated light in free space, where the light fields are naturally modeled using infinitely extended plane waves. Because the energy of a photon in such a plane wave is spread over a very large volume, the interaction (coupling) strength between atoms and light is extremely small. Researchers are therefore looking at ways of increasing the strength of these interactions by confining light in the space between two opposing mirrors (i.e., a cavity). This will strengthen the coupling of light to an atom situated inside this cavity. This field—which is called cavity QED—has been attracting attention because it allows optical responses to be controlled at a single atom level, which is a fundamental requirement for the implementation of quantum information technologies.

The superconducting quantum bits (qubits) that have been studied with the aim of implementing quantum information technologies in the microwave regime have energy levels resembling those of atoms. For this reason they are called *artificial atoms*. Their greatest advantage is the design flexibility of superconducting circuits, enabling the design of systems where superconducting qubits interact with superconducting resonators. This system, which is called a circuit QED system, can achieve coupling of unprecedented strength between superconducting qubits and microwave photons confined inside a superconducting resonator circuit. Using a circuit QED system, we have successfully demonstrated strong coupling several orders of magnitude stronger than in the optical cavity QED regime. This article introduces the new physical phenomena that we have observed as a result.



(a) Cavity QED

(b) Circuit QED

Weak coupling, Jaynes-Cummings model

$$H_{JC} = \underbrace{\frac{1}{2}\hbar\Delta\hat{\sigma}_z}_{\text{Atom}} + \underbrace{\hbar\omega_0\hat{a}^{\dagger}\hat{a}}_{\text{Light}} + \underbrace{\hbar g\,(\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^{\dagger})}_{\text{Coupling}}$$

Strong coupling, Rabi model

$$H_{JC} = \underbrace{\frac{1}{2}\hbar\Delta\hat{\sigma}_z}_{\text{Atom}} + \underbrace{\hbar\omega_0\hat{a}^{\dagger}\hat{a}}_{\text{Light}} + \underbrace{\hbar g\hat{\sigma}_x\,(\hat{a} + \hat{a}^{\dagger})}_{\text{Coupling}}$$

(c) Hamiltonian

Fig. 1. Quantum electrodynamics and model Hamiltonians.

2. Cavity QED

The simplest model of interactions between atoms and light in QED consists of single-mode (single-wavelength) light interacting with a simple two-level atom. Such a system is thought, however, to be difficult to implement, as it is impossible to confine light to a single mode in free space (space of infinite extent). This led to the idea that if light is confined to a resonator comparable in size to its wavelength, then the wavelength will change from continuum of modes to discrete modes, one of which will be able to interact with the atom. This led to the emergence of cavity QED. These systems are generally classified according to three key parameters: (1) the coupling strength (g) between the atom and light, (2) spontaneous emission rate (γ) from the atom, and (3) loss rate (κ) of light from the resonator (**Fig. 1(a)**). The strong coupling regime is achieved when the coupling strength is greater than the other two parameters ($g > \gamma, \kappa$), while the system is said to be in the weak coupling regime when the converse holds ($g < \gamma, \kappa$). Even in the weak coupling regime, phenomena such as enhanced spontaneous emission from the atom due to coupling with the resonator (Purcell effect) are observed.

In general, interactions between the atom and light are weak, and it is not easy to achieve strong coupling even when using a resonator. A group led by Serge Haroche at the École Normale Supérieure in Paris prepared Rydberg atoms with electrons excited to very large orbitals with principal quantum numbers of n = 50 and 51. Because of the large size of the electron orbitals, the Rydberg atoms had dipole moments some 1250 times greater than that of a single atom, and they were able to couple strongly to the electric field of light. The researchers also reduced the spontaneous emission rate γ from the atoms by using circular electron orbitals with good symmetry and suppressed the loss rate of light κ from the resonator by creating a Fabry-Perot cavity with spherical mirrors made of superconducting niobium with low dissipation. As a result, they entered the strong coupling regime, where photons spontaneously emitted from an atom remain in the cavity and are once again absorbed by the atom. This repeated emission and absorption resulted in a phenomenon called vacuum Rabi oscillation [1]. This showed that it is possible for quantum information in the atoms to be transferred to photons, and vice versa. This property attracted attention as a fundamental technology of quantum information processing. Haroche received the 2012 Nobel Prize in physics in recognition of this achievement and his other contributions in the field.

3. Circuit QED

The basic element of a superconducting quantum circuit is an LC resonator consisting of an inductor of inductance L and a capacitor of capacitance C. The resonator has equally spaced energy levels, and if its temperature is sufficiently low compared with the level spacing, it is able to exhibit quantized level effects. Since the levels are equally spaced, though, it is not possible to form qubits or artificial atoms using two specific levels. However, by introducing a Josephson junction into the circuit (where it acts as a nonlinear inductance), we can produce a superconducting artificial atom. A Josephson junction has both an inductance component and a capacitance component, and the properties of the artificial atom vary according to the relationship between these components.

Magnetic flux is a good quantum number in a junction with greater inductive energy and produces an artificial atom that is more sensitive to magnetic fields, whereas electric charge is a good quantum number in a junction with greater capacitive energy and produces an artificial atom that is more sensitive to electric fields. The level spacing of superconducting artificial atoms produced in this way covers the microwave band from a few gigahertz to several tens of gigahertz. To enter the strong coupling regime between microwaves and superconducting artificial atoms, the microwaves must be confined inside a superconducting resonator with a strong field (magnetic or electric).

To develop a resonator that works well with superconducting artificial atoms arranged on a two-dimensional chip, we can choose from two types of resonators. One is a superconducting LC resonator consisting of lumped circuit elements, and the other is a distributed superconducting resonator consisting of a half-wave transmission line coplanar waveguide. We should design the superconducting artificial atom to an inductive or a capacitive regime to match the fields produced by each resonator (**Fig. 1(b)**). The most important feature of this system (circuit QED system) is that it is possible to artificially design both the atoms and the resonator, enabling the formation of an ultrastrong coupling regime that has not been possible to achieve in cavity QED.

Experiments that paved the way to modern circuit QED were performed independently and almost simultaneously in 2004 at Delft University of Technology and Yale University [2, 3]. The team at Yale University used a charge-type superconducting artificial atom with a coplanar superconducting transmission line resonator to realize strong coupling via an electric field. They observed vacuum Rabi splitting in the resonator's transmission spectrum. At NTT, we observed in 2006 vacuum Rabi oscillations using a magnetic flux type artificial atom coupled to a superconducting LC resonator [4].

These experiments in the strong coupling regime were reproduced well by the Jaynes-Cummings model (**Fig. 1(c)**), but two experiments in the ultrastrong coupling regime that did not satisfy this approximation were reported in 2010 [5, 6]. The spectra could not be reproduced by the Jaynes-Cummings model in the region where the coupling strength g of an artificial atom satisfies the condition $g > 0.1\Delta, 0.1\omega_0$ (where Δ is the atom's transition frequency and ω_0 is its light frequency). In our research, we have further intensified the coupling strength to produce the deep strong coupling regime ($g > \Delta, \omega_0$), and we confirmed the appearance of a new lowest energy ground state [7]. The coupling strengths that have so far been observed in circuit QED are compared in **Fig. 2**.

4. Flux qubits and LC resonators

The sample used in this research is shown in **Fig. 3**. The superconducting artificial atom we used was a flux-type device in which the superconducting current I_P flows anticlockwise |L> or clockwise |R>, while the superconducting resonator was a lumped element LC resonator. Under a suitable magnetic field, a superposition state between |L> and |R> is realized in the superconducting artificial atom, and it behaves as a quantum two-level system. In the superconducting resonator, the amount of stored energy is determined by the magnitude of the alternating current flowing in the loop, and the addition of each individual microwave photon excites the resonator in its equally spaced energy levels given by the resonant frequency. The alternating current in the resonator when there are zero microwave photons (vacuum state) is called the zero-point fluctuation current (I_{ZPF}). The artificial atom and the superconducting resonator are coupled via a magnetic field with coupling strength g. The coupling strength is expressed as the product of the coupling inductance L_C, I_P, and I_{ZPF}.

Unlike a charge-type artificial atom that couples to a resonator via electric fields, a flux-type atom can share the coupling inductance between the artificial atom and resonator, which makes it possible to take full advantage of L_C. When a Josephson junction is used as the coupling inductance, it is possible to achieve a much larger coupling inductance than with

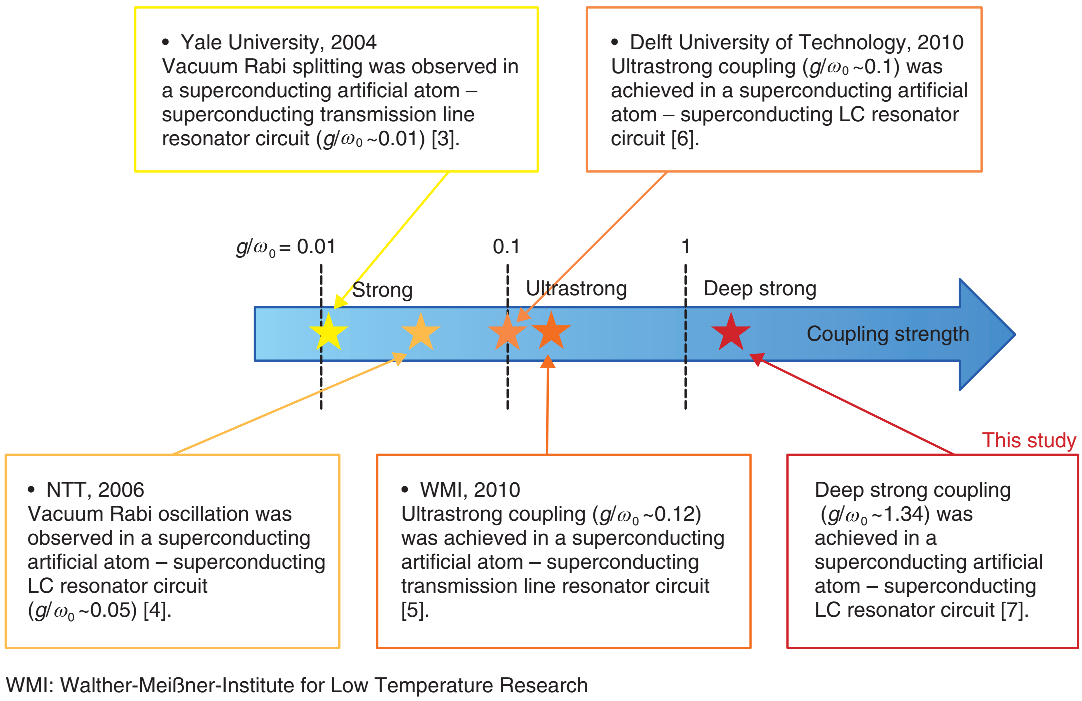


Fig. 2. History of coupling strength in circuit QED.

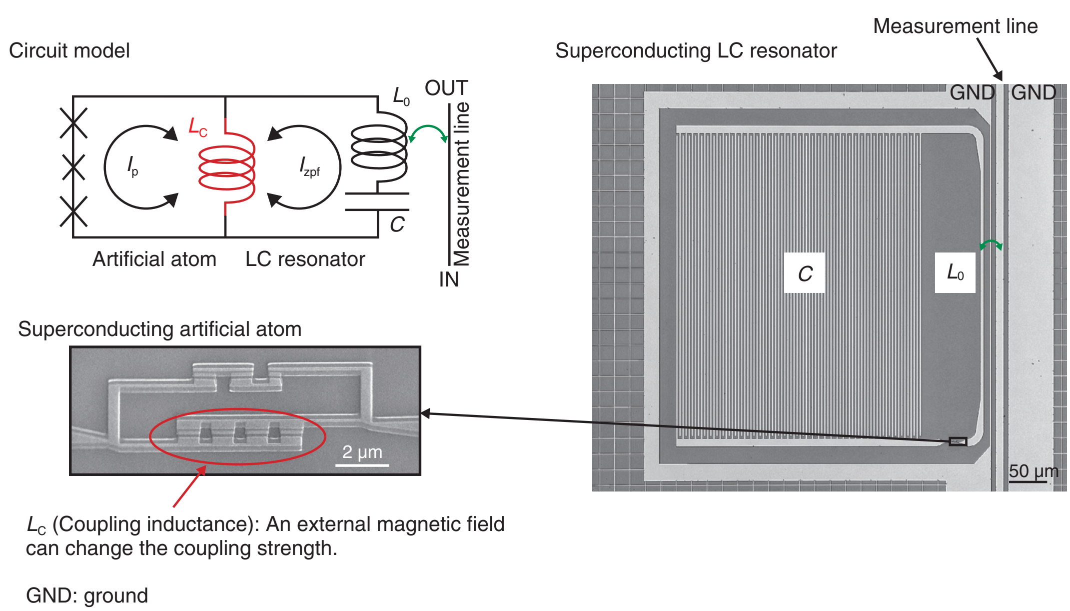


Fig. 3. Superconducting artificial atom – LC resonator coupled system.

a conventional linear circuit. On the other hand, when the resonator is designed with a small L_0 and large C (Fig. 3), it is possible to increase I_{ZPF} while keeping the resonant frequency constant. In this way, by making use of the flexibility in circuit design (a major feature of superconducting circuits), we produced a

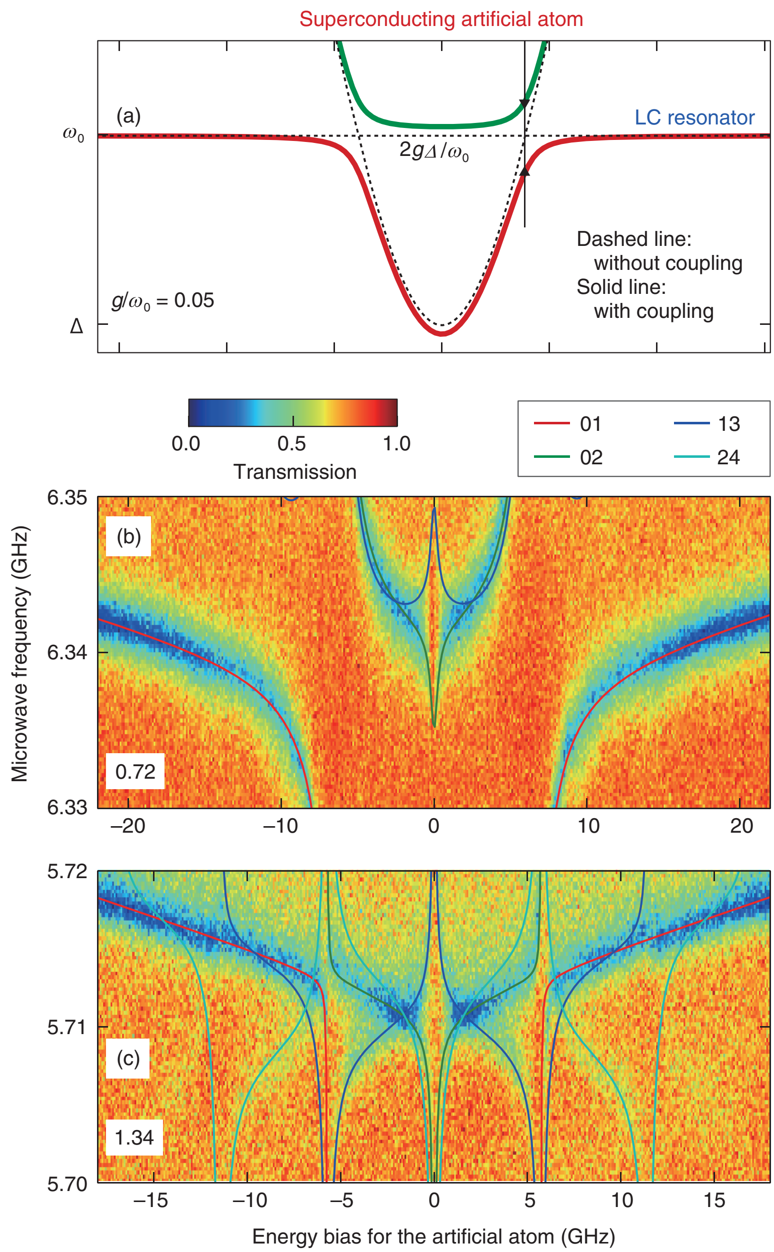
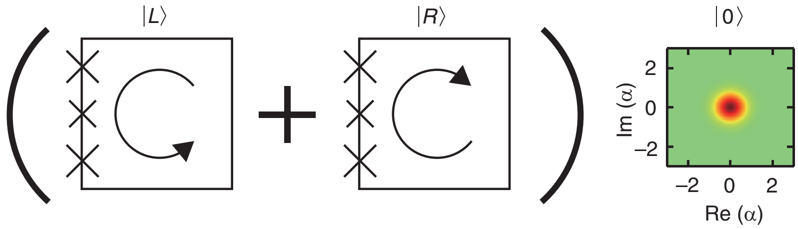


Fig. 4. Transmission spectra for the coupled system.

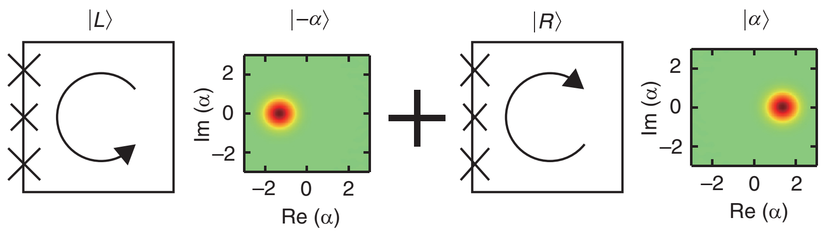
sample operating in the deep strong coupling regime.

5. Confirmation of deep strong coupling regime

In a system where a superconducting artificial atom and LC resonator are strongly coupled, anti-crossings of the energy levels (vacuum Rabi splitting) are observed at points where the transition energies of the two are equal (**Fig. 4(a)**). The size of these anti-crossings $2g\Delta/\omega_0$ represents the effective coupling strength. To measure the energy levels in this study, we measured the transmission characteristics of a microwave waveguide inductively coupled to the LC resonator (**Figs. 4(b)(c)**). At frequencies corresponding to the spacing between any two energy levels, absorption takes place and the microwave transmission intensity decreases. In Fig. 4(b), the vacuum Rabi splitting was observed and the signal disappeared at zero energy bias. In contrast, in Fig. 4(c), complex energy levels were observed including a



(a) Typical lowest energy state (ground state)



(b) New ground state: atom and light are entangled

Fig. 5. Energy ground state of the coupled system.

reduction of the vacuum Rabi splitting. These energy levels are well reproduced by simulations based on a model that does not use a rotating wave approximation (Fig. 1(c)). From the theoretical fits, the values of g/ω_0 are obtained respectively to be 0.72 and 1.34 for Figs. 4(b) and (c), indicating that the circuits are in the deep strong coupling regime.

At the point where the artificial atom has zero energy bias, the ground state of the uncoupled circuit is expressed as the product $(|L\rangle + |R\rangle)|0\rangle$ of the artificial atom's ground state $|L\rangle + |R\rangle$ and the resonator's vacuum state |0>. However, the ground state in the deep strong coupling regime is expected to be an entangled state (**Fig. 5**) of $|L\rangle|{-\alpha}\rangle + |R\rangle|\alpha\rangle$ (where $|\alpha\rangle$ and $|{-\alpha}\rangle$ are the microwave photon coherent states). Our numerical simulations reproduced these complex energy level structures very well, suggesting the existence of entanglement between the artificial atom and microwave photons. By measuring the artificial atom in a suitable way, we should be able to create a macroscopic microwave photonic superposition state (Schrödinger's cat state; $|{-\alpha}\rangle + |\alpha\rangle$) from this entangled state. This state has the degrees of freedom of multiple photons and is expected to have applications including noise-resilient quantum computing and precise frequency measurements.

6. Future prospects

In this research, we achieved an entangled state between a single superconducting artificial atom and microwave photons in the deep strong coupling regime. According to some theoretical studies, a similar ground state may not occur in the deep strong coupling regime for multiple artificial atoms and photons. Hence in the future, we plan to verify this theory by increasing the number of artificial atoms. Also, to improve the quantum state control techniques for quantum communication node technology and to achieve better control of ground states in multi-body systems, we plan to continue with research aimed at improving the techniques for manipulating these entangled states and clarifying the dynamics of light absorption and emission.

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