4-3 New Regime of Circuit Quantum Electro Dynamics

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Researchers at the National Institute of Information and Communications Technology (NICT), in collaboration with researchers at the NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation (NTT-BRL) and the Qatar Environment and Energy Research Institute (QEERI) have discovered qualitatively new lowest energy state of a superconducting artificial atom dressed with virtual photons. The discovery was made using spectroscopic measurements on an artificial atom that is very strongly coupled to the electromagnetic field inside a superconducting resonator. This result provides a new platform to investigate the interaction between light and matter at a fundamental level, helps understand quantum phase transitions and provides a route to applications of non-classical light such as Schrödinger cat states. It may contribute to the development of quantum technologies in areas such as quantum communication, quantum simulation and computation, or quantum metrology.

1 Introduction

NICT is developing ultra-high-precision atomic clocks, and NTT (Nippon Telegraph and Telephone Corporation) and NICT are jointly pursuing safe, energy-efficient communications. These technologies are indispensable to modern life and are based on the fundamental science of the interaction between light and matter at the single-photon level. Absorption and emission of light by/from any device is explained based on the interaction of light and atoms. A fundamental question in atomic physics, “How strong can the coupling of light and an atom be?,” has not been answered in spite of years of research, because it is not easy to find appropriate methods to realize very strong coupling. This situation changed with the advent of circuit quantum electrodynamics (circuit-QED) which enabled experiment of superconducting artificial atoms[*1] (quantum bits) instead of natural atoms.

2 Cavity quantum electrodynamics (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 a 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). 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.

[*1] A superconducting artificial atom denotes a superconducting quantum circuit with atom-like discrete energy levels. When the atom is approximately a two-level quantum system within a certain energy or temperature range, it is also called a quantum bit. In this paper, a superconducting artificial atom refers to a superconducting flux qubit shown in the red rectangle in Fig. 3. A superconducting flux qubit is actually a superconducting electric circuit containing several so-called Josephson junctions composed of an extremely thin, nanometer thick insulator sandwiched by superconductors. The qubit is capable of controlling the magnitude of energy level splitting within several GHz range by changing the bias magnetic flux penetrating the loop. If the energy splitting of a superconducting qubit is about several GHz, the qubit need to be operated at temperatures lower than approximately 0.1 K.

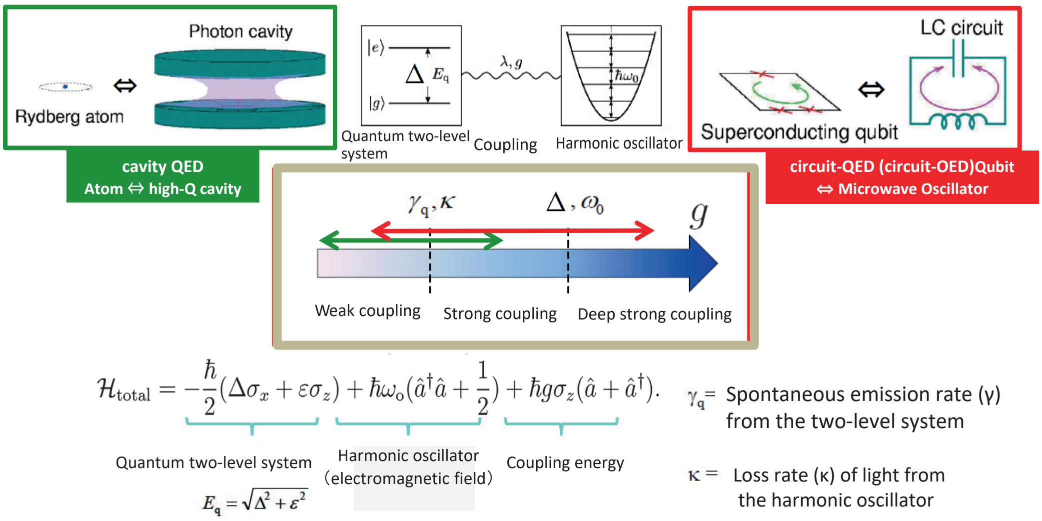


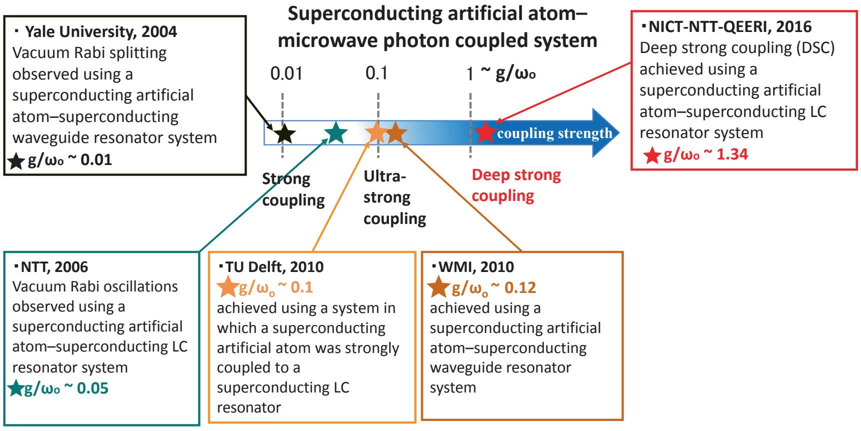
Fig. 1 Three coupling regimes of the resonator (circuit) quantum electrodynamics and the model Hamiltonian.

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 1,250 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 using a Fabry-Pérot cavity with spherical mirrors made of superconducting niobium with low dissipation (the resonator Q value as large as 10^8). 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]. Recent technological advancement enabled the resonator Q value to increase to its maximum limit (approximately 10^{10}) and photon relaxation time to extend. Consequently, photons in a resonator were quantified non-destructively using Rydberg atoms, and quantum feedback to stabilize the photon state in resonators was achieved using these atoms. 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. The two pioneers in the quantum technology field —David J. Wineland (NIST-Boulder) and Serge Haroche (Collège de France, ENS-Paris)— won the 2012 Nobel Prize in physics.

3 Circuit quantum electrodynamics (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, 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 su-



・Yale University, 2004
Vacuum Rabi splitting observed using a superconducting artificial atom–superconducting waveguide resonator system
★g/ω_0 ~ 0.01

・NICT-NTT-QEERI, 2016
Deep strong coupling (DSC) achieved using a superconducting artificial atom–superconducting LC resonator system
★g/ω_0 ~ 1.34

・NTT, 2006
Vacuum Rabi oscillations observed using a superconducting artificial atom–superconducting LC resonator system
★g/ω_0 ~ 0.05

・TU Delft, 2010
★g/ω_0 ~ 0.1
achieved using a system in which a superconducting artificial atom was strongly coupled to a superconducting LC resonator

・WMI, 2010
★g/ω_0 ~ 0.12
achieved using a superconducting artificial atom–superconducting waveguide resonator system

Fig. 2 History of coupling strength in circuit QED

The coupling strength between photons and a superconducting artificial atom increased by more than 100 times in the past 12 years. The coupling strength recently reached the DSC regime ($g/\omega_0 > 1$) for the first time in 2016 by the NICT-NTT-QEERI joint team (the red textbox on the upper right), which 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.

perconducting 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 reach an inductive or a capacitive regime to match the fields produced by each resonator (Fig. 1). 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. The first vacuum Rabi oscillations were observed by NTT in 2006 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, 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 $g \gtrsim 0.1\Delta, 0.1\omega_0$ (where Δ is the atom's transition frequency and ω_0 is the resonator's frequency). In our research, we have further increased the coupling strength to produce the deep strong coupling (DSC) regime ($g > \Delta, \omega_0$), and we confirmed the appearance of a new lowest energy state (ground state) [7][8]. The coupling strengths that have so far been observed in circuit QED are compared in Fig. 2.

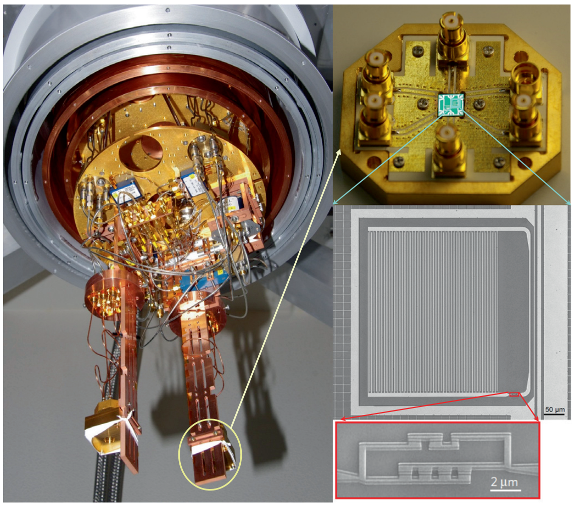


Fig. 3 Measurement system and superconducting quantum circuits used in experiments

(Left) Microwave measurement system incorporated into a dilution refrigerator.
Superconducting quantum circuits need to be precisely measured at the single microwave photon level while preventing thermal excitation. Therefore, the samples are cooled to cryogenic temperature (approx. 10 mK) using a dilution refrigerator. A superconducting quantum circuit is highly sensitive to magnetic noise and therefore is placed in a magnetic shield reducing the strength of the external magnetic field to about 1/1000.
(Top right) Measured sample chip placed in the holder
(Bottom right) A superconducting artificial atom coupled to a harmonic oscillator (both are made of aluminum) in the deep strong coupling state (red rectangle)

4 Results of theoretical research and experiments exploring novel energy states

It was predicted over 40 years ago that if the coupling is extremely strong, a qualitatively new lowest energy state (the ground state) of light and an atom should be realized. A debate soon started as to whether this prediction would still apply when realistic conditions are considered. Our research collaborator Dr. S. Ashhab (QEERI) and others conducted theoretical study several years ago to define conditions necessary to observe the novel ground state using a superconducting circuit [9].

During our recent experiment, we prevented our sample from thermal excitation at the single microwave photon level. Accordingly, we used a dilution refrigerator (Fig. 3) to cool the sample. We used a superconducting artificial atom with quantum properties similar to those of atoms made by microfabrication techniques and photons confined in a superconducting circuit. Specifically, we designed a circuit composed of an LC resonance circuit with large zero-point fluctuation current and a superconducting persistent-current qubit (Fig. 4). These components share a large Josephson inductance[*2], thereby enabling very strong magnetic coupling. We performed experiments in which we took spectroscopic measurements of the superconducting electric circuit (transmission spectrum measurements at the single photon level as shown in Fig. 5) and analyzed the obtained spectra. As a result, we confirmed a novel ground state as predicted [7]. The total energy of the artificial atoms in the circuit is the sum among the energy of the light involved, the energy of the atoms and the interaction energy between the light and atoms. By taking advantage of superconducting artificial atoms as the macroscopic quantum system[*3], we succeeded to make light-atom interaction energy larger than the energy of the light itself and the energy of the atoms themselves (i.e., we achieved $g > \Delta, \omega_0$ or the DSC regime).

It had been previously observed that the interaction energy between light and atoms —especially that generated when atoms are influenced by vacuum fluctuations of the electromagnetic field— produced only a tiny (less than 1 ppm) perturbation energy (a Lamb shift, for example)

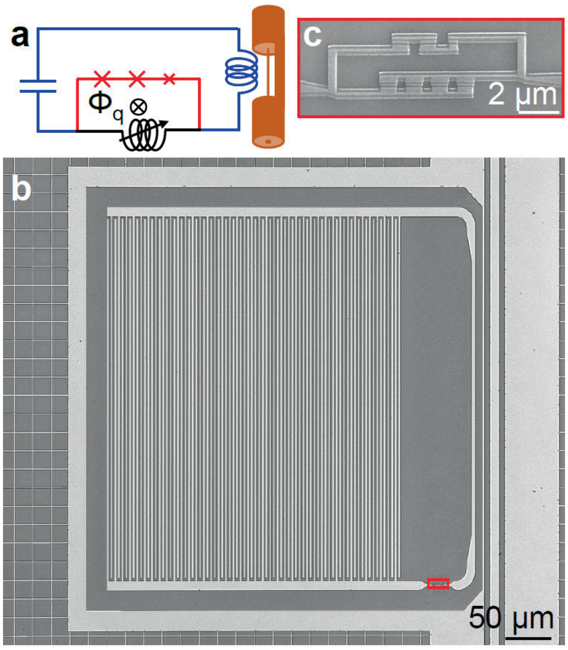


Fig. 4 Superconducting artificial atom – LC resonator coupled system

a. An equivalent circuit ("X" and "x" in the circuit represent Josephson junctions), an LC circuit (blue and black) and a superconducting artificial atom (red and black)

b. Superconducting artificial atoms integrated into a part of the quantum LC circuit (red rectangle)
The white parts are made of aluminum and the gray parts are silicon substrates.

c. Superconducting artificial atom (enlarged view of the red rectangle in b)
Four Josephson junctions are installed in parallel along the side shared by the artificial atom and the quantum LC circuit. The system's SQUID structure enables it to behave like a variable inductor (black part in the equivalent circuit in a) when different external magnetic fields are applied. As such, this system enables the realization of multiple different coupling strengths in the same sample.

[*2] Josephson inductance refers to a superconducting state inductance of a Josephson junction, a device composed of two superconductors sandwiching a very thin (atomic level) barrier layer. When the junction —which weakens superconductivity— receives external electromagnetic signals, it generates nonlinear responses unique to superconducting states. The highly sensitive magnetic field sensor SQUID (superconducting quantum interference device) contains multiple Josephson junctions distributed along its superconducting loop. SQUID takes advantage of superconducting current flowing through the loop which is highly sensitive to the magnetic field penetrating the loop. In our recent experiment, we actively used the large inductance of Josephson junctions to achieve strong coupling. We fabricated Josephson junctions in the part of the LC resonance circuit which is shared with a superconducting artificial atom (the variable inductor indicated in black in the equivalent circuit in Fig. 4a). This arrangement strengthened the coupling between the atom and the circuit to reach the DSC regime.

[*3] In a superconducting state, a tremendous number of electron pairs occupy the same quantum state. Under this condition, a phase-coherent quantum state emerges at a scale much larger than the atomic scale (i.e., the macroscopic scale). Accordingly, the use of superconductors can enable the current state of the artificial electric circuit —which is produced using microfabrication technology— to behave like a single massive electron pair. This type of a system is called a macroscopic quantum system. It is feasible to obtain physical quantities (in the forms of electric current, magnetic moment, polarization, etc.) on a much larger scale than the atomic scale while preserving quantum coherence. Other known examples of macroscopic quantum systems, besides superconductivity, include superfluidity, photons in a laser state and Bose-Einstein condensation in dilute atomic gas.

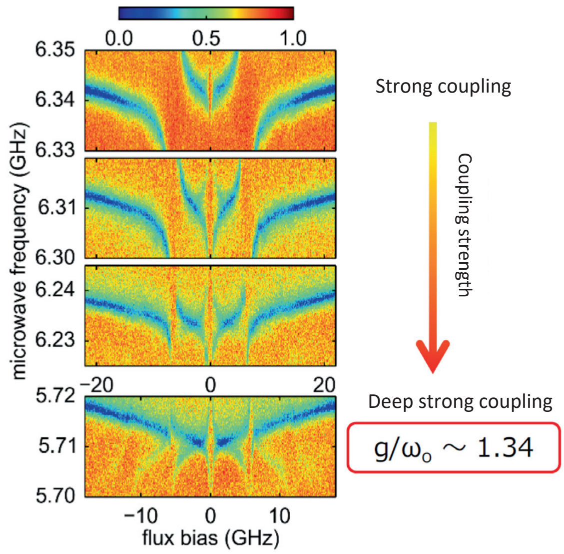
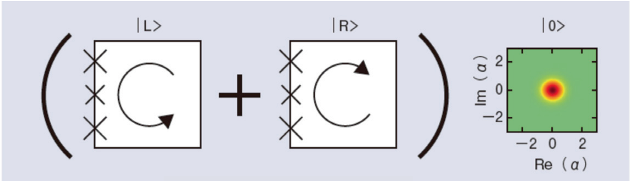


Fig. 5 Transmission spectra for the coupled system

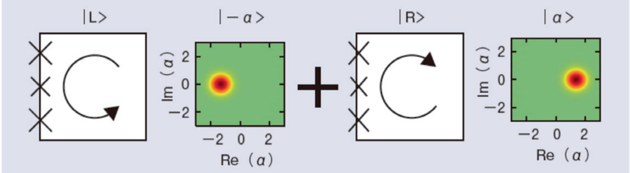
The horizontal and vertical axes represent the artificial atom's bias energy level and the input microwave frequency, respectively. When the atom is in the deep strong coupling state and its bias energy level is close to zero, complicated transmission spectra are observed. This can be explained only by the existence of the newly discovered DSC ground state consisting of the artificial atom and virtual photons

compared to the electronic transition energy of the atom. However, our experiments found that the interaction energy was greater than any other energy sources found in the artificial atoms in the circuit, and the size of the Lamb shift observed was estimated to be 87%, which was orders of magnitude greater than previously known.

When the interaction effect is as large as that found in our experiments, the minimum energy state (ground state) of the light-atom coupling system deviates conspicuously from the intuitive ground state. According to conventional common knowledge, the natural ground state of a light-atom coupling system occurs when atoms are in the lowest energy state and the electromagnetic field is in a vacuum state (i.e., the average photon number = 0) (Fig. 6 (a)). Surprisingly, we observed in our experiment that the interaction energy was greater than the photon energy or the excitation energy of the artificial atom. As a result, the average photon number in the ground state was estimated to be a finite value of 1.8, even though no external photon was injected into the system. In other words, the artificial atom was surrounded by vacuum fluctuations which were intensified by the large interaction energy (Fig. 6 (b)). Moreover, when the light-atom system was in the "deep strong coupling state," selection rules for quantum transition were observed due to the symmetry of the system. This indicates that light and atoms entangled[*4] in all energy states, including the ground state (Fig. 6).



(a) Typical lowest energy state (ground state)



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

Fig. 6 Energy ground state of the coupled system. (source : Fig. 5 of NTT Technical Review vol.13, pp.44-47, 2017. [8])

During this study, NICT carried out experiments and analysis, NTT fabricated samples and QEERI performed theoretical interpretation.

5 Future prospects

As we described above, a superconducting artificial atom is an aluminum-based superconducting electric circuit that behaves like a natural atom (in terms of spectroscopic spectra, state transitions, superposition of states and entanglement). It is analogous to an atom with a lead wire attached. The quantum state of a superconducting artificial atom can be controlled and measured by sending a microwave pulse train to it via a transmission line (lead wire). It is theoretically feasible to replicate the artificial atom thousands to tens of thousands of times using semiconductor microfabrication techniques. Superconducting artificial atoms behave like natural atoms from the quantum mechanical point of view. Through this research, it has been revealed that the range of energy states of light-atom coupling systems is much wider than previously known using natural atoms and suggested the possibility that many unknown energy states may be yet to be discovered.

In this research, we achieved an entangled state of a

[*4] Entanglement refers to a state in which quantum mechanical correlations exist among multiple particles. When two photons (or electrons, qubits, etc.) are entangled, they exhibit unique properties—the state of one photon will determine the state of the other, and their relationship is independent of the distance between them. Entanglement is a vital quantum state from the viewpoint of putting quantum cryptography and quantum computation into practice. Entanglement is also an important quantum system property actively used today.

single superconducting artificial atom and microwave photons in the deep strong coupling regime [7]. 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 [10]. 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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