NEWS RELEASE

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Success in controlling multi-photon transitions of a superconducting flux qubit
-- One step closer to realizing a quantum computer --

Nippon Telegraph and Telephone Corp. (NTT; Head Office: Chiyoda-ku, Tokyo; President: Norio Wada) in collaboration with the Japan Science and Technology Agency (JST; Kawaguchi, Saitama, President: Kazuki Okimura) have succeeded in flipping the supercurrent flow (quantum state transition) in one-, two-, and three-photon absorption processes by irradiating a superconducting flux qubit[*1] with resonant microwave photons (Fig. 1).
We have confirmed that quantum mechanics, which is usually applied to microscopic objects such as elementary particles and atoms, can also be applied to the macroscopic state[*2] (consisting of millions of Cooper pairs) in a superconducting flux qubit of six micrometers in size. The qubit is composed of three Josephson junctions[*3] of sub-micrometer scale and obeys the laws of quantum mechanics. It has proved to be a promising candidate as a quantum computer[*4] building block. We now plan to extend the coherence[*5] time of a qubit and this will take us one step closer to realizing a quantum computer.

<Background to the research>
A quantum computer, that makes use of the principles of quantum mechanics, is expected to exceed the rates achieved by even the fastest classical computer and perform huge calculations in parallel at ultra high speed. Such devices are now being developed in laboratories throughout the world. Promising candidates are nuclear spins, ions or neutral atoms in a cavity, and solid-state devices such as semiconductors or superconductors. The superconducting flux qubit is considered to be one of the most promising candidates as a building block of a quantum computer. However, only a one-photon transition process has thus far been demonstrated.

<Description and implication of the demonstration>
A superconducting flux qubit is a loop made of aluminum thin film with three Josephson junctions embedded in it and is roughly six micrometers in size (Fig. 2). The device is constructed using microfabrication technology. We prepare a quantum two-state system (a qubit) at 30 mK within a dilution refrigerator by applying a magnetic field of about half a flux quantum that penetrates the qubit loop. A qubit is a set consisting of the ground state and first excited state of this device. We can tune the qubit energy separation by adjusting the magnetic flux that penetrates the qubit loop. Each state is a quantum mechanical superposition of clockwise and counter-clockwise circulating supercurrents. By irradiating the qubit with microwave photons whose energy is in resonance with the qubit energy separation, we have succeeded in detecting 1 ~ 3 photon absorption transitions between the ground state and first excited state of the qubit by using a superconducting quantum interference device (SQUID)[*6]

detector, which we installed around the qubit (Fig. 3).
In addition, from a Ramsey interference experiment[*7] using a pair of resonant microwave pulses, we observed a characteristic oscillating pattern indicating that we had succeeded in achieving the coherent control of a flux qubit (Fig. 4). This is essential if quantum computation is to work.
These results imply that this device can be considered an ideal quantum two-state system (an artificial atom) even though it is of micrometer size and contains millions of Cooper pairs. Moreover, using resonant microwave pulses, we have acquired full control of this quantum two-state system and transformed it into an arbitrary quantum superposition state.

<Future research>
In order to obtain a sufficiently long operating time for the manipulation of multiple qubits, we will try to extend coherence time of our superconducting flux qubit.

These results will be presented on September 13th at an invited talk [13pYD-10] “Superconducting Flux Qubits” by Hideaki Takayanagi (NTT Basic Research Laboratories), in a symposium entitled ‘Progress in Physics of Superconducting Junctions’, which will form part of the Japan Physical Society meeting at Aomori University.

Figure 1 Control of a superconducting flux qubit by using resonant microwave pulses
Figure 2 Scanning electron micrograph of a superconducting flux qubit and a SQUID detector.
Figure 3 Experimental data of 1 ~ 3 photon absorption transitions.
Figure 4 Coherent oscillation of the qubit observed in a Ramsey interference experiment.

<Glossary>

*1 Quantum bit (qubit)
This is the fundamental building block of a quantum computer. 'Qubit' is another name for a quantum two-state system. It is called the qubit by comparison with the classical bit, which can have only one of two states 0 or 1. During calculation, the qubit can be in an arbitrary superposed state between |0> and |1>.

*2 Macroscopic state
This is a state that can be observed without considering the fact that involves a huge number of microscopic objects such as individual electrons or atoms. All the states that we can see or touch in everyday life are macroscopic states. A supercurrent, which contains millions of Cooper pairs, is also a macroscopic state.

*3 Josephson junction
This is a device that contains an Å(10^{-10} m) thick insulating layer sandwiched between a pair of superconductors. The superconductors on either side couple only weakly through the insulating layer, which means the superconducting state can be controlled by controlling the current and voltage. This controllability makes the Josephson junction an indispensable device in a superconducting circuit. Here, we use aluminum for the superconducting part and aluminum oxide for the insulating layer.

*4 Quantum computer
A quantum computer is a computer that processes information by performing

operations with a set of multiple quantum bits (quantum register). Parallel computation is possible in a quantum computer, because the quantum states can be superposed during calculations. If we obtain full control of n qubits, we can exponentially reduce the number of logical steps needed for a given calculation. For example, the quantum computer would require of the order of n steps while a classical computer would need 2 n steps. Thus, exponential speedup is possible. The high-speed realization of calculations over states corresponding to more than all the atoms in the universe will no longer be a dream once we obtain full control of just 500 qubits.

*5 Coherence (coherent)
This is the degree to which the oscillating quantity, namely the quantum mechanical state, maintains a near constant phase relationship. In general, coherence will decrease exponentially with time as a result of the noise originating from outside the system.

*6 Superconducting QUantum Interference Device (SQUID)
This is a device containing a superconductor loop that is equipped with a pair of Josephson junctions. As a result of the quantum interference effect, the maximum supercurrent through this device is a very accurate periodic function of the magnetic flux that penetrates the superconducting loop. We can make use of this property to realize an extremely accurate magnetic flux meter.

*7 Ramsey interference experiment
This is an experimental method that measures the decay of the free precession in a quantum two-state system. The origin of this approach is atomic physics. We use a microwave pulse that is resonant with the energy differenc of the two-state system. The first pulse turns the ground state | 0> into the quantum mechanical superposed state $(|0\rangle + e^{i\varphi}|1\rangle)/\sqrt{2}$. The time evolution of the phase (ϕ) of the superposed state can be measured during the delay time until the second pulse is reached.

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