Quantum coherence and entanglement of two coupled superconducting charge qubits

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We have studied quantum coherent dynamics of two coupled superconducting charge qubits[1]. Each qubit is based on a Cooper-pair box, a small superconducting island, coupled to a reservoir through a small Josephson junction. The qubits are electrostatically coupled to each other by a miniature on-chip capacitor formed by overlapping Al layers. The sample was fabricated by an angle evaporation of Al layers through a suspended mask formed by conventional electron-beam lithography.

In the charge regime when the charging energy of each qubit $E_{1,2}$ exceeds the Josephson energy$E_{J1,2}$, the Hamiltonian of the system can be reduced to the four-state Hamiltonian:

$$H = \sum_{n_1,n_2=0,1} E_{n_1 n_2}|n_1 n_2\rangle\langle n_1 n_2| - \frac{E_{J1}}{2}\sum_{n_2=0,1}(|0\rangle\langle 1| + |1\rangle\langle 0|)\otimes|n_2\rangle\langle n_2| - \frac{E_{J2}}{2}\sum_{n_1=0,1}|n_1\rangle\langle n_1|\otimes(|0\rangle\langle 1| + |1\rangle\langle 0|) \qquad (1)$$

where $E_{n_1n_2}$ is the electrostatic energy of the system corresponding to the charge configuration (n_1,n_2), and the four charge states $|00\rangle$, $|10\rangle$, $|01\rangle$ and $|11\rangle$ are used as a basis. Here the first and the second indices refer to the number of Cooper pairs in the first and the second qubit, respectively. By changing dc gate voltages we can control the initial state of the system. There is a special point in the energy diagram, that we call a double degeneracy point, where $E_{00} = E_{11}$ and $E_{10} = E_{01}$. By preparing the system in the $|00\rangle$ initial state and then bringing the system non-adiabatically to the double degeneracy point, we create conditions for coherent evolution of the system. Non-adiabatic shift of the system is done by a sharp control pulse applied to both qubits simultaneously. As a result of the evolution, the final state of the system is a superposition of all four charge states: $|\psi\rangle = c_1|00\rangle + c_2|10\rangle + c_3|01\rangle + c_4|11\rangle$, where the coefficients c_i depend on time and hence on the length of the control pulse. The problem can be solved analytically for a rectangular pulse shape. To readout each qubit, we attach a properly biased probe electrode to each Cooper pair box through a resistive tunnel junction. We then measure pulse induced probe currents I_1 and I_2 through the probes. Each current is proportional to the probability $p_{1,2}(1)$ of the corresponding qubit to be in state $|1\rangle$, i.e., $p_1(1) = c_2^2(t) + c_4^2(t)$ and $p_2(1) = c_3^2(t) + c_4^2(t)$. Thus, by measuring the probe currents we trace $p_{1,2}(1)$.

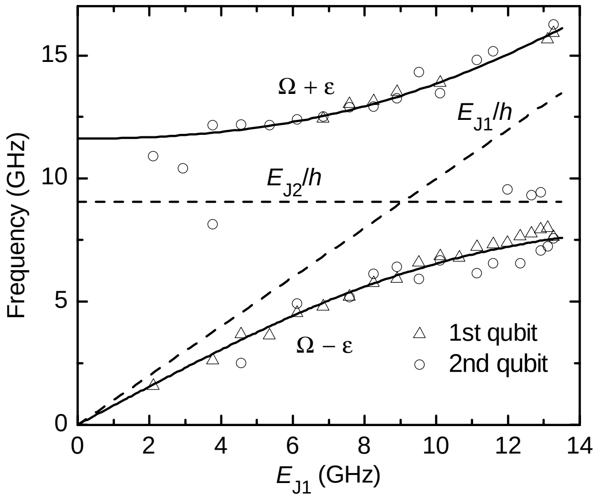

Fig. 1. Avoided level crossing of two coupled charge qubits.

The observed oscillations of I_1 and I_2 contained two frequency components in the spectrum, $\Omega + \varepsilon$ and $\Omega + \varepsilon$, that depend on the sample parameters and result in beatings. By tracing oscillations for different values of E_{J1}, we observed avoided level crossing in the energy spectrum as shown in Fig. 1. The observed beatings and avoided level crossing are direct evidence for the interaction between the qubits and in a remarkable quantitative agreement with the theoretical expectations.

Our experimental results show that the coherence time of the coupled qubit oscillations is a factor of four shorter compared to the case of single qubit oscillations. This fact is still to be understood. Nevertheless, even with short coherence time we were able to perform logic operation.

By adding one more pulse gate to the coupled qubit circuit we were able to address each qubit individually. This allowed us to demonstrate conditional gate operation, a prototype of the quantum C-NOT logic gate.

Our simulations[2] show that in the course of oscillations the qubits remain entangled most of the time.

[1]. Yu. A. Pashkin, T. Yamamoto, O. Astafiev, Y. Nakamura et al. *Nature* **421**, 823 (2003).
[2]. Yu. A. Pashkin, T. Tilma, D. V. Averin, O. Astafiev, T. Yamamoto et al. *IJQI* **1**, 421 (2003).