Quantum iSWAP gate in superconducting qubits

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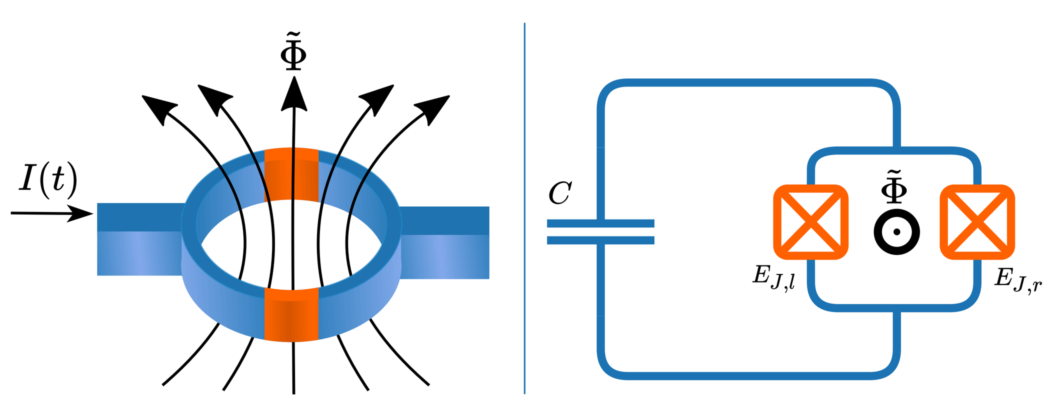
ABSTRACT

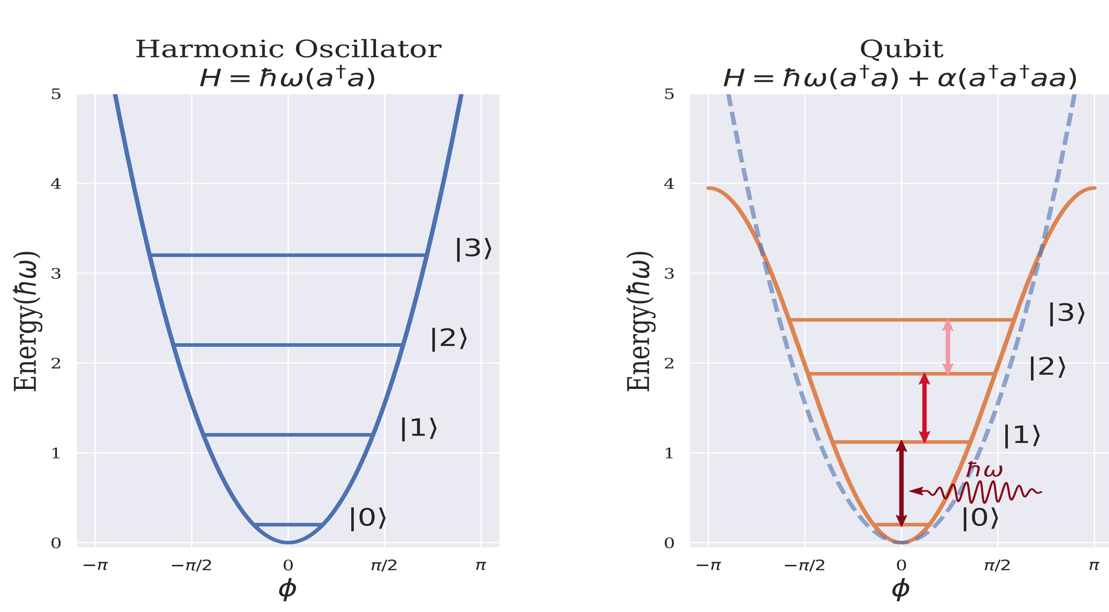
The field of quantum computation has gained significant attention in recent years due to the promise of significantly speeding up certain computational tasks. Among the various systems proposed for implementing these computers, artificial atoms built using superconducting circuits are one of the most promising frameworks. In these systems, quantum information is encoded and processed using devices constructed within superconducting circuits using lithography techniques, the so-called superconducting qubits (1). The main advantage of this method is the ability to incorporate multiple qubits into a single circuit. In our work, we present a system of three superconducting qubits in which we can coherently transfer information from the first qubit (Q_1) to a second qubit (Q_2), conditioned on the state of a control qubit (Q_c) in a behavior analogous to that of a transistor. By deriving the effective Hamiltonian of this system, we demonstrated that it implements the quantum iSWAP gate. Furthermore, despite the conventional treatment of the system as a perfect two-level system, we have shown that assuming a third energy level significantly modifies the system's dynamics in specific cases, a result that was experimentally verified (2). Our results emphasize that, even when not populated, the higher energy levels of superconducting qubits play a substantial role in the functioning of these devices. A role that must be considered when developing and controlling such superconducting systems.

ARTIFICIAL ATOMS

Artificial atoms are macroscopic superconducting circuits in which we can use macroscopic parameters to control the quantum behavior of the system. Typical superconducting qubits are composed of a superconducting ring with two Josephson junctions, which are small interruptions in the superconducting circuit.

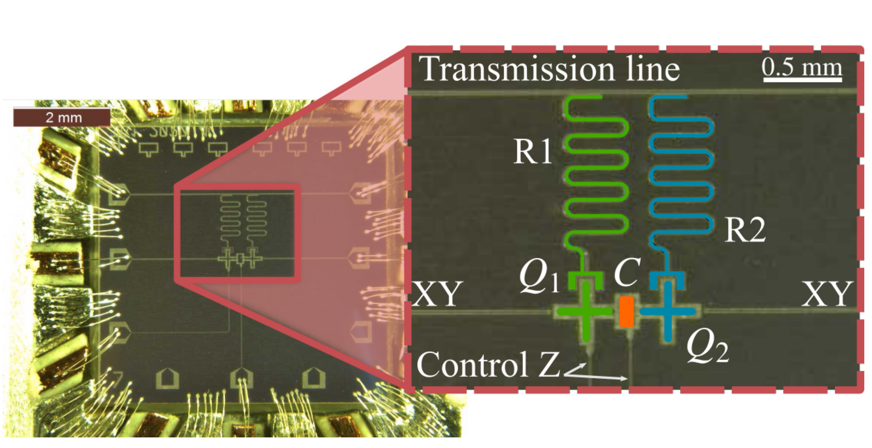


The role of the Josephson junction is to convert the harmonic behavior of the superconducting circuit into a slightly anharmonic oscillator. This anharmonicity helps preventing the qubit from populating higher excited states.



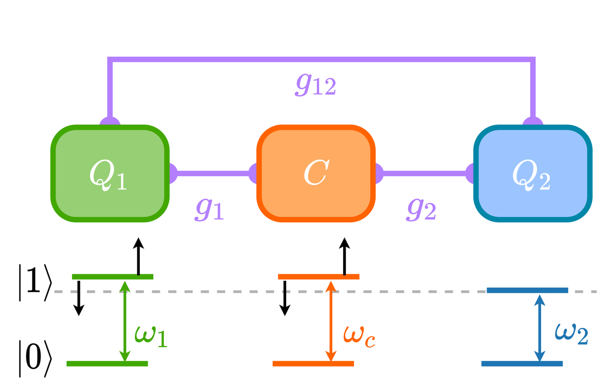
THE SUPERCONDUCTING CIRCUIT

The circuit we study is composed of two superconducting artificial atoms (Q_1 and Q_2) coupled via a superconducting loop (called coupler Q_C).



The Hamiltonian of this circuit can be written as

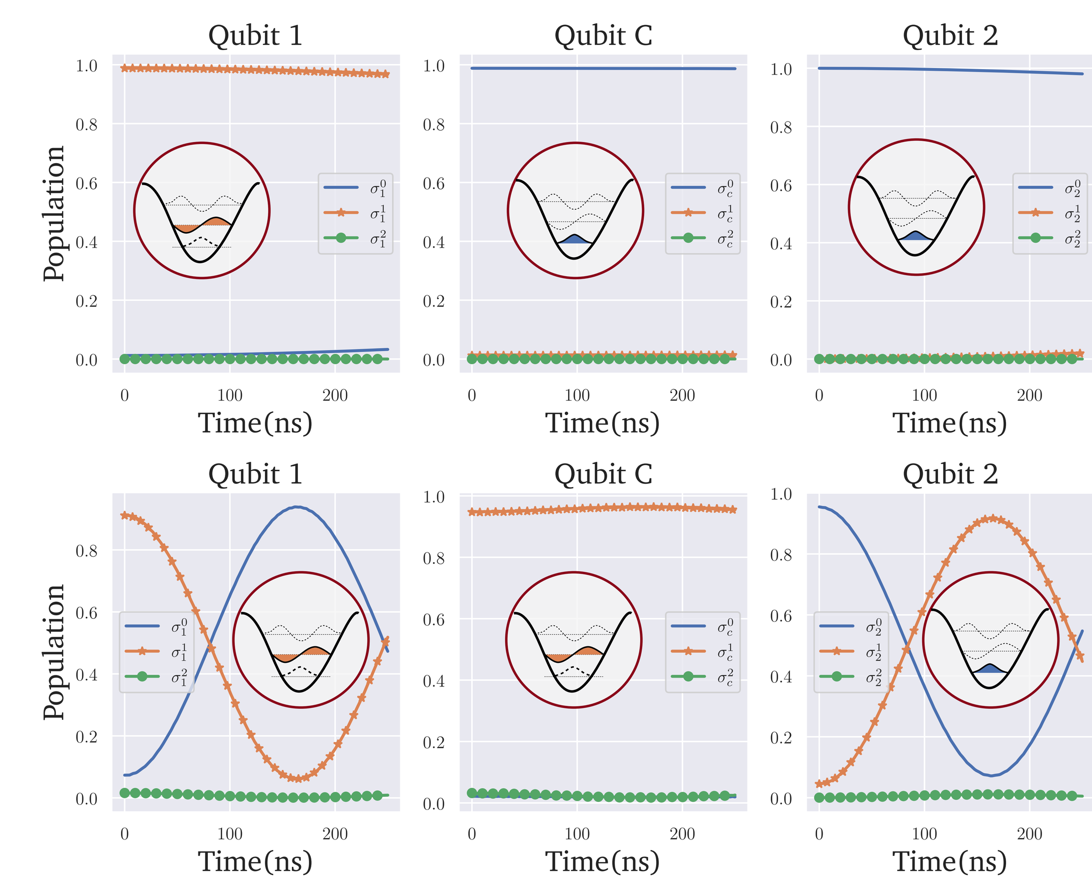
$$\frac{H}{\hbar} = \sum_{i=1,2,c}\left(\omega_i a_i^\dagger a_i + \frac{\alpha_i}{2} a_i^\dagger a_i^\dagger a_i a_i\right) + \sum_{i=1,2} g_i\left(a_i^\dagger a_c + a_i a_c^\dagger\right) + g_{12}\left(a_1^\dagger a_2 + a_1 a_2^\dagger\right),$$



with $a_i^\dagger$ (a_i) the creation (anihilation) operator, α_i the anharmonicity, ω_i the qubit frequency, g_i the coupler-qubit coupling, and g_{12} the coupling between Q_1 and Q_2. In our system $g_i \gg g_{12}$. And we define the dunning $\Delta = \omega_c - \omega$.

CONDITIONAL *i*SWAP GATE

We can define the frequencies of the circuit to achieve the behavior of a quantum transistor, allowing for the conditional transfer of information between the two qubits based on the state of the coupler.



EFFECTIVE DYNAMICS AND THE THIRD LEVEL

To simplify the system dynamics and allow us to gain more insights on its behaviour, we can derive the effective Hamiltonian.

$$H_{eff} \approx \frac{1}{i\hbar} H(t) \int_0^t H(t')dt' \bigg|_{RWA}$$

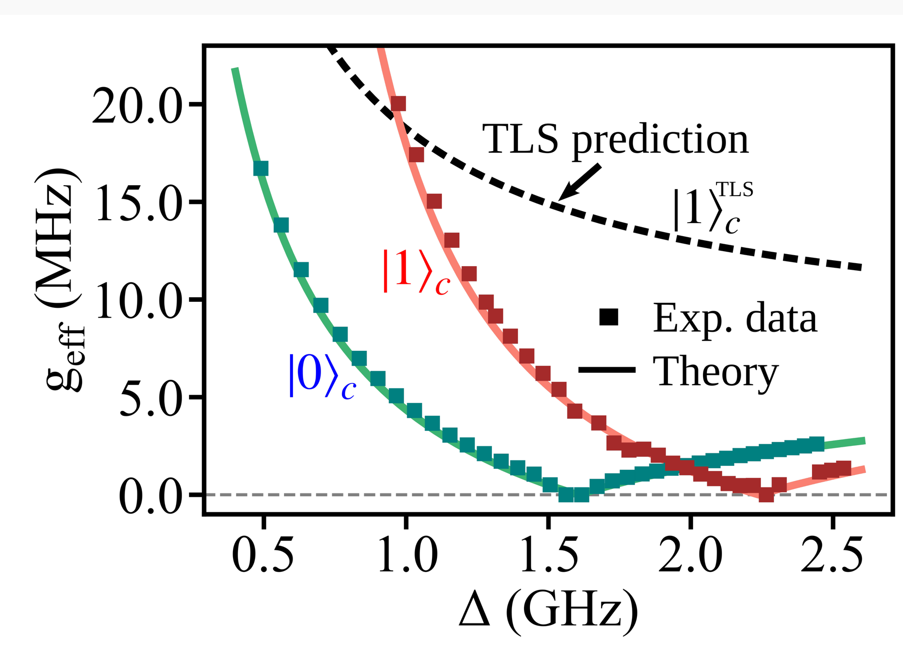
But in this scenario, we find two different results.

2 Level Approximation

$$g_{eff}^{|n\rangle_c}(\Delta) = g_{12} + (-1)^n \frac{g^2}{\Delta}$$

3 Level Approximation

$$\tilde{g}_{eff}^{|n\rangle_c}(\Delta) = g_{12} + g_1 g_2\left(\frac{2}{\Delta - \delta_{n1}\alpha_c} - \frac{1}{\Delta}\right)$$



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