Josephson Junction Quantum Computing

CNF Project #: 1362-05

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Abstract:

The laws of quantum physics provide intriguing possibilities for a tremendous increase in speed compared to classical computation [1]. Circuits made of superconductors and Josephson junctions are promising candidates for scalable quantum computation because of their compatibility with integrated-circuit fabrication technology [2-5]. The Josephson phase qubit [5] stands apart from other superconducting qubits because it does not require an optimal operating point [4]. Coupling of phase qubits is thus straightforward, allowing for multiple control methods. With recent improvements in coherence times and amplitudes, and the ability to measure both qubit states simultaneously, it is possible to use phase qubits to produce entangled states and measure them with high fidelity. We believe that demonstrations of quantum algorithms are also feasible.

Summary:

Josephson quantum bits (qubits) are constructed from superconducting integrated circuits. These “microwave atoms” can be thought of as non-linear microwave resonators formed from the non-linear inductance of a Josephson tunnel junction and its self-capacitance. Quantum behavior may be seen in these devices because of the extreme non-linearity of the Josephson junction-a single microwave photon has enough energy to significantly change the resonant frequency of the oscillator.

Single qubit logic operations are performed by injecting current pulses through the Josephson junction. Microwave pulses with a frequency resonant with the qubit quantum level spacing produces transitions between the quantum states, whereas quasi-DC pulses adjusts the quantum phase between the ground and excited states. The qubit state is measured by applying a strong pulse so that the excited state selectively tunnels to an external ground state. Once tunneled, the state can be easily distinguished by an on-chip superconducting quantum interference device (SQUID) amplifier.

A simple two-qubit logic gate may be constructed by simply coupling the two resonators with a capacitor [6]. This coupling produces a swap-type gate that, along with single qubit operations, has been shown to be a universal gate for quantum computation. This simple gate may be tested with a gate sequence that first places one of the qubits in its excited state, and then performs a swap operation such that the excited quantum state oscillates between the two qubits. Simultaneous measurements of both quantum states show that the occupation of the excited state is observed in only one qubit at a time (i.e. anti-correlated), as expected from quantum mechanics. It is also possible to apply a phase rotation to one of the qubits so that the oscillation halts; the measurements however remain anti-correlated.

Experiments are now under way to reduce the error rate of the gates by using improved materials and new circuit designs. We believe larger circuits can be constructed, possibly up to 5-10 qubits with current technology, enabling the demonstration of more complex quantum algorithms.

References:

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- The goal of the project is to understand the basic physics for building a Josephson junction quantum computer.
- Initial experiments test simple quantum logic gates.

Figure 1, above: Photomicrograph of a device with two Josephson junction quantum bits.

Figure 2, right: Coherent operations on coupled phase qubits. (a) Sequence of operations. A 180x pulse is first applied to qubit B, populating the 01 state. Following a free evolution period in which the qubits interact, the state occupation probabilities are measured using a current pulse that induce selective tunneling of the I state. For data in (c) and [(d)], a 90z [180z] pulse is applied to qubit B after 16 ns. (b) Plot of measurement probabilities of the states 01, 1, and 11 as a function of the free evolution time. (c) Plot of measurement probabilities for a sequence that creates the eigenstate of the coupling Hamiltonian. After the eigenstate is formed by the 90z pulse, it ceases to evolve with time. (d) As in (c), but with an 180z pulse. Here, the phase of the oscillation changes by 180 degrees.