Quantum Information processing using

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Superconducting circuits can behave like atoms making transitions between two energy levels. Such circuits can test quantum mechanics at macroscopic scales and be used to conduct atomic-physics experiments on a silicon chip.

Quantum Bits

The smallest unit of information that is manipulated in a classical computer is a classical bit, symbolically a "0" or a "1," realized in practice as a device which can be in either one or the other of two possible states. A quantum bit similarly has two states, but it has the strange possibility of being in both states simultaneously. This situation is called a superposition of the two states. Theorists envision the application of these qubits in quantum computing, a new kind of quantum parallel processing that may enable futuristic computers to tackle tasks that no ordinary classical computer can do, such as factoring large numbers and simulating large quantum systems. The practical challenge for realizing such quantum information processing is to find quantum mechanical systems that can serve as qubits.

Quantum Bits in Michigan

The Michigan effort in studying qubits for quantum information processing involves many Physics faculty members including **Paul Berman**, **Timothy Chupp**, **Luming Duan**, **Cagliyan Kurdak**, **Roberto Merlin**, **Christopher Monroe**, **Bradford Orr**, **Duncan Steel**, and **Georg Raithel**. Quantum information processing provides a fast growing and exciting natural bridge between atomic and condensed matter physics. Indeed, UM is planning the formation of a new Quantum Institute to cover all of these activities.

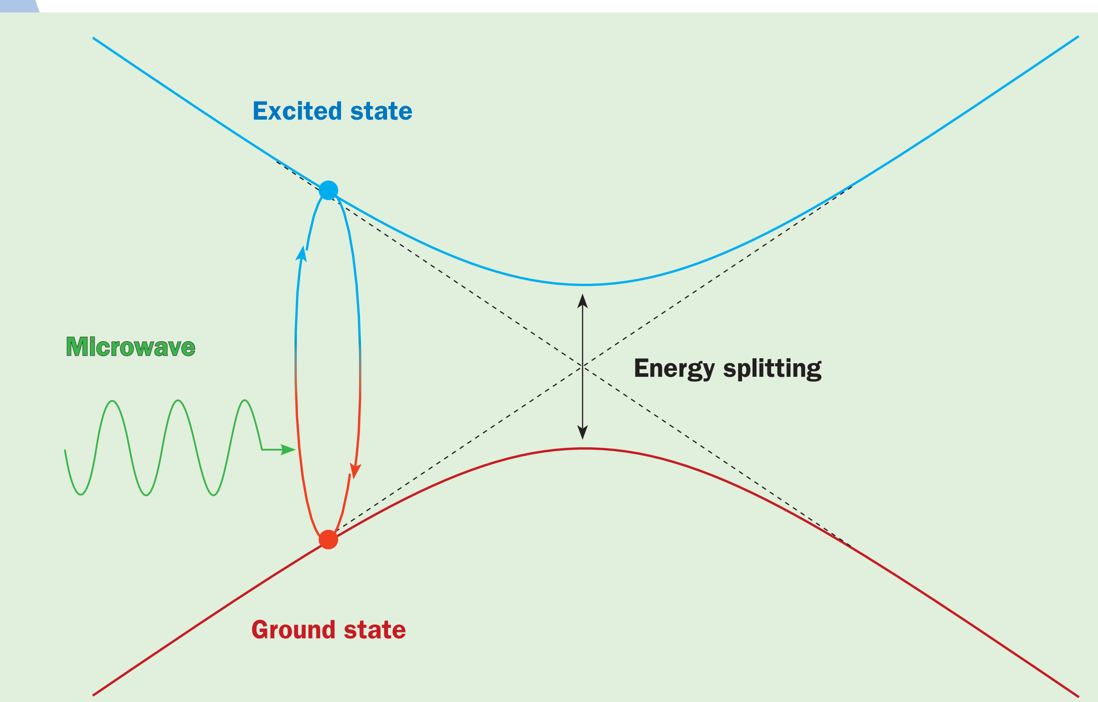
Quantum computing involves preparing, manipulating, and reading out the quantum states of a many-qubit system. Therefore, it is desirable to have qubits that can be individually controlled. Moreover, they should be scalable; that is, simply adding more qubits should create a larger circuit capable of more complex calculations. Several types of qubits satisfy these requirements. This brief summary will focus on one type of qubit: superconducting quantum circuits. These are currently being studied in **Franco Nori's** group, in collaboration with groups elsewhere in the US, Japan, China, Germany, Canada, and the Netherlands.

Solid State Quantum Bits

Very small solid-state devices can behave quantum mechanically. As the size of a bulk conductor becomes increasingly smaller, its quasi-continuous electron conduction band turns into discrete energy levels. One example is a quantum dot, in which electrons are confined to a small semiconducting or metallic box or island composed of millions of atoms. The problem is that the electron states of that island quickly decohere as the microscopic degrees of freedom strongly interact with the environment. A bulk superconductor, in contrast, is composed of many paired electrons that condense into a single-level state. This superconducting state involves macroscopic degrees of freedom and thus exhibits better quantum coherence. By reducing the size of the superconductor, one can reduce the coupling of the superconducting state to the environment and thereby further improve the quantum coherence. Various experiments on superconducting circuits have demonstrated as much, and those circuits are regarded as promising candidates of qubits that can process quantum information.

Quantum Circuits as Artificial Atoms

The electrons confined on small superconducting island collectively behave much like a single natural atom; so they can be interpreted as a single "artificial atom". Natural atoms and artificial atoms both have discrete energy levels and exhibit coherent quantum oscillations between those levels—so-called Rabi oscillations. But whereas natural atoms are usually driven using visible photons that excite electrons from one state to another, the artificial atoms in the circuits are driven by currents, voltages, and microwave photons. The resulting electric and magnetic fields control the tunneling of electrons between the superconducting island and nearby electrodes. The effects of those external fields on the circuits are analogues of the more familiar ways that natural atoms respond to electric and magnetic fields (the so-called Stark and Zeeman effects). One of the differences between quantum circuits and natural atoms is that atoms couple weakly to their environment whereas circuits couple strongly. Another distinction is that the energy scales of the two systems differ. One of the advantages of artificial atoms over naturally occurring atoms is that they can be lithographically designed to have specific characteristics, such as a large dipole moment or particular transition frequencies.



A microwave can induce (Rabi) oscillations between the ground state and the excited state of a qubit (or any quantum two-level system).

Superconducting Electronics

Quantum circuits made of Josephson junctions provide good qubits. Josephson junctions—superconducting grains or electrodes separated by an insulating oxide—act like nonlinear inductors in a circuit. The nonlinearity ensures an unequal spacing between energy levels, so that the lowest levels can be accessed using external fields. Two important energy scales determine the quantum mechanical behavior of a Josephson-junction circuit: the Josephson coupling energy and the electrostatic Coulomb energy for a single Cooper pair. In analogy to the usual position–momentum duality in quantum mechanics, the phase of the Cooper-pair wavefunction and the number of Cooper pairs are conjugate variables and obey the Heisenberg uncertainty relation.

There are several kinds of superconducting qubits realized in different regimes. The charge qubit is in the "charge regime" where the number n of Cooper pairs is well defined and the phase fluctuates strongly. The so-called flux and phase qubits are both in the phase regime, in which the phase is well defined and n fluctuates strongly. And the charge–flux qubit lies in the intermediate regime in which charge and phase degrees of freedom play equally important roles.

Circuits Mimicking Atoms

These type of superconducting circuits can behave like atoms, including exhibiting the so-called Rabi oscillations. Let us briefly review Rabi oscillations of an atom in a strong laser field. Consider an electromagnetic wave resonant with an atom transition frequency. First, it excites the atom from the ground state to the excited state. Therefore the probability amplitude of finding the atom in the excited state increases over time. Afterwards, when the atom reaches the excited state, the wave de-excites the atom, also known as stimulated emission. This periodic cycle of absorption-emission is called Rabi oscillations, and it occurs at a frequency that is proportional to the strength of the applied electric field driving these transitions. These oscillations are illustrated in the figure on page 14. During this cycle the atom is usually in a superposition of ground and excited state.

Future Challenges

One of the major obstacles to quantum computing is decoherence due to noise. This effect degrades the information carried by the qubit. Another central issue in future developments will be the efficient and nondissipative readout of qubit states. It is still too early to say which type of qubit will do best in addressing these challenges, and so win the race to realize a quantum computer in practice.

For superconducting qubits the status is that all quantum states on the so-called Bloch sphere—a geometrical representation of the states of a two-level system—can be reached; spin-echo techniques, borrowed from nuclear magnetic resonance, can reduce the effect of 1/f noise; and readout efficiency greater than 96% and a coherence quality factor of approximately 10^5 can be achieved. When techniques for manipulating two or three qubits become well established, the next step will be to build circuits with a larger number of qubits, increased readout efficiency, and lower decoherence. Such conditions would allow quantum computing with superconducting qubits.

Quantum Mechanical Circuitry

Even if no quantum computing is ever achieved using superconducting circuits, they still provide researchers with tools to test fundamental quantum mechanics in novel ways. For example, these artificial atoms can be used to simulate atomic physics using quantum circuits; researchers have already observed Rabi oscillations and interference patterns that are manifest during the phase evolution of a superconducting qubit. Moreover, the devices can also do basic tests of quantum mechanics, and study the striking quantum non-localities of quantum mechanical wave-functions (discussed in the celebrated Einstein-Podolsky-Rosen paper).

This article has touched on only a few of the many fundamental physics questions that can be addressed by the quantum control of macroscopic entangled states, not to mention the potential for technological applications. The research is extremely active worldwide, and one in which Michigan plays a leading role.

Left: Schematic diagram of a superconducting qubit circuit. A tiny "box" (shown in blue) with paired electrons (known as Cooper pairs) is driven by an applied voltage (green) though a capacitance. A Josephson junction, the barrier denoted by the "X," connects the box to a wire. Each junction has a capacitance and a coupling energy.

*Right: The electrostatic parabolic potential energy of the (blue) box is plotted as a function of the number **n** of excess electron pairs. The two lowest energy states (shown in red) are degenerate and are used as the quantum bit states. Those states are coupled via the junction energy, which controls the tunneling between them.*