ATOMIC PHYSICS AND QUANTUM INFORMATION PROCESSING WITH SUPERCONDUCTING CIRCUITS

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Artificial atoms, making transitions between discrete energy levels, can be made using superconducting circuits. Such circuits can used to conduct atomic-physics experiments on a silicon chip and test quantum mechanics at macroscopic scales.

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1. Bridge between Atomic and Condensed Matter Physics

Quantum information processing provides an exciting natural bridge between atomic and condensed matter physics. Quantum information processing 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 very brief overview of the field will focus on one type of qubit: superconducting quantum circuits [1-3]. These are currently being studied by many research groups. Additional information and many more references to other work can be found in Refs. [1-3].

2. 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" [1-3]. 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.

3. Superconducting Electronics

Quantum circuits made of Josephson junctions provide good qubits [1-3]. 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 ϕ of the Cooper-pair wave function and the number n 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 ϕ 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.

4. 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. During this cycle the atom is usually in a superposition of ground and excited state. Over the past decade, these oscillations have been observed in macroscopic artificial atoms embedded in superconducting circuits.

5. Different Circuits Mimicking a Variety of Artificial Atoms

5.1. *Charge qubit or Cooper-pair Box*

Figure 1(a) shows a charge qubit, known also as a Cooper-pair box (CPB; shown as a dashed blue square). This is driven by an applied voltage V_g (green) through the gate capacitance C_g to induce an offset charge $2e\, n_g = C_g V_g$. A Josephson junction, the barrier denoted by the ×, connects the box to a wire lead. Each junction has a capacitance C and a Josephson coupling energy E_J. The electrostatic energy of the CPB is equal to $E_C\ (n - n_g)^2$, where the charging energy $E_C = (2e)^2/2C$, is plotted as a function of the number n of excess electron pairs. The lowest energy states, $|0\rangle$ and $|1\rangle$ (shown in red on the right side of Fig. 1), are degenerate when $n_g = 0.5$, and are used as the qubit state basis. Those states are coupled via the junction energy E_J, which controls the tunneling between them.

5.2. *Magnetic Flux Loop (RF-SQUID)*

Figure 1(b) shows a magnetic-flux "box", or more precisely, a loop enclosing magnetic flux, which is the "magnetic analogue" of the electrostatic CPB shown in Fig. 1(a). A magnetic bias now replaces the electric bias: A current-driven magnetic field pierces the loop with a strength given by a mutual inductance

M. While an electric field prompts stored electron pairs to tunnel into or out of the CPB, a magnetic field pushes magnetic flux quanta Φ_0 into or out of the superconducting quantum interference device (SQUID) loop. The adjacent potential energy diagram (energy versus "phase drop ϕ along the barrier") plots a Josephson energy term (proportional to cosϕ) and an additional superimposed inductive energy term—proportional to $(\phi - \phi_{\text{ext}})^2 / 2L$, where L is the SQUID's inductance—as a function of the phase ϕ of the junction. The lowest energy states (shown in red) are superpositions of the clockwise and counterclockwise supercurrent states, $|\downarrow\rangle$ and $|\uparrow\rangle$, that flow in the SQUID loop; Δ here is the tunneling energy between the supercurrent states. Those energy states are degenerate when the externally applied magnetic flux $\phi_{\text{ext}} = \pi$.

5.3. *Flux Qubit: Magnetic Flux Loop with three junctions*

Figure 1(c) shows a three-junction flux qubit. This loop with three junctions works like a magnetic flux "box" in Fig. 1(b), except that one of the three junctions has a slightly smaller (~25% smaller) capacitance and coupling energy. The contour plot on the right of Fig. 1(c) shows the potential energy as a function of two junctions' phases. The two red dots inside the potential wells on the right correspond to the qubit basis states $|\downarrow\rangle$ and $|\uparrow\rangle$. Having several junctions, here three instead of one, provide a higher level of control over the potential energy of the circuit. Versions of this circuit using four junctions are now used by several research groups, since these are more symmetric and offer more control over the potential energy of the circuit.

5.4. *Magnetic Flux Loop (RF-SQUID)*

Figure 1(d) shows a so-called phase qubits where a current source biases a junction. Logic operations can be achieved by driving the qubit with a microwave field at frequency $(E_1 - E_0)/h$. Pulsing the qubit with a microwave field at a frequency $(E_2 - E_1)/h$ produces a transition from $|1\rangle$ to $|2\rangle$. One can then read the qubit's state by measuring the occupation probability of state $|2\rangle$.

6. 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 99% and a coherence quality factor of approximately 10^6 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.

7. 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 (see, e.g., [1-3], and the many references therein). 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 very short overview of the field 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. This research is extremely active worldwide.

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References

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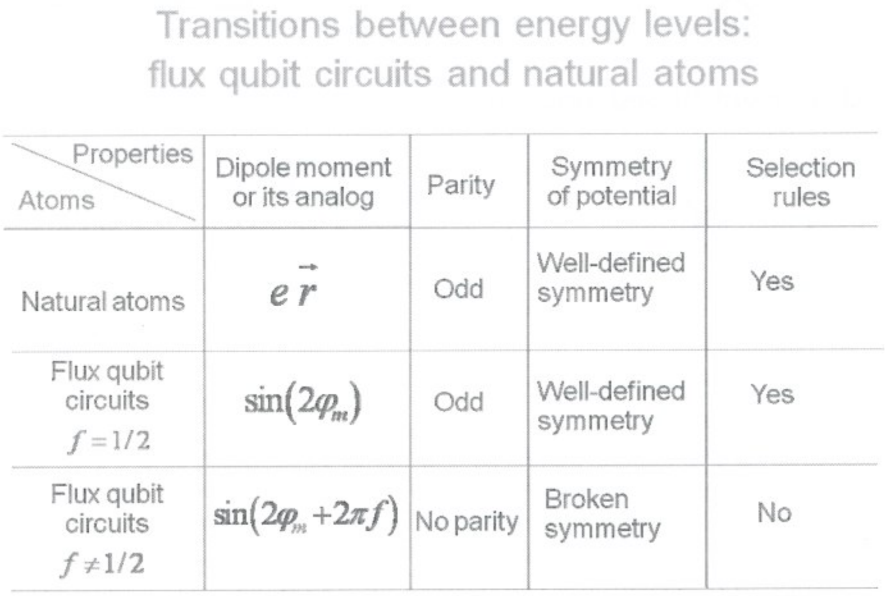
Table 1. Transitions between energy levels in atoms obey selection rules, like the electric-dipole selection rule. Artificial atoms have different types of selections rules [4].



Transitions between energy levels:
flux qubit circuits and natural atoms

Properties / Atoms	Dipole moment or its analog	Parity	Symmetry of potential	Selection rules
Natural atoms	$e\vec{r}$	Odd	Well-defined symmetry	Yes
Flux qubit circuits $f = 1/2$	$\sin(2\varphi_m)$	Odd	Well-defined symmetry	Yes
Flux qubit circuits $f \neq 1/2$	$\sin(2\varphi_m + 2\pi f)$	No parity	Broken symmetry	No

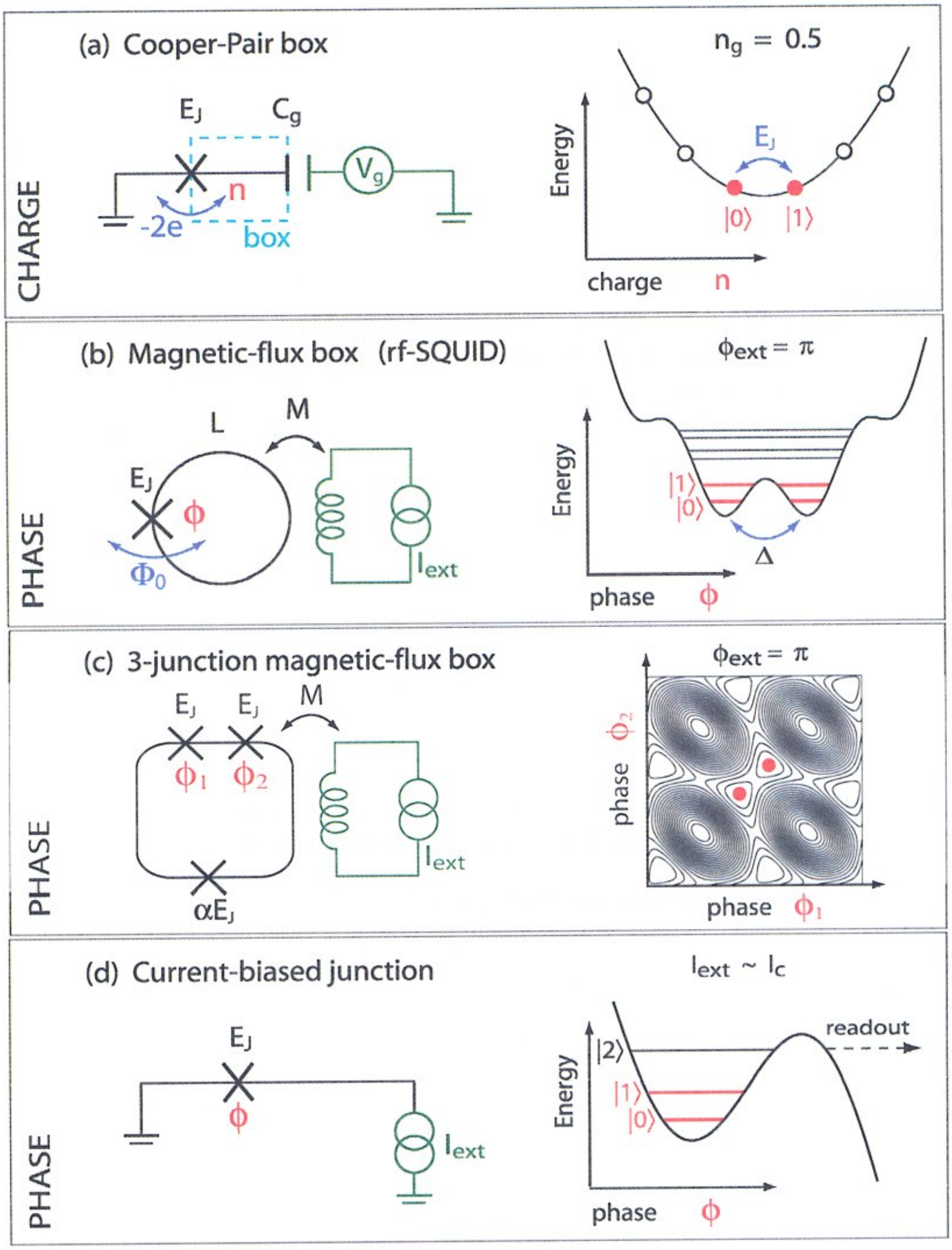


Fig. 1. Schematic diagrams of circuits (left side) and their corresponding energy levels (right side). These superconducting circuits can behave like atoms making transitions between discrete energy levels. Such circuits can used to conduct atomic-physics experiments on a silicon chip and test quantum mechanics at macroscopic scales.