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Laura Ost

NIST-UCSB Scientists Entice Superconducting Devices

(Boulder, Colo.) -- Two superconducting devices have been coaxed into a special, interdependent state that mimics the unusual interactions sometimes seen in pairs of atoms, according to a team of physicists at the National Institute of Standards and Technology (NIST) and University of California, Santa Barbara (UCSB). The experiments, performed at the NIST laboratory in Boulder, Colo., are an important step toward the possible use of "artificial atoms" made with superconducting materials for storing and processing data in an ultra-powerful quantum computer of the future.

The work, reported in the Feb. 25 issue of the journal Science, demonstrates that it is possible to measure the quantum properties of two interconnected artificial atoms at virtually the same time. Until now, superconducting qubits---quantum counterparts of the 1s and 0s used in today's computers---have been measured one at a time to avoid unwanted effects on neighboring qubits. The advance shows that the properties of artificial atoms can be coordinated in a way that is consistent with a quantum phenomenon called "entanglement" observed in real atoms. Entanglement is the "quantum magic" allowing the construction of logic gates in a quantum computer, a means of ensuring that the value of one qubit can be determined by the value of another in a predictable way.

"This opens the door to performing simple logic operations using artificial atoms, an important step toward possibly building superconducting quantum computers," says

John Martinis, who began the superconducting quantum computing effort at NIST and is now on the physics faculty at UCSB.

"Whether or not quantum computing becomes practical, this work is producing new ways to design, control and measure the quantum world of electrical systems," says Ray Simmonds, a NIST physicist and a co-author of the Science paper. "We have already detected previously unknown, individual nanoscale quantum systems that have never before been directly observed, a discovery that may lead to unanticipated advances in nanotechnology."

If they can be built, quantum computers--órelying on the rules of quantum mechanics, nature's instruction book for the smallest particles of matter--ósomeday might be used for applications such as fast and efficient code breaking, optimizing complex systems such as airline schedules, much faster database searching and solving of complex mathematical problems, and even the development of novel products such as fraud-proof digital signatures.

Superconducting circuits are one of a number of possible technologies for storing and processing data in quantum computers that are being investigated for producing qubits at NIST, UCSB and elsewhere around the world. Research using real atoms as qubits has advanced more rapidly thus far, but superconducting circuits offer the advantage of being easily manufactured, easily connected to each other, easily connected to existing integrated circuit technology, and mass producible using semiconductor fabrication techniques. A single superconducting qubit is about the width of a human hair. Two qubits can be fabricated on a single silicon microchip, which sits in a shielded box about 1 cubic inch in size.

The work reported in Science creates qubits from superconducting circuit elements called Josephson junctions. These devices consist of two superconducting pieces of metal separated by a thin insulating region with the special property of being able to support a "super flow" of current. Scientists have used Josephson junctions for more than 40 years to manipulate and measure electrical currents and voltages very precisely. The experiment creates artificial atoms using currents that are 1 billion times weaker than the current needed to power a 60-watt light bulb. Using Josephson junctions, scientists can create wave patterns in electrical currents that oscillate back and forth billions of times per second, mimicking the natural oscillations between quantum states in atoms. And, as in a real atom, the quantum states of a superconducting junction can be manipulated to represent a 1, a 0, or even both at once.

As described in the paper, the team of scientists measured the state of a superconducting qubit by applying a voltage pulse lasting 5 nanoseconds, and detecting a change in magnetic field through a simple transformer coil incorporated in the qubit. To detect the tiny variations in the magnetic field they use a superconducting quantum interference device (SQUID). If a signal is detected, the qubit is in the 1 (or excited) state; if no signal is detected the qubit is in the 0 state.

Through very precise timing, the team also was able to measure the two qubits simultaneously. This was key to avoid unwanted measurement crosstalk that destroys quantum information. The scientists were able to witness a pattern of quantum oscillations that is consistent with the entanglement needed for producing quantum logic gates.

NIST research on Josephson junction-based quantum computing, now led by Ray Simmonds, is part of NIST's Quantum Information Program (http://qubit.nist.gov/index.html), a coordinated effort to build the first prototype quantum logic processor consisting of approximately 10 or more qubits. John Martinis' research group within the UCSB Center for Spintronics and Quantum Computation, a part of the California Nanosystems Institute (CNSI) (http://www.cnsi.ucsb.edu/about/), is primarily focused on building a quantum computer based on Josephson junction quantum bits.

The work was supported in part by the Advanced Research and Development Agency.

As a non-regulatory agency of the U.S. Department of Commerce's Technology Administration, NIST develops and promotes measurement, standards and technology to enhance productivity, facilitate trade and improve the quality of life.

Background on Superconducting Qubits

The work reported in Science uses qubits made of Josephson junctions, in which a thin layer of non-conducting material is sandwiched between two pieces of superconducting metal. At very low temperatures, electrons within a superconductor pair up to form a "superfluid" that flows with no resistance and travels in a single, uniform wave pattern. The uniform electron-pair wave patterns leak into the insulating middle of the "sandwich," where their wave properties overlap and interfere with each other so that a superfluid can flow through the insulator. The current flows back and forth through the junction somewhat like a ball rolling back and forth inside a curved bowl. The energy in these oscillations can only be stored in discrete amounts or quanta.

In a Josephson junction qubit, the 0 and 1 states can be thought of as the two lowest-frequency oscillations of the currents flowing back and forth through the junction. The speed of these oscillations is typically billions of times per second. This behavior is similar to the way an atom's electrons oscillate naturally around its nucleus, forming discrete quantum states, hence the term "artificial atom."

The qubit also can be thought of as a child's swing rocking back and forth between its extreme forward and back positions. However, unlike an ordinary swing, a Josephson qubit can be in an unusual quantum state called a "superposition" in which it is oscillating at two different frequencies at once, in a state that is both 1 and 0 at the same time.

When two Josephson junctions are connected through a standard capacitor, the application of a small a.c. voltage pulse to the first qubit can cause the two qubits to oscillate between two combined states. In one combined state, the first qubit is excited (1) while the second is not (0); later in time the first qubit is fully relaxed (0) while the second one is fully excited (1). They oscillate between these extremes like two children on a swing set moving back and forth at the same speed, but in opposite directions. These oscillations occur only if the differences in energy between the 0 and 1 states are equal in both qubits. This behavior is indicative of the two qubits becoming entangled.

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