 VOL. 2 | NUMBER 6 | JUNE 2007

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Taming Quantum Fluxes

Challenges in realizing the dream of quantum computing

Future quantum computers are expected to solve problems within seconds that existing supercomputers couldn't solve in years. The Single Quantum Dynamics Research Group at RIKEN leads the world in developing this dream computer. The group studies quantum phenomena occurring in the microscopic world and aims to apply it to develop epoch-making devices and materials as well as information technology. Developing a quantum computer is one of the groups' ultimate objectives. This research is part of the activities of the Digital Materials Laboratory that oversees theoretical studies central to the genesis of new ideas to manipulate and utilize novel quantum phenomena.

Taming Flux Quanta

Superconductors exhibiting zero electrical resistance below a certain critical temperature are used to fabricate powerful magnets, or highly sensitive magnetic sensors in equipment such as magnetic resonance imaging systems (MRI) used in medical applications. Superconductors are also slated for use in power transmission lines and power storage equipment.

However, superconductors are sensitive to magnetic fields. When superconductors are exposed to an intense magnetic field, magnetic field lines penetrate the superconductor in the form of millions of ultra-fine threads, each one of these carrying a 'flux quantum' (Fig. 1). This quantum of flux is the minimum possible unit of magnetic flux, and is the magnetic analog of the electron charge, which is the quantum of electricity.

When applying a large current to a superconductor or when improving the accuracy of highly sensitive magnetic sensors based on superconducting devices, it is necessary to stop the motion of these flux quanta, since their motion dissipates energy. Flux quanta can be temporarily stopped, trapped, or 'pinned', by deliberately putting impurities in a pure crystal to form defects. However, for decades, precisely controlling the motion of flux quanta was difficult since their movement could not be observed.

Then, in the 1990s, a group at Hitachi, led by Akira Tonomura, developed the 'holography electron microscope' and directly visualized the movement of flux quanta. Tonomura went on to establish the Single Quantum Dynamics Research Group at RIKEN and was inaugurated as the group's director in October, 2001. He then visited the US and recruited Franco Nori as the Laboratory Head.

"Dr Tonomura told me to act as the 'glue' bonding several laboratories," laughs the Venezuelan-born Nori, since his name literally means 'glue' in Japanese. After graduating from the University of Illinois with a Masters and a PhD, Nori completed postdoctoral work at the University of California. He then became a professor at the University of Michigan before accepting the joint RIKEN position.

Nori's lifelong curiosity and penchant for building and tinkering with machines, devices, and computers stood him in good stead for a scientific career that has produced achievements well-received by the international scientific community.

Nori pioneered the research area of controlling the motion of tiny particles and flux quanta. One method for manipulating these is to form regular microscopic structures in superconductors. For example, triangular magnetic structures can trap flux lines moving inside a nearby superconducting layer (Fig. 2). For certain values of the externally applied magnetic field, three flux quanta (red) will be caught in one of the triangular structures. The flux quanta (blue) outside of the triangular structures can move freely. If an AC current is applied, the flux quanta can move freely within a confined area as the direction of the current changes. In contrast, the flux quanta caught in the triangular structures jump in the same direction of the next triangular element. Therefore, with microscopic structures embedded in materials, the direction in which flux quanta move can be controlled. A mechanism allowing movement only in a certain direction like this acts as a 'quantum diode' and is called a 'ratchet structure' (Fig. 3).

In 2005, Tonomura and colleagues succeeded in using the holography electron microscope to observe in detail unidirectional movement of flux quanta in a ratchet structure. According to Nori, the ratchet structure may be applicable to control other types of particles, in addition to flux quanta, and may see the development of a minute motor exploiting the energy of Brownian movement, where particles move randomly in all directions.

Manipulating flux quanta with applied currents

Nori's group also proposed the novel idea of manipulating flux quanta by controlling an applied AC current—an idea that was recently verified by experiments. "Imagine plates on a tablecloth," says Nori. "If the tablecloth is pulled slowly, the plates will move with it. And, if the tablecloth is successively pulled slowly-and-quickly, the plates can move in one direction only: the direction of slow pull. Similarly, billions of flux quanta can be manipulated at will by properly controlling the applied AC current," he explains.

Since building a special microscopic structure in a superconductor is unnecessary using this approach, this method may be advantageous for practical applications. Controlling at will the motion of flux quanta can enhance the performance of superconducting devices.

Quantum computers for super fast calculations

An ultimate goal of Nori's group is to develop circuit designs that could be useful in next-generation quantum information processors. Still in its very early stages, some of these early prototypes now use flux quanta to complete simple operations.

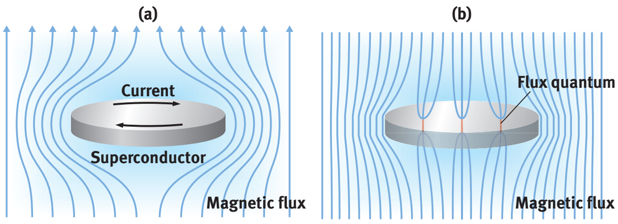

Figure 1: **A flux quantum.**
(a) A superconductor tends to repel magnetic fields. (b) However, when a superconductor is exposed to an intense magnetic field, this breaks up into billions of tiny magnetic filaments, each carrying a "flux quantum", the minimum possible amount of magnetic flux inside a superconductor.

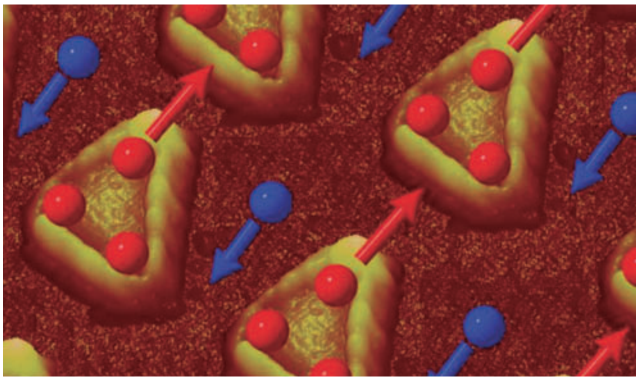

Figure 2: **Triangular magnetic structures that can trap flux quanta.**

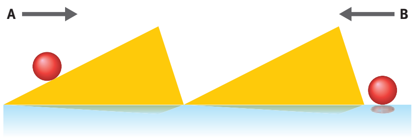

Figure 3: **Schematic diagram of a simple ratchet structure. It is easy to move a ball in the direction of A, but hard in the direction of B due to the steep uphill slope.**

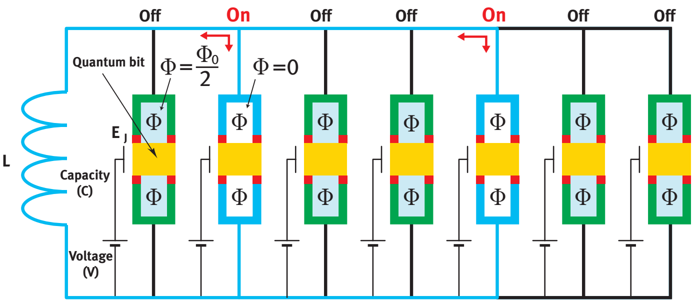

Figure 4: **Circuit design for integrating quantum bits.**
Quantum entanglement can be generated by coupling selected quantum bits, which are not necessarily adjacent to each other. This can be done by connecting several quantum bits with a common coil structure (inductance: L).

Existing computers and quantum computers calculate by modifying the two bit states '0' and '1' in a logic gate, but a quantum bit can represent the states of '0' and '1' simultaneously, thus allowing parallel processing of vast amounts of data.

In the past few years, several groups have begun experiments testing possible circuit designs that might be useful for these future computing devices. However, to solve a practical numerical calculation with a quantum computer, it is necessary to integrate hundreds of quantum bits in complex circuits, and achieve 'quantum entanglement', or strong interaction of specific bits.

Building a quantum computer with a superconductor

In 1999, a group at NEC led by Jaw-Shen Tsai succeeded in creating a quantum bit using a superconducting (Josephson-type) solid-state device. Solid-state devices have the potential to facilitate the integration of quantum bits to design circuits. Tsai was inaugurated as the Laboratory Head of the Quantum Coherence Laboratory, Single Quantum Dynamics Research Group at RIKEN. His group succeeded in 2002 in producing a logic gate generating quantum entanglement of two quantum bits.

The logic gate created by Tsai and colleagues couples two quantum bits directly and generates quantum entanglement. However, at this stage, only adjacent quantum bits generate quantum entanglement. Nori's group has proposed a circuit design that selectively induces interactions between specific quantum bits by coupling several quantum bits with a common coil structure (inductance) (Fig. 4).

With this design, it is theoretically possible to generate quantum entanglement of specific bits by integrating hundreds of quantum bits necessary for realizing a quantum computer. Although quantum computing devices are now being studied at different laboratories worldwide using various methods, currently, the realization of quantum entanglement is difficult and ideas for entanglement-generating circuits are limited. The Digital Materials Laboratory has been proposing circuit designs to overcome the many obstacles present in building these complex devices.

"It is necessary to quickly generate quantum entanglement of specific quantum bits such that they do not influence other quantum bits," says Nori, outlining future challenges to be overcome. "It is also a challenge to confirm that quantum entanglement has actually occurred, or to do many operations, or to perform quick read-outs of the outputs. Although some manufacturing errors are inevitable in any solid-state device, it is necessary to develop circuits and computational procedures (algorithms) which are robust against component variations."

Nori's group has published a series of new ideas for overcoming these very difficult problems. Explaining how novel ideas are produced, Nori says: "We often actively discuss with experimental teams. We always have visitors from all over the world. An intense and dynamic exchange of ideas is a strong point of our laboratory."

On realizing the dream of developing future quantum information technologies, Nori believes that: "Since the study of quantum information processing has just started, it is too early to forecast the concrete time of utilization. It is not known now which device or system (e.g., ion traps, atoms, photons, spins) will be more fruitful in the long run for this task. The possibility is still open to all. Therefore, at this point this is a very exciting area of research, full of open problems and challenging questions."

Nori is grateful to the outstanding leadership of Tonomura, and of Kohei Tamao and Ryoji Noyori, also from RIKEN. "Scientific leaders of such high caliber motivate others to also do top-quality science of high international visibility." ■

About the researcher

Professor Franco Nori was elected Fellow of the American Physical Society in 2002 "for innovative theoretical contributions to the study of vortex dynamics in superconductors, dynamical instabilities, Josephson junction arrays, and quantum interference." In 2003, he was elected Fellow of the Institute of Physics in the United Kingdom. He has received an "Excellence in Research Award" and an "Excellence in Education Award" from the University of Michigan, USA. He has given more than 200 presentations worldwide, and published more than 200 papers on his research, including numerous publications in the highest impact journals (Science, Nature, Nature Materials, Nature Physics, as well as over 45 publications in Physical Review Letters, which is widely considered to be the top journal in physics). He obtained a Masters and a PhD in Physics from the University of Illinois and completed postdoctoral work at the University of California. He then became a Professor at the University of Michigan and afterwards Laboratory Head at RIKEN.