Scientists observe how superconducting nanowires lose resistance-free state

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Even with today's invisibility cloaks, people can't walk through walls. But, when paired together, millions of electrons can.

The electrons perform this trick, called macroscopic quantum tunneling, when they pair up and move into a region of space that is normally off-limits under the laws of classical mechanics. The problem is that as millions of electrons collectively move through a superconducting nanowire, they use energy and give off heat.

The heat can build, transforming sections of the wire into a non-superconducting state. The process, called a phase slip, adds resistance to an electrical system and has implications for designing new nano-scale superconductors.

Now, scientists have observed individual phase slips in aluminum nanowires and characterized the nature and temperature at which they occur. This information could help scientists remove phase slips from nano-scale systems, which could lead to more reliable nanowires and more efficient nano-electronics, said Duke physicist Albert Chang.

The results appeared online Sept. 21 in Physical Review Letters.

The macroscopic quantum tunneling effect was first observed in a system called a Josephson junction. This device has a thin insulating layer connecting two superconductors, which are several nanometers wide and have a three-dimensional shape.

To study the tunneling and phase slips in a simpler system, however, Chang and his colleagues used individual, one-dimensional nanowires made of aluminum. The new observations are "arguably the first convincing demonstration of tunneling of millions of electrons in one-dimensional superconducting nanowires," said Chang, who led the study.

In the experiment, the wires ranged in length from 1.5 to 10 micrometers, with widths from five to 10 nanometers. Chang cooled the wires to a temperature close to absolute zero, roughly 1 degree Kelvin or -458 degrees Fahrenheit.

At this temperature, a metal's crystal lattice vibrates in a way that allows electrons to overcome their negative repulsion of one other. The electrons make pairs and electric current flows essentially resistance-free, forming a superconductor.

The electron pairs move together in a path in a quantum-mechanical space, which resembles the curled cord of an old phone. On their way around the path, all of the electrons have to scale a barrier or a wall. Moving past this wall collectively keeps the electrons paired and the superconducting current stable.

But, the collective effort takes energy and gives off heat. With successive scaling attempts, the heat builds, causing a section of the wire to experience a phase slip from a superconducting to a non-superconducting state.

To pinpoint precisely how phase slips happen, Chang varied the temperatures and amount of current run through the aluminum nanowires.

The experiments show that at higher temperatures, roughly 1.5 degrees Kelvin and close to the critical temperature where the wires naturally

become non-superconducting, the electrons have enough energy to move over the wall that keeps the electrons paired and the superconducting current stable.

In contrast, the electrons in the nanowires cooled to less than 1 degree Kelvin do not have the energy to scale the wall. Instead, the electrons tunnel, or go through the wall together, all at once, said Duke physicist Gleb Finkelstein, one of Chang's collaborators.

The experiments also show that at the relatively higher temperatures, individual jumps over the wall don't create enough heat to cause a breakdown in superconductivity. But multiple jumps do.

At the lowest temperatures, however, the paired electrons only need to experience one successful attempt at the wall, either over or through it, to create enough heat to slip in phase and break the superconducting state.

Studying the electrons' behavior at specific temperatures provides scientists with information to build ultra-thin superconducting wires that might not have phase slips. Chang said the improved wires could soon play a role in ultra-miniaturized electrical components for ultra-miniaturized electronics, such as the quantum bit, used in a quantum computer.

More information: Li, P. et al. *Phys. Rev. Lett.* 107, 137004 (2011) DOI:10.1103/PhysRevLett.107.137004

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