Superconductivity Traverses a Single Molecule Bridge

A single molecule provides a controllable connection between a normal metal and a superconductor.

By **Katherine Wright**

Researchers have caused a material's superconductivity to permeate into a nearby normal metal via a single molecule [**1**]. They showed that this effect could be controlled and say that this control could allow the creation of so-called Majorana quasiparticles, which many research teams are exploring as future quantum bits (qubits) for quantum computers.

The spread of superconductivity into a normal metal in contact with a superconductor has been studied for decades. These experiments are typically done with thin films of the materials. However, the microscopic mechanism underpinning the effect—a normal-to-super-current conversion known as Andreev reflection—can be hard to control, and control is essential for applications of the effect.

One such application involves the transfer of superconducting electron pairs (Cooper pairs) into ferromagnetic nanostructures, says Lorenz Meyer of Ilmenau University of Technology, Germany. Theorists predict that such a transfer could lead to the formation of exotic quantum states known as Majorana quasiparticles in the nanostructure. Researchers are trying to produce these states, which could potentially be used as qubits that are more robust than those used by current quantum processors.

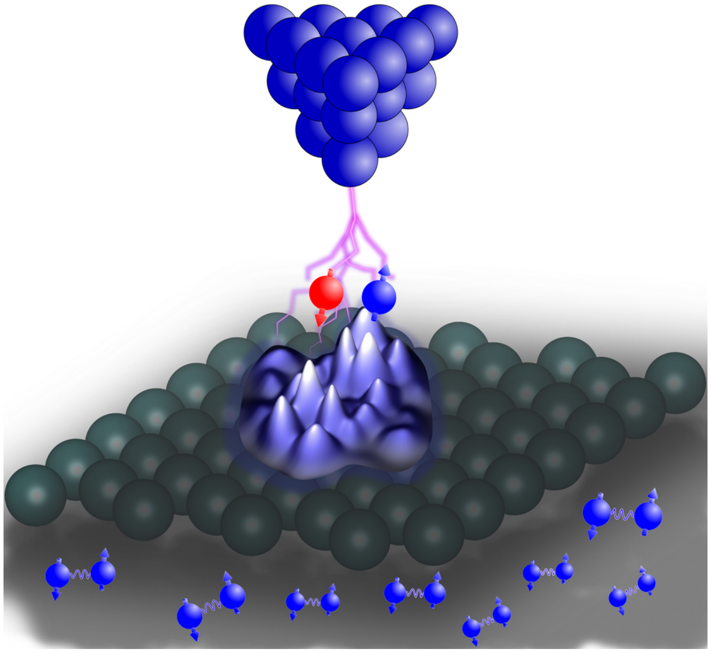
To create a controlled interface for the process, Meyer and his colleagues placed single molecules of phthalocyanine (a kind of dye) on a superconducting lead surface. A scanning-tunneling-microscope (STM) tip made of a normal metal was then lowered to approach and eventually to contact one of the molecules. "This is a special situation because the normal metal and the superconductor exhibit an interface that is reduced to a single molecule," Meyer says.

The researchers measured the current across this interface as they varied the height of the tip and the tip-to-surface voltage. The measurements showed that the phthalocyanine molecule has an electron orbital that changes as the STM tip gets closer. The energy of the orbital shifts toward the so-called Fermi level—the highest energy level that an electron can occupy at absolute zero temperature. The normal-to-super-current conversion process is expected to occur for electrons at the Fermi level. Once the orbital reaches the Fermi level, the team found that Andreev reflection of the junction is enhanced.

Meyer says that he and his colleagues think that the orbital shift is induced by a chemical interaction between the tip and the phthalocyanine. Because of the proximity between the tip and the molecule, the orbitals of the two overlap, giving rise to a partial filling of the lowest unoccupied molecular orbital. This filling shifts the orbital energy closer to the Fermi level.

The Andreev-reflection mechanism was originally conceived for complex macroscopic interfaces between normal metals and superconductors. "We have reduced the complexity of a normal-metal–superconductor hybrid structure to the atomic and molecular constituents of a well-defined interface," Meyer says. Such a simplified model system is easier to combine with state-of-the-art simulations that rely on a minimum of assumptions, which is favorable for gaining new insights.

In addition to revealing Andreev reflection, the data showed that the molecule became magnetic when touched by the tip. The team also tested another molecule, a variant of the phthalocyanine molecule that did not exhibit a shifting orbital.



First contact. A scanning tunneling microscope's (STM's) atomically sharp tip, made of normal-metal atoms (blue spheres), approaches a phthalocyanine molecule (blue and white peaks, representing the STM-generated map) on a superconducting lead surface (dark spheres). An electron (blue sphere with arrow above the molecule) can jump across the gap along various paths (jagged pink lines), and this jump is accompanied by the production of a hole (red sphere) that moves in the other direction, a process called Andreev reflection. Superconductivity in the lead is produced by Cooper pairs of electrons (paired spheres), some of which are generated by Andreev-reflection events.

Credit: L. Meyer/Ilmenau University of Technology

For this system no Andreev reflection and no magnetic effect were measured. "The clear difference between the results for the two molecules is striking, since the molecules are very similar—one with hydrogen atoms and the other without them," says Takashi Uchihashi, who studies quantum materials at the National Institute for Materials Science, Japan. "This means that you need to have a molecular-level control of the superconducting heterointerface if you try to design and control its functionality."

"This work introduces a novel approach to tuning the coupling between magnetism and superconductivity simply by adjusting the tip–sample distance in a superconductor-supported system," says He Zhao, who studies materials with exotic properties at Florida State University. He notes that understanding the interplay between magnetism and superconductivity—which are often at odds—is essential for exploring unconventional superconducting states.

Katherine Wright is the Deputy Editor of ***Physics Magazine***.

REFERENCES

1. L. Meyer *et al.*, "Control of Andreev reflection via a single-molecule orbital," **Phys. Rev. Lett. 134, 146201 (2025).**