Is a superconductor just a conductor without resistance?

-- Josephson Effect of Superconductors.

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Superconductors are discovered in 1911, when the scientist Onnes measured the resistance of the mercury at low temperatures. He found the resistance suddenly fell to zero at 4.15K when he was cooling the mercury. This is the first time that humans encounter a superconductor. Later, scientists found more superconductors, most of which metals or their compounds. They share the same property that the resistance disappears below a specific temperature T_c. Because of zero resistance, current can last without decay and heat emitting, even if there is no voltage on both sides.

The zero resistance property is so appealing to the electricity industry because there is an enormous amount of energy lost on the electricity transmission every year. News and proposals for updating the electricity system with superconductivity materials often appear on social media. However, the name 'superconductor' is a little bit confusing because it makes many people simply regard superconductors as conductors without resistance. In fact, superconductors have other lesser-known effects, one is the Josephson effect.

In 1962, a British graduate student Josephson predicted that, even if two blocks of superconductor are divided by a very thin layer of insulator (about $10^{-10}m$), there can be current passing from one superconductor to another [1]. This phenomenon is the DC (direct current) Josephson effect and the structure is called the Josephson junction. This effect is astonishing for two points. First, this current can appear even if no voltage is added to these two superconductors. Second, this current can pass through the insulator layer as if it is transparent. People may believe the first point reasonable, as superconductor has no resistance at all, but insulators do not transit electricity, how can two superconductors ignore the existence of the insulator between them?

To answer this question, we need to enter the microscopic quantum world. There, metals are built by periodically arranged atoms (lattice) and current is composed of lots of moving electrons. These electrons collide with the atoms, obtain a velocity backward, so the current is 'resisted'. Usually, electrons are much lighter than atoms, so atoms move slower than electrons. This enables the displaced atom to affect another electron passing by. Magically, if the second electron passes at a right time, or we say if 'the rhythm is fine', it may feel attracted by the previous electron! (There are about 10^{23} electrons so it is always possible to find many candidates meeting the 'fine-rhythm' condition.). Inspired by this mechanic, Bardeen, Cooper and Schrieffer developed the famous BCS theory for superconductors in 1957 [2], which says when a superconductivity material cools below T_c, two electrons on 'fine rhythm' will form a Cooper pair. Cooper pairs have an interesting quantum property that they do not 'collide' with the lattice, so they feel no resistance at all.

However, two electrons in a Cooper pair are actually very far apart, compared to the distance of two atoms (about 10^4 times larger). So, we obtain a strange image: inside a Cooper pair exist numerous other Cooper pairs, they must interact with each other intensively and thus are strongly correlated. Following this idea, we naturally imagine if the space scale of a Cooper pair is even larger than the distance of two superconductors, Cooper pairs from different superconductors will be correlated too. It is exactly this correlation (physically speaking, coherence) that causes the transport of Cooper pairs across the insulator layer: a Cooper pair just disappears on one side and appear on another side (Figure 1), by the magic power of coherence. This is an intrinsic quantum phenomenon and explanation of the DC Josephson effect.

Then, how is the value of the Cooper pair current determined? In 1950, Ginzburg and Landau once propose a theory, which claims a superconductor has a 'phase' as the alternating current does. After detailed analyzing and calculation, Josephson predicted that the current between two close superconductors are tuned by a sine function of their phase difference: $\sin\Delta\theta$. The experiments confirmed this soon after.

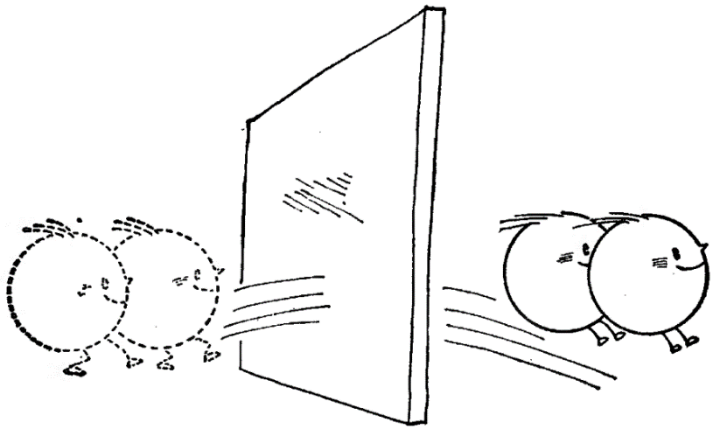

Figure 1: A cartoon describing a Cooper pair passing through the insulator layer [3].

This is not the end of the story. As the quantum mechanics tells us, the phase difference between two superconductors can be controlled by the magnetic flux (the magnetic induction intensity multiplied by the area, roughly speaking) across the junction area. Scientists soon realized the oscillation period of the current caused by the Josephson effect can help measure some weak electromagnetic fields. However, due to the limited size of a Josephson junction, its magnetic sensitivity is about $10^{-2}Gs$ (the earth magnetic field near the equator is about $0.3Gs$). To overcome the size limitation, scientists later designed the Superconducting Quantum Interference Devices (SQUID), which has two parallelly connected Josephson junctions on both sides of two superconductors and forms a circle. Here the loop current is tuned by the magnetic flux across the circle. Since the circle is much larger than a junction area, the magnetic sensitivity improves tremendously (about $10^{-7}Gs$). Now, SQUIDs are the most sensitive kind of magnetic field detectors in the world. Improved techniques based on SQUID even enable scientists to measure magnetic fields of $10^{-11}Gs$.

The SQUID is so sensitive that makes weak magnetic field research possible, especially biomagnetism ones [4]. Usually, electric and magnetic fields are two phenomena that appear together. We have learned a lot about the bioelectrical signals while still knowing little about magnetic ones because they are too weak to detect. Specifically, the magnetic field in the human brain is about $10^{-9}Gs$ and is beyond the capability of normal magnetic detectors. Also, such high accuracy measurements help the mineral exploration because some metals have distinct magnetic properties from the earth. Relevant applications of the SQUID are quite promising.

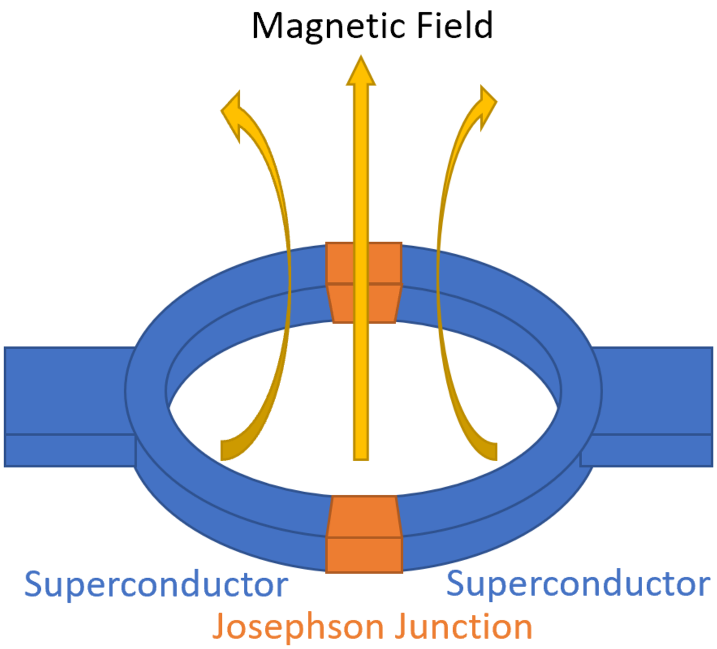

Figure 2: A schematic picture of a Superconducting Quantum Interference Devices (SQUID).

Superconductivity, so as the Josephson effect, is an intrinsic quantum effect. These quantum technologies have more advantages than saving energy from resistance. There are so many deep theories and interesting applications that superconductivity is truly a gem of basic sciences.

References

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