Magnetism relieves electrons of their resistance

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Looking for magnetic interactions: A technician adjusts the spectrometer which a team of physicists, headed by Oliver Stockert at the Institut Laue-Langevin in Grenoble, use to measure neutron scattering in a compound of cerium, copper and silicon. These experiments reveal the magnetic fluctuations of a material. According to this experiment, the superconductivity in $CeCu_2Si_2$ is caused by magnetic interactions. Image: P. Avavian for CEA Grenoble

(PhysOrg.com) -- Physics is sometimes just like a criminal investigation. Researchers gather one piece of evidence after another in order to solve a mystery - for example, the question as to how unconventional superconductivity is caused, something which is also of particular interest for technical applications.

An international team involving scientists at the Max Planck Institute for Chemical Physics of Solids has now provided the strongest evidence yet that magnetic interactions can bring about this form of zero-resistance current transport - something that physicists have been gathering evidence for, for some time. It is becoming more and more apparent that a notorious troublemaker can also be cooperative: conventional superconductivity in normal metals is namely easily destroyed by magnetic fields. The fact that magnetism makes unconventional superconductivity possible, however, could also provide clues in the search for new materials that transport current without loss in day-to-day applications. (Nature Physics, online publication, December 12, 2010)

The picture that physicists have of unconventional superconductors is gradually becoming clearer. These materials also include the complexly-structured ceramic materials which conduct current without losses, even at relatively high temperatures. These temperatures are still below minus 135 degrees Celsius, however - too cold for wide-scale everyday application. In order to systematically shift this limit to a higher value, physicists first have to understand how the superconductivity arises in these materials. "Our findings make an important contribution to this understanding," says Frank Steglich, Director at the Max Planck Institute for Chemical Physics of Solids in Dresden and head of the investigation. One of the things that the researchers have discovered is that the magnetic interactions in the material provide enough energy to put the material into the superconducting state.

The researchers working with Frank Steglich collaborated with colleagues from the Julich Center for Neutron Science at the Institut Laue-Langevin in Grenoble, the TU Dresden, Rice University in Houston, Texas and the Max Planck Institute for the Physics of Complex Systems in Dresden to investigate $CeCu_2Si_2$ - a chemical compound of cerium, copper and silicon. This compound was identified as the first unconventional superconductor more than three decades ago and consequently kicked off the search for new mechanisms of superconductivity. In the meantime, the researchers now understand how to change the electronic state of the material: a small deficiency in copper causes the material to become anti-ferromagnetic; with a tiny excess, it becomes a superconductor. The work here must always be carried out close to absolute zero - the material is therefore unsuitable for practical applications: "We are interested in understanding the principle, however," says Oliver Stockert, who has played a crucial role in the investigations at the Dresden Max Planck Institute. $CeCu_2Si_2$ is particularly well-suited to this purpose because, in this compound, electrons of a certain type, the so-called 4f electrons of the cerium atoms, are involved in both the superconductivity and the magnetism.

In the magnetic version of the material the spins of the 4f electrons, which turn them into tiny bar magnets, give rise to the anti-ferromagnetic order of the material: this can be imagined in a simple picture where the tiny magnets lie next to each other with alternating north and south poles. In the superconducting version of $CeCu_2Si_2$, 4f electrons flow into the reservoir from which Cooper pairs form - electron pairs whose quantum properties make them invisible to the crystal lattice and which can therefore move through it unhindered. Simultaneously, the anti-ferromagnetic order disappears and the individual magnetic moments of the 4f electrons are no longer visible to the outside. "In this respect, our cerium compound basically behaves as we would expect a conventional superconductor to do," says Oliver Stockert.

The physicist and his colleagues have, however, looked at the magnetic moments in the superconducting version in detail. To this end, they conducted experiments at the Jülich Centre for Neutron Science at the Institut Laue-Langevin in Grenoble which involved bombarding a sample of the superconducting material with neutrons that also have a spin and therefore a magnetic moment. They thus excited the magnetic moments in the $CeCu_2Si_2$, i.e. caused them to spin around, in simplified terms. This only worked when the energy of the neutrons exceeded a certain threshold, however. It is precisely this minimum of energy which is required to break up the superconducting electron pairs.

This on its own is not enough to prove that the magnetic exchange binds the Cooper pairs together in the unconventional superconductors. "The magnetic interactions in the superconducting material release ten times more energy than the formation of the Cooper pairs, however," says Oliver Stockert: "It seems apparent that the magnetic interactions therefore make the unconventional superconductivity possible." After all, nature does everything it can to save energy. And, in this respect, the magnetic exchange seems to be particularly advantageous, especially in the superconductor.

The team has gleaned this knowledge from extensive measurement data of neutron scattering. This not only told the researchers how the strength of the magnetic excitations changes with their energy, but that it also depends on the direction in which they propagate in the crystal. The theoretical physicists at the Max Planck Institute for the Physics of Complex Systems and Rice University have used this knowledge to calculate the energy saving for the magnetic exchange.

And the team found another clue to the magnetic go-between role in unconventional superconductivity: they repeated their experiments at different temperatures close to absolute zero. The closer they came to this point, the more pronounced the anti-ferromagnetic order became - physicists then say that the spin fluctuations become longer-lived close to magnetic order.

$CeCu_2Si_2$ is therefore not only the first unconventional superconductor, which was discovered by Frank Steglich more than 30 years ago, as Qimiao Si, participating theoretician from Rice University, emphasizes: "The compound is also distinguished by the fact that we are unequivocally able to identify the observed spin fluctuations as quantum-critical fluctuations." These fluctuations are based on a quantum effect, which is why the point in whose vicinity they occur is called the quantum-critical point. "The fact that we observe superconductivity around this point also provides evidence that magnetic interactions bring about the formation of the Cooper pairs," says Oliver Stockert.

It remains to be seen why the magnetic exchange in the superconductor gives rise to such a large energy gain. Moreover, the physicists have still to discover the extent to which their findings can be applied to those materials that become superconducting at relatively high temperatures. "We are certain that we are on the right track with our investigations, however", says Frank Steglich. He and his colleagues will therefore continue to gather evidence in order to solve the mysteries surrounding unconventional superconductivity.

More information: O. Stockert, J. Arndt, E. Faulhaber, C. Geibel, H. S. Jeevan, S. Kirchner, M. Loewenhaupt, K. Schmalzl, W. Schmidt, Q. Si and F. Steglich, Magnetically driven superconductivity in $CeCu_2Si_2$, *Nature Physics*, published online, December 12, 2010, DOI:10.1038/NPHYS1852

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