Puzzling new behaviour observed in high-temperature superconductors

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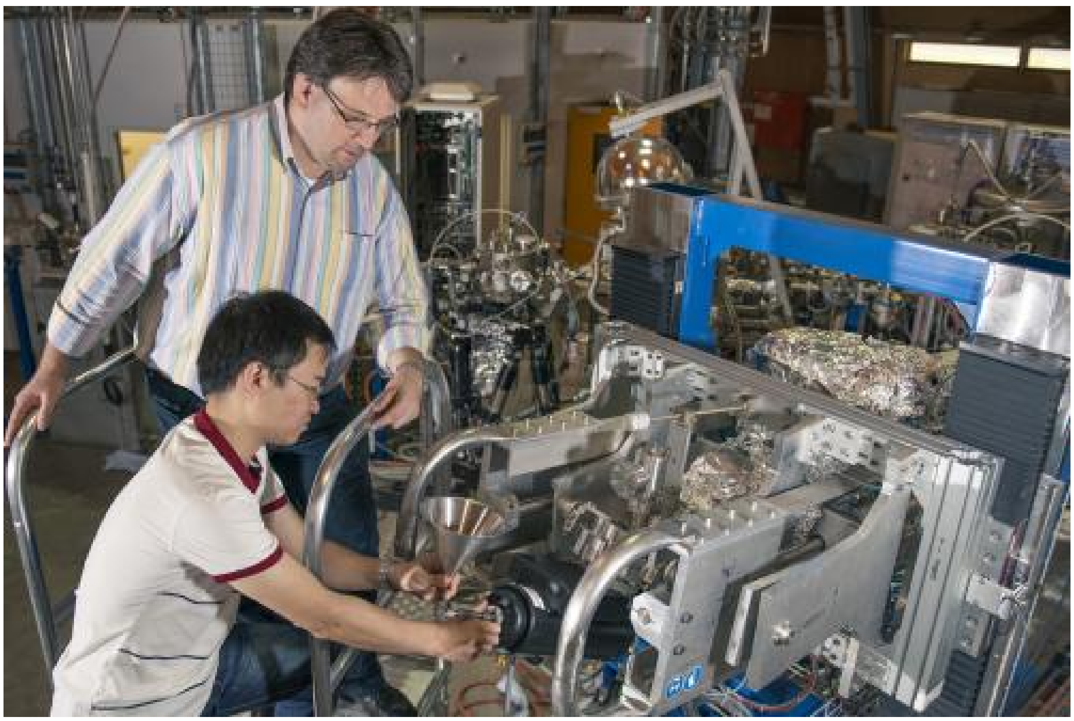

PSI researchers Thorsten Schmitt and Yaobo Huang at the ADRESS beamline at the SLS. Credit: Paul Scherrer Institute/Mahir Dzambegovic

An international team of researchers from SLAC National Accelerator Laboratory and Stanford University and the Paul Scherrer Institute (Villigen, Switzerland) has observed a new, unexpected kind of behaviour in copper-based high-temperature superconductors – materials that are capable of conducting electric current without any loss when cooled to low enough temperatures. Explaining the new phenomenon - a new, unexpected form of collective movement of the electrical charges in the material - poses a major challenge for the researchers. A success in explaining the phenomenon might be an important step toward understanding high-temperature superconductivity in general. The crucial experiments were conducted at the Paul Scherrer Institute's Swiss Light Source. The results of this project have been published in the journal *Nature Physics* on 19 October 2014.

Despite their name high-temperature superconductors have to be cooled heavily before they become superconducting. The name stems from the fact that the temperatures needed are not quite as low as for the more familiar conventional superconductors. "Materials that would also be superconducting at room temperature could help save a lot of energy," explains Thomas Devereaux, head of the research team SLAC and Stanford. "But in order to develop such materials, we have to understand what goes on inside them when they become superconducting. Our latest research results provide a key piece in this long-standing puzzle."

Copper oxide – a ceramic material – does not normally conduct electricity. However, it can become a superconductor if a small fraction of the atoms in the material is replaced with atoms of certain other elements, increasing or decreasing the number of electrons in the material – a technique dubbed "doping". In addition, the material still needs to be cooled heavily. Just how much, however, astonishingly depends on what kind of atoms have been replaced: for atoms that supply additional electrons, you have to cool the material to 30 kelvin, i.e. thirty degrees above absolute zero. But if you add atoms that reduce the number of electrons, it is sufficient to cool to 120 kelvin. One goal of the research project described was to discover the reason for this different behaviour under doping.

Showing the motion of charge carriers

In order to determine how doping alters the properties of the material, the researchers used a modern experimental technique based on x-ray light known as resonant inelastic x-ray scattering RIXS. The experiments were conducted on the RIXS instrument at the Paul Scherrer Institute's Swiss Light Source (SLS). "This facility currently boasts the highest resolution in the world and can reveal how individual charge carriers – the electrons - move under the stimuli of the incident X-rays. The results of such stimuli are excitations that can be imagined as waves spreading through the material if one of its properties changes somewhere," explains Thorsten Schmitt, the scientist responsible for this facility at PSI. These altered properties can be the distribution of the electrical charges or the magnetic order in the material. A magnetic order can emerge as the electrons inside some materials behave like tiny magnets. If these magnets are arranged in a regular pattern, this is referred to as a magnetic order. Waves can be induced in this order if individual magnets are moved out of position and this displacement travels from magnet to magnet. However, the excitation does not necessarily spread in the same direction in which the individual magnets have been moved – much like a water wave travels across the surface of the water although the individual water molecules only move up and down. For both the magnetic and the water wave, the direction of the wave's propagation as a whole is important, i.e. the direction in which the wave transports energy, which, in the case of the water wave, is used by a surfer, for instance.

Highest accuracy at PSI instrument

"In a RIXS experiment, you shine x-ray light onto the sample, which stimulates a magnetic wave in the sample," explains Schmitt. "The x-ray light transfers part of its energy to the magnetic wave in the process. By comparing the energy of the x-ray light entering the sample with that of the x-ray light leaving it, you can glean information on the properties of the magnetic waves stimulated – especially its energy." Schmitt goes on to explain why the measurements were conducted at PSI: "Nowhere else in the world can the energy of such excitations be measured as accurately as on our RIXS instrument at PSI."

The experiments revealed two puzzling things. "On the one hand, the magnetic energy transported by the excitation increased by an unexpectedly large extent in the materials with an electron surplus studied. On the other hand, the formation of new, collective excitations – a particular form of collective movement of the electrical charges – was detected in these very materials," reports Wei-Sheng Lee, the first author of the publication in *Nature Physics*. "However, it's a mystery as to why we haven't observed this phenomenon in electron deficient materials; after all, you would expect them to behave in a similar way to those with an electron surplus."

A long, uphill struggle towards understanding

The new discovery is one of the steps on the long, uphill struggle towards understanding high-temperature superconductivity.

Scientists have known why certain metals and simple alloys become superconducting if they are cooled to a few degrees above absolute zero since the 1950s. Their electrons join up to form pairs, which are held together by atomic oscillations that act as a kind of virtual adhesive. Above a certain temperature, however, the glue no longer holds because the increasingly stronger movement of the atoms in the superconductor separates the electrons and causes the superconductivity to disappear.

Since 1986, researchers have discovered a series of novel materials that become superconducting at higher temperatures between 30 and 120 Kelvin – the so-called high-temperature superconductors. The hope now is to eventually be able to produce superconductors that become superconducting at room temperature or even higher temperatures if we can improve our grasp of how these materials work.

How electrons form pairs

How exactly the electron pairing comes about remains unclear. Until recently, the assumption was that at higher temperatures the electron pairs are held together by strong magnetic excitations, which are generated by interactions between the electron spins. The latest computer simulations conducted by researchers from SLAC and Stanford University, however, reveal that high-energy magnetic interactions cannot solely be responsible for the formation of electron pairs and thus high-temperature superconductivity.

According to the latest results, Lee stresses, it is also unclear whether the newly observed collective excitation of the electrical charges are linked to electron pairing in the high-temperature superconductors studied. After all, it is not known whether the new effect is conducive to superconductivity in the materials studied or a hindrance.

"Theoretical physicists will now have to factor the new results into their explanations of the origin of high-temperature conductivity," says Schmitt.

More information: "Asymmetry of collective excitations in electron- and hold-doped cuprate superconductors." W. S. Lee, J. J. Lee, E. A. Nowadnick, S. Gerber, W. Tabis, S.W. Huang, V. N. Strocov, E. M. Motoyama, G. Yu, B. Moritz, H. Y. Huang, R. P.Wang, Y. B. Huang, W. B.Wu, C. T. Chen, D. J. Huang, M. Greven, T. Schmitt, Z. X. Shen and T. P. Devereaux *Nature Physics*, advance online publication 19 October 2014; DOI: 10.1038/nphys3117

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