Scientists measure energetic gaps in iron-based superconductors

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The scientists from the Faculty of Physics of the Lomonosov Moscow State University conducted a study evaluating the appearance of the superconducting state in the iron-based superconductors with two energetic gaps. Credit: The Lomonosov Moscow State University

Scientists from the Faculty of Physics of the Lomonosov Moscow State University conducted a study evaluating the appearance of the superconducting state in iron-based superconductors with two energetic gaps. The report on the study was published in the latest issue of the *Journal of Superconductivity and Novel Magnetism*.

The scientists have, for the first time in history, reliably and directly measured the energetic gaps of a number of iron-containing superconductors. According to Svetoslav Kuzmichev, who leads the research project, the results could allow scientists to solve some questions concerning the appearance of the superconductivity in the iron-containing materials.

The interesting thing for the physicists was a chance to measure the temperature dependencies of the two energetic gaps. The term "superconducting gap" refers to a range of energies that is forbidden for the conducting electrons.

In 1957, American physicists John Bardeen, Leon N. Cooper and John Robert Schrieffer developed the BCS theory explaining superconductivity phenomena, which received the Nobel Prize in 1972. Since then, there was only one such band, from the temperature of the transition to the superconductivity state to zero. But in 1959, the probable existence of two-gap superconductors was assumed by a Soviet physicist, V.A. Moskalenko, and his U.S. colleague, G. Suhl. The two scientists independently derived sets of equations describing mechanisms of such superconductivity. However, it wasn't until 2001 that the first two-band superconductor was found. It was quite simple in composition: magnesium diboride.

By that time, physicists doubted the possibility of two-gap superconductivity. Scientists preoccupied with superconductivity problems treated magnesium diboride as an exception that proves the rule. Only seven years later, in 2008, the phenomenon of two-gap superconductivity was experimentally confirmed in the iron-containing materials. Many laboratories all over the world started to use the superconductive 'ferrum,' the tally of the two-gap materials rose to dozens, and the exception became a rule. Eight years ago, it was considered that they could not exist at all, as magnetic fields kill superconductivity. Since the BCS theory, the absence of magnetic atoms in a superconductor seemed to be an indisputable condition.

According to this theory, superconductivity occurs because of the interaction of electrons and the crystal lattice vibrations, which results in building the so-called Cooper pairs of two electrons with opposite spins (the resulting spin is hence absent), so the electrons have a chance to move without colliding with the lattice.

As spin is the magnetic moment of a particle, in the presence of magnetic interactions, it seems impossible to preserve the resulting zero spin. According to Svetoslav Kuzmichev, the first author of the article and a senior research fellow at MSU, this fact was multiply confirmed in experiments with common superconductors. Addition of a tiny magnetic admixture or replacing any of the atoms with ferromagnetic ones in a superconductor led to a drastic decrease in superconductivity, including its total disappearance.

After the discovery of the iron-based conductors, the new class of materials came to prominence. Previously, scientists pursued high-temperature cuprates (cuprum-containing superconductors) and two-gap magnesium diboride. During the next eight years, the number of superconductors based on ferrum compounds with arsenic or selenium outnumbered all the superconductive cuprates, though understanding of the phenomenon did not come.

"It was found that the ferrum-arsenic or ferrum-selenium blocks are responsible for the appearance of the superconductivity," Svetoslav Kuzmichev says. "Almost all the scientists agree that although the outer magnetic field is suppressed, inside the blocks, its fluctuations may exist in the form of magnon quasiparticles. There is a high probability that they take part in the development of the superconductive state. However, the matter is so novel and our knowledge is so limited, that almost none of the suggested mechanisms of reaching superconductivity have yet been confirmed or refuted."

Iron-based superconductors are multi-band, which significantly complicates the understanding of the intricate processes accompanying superconductivity, regardless of the existence of BCS theory and its related equations.

Scientists calculated the tendency of the temperature behavior of the two superconductive gaps for a number of the iron-based superconductors and the non-iron magnesium diboride (with a partial replacement of magnesium with aluminium). For the first time in history, researchers made direct experimental measurements of those dependences and detected a convincing correlation of the calculations and the experimentally gained data. Moreover, they evaluated what contributes more to the superconductive state—an interband or an intraband pairing. In other words, they established the strength of the connection within a Cooper pair, which is formed by coupling electrons from the same or from two different bands. According to Kuzmichev, that is particularly important for understanding the mechanisms of iron superconductivity.

"Until now, such estimations of the gaps' characteristics were based on the indirect measurements," the scientist says. "For example, the correlation with temperature and other parameters of the superconductive state was measured, with the further extrapolation of the results for distinguishing the energetic gaps. Those were quite approximate measurements."

"The MSU Physical faculty professor Yaroslav Ponomarev (1938-2015) developed a 'break-junction' technique that helped us for the first time to measure directly the energetic gaps of the high-temperature superconductors up to the critical temperature of the superconductive transition, avoiding indirect measurement. This let us estimate the magnitude of the interband and the intraband electron pairing. As the result, we have shown that the crucial role in the mechanism of magnesium diboride superconductivity is played by the intraband pairing. The condensates interact weakly, and in the magnesium diboride, interband interaction is far weaker than in the iron-based superconductors.'

Kuzmichev hopes that this work could clarify the development of iron superconductivity. In terms of critical temperatures, such superconductors give way to cuprates—while the maximal temperature of the superconductive transition observed in ferrum-selenium films was about 85 K, for cuprate superconductors, it reaches up to 135 K. The main advantage of the iron superconductors, Kuzmichev says, is the unmatched current density that they carry.

"They can conduct the current with 10 to 100 times greater density than cuprates, even niobium alloys that are used today in superconductive magnets for generating extremely high fields for powerful accelerators and tokamaks. No other superconductor compares to them today, except high-purity magnesium diboride, which can carry currents with density up to a million ampere per square centimeter. In laboratory conditions, those numbers are impossible to prove directly, of course, though according to the existing estimations, such densities are absolutely attainable with the iron species. I suppose soon, we will have no alternative to them," the scientist concludes.

More information: S. A. Kuzmichev et al. Estimation of Intraband and Interband Relative Coupling Constants from Temperature Dependences of the Order Parameter for Two-Gap Superconductors, *Journal of Superconductivity and Novel Magnetism* (2016). DOI:

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