Iron age of high-temperature superconductivity

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An international collaboration including Russian physicists from Moscow, Chernogolovka and Yekaterinburg have studied one member of the recently discovered family of superconductors based on iron compounds and find this exotic form of superconductivity to have complex, multi-gap character. A fact of principal importance for understanding the mechanisms of superconductivity is that the superconducting gap width never becomes zero around the constant-energy Fermi surface. Results of this work were published in one of the leading physical journals of the world—*Physical Review B* journal.

After the discovery of high temperature superconductivity in complex copper oxides (cuprates), exotic superconductivity exhibiting certain unexpected properties was found also in certain layered iron-based compounds. And though the critical temperatures in these new substances are still lower than in cuprates, one can predict with certainty that in the field of condensed matter physics, an "iron age" should follow the current "copper age".

All the handbooks cite superconductivity as the ability of some metals to have strictly zero resistance below some temperature known as critical. This phenomenon is commonly applied in electromagnet construction for accelerators of charged particles (including the Large Hadronic Collider) and, for example, in nuclear magnetic resonance tomography, one of the most promising methods of medical diagnosis.

When in the year 1957 John Bardeen (known as the inventor of the semiconductor-based transistor) together with Leon Cooper and John Schrieffer explained the superconductivity mechanism (currently known as the "BCS mechanism" after the initials of the three authors), it seemed so mathematically elegant that was immediately accepted by the scientific community. Today it is still immune from criticism, but the physicists gradually come to the conclusion that the BCS theory only explains the foundation of the much more complicated phenomenology of superconductivity.

BCS explains metallic superconductivity by electron binding in the so-called Cooper pairs. Pair formation is initiated by electron interaction with phonons—disturbances of the metallic crystal lattice. For description of the conditions leading to superconductivity, the important concept of Fermi surface plays the principal role. This surface separates the quantum states occupied by electrons and vacant quantum states.

Note that Fermi surface is a surface in the momentum (or reciprocal) space rather than the usual coordinate space. In the framework of BCS, superconductivity is a consequence of existence of some energy gap near this surface—an energy range forbidden for electron states.

Fermi surface was initially considered spherical with the constant gap width. According to Alexander Vasiliev, one of the contributors of this study, chair of the Low-Temperature Physics and Superconductivity Department of the Physical faculty of MSU, the reality is much more complicated. The form of Fermi surface may be far from spherical and depends on numerous factors such as external pressure. Gaps, on the other hand, may be multiple. And the electron binding may be provided by some other means rather than lattice vibrations, in particular by oscillations of the magnetic sub-system.

Iron-based superconductors studied by the authors were discovered quite recently, in 2008. Immediately after being discovered, these compounds set a large number of questions before the investigators. And there are very few satisfactory answers to these questions. The authors selected iron selenide known for having the simplest lattice structure among all the iron-based superconductors, thus being the ideal target for a deeper study. Professor Vasiliev says such objects are studied in all the leading laboratories of the world.

In the experiment described, external field and temperature dependences of the critical parameters were studied, primarily of the so-called "first critical field" (the weakest magnetic field capable for penetrating the lattice). The obtained information proved to be of great importance for further analysis of the superconductivity mechanisms in iron-based superconductors. The breakthrough was enabled by the excellent quality of the superconductors produced by Dmitry Chareev in the crystal growth laboratories of MSU and the ingenious technique of experimental data reduction proposed by Belgian physicists Mahmoud Abdel-Hafiez and Victor Moshchalkov.

Experimental results argue that the iron selenide superconductivity originates either from strong modulation of the energy gap width or from existence of two energy gaps with the widths different by an order of magnitude. An important result, according to the authors, is that the gap width never becomes zero at the Fermi surface. The experimental results presented in this article may be of much help for the theorists currently developing the theory of one of the most enigmatic and intriguing quantum phenomena that finds more and more applications in modern technology.

More information: "Temperature dependence of lower critical field Hc1(T) shows nodeless superconductivity in FeSe." M. Abdel-Hafiez, J. Ge, A. N. Vasiliev, D. A. Chareev, J. Van de Vondel, V. V. Moshchalkov, and A. V. Silhanek. *Physical Review B*, 2013. doi: dx.doi.org/10.1103/PhysRevB.88.174512

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