Front. Phys. China, 2010, 5(2): 147–149
DOI 10.1007/s11467-009-0081-z

PERSPECTIVE

Progress and prospect on the research of new iron-based high-T_c superconductors

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Received October 30, 2009; accepted November 10, 2009

Since the discovery of high-T_c copper oxides, researches on high-T_c superconductors and their physical mechanism have become one of the hottest topics in condensed matter physics. In conventional superconductors, superconductivity occurs at very low temperatures. When superconductive, a material presents zero resistance and diamagnetism which is called Meissner Effect. The high-T_c superconductors are the materials whose superconducting transition temperatures are beyond the McMillan limit of 39 K. However, up to now, the mechanism of the copper oxide superconductors is still under debate.

The newly discovered iron-based superconductors are another kind of high-T_c superconductors following the discovery of $LaO_{1-x}F_xFeAs$ whose critical temperature is 26 K in 2008. The highest critical temperature reported for iron-based superconductors is 56 K observed in $Gd_{1-x}Th_xFeAsO$ [1–4]. Compared with copper oxide superconductors, the iron-based superconductors have some similarities, for instance, both of them have two-dimensional layered structures, short coherent length, and long penetration depth; however, they also show a lot of differences, for examples, iron-based superconductors display a multi-band structure, while copper oxide superconductors present a single-band structure. Therefore, these phenomenon undoubtedly provide ways for further researches on high-T_c superconductors. Researches on iron-based superconductors are very important for basic understanding of superconductivity. We cannot only learn the roles of relevant physics in superconductivity from another angle, but also broaden or revise the traditional views and even discover a new mechanism of carrier pairing in superconductors. On the other hand, iron-based superconductors show high critical magnetic fields and low anisotropy, and they also have a much better processing property than copper oxide superconductors, indicating promising applications in industry. The research on iron-based high-T_c superconductors, however, is still in a preliminary approach stage. The development in the mechanism of superconductivity may further optimize the structure of these materials, and consequently enhance the superconducting transition temperatures. The breakup in the properties of these materials could be useful for exploring the nature of materials and practical applications.

Until now, the newly discovered iron-based superconductors are mainly obtained by doping or other methods from two kinds of parent compounds, including FeAs-1111 and FeAs-122 phases. The compounds in the same series present similar structures. As for FeAs-1111 series, the most representative material is LaFeAsO, and others in this series can be obtained by replacing lanthanum with other rare-earth elements or arsenic with other phosphorus-group elements. In addition, FeAs-1111 series also include SrFeAsF by replacing SrF layer into LaO layer. It is currently believed that LaFeAsO is composited with FeAs layers acting as conductive layers and LaO layers acting as charge reservoirs. The superconductivity in doped LaFeAsO is like that in cuprates, and the carriers are transferred from doped LaO layer into FeAs layer where superconductivity occurs. $BaFe_2As_2$ is the parent material of the FeAs-122 series. Other materials in FeAs-122 series can be achieved by replacing alkaline-earth metal elements into Ba sites, such as $SrFe_2As_2$. $BaFe_2As_2$ with the tetragonal $ThCr_2Si_2$-type structure contains two identical FeAs layers, but they are separated by barium atoms instead of LaO sheets. Similar with LaFeAsO, the FeAs layers act as conductive layers while the barium layers act as charge reservoirs [5]. We can dope electrons or holes into the parent materials in order to modulate its physical properties. Superconductivity can be induced by doping in both classes as follows. Firstly, electrons or holes are doped into charge reservoir layers. In FeAs-1111 system, electron-doping can be achieved by either doping F into O sites or introducing deficiency of O ions. However, hole-doping is realized by replacing alkaline-earth metal atoms into lanthanum-group atoms. Replacing other alkaline-earth metal atoms into Ba sites can successfully introduce hole-type carriers in FeAs-122 system. The second way to realize superconductivity is doping electrons or holes into the conductive layers, such as replacing Fe ions with other transition-metal atoms or changing As atoms with P atoms. The third method to achieve superconductivity is applying high pressure on the undoped parent samples. In addition, scientists also have discovered FeAs-111 phase, FeAs-11 phase, and FeAs-426 phase. The representative one in FeAs-111 phase is NaFeAs, whose unit cell has a FeAs layer and two Na layers. The superconductors with the same structure can be obtained by replacing Na with Li or As with P [6]. Very recently, a new type of superconductors with FeAs-11 structure, tetragonal FeSe with T_c of 14 K, was reported. The crystal structure of FeSe is the same as the FeAs layers. The critical temperature can be improved to 15 K by Sb doping at Se sites. It was also reported that a large enhancement of superconducting transition temperature T_c of 37 K was observed under high pressure [7]. Sr_2VO_3FeAs is the parent material in FeAs-426 series. This compound consists of a stacking of antifluorite Fe_2As_2 layers and perovskite-type $Sr_4V_2O_6$ layers. Compared with LaO layers in FeAs-1111 series, the $Sr_4V_2O_6$ layers in Sr_2VO_3FeAs lead a much larger distance between two FeAs layers. Superconductivity can also be obtained by replacing V with Sc or As with P [8, 9].

The neutron-scattering experiments demonstrated that the parent materials of iron-based superconductors undergo an abrupt structural distortion which changes the symmetry from tetragonal to orthorhombic at low temperatures, and then, develop long-range antiferromagnetic-type spin-density-wave (SDW) order with a small moment and simple magnetic structure [12, 13].

The structural and magnetic transition is rapidly suppressed via doping or high pressure which can induce superconductivity. The relation between SDW and superconductivity is a central topic in the current research on iron-based high-T_c superconductors. SDW and superconductivity can coexist in an extended range of compositions for $SmFeAsO_{1-x}F_x$, $Ba_{1-x}K_xFe_2As_2$, and $Ba_{1-x}Co_x$ Fe_2As_2 [12, 13]. However, the same results cannot be observed in the $LaFeAsO_{1-x}F_x$ system. In the various iron-based superconductors the relationships between SDW and superconductivity, are different, indicating that a much complicated relation exists between structure, magnetism and superconductivity. Some key questions in iron-based high-T_c superconductors were intensively studied, such as the pairing symmetry of superconductive electrons and the mechanism of superconductivity. However, conflicting results were obtained by applying different experimental methods, such as angle-resolved photoemission spectroscopy (ARPES), scanning tunneling microscopy (STM), nuclear magnetic resonance (NMR), neutron scattering and so on. Therefore, high-quality single crystals are required in order to solve these problems. Recently, high-quality Co-doped single crystals have been fabricated in FeAs-122 system [14, 15]. Unfortunately, the growth of K-doped high-quality uniformed single crystals has been proven to be difficult [16]. On the other hand, the highest superconducting transition temperature in iron-based superconductors was reported to be about 56 K. According to the experience of cuprate superconductors, the structures with multiple CuO_2 layers in the unit cell may induce higher critical temperature. Therefore, scientists are looking forward to discover higher T_c iron-based superconductors with multilayer structures. The exploration of new iron-based superconductors with new types or multilayer structures becomes the main focus, but also the most difficult topics.

Some very important issues in iron-based superconductors are urgently need to be solved, including the relation between structure, magnetism and superconductivity, the pairing strength, distribution, and symmetry of superconducting electrons. The most effective way to solve these problems is the systematic investigation and analysis combined with multiple advanced experimental methods and high-quality single crystals. During the exploration of new types or multilayer structures in iron-based materials, it should be pointed out that such new structures may face the problems of metastability in thermodynamics. Therefore, in addition to the normal methods like solid-state reaction method and flux method, many extreme conditions (high-temperature and high-pressure) are taken into consideration in synthesizing materials. In this way, we can further detect the mechanism of superconductivity in iron-based superconductors in a broad perspective. Furthermore, different results in the pairing symmetry of superconducting electrons have been given in different materials. Even in the same kind of materials, if the experimental methods are different, the results are various. For instance, the nodeless symmetry was observed in $BaFe_{2-x}Co_xAs_2$ while the contrary result was found in $BaFe_2As_{2-x}P_x$. Some related works are being done nowadays and it is believed that they are very important for explaining the mechanism of superconductivity. We hope the mystery of superconductivity can be uncovered in the near future.

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