Iron Based Superconductors

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The phenomenon of superconductivity has a rich and interesting history, starting in 1911 when Kamerlingh Onnes discovered that upon cooling elemental mercury to very low temperatures, the electrical resistance suddenly and completely vanished below a critical temperature T_C of 4 K (-452 °F). This resistanceless state enables persistent currents to be established in circuits to generate enormous magnetic fields, and to store and transport energy without dissipation. Superconductors have other unique properties such as the ability to expel and screen magnetic fields, and quantum oscillations controlled by the magnetic field that provide extraordinary measurement sensitivity. Over the intervening years the number of superconducting materials has grown, with higher critical temperatures and improved metallurgical properties, and these have found their way into a number of technological applications such as MRI imaging systems for the health care industry. But the field was shocked in 2008 by the surprise discovery of a completely new class of superconductors based on iron. These iron-based superconductors have initiated a flurry of activity as researchers try to understand the origin of the superconductivity in these new materials, as well as develop them for potential use in devices. In this latter context, the new materials have quite high (relatively speaking) superconducting transition temperatures (T_C), and rather favorable current carrying capabilities that should make them useful in practical applications.

How does a metal become superconducting? In metals, electrons are free to move and provide electrical conduction, but collisions with other electrons, lattice vibrations, and impurities and defects in the material cause resistance, and thus energy dissipation, in the system. Superconductors circumvent this problem by binding two electrons together into pairs, and these pairs must all move together in a coordinated fashion. If the temperature is low enough there is insufficient thermal energy to break apart and disrupt these pairs, so collisions are not possible and they can move through the material without any interference—resistanceless conductivity. The extraordinary thing about this superconducting pairing is that electrons have the same charge and therefore strongly repel each other. So how can this bound state exist? It took half a century to unravel this mystery, but the pairing occurs for two electrons with equal and opposite *speeds*, rather than as two electrons "glued together". This unusual state of two electrons in a bound state is called a Cooper pair and is a fundamental property of all known superconductors, including the iron-based ones.

A quantitative and complete theory of superconductivity was developed in 1957, which explained that the pairing interaction originated from the lattice vibrations of the solid. This theory provided a thorough understanding for all the superconductors known at the time, and for all the "conventional" superconductors discovered since then. One cornerstone of this understanding is that any magnetic atoms in the lattice tend to break the Cooper pairs and ;therefore magnetism is very detrimental to the superconductivity. However, in 1986 a new class of "high temperature" superconductors was discovered that completely contradicted this rule. These were oxides in which the crystal structure contained sheets of copper and oxygen—called "cuprates". Oxides typically aren't even conductors let alone superconductors, but more surprising was that the copper ions carry a magnetic spin (like a compass needle), which is the kiss of death for conventional superconductors. Moreover, it turns out that the magnetism is not only tolerated in the cuprates, but appears to play a key role in the Cooper pairing. Up until 2008, all known "high temperature" superconductors exhibited two essential ingredients: copper-oxygen planes of atoms, and magnetic moments on the copper. Hence it was thought that these two properties were essential to achieve "high T_C" superconductivity.

Then the iron-based high T_C superconductors were discovered. The atomic structure and bonding of a material controls its properties, and for the iron systems there are four different structure types that have been identified so far, typified by LaFeAsO, $SrFe_2As_2$, LiFeAs, and Fe(Te-Se). The structure for the first two types, which have the highest T_C's, are shown in Fig. 1. The common structural feature is a layer of Fe and As atoms (like the Cu-O layer for the

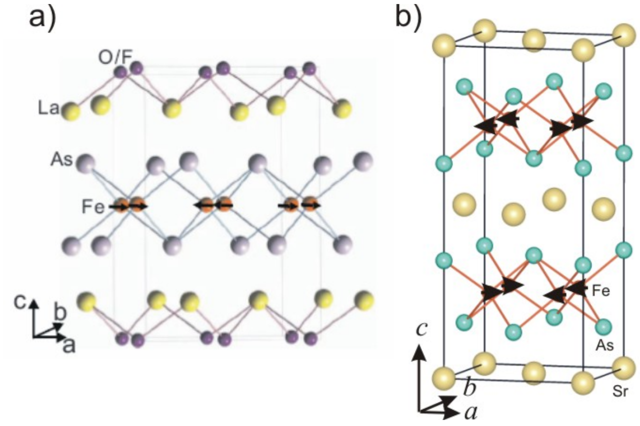

Fig. 1. The basic building blocks of the atomic structure for the two types of iron-based superconductors with high critical temperatures T_C. (a) LaFeAsO, and (b) $SrFe_2As_2$. The feature common to the iron superconductors is a metallic layer of iron bonded to arsenic atoms; the iron atoms form a square array with the arsenic atoms above and below the iron plane. The iron-arsenic layer is sandwiched between layers of La-O, or Sr. This basic structural unit is then repeated in all three directions *ad infinitum* to form the macroscopic crystal structure of the material. Below room temperature the structure distorts slightly so that the iron lattice is no longer exactly square, and the iron moments order in an antiferromagnetic arrangement, which means that half point in one direction, and half in the opposite direction. The iron magnetism is a key ingredient for all aspects of these materials.

cuprates), which is separated by a non-iron layer such as La-O (for LaFeAsO) or Sr (for $SrFe_2As_2$). These materials undergo a small structural distortion below room temperature along with the development of magnetic order, and are metals but not superconductors. Like the cuprates, superconductivity is achieved by chemically substituting, or "doping", the system to change the electronics. In $SrFe_2As_2$ for example, we can start with the Sr, (or Ba, or Ca) and dope that site with K. For the LaFeAsO we can substitute fluorine for oxygen. An example of how the properties change and the superconductivity develops with doping is shown in Fig. 2 for the CeFeAsO system as fluorine is substituted for oxygen. As the F content increases, the temperature where magnetic order develops is lowered, and the magnetic order is completely suppressed before superconductivity develops. However, fluctuating iron magnetic moments are still present in the superconductivity regime. Similar phase diagrams are found for the other types of iron-based materials, and this general type of phase diagram is also found for the cuprate systems.

The iron-based superconductor T_C's are too high to be explained by the conventional theory, and have a number of additional features in common with the cuprates. They contain iron-arsenic (or selenium) layers of atoms, the iron atoms have magnetic moments, the superconductivity is established by Cooper pairs, and magnetism is known to play a key role in the superconducting state. But they have a number of important differences as well. The undoped, "parent" materials in both cases exhibit magnetic order, but the iron-based systems are metals while the cuprates are insulators, which means that there are fundamental differences in the electronics of these materials. For the cuprates, the Cu and O atoms are in the same thin layer, and this renders the superconducting properties highly anisotropic, being very good within the layer and poor along the direction between the layers. This makes it difficult (and thus expensive) to fabricate wires. The structures in Fig. 1 show that the iron-arsenic layers are thick—the As atoms are positioned well off from the plane of iron atoms, and this makes the superconducting properties much

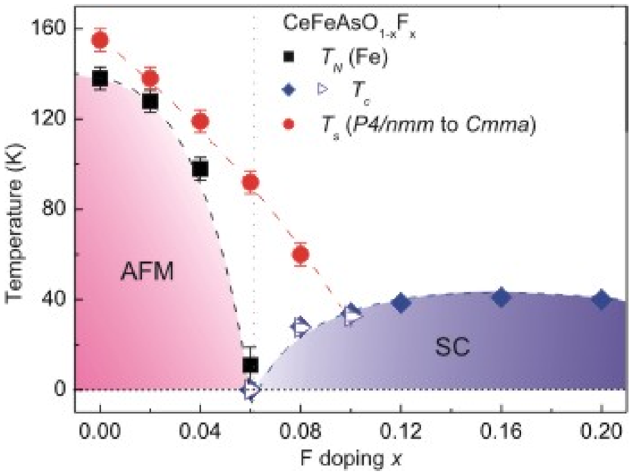

Fig. 2. Phase diagram for $CeFeAsO_{1-x}F_x$, where the fluorine substitution for oxygen changes the electronics. With increasing fluorine content the magnetic order disappears, and then the superconductivity regime appears. The basic behavior with doping is the same for all the iron-based high T_C materials, and also has some similarities to the phase diagrams for the copper-oxide superconductors.

closer to isotropic. This is especially the case when high magnetic fields or large currents are required, which is a very important advantage for applications. The different natures of the anisotropy originate from a fundamental difference in the pairing—for the cuprates the Cooper pairs prefer to be in the Cu-O planes and are highly anisotropic, while for the iron-based systems they are almost isotropic.

The superconducting transition temperature is one important parameter of a superconductor, but not the only property of interest. The size of the magnetic field that a superconductor can support (or the related maximum current) before the superconducting state collapses is another vital property—the higher the critical field (called H_{C2}) the better. For applications, the cost of the raw materials is important, as are the metallurgical properties which dictate the ease of fabrication and consequent cost effectiveness. For example, cuprate superconductors have been around for 23 years with their high transition temperatures and large critical fields (Table 1), but because of the difficulty and cost of making wires, the superconducting magnets used in MRI systems are still made from conventional Nb(Ti) wire, which must be cooled with (expensive) liquid helium to very low temperature (4 K, -452 °F).

A few examples of prototype materials for the three classes of superconductors are listed in Table 1. The iron-based superconductors exhibit values of T_C that exceed those of all superconductors except some of the cuprates, while their critical magnetic fields are unsurpassed, making them particularly attractive for applications requiring large magnetic fields and large currents. In the short time since they were discovered, there are already four different general types of iron systems, with many chemical substitutions already possible. Perhaps more types of materials will be discovered and the T_C's could be higher, but the chemical versatility already available is one of the dramatic strengths of the new iron-based materials. It is already opening up new research avenues to probe the origin of the superconductivity and has fostered hopes that this may ultimately lead to a complete theoretical understanding for both classes of high-T_C superconductors. The chemical flexibility will also allow scientists and engineers to tailor the properties for specific commercial technologies, which may include high magnetic field applications like medical MRI imaging, high magnetic fields for scientific research, energy storage technologies, and more efficient transfer of electricity over regional power grids. The discovery of this new class of superconductors based on iron has tremendously revitalized the field of superconductivity, and should provide many more surprises and promises for the future.

For additional information, see …

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Table 1. Examples of superconducting materials for the three different types of superconductors, the conventional materials where the Cooper pairing originates from lattice vibrations, the layered copper-oxide (cuprate) materials, and the new iron-based superconductors. Representative critical fields quoted are in Tesla—for comparison the earth's magnetic field is about 0.00005 Tesla (~1/2 gauss); (1 Tesla = 10,000 gauss). Then for Hg, H_{c2} = 450 gauss.

Material	Type	T_C, K (°F)	Pairing	Critical Field (H_{C2}) in Tesla	Date
Hg	Conventional	4 (-452)	Lattice	0.045 (450)	1911
Nb_3Sn	Convention	18 (-427)	Lattice	30	1954
Nb(Ti) wire	Conventional	10 (-442)	Lattice	15	1962
$La_2CuO_{4.1}$	Cuprate	42 (-384)	Magnetic	100	1986
$YBa_2Cu_3O_7$	Cuprate	90 (-298)	Magnetic	250	1987
MgB_2	Conventional	39 (-389)	Lattice	20	2001

LaFeAs(O,F)	Iron-based	26 (-413)	Magnetic	56	2008
SmFeAs(O,F)	Iron-based	56 (-359)	Magnetic	250-300	2008
$(Ba,K)Fe_2As_2$	Iron-based	37 (-393)	Magnetic	75	2008

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