Family Differences

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Iron-based superconductors may share a name, but look a bit more deeply and as with any family, their individual traits become more obvious. **UT Distinguished Physics Professor Elbio Dagotto (http://sces.phys.utk.edu/)** has mined recent studies of these materials and outlines their similarities, as well as their differences, in "**The unexpected properties of alkali metal iron selenide superconductors (http://rmp.aps.org/abstract/RMP/v85/i2/p849_1)**." The paper appears in the prestigious journal *Reviews of Modern Physics* as a colloquium: a special article describing recent work with a broad appeal across sub-disciplines, particularly at the frontiers of physics.

The alkali metal iron selenides are the most recent arrival in the superconductor clan, whose roots go back more than a century. Since the early 1900s, scientists have been acquainted with superconductivity —electric current flowing with zero resistance. Over the years they ascertained that the origin of this phenomenon was in the pairing of electrons, which normally repel one another. What prompts electron pairing has proven to be a greater mystery, however. In the so-called conventional superconductors, vibrations in the crystal lattice-like structure of the material induce the electrons to pair up. Yet there is a critical temperature (T_c) just below which superconductivity occurs, and in the conventional materials this threshold was much lower than room temperature, limiting their practical applications. In the 1980s, materials made from copper and oxygen (called cuprates) were found to have a much higher T_c, but the electron pairing could not be explained by lattice vibrations, and the critical temperature was still too low to be practical. Still, for the next 20 years the cuprates seemed the best candidates to advance the f ield. That changed in 2008, however, when iron-based materials jumped to the forefront. Scientists (including **UT Physics Professor Pengcheng Dai's group** began publishing studies at a rapid rate, showing certain iron-based materials became superconductors at ever-increasing T_c. Dai and Dagotto, in fact, provided an overview of these studies in a ***Nature Physics* *(http://www.phys.utk.edu/news/2012/news_npreview_10032012.html)*** paper published in October 2012.

Iron superconductors have one of two baseline compositions: layers of iron and arsenic (pnictides) or iron and selenium (selenides). These layers are viewed as critical components of these materials, just as copper-oxide layers are in the cuprates. In this latest colloquium, Dagotto focuses on recent developments surrounding a still-emerging group of materials within the iron superconductor framework: iron selenides with layers of alkali metal elements, a field that first appeared in the scientific literature in 2010.

Alkali metals (lithium, sodium, or potassium, for example) are shiny, soft, and highly reactive. Iron selenides that incorporate layers of these metals are proving interesting to scientists because of their microscopic properties. They have critical temperatures comparable to those of iron pnictides, for example, and may share with the latter a common mechanism to generate magnetic and conducting states. Yet some iron selenides are magnetic insulators, which is more characteristic of the cuprates. Dagotto's review covers experiment and theory investigations devoted to these newer materials and their potential to alter current ideas about superconductivity in iron-based materials.

Competition, Coexistence, and Two-Leg Ladders

A key point illuminated in Dagotto's review is that alkali metal iron selenides have what might be (very loosely) categorized as multiple personalities. These materials exhibit phase separation: they can have both superconducting and magnetic states, which compete, or maybe cooperate, with one another. The coexistence of these states is also reported in pnictides. These properties pose interesting questions for materials scientists: if magnetism and superconductivity coexist at the microscopic level, does magnetism induce superconductivity, or suppress it? (This question arises in the cuprates as well.) Dagotto's colloquium points out that while some studies show the states coexist, others show them with a physical separation.

To fully understand these newest additions to the family, scientists have to take a look at their parents. They can create samples of materials (UT's **Haidong Zhou)** does just that), but they still have to pin down the characteristics of these "parent compounds" to understand their evolution. (The selenides, for example, may have insulating parent compounds, while pnictide parents have metallic states.) Parent compounds serve as a starting point where a few calculated tweaks can significantly influence a material's behavior. A given crystalline material has a prescribed structure of electrons and holes (the latter are simply spots for an electron that can behave as particles, but are in fact empty). By "doping" the sample—adding or removing electrons—scientists can alter its properties. In this new class of selenides, for example, some studies have found that electron doping a semiconducting parent compound leads to superconductivity. Yet there is more work to be done; and Dagotto points out the discussion on parent compound states as they relate superconductivity remains fluid.

Other experimental work illuminates further differences between these types of selenides and their cousins, the iron pnictides. In their *Nature Physics* review, Dagotto and Dai pointed out the potential role of Fermi surface nesting in the superconducting behavior of iron pnictides. A Fermi surface is a quantum mechanical construct that predicts the electronic properties of crystalline materials. The shape of a Fermi surface is determined by how atoms in a material are arranged, as well as by how many electrons are available to conduct electricity. How those electrons behave at or near the Fermi surface inf luences the material's properties, including electrical resistance. "Fermi surface nesting" refers to the connection of two such surfaces via a unique lattice vector. While this concept may explain the magnetic —and potentially superconducting—origins in the iron pnictides, experiments indicate that it has no bearing on superconductivity in the alkali metal iron selenides and also appears to be an insufficient explanation even for the pnictides. Yet another difference between the two classes of materials is that all 245 iron selenides have a common crystalline and magnetic structure—setting them apart from the pnictides, which exhibit structural differences even among themselves.

Dagotto covers the work of scientists the world over, explaining how in just a few short years they've used a wide range of experimental techniques to investigate these materials. Electrons do much of the heavy lifting in these studies. Beams of electrons may be sent through a sample material, for example, with scientists capturing images of the resultant interactions (transmission electron microscopy). Or they might fire photons at a sample, the impact of which frees (emits) electrons, whose escape routes (via their angular distribution and kinetic energy) reveal information about the sample material's electronic states. **Norman Mannella (http://www.phys.utk.edu/mannella/research.html)** has implemented this technique (called angle-resolved photoemission spectroscopy, or ARPES) for the study of a variety of materials at UT. It is one of many approaches used to coax the alkali metal iron selenides into giving up their secrets, and Dagotto's colloquium weaves together their collective f indings to provide a current picture of where the field stands. He also incorporates important work in theory, including the sophisticated calculations researchers have employed to understand factors such as the influence of electron-electron correlations in both the selenides and pnictides. As with experimental results, theoretical findings have also pointed to the presence of competing phases. Dagotto also pays attention to other interesting theory approaches in the field, including the idea of "two-leg ladders;" selenides with a long direction (legs) and a short direction (rungs) whose quasi-one-dimensional structure allows for more accurate theory work, improving the back-and-forth comparison between theory and experiment. With such rich territory to explore, there are myriad opportunities for scientists like **Adriana Moreo (http://sces.phys.utk.edu/)**, who also carries out theoretical work on iron-based superconductors at UT.

In this detailed colloquium citing hundreds of references, Dagotto points out how research into high-temperature superconductors has steadily advanced in a short period of time. With deeper investigations into the alkali metal iron selenides, which appeared just three years ago, scientists are challenging prevailing ideas about the pnictides, which is still a young field. Further studies may find common ground among the two, providing a foundation for understanding iron-based superconductors in general.