Superconductivity

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Superconductivity is a phenomenon found in a variety of materials. The members of our group investigated several superconducting systems, which may be grouped into five categories, Recent results on $MoTe_2$ are reported elsewhere (S. A. Medvedev et al.).

Iron-based superconductors

Fe-based superconductors appear in “1111,” “122,” “111,” and “11” type crystal structures that have a common motif of edge-sharing FeAs or FeSe tetrahedra. Within the “122” type two substitution series $EuFe_{2-x}T_xAs_2$ (T = transition metal) were investigated, both containing the strongly magnetic Eu^{2+} species. The mother compound $EuFe_2As_2$ has an anti-ferromagnetic ground state that is gradually suppressed by substitution of Fe with Co or by Ru. The onset of superconductivity is reported for Co substitution at $x \approx 0.2$ and for Ru substitution at $x = 0.5$. Our investigations together with EPR methods (co-operation with the University Augsburg) and DFT calculations for the Ru series [1] give a clear picture of strongly reduced electronic densities of states with increasing x of the nominally isoelectronic Ru. This reduction is equally caused by structural effects as well as by the direct change of the transition-metal states. The presence of Eu^{2+} spins ($S = 7/2$) has almost no effect on the electronic and magnetic properties of the Fe(Co)As layers. Therefore, the evolution of magnetic fluctuations of the layers can be successfully probed by Eu EPR even in such a concentrated system [2].

Nonmagnetic analogs to iron superconductors

Iron-based pnictogen and chalcogenide superconductors often have “nonmagnetic” analogs which are superconductors that crystallize in the same structure but consist of only nonmagnetic elements. Often these analogs have a much lower superconducting T_c, supporting the argument that the magnetic element, viz. iron, is important for enhancing T_c [3]. For example, SnO, which crystallizes in the same crystal structure as FeSe, has a similar Fermi surface and exhibits the same pressure dependence of T_c, albeit with a much lower T_c [3]. The analysis of SnO showed that the Fermi surface topology and the degree of nesting are important for superconductivity; however, the spin fluctuations are not essential for the presence of superconductivity in “11” structures, rather they increase the coupling and thereby the T_c.

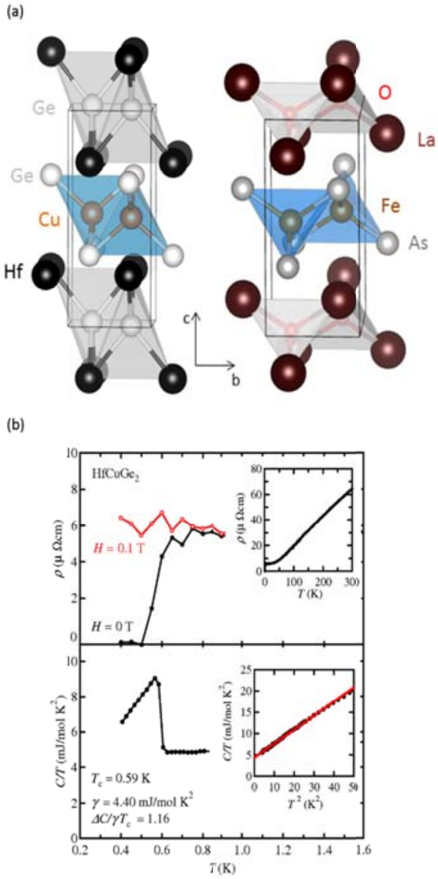

Fig. 1: Crystal structure of $HfCuGe_2$ *[7] and its relation to the Fe-based superconductor LaOFeAs. (b) Resistivity and specific heat of* $HfCuGe_2$ *proving bulk superconductivity below 0.6 K.*

In the case of LiFeAs, the superconductor NaAlSi (T_c = 7 K) [4] can be viewed as its nonmagnetic analog. The Fermi surfaces of the two compounds show similarities [5]. Our investigations of NaAlSi under high pressure [6] showed that T_c initially increases with p and is then suppressed rather quickly beyond $p \approx 5$ GPa. This behavior cannot be attributed to a structural phase transition as proven by x-ray diffraction experiments under pressure. Although pressure has a strong effect on superconductivity, DFT calculations demonstrate that it does not significantly alter the electronic structure. Similarly, a comparison of NaAlSi with non-superconducting NaAlGe showed that the electronic structure cannot explain the different behavior regarding superconductivity. The fact that the density of states does not change around the Fermi level enforces the idea of a non-BCS model for NaAlSi but does not prove it. A thorough study will be required to determine what the dominant factors are which determine T_c in analogs of iron superconductors.

In a different project [7], we observed bulk superconductivity with $T_c = 0.6$ K in the intermetallic compound $HfCuGe_2$ (Fig. 1), which is structurally related to the "1111" Fe-based superconductors but contains only nonmagnetic elements. These findings indicate that superconductivity tends to run in certain structure types, and the observed very low T_c supports the argument that the presence of magnetic Fe is important for obtaining enhanced T_c in this family.

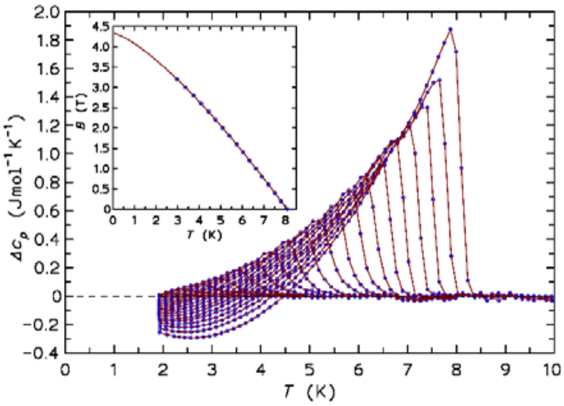

Fig. 2: Specific heat anomaly of the type-II superconducting clathrate $Ba_{8-x}Si_{46}$ *[12] in magnetic fields. The inset shows the upper critical field* $B_{c2}(T)$ *determined from the midpoint temperatures of the transition steps in the measured magnetic fields.*

Germanide and silicide superconductors

Another complex is the advanced investigation of superconducting Pt-Ge compounds with filled skutterudite structure (general formula MPt_4Ge_{12}, M = Sr, Ba, La, Pr). While basic superconducting properties are known, the order parameters are still under debate for the most prominent members $LaPt_4Ge_{12}$ and $PrPt_4Ge_{12}$. (cf. Scientific Report MPI-CPFS 2009-2010, p.59-62). For high-quality single crystals of $PrPt_4Ge_{12}$, high-resolution data of the penetration depth (obtained by the MPI partner group at Zhejiang University, China) as well as specific heat data can be consistently described by a multigap model [8].

The new metastable silicide and germanide superconductors $CaGe_3$, $CaSi_3$, YSi_3, and $LuSi_3$ obtained by high-pressure high-temperature syntheses were investigated [9,10]. In addition, the superconducting parameters of the new cage compounds $Ba_3Ge_{13}Ir_4$ and $Ba_3Ge_{13}Rh_4$ were determined [11]. For the type-I clathrate $Ba_{8-x}Si_{46}$, the focus was on enhancing the thermoelectric properties, but also the superconducting properties were investigated (cf. Fig. 2) [12].

Boride superconductors

In a large international collaboration, the novel boride FeB_4 was studied [13]. Remarkably, its existence and superconductivity were successfully predicted before the synthesis of samples at high pressure. The obtained single crystals proved to be highly incompressible and superconducting below a T_c of 2.9 K. FeB_4 is a rare example of a conventional electron-phonon coupling superconductor with iron.

A remarkable π-electron superconductor

Another superconductor with both exotic and otherwise very conventional aspects is a Bi-Te-Cl compound synthesized in the group of M. Ruck (MPI-CPfS and TU Dresden). $Te_4[Bi_{0.74}Cl_4]$ is a one-dimensional metal [14] with structural similarities to the organic superconductors of the $(TMTSF)_2X$ family. In the incommensurately modulated structure, the Te species form stacks of π electron systems, leading to high electrical conductivity. The compound undergoes a superconducting transition at 7.15 K. Recently, we collected evidence that the superconducting state of this structurally complex material is surprisingly simple. It is a type-I superconductor with a single *s*-wave energy gap and strong electron-phonon coupling.

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