Properties of heavy fermion superconductivity: A brief introduction

Term paper for superconductivity class, Fall 2004

Han-Oh Lee

Introduction

Many of Ce, U, Yb compounds, which have localized *f*-electrons, are generally called heavy Fermion systems. These are metallic materials with very large electronic effective mass, 100 or more times larger than the bare electron mass, arising from an antiferromagnetic interaction between conduction electrons and the local magnetic moments (Kondo effect) residing on a sub-lattice of atoms in the metal. There exists an indirect intersite interaction between the local moments as well, which compete with Kondo effect, causing a variety of ground states in this system and hence making it attractive to study. [1-2]

One of the most attractive and elusive phenomena of this heavy fermion system is the appearance of the superconductivity in a few compounds. In the framework of the BCS theory, magnetic impurities in a metal will strongly destroy the superconducting transition temperature since its interaction with two electrons in a spin singlet state will break the pairing. Thus, a heavy fermion system, which has local moment strongly affecting the system at low temperature, will tend to oppose formation of the superconducting state. However, since the superconductivity in $CeCu_2Si_2$ was discovered by Steglich at 1979[3], a few U-based and Ce-based heavy fermion superconductors have been discovered.

Unlike the conventional superconductors, these superconductors cannot be explained by the BCS theory, as they display a rich variety of unexpected properties. This provides us good opportunity to enhance our knowledge of superconductivity and also of strongly correlated electronic system. In this paper, brief introduction to the properties of the heavy fermion superconductors will be presented.

Characteristics of heavy fermion superconductivity

Generally, one of common features of the heavy fermion superconductors is the large values of the electronic specific heat coefficient(C_p/T) at T_c, order of a few hundreds to even thousands mJ/mol-K^2, indicating the heavy quasiparticles participate in the superconducting pairing. Figure1 shows C_p/T of UBe_{13}, which is particularly clear case for this feature. One can also notice here that the C/T has power law dependence below T_c instead of exponential decay expected from s-wave pairing symmetry. This indicates the existence of the nodes in the superconducting gap, suggesting unconventional gap structure. Another indication of the non s-wave pairing of these systems is in their sensitivity to the non-magnetic impurities in contrast to the conventional superconductors where dilute concentrations of non-magnetic impurities have little effect on the superconducting parameters. Non-magnetic impurities like Y, La, and Th strongly affect the pair breaking as well as magnetic impurity like Gd in these system. Since non-magnetic impurity scattering suppresses an anisotropic Cooper pair wave function, it has been interpreted as evidence for non s-wave pairing. Although impurities usually destroy the superconducting transition in most cases of heavy fermion superconductors, an interesting, spectacular feature has been found in $U_{1-x}Th_xBe_{13}$ system. As shown in Figure2, the system has double superconducting transitions with 3.3% Th doped in U site[4]. Evidence for more than one superconducting phase below T_c has also been accumulated for UPt_3. The B-T phase diagram of UPt_3 is displayed in Figure3, showing strongest evidence for the unconventional superconductivity in heavy fermion superconductors[5].

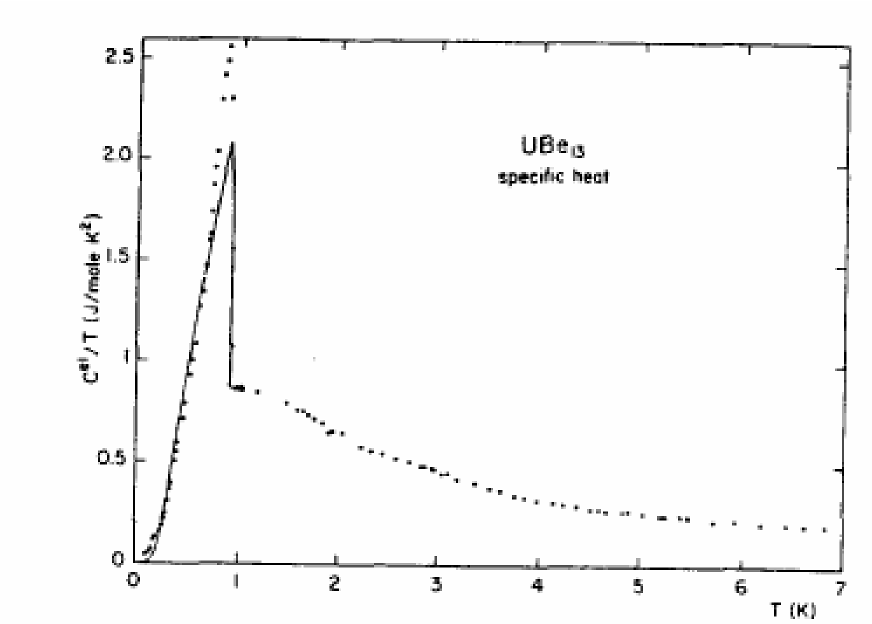

Figure.1 specific heat divided by temperature in UBe_{13} after subtracted phonon contributions

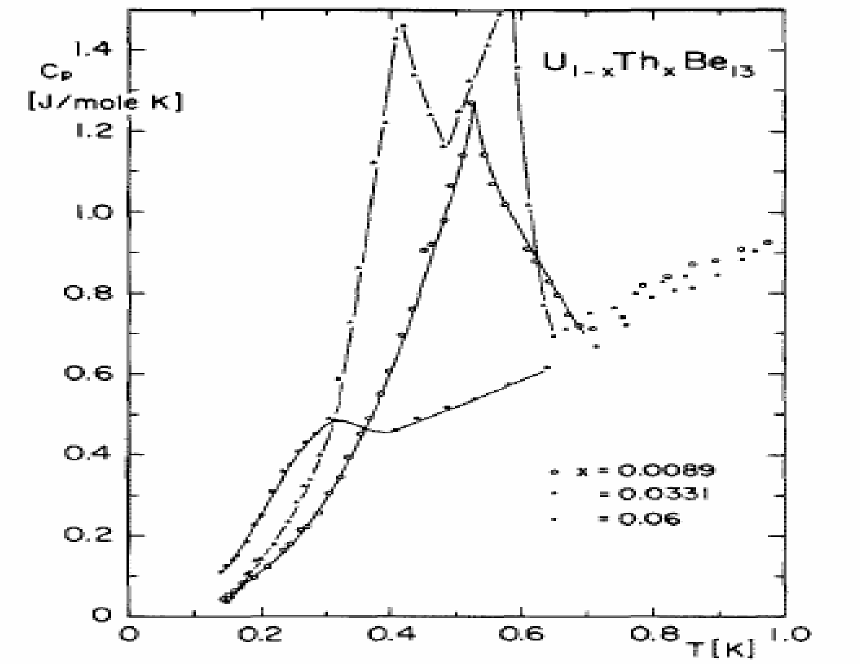

Figure.2 specific heat versus temperature in $\mathbf{U_{1-x}Th_xBe_{13}}$ **with three values of x**

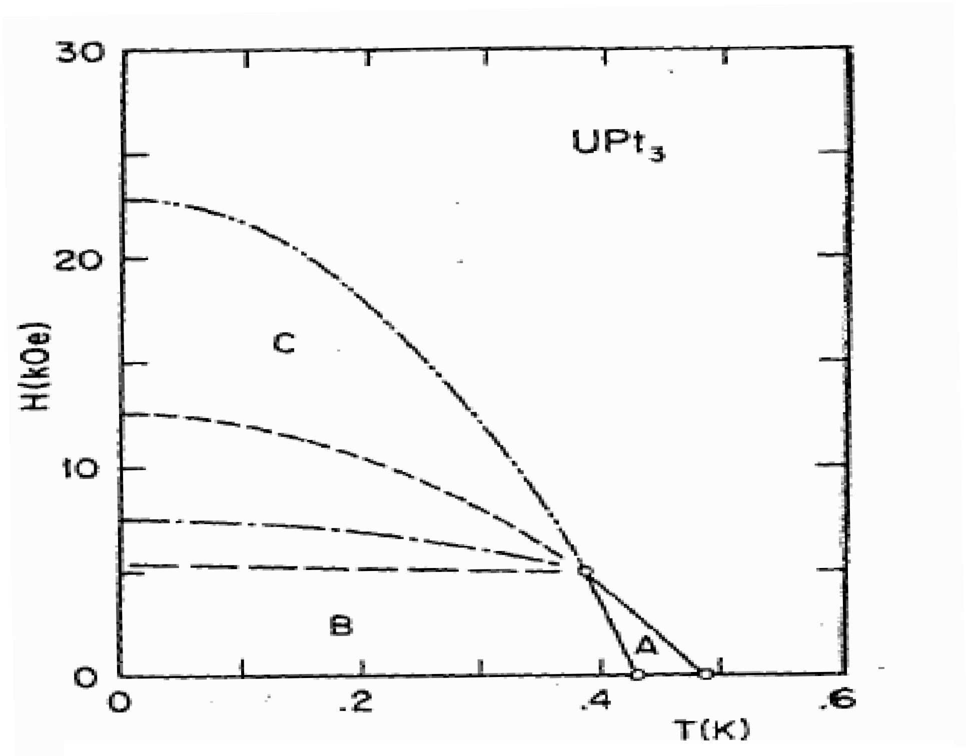

Figure.3 Schmatic superconducting phase diagram of UPt_3

Interplay of magnetism and superconductivity in heavy fermion materials is another remarkable issue. This interplay has shown considerable variety by showing competition, coexistence, and/or coupling of the magnetic and superconducting order paramaeters.[6] $CeCu_2Si_2$ appears to show competition between magnetism and superconductivity , each existing in its own domain. In a few U-based compounds like URu_2Si_2, UPd_2Al_3, and UNi_2Al_3, on the other hand, magnetic order coexists with superconductivity in microscopic scale without strong interaction with each other, as evidenced by neutron scattering and μSR experiment. Furthermore, UPt_3, which is antiferromagnetic below T_N = 5K with a small moment($\mu = 0.02\mu_B$), shows a coupling between the superconducting and magnetic order parameters, that is, magnetic order is affected by the onset of superconductivity.

While the pairing mechanism in heavy fermion superconductivity is not simply understood yet, which is also a problem in high T_c superconductors, there is an idea that the superconducting pairing is mediated by magnetic interaction, so called, magnetic glue. This has been suggested from the pressure induced superconductivity in $CeIn_3$ (see figure4) and $CePd_2Si_2$, which occurs with suppression of magnetism with increasing pressure by enhancing hybridization between conduction electrons and local moments[7].

Crystal structures favored by superconductivity empirically are different for phonon mediated, heavy fermion, and high T_c cuprate superconductors. For instance, while high symmetry is favorable for conventional phonon mediated superconductors and layered structure for cuprates, superconductivity appears with cubic, tetragonal, hexagonal type of crystal structures in heavy fermion superconductors. Not many are known for the relationship with structure in condensed matter state yet though.

With these various exotic behaviors, it is still difficult to understand the origin of the superconductivity and pairing mechanism in heavy fermion superconductivity.

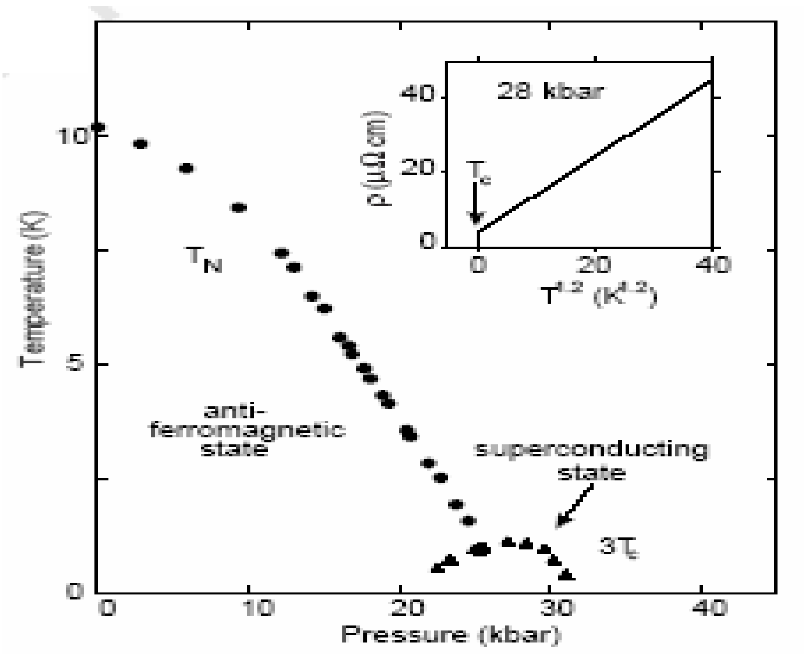

Figure.4 Phase diagram of temperature and pressue of $CeIn_3$

Summary

In summary, I have briefly introduced heavy fermion superconductivity with its unconventional behavior in physical properties, interplay with magnetism, and superconducting pairing mechanism. Although transition temperatures in the heavy fermion superconductors are low (less than 2~3K), these systems are particularly interesting in a sense that they provide clues to understand mechanisms of strongly correlated system as well as to give examples of other classes of superconductors.

References

[1] N, Grewe, F. Steglich, *Handbook on the Physics and Chemistry of the Rare Earths*, **14**, 343 (1991)

[2] G. R. Stewart, *Rev. Mod. Phys*. **58**,755 (1984)

[3] F. Steglich, *et al*., *Phys. Rev. Lett*. **43**, 1892 (1979)

[4] H.R. Ott, H. Rudigier, Z. Fisk, and J. L. Smith, *Phys. Rev. B*, **31**, 1651 (1985)

[5] R.A. Fisher, et al., *Phys. Rev. Lett*., **62**, 332 (1989)

[6] R. H. Heffner, *J. Alloys and Compounds*, **213-214**, 232 (1994)

[7] N. D. Mathur, *et al*., *Nature*, **394**, 39 (1998)