Properties of Heavy Fermion Systems

Mengshu Liu

Course: Solid State Physics II,Instructor: Dr.Elbio Dagotto

Department of Physics and Astronomy, UTK, USA, Email:mengshu@utk.edu

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Abstract

Heavy Fermions are a subgroup of materials with intermetallic coumpounds containing f-electron elements. These materials exhibit highly correlated electronic behavior at low (helium) temperatures, with conduction electron masses 10-1000 times larger then the value expected from free-electron theory. Properties and conceptual understanding of this system is given in the introduction part, following with an introduction of Kondo effect in the second section. At last, one of the most compelling exotic properties of heavy fermions, superconductivity, is discussed in detailed in the third section.

1 Introduction

The term 'heavy Fermion' is introduced to describe materials with electronic states having energy orders several magnitudes smaller than in other ordinary metals. If we write the energy $\varepsilon(k)$ in a free-electron form ($\varepsilon(k) = \hbar^2 k^2/2m^*$), since the wave vector $\mathbf{k}$ depending on the interatomic spacing, is simlar to normal metals, the effective mass m^* must be of several orders larger than of a bare electron. These materials are intermetallic compounds with rare earth or actinide atom which have a partially filled $4f$ or $5f$ electron shells. Typical heavy fermions are CeA_{l3}, $CeCuSi_2$, $CeCu_6$, UBe_{13}, UPt_3 (Fig.1), UCd_{11}, U_2Zn_{17}, $NpBe_{13}$, varying from metals, superconductors, magnets, and insulators.

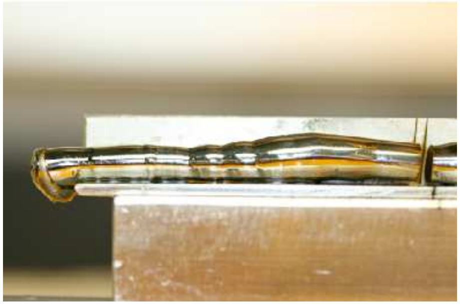

Figure 1: 20 grams of UPt_3 single crystals grown at Northwestern University

This very large effective mass of conduction electron can be proven by the very large specific heat $C_p$of the system at low temperature. In a usual metal, the heat capacity of metals consists of the electron part and the phonon part, which can be written as,

$$C = C_e + C_{ph} = \gamma T + AT^3$$

with Constant γ and A. The linear term is dominant at low temperature, and the constant γ in this linear electron term is proportional to the effective electron mass m^*. Therefore, Specific heat can be a good indicator of effective electron mass. $CeAl_3$ has a γ around 1620 $mJ/moleK^2$(Fig.2), $CeCu_2Si_2$ around 1100$mJ/moleK^2$, $CeCu_6$ around 1600 $mJ/moleK^2$, UPt_3 around 420 $mJ/moleK^2$, etc. While for Cu, it is only around 1 $mJ/moleK^2$.

One common figure unique in this group of heavy Fermions is the existence of a partially filled $4f$ or $5f$ shell. Like in heavy Fermion $CeAl_3$, Ce^{3+} contains one electron in the $4f$ shell, while in ordinary $LaAl_3$, La^{3+} has no f shell electron. It is therefore natural to associate heavy fermion behaviors with an instability of the f configuration, and this could be expected to be sensitive to details of the f elements' chemical environment. While something similar might be expected to occur in the d shells, the specialty of the f shell is that it is an inner shell and generally not involved in chemical bonding. At room or higher temperatures, heavy Fermion systems stay in their normal state; At low temperatures, many anomalies appears. The role of the f electron is that, at room temperatures and above, the f shell electrons stay on their atomic site, and the system behaves as a weakly interacting collection of f-electron moments and conducting electrons with quite ordinary masses.

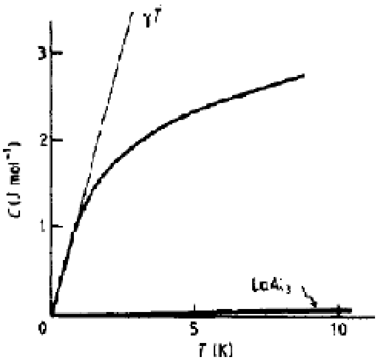

Figure 2: Schematic plot of the specific heat $C(T)$ for $CeAl_3$. It is also the first discovered heavy Fermion [2]. For comparison, the value of a similar ordinary compound $LaAl_3$ is also shown [1].

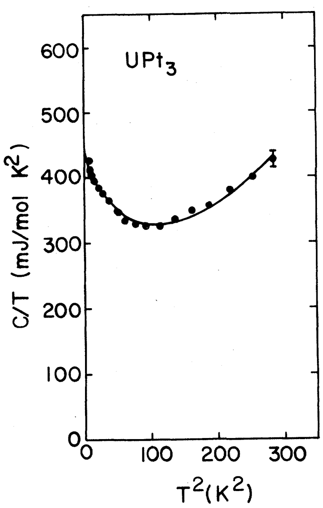

Figure 3: Specific heat in the normal state of flux-grown single crystals of UPt_3 [3]. The line through the data is a least-squares computer fit of the data to $C = \gamma T + AT^3 + \delta T^3 lnT$.

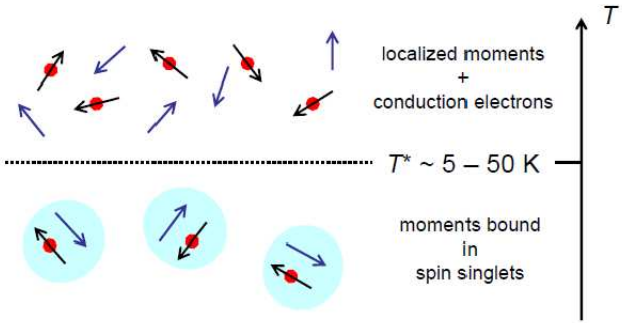

Figure 4: From Hua Chen's Presentation in previous semester.

At low temperatures the f-electron moments become strongly coupled to the conduction electrons and to one another. They form a antiferromagnetic singlet electron pair with the conduction electrons, and the conducting electron effective mass is typically 10 to 1000 times of the bare electron mass.

The theoretical problem of a localized spin interacting antiferromagnetically with a sea of conduction electrons is the celebrated Kondo effect, whose solution is one of the outstanding achievements of many-body physics, and which will be discussed more in detail in the next section.

2 Kondo Effect and Kondo Lattice

The previously discussed problem of antiferromagnet interactions between f electrons and Fermin sea can be treated as a magnetic impurity problem in metals, with the f electrons being the impurities appearing periodically. A very significant advance in the theory of magnetic impurities was an explanation by J. Kondo in 1964 [4].

One manifestation of the effect magnetic impurities has been known since the early 30s. This is the observation of a resistance minimum with decrease of temperature because it is dominated by phonon scattering which decreases rapidly at low temperatures (Fig.5). It was only recognized later that this minimum was an impurity effect associated with magnetic impurities [5]. Kondo calculated the resisitivity and introduced a new logarithmic term to explain the minimum. The temperature dependence of the resistance

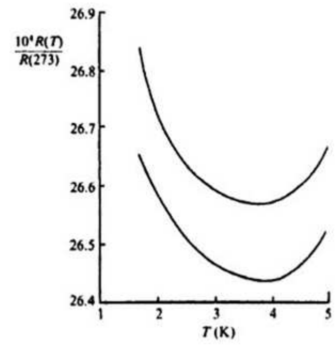

Figure 5: The minimum in the electrical resistivity of Au. (de Haas, de Boer and Van den Berg, 1934)

including the Kondo effect is written as,

$$\rho(T) = \rho_0 + aT^2 + c_m \ln\frac{\mu}{T} + bT^5$$

where ρ_0 the residual resistance, aT^2 shows the contribution from the Fermi liquid properties, and the term bT^5 is from the lattice vibrations [4]. Jun Kondo derived the third term of the logarithmic dependence, and his calculation was based on a model called the Anderson Model, where it is assumed that there is already a local magnetic moment associated with a spin S which is coupled via an exchange interaction J with the conduction electrons (Fig.6).

$$H = \sum_{\sigma} \epsilon_f f_\sigma^\dagger f_\sigma + \sum_{<j,j'>\sigma} t_{jj'} c_{j\sigma}^\dagger c_{j'\sigma} + \sum_{j,\sigma} (V_j f_\sigma^\dagger c_{j\sigma} + V_j^* c_{j\sigma}^\dagger f_\sigma) + U f_\uparrow^\dagger f_\uparrow f_\downarrow^\dagger f_\downarrow$$

where the f operator corresponds to the annihilation operator of an impurity, and c corresponds to a conduction electron annihilation operator, and labels the spin. The onsite Coulomb repulsion is U, which is usually the dominant energy scale, t'_{jj} the hopping strength from site j to site j', and the hybridization term which allows the previously localized f electron to become mobile and interact with conduction electrons [6]. Kondo showed that this interaction leads to singular scattering of the conduction electrons near the Fermi level and a $\ln T$ contribution to the resistivity. The $\ln T$ term increases at low temperatures for an antiferromagnetic coupling and when this term is

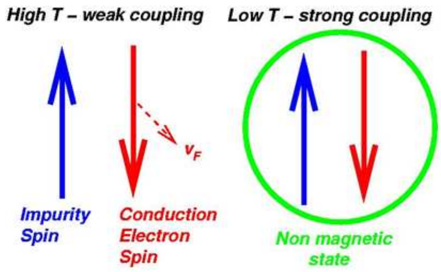

Figure 6: Schematic illustration of the Kondo effect. (From Wikipedia)

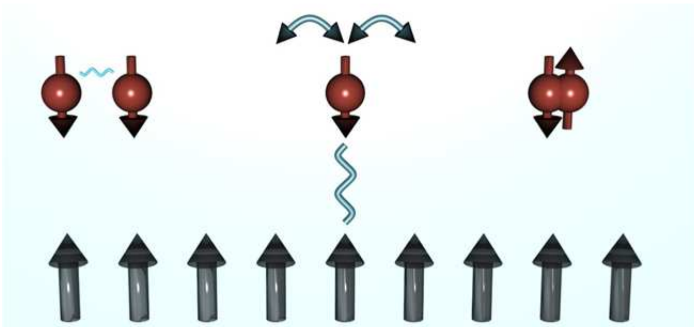

Figure 7: The Kondo lattice model. The conduction electrons are depicted in the upper row (green), and the localized electrons are depicted as bolt arrows in the lower row (red) [9].

included with the phonon contribution to the resistivity, it is sufficient to explain the observed resistance minimum.

In heavy Fermion systems, the magnetic impurities appear periodically. The relevant model is then the periodic Anderson model.

$$H = \sum_{j,\sigma} \epsilon_f f_\sigma^\dagger f_\sigma + \sum_{<j,j'>\sigma} t_{jj'} c_{j\sigma}^\dagger c_{j'\sigma} + \sum_{j,\sigma} (V_j f_\sigma^\dagger c_{j\sigma} + V_j^* c_{j\sigma}^\dagger f_\sigma) + U \sum_j f_\uparrow^\dagger f_\uparrow f_\downarrow^\dagger f_\downarrow$$

The heavy Fermion systems are Kondo lattice systems with large effective mass (Fig.7).

3 Superconductivity in heavy Fermion systems

Among many exotic properties of heavy Fermion systems is the appearance of superconductivity in some compounds. This superconductivity seems to be unconventional, with an underlying mechanism different from the BCS theory, in the framework of which, the magnetic impurities in a metal will strongly destroy the superconducting phase since its interaction with two electrons in a spin singlet state will break this pairing. Thus, conventionally, a heavy Fermion system, which has local moment strongly affecting the system at low temperature, should tend to oppose the formation of the superconducting state. However, since the superconductivity in $CeCu_2Si_2$ was discovered by Steglich at 1979 [7], a few more U-based and Ce-based heavy fermion superconductors have been discovered.

A number of control parameters like substitution, pressure, magnetic field or valency allows to change the relevant interactions and thus the ground state of such systems. While dilute concentrations of non-magnetic impurities in conventional s-wave superconductors have little effect on the superconducting parameters, heavy Fermions have a active response to the addition of non-magnetic impurities (Fig.8). In Fig.8, the adding of minute amounts of thorium (a non-magnetic impurity, which primarily ats to increase the system volume) to UBe_{13}, causes a decreasing for T_c until, at an impurity concentration of around 2%, a cusp of T_c. And the further adding of thorium leads to an increase in T_c. The application of pressure (P) to the system also shifts the transitions; For $P \geq 9$ kbar, superconductivity is completely supressed for a range of concentrations; at 12 kbar,that range is between 2.5% to 4.5% of thorium. This remarkable phase diagram results from the highly concentration-dependent interplay between antiferromagnetic moment fluctuations and superconductivity.

A schemetic explaination for the function of pressure applying is shown in Fig.9. While magnetism is "suppressed" for the left figure, since the $4f^1$ electron is squeezed out of the $4f$ shell, the magnetic state is stabilised for the right figure, and non-magnetic systems can become magnetic by the application of pressure.

Another anomaly in heavy Fermion superconductors different from con-

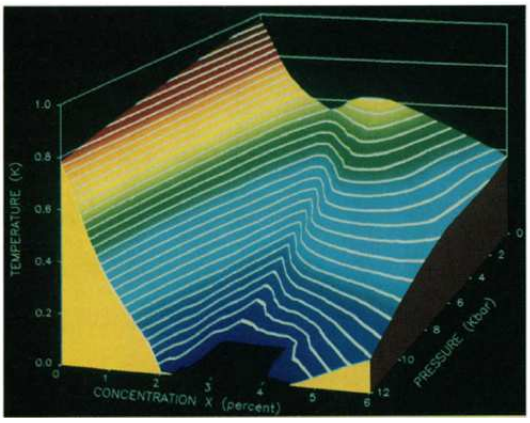

Figure 8: The superconducting transition temperature (T_c) surface in pressure and concentration (x) space for $Th_xU_{1-x}Be_{13}$ [8]

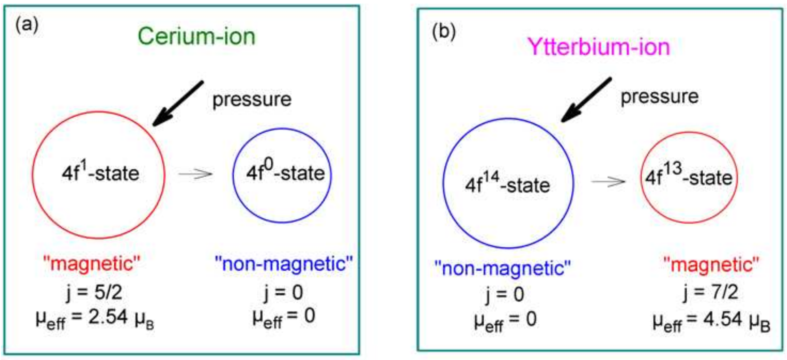

Figure 9: schemetic explaination for the function of pressure application.

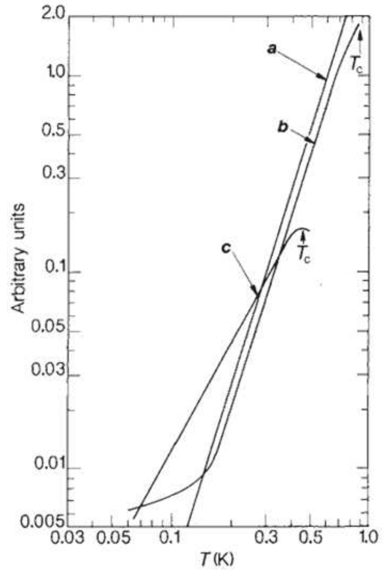

Figure 10: Power laws in various physical properties below T_c in UBe_{13} and UPt_3.

ventional superconductors is its power-law-type temperature dependence of various properties in the superconducting state. In Fig.10, a is the specific heat of UBe_{13} ($\propto T^3$); b, inverse spin-lattice relaxation rate of ^9Be in UBe_{13} ($\propto T^3$); c, ultrasonic attenuation in UPt_3 ($\propto T^2$) [10]. This is an indicator of an anisotropic superconductivity, because conventional isotropic superconductivity would result in exponential temperature dependences for all these physical quantities. The observation of such power-law behaviour is taken by many as evidence for anisotropic superconductivity. Unfortunately, we still lack a decisive way to determine the detailed symmetry of the superconducting state.

4 conlusion

It is clear from the above that heavy Fermion systems represent an exciting new class of materials. They do not fit into the traditional classifications of materials, so it is one of the most challenging and attractive areas in condensed matter physics. Kondo Effect is used to explain the minimum of resistivity at low temperature, and heavy Fermions are Kondo lattice with large specific heat coefficients. We also discussed the superconductivity in heavy Fermions which is different from conventional S-wave superconductor. The confirmation of a second mechanism for superconductivity will shed new light on the origin of superconductivity.

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