UBe_{13} An unconventional heavy fermion superconductor

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Abstract

UBe_{13} is an unconventional heavy fermion superconductor whose anamalous properties have defied widely accepted and agreed theoritical explanation of any kind.In this paper I will be highlighting some of these interesting properties mainly the behavior of specific heat, hall effect, resistivity and magnetic susceptibility, with supporting experimental data wherever possible.UBe_{13} belongs to a class of heavy fermion superconductors which includes $CeCu_2$, UBe_{13}, UPt_3, URu_2Si_2, UNi_2Al_3, UPd_2Al_3 which are characterised by their NFL like properties, which defies our current knowledge about the behavior of metallic compounds (which is primarily based on Landau's Fermi Liquid Theory).

1 Introduction

Before we discuss the NFL behavior and anamalous properties of UBe_{13}, it would be a good idea to become familiar with these terms –

A.**Fermi Liquid Theory:**The underlying principle of this theory (quasiparticle description) is that a one to one mapping of the non-interacting electron states to the interacting electron states is assumed to be asymptotically close to the fermi energy level.The states can then be described in terms of quasiparticles which have an effective mass and magnetic moment through their interactions with other quasi particles in the surrounding medium.Also the energy width of the quasiparticle excitation should vanish more rapidly than their energy position as the fermi level is approached.FLT predicts the following:

i. Specific heat has the form $C \sim \gamma T$; $\sim \gamma$ is independent in the temperature range $T \to 0$.
ii. A pauli like spin susceptibility χ independent of temperature
iii.A temperature dependent electrical resistivity contribution $\Delta\rho \sim aT^2$ arising from particle-particle collisions [1].

UBe_{13} shows a departure from this in most of it's properties and is characterized by:

1. huge values for the effective mass of the quasiparticles
2. logarithmic temperature dependance of specific heat
3. anamalous Hall's effect
4. unusual pressure dependence of the magnetic susceptibility
5. unusual dependence of resistivity on pressure and magnetic field as a function of temperature [2]

The f-shell radius ($r_{5f} \sim 0.7A$) of UBe_{13} is very large.The nearly localised f-electrons found in this case form narrow bands at low temperatures with enormous effective masses (heavy fermions) that exhibit superconductivity, magnetism or both phenomena.The f-electrons are thus generally regarded as being responsible for the unusual properties.The $5f^3$(magnetic ground state doublet) and the $5f^2$(non-magnetic ground state doublet) confiruration of the U-atom are energetically nearly degenerate [4].

It is interesting to note that the resistance, specific heat, susceptibility and magnetoresistance measurements indicate that the fermi liquid behavior is restored at low temperatures under an applied pressure.Thus UBe_{13} is a metal with a turnable fermi temperature(!) such that $T_f < T_c$ at ambient pressure.

B.**Heavy fermion compounds:**Intermetallic compounds in which the effective mass of the conduction electrons (as obtained from the specific heat measurements – they have huge values of the linear coefficient γ of the electronic specific heat) is order of 10^2 more than the normal electron mass.One of the metallic constituents in the compound is made up of f-atoms with partially filled f-orbital (eg. U) and the other constituent is a non f-atom.Also the f-atom is heavier than the non f-atom.The atomic weight of U is 238.02 while that of Be is 9.01 [**?**].

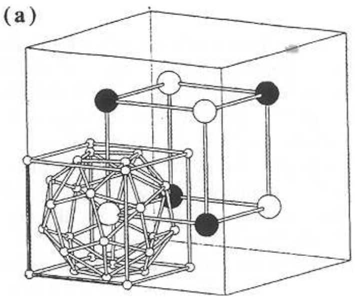

Figure 1: *Crystallographic structure of the MBe_{13} compounds.The two different bravais lattices of the M atoms are shown as open and black spheres.Each M atom is surrounded by a polyhedron of 24 Be atoms (small open spheres) [3]*

The above figure illustrates the general structure of MBe_{13} compounds.

2 Specific Heat

γ is strongly dependent on temperature below $\sim 10K$ and attains a value 1J/mole-K near 1K thereby indicating that it has a low degeneracy temperature T_0.It also shows a large specific heat jump at the superconducting critical temperature $T_c(\sim 0.85K)$ of $\sim \gamma T_c$,which compares favorably with the BCS theory ($\sim 1.48T_c$).This shows that the heavy electron responsible for high γ values are the same ones which are involved in the superconductivity.The specific heat is very weakly dependent on the magnetic field (upto $\sim 10T$) but is highly sensitive to pressure and the magnetic neutron scattering cross-section has a quasielastic peak at about 1MeV.It has also been noted that there is a logarithmic divergence of the linear term in the specific heat.

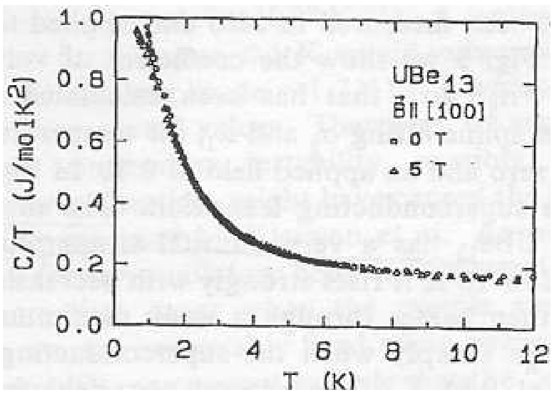

Figure 2: *specific heat of UBe_{13} in the normal phase plotted as C/T vs T,in zero and an applied field of 5T [5]*

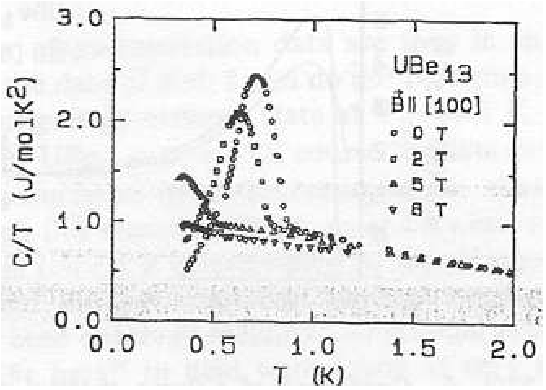

Figure 3: *specific heat of UBe_{13} at the superconducting transition as a plot of C/T vs T for fields as indicated [5]*

As we can see the influence of a magnetic field of 5T becomes visible below $\sim 2K$.The rise of C/T with decreasing temperature and the weak influence of a relatively large magnetic field is characteristic for heavy fermion systems.Also the second figure highlights the value of the specific heat at the superconducting temperature $T_c = 0.85K$. The specific heat still rises with decreasing temperature on entering the superconducting state and with the supression of T_c by magnetic field continues to rise down to 0.3K (where measurements stop).This clearly shows that the superconducting instability does not occur in a fermi liquid normal phase [5].

3 Anamalous Hall Effect

It is one of the striking features of heavy fermion systems like UBe_{13}.A rapid increase in the Hall coefficient R_H to positive values is observed when heavy mass formation starts.It has been suggested that it could be due to a reduction in the number of free electron charge carriers.At temperatures below the characteristic Kondo temperature (T_K),a different behavior is observed.At $T_K/3$ a prounced maxima which scales with T_K is seen followed by a gradual decrease of the anamalous content of the Hall effect [6].

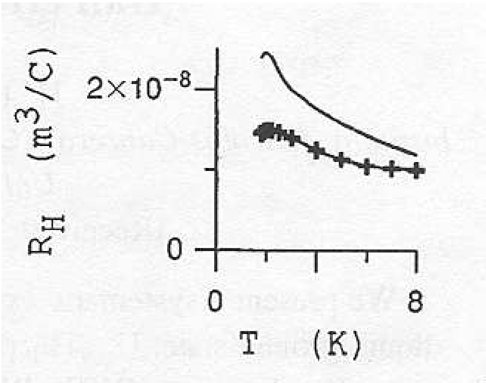

Figure 4: *$R_H(T)$ for UBe_{13} single crystal (line) and UBe_{13} polycrystal (crossed lines) when measured in a magnetic field of $H = 2T$ [6]*

As we can see here the Hall resistivity is linear against the magnetic field in the temperature range 1.9–10K (for H < 6T).In case of conventional heavy fermions with FL ground state there is a strong non-linearity of the Hall effect in the low field region.

4 Resistivity

The electrical resistivity at the superconducting transition is very large (order 80–100 $\mu - \Omega - cms$ and is reversibly supressed by applied pressure and magnetic field).There is no region in the ambient pressure or ambient field in which aT^2 coefficient is visible in resistivity (rather a linear term is present).Morever,in applied magnetic field a non-trivial scaling law describes the negetive magnetoresistivity (specifically $\rho(T,H)/\rho(T,0) \sim f(H/[T-T_0]^{\beta})$; $\beta = 1, T_0 = 0$ and $\beta = 0.6$, $T_0 = -0.6K$). The normal state resistivity of UBe_{13} is very unusual.The value of transition is very large for even the best crystal samples (order of $100\mu\Omega$).It has been observed that sharp resistive superconducting transitions persist even in applied magnetic field.Also,the resistivity is strongly and reversibly supressed with the application of pressure and magnetic field.Pressure also restores curvature to the resistivity and a clear window of T^2 coefficient opens up.

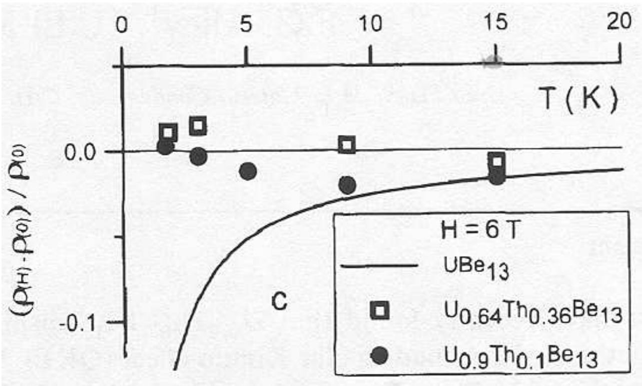

Figure 5: *Temperature dependence of the normalised magnetoresistivity in the $H = 6T$ for UBe_{13}*

[1]

5 Magnetic Susceptibility

The susceptibility has a very different pressure dependence than the specific heat (it's more weakly pressure dependent).Also, it has a very different energy scale than the specific heat (has a much higher energy scale).This could be due to the susceptibility being dominated by strong anti-ferromagnetic correlations while the specific heat is dominated by the Kondo effect or if the susceptibility had a very different origin than the specific heat.In fact one of the leading model for the compound - the Quadrupolar Kondo Effect supports this view [7].

We can see that the general shape of the curve remains generally unchanged with pressure.Only a small relative effect can be observed from fig.6 where the magnitude of the

[1] the residual resistivity is seen to diminish with increasing pressure

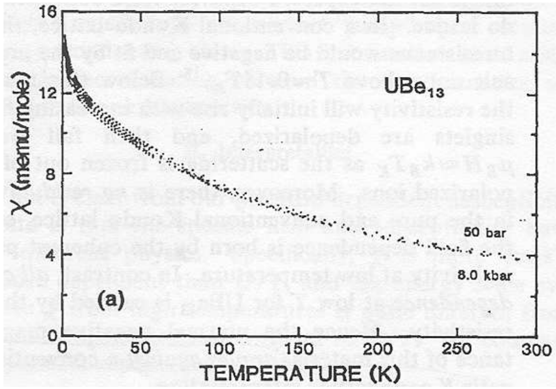

Figure 6: *the magnetic susceptibility χ of UBe_{13} is plotted as a function of temperature $\chi(T)$ at pressures of 0.001,1.2,2.7,4.3 and 8.0 kbar for T from 1.5K to 300K [7]*

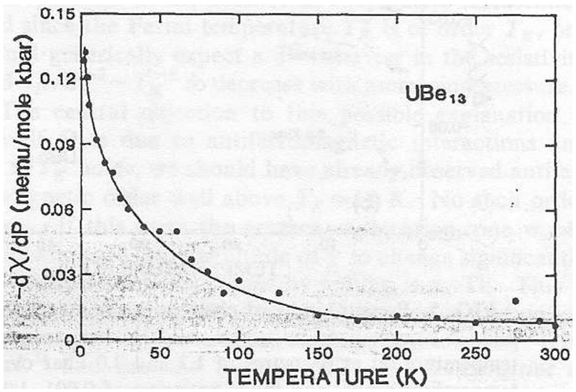

Figure 7: *slopes $-d\chi/dP$ of plots of χ versus P as a function of temperature.(mag. field of $H = 1T$ was used for this data [7]*

pressure dependent depression of χ decreases monotonically with increasing temperature with χ being almost pressure independent at high temperatures $T >> \Theta_D$; Θ_D is the Curie-Weiss temperature.

At any given temperature, χ is seen to be linearly dependent on P as can be inferred from fig.7. The relative effect of pressure is more clearly shown in Fig.8.we can also see that the secondary peak in the resistivity near 8K is supressed with pressure.The same is the case for the large apparent residual resistivity at T_C.This result is not compatible with any fermi liquid picture of the material anyone can draw.

6 Conclusions

As we saw the heavy fermion superconductor UBe_{13} shows a wide range of NFLproperties.The reason why no rigorous theoritical theories were put forward in this paper was because it has not been possible to develop a comprehensive theoritical model for the compound which explains all it's properties such as it's heavy effective mass, anamalous transport properties (resistivity),anamalous thermodynamic properties (susceptibility, Hall effect,magnetization), till now.

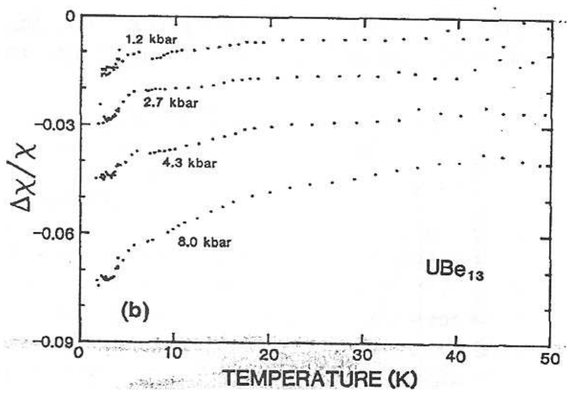

Figure 8: *pressure induced changes in the magnetic susceptibility normalised by χ at $P = 0.001kbar$,as a function of temperature at pressures 0.001,1.2,2.7,4.3,8.0 kbar at T below 50K [7]*

7 Acknowledgements

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