Intrinsic anomalous behaviour of an 'exotic' superconductor URu_2Si_2

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Abstract

URu_2Si_2 is an 'atypical' heavy fermion superconductor,which has unusual superconducting and normal state physical properties.These properties include a moderately high specific heat coefficient,large value of electrical resistivity and large magnetic susceptibility.Tranport,thermal and magnetic data for URu_2Si_2 indicate an energy gap of $\sim 11meV$ over a portion of the Fermi surface.It also exhibits anisotropic Josephson effects in point contacts with Nb.Most recent works suggest that below $T_N \sim 17K$,the ^{29}Si NMR line in URu_2Si_2 exhibits a previously unobserved field-independent nearly isotropic contribution to the line width,which increases to $\sim 12G$ as $T \rightarrow 0$.

1 Introduction

Superconductors,materials that have no resistance to the flow of electricity,below a certain temperature,are one of the great frontiers of scientific discovery.Since 1911,when superconductivity was first observed by H.K.Onnes in Hg at 4 K,several classes of new superconductors have been discovered.These include high-Tc superconductors(with$T_c \sim 138K$) and several 'atypical superconductors'like ceramic superconductors,organic superconductors,Borocarbides,heavy fermions and so on.**'Heavy Fermions'** are intermetallic compounds in which the effective mass of the conduction electrons is several hundred times greater than that of a free electron.One of the constituents of such compounds is usually a massive f-atom element with partially filled f-orbital(eg. U),and the rest are non-f atom elements.Superconductivity in such compounds was first discovered in 1979(Steglich et.al,1979).They exhibit low-temperature superconductivity,usually in the range of Type **I** superconductors,which severly limits their usefulness.However,they possess certain anomalous properties- both normal state and superconducting ,due to which they are often called "exotic superconductors".We will study these properties in one such heavy-fermion superconductor,URu_2Si_2.

2 Crystallography of URu_2Si_2

URu_2Si_2 is one of the heavy fermion superconductors,in which the effective mass of the conduction electrons is roughly 1000 times the mass of an electron.It was reported to be superconducting at $\sim 1.5K$ in the year 1985 by Schlabitz and his co-workers.
Crystal system:Tetragonal
Space group:P4/mmm
Lattice parameters:(in Å)
a=b=4.129
c=9.575

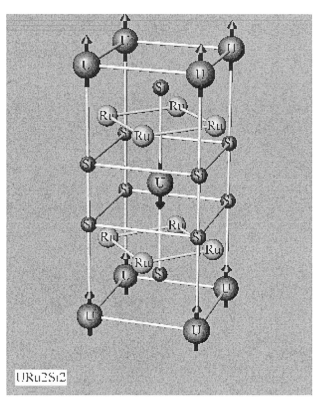

Figure 1: *Crystallographic structure of URu_2Si_2[3]*

3 Resistivity and Magnetic susceptibility

Electrical resistivity ρ vs temperature T data between $\sim 80K$ and 300 K is shown in Fig.2(a).The shape of curve is similar to that of many hybridized f-electron rare-earth and actinide compounds,particularly the rapid decrease in with decreasing temperature. has a large magnitude of 2.46 mΩ-cm at 300 K.There is an abrubt drop in below 1.7 K,due to the onset of superconductivity.The small ,but sharp peak at 17.2 K resembles the type of anomaly that would be expected for a charge- or spin- density wave(CDW or SDW) transition.The anomaly in at 17.2 K is insensitive to applied magnetic fields,shifting downwards in temperature by only $\sim 0.1K$ in a field of 6T(see inset of Fig.2(a)).There is an approximate linear dependance of with T between T_c and $\sim 8K$.The magnetic susceptibility χ vs T of URu_2Si_2 between 2 and 300 K is shown in Fig.2(b).There is a rounded maximum near 55 K in the $\chi(T)$ data,which correlates with a similar maximum of 70 K in the ρ(T) data.A small but distinct change in slope in at 18 K (see inset of Fig.2(b)) accompanies the phase transition.The increase in ρ and decrease in χ as T is decreased through 18 K could result from a change in the Fermi-surface topology associated with the formation of a CDW or SDW.

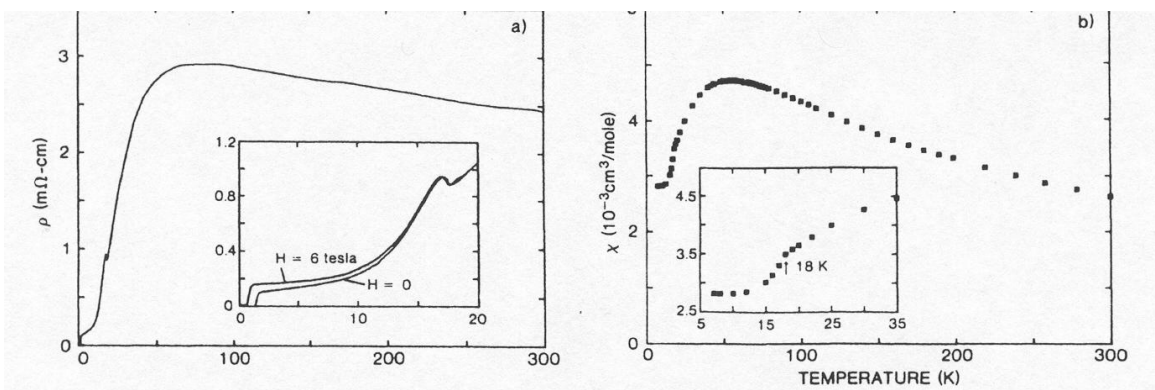

Figure 2: *(a)Electrical resistivity ρ vs temperature T for URu_2Si_2 between 80 mK and 300 K.Inset:ρ vs T between 80 mK and 20 K in magnetic fields of 0 and 6T.(b)Magnetic susceptibility χ vs temperature for URu_2Si_2 between 2 and 300 K.Inset:χ vs T in the vicinity of the phase transition at $\sim 17.5K$[3]*

4 Specific heat

URu_2Si_2 has a large value of specific heat coefficient ,γ =75mJ/mole-K^2.Fig.3 shows the plot of C/T vs T^2 between 0.6 and 500 K^2.A linear extrapolation to 0 K of the C/T vs T^2 data in the normal state above 1.5 K yields a value of $\sim 65.5mJ/mole-K^2$. This represents the 0 K value of the specific-heat coefficient γ in the absence of superconductivity.This value is compatible to the value given by Schlabitz and co-workers(75mJ/mole-K^2).

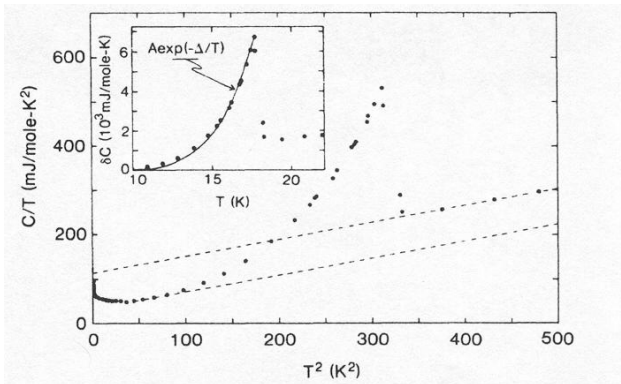

Figure 3: *specific heat of C divided by temperature T vs T^2 for URu_2Si_2 between 0.6 and 500 K^2.Inset:Estimated specific heat δC vs T associated with the apparent CDW or SDW transition at* $\sim$ 17.5 *K.The solid line represents the function A exp(-Δ/T) where A =9890 J/mole-K and Δ =129 K[3]*

5 Bulk Superconductivity below 1.5 K

Fig.4(a) and 4(b),respectively,are H_{c2} vs T and C/T vs T data that pertain to the superconducting state.The H_{c2} vs T is very steep with an initial slope of (-dH_{c2}/dT) at T_c =9.2T/K.Using the relation(-dH_{c2}/dT) at T_c =4.44$\gamma\rho$ for Type **II** superconductors,with γ =65.5 mJ/mole-K^2 and $\rho(2K)$ = 1.04 $\times$ $10^{-4}\Omega$-cm,we calculate (-dH_{c2}/dT) at T_c = 6.2T/K,in agreemen

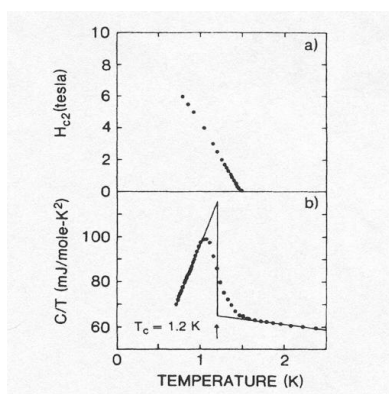

Figure 4: *(a)Upper critical magnetic field H_{c2} vs temperature for URu_2Si_2.(b)Specific heat C divided by temperature T vs T for URu_2Si_2.[3]*

6 Partially gapped Fermi surface

The phase transition in URu_2Si_2 at 17.5 K appears to involve the development of a CDW or SDW out of the heavy-electron system,which opens an energy gap of $\sim$ 11 meV over a portion of the Fermi surface.The portion of the Fermi surface that is not gapped by the CDW or SDW is removed by the superconductivity that occurs below 1.5 K,resulting in an energy gap $\sim$ 0.01 meV over the remainder of the Fermi surface.

7 Anisotropic Josephson effects in point contacts between URu_2Si_2 and Nb

URu_2Si_2 exhibits extremely anisotropic Josephson current unlike a conventional superconductor.This is a characteristic and intrinsic feature of URu_2Si_2. Point contacts were fabricated by pressing etched Nb needles onto the surface of single crystals of URu_2Si_2.Fig.5(a) and 5.(b) show point-contact characteristic obtained for a contact aligned along the a-b direction and along the c-direction respectively.Fig.5(a) shows a pronounced structure at about 0.1mA,which appears to be below the superconducting transition temperature of Nb of $T_c \sim 9.2K$.Below the superconducting transition temperature of URu_2Si_2 the contact resistance drops again at low bias and becomes zero within experimental resolution.However,the contacts obtained in c-direction show a comletely different behavior,as shown in Fig.5(b).The structure of dV/dI occurs at about 0.1meV,as in a-b contacts.But,there is no indication of additional structure at and below the superconducting transition temperature of URu_2Si_2.Thus,experimental study of point contacts between Nb and URu_2Si_2 show that a Josephson current is observed below the transition temperature of URu_2Si_2 in contacts aligned along the a-b direction of the tetragonal structure,whereas it is absent in contacts alinged along the c direction.

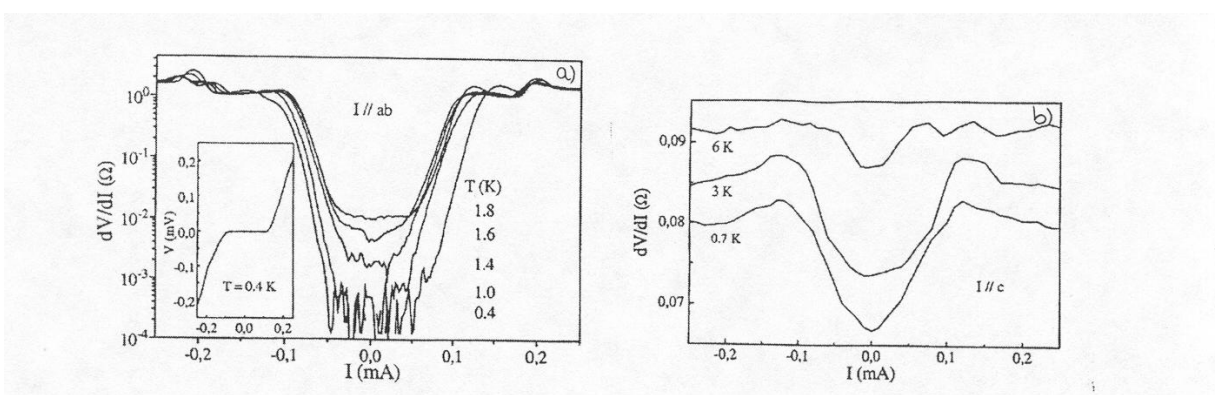

Figure 5: *(a)Differential resistance dV/dI of a point contact between URu_2Si_2 and Nb vs bias current I applied parallel to the a-b direction at various fixed temperatures given in the figure .Inset:the same data at T$\sim$ 0.4K shown in a plot of V vs I. (b)Differential resistance dV/dI of a point contact between URu_2Si_2 and Nb vs bias current I applied along c-direction at various fixed temperatures given in the figure.[4]*

8 Unconventional order parameter

The extreme anisotropy of Josephson current in URu_2Si_2 contacts with Nb is very unusual in a metallic point contact and provides strong evidence for an unconventional order parameter(OP) in URu_2Si_2 with a symmetry such that Josephson current along the c direction is zero.It has an even-parity B_{1g} (d-wave) symmetry,shown in Fig.6,which shows two line nodes and maximum gap values along the a and b axes,unlike s-wave symmetry in usual superconductors.

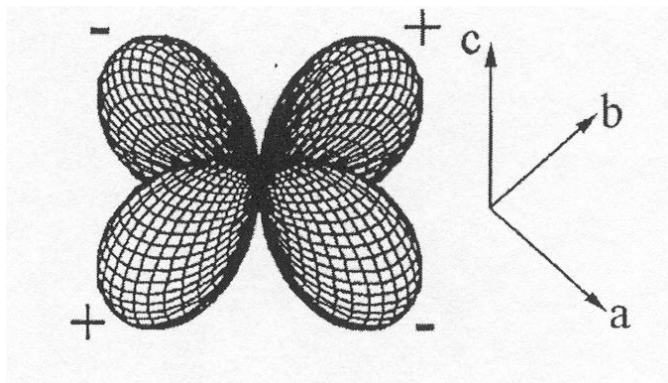

Figure 6: *A possible order parameter for URu_2Si_2(B_{1g}symmetry)."+" and "-" signs refer to the phase of the OP[4]*

9 'Hidden Order' in URu_2Si_2

NMR study at ambient pressure and low magnetic field strengths(below 6T) show an unambiguous,field-independent nearly isotropic component λ of the linewidth which increases below T_N to about 12G at 4.2 K.Results suggest that λ is not related to the static magnetization of the sample, rather it is due to the coupling of ^{29}Si nulcei and the "hidden order"in the system.The sample used was a fine powder(particle size $\sim 50\mu$m)embedded in Stycast 1266 epoxy and oriented in a field of 9.4T.Alignment of order $90\% - 95\%$ was estimated for the c-axis orientation by comparing the magnetic susceptibility for both transverse (H $\perp$ c) and (H $\parallel$ c) external fields with that of a single crystal under similar conditions. Spectra for (H $\perp$ c) and (H $\parallel$ c)(Fig.7.(a) and 7(b) respectively) consisted of a single narrow line.Each line is fitted to a Lorentzian function of half width at half maximum(HWHM) (H,T),which we find can be written as Γ^2(H,T) = Γ_m^2(H,T) + λ^2(T). Here Γ_m is the contribution due to the sample magnetization(a term proportionalto H), and λ is the new contribution to the linewidth that vanishes above T_N.Fig.7(a) shows that the line shape doesnot change with the field orientation θ.Separating Γ into two components is compelled by its field dependence,which is shown in Fig.7(c).The slope($\sim$ $6.4G/T$) (dashed-line fit) for H $\parallel$ c is more than 10 times greater than that for H $\perp$ c due to the large magnetic anisotropy of the system.

The above results can be discussed using two possible arguments,neither of which turns out to be satisfactory:

(i)disordered U-moment freezing,and

(ii)inhomogeneous antiferromagnetism

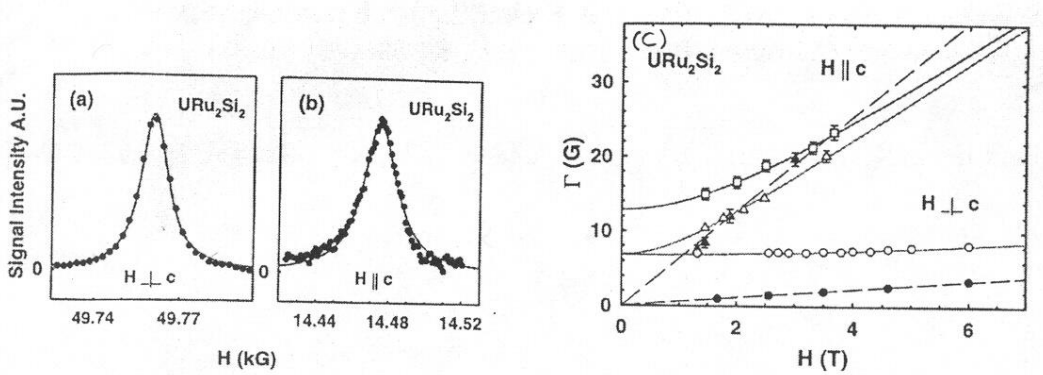

Figure 7: *^{29}Si NMR spectra in URu_2Si_2 at T = 14.5 K for (a) H ⊥ c, (b) H ∥ c.Curves fit to Lorentzian functions of HWHM Γ(H,T) and (c)Field dependence of the ^{29}Si linewidth Γ in URu_2Si_2.Circles:H ⊥ c,T =14.5 K(open)and T=40 K(filled).Filled triangles: H ∥ c,T =20 K.Open triangles:H ∥ c,T=14.5 K.Squares: T =4.2 K.Curves:one-(dashed) and two-(solid)component fits to the linewidth [4]*

Combined NMR,ND,μSR experiments rule out these scenarios.On the contrary,the suggestion of orbital antiferromagnetism as the hidden order and source of the extra ^{29}Si linewidth by Chandra et al. is a more viable possibility.

10 Conclusion

It is self-evident by now that the heavy fermion superconductorURu_2Si_2 possesses intrinsic anomalous properties.Understanding the normal state and superconducting behaviour of this material has proven to be very challenging and hence,a substantial amount of work has been done in this field over the years.Indeed,the physics of this material is very young and exciting.

11 Acknowledgement

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