MAGNETIC PROPERTIES OF HEAVY FERMION SUPERCONDUCTORS CeRHIn₅ AND Ce₂RhIn₈

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Some recent neutron scattering works on CeRhIn₅ and Ce₂RhIn₈, together with related resistivity and specific heat measurements, are summarized. In spite of its layered crystal structure, CeRhIn₅ is shown to be 3 dimensional both magnetically and in transport. We also find that the Fisher-Langer behavior is closely followed in CeRhIn₅. This may circumvent the Kondo lattice model and support applying established Fermi-liquid superconductivity theory to heavy fermion superconductors.

1 Introduction

Three materials, CeMIn₅ (M=Rh, Ir, Co), of the same HoCoGa₅ crystal structure recently have been added to the list of Ce-based heavy fermion superconductors. Previously, the list contained only one ambient pressure superconductor, CeCu₂Si₂ (T_C = 0.7 K). The others, CeCu₂Ge₂ (T_C = 0.64 K at 10 GPa), CePd₂Si₂ (T_C = 0.5 K at 2.5 GPa), CeRh₂Si₂ (T_C = 0.35 K at 0.9 GPa), and CeIn₃ (T_C = 0.2 K at 2.5 GPa), superconduct only under high pressures. Of the three new materials, the Ir and Co compounds are ambient pressure superconductors with T_C = 0.4 K and 2.3 K respectively, while the Rh compound superconducts at 2.1 K above 1.6 GPa.

CeMIn₅ is structurally related to the previously known superconductor CeIn₃ by alternately stacking CeIn₃ and MIn₂ layers. Particularly, it is interesting to compare CeIn₃ and CeRhIn₅, both of which are antiferromagnets at ambient pressure. The optimal T_C of the layered compound is 10 times that for cubic CeIn₃. In terms of the strength of magnetic interactions as represented by the Néel temperature, T_C/T_N of CeRhIn₅ is 28 times that for CeIn₃. In term of the Fermi energy via the Sommerfeld constant, the enhancement of T_C/E_f \sim T_C^γ from CeIn₃ to CeRhIn₅ is an even more impressive value of 35. Monthoux and Lonzarich recently argued that 2-dimensional (2D) magnetic fluctuations are superior to 3D magnetic fluctuations in elevating T_C. It is, therefore, natural to ask whether this mechanism is working for CeMIn₅. de
Haas-van Alphen (dHvA) measurements on CeRhIn$_5$, CeIrIn$_5$ and CeCoIn$_5$ have provided evidence for the existence of 2D Fermi sheets in addition to 3D ones.[11,12,13] Aspects of magnetic measurements, such as a small $\beta$ critical exponent, have been used to suggest magnetic 2-dimensionality. However, we are going to show with neutron scattering and bulk measurements that at least for CeRhIn$_5$, both magnetic and transport properties are 3D.[14] Furthermore, the close relation among resistivity, specific heat and antiferromagnetic fluctuations in the neighborhood of $T_N$, in the fashion illustrated by Fisher and Langer, indicates the Kondo lattice of CeRhIn$_5$ has been renormalized at low temperatures to weakly coupled subsystems of local magnetic moments and heavy fermions. If this holds true at the critical pressure for CeRhIn$_5$ and also true for CeIrIn$_5$ and CeCoIn$_5$, one can bypass theoretical difficulties posed by the Kondo lattice model, and directly treat superconductivity in these new heavy fermion materials with a Fermi liquid model using the experimentally measured magnetic fluctuation spectra for the bosons.

2 Experimental Results and Discussions

![Diagram of magnetic structures of Ce,RhIn$_{3n+2}$](image)

$\text{Ce}_n\text{RhIn}_{3n+2}$

$n=1$: CeRhIn$_5$

$n=2$: Ce$_2$RhIn$_8$

$n=\infty$: CeIn$_3$

Fig. 1 shows magnetic structures of Ce$_n$RhIn$_{3n+2}$ (n=1, 2 and $\infty$) deter-

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mined with neutron diffraction. Notice that the nearest neighbor (n.n.) antiferromagnetic pairs of the three materials have identical local environments. The pairs separated by the RhIn$_2$ layer are collinear for n=2 but are incommensurate for n=1. The incommensurate magnetic structure of CeRhIn$_5$ is found to transform to a commensurate one by a 2-3 T magnetic field applied in the layer at low T. An additional incommensurate antiferromagnetic component appears below 1.4 K for Ce$_2$RhIn$_8$. They suggest competing magnetic interaction between the Ce pairs. The $T-H$ phase diagram also reveals the Néel point as a multicritical point. This explains the small $\beta$ critical exponent.

Now let us address the dimensionality issue. Fig. 2 shows antiferromagnetic fluctuations along the c-axis for CeRhIn$_5$. There exists strong intensity modulation in step with magnetic Bragg peaks, which are marked by the crosses. This directly contradicts the idea that CeRhIn$_5$ is a formally 2D magnetic system. Magnetic correlation lengths along the c axis and in-plane have the same order of magnitude and evolve with temperature in a similar fashion. This also contradicts a 2D magnetic model for CeRhIn$_5$. From the correlation lengths, it is deduced that the magnetic interaction for the further separated n.n. Ce pairs along the c axis is weaker than that for the n.n. Ce pairs.

Figure 2. Instantaneous magnetic correlation function $S(q)$ measured along the c-axis at various temperatures. The open circles indicate background. From ref. [3].
Fig. 3 shows resistivity measured with current in-plane and along the $c$ axis for CeRhIn$_5$. At lowest temperatures, resistivity out of plane, $\rho_c$, is comparable to the in-plane $\rho_a$. At higher temperatures, $\rho_c$ is even smaller than $\rho_a$. This clearly rules out for CeRhIn$_5$ 2D electronic transport, which requires $\rho_c \gg \rho_a$. Although there is 2D band at the Fermi energy as revealed in the dHvA experiments, 3D bands clearly dominate in transport.

The single impurity Kondo model of $N$ electrons has very complex behavior at finite temperatures. It however renormalizes to a simple $N-1$ electron system at $T=0$. It is also possible for the Kondo lattice model, which describes a heavy fermion system, to renormalized to a simple system at low $T$. But a reliable theoretical prediction for possible states in a real material is difficult.

Fig. 4 compares the intensity of antiferromagnetic fluctuations at magnetic Bragg point, derivative of resistivity, and magnetic part of specific heat for CeRhIn$_5$. These quantities are remarkably similar. Fisher and Langer have considered a model which can be regarded as the Kondo lattice model at the small Kondo interaction limit and which can be solved with the Born approximation. They predict the behavior for the three quantities shown in Fig. 4. The Fisher-Langer theory is a great success for ferromagnets such as Fe and Ni and is reasonably successful for antiferromagnets such as PrB$_6$. We already know from specific heat that bare electrons are renormalized to heavy
Figure 4. Intensity of magnetic fluctuations $S(Q) - \langle M \rangle^2$, derivative of resistivity, and magnetic specific heat as a function of temperature. From Ref. [14].

electrons in CeRhIn$_5$, and from neutron diffraction that magnetic moment of Ce ion has been renormalized to 0.37$\mu_B$ at low temperatures. The Fisher-Langer behavior in Fig. 4 indicates that the Kondo interaction in CeRhIn$_5$ has been renormalized to the small value limit at low T.

A fermion system weakly coupled to localized moments, whose magnetic excitation spectra can be measured with inelastic neutron scattering, is much easier for theoretical treatment than the Kondo lattice model. Established theory for superconductivity may be readily applied to such a system. The Fisher-Langer behavior, therefore, may be used as the indicator for heavy fermion materials which have approached such a tractable fixed point.

3 Summary

Magnetic structures of CeRhIn$_5$ and Ce$_2$RhIn$_8$ have been determined with neutron diffraction. Several phase transitions, including commensurate-incommensurate transitions, are induced by magnetic field applied in the basal plane. From neutron scattering measurement of the spatially dependent magnetic fluctuations and resistivities measured in the basal plane and along the c axis, CeRhIn$_5$ is concluded to be a 3D system both magnetically and in transport. The Fisher-Langer behavior in CeRhIn$_5$ suggests that the
Kondo lattice of this material is renormalized to heavy Fermi liquid weakly interacting with magnetic excitations of the local moments. Critical behavior of magnetic order, which exists in some heavy fermion materials, thus, can be used to probe the Kondo renormalization process.

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