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Specific heat of CeRhIn₅: pressure-driven transition from antiferromagnetism to heavy-fermion superconductivity

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Abstract

CeRhIn₅ is known to show an unusual transition at a critical pressure of ~ 15 kbar. Specific-heat data show a gradual change in the zero-field “magnetic” specific-heat anomaly from one typical of antiferromagnetic (AF) ordering at ambient pressure to one more characteristic of a Kondo singlet ground state at 21 kbar. However, at 15 kbar there is a discontinuous change from an AF ground state to a superconducting ground state, and evidence of a weak thermodynamic first-order transition. Above the critical pressure, the low-energy excitations are characteristic of superconductivity with line nodes in the energy gap, and, at intermediate pressures, of extended gaplessness.

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Keywords: Specific heat; Pressure-driven transition; Antiferromagnetism; Superconductivity; Heavy fermion; CeRhIn₅

At ambient pressure heavy-fermion (HF) CeRhIn₅ is an antiferromagnetic (AF) that becomes superconducting (SC) abruptly at a critical pressure (P_c) ~ 15 kbar [1]. Its phase diagram is different from that of any other Ce HF compound, and the abrupt change at P_c suggests a “first-order-like transition” [1]. The ground states, AF below P_c and HF/SC above, both evolve continuously with increasing P , but at P_c there is a discontinuous change.

Specific heats (C) are shown in Fig. 1. The electronic component (C_e) is derived by subtracting C for LaRhIn₅ [1]. As P increases the “magnetic” specific-heat anomaly becomes broadened and reduced in amplitude. A second anomaly, associated with the SC state, first appears at 16 kbar. The characteristic T 's derived from C_e and the resistivity (ρ) [1] are compared in Fig. 2. The T of the magnetic-anomaly maximum ($T_{\max}$) tracks the Néel

temperature (T_N) deduced from ρ for $P \leq 10$ kbar, but then shifts to lower T . Values of the SC transition temperature (T_c) are in agreement with values determined from ρ .

The T dependence of C_e at low T is discontinuous at P_c . For all P , the lowest-order term in C_e is $\gamma(H)T$. For $P < P_c$, the second term is $B_{\text{AFSW}}(H)T^3$ which corresponds to a spin-wave contribution expected for an AF; for $P > P_c$, it is $B_2(H)T^2$ characteristic of certain HF SC's.

At 21 kbar and $H = 0, 50$, and 70 kOe, C_e is shown in Fig. 3. $T_c(H)$, assuming a parabolic T dependence, extrapolates to $H_{c2}(0) = 159$ kOe. The $B_2(0)T^2$ term indicates line nodes in the energy gap and is commonly attributed to a d-wave order parameter in HF compounds [2]. The value of $\gamma(0) = 0$ shows that the Fermi surface (except for the line nodes) is fully gapped, and the SC is both complete and bulk at 21 kbar.

$\gamma(H)$ is proportional to H as shown in Fig. 4(b), and extrapolation to $H_{c2}(0)$ gives $\gamma = 382 \text{ mJ K}^{-2} \text{ mol}^{-1}$ for the normal-state. In Fig. 3 interpolation of the normal-state $C_e(C_{\text{en}})$ between 1.7 and 0 K must give the same entropy (S_e) at T_c as that for $H = 0, 50$, and 70 kOe. The

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Fig. 1. Plots of C/T vs. T for representative values of P . Fig. 2. Phase diagram for CeRhIn₅. Fig. 3. $C_e(T)/T$ vs. T for $P = 21$ kbar and $H = 0, 50, 70$ kOe. Fig. 4. (a) $\gamma(0)$ vs. P and (b) $\gamma(H)$ vs. H for $P = 21$ kbar.

shape is similar to that of Kondo singlet-ground-state ordering, and very different from AF ordering. For the SC transition $\Delta C_e(T_c)$ is relatively small as a consequence of the T dependence of both C_{en} and C_{es} , and the requirement of the equality of S_e for the SC and normal states at T_c .

Fig. 5. $S_e(P)$ vs. P showing features at 12 and 15 kbar.

The P dependence of $\gamma(0)$ is displayed in Fig. 4(a) with the AF values interpolated to the 21-kbar normal-state value and the SC values extrapolated to the AF curve at P_c . The curves represent a normal-state γ and a measure of the density of quasiparticle excitations. For $H = 0$ and $P \geq P_c$, the SC transition leaves a $\gamma(0)$ that varies between the normal-state value at P_c and zero at 21 kbar. On the SC side of the phase boundary at P_c , $\gamma(0)$ is the same in the SC and normal states and $\Delta C_e(T_c) = 0$. With increasing P , $\gamma(0) \rightarrow 0$ and $\Delta C_e(T_c)$ increases, but with essentially no increase in T_c . The extended gapless regions on the Fermi surface of SC's with d-wave pairing [3] suggest a basis for this behavior. Below a critical value of the pairing potential the gap vanishes and there is a density of low-energy quasiparticle states. With increases in the pairing potential a gap appears and grows in amplitude while the quasiparticle density of states decline and go to zero for sufficiently high amplitudes.

Isotherms, $S_e(P)$ vs. P , obtained by integration of $C_e(T)/T$, are shown in Fig. 5. Discontinuities near 12 kbar in $(\partial S_e / \partial P)_T$ and at 15 kbar in S_e correspond to second- and first-order transitions. The second-order transition could be a change in the volume thermal expansion. The discontinuity in S_e is a transition from the AF state to the SC state that includes a small first-order component, which terminates at a critical point in the vicinity of the magnetic ordering T .

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