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Specific heat of $CeRhIn_5$: the pressure-driven transition from antiferromagnetism to heavy-fermion superconductivity

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Abstract

$CeRhIn_5$ has an unusual transition at a critical pressure of ∼15 kbar. Specific-heat data show a gradual change in the zero-field 'magnetic' anomaly from one typical of antiferromagnetic (AF) ordering at ambient pressure to one that is 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, with evidence of a weak thermodynamic first-order transition. For pressures near 12 kbar, there is a pressure-dependent, second-order transition. The low-energy excitations above 15 kbar are characteristic of superconductivity with line nodes in the energy gap, and with extended gapless behaviour at intermediate pressures less than 21 kbar.

Resistivity (ρ) measurements on $CeRhIn_5$ under pressure (P) have shown an unusual relation between antiferromagnetic (AF) and superconducting (SC) phases [1]. In other Ce-based heavy-fermion (HF) compounds, $CeIn_3$ [2] and $CePd_2Si_2$ [2], superconductivity appears in a narrow window of T and P at a quantum critical point at which the AF ordering is driven to $T = 0$. In $CeRhIn_5$, the Néel temperature (T_N) is essentially constant to a critical pressure (P_c) of ∼15 kbar, at which AF order disappears and SC, with an approximately P-independent critical temperature (T_c), appears. We report measurements of the specific heat (C) under pressure [3] that give additional information about the magnetic and SC phases, and on the transition.

The general shape of the specific-heat anomaly associated with magnetic ordering, out of which SC develops, changes continuously with increasing P from one typical of AF ordering at $P = 0$, to a different form at 21 kbar (see figure 1). At 21 kbar the shape of the anomaly, and the decrease in C for T below the maximum, to a constant C/T, is very similar to that in $CeAl_3$ [4],

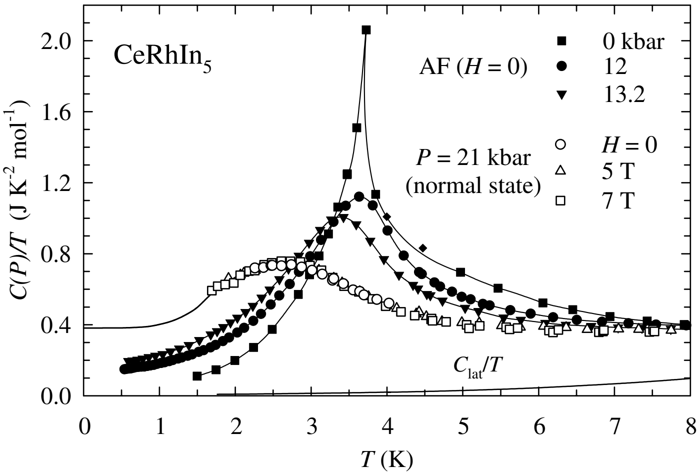

Figure 1. $C(P)/T$ versus T for $\mathrm{CeRhIn_5}$ in the normal and AF states.

which is associated with the formation of a Kondo-singlet ground state. In $\mathrm{CeAl_3}$, however, the anomaly is dependent on magnetic field (H), whereas for $\mathrm{CeRhIn_5}$ it is independent of H. $\mathrm{URu_2Si_2}$ shows a much broader maximum in C/T and a less conspicuous decrease at lower T, but the anomaly is independent of H [5]. In that case, however, a significant fraction of the magnetic entropy (S_e) appears at an anomaly at a much higher T that is associated with a charge- or spin-density-wave ordering [5, 6]. Neither the origin of the low-T anomaly, out of which superconductivity forms, nor its relation to the charge/spin-density-wave ordering is clear. The 21 kbar anomaly in $\mathrm{CeRhIn_5}$ shows some similarities to anomalies in $\mathrm{CeAl_3}$ and $\mathrm{URu_2Si_2}$, but they do not provide a basis for identifying the mechanism of the ordering.

Although the magnetic anomaly in $C_e = C - C_{lattice}$ evolves with increasing P without a discontinuity in its general shape, the T-dependence of C_e at low T is discontinuous at P_c. C_e/T has positive curvature for $P < P_c$, but zero curvature for $P > P_c$ as $T \to 0$. For all P, the lowest-order term in C_e is $\gamma(H)T$. For $P < P_c$, the second term is $B_{AFSW}(H)T^3$ corresponding to the spin-wave contribution for an AF. When $P > P_c$ it is $B_2(H)T^2$, corresponding to unconventional SC with line nodes in the energy gap (d-wave pairing). This behaviour is illustrated in figure 2. With increasing P, $B_{AFSW}(0)$ increases monotonically, which corresponds to a linear-in-P decrease in the spin-wave stiffness that is proportional to the product of the moment and the exchange interaction.

The P-dependence of $\gamma(0)$ is shown in figure 3. Experimental AF values are interpolated to the 21 kbar normal-state value, which is derived from an extrapolation of the mixed-state data to the critical field $H_{c2}(0)$ (see the inset in figure 3). The curve represents a normal-state γ that measures the density of low-energy quasiparticle excitations, which increase monotonically from ambient P to 21 kbar. Experimental SC values are extrapolated to the AF curve at $P_c = 15$ kbar where there is a discontinuity in slope. For $H = 0$ and $P \geqslant P_c$, there is a transition to the SC state that leaves a 'residual' $\gamma(0)$ varying between the normal-state value at P_c and zero at 21 kbar. The finite $\gamma(0)$ in the SC state indicates gapless behaviour, which evolves to a fully gapped state at 21 kbar except for the nodes. The extended gapless regions on the Fermi surface of SCs with d-wave pairing [7] suggest a basis for this behaviour. Below a critical value of the pairing potential the gap vanishes and there is a density of low-energy quasiparticle states. As the pairing potential increases a gap appears and grows in amplitude while the quasiparticle density of states decline and go to zero for sufficiently high amplitudes.

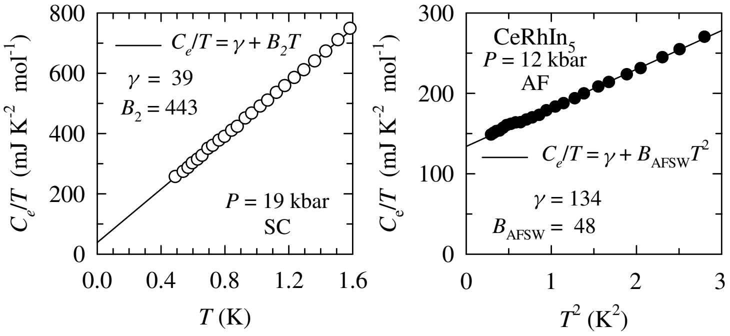

Figure 2. The low-T behaviour of C_e/T for the SC and AF phases.

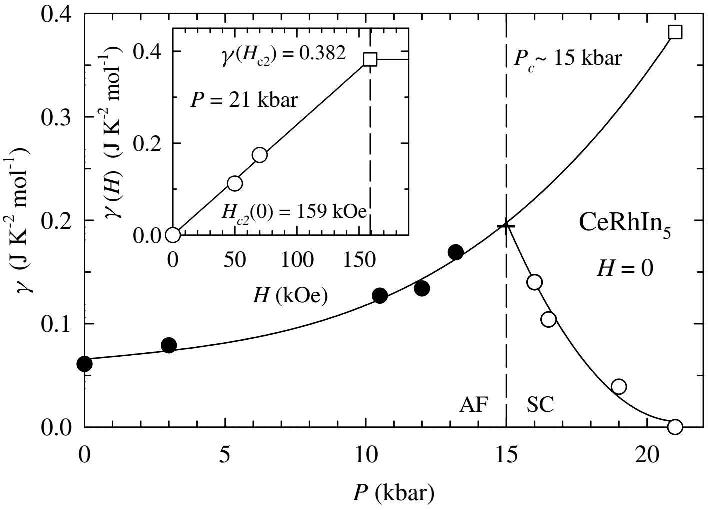

Figure 3. $\gamma(P)$ versus P for the AF, normal, and SC phases.

For $P = 21$ kbar and $H = 0$, 50, and 70 kOe, C_e/T versus T is shown in figure 4. The values of $T_c(H)$ do not extend to sufficiently high values of H to establish the form of $H_{c2}(T)$, but on assuming a parabolic T-dependence they extrapolate to $H_{c2}(0) = 159$ kOe. For $T < T_c(H)$, $C_e(H) = \gamma(H)T + B_2(H)T^2$. This dependence of C_e on T and H is characteristic of a certain group of HF superconductors that includes URu$_2$Si$_2$ [5]. The $B_2(0)T^2$ term is associated with line nodes in the energy gap and an 'unconventional' order parameter [7]. For this P, $\gamma(0) = 0$ and C_e in the SC state is $C_{es} = B_2(0)T^2$ with the Fermi surface (except for the nodes) fully gapped. For $T \leqslant T_c(H)$, $C_e(H)$ conforms to expectations for SC material, and, by that criterion, the SC at 21 kbar is complete and bulk.

C_e in the normal state (C_{en}) is defined at 21 kbar. For $T > T_c(H)$, C_{en} is independent of H and determined to 1.7 K. Extrapolation of $\gamma(H)$ to $H_{c2}(0)$ (see figure 3) gives $\gamma = 382$ mJ K^{-2} mol^{-1} for the normal-state value, the 0 K intercept of C_{en}/T in figure 4. C_{en}/T versus T must have the same S_e at $T_c(0)$ as that derived from the data for $H = 0$, 50, and 70 kOe, and the curve in figure 4 is a smooth, plausible interpolation that satisfies this criterion. The discontinuity in C_e at $T_c(0)$ is relatively small. $\beta \equiv \Delta C_e(T_c)/C_{en}(T_c)$ is 1.43 for a BCS superconductor, but is only 0.36 for CeRhIn$_5$. This smaller value is a consequence

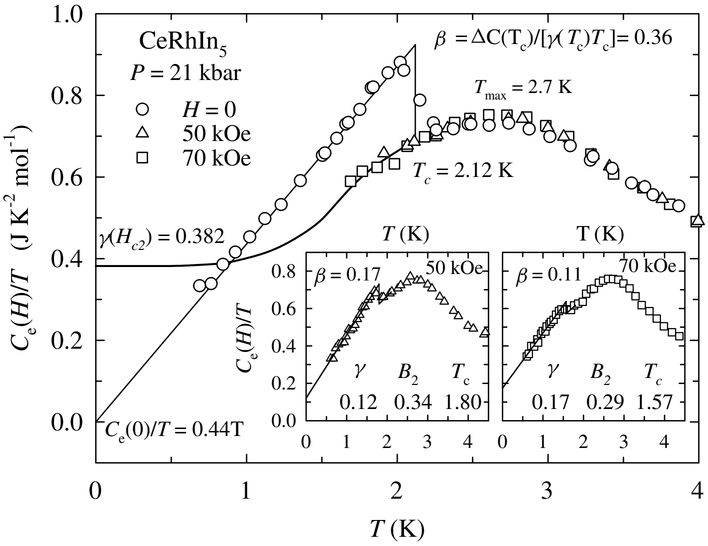

Figure 4. $C_e(H)/T$ versus T at 21 kbar for $H = 0$, 50, and 70 kOe.

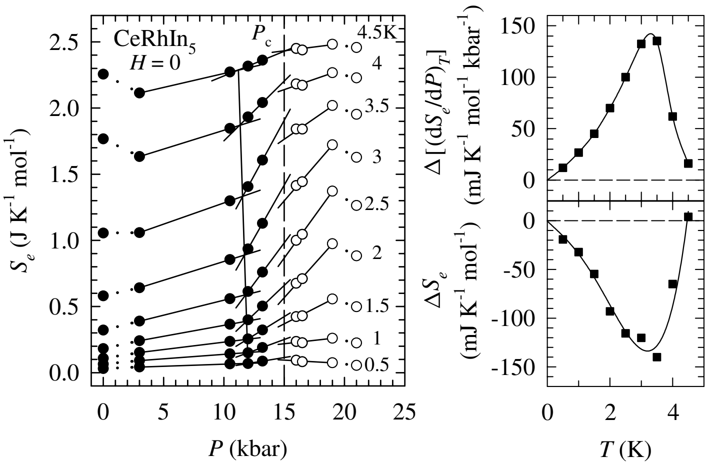

Figure 5. S_e versus P on isotherms showing first- and second-order transitions.

of the T-dependence of C_{en} and C_{es}, and the thermodynamic requirement that S_e for the SC and normal states be equal at T_c, with no need for any microscopic interpretation.

Isotherms of $S_e(P)$ versus P, obtained by integration of $C_e(T)/T$, are shown in figure 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, and which terminates at a critical point in the vicinity of the magnetic ordering T.

Acknowledgments

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