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 $\sim$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 ($\rho$) 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$_2$Si$_2$ [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 $\sim$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],
which is associated with the formation of a Kondo-singlet ground state. In CeAl$_3$, however, the anomaly is dependent on magnetic field ($H$), whereas for CeRhIn$_5$ it is independent of $H$. URu$_2$Si$_2$ 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 ($S_m$) 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 CeRhIn$_5$ shows some similarities to anomalies in CeAl$_3$ and URu$_2$Si$_2$, 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 $\gamma$ 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 $P \geq P_c$, 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.
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Figure 2. The low-$T$ behaviour of $C_T/T$ for the SC and AF phases.

For $P = 21$ kbar and $H = 0, 50$, and $70$ kOe, $C_T/T$ 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 $T < T_c(H)$, $C_T(H) = \gamma(H)T + B_2(H)T^2$. This dependence of $C_T$ 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 $C_T$ in the SC state is $C_{en} = B_2(0)T^2$ with the Fermi surface (except for the nodes) fully gapped. For $T \leq T_c(H)$, $C_T(H)$ conforms to expectations for SC material, and, by that criterion, the SC at 21 kbar is complete and bulk.

$C_T$ 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 $S_c$ 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 $C_T$ at $T_c(0)$ is relatively small. $\beta \equiv \Delta C_T(T_c)/C_{en}(T_c)$ is 1.43 for a BCS superconductor, but is only 0.36 for CeRhIn$_5$. This smaller value is a consequence...
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 $T$. 

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**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.
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