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Low-temperature phase diagram of YbBiPt

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Resistivity measurements are reported on the cubic heavy-fermion compound YbBiPt at ambient and hydrostatic pressures to ≈19 kbar and in magnetic fields to 1 T. The phase transition at $T_c=0.4$ K is identified by a sharp rise in resistivity. That feature is used to build low-temperature H-T and P-T phase diagrams. The phase boundary in the H-T plane follows the weak-coupling BCS expression remarkably well from T_c to $T_c/4$, while small hydrostatic pressure of ≈1 kbar suppresses the low-temperature phase entirely. These effects of hydrostatic pressure and magnetic field on the phase transition are consistent with an spin-density-wave (SDW) formation in a very heavy electron band at $T=0.4$ K. Outside of the SDW phase at low temperature, hydrostatic pressure increases the T^2 coefficient of resistivity, signaling an increase in heavy-fermion correlations with hydrostatic pressure. The residual resistivity decreases with pressure, contrary to trends in other Yb heavy-fermion compounds.

Interest in the compound YbBiPt has been sparked by the very large coefficient of the linear-in-temperature contribution to the heat capacity, $\gamma=8$ J/mol K^2, that develops at low temperatures.[1] If a substantial part of that heat capacity is due to the heavy-fermion nature of the ground state, that value of γ makes YbBiPt the "heaviest" fermion compound known to date. Inelastic neutron scattering[2] suggests that some fraction of this large γ may be due to the existence of low-lying crystal-field excitations; however, separation of these and intrinsic heavy-fermion contributions has not been possible. The heat capacity data also revealed a phase transition at 0.4 K as a small, but rather sharp, peak in the C vs T curve. It is the nature of that transition that is the subject of this article, together with the clues it may provide to the properties of the ground state of the system. To address these questions we have studied the electrical resistivity as a function of pressure and applied magnetic fields and we argue that these results are consistent with the development of a spin-density wave (SDW) below 0.4 K in a heavy-mass band of conduction electrons.

Single-crystal samples of YbBiPt were grown from an excess Bi flux.[3] X-ray diffraction confirms the samples to be face-centered cubic with the half-Heusler structure at room temperature. Neutron diffraction shows no evidence for a structural transition to 27 K.[2] Resistance measurements were made in standard four-probe and Montgomery[4] configurations. Pressure was generated in a self-clamping Be-Cu cell with Fluorinert FC-75 as the hydrostatic pressure medium. The pressure at low temperatures was established from the shift in the superconducting transition of a piece of high-purity lead mounted near the sample.

Results of four-probe ac resistivity measurements under hydrostatic pressure below ≈4 kbar are displayed in Fig. 1 for the rod-shaped sample in which the current flow was close to being parallel to the (100) crystallographic direction. Data for $P=0$ kbar curve show a sharp kink at $T=0.4$ K. The rise in resistivity below T_c suggests a decrease in the number of conduction electrons that could arise from partial gapping of the Fermi surface. Combination of this effect and the magnetic nature of the transition[1] suggests SDW as a candidate for the nature of $T=0.4$ K transition. The curve at $P=0.78$ kbar displays similar behavior, with the transition temperature shifted very slightly downward; however, application of 1.20 kbar suppresses any resistive signature for the low-temperature phase transition. The inset in Fig. 1 shows the P-T phase diagram, with data points identified from the kinks in the resistivity curves, as in Fig. 1, as function of pressure. The point at $P=0.84$ kbar is obtained from a curve not shown in the Fig. 1. The dashed line represents the approximate pressure above which there is no resistive signature for a phase transition. The dotted line through the data points corresponds to the pressure dependence of the transition temperature of $(dT_c/dP)_{P\rightarrow 0}=-14$ mK/kbar. The behavior of the transition temperature is highly nonlinear, and

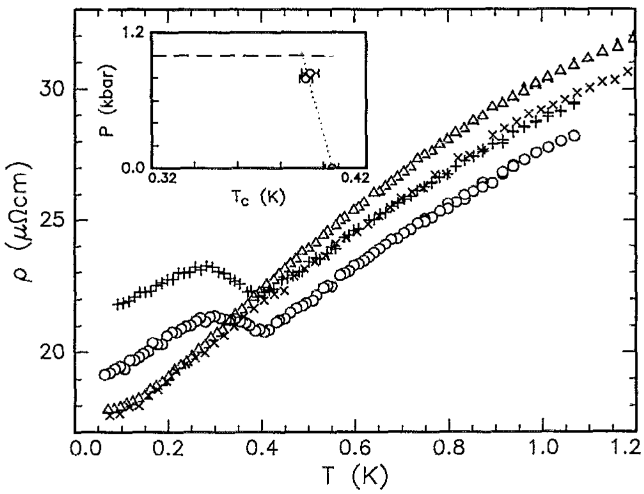

FIG. 1. Resistivity of a single-crystal rod-shaped sample of YbBiPt under hydrostatic pressure: (○) 0 kbar; (+) 0.78 kbar; (×) 1.20 kbar; (△) 3.92 kbar. Inset: transition temperature T_c vs applied hydrostatic pressure, obtained from the kinks in curves shown in the main body of the figure. Dashed line: approximate pressure that suppresses the low-temperature phase. Dotted line passes through the data points, with a slope $(dT_c/dP)_{P\rightarrow 0}=-14$ mK/kbar. The low-temperature phase is suppressed by pressure between 0.84 and 1.20 kbar.

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very strong. Hydrostatic pressure has been an important tool for investigating the SDW transition in Cr. The transition temperature is suppressed rapidly by pressure, at the rate of $(dT_N/dP)_{P\rightarrow 0}=-5.1$ K/kbar.[5] Such a strong dependence on pressure is seen as a consequence of the delicate Fermi surface nesting that results in a SDW transition. The high sensitivity to relatively small pressure on the order of 1 kbar is consistent with the 0.4 K transition in YbBiPt being due to a Fermi surface instability. Extending the analogy with Cr,[6] analysis of data similar that of Fig. 1 for $P=0$ kbar (Ref. 7) results in a value for a weak-coupling SDW gap of $\Delta(T=0)/k_BT_c=1.65\pm0.15$. This is close to the minimum value of 1.764 for the two-band model of itinerant antiferromagnetism.[8] For comparison, in Cr it was found[6] that $\Delta(T=0)/k_BT_N=2.3$.

To further investigate this transition we performed a series of resistance measurements in a magnetic field. The two samples used were of a "Montgomery type," thin square platelets, each oriented to have one pair of long edges along the magnetic field. Both samples displayed anisotropic resistivity,[7] and the direction of the largest increase in V/I was longitudinal for one of the samples and transverse for the other. One reason for choosing such a geometry was the expectation that magnetic field might reorient the SDW domains with different order parameters, as was demonstrated for Cr,[9] and produce a single-domain sample. In one of the samples we indeed observed a small downward kink in V/I, in the direction which had a larger resistivity at zero field, while sweeping temperature at a fixed field of 2.5 kG. This would imply that reversal of the direction of the larger resistivity has taken place. However, temperature sweeps in fields greater than 2 kG are increasingly difficult since the phase boundary of the low-temperature phase becomes rather independent of temperature, as described below.

Figure 2(a) displays results of temperature sweeps for one of the samples described above in which the excitation current was transverse to magnetic field. The phase transition temperature is easily identified by sharp kink in V/I. Figure 2(b) shows V/I at 350 mK for the same sample but with the current flow parallel to the applied field. We identify the sharp kink at 2.1 ± 0.1 kG in the derivative with respect to H as the transition magnetic field for that temperature. This identification is consistent with the results of the temperature sweep at 2 kG, which gives a transition temperature of 350 ± 10 mK. Similar identifications were then made for magnetic field sweeps at 100 and 200 mK.

Figure 3 displays the resulting magnetic-field temperature phase diagram for the low-temperature phase of YbBiPt. The solid curve is the functional dependence of the BCS energy gap scaled to pass through the points $T_c=0.4K$, $H=0$ on the x axis and $T=0$, $H=3.1$ kG on the y axis. The curve fits the data very well, indicating the weak-coupling nature of the transition in the whole temperature range studied. In contrast to Cr, in which T_N is independent of magnetic fields up to $H=16$ T,[10] YbBiPt follows mean field behavior expected of an itinerant antiferromagnetism.

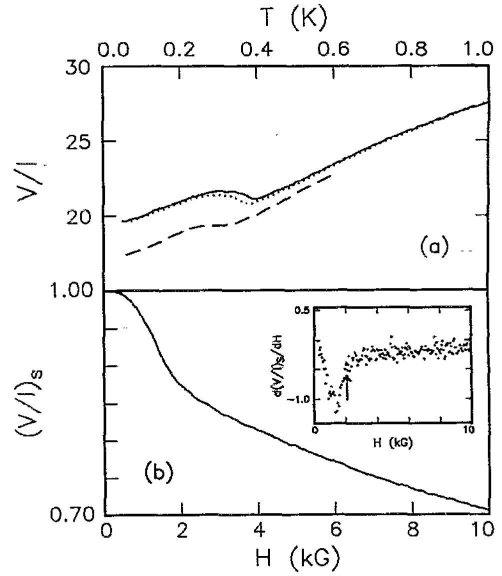

FIG. 2. (a) Temperature sweeps at constant magnetic field: (solid line) $H=0$ kG; (dotted line) $H=1$ kG; (dashed line) $H=2$ kG. Kinks in V/I curves are taken as signaling transition temperatures for given fields. (b) Magnetic-field sweep at a constant temperature of $T=350$ mK, $(V/I)_s=(V/I)/[V/I(H=0)]$. Inset: derivative of the curve shown in (b). The sharp kink indicated by the arrow at a field $H=2.1\pm0.01$ kG represents the phase transition at $T=350$ mK.

We now turn our attention to the resistive behavior of YbBiPt at pressures sufficiently high that evidence for a phase transition is not found. Figure 4 shows the temperature-dependent resistivity at pressures between ≈4 and 19 kbar. Data for all curves can be fit very well by $\rho(T)=\rho_0+AT^2$ below $T=300$ mK, as expected for a Fermi liquid. In this Fermi liquid regime $\sqrt{A}$ was shown[11] to be proportional to γ for a large number of Ce and U heavy-fermion compounds. The inset in Fig. 4 shows A as a function of pressure and indicates an increase in the heavy-fermion correlations with pressure. Similar systematics with pressure are observed in other Yb heavy-fermion compounds.[12] The decrease of the residual resistivity ρ_0 with

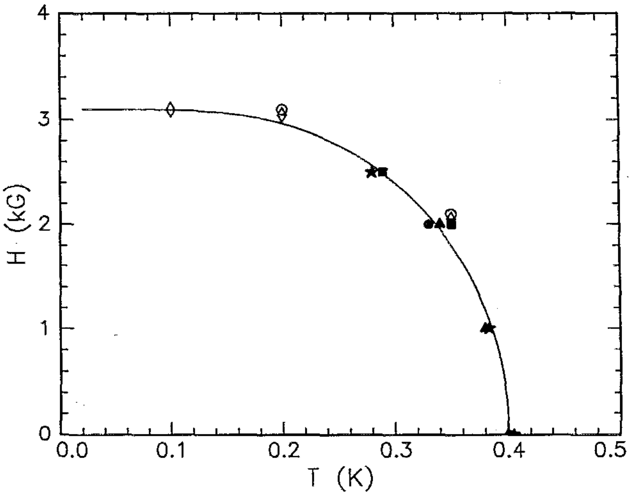

FIG. 3. Magnetic-field temperature phase diagram for the low-temperature phase of YbBiPt. The solid and open symbols are results of the temperature and magnetic field sweeps, respectively. The solid line is a BCS curve fixed by the points $H,T=0$ and $H=0$, T_c.

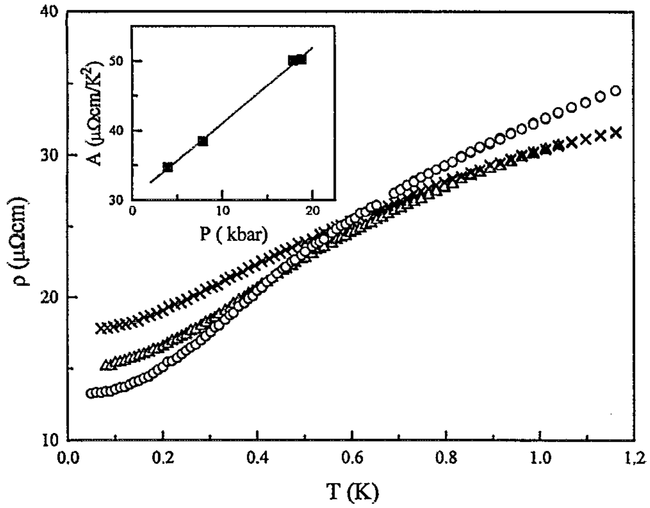

FIG. 4. Resistivity of YbBiPt in the high-pressure phase: (○) 18.79 kbar; (△) 7.83 kbar; (×) 3.92 kbar. Inset: T^2 coefficient of $\rho(T)$ vs pressure; straight line is a guide to the eye.

pressure, however, is rather anomalous. In other Yb compounds the residual resistivity increases with pressure, possibly reflecting its Kondo hole origin.[13] The decrease of ρ_0 with pressure in YbBiPt may be due to purely band-structure effects. The REBiPt series (RE is an element of the rare-earth series) exhibits a systematic progression from small gap semiconductor in Nd to metallic behavior in Yb,[14] as the RE series is traversed from the left- to right-hand side, i.e., as the size of the RE ion diminishes. Pressure would reduce the volume of the unit cell of YbBiPt even further, possibly increasing the carrier density and reducing resistivity.

In summary, the phase boundary in the H-T plane of the low-temperature state of YbBiPt follows the weak coupling BCS-like expression expected of an SDW transition. This identification is supported further by the extreme pressure dependence of the transition temperature, *with the low-*temperature phase being suppressed by pressures of ≈1 kbar. Above that pressure-induced transition, the heavy-fermion nature of YbBiPt appears to be enhanced further with increased pressure. We suggest that investigating YbBiPt at higher pressures yet may yield interesting information on a transition regime between heavy-fermion and antiferromagnetic behaviors.

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[1] Z. Fisk, P. C. Canfield, W. P. Beyerman, J. D. Thompson, M. F. Hundley, H. R. Ott, E. Felder, M. B. Maple, M. A. Lopez de la Torre, P. Visani, and C. L. Seaman, Phys. Rev. Lett. **23**, 3310 (1991).
[2] R. A. Robinson, M. Kohgi, T. Osakabe, P. C. Canfield, T. Kamiyama, T. Nakane, Z. Fisk, and J. D. Thompson, Physica B **186-188**, 550 (1993); R. A. Robinson (unpublished).
[3] P. C. Canfield and Z. Fisk, Philos. Mag. B **65**, 1117 (1992).
[4] H. C. Montgomery, J. Appl. Phys. **42**, 2971 (1971).
[5] T. Mitsui and C. T. Tomizuka, Phys. Rev. **137**, A564 (1965).
[6] D. B. McWhan and T. M. Rice, Phys. Rev. Lett. **19**, 846 (1967).
[7] R. Movshovich, A. Lacerda, P. C. Canfield, J. D. Thompson, and Z. Fisk (to be published).
[8] P. A. Fedders and P. C. Martin, Phys. Rev. **143**, 245 (1966).
[9] W. B. Muir and J. O. Ström-Olsen, Phys. Rev. B **4**, 988 (1971).
[10] Z. Barak, E. Fawcett, D. Feder, G. Lorincz, and M. B. Walker, J. Phys. F **11**, 915 (1981).
[11] K. Kadowaki and S. B. Woods, Solid State Commun. **58**, 307 (1986).
[12] J. D. Thompson, H. A. Borges, Z. Fisk, S. Horn, R. D. Parks, and G. L. Wells, in *Theoretical and Experimental Aspects of the Valence Fluctuations and Heavy Fermions*, edited by L. C. Gupta and S. K. Malik (Plenum, New York, 1987), p. 151.
[13] T. Graf, J. M. Lawrence, and J. D. Thompson (private communication).
[14] P. C. Canfield, J. D. Thompson, W. P. Beyerman, A. Lacerda, M. F. Hundley, E. Peterson, and Z. Fisk, J. Appl. Phys. **70**, 5800 (1991).