Available online at www.sciencedirect.com
ScienceDirect
Journal of Magnetism and Magnetic Materials 310 (2007) 712–714
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Upper critical field (H_{c2}) scaling near a quantum critical point in the heavy-fermion compound $CeRhIn_5$

Tuson Park*, J.L. Sarrao, J.D. Thompson

Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Available online 3 November 2006

Abstract

We have measured the specific heat of $CeRhIn_5$ at extreme conditions of low temperatures (T), high pressures (P), and high magnetic fields ($H \perp c$-axis). Discrete forms of the upper critical field H_{c2} scaling are observed below and above the critical pressure $P_{c1}(=1.75)$ GPa. For $P<1.75$ GPa, where unconventional superconductivity and magnetism coexist, H_{c2} linearly increases with decreasing temperature. For $P>2.35$ GPa, where only unconventional superconductivity is observed up to the normal state, H_{c2} shows normal behavior, saturating at low temperatures. In the intermediate pressure, $1.75\,\text{GPa}<P<2.35\,\text{GPa}$, where applied magnetic field induces magnetism in the mixed superconducting state, H_{c2} shows a crossover from normal temperature dependence to the unusual linear T dependence. These observations delineate the interplay between superconductivity and antiferromagnetic fluctuations that exist in the vicinity of the quantum critical point.

PACS: 74; 75; 65

Keywords: CeRhIn5; Phase diagram; Quantum criticality; Upper critical field; Pressure-induced superconductivity

The heavy-fermion compound $CeRhIn_5$ is a model unconventional superconductor that reveals superconductivity when long-range antiferromagnetic (AFM) order is suppressed under pressure. Recently, a specific heat study revealed magnetism in the mixed superconducting state of $CeRhIn_5$, suggesting a common relationship among hidden magnetism, quantum criticality, and unconventional superconductivity in cuprate and heavy-electron systems [1]. The details of how magnetic fluctuations interplay with superconductivity, however, have been rarely studied. Here, we report disparate forms of the upper critical field scaling below and above a critical pressure P_{c1}, where the AFM order is suppressed to zero temperature in the pressure-tuned heavy-fermion superconductor $CeRhIn_5$, reflecting the interplay between superconductivity and antiferromagnetic fluctuations near the critical point P_{c1}.

The temperature–pressure ($T-P$) phase diagram of $CeRhIn_5$ is shown in Fig. 1, which is typical of unconventional superconductors, including heavy fermion compounds, organics, and high-T_c cuprates: in high-T_c cuprates, the control parameter (x-axis) is chemical substitution. With increasing pressure, the magnetic transition temperature (T_N) due to the incommensurate antiferromagnetic state with $\mathbf{Q}=(0.5, 0.5, 0.297)$ goes through a maximum at 0.55 GPa and then decreases. With further increasing pressure, superconductivity is induced within the antiferromagnetic state and coexists microscopically [2]. At P_{c1}, where T_N becomes equal to T_c, the long-range AFM order sharply disappears. This first-order or weakly first-order transition at P_{c1} is puzzling in that it does not ensure its clear connection to strange metallic behavior or non-Fermi liquid behavior observed in the normal state above the superconducting dome. Recently, it was found that the magnetism is hidden by unconventional superconductivity and can be revealed by applying a magnetic field, resolving the dichotomy because it now provides a smooth evolution of T_N into the superconducting dome, terminating at P_{c2}, an antiferromagntic quantum critical point [1]. Our phase diagram determined by specific heat measurements reveals several crucial aspects that have not been appreciated previously. First, the superconducting

*Corresponding author. Tel.: +1 505 667 9546; fax: +1 505 665 7652.
E-mail address: tuson@lanl.gov (T. Park).

0304-8853/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2006.10.276

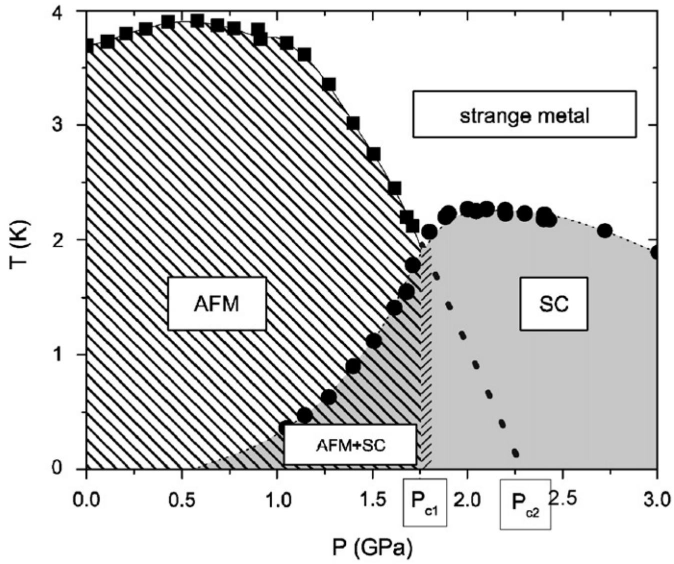

Fig. 1. Temperature–pressure ($T-P$) phase diagram of $CeRhIn_5$ determined from specific heat measurements at $H = 0$ kOe. AFM and SC stand for antiferromagnetic and superconducting states, respectively. P_{c1} and P_{c2} are explained in the text.

phase in the AFM state now extends well below the critical pressure P_{c1}, delineating that the SC phase is a bulk property, not a filamentary phase as has been speculated before [3]. The experimentally determined T_c is 0.36 K at 1.05 GPa and can be smoothly extended to 0 K at 0.55 GPa, where T_N is of maximal value. Second, the superconducting dome is asymmetric: T_c changes slowly with pressure for $P > P_{c1}$, while T_c is dramatically suppressed with decreasing pressure for $P < P_{c1}$, indicating an interplay between magnetism and superconductivity. The sharp suppression of T_c in the coexisting phase has been also reported in $CeCu_2Si_2$, another family of heavy fermion superconductors [4].

The interplay between magnetism and unconventional superconductivity is also manifested in the upper critical field of $CeRhIn_5$. Fig. 2a representatively shows H_{c2} as a function of reduced temperature $t = T/T_{c0}$, where T_{c0} is the SC transition temperature at zero field and is 1.41, 2.27, and 2.18 K for 1.62, 2.1, and 2.45 GPa, respectively. For $P > P_{c2}$, which is represented by $P = 2.45$ GPa (circles), the temperature dependence of H_{c2} is similar to that of $CeCoIn_5$, where $H_{c2}(0)$ is strongly limited due to Pauli limiting effects. The Maki parameter $\alpha(= H^0_{c2}/H_P)$ of $CeRhIn_5$, which is a measure of the relative strength of the orbital limiting field H^0_{c2} and the Pauli field H_P, is 6.3 ± 0.8 in the weak coupling limit. Considering that $CeRhIn_5$ is in the very clean limit with mean free path of order microns, this sufficiently large α (for $\alpha > 1.8$) suggests this pressure-induced superconductor as an ideal candidate to explore the inhomogeneous superconducting phase or Fulde and Ferrell and Larkin and Ovchinnikov (FFLO) state [5]. At $P = 1.62$ GPa (triangles), where superconductivity coexists with the incommensurate AFM state, H_{c2} becomes surprisingly linear down to lowest temperature ($t = 0.2$).

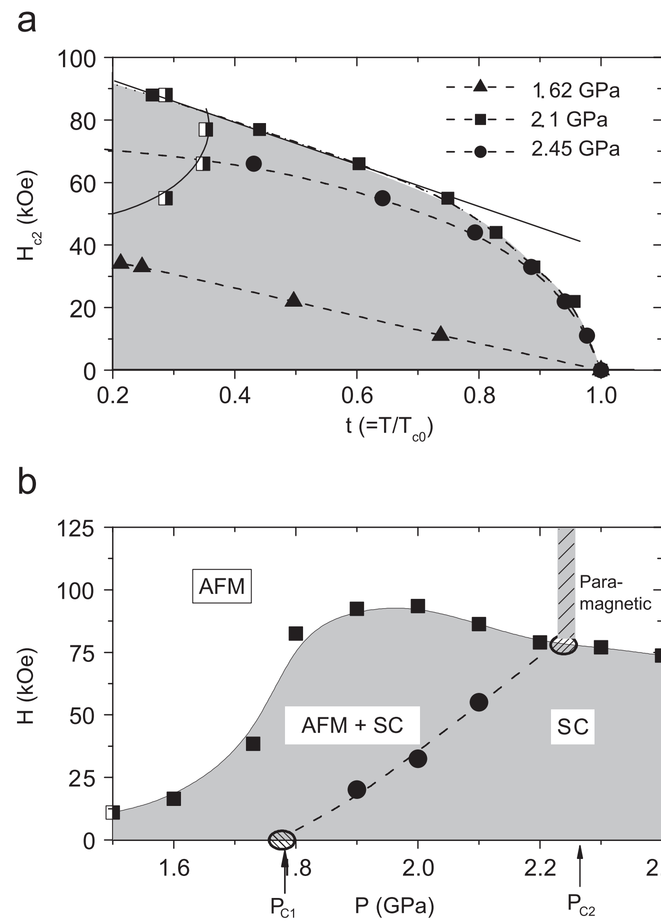

Fig. 2. (a) Upper critical field (H_{c2}) versus reduced temperature T/T_{c0} at 1.62 (triangles), 2.1 (squares), and 2.45 GPa (circles), where T_{c0} is SC transition temperature at zero field and is 1.41, 2.27, and 2.18 K, respectively. The half-filled squares describe field-induced magnetism at 2.1 GPa. Magnetic field is applied parallel to ab-plane. Lines are guides to eyes. (b) $H-P$ phase diagram at 650 mK, which represents a $T = 0$ K quantum phase transition [1]. Squares and circles describe the upper critical field H_{c2} and field-induced transition H_M from a pure SC state to the coexisting phase of SC and AFM states, respectively. The two critical pressures P_{c1} and P_{c2} are explained in the text.

Recently, a linear-T dependence of H_{c2} is also reported in the pyrochlore superconductor KOs_2O_6, which is argued to be due to band effects [6]. In $CeRhIn_5$, the pure band effects, however, may be less relevant than in KOs_2O_6. Above the critical pressure P_{c1} (squares in Fig. 2a), where only superconductivity is observed for $H = 0$, the H_{c2} shows normal behavior near T_c, similar to high-pressure data for $P > P_{c2}$. At this pressure, applied magnetic field induces long-range magnetic order in the superconducting state (see Fig. 2b) and the H_{c2} temperature dependence changes from normal to linear behavior near a field value at which field-induced AFM appears, suggesting that the AFM order is crucial to the anomalous T-linear H_{c2}.

We have reported a comprehensive $T-P$ phase diagram of the heavy-fermion compound $CeRhIn_5$, which shows bulk superconductivity in the AFM state well below P_{c1}. The strong asymmetry of the superconducting dome below and above P_{c1} and the disparate forms of upper critical field scaling strongly suggest the interplay between antiferromagnetic fluctuations and unconventional superconductivity. To finish this brief report, it seems fitting to note a theoretical work that has raised the possibility of exotic superconductivity, such as odd-frequency p-wave spin singlet state in the vicinity of a quantum critical point [7].

References

[1] T. Park, et al., Nature 440 (2006) 65.
[2] T. Mito, et al., Phys. Rev. Lett. 90 (2003) 077004.
[3] G. Knebel, et al., J. Phys.: Condens. Matter 16 (2004) 8905.
[4] P. Gegenwart, et al., Phys. Rev. Lett. 81 (1998) 1501.
[5] L.W. Gruenberg, et al., Phys. Rev. Lett. 22 (1966) 996.
[6] Shibauchi, et al., cond-mat/0603309
[7] Y. Fuseya, et al., J. Phys. Soc. Japan 72, 2914.