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Authors
Tokiwa, Y
Ronning, F
Thompson, JD
et al.

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Effects of Cd-doping on high-field low-temperature superconducting state in $CeCoIn_5$

Y. Tokiwa[a,*], F. Ronning[a], J.D. Thompson[a], R. Movshovich[a], L.D. Pham[b], Z. Fisk[c]

[a]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[b]University of California, Davis, CA 95616, USA
[c]University of California, Irvine, CA 92697-4573, USA

Abstract

We report specific heat of $CeCo(In_{0.975}Cd_{0.025})_5$ in magnetic field along basal plane. The superconducting transition is not sharp first order-like in high fields and the specific heat at field 12 T displays a sharp peak anomaly at 0.14 K inside the superconducting state. The anomaly is larger and sharper than that for the proposed Fulde–Ferell–Larkin–Ovchinnikov state in pure $CeCoIn_5$.

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Keywords: Phase transition; FFLO state; Superconductivity

1. Introduction

The discovery of heavy-fermion superconductivity in $CeCoIn_5$ [1] has lead to numerous investigations of this compound. $CeCoIn_5$ has the highest superconducting (SC) transition temperature $T_c = 2.3\,K$ among heavy fermion compounds, and the power-law temperature dependence of the specific heat and thermal conductivity at $T \ll T_c$ indicates a nodal SC gap [2]. Interestingly, in high magnetic fields within the basal plane of this tetragonal compound, specific heat shows an anomaly inside the SC state, forming an additional phase in the low-temperature/high-field corner of the SC state [3,4]. The specific heat and magnetization of $CeCoIn_5$ show that the SC transition becomes first order in a similar range of magnetic field [3,5]. $CeCoIn_5$ satisfies all the theoretical requirements for formation of the anisotropic superconducting FFLO state, such as strong Pauli limiting indicated by a large Maki parameter, and the sample is clearly in the clean limit, with a long electron mean free on the order of few microns within the superconducting state at low temperature. Furthermore, the quasi-2D nature of Fermi surface in $CeCoIn_5$ likely provides nesting, which stabilizes the FFLO state. Because of the above mentioned favorable conditions, it was suggested that the additional low-temperature/high-field SC phase might indeed be the long sought after FFLO state [3,4]. The transition to the proposed FFLO state has also been studied by, among others, magnetization, ultrasound velocity, and thermal conductivity [6–8]. However, an NMR study as found evidence of magnetic order, with the field modulation on the scale of a crystalline unit cell, suggesting that the low-temperature/high-field state is not a simple FFLO state, but at least a combination of FFLO and local antiferromagnetic order [9]. This field-induced magnetic order may take place within the vortex cores. There are several indications of a near lying magnetic ground state in $CeCoIn_5$. $C/T(T)$ diverges logarithmically at H_{c2}, and the quadratic coefficient $A(H)$ in resistivity also diverges as field is decreased towards H_{c2}. These results indicate a field-induced quantum criticality and the existence of a magnetic instability close to H_{c2} [10,11]. Furthermore, the phase boundary of the field-induced antiferromagnetic (AFM) state in H–T phase diagram of superconducting $CeRhIn_5$ under pressure is very similar to that of the FFLO phase in $CeCoIn_5$ [12]. There is, however, an important

*Corresponding author. Tel.: +1 505 412 3995.
E-mail address: ytokiwa@lanl.gov (Y. Tokiwa).

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qualitative difference between the two systems: in $CeRhIn_5$ the field-induced transition persists into the normal state, above H_{c2}, whereas in $CeCoIn_5$ the field-induced phase only exist within the superconducting phase. Nevertheless, it is still possible that the magnetism in vortex cores coexists with the FFLO state. The intriguing outstanding question before us is why the local magnetic order in the proposed FFLO state of $CeCoIn_5$ does not propagate into the normal state?

Recently a new effective tool for investigation of the 115 compounds was discovered. Pham et al. have shown that Cd-doping on In sites appears to act like negative pressure and is a very effective way to change the ground state of $CeCoIn_5$ [13]. Slight Cd-doping of nominal 7.5% induces antiferromagnetism and further Cd-doping suppresses superconductivity and monotonically enhances the AFM transition temperature T_N. Application of pressure reversibly suppresses AFM state and leads back to a superconducting ground state. The temperature/Cd-doping phase diagram of $CeCoIn_5$ in fact looks like a mirror image of the temperature/pressure phase diagram of $CeRhIn_5$. Therefore, to push the analogy even further, a small amount of Cd-doping may stabilize antiferromagnetism around H_{c2}. It has been shown that hydrostatic pressure enhances the transition temperature of the FFLO state [14]. If the effect of Cd-doping is indeed equivalent to negative pressure, we may then expect the suppression of the FFLO state with Cd-doping.

In order to investigate the effect of small Cd-doping on the high-field and low-temperature SC state of $CeCoIn_5$, we have performed specific heat measurements on a high quality single crystal of $CeCo(In_{0.975}Cd_{0.025})_5$ at low temperatures and high magnetic fields, utilizing a quasi-adiabatic heat-pulse technique.

2. Results

Fig. 1 compares electronic specific heat divided by temperature $C_{el}(T)/T$ of pure and 2.5% Cd-doped samples at 11 and 12 T, respectively. The contribution from nuclear Schottkey anomaly was subtracted. Strikingly, C_{el}/T of $CeCo(In_{0.975}Cd_{0.025})_5$ shows only a second order SC anomaly at 0.6 K, while that of $CeCoIn_5$ displays a very sharp first order-like anomaly at 0.5 K. The critical temperature T_0, below which the SC transition in $CeCoIn_5$ becomes first order, was reported to be 1 K [3].

Even though in the doped compound $T_c = 2.1$ K at zero field is comparable to that of $CeCoIn_5$ and $T_c = 0.6$ K is well below 1 K, no sharpening of the SC transition is observed. Since $CeCo(In_{0.975}Cd_{0.025})_5$ has a larger H_{c2}, T_c at 12 T is still higher than that of pure compound at 11 T. Most interestingly, there is an additional anomaly at 0.14 K inside the SC state. This anomaly is qualitatively different from that of the FFLO transition in the pure $CeCoIn_5$. The peak height is substantially higher than the step associated with the FFLO transition and the anomaly is symmetric, while that of the FFLO transition is asymmetric, typical for a second order transition. These differences may indicate diverse origins of the two transitions, and may be related to the disappearance of the first order SC transition. It is possible that once the Cd-doped system loses one of the requirements for FFLO state, which is a first order SC transition in this case, the FFLO state can not form and, instead, AFM order appears. To clarify the nature of the transition found in $CeCo(In_{0.975}Cd_{0.025})_5$, further investigations on compounds with different Cd concentrations are in progress.

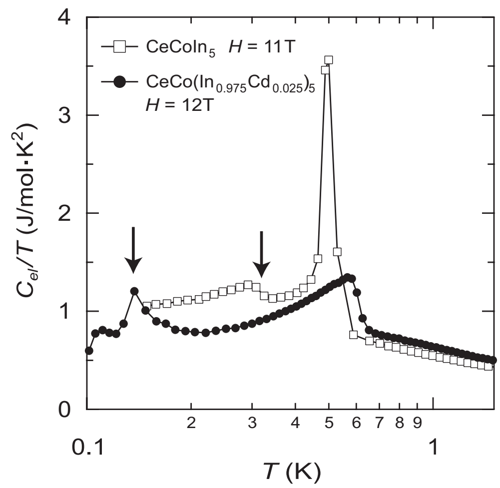

Fig. 1. Electronic specific heat divided by temperature C_{el}/T of $CeCoIn_5$ (open squares) [3] and $CeCo(In_{0.975}Cd_{0.025})_5$ (solid circles) at magnetic field 11 T and 12 T along [1 0 0], respectively. Arrows indicate phase transitions inside superconducting state.

3. Summary

We have performed specific heat measurement of $CeCo(In_{0.975}Cd_{0.025})_5$ to investigate its high-field low-temperature SC state. We found no sharpening of SC transition in high fields in the 2.5% Cd-doped compound, showing that Cd-doping of only 2.5% kills the first order nature of SC transition. Most importantly, specific heat shows an additional transition in the SC state at 0.14 K.

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