Coexistence of antiferromagnetism and superconductivity in $CeCo(In_{0.9}Cd_{0.1})_5$: A spin lattice relaxation study

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Abstract

We present an In(1) NQR study on the heavy-fermion (HF) compound $CeCo(In_{1-x}Cd_x)_5$ ($x = 0.10$). Bulk measurements indicate that Cd doping acts as an electronic tuning agent in $CeCoIn_5$, and that superconductivity (SC) and antiferromagnetism (AFM) may coexist at ambient pressure for $0.05 < x < 0.15$. For $x = 0.10$, the nuclear spin lattice relaxation rate shows a broad peak at the Néel temperature $T_N = 2.8$ K, with a subsequent onset of SC at $T_c \simeq 1.2$ K. Our results provide strong evidence for microscopic coexistence of these two ground states. The nuclear magnetization recovery curves in both the ordered and mixed states reveal a single T_1-component, which suggests a homogeneous nature of the Ce-4f^l electronic state.

The magnetism and unconventional superconductivity (SC) in heavy-fermion (HF) materials undoubtedly are intimately connected [1–4]. Understanding the interplay between these two ground states is of fundamental interest in condensed-matter physics. Special attention has been focused on the family CeMIn$_5$ (M = transition metal) which displays a variety of phenomena such as pressure-induced SC [5], non-Fermi liquid behavior [6,7], and coexistence of antiferromagnetism (AFM) and SC when the system is close to a quantum critical point (QCP) [8,9]. The recent discovery of a new Ce-based compound $CeCo(In_{1-x}Cd_x)_5$ has opened a way to systematically investigate the evolution from the SC to AFM state as a function of chemical substitution [10]. L. Pham and coworkers have shown that $CeCoIn_5$ ($T_c = 2.3$ K) can be Cd (hole) doped and SC gives way continuously to an AFM ground state with a range of coexistence for a few

percent doping (see inset of Fig. 1). Further, the ground state can be reversibly tuned with applied hydrostatic pressure [10]. However, whether the coexistence of these two phases is homogeneous or they are spatially segregated has remained unresolved.

Since neutron scattering experiments are difficult in these materials due to the absorption of neutrons by In, nuclear quadrupole resonance (NQR) is often the primary source of microscopic information about the magnetic structure and the low-energy spin dynamics. Indeed, analysis of In(2) spectra in the AFM state of $CeCo(In_{1-x}Cd_x)_5$ [11] revealed an internal field $H_{int} \simeq 2.3$ kOe, similar to that observed in CeRhIn$_5$ (2.7 kOe) and also in the field-induced magnetic phase of pure $CeCoIn_5$ [12,13]. This result suggests an ordered moment $\sim 0.7\mu_B$ in the $CeCo(In_{1-x}Cd_x)_5$ system which persists down below $T_c \simeq 1.2$ K for $x = 0.10$ [11].

In this paper, we report In(1) NQR data focused on a powder sample of $CeCo(In_{1-x}Cd_x)_5$ with nominal $x = 0.10$. Single crystals were gently crushed into a powder to allow maximal rf penetration. Measurements below

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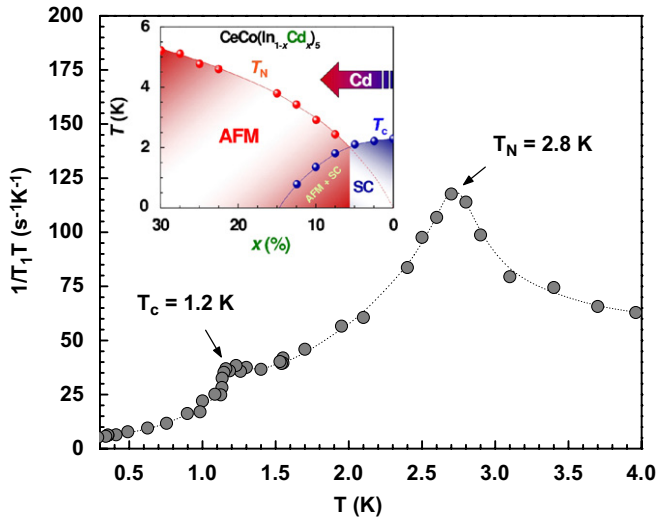E-mail address: rurbano@lanl.gov (R.R. Urbano).

Fig. 1. T dependence of $1/T_1 T$ for $CeCo(In_{0.9}Cd_{0.1})_5$. T_N and T_c are indicated by arrows. Inset: T_N (red) and T_c (blue) vs. x (the nominal Cd doping) in $CeCo(In_{1-x}Cd_x)_5$ [10].

Fig. 2. Normalized nuclear magnetization curves of the In(1) at different T's around $T_c \simeq 1.2\,K$ for $CeCo(In_{0.9}Cd_{0.1})_5$. The dotted lines are simulations using Eq. (3) for different α's and β's (see text). Inset: time dependence of the decay curves as a function of T.

1.4 K were performed by using a ^{3}He/^{4}He dilution refrigerator. $1/T_1$ was measured by the *inversion-recovery* method $(\pi - t_{wait} - \pi/2 - \tau - \pi - \tau - \text{echo signal})$ at the peak of the In(1) $3\nu_Q$ transition $(\pm \frac{5}{2} \leftrightarrow \pm \frac{7}{2}; I = \frac{9}{2})$.

Fig. 1 shows the T dependence of $1/T_1 T$. Two clear features are discernable. We associate the broad peak at 2.8 K with the Néel ordering temperature T_N at which $1/T_1$ increases due to critical slowing down [11]. A second anomaly shows up at 1.2 K, below which $1/T_1 T$ is further suppressed. We interpret this feature as the opening of a SC gap at $T_c \simeq 1.2\,K$. These temperatures correspond well with those obtained from bulk specific heat measurements [10]. The clear decrease in $1/T_1 T$ below T_c at the In(1) site, together with the measured $H_{int} \simeq 2.3\,kOe$ in the SC state at the In(2) site [11], provides convincing evidence for the coexistence of SC and AFM for $x = 0.10$.

Further evidence for homogeneous coexistence is found in the decay curves of the nuclear magnetization. Fig. 2 shows the decay curves in the ordered state $(T < T_N)$ for temperatures above and below T_c. The data are well fit by a single component of T_1 to the theoretical curve for the In(1) $3\nu_Q$ transition:

$$M(t) = M_0[1 - f \phi(t/T_1)], \qquad (1)$$

where M_0 is the equilibrium magnetization, f is an experimental parameter of the inversion fraction, and for $I = \frac{9}{2}$ at the $3\nu_Q$ transition the decay function is given by $\phi(t' \dot{=} t/T_1)$ [14]:

$$\phi(t') = \frac{729e^{-36t'}}{2860} + \frac{147e^{-21t'}}{220} + \frac{5e^{-10t'}}{572} + \frac{3e^{-3t'}}{44}. \qquad (2)$$

As seen in Fig. 2, the data (normalized by T_1 for different T's) are well fit by a single component of T_1 (solid lines). On the other hand, if the ground state were characterized by an inhomogeneous mixture of both SC
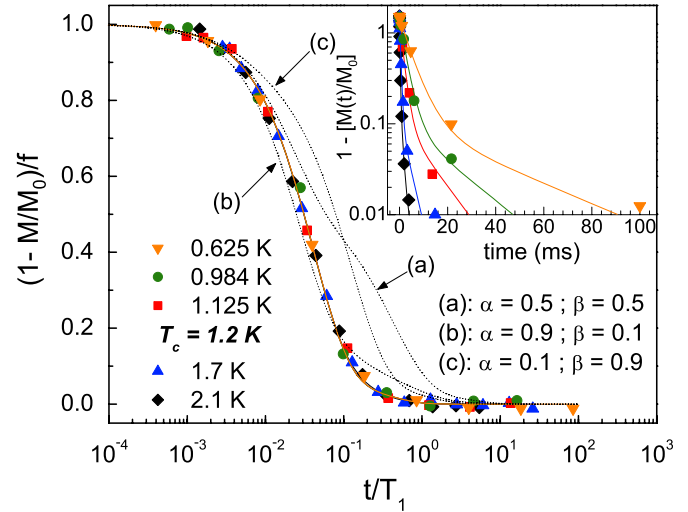
and AFM regions spatially segregated, then one would expect a decay curve composed of two T_1-components with different values [15]. The dotted lines in Fig. 2 represent simulated curves considering two T_1-components using

$$\phi(t') \dot{=} \phi\left(\frac{t}{T_1}\right) = \alpha\phi\left(\frac{t}{T_1^{short}}\right) + \beta\phi\left(\frac{t}{T_1^{long}}\right) \qquad (3)$$

for different combinations of α and β. In this case, the time axis was scaled using the weighted averaged $1/T_1^{avg} = \alpha(1/T_1^{short}) + \beta(1/T_1^{long})$. Clearly, this scenario does not fit our data. If we use Eq. (3) to fit the data, the best result gives $\alpha = 0.95(5)$ and $\beta = 0.05(5)$, despite a poor quality of fit. This result is close to the curve (b) in Fig. 2. Evidently, the fit is poor for $t/T_1 \gtrsim 0.5$.

Therefore, we conclude that the recovery curves reveal a single T_1-component characteristic of a homogeneous electronic environment, and that AFM and unconventional SC coexist microscopically in $CeCo(In_{1-x}Cd_x)_5$ system for $0.05 < x < 0.15$.

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