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

R.R. Urbano$^a$, B.-L. Young$^b$, N.J. Curro$^a$, J.D. Thompson$^a$, L.D. Pham$^c$, Z. Fisk$^d$

$^a$Los Alamos National Laboratory, Los Alamos, NM 87545, USA
$^b$Department of Electrophysics, National Chiao Tung University, Engineering Building VI, Hsinchu 300, Taiwan
$^c$University of California, Davis, CA 95616, USA
$^d$University of California, Irvine, CA 92697, USA

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 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...
1.4 K were performed by using a 3He/4He dilution refrigerator. 1/T1 was measured by the inversion-recovery method \((\pi - t_{\text{wait}} - \pi/2 - \tau - \pi - \tau - \text{echo signal})\) at the peak of the In(1) \(3v_Q\) transition \((\pm 1\leftrightarrow \pm 5, I = 9/2)\).

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 \(T_c \approx 1.2\) K. These temperatures correspond well with those obtained from bulk specific heat measurements \([10]\). The clear decrease in \(1/T_1 T\) below \(T_N\) at the In(1) site, together with the measured \(H_{\text{int}} \approx 2.3\) 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) \(3v_Q\) transition:

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

where \(M_0\) is the equilibrium magnetization, \(f\) is an experimental parameter of the inversion fraction, and for \(I = 9/2\) at the \(3v_Q\) transition the decay function is given by

\[
\phi(t) = \frac{729e^{-36r}}{2860} + \frac{147e^{-21r}}{220} + \frac{5e^{-10r}}{572} + \frac{3e^{-3r}}{44}. \tag{2}
\]

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

\[
\phi(t') = \phi\left(\frac{t}{T_1}\right) = z\phi\left(\frac{t}{T_{1\text{short}}}\right) + \beta\phi\left(\frac{t}{T_{1\text{long}}}\right) \tag{3}
\]

for different combinations of \(z\) and \(\beta\). In this case, the time axis was scaled using the weighted averaged \(1/T_1^{\text{avg}} = \alpha(1/T_1^{\text{short}}) + \beta(1/T_1^{\text{long}})\). Clearly, this scenario does not fit our data. If we use Eq. (3) to fit the data, the best result gives \(z \approx 0.95(5)\) 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(In1−xCdx)5 system for 0.05 < \(x\) < 0.15.

We thank T. Park, R. Movshovich, and F. Ronning for enlightening discussions. L.D. Pham and Z. Fisk acknowledge support from NSF-DMR-0533560 and B-L. Young thanks support from the MOE ATU Program. Work at LANL was performed under the auspices of the US DOE.

References