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Authors
Ohishi, K
Heffner, RH
Spehling, J
et al.

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Magnetism and superconductivity in heavy fermion superconductor $CeCo(In_{0.97}Cd_{0.03})_5$

K. Ohishi [a,*], R.H. Heffner [a,b], J. Spehling [c], G.J. MacDougall [d], T.U. Ito [a,e], W. Higemoto [a], A. Amato [f], D. Andreica [f,g], G. Nieuwenhuys [f], H.H. Klauss [c], G.M. Luke [d], J.D. Thompson [b], A.D. Bianchi [h], Z. Fisk [h]

[a] Advanced Science Research Center, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan
[b] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[c] Institute for Physics of Solids, TU Dresden, Dresden, Germany
[d] Department of Physics and Astronomy, McMaster University, Ontario, Canada L8S-4M1
[e] Department of Physics, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan
[f] Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institut, Villigen, Switzerland
[g] Faculty of Physics, Babes-Bolyai University, 400084 Cluj-Napoca, Romania
[h] University of California Irvine, Irvine, CA 92697, USA

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ABSTRACT

Zero field (ZF) and transverse field (TF) muon spin relaxation and rotation (μSR) experiments have been carried out in the Cd-doped heavy fermion superconductor $CeCoIn_5$ to investigate its superconducting state. The ZF-μSR results in $CeCo(In_{0.97}Cd_{0.03})_5$ revealed that no spontaneous magnetic field was induced below its superconducting transition temperature (T_c), indicating no evidence for time reversal symmetry breaking. The muon Knight shifts obtained from TF-μSR measurements decrease significantly below T_c, consistent with a spin-singlet state as in the parent compound $CeCoIn_5$, which is a d-wave superconductor.

1. Introduction

The heavy fermion superconductor $CeCoIn_5$ has the highest critical temperature ($T_c = 2.3\,K$) of the known Ce-based materials [1]. Recently, it has been found that Cd substitution on the In site drives this system towards antiferromagnetism (AFM) [2]. Remarkably, applying pressure can reverse this effect. Recent nuclear magnetic resonance (NMR) and nuclear quadrupolar resonance studies [3] suggest that the magnetism develops locally in the vicinity of the Cd atoms. Neutron scattering experiments [4] on a sample with a nominal [2] Cd concentration of 10% showed the coexistence of superconductivity and AFM. The AFM order develops with the commensurate wave vector $Q_{AF} = (\frac{1}{2}, \frac{1}{2}, \frac{1}{2})$, and the magnetic intensity does not increase below T_c. We performed zero-field (ZF) and transverse-field (TF) muon spin relaxation and rotation (μSR) measurements on single crystalline samples of $CeCo(In_{1-x}Cd_x)_5$ ($x = 0.03, 0.10$ and 0.15). In this paper, we present preliminary results for the $x = 0.03$ sample.

2. Experimental

Single crystals of $CeCo(In_{0.97}Cd_{0.03})_5$ were grown as flat plates with the *c*-axis normal to the surface using a standard In-flux technique [2]. At $x = 0.03$, the superconducting transition has been suppressed slightly from 2.3 K to $T_c \simeq 2.2\,K$. ZF-μSR was carried out at the M15 beamline at TRIUMF, Vancouver, Canada, and TF-μSR was performed at the LTF on the πM3 beamline at the Paul Scherrer Institute (PSI), Villigen, Switzerland, with *c*-axis parallel to the applied field. The crystals were mounted on a thin GaAs backing and Ag plate at TRIUMF and at PSI, respectively.

3. Results and discussions

Fig. 1 shows the time evolution of the muon spin polarization in $CeCo(In_{0.97}Cd_{0.03})_5$ at 3.5 and 0.1 K under zero applied field. The muon spin depolarization observed at 3.5 K is due to static, random local fields which originate from the magnetic dipole moments of Co, In and Cd nuclei and the fluctuation of 4f spins. These spectra can be fitted by

$$A_0P(t) = A_1 \exp(-\lambda t)G_{KT}(\Delta, t) + A_2, \quad (1)$$

$$G_{KT}(\Delta, t) = \frac{1}{3} + \frac{2}{3}(1 - \Delta^2 t^2)\exp(-\frac{1}{2}\Delta^2 t^2), \quad (2)$$

* Corresponding author. Present address: Advanced Meson Science Laboratory, RIKEN (The Institute of Physical and Chemical Research), Wako 351-0198, Japan. Tel.: +81 48 467 9355; fax: +81 48 462 4648.
E-mail address: kazuki.ohishi@riken.jp (K. Ohishi).

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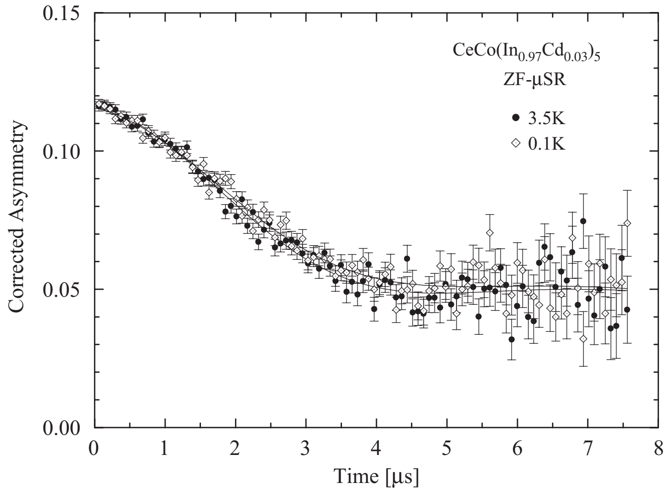

Fig. 1. ZF-μSR time spectra in $CeCo(In_{0.97}Cd_{0.03})_5$ above and below T_c.

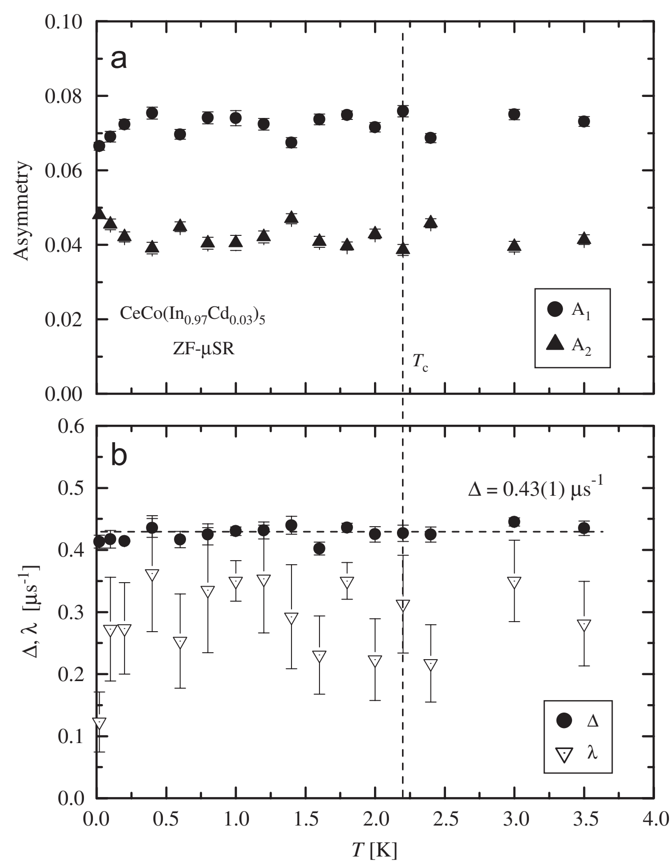

Fig. 2. Temperature dependence of (a) asymmetries and (b) relaxation rates under ZF.

where A_0, A_1 and A_2 are the total positron decay asymmetry, asymmetry from muons stopping in the sample and that from muons which missed the sample, G_{KT} is the Kubo–Toyabe function [5], Δ/γ_μ is the nuclear dipolar field at the muon site with γ_μ being the muon gyromagnetic ratio ($= 2\pi \times 135.54\,\mathrm{MHz/T}$), and λ is the relaxation rate from the 4f spins. The first term on the right-hand side of Eq. (1) corresponds to the signal from the sample, and the second term corresponds to that from muons which stopped outside the sample. Fig. 2 shows the temperature dependence of the fitted parameters. We have observed little change in the time spectra with decreasing temperature down to 20 mK, which is confirmed in Fig. 2, where the partial asymmetries, Δ and λ of those spectra are independent of temperature from 3.5 K to 20 mK. This result clearly demonstrates the absence of magnetism in $CeCo(In_{0.97}Cd_{0.03})_5$, consistent with the parent compound. The averaged value of $\Delta = 0.43(1)\,\mu s^{-1}$ is also consistent with that in $CeCoIn_5$ [6].

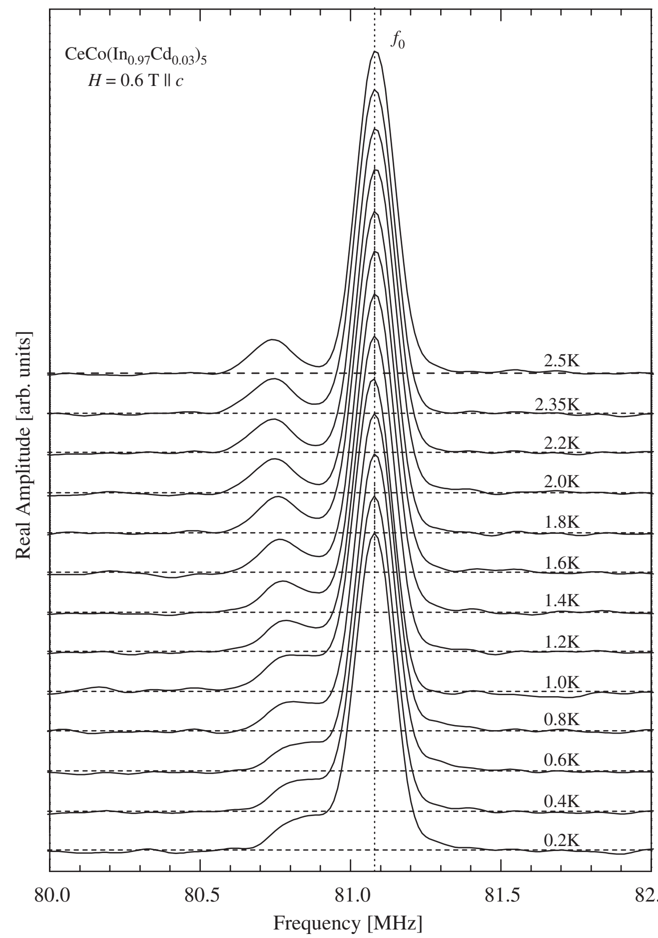

Fig. 3. The FFT spectra at various temperatures with $H = 0.6\,\mathrm{T}$.

Fig. 3 shows the fast Fourier transform (FFT) of the μSR spectra obtained in $CeCo(In_{0.97}Cd_{0.03})_5$ with $H = 0.6\,\mathrm{T}$ at various temperatures. Previous muon Knight shift results in $CeCoIn_5$ [7] and in the isostructural material $CeRhIn_5$ [8], show two different shifts, one negative and one positive. As shown in Fig. 3, two distinct peaks are clearly observed. A large background peak from the silver cold finger is seen at $f_0 = 81.08\,\mathrm{MHz}$, and, therefore, the positive shift from the sample is difficult to resolve due to its overlap with this background peak. Thus, we focus on the negative shift in order to discuss the temperature dependence of the Knight shift. We analyzed the μSR time spectra with a sum of two components with Gaussian damping,

$$A_0 P(t) = \sum_{i=1,2} A_i \exp(-\sigma_i^2 t^2) \cos(2\pi f_i t + \phi), \tag{3}$$

where the components $i = 1$ and 2 are from the sample and silver plate, respectively. The muon Knight shift K is then defined as follows:

$$K = \frac{f_1 - f_2}{f_2} = K_\mu + K_{\mathrm{dem}} + K_{\mathrm{dia}}. \tag{4}$$

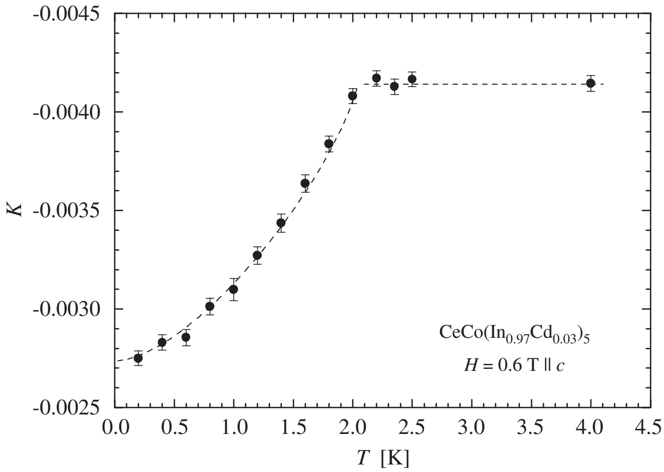

Fig. 4. Temperature dependence of muon Knight shift K. The dashed line shows the guide for the eyes.

Here K_μ is proportional to the local spin susceptibility χ_{spin}, K_{dem} is the demagnetization and Lorentz field correction and K_{dia} is the diamagnetic correction from the supercurrents below T_c. Note that $f_2 \sim f_0 = \gamma_\mu H/2\pi$, since $K = 94$ ppm in Ag [9]. We note that the large $i = 2$ peak (mostly from Ag) may be contaminated to some extent by the positive shift component from the sample. In this case, a slight temperature dependence may appear in f_2, especially below T_c. Therefore, we fixed the value of f_2 at an average value obtained for $T > T_c$ to obtain the shift K of the $i = 1$ component. The temperature dependence of K is shown in Fig. 4. No corrections for K_{dem} or K_{dia} have been made to these data. Note, however, that diamagnetic corrections will further decrease the magnitude of $K_\mu \propto \chi_{spin}$ below T_c. The decreased magnitude of K below T_c therefore suggests that the local spin susceptibility decreases in the superconducting state, qualitatively consistent with previous NMR [10,11] results in the d-wave [12] superconductor $CeCoIn_5$. Thus, these provisional TF-μSR results in $CeCo(In_{0.97}Cd_{0.03})_5$ are consistent with those of a spin-singlet superconductor.

In conclusion, we have observed temperature-independent ZF-μSR spectra down to 20 mK, setting a limit on the ordered magnetic moment $\mu < 0.005\mu_B$, and ruling out a time-reversal-symmetry-breaking state in the superconducting phase. In addition, a decrease in the magnitude of the muon Knight shift K below T_c in $CeCo(In_{0.97}Cd_{0.03})_5$ suggests spin-singlet pairing. A more detailed analysis of the results and a discussion of the TF linewidths will appear subsequently [13].

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