Unconventional superconductivity in $CeIn_3$: ^{115}In-NQR study under pressure

Shinji Kawasaki [a,1], Yu Kawasaki [a], Takeshi Mito [b], Guo-qing Zheng [a], Yoshio Kitaoka [a], Shingo Araki [c], Rikio Settai [d], Yoshichika Ōnuki [c,d]

[a] *Department of Physical Science, Graduate School of Engineering Science, Osaka University, Machikaneyama-cho, 1-3 Toyonaka, Osaka 560-8531, Japan*

[b] *Faculty of Science, Kobe University, Kobe, Hyogo 657-8501, Japan*

[c] *Advanced Science Research Center, Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan*

[d] *Department of Physics, Graduate School of Science, Osaka University, Machikaneyama-cho, 1-3 Toyonaka, Osaka 560-0043, Japan*

Abstract

We report evidences for bulk nature and unconventional superconductivity in $CeIn_3$ at $P = 2.65$ GPa revealed by the measurements of nuclear-spin-lattice-relaxation time (T_1) and ac-susceptibility (ac-χ). Both the measurements of ac-χ and T_1 have pointed to a superconducting transition at T=95 mK, which is very much lower than an onset temperature $T_{onset} = 0.15$ K at zero resistance. The temperature dependence of $1/T_1$ shows no coherence peak just below T_c, indicative of an unconventional nature for the superconductivity.

Key words: heavy-fermion; $CeIn_3$; NQR; pressure-induced superconductivity

1. Introduction

Recently, Hegger *et al*. discoverd the new heavy-fermion(HF) pressure(P)-induced superconductor $CeRhIn_5$[1]. It is suggested that the difference of crystal and magnetic dimensionality in $CeIn_3$ and $CeRhIn_5$ plays a dominant role in the large difference in T_c under P in both the compounds[1–3]. $CeIn_3$ orders antiferromagnetically ($T_N = 10$ K) at $P = 0$ with an ordering vector $\mathbf{Q} = (1/2,1/2,1/2)$[4]. T_N monotonically decreases with P and superconductivity appears below $T_c \sim 0.2$ K at a critical pressure $P_c = 2.55$ GPa, but the evidence for a bulk superconductivity in $CeIn_3$ has not been established because its superconductivity under P is observed only in the resistivity measurements[5–7]. It is still unclear whether any problem concerning a sample surface or its quality that could prevent the onset of bulk P-induced superconductivity is ruled out or not. Here, we report measurements of $1/T_1$ and ac-susceptibility(ac-χ) at P =2.65 GPa down to T = 50 mK which provide evidence for unconventional and bulk nature of superconductivity in $CeIn_3$.

1 E-mail:shinji@nmr.mp.es.osaka-u.ac.jp

2. Experimental detail

The single crystals of $CeIn_3$ were grown by Czochralski method and moderately crushed into grains in order to make rf pulses penetrate into samples easily. To avoid some crystal distortions, however, the size of the grains is kept with diameters larger than 100 μm. Measurement of $1/T_1$ was made by the conventional saturation-recovery method in the temperature (T) range of 0.05−100 K at P = 2.65 GPa. The ac−χ was measured by using an *in-situ* NQR coil. Hydrostatic pressure was applied by utilizing a NiCrAl-BeCu piston-cylinder cell, filled with Si-based organic liquid as a pressure-transmitting medium.

3. Experimental results

Figure 1. shows the T dependencies of $1/T_1$ at $P = 0$ and 2.65 GPa. At $P = 0$, the antiferromagnetic(AF) order occurs at $T_N = 10$ K evidenced from the rapid decrease of $1/T_1$. It was reported that T_N monotonically decreases with P and eventually is reduced to $T_N = 5$ K at $P = 2.35$ GPa. At this pressure, it is noteworthy that $1/T_1$ starts to decrease below $T^* \sim 15$ K. This is defined as a characteristic temperature below which the system crosses over to the itinerant HF regime[8]. At pressures exceeding $P = 2.35$ GPa, the internal field at the ^{115}In site due to the AF ordering decreases, revealing a same P dependence as T_N does[9,10]. At $P = 2.65$ GPa, it is remarkable, as presented in Fig. 1, that $1/T_1$ shows a significant decrease below $T^* \sim 30$ K, followed by a behavior of $T_1T =$ const. that is characteristic for the Fermi-liquid state to be realized below $T_{FL} = 5$ K. This result proves that the Fermi-liquid description is valid over a wide T range from 0.1 to 5 K. Any trace of AF spin fluctuations at $P = 2.65$ GPa is not appreciable due to an increase of the hybridization of Ce-4f electrons and conduction electrons as discussed in the previous paper[8]. This is in good agreement with the resistivity measurement[7]. The superconducting(SC) transition is evidenced by the $1/T_1$ and ac-χ measurements at $P = 2.65$ GPa. Below $T_c = 95$ mK, $1/T_1$ starts to decrease suddenly, signaling the onset of bulk SC transition as seen in Fig. 1. The absence of the coherence peak in $1/T_1$ just below T_c seems to be rather consistent with an anisotropic SC gap. The T_1 measurement below 50 mK was too hard to determine the nodal structure because of a heat-up problem arising from the exciting rf pulses. The SC transition is also corroborated by the ac$-\chi$ measurement. The T dependence of the ac$-\chi$ at $P = 2.65$ GPa is shown in Fig. 1 inset. The ac$-\chi$ decreases largely below $T_c \sim 95$ mK due to the SC diamagnetism, indicating a clear signature of a SC transition. Note that the T_c probed by the T_1 and ac$-\chi$ measurements is lower than $T_c^\rho = 0.15$ K at zero resistance on the same sample[6]. This suggests that the surface of the sample makes a short cut for the electrical current flow, exhibiting a rather higher T_c value than that for the bulk. This phenomenon is similar to the SC characteristics in $CeIrIn_5$, in which the bulk $T_c \sim 0.4$ K confirmed by the measurements of the specific heat, the susceptibility[3], and the NQR measurements[11] is much lower than $T_c \sim 1$ K determined by the zero resistance. A reason why this inconsistency occurs is still unresolved.

In conclusion, we have provided evidences for the unconventional superconductivity in $CeIn_3$ below $T = 95$ mK at $P = 2.65$ GPa on the basis of the measurements of T_1 and ac-susceptibility. $1/T_1$ reveals no coherence peak just below T_c =95 mK, indicative of unconventional superconductivity.

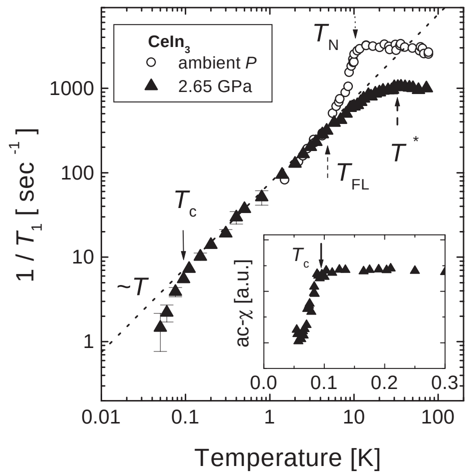

Fig. 1. T dependence of $^{115}(1/T_1T)$ in $CeIn_3$ at $P = 0$ and 2.65 GPa. The dotted line indicates a relation of $^{115}(1/T_1T)$ = const.. The inset shows T-dependence of ac-χ at $P = 2.65$ GPa.

Acknowledgements

This work was supported by the COE Research (10CE2004) in Grant-in-Aid for Scientific Research from the Ministry of Education, Sport, Science and Culture of Japan. One of the author (Yu Kawasaki) has been supported by JSPS Research Fellowships for Young Scientists.

References

[1] H. Hegger, *et al.*, Phys. Rev. Lett. **84**, 4986 (2000).

[2] A. L. Cornelius, *et al.*, Phys. Rev. B **62**, 14 181 (2000).

[3] C. Petrovic, *et al.*, Europhys. Lett. **53**, 354 (2001).

[4] P. Morin, *et al.*, J. Low Temp. Physics **70**, 377 (1988).

[5] N. D. Mathur, *et al.*, Nature **394**, 39 (1998).

[6] T. Muramatsu *et al.*, Ph. D. Thesis, Osaka University (2001), unpublished.

[7] G. Knebel, *et al.*, Phys. Rev. B. **65**, 024425 (2002).

[8] S. Kawasaki, *et al.*, Phys. Rev. B. **65**, 020504(R) (2002).

[9] Y. Kohori, *et al.*, Physica B **281 & 282**, 12 (2000).

[10] C. Thessieu, *et al.*, Physica B. **281-282**, 9-11 (2000).

[11] G. -q. Zheng, *et al.*, Phys. Rev. Lett. **86**, 4664 (2001).