Novel Superconductivity in CeIr(In$_{1-x}$Cd$_x$)$_5$ Studied by In-NQR Measurements

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Abstract. We report the superconducting characters in CeIrIn$_5$ studied by In-NQR measurements under pressure ($P$). In CeCoIn$_5$ and CeRhIn$_5$, the occurrence of superconductivity (SC) is related with the antiferromagnetic spin fluctuations (AFM-SFs) originating from the antiferromagnetic quantum-critical point (AFM-QCP). The high-$T_c$ SC ($T_{c_{\text{max}}} > 2$ K) is realized in both compounds. However, in CeIrIn$_5$ which is apart from the AFM-QCP, SC occurs even without AFM-SFs and the quite small value of $T_{c_{\text{max}}} \sim 1$ K is observed around $P = 3$ GPa. The mechanism of SC in CeIrIn$_5$ may be different from that in CeCoIn$_5$ and CeRhIn$_5$.

1. Introduction

Recently two SC domes have been reported as a function of pressure ($P$) on CeCu$_2$(Si$_{1-x}$Ge$_x$)$_2$ [1]; one dome (SC1) is formed around the antiferromagnetic quantum-critical point, whereas another one (SC2) emerges under the heavy-fermion (HF) state without any signature for AFM-SFs because the system is far from the AFM-QCP. Although a possible origin of SC2 has not been identified, a new type of pairing mechanism is suggested to mediate the Cooper pairs in HF systems besides AFM-SFs. The presence of two SC domes has been also suggested in CeRh$_{1-x}$Ir$_x$In$_5$ [2, 3], as shown in Fig. 1.

The heavy-fermion (HF) compounds CeTIn$_5$ (T = Co, Rh) [4, 5, 6] revealed an intimate relationship between antiferromagnetism and superconductivity. CeCoIn$_5$ is a superconductor with $T_c = 2.3$ K at ambient $P$ and $T_c$ reaches 2.6 K which is the highest $T_c$ in Ce-based HF compounds around 1.5 GPa. The NQR measurements suggested the existence of line-nodes in the gap function [7]. It was suggested from the thermal conductivity measurements that the pairing symmetry most likely belongs to $d_{x^2-y^2}$-wave, implying that the anisotropic antiferromagnetic fluctuation is relevant to the superconductivity [8]. In CeRhIn$_5$, the incommensurate AFM order with $T_N = 3.8$ K appears at ambient $P$, but SC occurs under high $P$. We have shown that the tetracritical point, where the AFM, AFM+SC, SC, and PM phases are in contact, exists at

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Figure 1. Phase diagrams for CeIrIn$_5$ as functions of Ir concentration and $P$ [11]. The triangle data indicate $T_N$. The circle and square [12] data indicate $T_c$.

Figure 2. The $P$–$T$ phase diagram in CeRh$_{0.4}$Ir$_{0.6}$In$_5$. The inset shows the $T$ dependence of $1/T_1$ between 0 and 2.37 GPa.

$p_{\text{tetra}} \sim 1.98$ GPa and $T_c$ reaches the maximum value ($\sim 2.2$ K) at approximately 2.5 GPa from the AFM-QCP, which lies at $P_{\text{QCP}} \sim 2.1$ GPa [9]. In both CeCoIn$_5$ and CeRhIn$_5$, AFM-SFs are observed in the $P$ range where the unconventional SC appears, suggesting the intimate relation between AFM and SC.

On the contrary, our previous NQR study showed that the unconventional superconductivity in CeIrIn$_5$ under $P$ is realized in the HF state without AFM-SFs [10]. $T_c$ reaches the maximum value $\sim 1$ K around 3 GPa. It should be noted that this $T_c$ value is about a half smaller than those (> 2 K) in CeCoIn$_5$ and CeRhIn$_5$, indicating that the SC mechanism in CeIrIn$_5$ is different from that in CeCoIn$_5$ and CeRhIn$_5$, where AFM-SFs may be responsible for the occurrence of the unconventional SC.

2. Experimental Procedure

For obtaining NQR measurements, CeIr(In$_{0.925}$Cd$_{0.075}$)$_5$ grown by the self-flux method was modestly crushed into a coarse powder to allow RF pulses to easily penetrate the sample. Hydrostatic pressure was applied using a NiCrAl-BeCu piston-cylinder cell filled with a Si-based organic liquid as the pressure-transmitting medium. To calibrate the pressure at low temperatures, the shift in the $T_c$ of Sn metal was monitored by using the resistivity measurements. CeRhIn$_5$ consists of alternating layers of CeIn and RhIn$_4$. There are two In sites per unit cell, denoted by In(1) and In(2). In(1) and In(2) are located in the CeIn and RhIn$_4$ layers, respectively. The measurements for the $^{115}$In-NQR ($I = 9/2$) spectrum were mainly performed at the $2\nu_Q$ transition at In(1) in CeIr(In$_{0.925}$Cd$_{0.075}$)$_5$. Here, $\nu_Q$ is defined by the NQR Hamiltonian, $\mathcal{H}_Q = (h\nu_Q/6)[3I_z^2 - I(I + 1) + \eta(I_x^2 - I_y^2)]$, where $\eta$ is the asymmetry parameter of the electric field gradient. $\nu_Q$ is estimated as 6.1 MHz for In(1) at $P = 0$.

3. Results and discussion

As shown in Fig. 1, $T_c$ increases by Rh substitution or $P$ in CeIrIn$_5$. It is likely that there are two mechanisms to increase $T_c$ in CeIrIn$_5$. In order to investigate whether SC1 continuously changes into SC2, we made the NQR measurements under $P$ in CeRh$_{0.4}$Ir$_{0.6}$In$_5$. The inste of Fig. 2 shows the $T$ dependence of $1/T_1$ for various pressures in CeRh$_{0.4}$Ir$_{0.6}$In$_5$. The large enhancement of $1/T_1T$ on cooling down to $T_c = 0.9$ K due to the existence of AFM-SFs are observed. It is expected that SC1 is realized at ambient $P$ in CeRh$_{0.4}$Ir$_{0.6}$In$_5$. $T_c$ slightly increases at $P = 0.47$
GPa, but the anomaly in $1/T_1 T$ at $T_c$ disappears 2.37 GPa, indicating that SC1 is suppressed and SC2 is not induced by $P$ in CeRh$_{0.4}$Ir$_{0.6}$In$_5$. It is remarkable that the change from SC1 to SC2 is not continuous on pressure axis, suggesting that the nature of SC2 is completely different from that of SC1.

We made the NQR measurements in Cd-doped CeIrIn$_5$ to investigate the nature of SC2. Fig. 3 shows the $T$ dependence of $1/T_1 T$ in CeIr(In$_{0.925}$Cd$_{0.075}$)$_5$. The open-circle data corresponds to the results at 0 GPa in CeIrIn$_5$.

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\begin{align*}
\text{Figure 3. } & T \text{ dependence of } 1/T_1 T \text{ in CeIr(In}_{0.925}\text{Cd}_{0.075})_5. \text{ The open-circle data corresponds to the results at 0 GPa in CeIrIn}_5.
\end{align*}
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In conclusion, It is suggested from the present NQR measurements that the mechanism of SC2 is different from that of SC1 in which AFM-SFs may play a vital role in mediating the Cooper pairing. We found that SC2 may be not weak for the impurity scattering since the decrease in $T_c$ is not observed at high $P$ in Cd-doped CeIrIn$_5$, as compared with $T_c$ in pure CeIrIn$_5$. However, currently, the detailed mechanism of SC2 remains unknown.

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References

[1] H. Q. Yuan, F. M. Grosche, M. Deppe, C. Geibel, G. Sparn, F. Steglich, Science 302, 2104 (2003).
[2] P. G. Pagliuso, C. Petrovic, R. Movshovich, D. Hall, M. F. Hundley, J. L. Sarrao, J. D. Thompson, and Z. Fisk, Phys. Rev. B 64, 100503 (2001).
[3] M. Nicklas, V. A. Sidorov, H. A. Borges, P. G. Pagliuso, J. L. Sarrao, and J. D. Thompson, Phys. Rev. B 70, 020505(R) (2004).
[4] C. Petrovic, P. G. Pagliuso, M. F. Hundley, R. Movshovich, J. L. Sarrao, J. D. Thompson, Z. Fisk, and P. Monthoux, J. Phys.: Cond. Mat. 13, L337 (2001).
[5] H. Hegger, C. Petrovic, E. G. Moshopoulou, M. F. Hundley, J. L. Sarrao, Z. Fisk, and J. D. Thompson, Phys. Rev. Lett. 84, 4986 (2000).
[6] T. Muramatsu, T. C. Kobayashi, K. Shimizu, K. Amaya, D. Aoki, Y. Haga, and Y. Onuki, J. Phys. Soc. Jpn. 70, 3362 (2001).
[7] M. Yashima, S. Kawasaki, G.-q. Zheng, Y. Kitaoka, H. Shishido, R. Settai, Y. Haga, and Y. Onuki, J. Phys. Soc. Jpn. 73, 2073 (2004).
[8] K. Izawa, H. Yamaguchi, Yuji Matsuda, H. Shishido, R. Settai, and Y. Onuki, Phys. Rev. Lett. 87, 057002 (2001).
[9] M. Yashima, S. Kawasaki, H. Mukuda, Y. Kitaoka, H. Shishido, R. Settai, and Y. Onuki, Phys. Rev. B 76, 020509(R) (2007).
[10] S. Kawasaki, G.-q. Zheng, H. Kan, Y. Kitaoka, H. Shishido, and Y. Onuki, Phys. Rev. Lett. 94, 037007 (2005).
[11] S. Kawasaki, M. Yashima, Y. Mugino, G.-q. Zheng, H. Kan, H. Mukuda, Y. Kitaoka, H. Shishido, and Y. Onuki, Phys. Rev. Lett. 96, 147001 (2006).
[12] T. Muramatsu, T. C. Kobayashi, K. Shimizu, K. Amaya, D. Aoki, Y. Haga, and Y. Onuki, Physica C 388-389, 539 (2003).