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UNCONVENTIONAL SUPERCONDUCTIVITY AND QUASI-2D MAGNETIC FLUCTUATIONS IN Ce(Ir,Rh)In_5*

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The ^{115}In nuclear spin–lattice relaxation rate ($1/T_1$) measurements are reported for the heavy fermion (HF) compounds Ce(Ir,Rh)In_5 along with their La analogs La(Ir,Rh)In_5. $1/T_1$ for Ce(Ir,Rh)In_5 is enhanced by one order of magnitude over that in La(Ir,Rh)In_5, indicating strong magnetic fluctuations in these compounds. It is evidenced that $CeIrIn_5$ is located near a quantum critical point, with quasi-2D spin fluctuations. Also in $CeIrIn_5$, $1/T_1$ follows a T^3 variation below $T_c = 0.40$ K, indicating unconventional superconductivity with line-node gap. These aspects are reminiscent of the high-T_c copper oxides and suggest the importance of the magnetic fluctuations for the occurrence of the unconventional superconductivity in these HF compounds.

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1. Introduction

The emergence of superconductivity in cerium Ce-based heavy fermion (HF) compounds is one of the most intriguing phenomena in strongly correlated electron systems [1]. Since this class of superconductivity usually occurs near a quantum critical point (QCP) realized by the application of high pressure, knowledge about it is still limited because of difficult experimental conditions. The recently discovered new family of Ce-based heavy electron systems, $CeMIn_5$ (M = Rh, Ir) with M = Ir being superconductors already at ambient pressure [2, 3], are good candidates for studying the nature of the superconductivity near a QCP, the interplay between magnetic

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excitations and superconductivity, *etc.* In particular, $CeIrIn_5$ is suitable for studies using microscopic experimental probes that can be applied more easily at ambient pressure.

$CeMIn_5$ consists of alternating layers of $CeIn_3$ and MIn_2. $CeRhIn_5$ is an antiferromagnet at $T_N = 3.8\,K$ [2], while $CeIrIn_5$ is a superconductor with $T_c = 0.4\,K$ at ambient pressure [3]. Here, we report measurements by the ^{115}In nuclear quadrupolar resonance (NQR) in $Ce(Ir,Rh)In_5$ along with their La analogs [4]. We find that $CeIrIn_5$ is much more itinerant than other Ce-compounds including $CeRhIn_5$ and show that this compound is located near a QCP with anisotropic spin fluctuations due to the layered crystal structure. The power-law T-variation of $1/T_1 \propto T^3$ below $T_c = 0.40\,K$ indicates that the superconductivity is of unconventional type with an anisotropic gap.

2. Experimental results

Single crystals were grown by the In-flux method as in Ref. [2]. NQR results for the In(1) site in the $CeIn_3$ plane are discussed here. Fig. 1 shows $1/T_1$ as a function of T in the temperature range of $0.09\,K \leq T \leq 100\,K$. Remarkably, the normal state $1/T_1$ in $CeIrIn_5$ shows strong T dependence up to 100 K. This contrasts with that in $CeRhIn_5$, where $1/T_1$ becomes

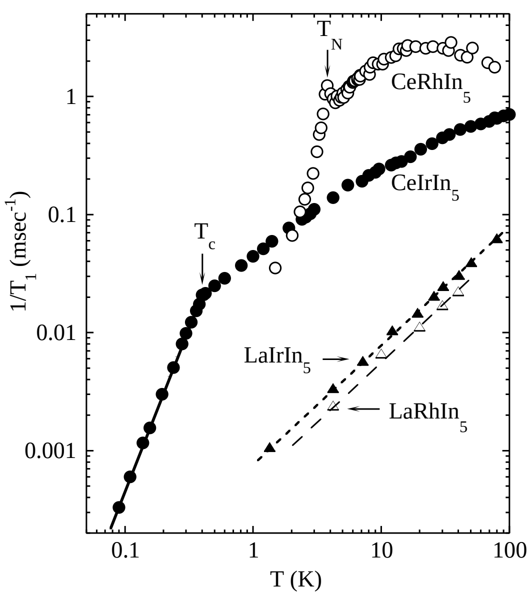

Fig. 1. T-dependence of $^{115}(1/T_1)$ for $Ce(Ir,Rh)In_5$ and the reference compounds $La(Ir,Rh)In_5$. The solid and dashed lines indicate the $1/T_1 \propto T^3$ and $1/T_1 \propto T$ relations, respectively.

T-independent above the Kondo temperature, $T_K \sim 15\,\mathrm{K}$ as in other HF compounds [5, 6]. This result indicates that the $4f$ electrons in $CeIrIn_5$ are much more itinerant. In the figure, the $1/T_1$ for La(Ir,Rh)In_5 is also shown for comparison. It is seen that $1/T_1T$ of Ce(Ir,Rh)In_5 is largely enhanced over that in their respective La analogs. Also note that a T_1T = const. relation is not obeyed. These aspects indicate that $1/T_1$ in Ce(Ir,Rh)In_5 is dominated by the antiferromagnetic spin fluctuations (SFs).

In Fig. 2 we show T_1T above T_c as a function of T for $CeIrIn_5$. In order to inspect the contribution due to the $4f$ spins alone, we subtracted the $1/T_1$ for $LaIrIn_5$ which represents other relaxations including the In orbital contribution. Namely, the data in Fig. 2 correspond to $1/T_1T = 1/T_1T(CeIrIn_5) - 0.81\,\mathrm{sec^{-1}K^{-1}}$ ($LaIrIn_5$). As seen in the figure, the data can be fitted to a relation of $T_1T = C(T+\theta)^{\frac{3}{4}}$ with $\theta = 8\,\mathrm{K}$ and $C = 4.75\,\mathrm{msecK^{\frac{1}{4}}}$.

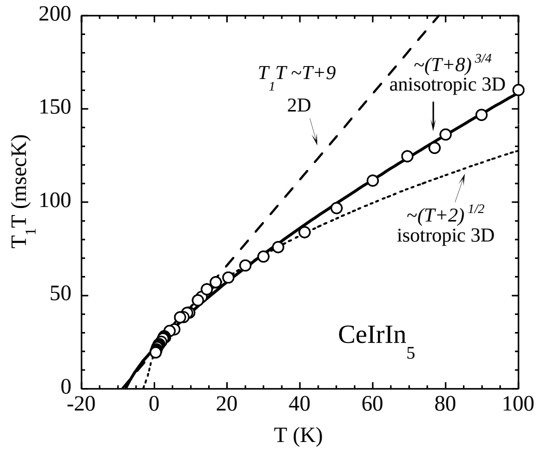

Fig. 2. T_1T plotted as a function of T for $CeIrIn_5$ above T_c. The broken line, solid and dotted curves are the T-variations of $T_1T \propto T+\theta$ (2D SFs), $T_1T \propto (T+\theta)^{3/4}$ (anisotropic SFs) and $T_1T \propto (T+\theta)^{1/2}$ (3D SFs), respectively.

This unique T-dependence of $1/T_1T$ has never been observed in other HF compounds. This result points to *anisotropic* AF spin fluctuations, due to the *layered* crystal structure of $CeIrIn_5$. When the SF dispersion in one direction (z-direction) is flat, as modeled by $\chi(Q+q)^{-1} = \chi_Q^{-1} + a_1(q_x^2+q_y^2) + a_2q_z^4$ instead of isotropic quadratic dispersion, it is shown that $1/T_1T \propto \chi_Q^{3/4} \propto (T+\theta)^{-3/4}$. Here $\chi(q)$ is wave–vector (q)-dependent spin susceptibility. This anisotropic SF model explained the anisotropic dynamical susceptibility in the paramagnetic state of YMn_2 [7]. Indeed, the same T-variation as found here was observed in paramagnetic YMn_2 under pressure [8]. Therefore, it is suggested that the spin fluctuation in $CeIrIn_5$ is anisotropic (quasi two dimensional). In fact, $CeIrIn_5$ has a layered crystal structure. Because of this 2D-like structure, a weaker magnetic correlation along the c-axis can be expected.

Next, we discuss the superconducting (SC) state. As seen in Fig. 1, $1/T_1$ drops abruptly at $T = 0.40$ K, with no coherence peak just below T_c, and decreases in proportion to T^3 upon further lowing T. This behavior is not compatible with isotropic s-wave gap, but indicates that the SC energy gap is anisotropic. An anisotropic gap generally reduces the divergence of the density of states (DOS) seen in the BCS superconductors, and the finite DOS below the largest gap amplitude gives rise to a T^n ($n = 3 \sim 4$) variation of $1/T_1$ at low T.

The anisotropic magnetic fluctuations and the non s-wave superconductivity are reminiscent of those in high-T_c copper oxides where an intimate relationship between the magnetic fluctuation spectral and the T_c value has been revealed [9, 10]. Future works include the clarification of the possible likewise relation in this class of heavy fermion compounds.

3. Conclusion

In conclusion, we find that $CeIrIn_5$ is much more itinerant than $CeRhIn_5$. We further find that $1/T_1T$, subtracting that for $LaIrIn_5$, follows a $(\frac{1}{T+\theta})^{\frac{3}{4}}$ variation with a small θ=8 K, which indicate quasi 2D spin fluctuations near a QCP. Below $T_c = 0.40$ K, $1/T_1$ decreases in proportion to T^3, indicating unconventional superconductivity with an anisotropic energy gap. As in the high-T_c cuprates, the anisotropic magnetic fluctuations may play an important role in the occurrence of the non s-wave superconductivity.

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