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^{115}In NQR studies of $CeRhIn_5$ and $CeCoIn_5$ under high pressure

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Abstract

We have carried out ^{115}In nuclear quadrupole resonance (NQR) measurements in $CeRhIn_5$ and $CeCoIn_5$ under presure P. The nuclear spin-lattice relaxation rates, $1/T_1$, of ^{115}In indicated that the anisotropic superconductivity with line nodes occurred near an antiferromagnetic state. The application of P suppressed the antiferromagnetic, AF, spin fluctuations and moves the system away from the AF state to the non-magnetic Fermi liquid state. The P dependence of $1/T_1$ in the superconducting state of $CeCoIn_5$ shows that the magnitude of the superconducting energy gap scales with its T_C up to 3.0 GPa.
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Keywords: ^{115}In NQR; $CeCoIn_5$; $CeRhIn_5$; Superconductivity; Heavy fermion

The occurrence of superconductivity in strongly correlated f-electron system has intrigued researcher for two decades. The existence of ferromagnetic, F, or antiferromagnetic, AF, spin fluctuations has led to the prediction that superconductivity with non-s-wave symmetry, mediated by magnetic electron–electron coupling, is realized. Before 1995, $CeCu_2Si_2$ and $CeCu_2Ge_2$ were the only superconducting members of 4f-heavy fermion class. However, $CePd_2Si_2$, $CeRh_2Si_2$, $CeIn_3$, $CeNi_2Ge_2$ have shown to become superconducting under pressure, P, which all have very low superconducting temperature, T_C. Owing to the experimental difficulty, little knowledge of the superconductivity was observed in these systems. Recently new superconductors $CeTIn_5$ (T = Co, Rh and Ir) [1], which have higher T_C than other compounds, have been observed. This system is suitable for microscopic measurements [2]. The ground state of $CeRhIn_5$ at ambient pressure is antiferromagnet, and the application of a pressure of about 1.7 GPa induces a transition to the superconducting state with the critical temperature T_C of 2.1 K [1]. In $CeCoIn_5$, the superconductivity appears below 2.3 K at ambient pressure [4]. It is an important theme of heavy fermion system to understand the interplay of magnetism and superconductivity.

Nuclear quadrupole resonance (NQR) is a powerful method for the study of magnetism and superconductivity, i.e., the spectrum and the nuclear spin lattice relaxation rate, $1/T_1$, provide valuable information on the magnetic structure, the fluctuations of the magnetic moments and also the superconducting energy gap Δ. In this paper, we report the results of the nuclear quadrupole resonance of $CeRhIn_5$ and $CeCoIn_5$ under pressure up to 3.0 GPa. The NQR were performed with the signals from ^{115}In located at the Ce–In plane where In ions are surrounded by Ce ions. The $1/T_1$ was determined by the recovery of the nuclear magnetization after the saturation pulse. To obtain the hydrostatic pressure, P, a BeCu/NiCrAl cylinder cell and WC piston was used with a mixture of Fluorinert 70 and 77 as a P-transmitting medium. Figs. 1 and 2 show T- and P-dependences of $1/T_1$ obtained in $CeRhIn_5$ and $CeCoIn_5$. At ambient P, $1/T_1$ varies close to

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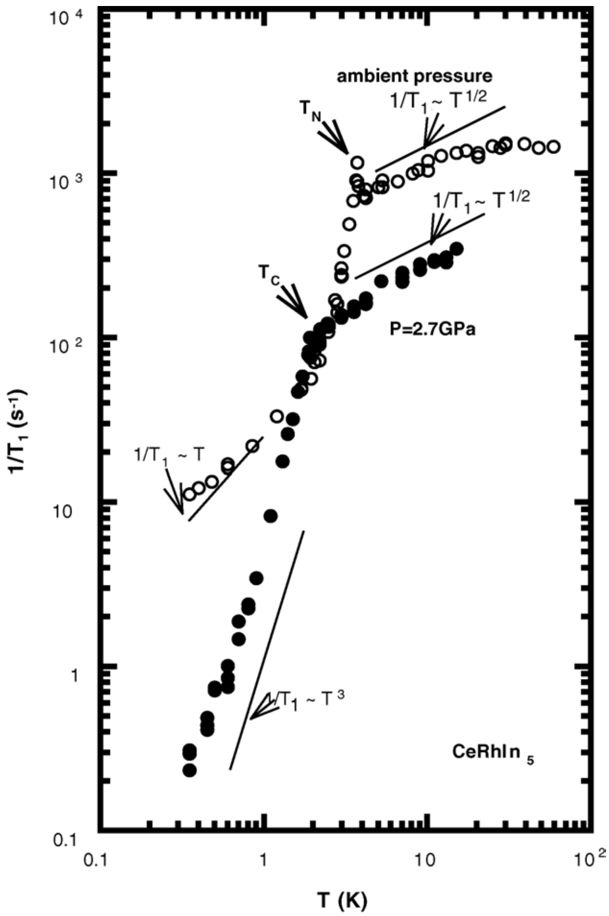

Fig. 1. T dependence of $1/T_1$ of ^{115}In in $CeRhIn_5$. T_N represents the Néel temperature of 3.7 K at ambient pressure.

$T^{1/2}$ in $CeRhIn_5$, and $T^{1/4}$ in $CeCoIn_5$. These T-dependences differ from the issue expected in simple Fermi liquid state ($1/T_1 \propto T$). The $1/T_1T$ reveals the spin-fluctuation character from the q averaged dynamical susceptibility $\chi''(q, \omega)$. The deviation from the Fermi liquid behavior ($1/T_1 \propto T$) indicates the presence of the magnetic correlation in the material, which is explained by the spin fluctuation theory developed around the AF instability.

The T-dependence of $1/T_1$ ($1/T_1 \propto T^{1/2}$) in $CeRhIn_5$ is expected in AF or nearly AF system [5]. The much weaker T-dependence ($1/T_1 \propto T^{1/4}$) observed in $CeCoIn_5$ is expected in the system located at AF quantum critical point. The T-dependence at AF quantum critical point is $T^{1/4}$ in the three-dimensional (3D) case and $-\text{In}T$ in the two-dimensional (2D) case. The interpolation of 2D- and 3D-cases shows that T-dependence of $T^{1/4}$ exists even in the quasi 2D-system [6]. As a lot of measurements have indicated quasi 2D character of the $CeCoIn_5$, we expect that this system located at the AF quantum critical point of the quasi-2D case. With increasing P, the value of $1/T_1$ in $CeCoIn_5$ is strongly suppressed and the T dependence becomes large. This result shows that P moves $CeCoIn_5$ away from the AF instability. The Fermi liquid behavior ($1/T_1 \propto T$) was observed at the high P region,

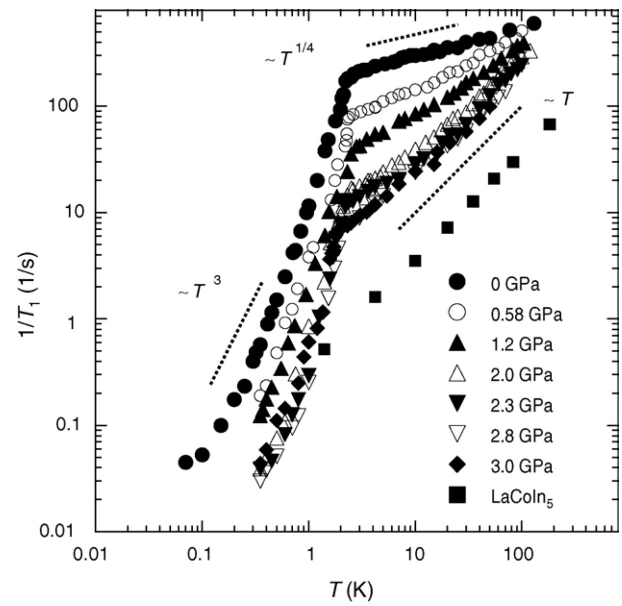

Fig. 2. T dependence of $1/T_1$ of ^{115}In in $CeCoIn_5$ under pressure. $1/T_1$ of ^{115}In in $LaCoIn_5$ is from ref. [3].

which shows the system moved close to the Fermi liquid state.

In the superconducting state of $CeRhIn_5$ at $P = 2.7$ GPa, $1/T_1$ decreases rapidly below T_C and varies nearly proportionally to T^3 at low temperatures. Fig. 3 shows the normalized T dependence of $1/T_1$ of $CeCoIn_5$, which shows the similar behavior is also observed and the P dependence is very small.

Unconventional superconductivity is characterized by the superconducting gap structure which has nodes along certain direction. Generally, the energy gap has points or line nodes, which satisfy the group theoretical restriction arising from

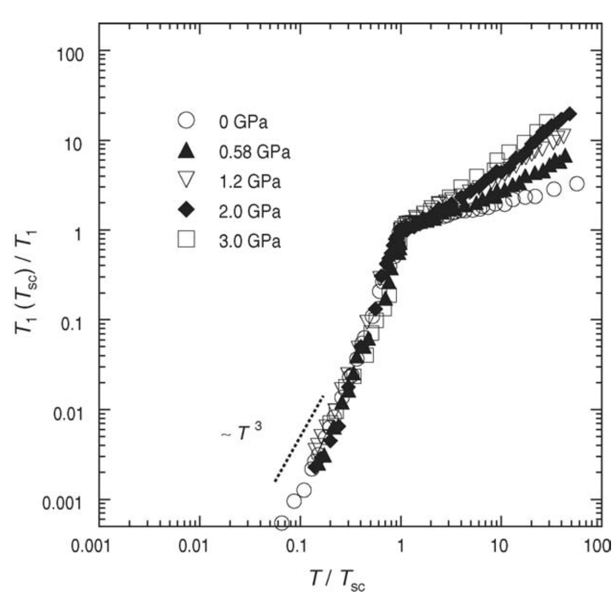

Fig. 3. T dependence of normalized $1/T_1$.

the crystal symmetry. In most of the case, the detailed structure of the gap function is remaining as an unresolved issue. However, a crude evaluation of $1/T_1$ would be possible by the polar model $\Delta = \Delta_0 \cos\theta$, since $1/T_1$ would likely be insensitive to points nodes in the presence of line nodes. In the pole model, the maximum value of the gap, Δ_0, appears at poles ($\theta = 0$) in the k space, and there is a line node at the equator ($\theta = \pi/2$). If we calculate T_1, tentatively assuming $2\Delta_0 = 9$–$10k_BT_C$ for $CeCoIn_5$, and $8k_BT_C$ for $CeRhIn_5$, the experimental values are reproduced well. The nearly T^3 law of $1/T_1$ is reminiscent of the relaxation behavior in many heavy fermion superconductors.

In conclusion, the T-dependence of $1/T_1$ in the normal state of $CeCoIn_5$ under high P has shown that applied P moves the system from the AF critical point at ambient P to nearly Fermi liquid state. In the superconducting state, $1/T_1$ has indicated that an anisotropic superconductor with line nodes appears. The ratio of the superconducting energy gap to its T_C does not depend on P for $P \leq 3.0$ GPa

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