MAGNETIC PROPERTIES OF $CeRhIn_5$ UNDER PRESSURE PROBED BY ^{115}In-NQR*

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We report the pressure (P)- induced evolution of the antiferromagnetism in $CeRhIn_5$ which undergoes a superconducting transition at $T_c\sim$ 2.1 K at pressurs exceeding $P_c\sim$ 1.6 GPa. From measurements of ^{115}In nuclear-spin-lattice-relaxation time (T_1) under P, we found that Néel temperature T_N is reduced above P = 1.23 GPa, which is accompanied by an emergent *pseudogap* behavior.

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1. Introduction

Since the discovery of cerium (Ce) based heavy-fermion (HF) superconductivity in $CeCu_2Si_2$ [1], many experimental works on $CeCu_2Ge_2$, [2] $CeIn_3$ [3–5] and $CePd_2Si_2$ [6] have suggested that antiferromagnetism and superconductivity are closely related each other. The discovery of pressure (P)-induced HF superconductivity in Ce-based antiferromagnetic (AF) compounds has stimulated further experimental works under P [7–10].

A HF AF $CeRhIn_5$ undergoes a P induced superconducting (SC) transition at a lower critical $P\sim 1.6$ GPa, yet reaching a $T_c\sim$ 2 K [7] higher than previous examples. Systematic studies on $CeRhIn_5$ seem to allow us

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to unravel an interplay between antiferromagnetism and superconductivity under P. $CeRhIn_5$ forms in the tetragonal $HoCoGa_5$ structure that is composed of alternating layers of $CeIn_3$ and $RhIn_2$ stacked sequentially along the [001] direction [7]. It orders antiferromagnetically with an incommensurate wave vector (1/2, 1/2, 0.297) [11]. The Néel temperature T_N= 3.8 K at P = 0 slightly increases up to $P \sim 1.0$ GPa, followed by an onset of superconductivity at $T_c = 2.1$ K at pressures exceeding a critical pressure $P_c \sim 1.63$ GPa [7]. In the previous paper [10], the ^{115}In-NQR study of $CeRhIn_5$ has clarified the P-induced anomalous magnetism and unconventional superconductivity. In the AF region, T_N which is evidenced from clear shift and splits of NQR spectrum exhibits a moderate increase up to $P = 1.0$ GPa, but decreases above $P = 1.23$ GPa. By contrast, the internal field $H_{\rm int}$ at the In(1) site, that is associated with the magnetic ordering, is almost linearly reduced against increasing P. Note that the In(1) site is equivalent to the In site in the $CeIn_3$. In the SC region at $P = 2.1$ GPa, it was reported that the $1/T_1$ reveals a T^3 dependence without the coherence peak just below T_c, consistent with the existence of line-node gap [10]. It is, however, not yet clear in $CeRhIn_5$ how antiferromagnetism evolves into superconductivity with increasing P. Here, we focus on magnetic properties of $CeRhIn_5$ near $P_c \sim 1.6$ GPa probed by ^{115}In-NQR T_1 measurements in $P = 0 - 1.6$ GPa.

2. Experimental result

The ^{115}In ($I = 9/2$)-NQR spectrum at the paramagnetic state consists of four transitions that are equally spaced with a quadrupole frequency $n \times \nu_Q$ with n= 1, 2, 3 and 4. $1/T_1$ was measured at the transitions of 2 ν_Q ($\pm 3/2 \leftrightarrow \pm 5/2$) and 3 ν_Q ($\pm 5/2 \leftrightarrow \pm 7/2$) at the In(1) site, using the conventional saturation-recovery method in the $T = 1, 4 - 100$ K at P=0.46, 1.23, and 1.6 GPa. Hydrostatic pressure was applied by utilizing a BeCu piston-cylinder cell, filled with Daphne oil (7373) as a pressure-transmitting medium. To calibrate a value of pressure at low temperatures, the shift in T_c of Sn metal under P was monitored by resistivity measurement.

The T dependence of $1/T_1T$ below 10 K is shown in Fig. 1 at P = 0.46, 1.23, and 1.6 GPa. At the respective values of P, it is clearly seen that AF order occurs at T_N=4.0, 3.6 and 2.8 K, as evidenced by the clear peak in $1/T_1T$ due to critical magnetic fluctuations toward the AF ordering. This indicates that T_N reduces above $P = 1.23$ GPa as P approaches $P_c \sim$ 1.63 GPa. At $P = 1.23$ and 1.6 GPa, $1/T_1T$ shows a broad peak around $T_{\rm PG}$ well above T_N. This resembles the pseudogap behavior found in high-T_c copper oxide superconductors [12]. Likewise, when P approaches the critical pressures P_c, the low-energy spectral weight of magnetic fluctuations is suppressed before an ordering occurs. We note that the pseudogap behavior has been found in either two- or lower-dimensional strongly correlated electron systems [12]. Very recently, in CeRhIn$_5$, anisotropic three dimensional AF fluctuation was reported from neutron scattering at $P = 0$ with an energy scale of less than 1.7 meV at temperatures as high as 3 T_c [13]. On the other hand, as P further increases up to $P = 2.1$ GPa where the SC transition appears, $1/T_1T$ continues to increase down to $T_c = 2.2$ K without any signature for the pseudogap behavior as seen in the previous report [10]. The T variation of $1/T_1T$ is consistent with the three dimensional AF Fermi-liquid model described by the self-consistent renormalized (SCR) theory for nearly AF metals [10, 14]. Thus the P-induced evolution in the magnetic fluctuations, from a magnetic regime of reduced dimensionality to a more isotropic one, may take place in a narrow P window of 1.6–2.1 GPa, when the AF order evolves into the SC one. The pressure-temperature phase diagram for CeRhIn$_5$ is summarized in Fig. 2.

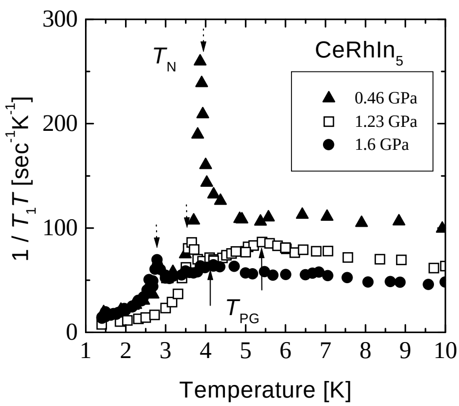

Fig. 1. T dependence of 1 / T_1 at $P = 0.46$, 1.23 and 1.6 GPa. The solid and dotted arrows indicate $T_{\rm PG}$ and $T_{\rm N}$.

In conclusion, we have reported the P-induced evolution of the magnetic properties in CeRhIn$_5$ on the basis of the ^{115}In-NQR T_1 measurements. In the itinerant antiferromagnet CeRhIn$_5$ at $P = 0$, $T_{\rm N}$ slightly increases up to $P = 1.0$ GPa, but it turns to decrease at $P = 1.23$ GPa when approaching $P_c \sim 1.63$ GPa at which superconductivity sets in. This reduction in $T_{\rm N}$ coincides with the emergence of the pseudogap behavior that is evidenced by the suppression in $1/T_1T$ above $T_{\rm N}$. This P-induced evolution in the magnetic fluctuations, from a magnetic regime of reduced dimensionality to a more isotropic one, may take place in a narrow P window of 1.6–2.1 GPa when the AF order evolves into the SC one.

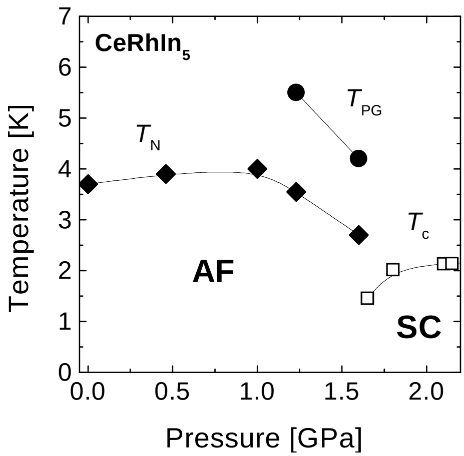

Fig. 2. P–T phase diagram for $CeRhIn_5$. The open marks are determined from ac-susceptibility measurement [10].

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