Magnetic Properties of $CeRu_2Si_2$ at Ultra Low Temperatures

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Abstract

We simultaneously measured the ac susceptibility and dc magnetization of the heavy fermion (HF) compound $CeRu_2Si_2$ in various small magnetic fields at temperatures down to 170μK. The susceptibility and magnetization increased below 50mK followed by Curie law with small magnetic moment $0.02\mu_B$/Ce. In fields higher than 0.20mT, the susceptibility showed the peak, the temperature (T_M) and height of which shifted higher and lower with increasing the field, respectively. In addition, approaching T_M, increase in the static magnetization became a plateau in the fields higher than 0.39mT. These results reflect the spin fluctuation of the itinerant $4f$ electron.

Key words: heavy fermion; itinerant magnetism; spin fluctuation; ac susceptibility and dc magnetization

$CeRu_2Si_2$ is well-known HF compound with an electronic specific-heat coefficient $\gamma \sim 350$ mJ/K^2 mol [1]. Nevertheless in the enhanced Pauli paramagnetic region below Kondo temperature $T_K = 20$ K [2], three antiferro (AF) magnetic short-range correlations have been reported by neutron measurements [2,3]. And these correlations induce the long-range AF order by substitution of a small amount of La for Ce or Rh for Ru [4]. Recently the pseudo-metamagnetic behavior at $H_M = 7.8$ T below 10 K was explained as the induced ferromagnetic fluctuation by the magnetic field [5]. Accordingly $CeRu_2Si_2$ is thought to be vicinity of the magnetic order phase, which is caused by the spin fluctuation of the strong correlated $4f$ electrons. However the magnetic ground state has been unclear down to a few milli kelvin temperatures [6]. We report the magnetic properties of $CeRu_2Si_2$ at micro kelvin temperatures in this article.

The single crystal of $CeRu_2Si_2$ was prepared by the Czochralski pulling method with starting materials Ce (99.99%), Si (>99.999%) and Ru (99.99%) and purified by a solid state transport method. The ac susceptibility and static magnetization of $CeRu_2Si_2$ were measured simultaneously in a static field $0.016 \leq B \leq 6.21$ mT by an ac impedance bridge using a SQUID magnetometer. All of the ac susceptibility measurements were performed at a frequency of 16 Hz with an excitation field below 0.75 μT parallel with the static field. The measurement cell was surrounded by Nb superconducting magnetic shield covered by a mu metal shield to suppress any external stray field. The cooling method and thermometers were described in our previous report [6].

Figure 1 shows the temperature dependence of the inphase (χ') of the ac susceptibility in various magnetic fields. The ac susceptibility was measured during cooling and warming, and the results showed no appreciable hysteresis in either procedure. The temperature dependence of the ac susceptibility above $\sim$50 mK shows a plateau due to the Pauli paramagnetic susceptibility. On the other hand, below $\sim$50 mK, we observed an excess susceptibility over the Pauli paramagnetic susceptibility which obeyed the Curie-Weiss law. The ac susceptibility monotonically increased in 0.016 mT. In fields higher than 0.20 mT, the ac susceptibility showed the peak. These peak temperature

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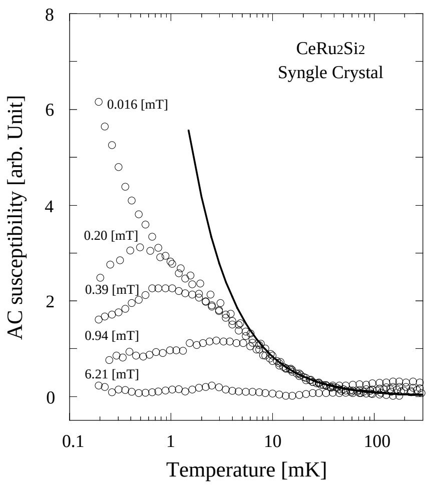

Fig. 1. Temperature dependence (on a logarithmic scale) of the ac susceptibility of $CeRu_2Si_2$ at various applied magnetic fields. The amplitude of applied magnetic field is indicated in the figure. Solid curve in the figure shows the Curie-Weiss law.

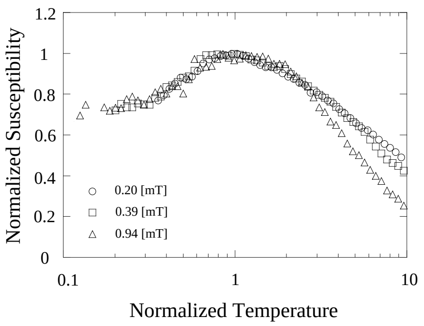

Fig. 2. Universality of the χ' of the $CeRu_2Si_2$ in the fields between 0.20 and 0.94 mT. The vertical axis is normalized χ' by the peak height ($\chi_{\rm P}$). The horizontal axis is temperature normalized by $T_{\rm M}$.

($T_{\rm M}$) shifted higher and the height of the susceptibility were suppressed with increasing applied magnetic field. The ac susceptibility, however, deviated from the Curie-Weiss law as it approached to $T_{\rm M}$. Below $T_{\rm M}$, we found universality of the ac susceptibility in the fields from 0.20 to 0.94 mT, as shown in Figure 2. We normalized χ' at the peak height of χ' ($\chi'_{\rm p}$) and temperature by $T_{\rm M}$. There was no appreciable magnetic field dependence below $T_{\rm M}$.

The dc magnetization also showed the Curie-Weiss behavior below ~50 mK at each applied magnetic fields. The effective magnetic moment $\mu_{\rm p}$ turned out to be 0.020 $\pm$ 0.003 $\mu_{\rm B}$/unit cell and independent of the magnetic field applied. The order of $\mu_{\rm p}$ is in agreement with the ultra-small static moment observed by μSR experiment [7]. The magnetization, however, became a flat and showed a plateau in fields higher than 0.39mT below $T_{\rm M}$, after subtracting another ultra low temperature contribution. The saturated magnetic moment $\mu_{\rm s}$ became larger in higher applied magnetic fields. It is the remarkable result that the ratio of the $\mu_{\rm s}$ to $\mu_{\rm p}$ is calculated as order of $\sim 10^3$. The detail of the analysis for the dc magnetization will be reported soon elsewhere.

In discussion, we first consider the impurity effect, which is a matter of argument in intermetallic compounds. The impurity effect was clearly denied by following facts. The field depending behavior of the $T_{\rm M}$ is implied as the spin-glass transition of the impurities occur on this sample. However, the quadrature component of the ac susceptibility did not indicate the divergence at $T_{\rm M}$. In addition, the static magnetization showed good agreement in the results obtained on zero field cooling and field cooling. And the result also could not be explain by isolated localized impurity effect.

Our result can be explained by intrinsic itinerant f electrons with spin fluctuation. The large value of $\mu_{\rm P}/\mu_{\rm S}$ supports the itinerant weak ferromagnet. The magnetic correlation in $CeRu_2Si_2$, however, is determined to be an antiferro magnetic short-range correlation [2,3]. Based on the Self Consistent Renormalization theory, the uniform susceptibility of an itinerant weak antiferromagnetic compound should not obey the Curie-Weiss law without including ferromagnetic fluctuation [8]. Accordingly, we must conclude that the fluctuating electron system with an antiferro magnetic correlation was frustrated, and the magnetic field induced the pseudo-ferromagnetic component in this compound.

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