Magnetic Properties of Itinerant Ferromagnet LaCo$_2$P$_2$

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Abstract

We synthesized a single crystalline sample of LaCo$_2$P$_2$ and measured its magnetization. We estimated parameters of spin fluctuations from Arrott plots and $M^4-H/M$ plots by using Takahashi’s itinerant-electron theory of spin fluctuations. From these plots, the magnetic properties of LaCo$_2$P$_2$ have been found to agree with the Takahashi’s itinerant-electron theory.

Key Words: Itinerant electron, Ferromagnet, Layered pnictide, Magnetization

I. INTRODUCTION

Many layered compounds with ThCr$_2$Si$_2$ type structure have been discovered and found to various physical properties such as superconductivity and magnetic ordering. Iron or nickel based pnictides have been found to exhibit the exotic superconductivity [1, 2]. On the other hand, though cobalt is between iron and nickel in the periodical table, cobalt-based pnictides do not show any superconductivities but show various magnetic orderings, e.g. ACo$_2$P$_2$ ($A =$ alkaline earth metals, rare earth metals) is itinerant antiferromagnetic, itinerant ferromagnetic or Pauli paramagnetic depending on $A$ [3-5]. In ACo$_2$P$_2$, the Co$_2$P$_2$ layers formed of edge-sharing tetrahedral CoP$_4$ and $A$ layers are stacked alternately along the $c$-axis. The distance between neighboring Co$_2$P$_2$ layers can be controlled by changing the $A$ cation. In the case of $A =$ Ca, Ce, a strong P-P interaction exists between neighboring Co$_2$P$_2$ layers and electronic structures are of three-dimensional characters rather than two-dimensional. In this case, a ferromagnetic ordered Co$_2$P$_2$ layers stack antiferromagnetically [5, 6]. In the case of $A =$ La which has a large atomic radius, the P-P interaction is weaker and its electronic structure has two-dimensionality. In addition LaCo$_2$P$_2$ exhibits an itinerant ferromagnet where Co moments lie in the Co$_2$P$_2$ layer [4]. In LaCo$_2$P$_2$, the intralayer interaction is ferromagnetic.

As a theoretical approach of itinerant electron magnetic compounds, the self-consistent renormalization (SCR) theory of spin fluctuations succeeded in clarifying the nature of nearly and weakly itinerant (anti-)ferromagnetic systems [7-9]. After that, Takahashi developed the SCR theory by assuming a conservation of the total amplitude of sum of zero point and thermal spin-fluctuations against temperature [10]. With Takahashi’ theory, we can estimate parameters of spin fluctuations from only the static magnetization process in the case of an itinerant ferromagnet. To study the ACo$_2$P$_2$ system from the view point of spin-fluctuations, we synthesized single crystals of LaCo$_2$P$_2$ and investigated their magnetizations.

II. EXPERIMENTAL

Single crystals of LaCo$_2$P$_2$ ware prepared from tin flux method [11]. The mixtures with the atomic ratio of La:Co:P:Sn = 1.6:2.0:2.0:15 were sealed in evacuated silica tubes and heated at 1273 K for 2 days and then slowly cooled to 873 K at 4 K/ min. The excess tin was dissolved in dilute HCl. Plate-like single crystals were obtained with a typical size of $0.3 \times 0.3 \times 0.01$ mm. The electrical resistivity along the $a$ axis was measured by a standard dc four-probe method. X-ray powder diffraction analysis confirmed that samples are in pure single phase. Magnetizations ($M$) of LaCo$_2$P$_2$ were measured as functions of temperature ($T$) and magnetic field ($H$) by using MPMS (Quantum Design Inc.). With the magnetic field applied along $a$ or $c$ axis, the $M$ vs $H$ curves were measured with decreasing $H$ from 7 to 0 T.

III. RESULTS

The resistivity $\rho$ decreases with decreasing temperature and drops at 133 K as shown in Fig. 1. The residual resistivity $\rho_0$ and the residual resistivity ratio (RRR) are 0.41 $\mu$Ω cm and 190, respectively, reflecting the high quality of the single crystals. In the low temperature region $\rho(T)$ can be well fitted to the function $\rho(T) = \rho_0 + AT^2$ as shown in the inset of Fig.1. In the SCR theory, resistivity of itinerant ferromagnet is proportional to $T^2$ at low temperature region. In two dimensional or three dimensional ferromagnetic metal, $\rho(T)$ obeys $-T^{4/3}$ or $-T^{5/3}$ above $T_C$. In the case of LaCo$_2$P$_2$, $\rho(T)$ has
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The resistivity $\rho$ of LaCo$_2$P$_2$ is shown in Figure 1. The inset shows the resistivity against $T^2$.

Figure 2 shows isothermal magnetization ($M$) curves measured at 2 to 300 K for single crystals of LaCo$_2$P$_2$ with the magnetic field $H$ parallel to the $a$ and $c$ axes. The magnetization quickly tends to saturate in $H$ parallel to $a$. On the other hand, saturation fields are much larger in $H$ parallel to $c$. This compound has large magnetic anisotropy, therefore we only used magnetization curves in $H$ parallel to $a$ in the following analysis. The magnetization with zero field $M_0$ and the Curie temperature $T_C$ are determined from the Arrott plots ($M(T, H)^2$ vs $H/M(T, H)$ plots). According to the Landau theory, the free energy ($F$) can be expanded by the order parameter. Here, the magnetic field $H$ is defined by $H = \partial F/\partial M$, and written as

$$H = a(T)M(T, H) + b(T)M(T, H)^3 + c(T)M(T, H)^5 + \ldots,$$

where $a(T)$, $b(T)$, and $c(T)$ are coefficients at finite $T$. With neglecting sixth and higher power terms of $M(T, H)$, the equation (1) is transformed as

$$M(T, H)^2 = -a(T)/b(T) + 1/b(T) \cdot H/M(T, H) = M_0(T)^2 + 1/b(T) \cdot H/M(T, H).$$

From Arrott plots, therefore, $T_C$, $M_0$ and the susceptibility $\chi$ are determined as the temperature where $M_0$ becomes zero, intercepts of $M^2$ and $H/M$ axes. According to Takahashi’s theory of spin fluctuations [10], $F_1$ is the normalized coefficient of $M^4$ terms in the Landau expansion of free energy, which can be written as

$$F_1 = 4T_C^2/15T_0,$$

with spin-fluctuation parameters. Here, $T_0$ and $T_A$ are the energy width of the dynamical spin-fluctuation spectrum and the dispersion of the static magnetic susceptibility in the wave vector $q$-space, respectively. In addition to the equation (3), the SCR theory leads to the following relation:

$$T_C = (60c)^{1/4} P_s^{3/2} T_A^{3/4} T_0^{-1/4},$$

where $c$ and $P_s$ are a constant approximately equal to 0.3353 and the spontaneous magnetization in the ground state, respectively [7]. We can estimate $T_0$ and $T_A$ by the equations (3) and (4). Figure 3 shows Arrott plots and $M^4$ vs $H/M$ plots for single crystals of LaCo$_2$P$_2$ for $H$ parallel to $a$-axis. In the low temperature region, $M^2$ shows a good linearity under high magnetic field and $F_1$, $T_0$ and $T_A$ can be estimated as $1.26 \times 10^4$ K, 914 K and $6.58 \times 10^3$ K, respectively. In the vicinity of $T_C$, however, the Arrott plots show convex curvature. According to the Takahashi’s theory [10], the sixth term of the free energy is dominantly effective to the magnetization process around $T_C$. In this theory, second and fourth power terms are zero at $T_C$, thus the magnetization obeys following relation:

$$M^4 = 1.17 \times 10^{10}(T_C^2/T_A^*)(H/M),$$

where $T_A^*$ is the $T_A$ estimated from $M^4$ vs $H/M$ curve at $T_C$. Here, $M$ and $H$ are expressed in units of emu/mol and Oe, respectively. Therefore, we can check the consistency between experimental results and Takahashi’ theory of spin...
fluctuations with comparing $T_A$ and $T_A^*$. The $M^4$ vs $H/M$ curve at $T_C=133$ K shows good linearity as shown in Fig. 3(b).

We obtained $T_A^*$ as $6.41 \times 10^3$ K from the value of the slope, which is quite similar to $T_A=6.58 \times 10^3$ K. Our results have been found to agree with Takahashi’s theory of spin fluctuations.

IV. CONCLUSION

We synthesized single crystals of LaCo$_2$P$_2$ and measured their magnetizations. In the vicinity of $T_C$, Arrott plots were found to show convex curvature and $M^4$ vs $H/M$ plots to show a good linearity. From these plots, $T_A$ was cross-checked and confirmed its consistency. Our results were found to show a good agreement with Takahashi’s theory of spin fluctuations.

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