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Magnetic and Transport Properties of New Ternary Rare Earth Compounds with Emphasis on CePtP

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We have synthesized for the first time CePtP single crystals and found that they crystallize in a hexagonal YPtAs-type structure. The transport and magnetic properties indicate a strong anisotropy. The electrical resistivity within the c-plane behaves like a metal and has a small value, while it shows a much large value along the c-axis. From the magnetic and specific heat measurements, it is revealed that CePtP has successive magnetic phase transitions with T_C and T_N of 3.1 and 1 K, respectively. Below T_N, the magnetization curve along the c-axis at 0.45 K increases with successive anomalies and reaches to 2.14 μ_B, the saturation magnetization of Ce^{3+} with $J = 5/2$. The magnetic anisotropy is strong and the easy axis of magnetization lies along the c-axis, which is quite different from other CePtX (X=Sb, As) compounds. Furthermore, the suppression of the entropy suggests the existence of two dimensional features in this system.

KEYWORDS: CePtP, magnetic anisotropy, successive transitions, two dimensional system

Recently, ternary cerium based compounds have been intensively investigated because of their variety of unusual physical properties. Among them, CePdX[1-3] and CePtX[4-7] (X=Sb, As), which have a hexagonal structure, show a strong anisotropy in transport and magnetic properties. In these system, ρ along the c-axis exhibits weak temperature dependences and is two orders of magnitude larger than that within the c-plane, which behaves like an usual metal. As for magnetic properties, both CePdSb and CePdAs are ferromagnets.[3] In particular, CePdSb has attracted much attention because of its high-ordering temperature ($T_C = 17$ K) compared to that of the isostructural GdPdSb ($T_N = 15.5$ K).[1] Moreover, both compounds have an easy axis of magnetization within the c-plane and exhibit similar anisotropy. In CePtX system, on the contrary, the magnetic states vary strongly with variation of pnictogen. CePtSb is a ferromagnet ($T_C = 4.5$ K) with an easy axis within the c-plane and shows the strong anisotropy like as observed in CePdX. CePtAs, on the other hand, is an antiferromagnet with T_N=1 K and the anisotropy between the c-axis and the c-plane becomes very small.[6,7] Furthermore, the metamagnetic anomaly is observed in the magnetization curve below T_N. In order to study the variation of the magnetic state of CePtX systematically, we have synthesized for the first time CePtP and investigated the physical properies. In this paper, we report the experimental results of the electrical resistivity, magnetic susceptibility, magnetization and specific heat of CePtP.

The single crystals of CePtP used in this experiment were grown by the Bridgman method with tungsten crucibles. The X-ray diffraction study confirms that CePtP crystallizes in the YPtAs type hexagonal structure as same as CePtAs and has two inequivalent Ce sites which is slightly different from that of CePtSb of hexagonal LiGaGe type with one symmetry site (Fig. 1). (Although we have reported that the crystal structure of CePtAs was LiGaGe-type in the previous papers,[6,7] it becomes clear that LaPtAs crystallizes in LiGaGe-type, but CePtAs crystallizes in the YPtAs type structure.) The local symmetries of Ce-I and Ce-II are trigonal and hexagonal, respectively. Lattice parameters calculated from the diffraction pattern are $a = 4.194$ Å and $c = 16.02$ Å.

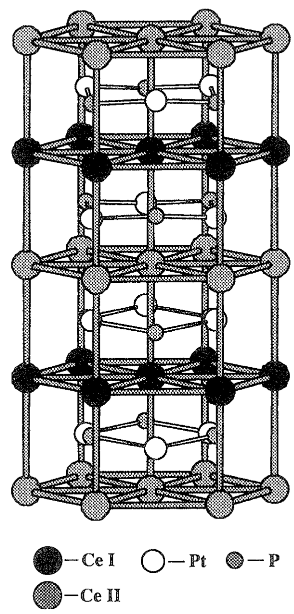

Fig. 1. The crystal structure of YPtAs-type.

The temperature dependences of the electrical resitivity along the a-axis ρ_a and the c-axis ρ_c are shown in Fig. 2. The ρ_a has small value and shows usual metallic behavior. The ρ_c, on the other hand, is much larger than ρ_a and the ratio ρ_c/ρ_a increases from 35 to 118 with decreasing temperature from 300 to 2 K. Moreover, both ρ_a and ρ_c exhibit anomaly at around 3.1 K, which correspond to the magnetic transition as mentioned in the following. Nearly the same anisotropic behavior is observed in the

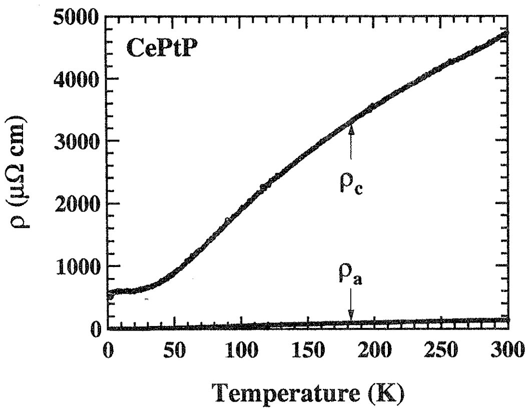

Fig. 2. The temperature dependences of the electrical resitivity of CePtP along the a-axis (ρ_a) and the c-axis (ρ_c).

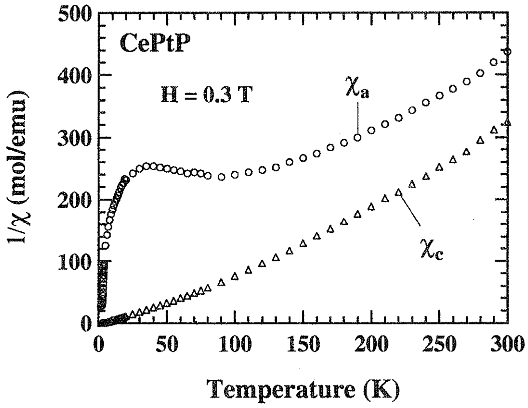

Fig. 3. The temperature dependences of the inverse magnetic susceptibility of CePtP along the a-axis (χ_a) and the c-axis (χ_c).

isostructural compound CePtAs.[6] In that system, the fact that LaPtAs, the reference compound for CePtAs as the second best, also shows the same anisotropy suggests that the strong anisotropy of ρ is originated from the shape of non-f Femi surface of La compound. We can consider that it is also the same case in CePtP.

The temperature dependences of the inverse magnetic susceptibility along the a-axis χ_a and the c-axis χ_c are shown in Fig. 3. χ_a shows the Curie Weiss behavior above 150 K. On the contrary, χ_c deviates from the Curie Weiss law below 150 K and shows the strongly anisotropic behavior. Effective Bohr magnetons, μ_{eff}, estimated above 200 K are 2.54 and 2.42 for χ_a and χ_c, respectively, which indicate that f electrons are well localized in this system. As shown in Fig. 4, χ_c has anomalies at around 3.1 K and 1 K. These anomalies are also observed in the result of the specific heat C as shown in Fig. 4, which indicate that magnetic phase transitions occur at each temperature.

The field dependences of magnetizaion for the magnetic field along the a-axis M_a and the c-axis M_c were measured at several temperatures. Figure 5 shows the results measured at 2 K. M_c increases ferromagnetically at low field and reaches to about $2\,\mu_B$ under 5 T. M_a, on the other hand, increases monotonically with increasing field and is much smaller than M_c, which confirms that the c-axis is an easy axis. In Arrot plots for M_c, using the general expression ${M_c}^2 = A(T_C - T) + B(H/M_c)$,

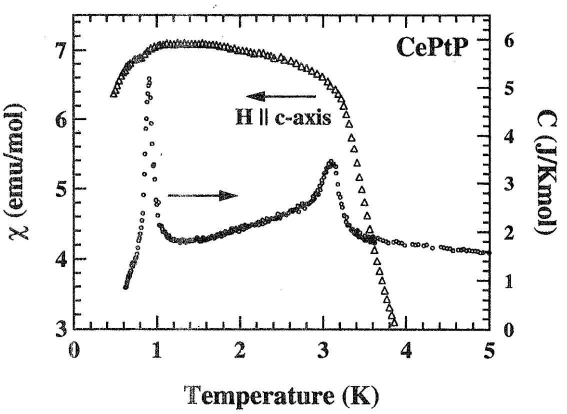

Fig. 4. Magnetic susceptibility along the c-axis and the spcific heat at low temperature.

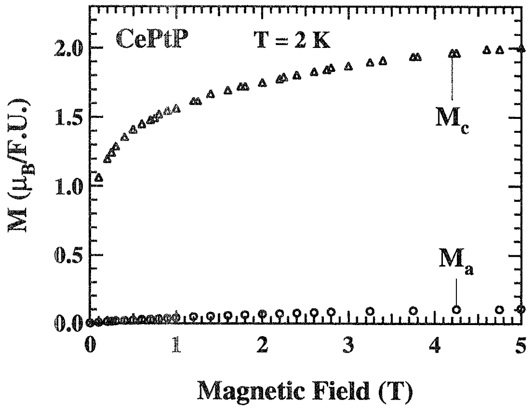

Fig. 5. Magnetization curve of CePtP along the a-axis (M_a) and the c-axis (M_c) at 2 K.

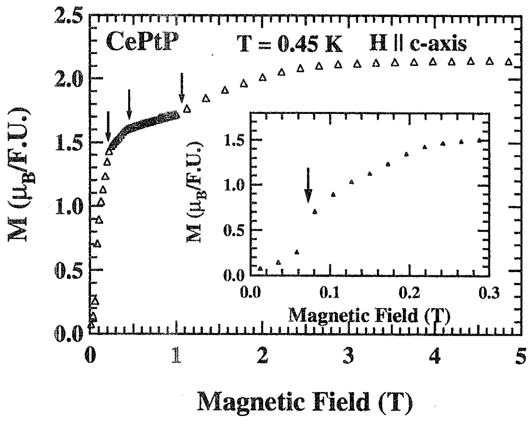

Fig. 6. Magnetization curve of CePtP along the c-axis at 0.45 K. The low-field region is shown in the inset.

where A and B are constants, we find parallel lines and the zero of the first term is found at around 3.1 K. Therefore, anomaly at 3.1 K corresponds to the ferromagnetic phase transition with ordered spins along with the c-axis. Figure 6 shows the results of M_c, the easy direction of magnetization, measured at 0.45 K. M_c shows successive anomalies as is indicated by arrows, and is saturated to $2.14\,\mu_B$ above 3 T, which is the saturation magnetization calculated for Ce^{3+} with $J = 5/2$. Moreover, metamagnetic behavior is observed at around 0.08 T as shown in the inset. M_c dependence at 0.45 K, in addition to the decrease of χ_c below 1 K, are clear evidence to sug-

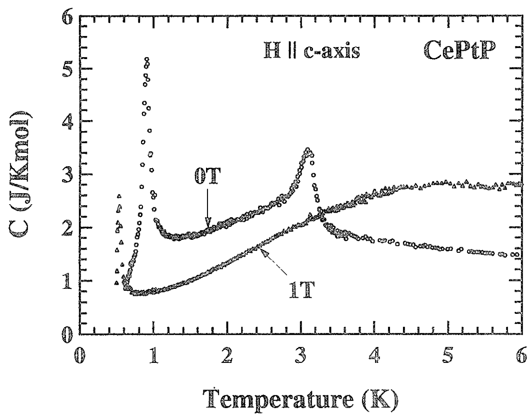

Fig. 7. The temperature dependences of the specific heat under the field of 1 T along the c-axis. The result in the zero field is also plotted.

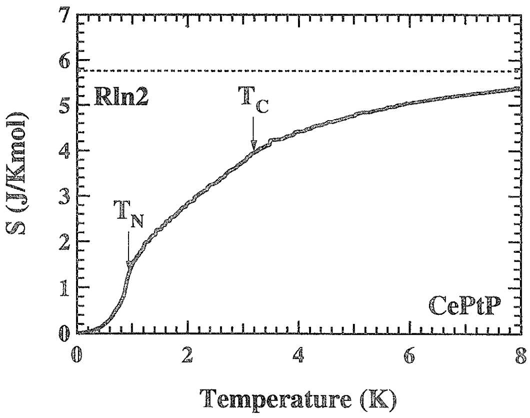

Fig. 8. The temperature dependences of the entropy S in the zero field.

gest that the antiferromagnetic phase transition occurs at 1 K.

It should be noted that the anisotropy of the magnetic properties of CePtX (X=Sb, As, P) vary drastically with a variation of pnictogen. In CePtSb, the easy direction exists within the c-plane, and χ_a and χ_c dependences are just like χ_c and χ_a of CePtP, respectively.[8] As for CePtAs, the anisotropy is very small and both χ_a and χ_c obey the Curie Weiss law above 50 K.[6,7] One of the explanations for the variation of the anisotropy, especially the change of the easy axis of magnetization, is that $|5/2>$ component in the ground state split by the crystalline field of Ce-I site increases with variation of pnictogen from Sb to P. In CePtX, the nearest Ce-Ce distance within the c-plane decreases from CePtSb to CePtP, although that of between c-plane is scarcely changed. It can be considered, as a result, that f orbital tends to expands within the c-plane rather than along the c-axis because of the advantages for coulomb energy, leading to the enlargement of $|5/2>$ component in the ground state wave function. Based on the calculation of a crystalline field of CePtX, using a point charge model with an ionic configuration of $Ce^{3+}Pt^0X^{3-}$, the contribution of $|1/2>$ in the ground state of CePtSb is larger than that of $|5/2>$, in qualitative agreement with the neutron study,[5] resulting in the large moment within the c-plane. As for the result of CePtP, the ground state of Ce-I site mainly consists of $|5/2>$ and the magnetic moment exists along the c-axis, in good agreement with the magnetization measurements. As for Ce-II site of CePtAs and CePtP, ground state is of $|5/2>$.

Finally, we show the thermal properties of CePtP. Figure 7 shows the temperature dependences of the specific heat under the field of 1 T along with the c-axis. The result measured in the zero field is also plotted for comparison. By applying magnetic field, the peak at 3.1 K disappears and another broad maximum is observed around 5 K. On the contrary, the peak at 1 K shifts toward lower temperature. Such responses of the peak to the magnetic field are typical for ferromagnet (higher peak) and antiferromagnet (lower peak) respectively and consistent with the magnetic behaviors. Figure 8 shows the temperature dependences of the entropy S in the zero field, obtained by integrating C/T for T. S at T_N and T_C are 1.5 and 3.9 J/Kmol, respectively, which are much smaller than $R\ln 2$ expected from the ground state doublet split by the crystalline field. This indicates that short range magnetic interaction persists at high temperature compared with the transition temperatures and this system may be suitably described as quasi-two-dimensional system. Such a feature of C, or S, is also observed in the metamagnetic CePtAs,[6,7] but not found in usual ferromagnet CePtSb. It is suggested that the anomalous behaviors in the magnetization curves of CePtP, also in CePtAs, may arise from this two-dimensionality, and we need more detailed studies to make clear the origin of these anomalies.

In summary, the physical properties of CePtP have been experimentally studied. By comparison with the results of CePtAs, the strong anisotropy observed in the electrical resistivity should originate essentially from the non-f Fermi surface of La compound. Magnetic properties also show strong anisotropy with easy direction along the c-axis. It is suggested that the variation of the magnetic anisotropy in CePtX system arises mainly from the stabilization of $J_Z = |5/2>$ state of trigonal site due to contraction of a-axis with X from Sb to P. Furthermore, the curious behaviors, such that successive magnetic transitions or anormalous magnetization curve along the c-axis below T_N, may be originated from the two-dimensionality of magnetic interactions suggested from the suppression of the entropy.

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