# Field-induced ferromagnetic transition in $PrInNi_4$

Naohito Tsujii [1] Hideaki Kitazawa, Hiroyuki Suzuki, Giyuu Kido, Motoharu Imai

*National Institute for Materials Science, Tsukuba 305-0047, Ibaraki, Japan*

**Abstract**

Magnetic and electrical properties of new ternary compounds $R$InNi$_4$ with $R$ = Ce, Pr and Tm have been investigated. The magnetic susceptibility $\chi$ and the electrical resistivity $\rho$ show the absence of magnetic order in these systems down to 2 K at low fields. $\chi$ of CeInNi$_4$ indicates that the Ce ion is close to $Ce^{4+}$ state. For PrInNi$_4$, while $\chi$ at the field of $H$ = 0.1 T shows a characteristic behavior of a nonmagnetic ground state due to a crystal field splitting, the magnetization $M$ for $H \geq 0.75$ T reveals the presence of a ferromagnetic transition at $T_c \sim 3$ K. Moreover, the $M$ vs. $H$ for $T \leq 4$ K exhibits a metamagnetic transition at $H_c \sim 1$ T. It is suggested that a significant mixing of the crystal field levels is relevant to the field-induced transition in PrInNi$_4$.

*Key words:* ferromagnetic transition ; nonmagnetic ground state ; metamagnetic transition

Rare-earth intermetallics with the cubic MgSnCu$_4$-type structure show a variety of interesting magnetic properties, including the valence-transition in YbInCu$_4$ [1,2] and the antiferromagnetic phase with a partially-disordered magnetic structure in GdInCu$_4$ [3]. The series $R$InNi$_4$ ($R$ = rare earth) has been relatively unstudied, and only recently it has been reported that YbInNi$_4$ orders ferromagnetically with a reduced spontaneous moments [4]. The compounds with Ce, Pr and Tm ions are also expected to show interesting phenomena from the viewpoint of mixed-valence or quadrupolar effect. In this paper, we report the magnetization and resistivity of $R$InNi$_4$ with $R$ = Ce, Pr and Tm.

Polycrystalline samples of $R$InNi$_4$ ($R$ = Ce, Pr and Tm) were prepared by the same procedure described in ref. [5]. X-ray diffraction reveals that all the three systems crystallize in the MgSnCu$_4$-type structure. The lattice constants were determined to be a = 7.076, 7.144, and 6.996 Å for $R$ = Ce, Pr and Tm, respectively.

Figure 1 shows the magnetic susceptibility $\chi$ of $R$InNi$_4$ as functions of temperature $T$. For all the three systems, no evidence of magnetic order is observed. $\chi$ of PrInNi$_4$ and TmInNi$_4$ show Curie-Weiss behavior, and the effective magnetic moments are consistent with those expected for $Pr^{3+}$ and $Tm^{3+}$ ions. On the other hand, $\chi$ of CeInNi$_4$ is almost independent to $T$ and shows small values less than $1\times10^{-3}$ emu/mol.

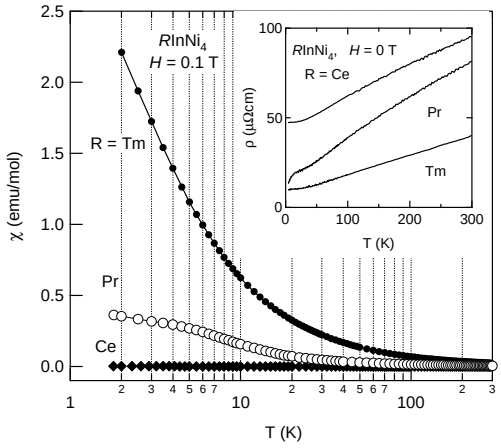


Fig. 1. Temperature dependence of the magnetic susceptibility of $R$InNi$_4$ with $R$ = Ce, Pr and Tm at 0.1 T. Inset shows temperature dependence of the electrical resistivity measured at zero fields.

[1] Corresponding author, E-mail: TSUJII.Naohito@nims.go.jp

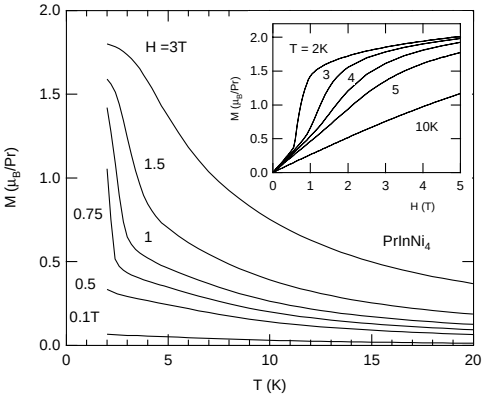


Fig. 2. Temperature dependence of the magnetization of $PrInNi_4$ measured at the applied fields of $H = 0.1$, 0.5, 0.75, 1, 1.5 and 3 T. Inset shows field dependence of the magnetization measured at the temperatures of $T = 2$, 3, 4, 5, and 10 K.

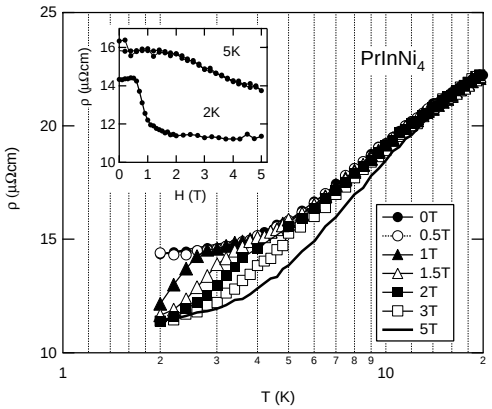


Fig. 3. Temperature dependence of the electrical resistivity of $PrInNi_4$ measured at fixed fields. Inset shows field dependence of the resistivity at 2 K and 5 K.

This indicates that the Ce ion is close to $Ce^{4+}$, consistent with the significantly smaller lattice constant of $CeInNi_4$ than that of $PrInNi_4$. For $PrInNi_4$, $\chi$ shows a saturation behavior below 10 K. This is characteristic of a nonmagnetic ground state due to a crystal-field (CF) splitting with an excited level approximately 10-20 K above the ground state [5].

The inset of Fig. 1 shows the electrical resistivity $\rho$ as functions of $T$. $\rho$ of $CeInNi_4$ and $TmInNi_4$ show no anomaly. For $PrInNi_4$, $\rho$ shows a downturn below about 20 K. This is attributed to the CF splitting, consistent with the $\chi$-$T$ data.

Figure 2 shows the magnetization $M$ of $PrInNi_4$ as functions of $T$. $M$ for $H = 0.1$ and 0.5 T show no evidence of magnetic ordering. For $H = 0.75$ T, one finds an abrupt increase in $M$ at 3 K, indicating a ferromagnetic transition at $T_c \sim 3$ K. For $H \geq 1$ T, $T_c$ shifts to higher $T$ with increasing $H$. Magnetic moments at low $T$ are close to 2 $\mu_B$. Such a large moments cannot be explained by the Van-Vleck contribution. We therefore propose that a significant mixing of the CF levels occurs due to ferromagnetic interaction. This is also suggested by the calculation based on the CF effect and ferromagnetic interaction [6].

The inset of Fig. 2 shows $M$ of $PrInNi_4$ as functions of $H$ measured at various $T$. For $T = 2$ K, a metamagnetic transition is seen at $H_c = 0.65$ T. This is attributed to a nonmagnetic-ferromagnetic (N-F) transition. It should be noted that N-F transitions by field have been only observed in limited systems such as itinerant electron systems like $YCo_2$ or $Co(S,Se)_2$ [7], and the localized moment system $CsFeCl_3$ [8]. $PrInNi_4$ is therefore a rare example of a localized moment system with a N-F transition induced by field. This unusual transition may be a result of a competition of the CF splitting and ferromagnetic interaction.

Figure 3 shows $\rho$ vs. $T$ for $PrInNi_4$ measured at various $H$. For $H \leq 0.5$ T, $\rho$ shows no anomaly, suggesting the absence of magnetic ordering. For $H \geq 1$ T, $\rho$ drops at around $T_c$. This provides the evidence that the magnetic ordered state evolves only under magnetic fields.

It is notable that in Fig. 3, $\rho$ above $T_c$ is not largely affected by $H$. This suggests that the mixing of the CF levels develops rapidly around $T_c$. This is supported by the $\rho$ vs. $H$ curve, shown in the inset of Fig. 3. For 2 K, $\rho$ drops abruptly at $H = 0.7$ T due to the N-F transition. Notably, $\rho$ is almost flat for $H < 0.5$ T and $H > 1$ T, suggesting an abrupt change of the electronic state by the mixing of the CF levels. On the other hand, $\rho$ at 5 K decreases linearly with increasing $H$, indicating a gradual mixing of the CF levels.

Finally, we note the result of a preliminary specific heat measurement, which indicates that the lowest CF level in $PrInNi_4$ is the nonmagnetic doublet $\Gamma_3$. Since the $\Gamma_3$ state has a quadrupolar moment, the correlation of the N-F transition and the quadrupolar moment is of interest, and is to be studied.

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