High-field metamagnetism of giant anisotropy antiferromagnet PrCo$_2$Ge$_2$

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Abstract. We report on anisotropy of magnetic, transport and elastic properties in the PrCo$_2$Ge$_2$ single crystal measured down to 2K and magnetic fields up to 14T. The zero field data reflects two anomalies, $T_N = 28$ K and order-to-order transition at $T_R = 8$ K. Within application of magnetic field along the c-axis these transitions join each other in field about 9 T. The properties measured at 2K with respect to the magnetic field applied along the c-axis reflect two field-induced transitions (2 T and 10 T). The high field transition is accompanied by significant drop in magnetoresistance (5%) and magnetostriction ($7 \times 10^{-3}$).

1. Introduction
Within the large family of tetragonal ThCr$_2$Si$_2$ compounds, the extraordinary large magnetic anisotropy has been reported for Pr compounds. These compounds crystallize in the body-centered structure with space group I4/mmm. The physical, especially magnetic properties reflect the layered nature of this structure, which can be described as layers of atoms of the same kind (R-T-X-T) stacked along the tetragonal axis. Due to the strong magnetocrystalline anisotropy, the Pr moments are usually confined along the c-axis, leaving the magnetization along the direction within the basal plane to mimic paramagnetic behavior irrespective to the type of magnetic ordering.

The studies on neighboring compound PrCo$_2$Si$_2$ revealed three different magnetic phases below $T_N = 30$ K connected with change of magnetic structure [1]. For the field applied along the c-axis the transition between phases reflects itself as a step like transition on the magnetization measured in low temperatures.

In this work we present results of preparation, X-ray and microprobe characterization of PrCo$_2$Ge$_2$ single crystal and subsequent study of the magnetization, specific heat, electrical resistivity and thermal expansion as a function of temperature and magnetic field.

2. Results
PrCo$_2$Ge$_2$ sample was prepared by modified Czochralski method in tri-arc furnace using elements of at least 3N purity. We obtained 1.4 cm long monocrystalline ingot with maximum diameter 0.5 cm. The quality of the sample was checked by microprobe and X-ray diffraction ($a = 405$ pm, $c = 1021$ pm) showing that the sample is single-phase and monocrystalline. The commercial PPMS apparatus was used for the measurement of specific heat (double relaxation method), magnetization (extraction method), resistivity and thermal expansion and magnetostriction (microdilatometric capacitance cell [2]).
The temperature dependence of the specific heat is shown in Figure 1(a). The curve recorded without magnetic field reflects the order-to-order transition at $T_R = 8$ K as a wide bump and peaked shaped signature of antiferromagnetic ordering at 28 K. The low temperature upturn below ~ 8 K is probably caused by the crystal field (CF) contribution; however, an additional experiment below 2 K would clarify the scenario. The anomalies are moving with application of magnetic field (along the c direction) to each other and in fields above 9 T are visible only as one wide bump, which is almost suppressed in 14 T. The residual bump on the 14 T curve is originated by the Schottky type contribution due to the CF splitting of the Pr ion ground state multiplet. With application of the magnetic field the ground state degeneracy is lifted and the CF level scheme is modified. As a consequence, the specific heat data exhibit wide-ranging anomalies also in the field induced ferromagnetic state.

The temperature dependence of magnetization in various fields is presented in the Figure 2(b). While the 2 T and 4 T curves show both anomalies following similar trends as observed in the heat capacity data, the higher-field data comprise only one pronounced peak attributed to the paramagnetic

Figure 1 (a) Specific heat measured with respect to the temperature for several magnetic field applied along the c-axis. The line is data obtained on nonmagnetic analogue LaCo$_2$Ge$_2$. (b) Temperature dependence of resistivity without field and under magnetic field 14T (applied along c-axis) and its difference. (c) Temperature dependence of thermal expansion measured along main directions (reference at $T_N$). (d) Longitudinal magnetostriction measured for field applied along the c-axis. The inset shows a detail of low field transition.
antiferromagnetic transition. The suppression of the lower-lying effect occur due to large increase of magnetization in fields in the vicinity of the field-induced metamagnetic transition as confirmed by magnetization isotherm measurements above 20 K (not shown). The magnetization curve at 2 K is depicted in the Figure 2(a), there are visible two field-induced transitions – at 2 T and 10 T for field applied along the c-axis. The saturated magnetic moment value reaches 3.29 $\mu_B$ (at 2 K). There is a small ferromagnetic contribution (~0.2 $\mu_B$ at 2 K) indicating additional ferromagnetic component in ordered state. There is only a paramagnetic-like response observed in the perpendicular direction.

The temperature dependence of resistivity is shown in the Figure 1(b). The $T_N$ related anomaly is clearly visible as a transition from the Debye-like behavior to almost quadratic dependence ($R \sim T^2$). The $T_N$ anomaly is visible only in the derivative or the difference. Both transitions are smeared out in the field of 14 T applied along $c$-axis. The application of magnetic field (14T) along the $a$-axis does not change the zero-field temperature evolution of resistivity. The low-field metamagnetic transition is not visible on the 2 K magnetoresistance curve, whereas 10 T transition is accompanied by 5% decrease in magnetoresistance (Figure 2a). The thermal expansion measurement shows a contraction along the $c$-axis and prolongation along the $a$-axis below the $T_N$ (Figure 1(c)), there are no clear anomalies in the vicinity of $T_N$. These two opposite effects almost compensate each other (due to higher multiplicity of $a$-axis) and the resulting volume change reflects only slight change in the vicinity of $T_N$. The magnetostriction measured along the $c$-axis for field applied longitudinally shows a small step ($\sim 1 \times 10^{-5}$) at the 2 T transition and large expansion ($\sim 7 \times 10^{-3}$) along $c$-axis for high field transition.

3. Conclusions
The presented results provide a general overview concerning the anisotropy and connected physical properties in the single crystal PrCo$_2$Ge$_2$. There are two visible transitions on the temperature dependencies of physical properties connected with antiferromagnetic ordering and with change of magnetic structure. At 2 K there are two field-induced transitions for field applied along the $c$-axis. The 10 T transition is connected with remarkable anomalies in transport and elastic properties. There is no significant influence of physical properties if field is applied perpendicularly.

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References
[1] Sugiyama K, Yonenobu K, Date M, Shigeoka T and Fujii H 1992 Physica B 177 275
[2] Rotter M, Muller H, Gratz E, Doerr M, Loewenhaupt M 1998 Rev. of Sci. Instr. 69 2742