Low temperature magnetotransport in RB₆ (R = Pr, Nd)

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Abstract. Low temperature magnetoresistance (MR) has been studied on RB₆ (R=Pr, Nd) single crystals at temperatures in the range 2–20 K in magnetic fields $H \leq 8$ T. The small and negative MR is observed in paramagnetic (PM) phase and it changes to a large positive MR effect in antiferromagnetic (AFM) states of PrB₆ and NdB₆. The analysis of the experimental data allowed us to deduce three contributions to MR in PrB₆ and NdB₆. In addition to the main Brillouin type negative component $-\Delta \rho / \rho \sim M_{loc}^2 \sim H^2$ which is interpreted in terms of K. Yosida theory both the linear and nonlinear magnetic contributions were also established. The detailed analysis permitted us to interpret the last component in terms of the MR response from ferromagnetic (FM) nanodomains embedded in the metallic RB₆ matrix. The results of the study allow to conclude in favour of the concurrence between AFM and FM interactions as the reason of incommensurate (IC) magnetic structure formation in RB₆ (R=Pr, Nd).

1. Introduction

Nowadays among all strongly correlated electron systems the rare earth hexaborides (RB₆) have attracted much attention due to their extraordinary physical properties and unusual ground state formation to be depend on the rare earth ion. For instance, LaB₆ is nonmagnetic metal [1] and CeB₆ is usually considered as a dense Kondo system with the heavy fermion type behaviour [2] while PrB₆ and NdB₆ are the local magnetic moment (LMM) antiferromagnets (AFM) [3]. The valence–fluctuating system SmB₆ is a narrow band semiconductor with the gap value $E_g \sim 19$ meV [4] and the compound with colossal magnetoresistance EuB₆ is ferromagnet which demonstrates the semimetallic behaviour [5].

The magnetic properties of these compounds are essentially influenced by the filling of internal 4f–shell, especially in the light RB₆ (R=La, Ce, Pr, Nd). In particular, CeB₆ and PrB₆ have the intermediate magnetic phases: antiferroquadrupolar phase was found in CeB₆ above $T_s(CeB₆) \sim 2.3$ K in [2] and IC antiferromagnetic state was detected in PrB₆ in the interval $T_s \sim 4.2$ K $< T < T_s(PrB₆) \sim 7$ K [6]. On the contrary, the only one AFM state was established in NdB₆ [7]. Note that the genesis of intermediate phases in CeB₆ and PrB₆ is the subject of discussion up to now [6, 8], so, the aim of present study was to investigate magnetotransport properties of the light hexaborides RB₆ (R=Pr, Nd).

2. Experimental details

The high quality single crystals of investigated RB₆ (R=Pr, Nd) compounds were grown by the crucible–less inductive zone melting in the inert gas atmosphere. To provide the necessary conditions
for high precision MR measurements both the high relative accuracy of magnetic field ($\Delta H/H \sim 10^{-5}$ at 8 T) and temperature stabilization ($\Delta T \sim 0.01$ K) were achieved using the precision superconducting magnet power supply SMPS–120 and temperature controller TC1.5/300 (Cryotechnics and Electronics Ltd.) together with temperature sensor CERNOX 1050 (LakeShore Cryotronics) correspondingly.

The comprehensive study of low temperature MR has been carried out on the high quality PrB$_6$ and NdB$_6$ single crystals at temperatures 2–20 K and in magnetic fields up to 8 T.

3. Results and discussion

The temperature dependences of electrical resistivity for PrB$_6$ and NdB$_6$ in $H=0$ T and $H=7$ T are presented in figure 1a and 1b correspondingly. The drastic decrease of $\rho(T)$ observed at low temperatures in both compounds corresponds to the AFM transitions at $T_N(\text{PrB}_6) \sim 7$ K and

![Figure 1](image1.png)

**Figure 1.** The temperature dependences of resistivity $\rho(T)$ for PrB$_6$ (a) and NdB$_6$ (b) at $H=0$ T and $H=7$ T.

Figure 2. Field dependences of $\Delta \rho(H)/\rho$ for PrB$_6$ (a, b) and for NdB$_6$ (c, d) in AFM (a, c) and PM (b, d) states correspondingly. The curves $\Delta \rho(H)/\rho$ are shifted from each other for convenience.

![Figure 2](image2.png)
The positive magnetoresistance was found in magnetically ordered phases of PrB₆ and NdB₆ (Figure 2a, 2c). However, the increasing of temperature is accompanied with the drop and the polarity changes of $\Delta \rho / \rho$ for PrB₆ and NdB₆ (Figure 2a, 2c). As a result, the PM state of these compounds is characterized by the small negative magnetoresistance in the whole range of magnetic field up to 8T (Figure 2b, 2d correspondingly).

The high accuracy of the data obtained allow us to make the procedure of the numerical derivation of $\Delta \rho(H)/\rho$. It was found that the behaviour of $d(\Delta \rho/\rho)(H)/dH$ for PrB₆ and NdB₆ can be well fitted by the linear dependence $A+BH$ in the fields $H>3$ T. Finally, from this procedure three contributions to MR in PrB₆ and NdB₆ were deduced (Figure 3a–b and 4c–d correspondingly): (I) the quadratic Brillouin type component ($-B(T)H^2$), (II) the linear ($-A(T)H$) and (III) nonlinear magnetic ($D(T,H)$) ones. The existence of the components (I)–(III) may be interpreted in terms of several regimes in the magnetic scattering in PrB₆ and NdB₆. Namely, in paramagnetic phase of PrB₆ and NdB₆ there exists only one Brillouin type negative contribution (I) caused by the magnetic scattering of charge carriers on R³⁺ LMM. The transition to AFM state leads to the appearance of additional two parts (II) and (III) that should be understood as new magnetic features of scattering.

The negative Brillouin type component (I) may be interpreted in the framework of K. Yosida theory [9] which describes the scattering of charge carries on LMM by the relationship between the MR and local magnetization $M_{loc}$

$$-\Delta \rho / \rho \sim M_{loc}^2 \sim H^2$$

To extend the approach [9] and explain the appearance of three various contributions (I)–(III) in MR the authors of [10] adduce the phenomenological conception of spin polarons embedded in the metallic matrix. So, additionally to the $M_{loc}$ the contribution from ferromagnetic nanodomains $m_{loc}$ was included in equation (1). In the low magnetic fields the equation may be rewritten

$$-\Delta \rho / \rho \sim (M_{loc} + m_{loc})^2 \sim BH^2 + A(M_{loc} \cdot m_{loc}) + D_0(m_{loc})^2$$

The temperature dependences of (I)–(III) contributions (coefficients $B(T)$, $A(T)$ and $D_0(T)$ correspondingly) presented on Figure 4a–c for PrB₆ and on Figure 4d–f for NdB₆ demonstrate the
drastic changes in vicinity of the magnetic phase transition temperatures $T_N$, $T_M$ in these compounds. In particular for PrB$_6$, the amplitude of magnetic component (III) changes its polarity at $T\sim T_M$, conforming to the transition from commensurate to incommensurate phase. In the case of NdB$_6$ pronounced anomalies are also recorded at $T^*\sim 4$ K for all three contributions. The behaviour of magnetic contribution $D_0$ likely indicates the transformation of magnetic structure of NdB$_6$ around $T^*$. Such transformation may be connected with the traces of the second order phase transition which is similar to that one observed in the case of PrB$_6$. But the last hypothesis requires the further investigation.

In summary, we have performed the precision measurements of MR in PrB$_6$ and NdB$_6$ at temperatures 2–20 K and in magnetic fields up to 8 T. The results and undertaken analysis allow to conclude in favour of the concurrence between AFM and FM interactions as the main reason of incommensurate magnetic structure formation in RB$_6$ (R=Pr, Nd).

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