Anisotropy of magnetoresistance in Pr\textsuperscript{11}B\textsubscript{6} and NdB\textsubscript{6}

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Abstract. The anisotropy of magnetoresistance (MR) is studied in magnetic phases of Pr\textsuperscript{11}B\textsubscript{6} and NdB\textsubscript{6} by sample rotation technique in fixed magnetic field (\(\mu_0 H \leq 8T\)) to be perpendicular to the axis of rotation \(I||<110>\). The obtained \(\rho(\phi, T_0, H_0)\) data allowed us to estimate the maximal value of MR anisotropy which approaches the values \(\sim 18\%\) and \(\sim 8\%\) for PrB\textsubscript{6} and NdB\textsubscript{6} in commensurate (C) phase (\(T< T_M \sim 4.6K\) for PrB\textsubscript{6} and \(T<T_N \sim 7.7K\) for NdB\textsubscript{6}) at \(T=2.8K\) in the field interval \(3T \leq \mu_0 H \leq 4T\). In the vicinity of phase boundary to incommensurate (IC) magnetic phase of PrB\textsubscript{6} (\(T_M < T<T_N \sim 6.7K\)) the strong enhancement MR anisotropy along the direction \(H||<110>\) is obtained. The behavior of the field dependencies of MR for PrB\textsubscript{6} indicates an existence of new magnetic phase at \(T<T_M\) for the direction \(H||<110>\). The analysis of \(\Delta \rho/\rho(\phi, T_0, H_0)\) data allowed us to conclude about a significant role of 5d-spin polarization in the formation of magnetically ordered state in these compounds.

1. Introduction

Hexaborides PrB\textsubscript{6} and NdB\textsubscript{6} are antiferromagnetic (AFM) metals which are placed in the family of RB\textsubscript{6} between CeB\textsubscript{6} and SmB\textsubscript{6}. The filling of internal 4f-shell in the row of RB\textsubscript{6} (R=Ce, Pr, Nd) leads to depression of intermediate magnetic phase. In particular, CeB\textsubscript{6} and PrB\textsubscript{6} have the intermediate magnetic phases: spin density wave AFM phase was found in CeB\textsubscript{6} above \(T_N(CeB_6) \sim 2.3K\) in [1] and IC AFM state was detected in PrB\textsubscript{6} in the interval \(T_{AFM} \sim 4.2K < T < T_N(PrB_6) \sim 7K\) in [2]. On the contrary, the only one AFM state (\(T_N \sim 8K\)) was established in NdB\textsubscript{6} for \(\mu_0 H \leq 15T\) [3]. Moreover the strong dependence of H-T phase boundary on magnetic field orientation was detected in these compounds [2-4] (see also Fig.1). For instance, the authors of [2] established the transition to simple collinear magnetic structure in magnetic field \(\mu_0 H \sim 2T\) for direction \(H||<110>\) in PrB\textsubscript{6}. Neodymium hexaboride is also characterized by the magnetic transition in high magnetic fields \(\mu_0 H \geq 15T\) only for direction \(H||<111>\) [3]. The investigation of angular dependence of resistivity and transverse magnetoresistance may be considered as appropriate tool for testing the magnetic anisotropy and it was undertaken here to get detailed information of the nature of magnetic phases and magnetic interactions in RB\textsubscript{6} (R=Pr, Nd).

2. Experimental details

The high quality single crystals of investigated RB\textsubscript{6} (R=Pr, Nd) compounds were synthesized by
Figure 1. The magnetic H-T phase diagram for (a) PrB$_6$ and (b) NdB$_6$. The data are taken from [2-4]. The experiment on panel (a) represents the results obtained from MR analysis.

the crucible-free inductive zone melting. The angular dependencies of resistivity $\rho(\phi, T_0, H_0)$ have been measured by sample rotation technique [1] in fixed magnetic field to be perpendicular to the axis of rotation (see the inset on Fig.2b) where the current configuration $I||<110>$ was applied.

The comprehensive study of transverse magnetoresistance anisotropy has been carried out on the high quality Pr$_{11}$B$_6$ and NdB$_6$ crystals at low temperatures 2–9K in magnetic fields up to 8T.

3. Results and discussion

The obtained angular dependencies of normalized resistivity $\rho(\phi, T_0, H_0)/\rho(0, T_0, H_0)$ for NdB$_6$ and PrB$_6$ are presented on Fig.2 and Fig.3 correspondingly. For both compounds the essential influence of the orientation in magnetic field is obtained. In particular the curves of normalized resistivity for NdB$_6$ are characterized by two minimums corresponding to orientation of magnetic field $H$ along $<110>$ and $H||<100>$. At the same time the shape of the minimum corresponding to $H||<110>$ direction evolves with temperature (Fig.2b). The increasing of the temperature in the interval $T^*~4K<T<T_N~7.7K$ is accompanied by the visible decreasing of this minimum (Fig.2b). For convenience the temperature dependence of transverse magnetoresistance anisotropy for NdB$_6$ is also presented for magnetic field $\mu_0H=4T$ on Fig.4a.

The behavior of the angular dependent resistivity in NdB$_6$ reveals the distinctive point around $T^*~4K$. It is evident that the character of scattering process is changing along the direction $H||<110>$ in AFM phase of NdB$_6$. Moreover in accordance with results obtained in [5] from analysis of magnetoresistance the peculiarity at $T^*$ may represent possible changing in magnetic structure of NdB$_6$. In particular this point is distinct on temperature dependencies of the amplitude of magnetic contribution to magnetoresistance [5]. This result correlates with assumption about the formation of small 5d-magnetic polaron (ferrons) embedded in the metallic matrix of the hexaboride [5].

The anisotropy of resistivity in magnetic field for PrB$_6$ is shown on Fig.3 for (a) AFM IC phase and (b) AFM C phase ($T_M~4.6K$ for Pr$_{11}$B$_6$). The shape of the curve $\rho(\phi)/\rho(0)$ in AFM IC state Fig.3a is similar to the case of NdB$_6$. In the limit of the low magnetic fields the curve takes the shape of meander that is shifted in phase by 90$^0$ with respect to the maxima for NdB$_6$. However in high magnetic fields $\mu_0H\geq4T$ there are small minimum in the vicinity of orientation $H||<100>$ and deep minimum along $<110>$ direction. The transition to AFM C state is accompanied by arising of the strong anisotropy of resistivity, Fig.3b. The huge positive peak appears at high magnetic fields $\mu_0H\geq4.5T$ in narrow angular interval in the immediate vicinity of the direction $H||<110>$.

Taking into account very strong anisotropy of resistivity in magnetic field it was of interest to
Figure 2. The angular dependencies of magnetoresistance $\rho(\phi)/\rho(0)$ for NdB$_6$ (a) at temperatures $T<T^*$ and (b) $T>T^*$. The vertical lines designate solid $\mathbf{H}||<110>$, dash-$\mathbf{H}||<100>$, and dash-dot $\mathbf{H}||<111>$ directions. The inset on panel (b) shows the field-current configuration of the experiment. The data at $T=9K$ (PM phase) are presented for comparison.

carry out the MR investigation for the direction $\mathbf{H}||<110>$ in PrB$_6$. The results of the study are presented on Fig.4b (upper curves for $\mathbf{H}||<110>$ and lower two curves for $\mathbf{H}||<001>$ orientations). Fig.4b demonstrates the strong magnetoresistance enhancement with increasing of magnetic field and hysteresis that observed for sweep up and sweep down magnetic field changes for temperatures

Figure 3. The angular dependencies of magnetoresistance $\rho(\phi)/\rho(0)$ for PrB$_6$ in (a) AFM IC and (b) AFM C magnetic phases correspondingly. The vertical lines designate solid $\mathbf{H}||<110>$, dash-$\mathbf{H}||<100>$, and dash-dot $\mathbf{H}||<111>$ directions. The data at $T=9K$ (PM phase) are presented for comparison.
Figure 4. The anisotropy of magnetoresistance for (a) NdB₆ and (b) PrB₆. The panel (a) represents the temperature dependencies of \( \rho(\phi)/\rho(0) \) for directions \( H \| <111> \) and \( H \| <110> \) at \( \mu_0 H = 4T \). The panel (b) demonstrates the field dependencies of \( \Delta \rho/H \| <110> \) and \( \Delta \rho/H \| <001> \) in AFM phase of PrB₆.

The high accuracy of the data obtained allowed us to make the procedure of numerical derivation of \( \Delta \rho/\rho \). It was found the existence of two peculiarities on the curves of \( d(\Delta \rho/\rho)(H)/dH \) at \( T \leq 4.8K \). This finding indicates an existence of a new magnetic phase AFM₂ for the direction \( H \| <110> \) at low temperatures (see Fig.1b). The magnetic phase diagram of PrB₆ was investigated previously by magnetization [2] and with the help of the longitudinal magnetoresistance [4] measurements (see Fig.1b). However there was existed a large discrepancy between \( T_m(H) \) data from [2] and [4]. This distinction may be explained in this our study where the new AFM₂ phase was found. In the view of magnetic hysteresis we suppose that new magnetic phase may have the ferromagnetic nature. Similar conclusions were deduced from the results of MR investigation [5]. The analysis of magnetoresistance in [5] showed on the formation of magnetic nanoclusters from the pair of localized magnetic moments of Pr³⁺ ions and 5d-ferrons in AFM phase of PrB₆.

In summary we have performed the precision measurements of MR anisotropy in Pr₁₁B₆ and NdB₆ at temperatures 2-9K in magnetic field up to 8T. The results of the data obtained indicate on the noticeable magnetic anisotropy and the significant role of 5d-spin polarization in the formation magnetically ordered state in these RB₆ compounds.

References
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