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## Magnetic and Transport Properties of $\text{CeCo}_{12}\text{B}_6$ and $\text{CeFe}_2\text{Co}_{10}\text{B}_6$ Compounds under Pressure

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Study of pressure effects on magnetic and transport properties of  $\text{CeCo}_{12}\text{B}_6$  and  $\text{CeFe}_2\text{Co}_{10}\text{B}_6$  was performed in temperature range 5–300 K at pressures up to 9 kbar. The significant decrease in the Curie temperature  $T_C$  as a consequence of Fe substitution from  $(135 \pm 1)$  K to  $(85 \pm 1)$  K is not accompanied by the changes of saturation magnetization. The decrease in  $T_C$  with pressure is the same for both samples —  $\Delta T_C / \Delta p \approx -0.5$  K/kbar. The relative decrease in saturation magnetization with pressure is about 0.3%/kbar for both samples. Pressure induced resistivity changes were below 1%. The relatively low pressure effect on both the  $T_C$  and magnetization can be attributed to the hybridization as a consequence of small distances between the Co and B atoms.

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### 1. Introduction

The  $\text{RCo}_{12}\text{B}_6$  borides (R = rare earth) exhibit low Co magnetic moment and ordering temperatures below room temperature. They crystallize in the rhombohedral structure of the  $\text{SrNi}_{12}\text{B}_6$  type (space group  $R\bar{3}m$ ) [1]. Co atoms are located on two crystallographically inequivalent sites, the rare-earth ions and boron atoms occupy one additional site each. Their ordering temperatures below 300 K and low Co magnetic moment —  $0.45 \mu_B/\text{Co}$  atom for  $\text{YCo}_{12}\text{B}_6$  — are attributed to hybridization of B( $p$ ) and Co( $d$ ) electrons bands as a consequence of small distances between Co and B atoms (2.05 Å) [2]. Due to tetravalent state of Ce ions [2], we assume that there is no moment in Ce sublattice.

Magnetic properties of these compounds can be easily studied both in the paramagnetic and magnetically ordered state. Previous investigation has led to remarkably different values of Co magnetic moments in magnetically ordered state ( $\mu_{\text{Co}} \approx 0.45 \mu_{\text{B}}$ ) and in the paramagnetic state ( $\mu_{\text{Co}} \approx 2.0 \mu_{\text{B}}$ ). This behavior was attributed to the itinerant character of magnetism in these compounds [2].

Both the magnetization and the Curie temperatures are about 15–20% lower than for the isotype compounds containing light rare earths or Y ( $T_{\text{C}} = 134.3 \text{ K}$  for  $\text{CeCo}_{12}\text{B}_6$  [2]). This behavior was attributed to the tetravalent state of Ce in  $\text{CeCo}_{12}\text{B}_6$  [2]. The substitution of Co atoms with Fe atoms in the  $\text{CeCo}_{12}\text{B}_6$  compound leads to a continuous decrease in the transition temperatures and to the disappearance of magnetic order,  $\text{CeCo}_4\text{Fe}_8\text{B}_6$  being a paramagnetic material down to 4 K. The destabilization of ferromagnetic order by Fe substitution in  $\text{RCo}_{12}\text{B}_6$  compounds was observed in compounds with La and Nd [3, 4]. It was attributed to the presence of antiferromagnetic interactions in Fe sublattice and to the low stability of iron magnetic moment.

In order to get information about the role of volume in stability of Co magnetic moment, itinerant character of magnetism and exchange interactions we performed studies of both magnetic and transport properties of  $\text{CeCo}_{12}\text{B}_6$  and  $\text{CeFe}_2\text{Co}_{10}\text{B}_6$  compounds under hydrostatic pressures. Details are already given in the experimental section.

## 2. Experimental

Samples were prepared using the method described in [1]. The crystal structures were determined by X-ray powder diffraction and the samples were found to be approximately single phase (< 5% impurities, probably  $\text{Co}_2\text{B}$ , observed in scanning electron microscopy (SEM)) [5]. The resistivity of the studied compounds was measured in temperature range 5–300 K in close-cycle refrigerator using lock-in amplifier and standard four-point method. The piston cylinder Cu–Be cell and manganin pressure sensor was used for determining the pressure inside cell for resistivity measurements up to 9 kbar. Magnetization studies were performed in commercial SQUID magnetometer (Quantum design) in magnetic field range 0–5 T. The magnetic isotherms were measured at temperatures 5, 20, 50, 80, and 120 K. Miniature Cu–Be pressure cell was used. Pressure was determined by measuring superconducting transition temperature of pure Pb (5N) sample.

## 3. Results and discussion

Change of character temperature dependence of resistivity, corresponding to magnetic phase transition, was observed at temperatures  $T \approx 140 \text{ K}$  and  $T \approx 85 \text{ K}$  for  $\text{CeCo}_{10}\text{B}_6$  and  $\text{CeFe}_2\text{Co}_{10}\text{B}_6$ , respectively. The results obtained at ambient pressure (together with the fit from data under transition temperature) are presented in Fig. 1a. It is hard to make any conclusions about magnetic structure

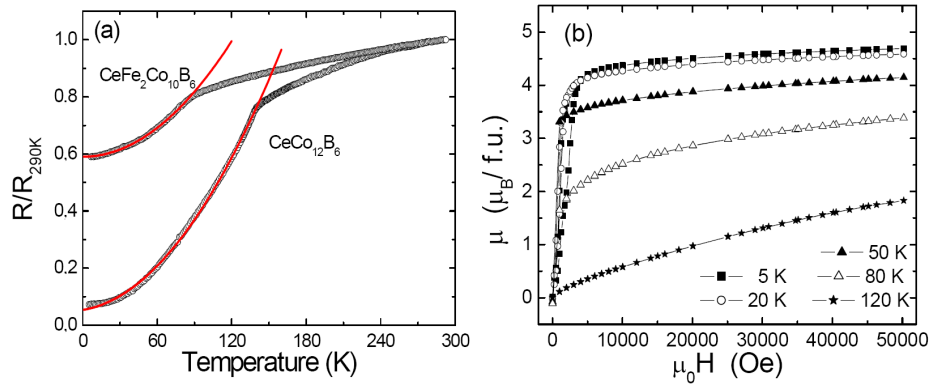


Fig. 1. (a) Temperature dependence of resistivity at ambient pressure and its parabolic fit for both samples; (b) magnetization curves of  $CeFe_2Co_{10}B_6$  for various temperatures at ambient pressure.

from resistivity data, but the observed parabolic behavior of temperature dependence of resistivity is in agreement with paramagnetic–ferromagnetic transition observed in magnetization measurements, see below. Deviation of measured data and fitted parabolic dependence is rather small (less than 1%). Pressure effect on resistivity values was negligible, well comparable with the pressure induced changes of sample dimensions.

The magnetic ordering temperatures determined as a minimum of the derivatives of low field magnetization vs. temperature curves (measured at 100 Oe). Obtained values are  $T_C = (135 \pm 1)$  K and  $T_C = (85 \pm 1)$  K for  $CeCo_{12}B_6$  and  $CeFe_2Co_{10}B_6$  samples, respectively. These values are in good agreement with those deduced from resistivity measurements and with the results of previous works [2, 5]. The saturation magnetization of both compounds obtained from magnetic isotherms have similar magnitude:  $4.8 \mu_B/f.u.$  and  $4.7 \mu_B/f.u.$  for  $CeCo_{12}B_6$  and  $CeFe_2Co_{10}B_6$ , respectively. The magnetic isotherms measured at different temperatures at ambient pressure on  $CeFe_2Co_{10}B_6$  sample are presented in Fig. 1b. The magnetic ordering temperatures of both samples decrease linearly with pressure. The data determined from resistivity measurements and low field magnetization measurements are well comparable. The changes of ordering temperatures for both samples are practically the same,  $\Delta T_C/\Delta p = -0.5 \pm 0.1$  K/kbar. The saturation magnetization linearly decreases with pressure for both samples. The pressure slopes  $\Delta M_S/\Delta p$  at 5 K for  $CeCo_{12}B_6$  sample reached the value  $\Delta M_S/\Delta p = -0.015 \pm 0.001 \mu_B/(f.u. \text{ kbar})$ . The saturation magnetization of  $CeFe_2Co_{10}B_6$  is slightly more pressure sensitive,  $\Delta M_S/\Delta p = -0.017 \pm 0.001 \mu_B/(f.u. \text{ kbar})$ . The results obtained on  $CeFe_2Co_{10}B_6$  sample are visualized in Fig. 2b. Contrary to the clearly ferromagnetic behavior of  $CeCo_{12}B_6$  compound, the low field part of the 5 K magnetic isotherm measured on  $CeFe_2Co_{10}B_6$  sample is rather complex — see Fig. 2a. Pressure enhancement of this low field anomaly can be attributed

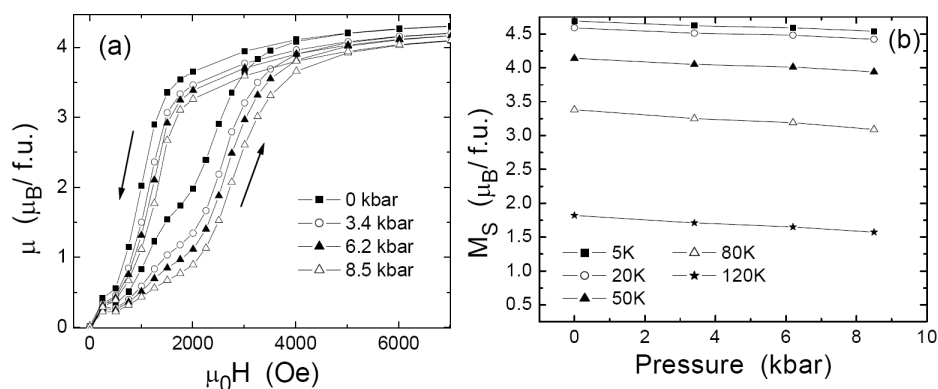


Fig. 2. (a) Magnetization curves for  $\text{CeFe}_2\text{Co}_{10}\text{B}_6$  at various pressures for  $T = 5$  K; (b) pressure induced decrease in saturation magnetization of  $\text{CeFe}_2\text{Co}_{10}\text{B}_6$  sample.

most probably to the well known stabilization of antiferromagnetic interactions by pressure.

We can conclude that the effect of pressure on magnetic properties of  $\text{CeCo}_{12}\text{B}_6$  and  $\text{CeFe}_2\text{Co}_{10}\text{B}_6$  compounds is rather small. Possible reason could be the remarkable role of the hybridization as a consequence of small distances between the Co and B atoms. Similarly a volume stability of highly reduced Co moment was recently observed for tetravalent Th state in  $\text{ThCo}_4\text{B}$  compound [6]. Neutron diffraction studies are necessary to get information about the magnetic ground state of  $\text{CeFe}_2\text{Co}_{10}\text{B}_6$  compound.

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