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Abstract. We present the results of a complex experimental study of the electron transport phenomena in doped manganites of the SmMnO$_3$ system. The temperature dependences of the resistivity, thermopower, and Nernst coefficient were measured in different applied magnetic fields. Specific features of these dependences in different temperature ranges were revealed and discussed. Besides, all the studied transport coefficients demonstrate a similar behavior near the temperature of the magneto-ordered transition, $T_c$. The effects of the colossal magnetoresistance, colossal thermopower, and colossal Nernst coefficient were observed to be qualitatively analogous; all of them show a sharp rise at $T \approx T_c$. It was also found that the value of the Nernst coefficient at temperatures below $T_c$ depends strongly on the applied magnetic field thus demonstrating the anomalous behavior analogous to the one of the Hall coefficient.

1. Introduction

Materials demonstrating the colossal magnetoresistance (CMR) effect (the so-called manganites with a general formula $R_{1-x}A_x$MnO$_3$, where $R$ is a rare-earth metal, $A$ is an alkaline-earth metal) have attracted considerable interest from both practical and fundamental points of view. On the one hand, manganites are considered as perspective materials for applications in magnetic storage systems, magnetic sensors, optoelectronics, and spintronics (see, for example, [1] as a review). On the other hand, they are characterized by a very complicated magnetic phase diagram, a presence of different types of ordering, and a strong coupling between charge, spin, and orbital degrees of freedom associated with Mn ions. As a result, manganites are fascinating systems allowing one to study different intriguing material properties associated with the existence of strong correlation effects. This is why a huge number of papers devoted to both experimental and theoretical investigations of manganites have been published (reviews of the main results can be found in [2-6]). Nevertheless, despite a lot of models proposed and developed to describe unusual properties of manganites, the nature of the CMR effect remains unclear.

One of the widely used methods for studying manganite properties is the experimental investigation of the transport coefficients. First of all, some of them demonstrate an anomalous behavior near the temperature of the magneto-ordered transition, $T_c$, that is a direct consequence of the CMR effect. Second, their temperature dependences both above and below $T_c$ are well known to be characterized by some specific features [2, 6–11] and the questions on their correct description and analysis, as well as on the conduction mechanisms realized in manganites in different temperature ranges call for further investigations. However, most of papers are concentrated, alongside with the magnetization study, on the resistivity, $\rho$, and magnetoresistance effect. The thermopower, $S$, which is sensitive to the type of the charge carriers contributing to the conduction process and the energy spectrum structure has also been widely investigated [6–11] including its modifications under applied magnetic field [7, 8, 12–15]. At the same time, only a few papers have been devoted to the
experimental study of the Nernst effect. Note that the Nernst coefficient, $Q$, in both electron- and hole-doped manganites also demonstrates an anomalous behavior at $T \leq T_c$ [16–20]. According to the classical theory of the electron transport, this magnetotransport coefficient is sensitive not to the charge-carrier type, but to the scattering mechanism. This is obviously of interest to consider the Nernst data together with results on other transport coefficients obtained on the same samples of varied composition, since it is such a comparative analysis that could clarify the nature of the CMR effect.

For the above reasons, this paper aims to perform the complex experimental study of the transport coefficients (the resistivity, thermopower, and Nernst coefficient) in doped manganites of the SmMnO$_3$ system and to reveal the specific features of the modification of their temperature dependences near the temperature of the magneto-ordered transition when applying the magnetic field.

2. Samples and Experimental Details
Ceramic Sm$_{1-x}$Ce$_x$Sr$_y$MnO$_3$ samples with different cerium and strontium contents ($x = 0.05, 0.1, y = 0.35, 0.4$) were used for investigations. All the samples were prepared by the standard solid-state processing technique from high-purity oxides. X-ray diffraction analysis has shown all the samples to be almost of single phase with amount of foreign impurities not exceeding 1–2 %. The sample homogeneity was controlled by measuring the local values of the thermopower in various points on the sample surface at room temperature.

The $\rho(T)$ dependences were measured by the standard four-probe low-frequency ac ($f = 20$ Hz) method. The thermopower was measured by a differential method relative to copper electrodes at the temperature difference between the two ends of a sample of about 2 K and then calculated by correcting for the absolute thermopower of copper. For studying the magnetic field influence on these coefficients, as well as for the Nernst coefficient measurements a constant magnetic field of varied magnitude (up to $H = 1.8$ T) was applied to a sample. To increase the Nernst signal and to exclude a contribution of even magnetic effects to the measured Nernst voltage we used thin samples (of about 1 mm in the $\nabla T$ direction) and a reversible magnetic field. The temperature difference between the two ends of a sample was about 10 K. Details of the Nernst coefficient measurements can be found elsewhere [21]. All the transport coefficients were measured in the temperature range of $T = 77–310$ K. The absolute error in determining the Nernst coefficient values when measuring the $Q(T)$ dependences did not exceed 10 %, the minimal securely fixed $Q$ value at $T = 300$ K was about 0.1 nV/(K∙T).

3. Experimental Results and Discussion
Figure 1 shows the temperature dependences of the resistivity for the Sm$_{0.55}$Sr$_{0.45}$MnO$_3$ and Sm$_{0.45}$Ce$_{0.05}$Sr$_{0.45}$MnO$_3$ samples at various magnetic fields $H$, for other samples they are qualitatively analogous. The resistivity increases strongly with decreasing temperature, has a sharp peak near the temperature of the magneto-ordered transition, and then falls down. Two points should be noted. First, a weak cerium doping leads to a strong decrease in the $T_c$ value (from 143 K for cerium-free sample down to $\approx$90 K and $\approx$75 K for samples with $x = 0.05$ and 0.1 correspondingly, independently of the cerium position in the lattice). Second, the $\rho(T)$ curves in the temperature range of $T = T_c–300$ K fit well by simple exponential functions and despite the absolute values of the resistivity differ essentially for samples of various compositions, the resistivity activation energy remains almost unchanged being about 50 meV. This indicates the characteristics of the conduction process above $T_c$ not to be influenced by the cerium doping. As magnetic field increases, the peak on the $\rho(T)$ curves shifts to higher temperatures and the maximal resistivity value decreases that is typical for manganites of different systems [1–3, 5].

The $S(T)$ dependences measured at zero magnetic field and at $H = 1.5$ T for samples of the Sm$_{0.55}$Sr$_{0.45}$MnO$_3$ and Sm$_{0.5}$Ce$_{0.05}$Sr$_{0.45}$MnO$_3$ compositions are presented in figure 2. The thermopower is negative over the whole measured temperature range. For all the studied samples cerium doping leads to a slight increase in the absolute value of the thermopower at $T = 300$ K. At temperatures far
from the magneto-ordered transition, the $S(T)$ dependences are rather weak. Below $T_c$, the thermopower has a very small value and demonstrates a metallic-like behavior. Above $T_c$, i.e., in the paramagnetic phase, the thermopower has a value of several tens of $\mu$V/K and changes almost linearly with temperature. However, in the cerium-free sample the absolute $S$ value decreases with increasing temperature (see figure 2 (a)), while in all cerium-containing samples it increases with a varying slope. The latter indicates, contrary to the case of the resistivity, that the charge-carrier parameters are influenced by the cerium doping. It should be also noted that, as a whole, the thermopower temperature dependences in Sm-based manganites are not as complicated as in the case of La-based ones [8, 11, 13, 14]. At temperatures near $T_c$, the absolute value of the thermopower falls dramatically and the temperature of this drop increases with increasing magnetic field. This obviously points to a strong modification of the charge-carrier system properties occurring at the transition to the magneto-ordered state. Thus the thermopower behavior near $T_c$ corresponds qualitatively to that of the resistivity.

The Nernst coefficient for all the investigated samples demonstrates a similar behavior. For example, the experimental data obtained on the Sm$_{0.55}$Sr$_{0.45}$MnO$_3$ and Sm$_{0.55}$Ce$_{0.05}$Sr$_{0.45}$MnO$_3$ samples are presented in figure 3. The Nernst coefficient is positive over the whole temperature range studied (both above and below $T_c$) and its values at $T = 300$ K are extremely low (about 1–2 nV/(K·T) depending on the sample compositions). Besides, one can see that there are two temperature ranges on
the $Q(T)$ dependences differing in both the temperature behavior of the Nernst coefficient and the character of the magnetic field influence on its value.

Firstly, at $T > T_c$, the $Q$ value increases very rapidly with decreasing temperature. Like the case of the resistivity, the $Q(T)$ curves can be fitted by an exponential law, but with a different activation energy. For the Sm$_{0.55}$Sr$_{0.45}$MnO$_3$ sample its value is 46 meV that corresponds well to the resistivity activation energy, while for cerium-containing samples it is equal to 15–20 meV, i.e., more than twice less in comparison with the resistivity case. At temperatures sufficiently lower $T_c$, the Nernst coefficient also increases with decreasing temperature, but rather weakly (see figure 3 (a), an analogous $Q$ behavior at $T < T_c$ was observed in the Sm$_{0.55}$Ce$_{0.05}$Sr$_{0.45}$MnO$_3$ sample, for other samples the corresponding temperature range was not observed due to a limited measurement range). Note that for some samples a character of the $Q(T)$ dependences measured in low magnetic fields (up to 0.3 T) does not change at the transition to the magneto-ordered state, so that the Nernst coefficient at $T < T_c$ continues to increase rapidly (see figure 3 (a)). Understanding the physical reasons for the observed peculiarities of the temperature dependence of the Nernst coefficient both above and below $T_c$ and choosing an adequate model allowing one to describe and to explain simultaneously all the specific features of the temperature dependences of the transport coefficients call for further investigations.

**Figure 3.** Temperature dependences of the Nernst coefficient at various magnetic fields for Sm$_{0.55}$Sr$_{0.45}$MnO$_3$ (a) and Sm$_{0.55}$Ce$_{0.05}$Sr$_{0.4}$MnO$_3$ (b) samples

**Figure 4.** Dependence of the Nernst voltage measured at a temperature below $T_c$ on applied magnetic field for selected samples. Dashed lines show expected classical dependences
Secondly, at $T > T_c$, the $Q(T)$ dependences measured in different magnetic fields coincide completely with each other that corresponds to the classical theory of the electron transport phenomena. Let us remind that the Nernst coefficient is determined as $Q = \frac{d \cdot U_Q}{H \cdot l \cdot \Delta T}$, where $d$ is the sample thickness in the $\Delta T$ direction, $U_Q$ is the measured Nernst voltage, $H$ is an applied magnetic field, $l$ is a distance between the Nernst leads, $\Delta T$ is the temperature difference applied to a sample. Thus, normally $Q = \text{const}(H)$ or $U_Q$ is proportional to $H$. However, in the magneto-ordered state (at $T < T_c$), the Nernst coefficient demonstrates an anomalous behavior. Its value depends strongly on the applied magnetic field decreasing with an increase in $H$ (for instance, for the Sm$_{0.55}$Sr$_{0.45}$MnO$_3$ sample at $T = 100$ K the $Q$ values measured in magnetic fields of $H = 0.3$ T and $1.8$ T are equal to $35$ nV/(K·T) and $8$ nV/(K·T), correspondingly, see figure 3). As a result, the dependence of the Nernst voltage on the applied magnetic field differs from the classical case (see figure 4). In this respect, it should be noted that the Hall coefficient in manganites is known to demonstrate an analogous anomalous behavior at $T < T_c$, depending also on the applied magnetic field [6, 8, 13]. Both these anomalous effects have obviously the same nature caused by a combined effect of the external (applied) and internal (induced by directionally oriented magnetic moments inside a sample) magnetic fields on the measured value of magnetotransport coefficients.

One can see from figure 4 that for all samples even in low magnetic fields the obtained $U_Q(H)$ dependences deviate from the expected classical ones smoothing out with increasing magnetic field, while in high fields the type of the $U_Q(H)$ curve is different depending on the sample composition that can be related to different magnetic structures of specific samples. In our opinion, the observed weakening of the $U_Q(H)$ dependence as compared to the classical linear one can be explained within the phase separation model repeatedly used to explain unusual manganite properties [1, 2, 5, 6]. We believe that the results obtained for the Nernst coefficient in the magneto-ordered state can be associated with the existence of an additional paramagnetic phase preventing the charge-carrier transfer.

At last, let us look at the Nernst coefficient behavior near the temperature of the magneto-ordered transition (see figure 3). For all the studied samples, if the applied magnetic field exceeds $0.3$ T, the Nernst coefficient demonstrates a maximum at $T \approx T_c$ shifting slightly to high temperatures with increasing $H$ (like the case of the $\rho(T)$ dependences) and falls with further decrease in temperature, so that the higher the applied magnetic field, the stronger the Nernst coefficient decrease. Like the resistivity case, increasing magnetic field suppresses the value of the Nernst coefficient at temperatures $T < T_c$.

**Figure 5.** Magnetoresistance at various magnetic fields as a function of temperature for Sm$_{0.55}$Sr$_{0.45}$MnO$_3$ (a) and Sm$_{0.55}$Ce$_{0.05}$Sr$_{0.4}$MnO$_3$ (b) samples
Figure 6. Magnetothermopower at $H=1.5$ T as a function of temperature for Sm$_{0.55}$Sr$_{0.45}$MnO$_3$ (a) and Sm$_{0.5}$Ce$_{0.05}$Sr$_{0.45}$MnO$_3$ (b) samples

Figure 7. Fractional change of the Nernst coefficient at various magnetic fields as a function of temperature for Sm$_{0.55}$Sr$_{0.45}$MnO$_3$ (a) and Sm$_{0.5}$Ce$_{0.05}$Sr$_{0.45}$MnO$_3$ (b) samples

It can be thus stated that the temperature dependences of all the three studied transport coefficients are characterized by a similar anomalous behavior near the temperature of the magneto-ordered transition. This can be clearly demonstrated by a comparison of the temperature dependence of the CMR effect with the ones of the colossal magnetothermopower and the colossal Nernst effect defined as a fractional change of the $Q$ value measured in a fixed $H$ value relative to the one measured in a lowest magnetic field ($H=0.3$ T). The temperature dependences of these effects for some of the studied samples are presented in figures 5–7. As temperature decreases, all of them show a sharp rise at $T\approx T_c$, the higher the applied magnetic field, the larger the values of all these effects. Note that the CMR effect has a tendency to saturate in a high magnetic field whose value decreases with increasing cerium content, while in case of the colossal Nernst effect such saturation is not observed. Besides, contrary to the case of the magnetoresistance and magnetothermopower effects, the magnitude of the colossal Nernst effect does not demonstrate a sharp peak near $T\approx T_c$ remaining almost unchanged in the whole temperature range of $T\leq T_c$ (see figure 7 (a)).

In our opinion, the experimental results on the temperature dependences of the resistivity, thermopower, and Nernst coefficient and a character of their modification under applied magnetic field obviously indicate that the transition to the magneto-ordered state in manganites is accompanied
by a significant modification in parameters of the charge-carrier system including changes in both the concentration and mobility of the charge carriers.

4. Conclusions
In summary, this paper presents the results of the complex experimental study of the temperature dependences of the resistivity, thermopower, and Nernst coefficient in manganites of the Sm$_{1-x}$Ce$_x$Sr$_y$MnO$_3$ system. The common peculiarities of these dependences characteristic of different temperature ranges (both above and below the temperature of the magneto-ordered transition) were revealed. Besides, the $\rho(T)$, $S(T)$, and $Q(T)$ dependences were observed to be characterized by a qualitatively similar behavior near $T_c$ that is related to a significant modification of the charge-carrier system parameters occurring at the transition to the magneto-ordered state. Special attention is paid to the Nernst coefficient demonstrating an anomalous behavior at $T \leq T_c$. The value of $Q$ in this temperature range was observed to be strongly dependent on the applied magnetic field, so that the $U_Q(H)$ dependence is smoothed with increasing $H$. This is more probably due to the existence of an additional paramagnetic phase at temperatures below $T_c$ and can be considered as an evidence in favor of the phase separation model.