ORDER, DISORDER, AND PHASE TRANSITION \_ IN CONDENSED SYSTEM

# Negative Oxygen Isotope Effect in Manganites with an Ordered Cation Arrangement in a High Magnetic Field

A. N. Taldenkov<sup>a,\*</sup>, V. V. Snegirev<sup>b</sup>, N. A. Babushkina<sup>a</sup>, V. S. Kalitka<sup>c</sup>, and A. R. Kaul<sup>c</sup>

<sup>a</sup> Russian Research Centre "Kurchatov Institute," pl. Kurchatova 1, Moscow, 123182 Russia
<sup>b</sup> Physical Faculty, Moscow State University, Moscow, 119991 Russia

<sup>c</sup> Chemical Faculty, Moscow State University, Moscow, 119991 Russia

\*e-mail: box-n3@bk.ru

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**Abstract**—The oxygen isotope effect in  $PrBaMn_2^{16-18}O_{5.97}$  manganite with an ordered cation arrangement is studied. The field dependences of magnetic susceptibility and magnetization are measured in the temperature range 100–270 K and magnetic fields up to 32 T. A significant increase in the temperature of the spin-reorientation antiferromagnet—ferromagnet phase transition is detected in samples enriched in heavy oxygen <sup>18</sup>O (negative isotope effect). The transition temperature and the isotope effect depend strongly on the magnetic field. An *H*–*T* phase diagram is plotted for samples with various isotope compositions. An analysis of the experimental results demonstrates that the detected negative isotope effect and the giant positive isotope effects are discussed in terms of the double exchange model under a polaron narrowing of the free carrier band.

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### 1. INTRODUCTION

Doped manganese oxides  $R_{1-x}B_xMnO_3$  (R is a rareearth metal, B is a Group I or II metal), which are the limiting three-dimensional representatives of the large family of layered manganites  $(R_{1-x}B_xMnO_3)_n(R_{1-x}B_xO)$ , have attracted close attention. They exhibit competition between various types of ferromagnetic (FM) and antiferromagnetic (AFM), charge, and orbital ordering under a strong electron-phonon interaction. In this case, a small change in external parameters, such as the degree of doping, the ionic radius, a magnetic field, a pressure, the number of layers n, and the degree of cation disordering, can change a ground state and affect the magnetic, structural, and electrophysical properties of manganites. In particular, the colossal magnetoresistance effect is observed (see review [1]). One of the unexpected manifestation of these properties is a giant positive oxygen isotope effect, i.e., a decrease in the FM ordering temperature  $(T_{FM})$  in doping by heavy oxygen <sup>18</sup>O [1–5]. The shift of critical temperature  $T_c$  is maximal during magnetic reorientation FM-AFM transitions upon doping by heavy oxygen. In most cases, these transitions are accompanied by a metal-insulator transition with charge ordering (CO). The magnitude and the sign of the isotope effect are characterized by the isotope exponent

$$\alpha = -\frac{\partial \ln T_c}{\partial \ln M M_0} = -\frac{M_0 \partial T_c}{T_c \partial M_0}$$
(1)  
=  $-\frac{(M_0 + 16)[T_c(M_0) - T_c(M_0 = 16)]}{(M_0 - 16)[T_c(M_0) + T_c(M_0 = 16)]},$ 

where  $M_{\rm O}$  is the average oxygen mass in an enriched sample. If critical temperature  $T_c$  depends linearly on

phonon oxygen mode frequency  $\omega$ ,  $T_c \propto \omega \propto M_0^{-1/2}$ , we have  $\alpha = 1/2$ . In manganites,  $\alpha$  can be significantly higher than unity; in some cases, the isotope effect in manganites is so high that a heavy-oxygen-induced FM-AFM (CO) transition, which is accompanied by a metal-insulator transition, appears [6-8]. Obviously, the difference determination of  $\alpha$  cannot be applied in this case, and the dependence of  $T_c$  on average oxygen mass  $M_0$  should be measured and differentiated (as was done in [9, 10]) to calculate  $\alpha$ . Along with a giant positive isotope effect, optimally doped  $(x \approx 0.10 - 0.35)$  and half-doped  $(x \approx 0.5)$  manganites exhibit a large negative isotope effect, i.e., an increase in the FM-AFM (CO) transition temperature in doping by heavy oxygen  ${}^{18}O$  [11–13]. A decrease in the oxygen mass in manganites always stabilizes the highconducting FM phase; that is, the field of this phase widens.

A detailed microscopic explanation of the giant isotope effect has not yet been proposed. Researchers usually apply double exchange models with allowance for the polaron narrowing of the free carrier band to qualitatively discuss the mechanisms that cause the giant isotope effect.

Based on the positive isotope effects detected in manganites of various compositions, the authors of [14] found the following empirical relationship connecting  $\alpha$  and critical temperature  $T_c$ :

$$\alpha = G_0 \exp(-T_c/T_0). \tag{2}$$

The parameters were  $G_0 \approx 23$  and  $T_0 \approx 60$  K. This exponential relationship was detected later in other manganites [15, 16]. The fact that condition (2) is met over a wide range up to  $\alpha > 10$  can point to its fundamental character [17].

The purpose of this work is to suggest a general description of the isotope effects of both signs. In terms of this approach, we have to test whether condition (2) is met in the case of the negative isotope effect, since the results obtained in [11-13] are rather conflicting. The choice of the material for solving this problem is caused by the existence of a large negative isotope effect and the possibility of the maximum transition temperature variation at other constant parameters of a sample using, e.g., a magnetic field. Our preliminarily study [16] showed that ordered barium manganites RBaMn<sub>2</sub>O<sub>6</sub> meet necessary conditions. In these compounds, MnO<sub>2</sub> planes alternate with RO and BaO planes, BaO-MnO-RO-MnO, R and Ba cations are ordered due to the formation of ordering of oxygen vacancies. These oxygen vacancies form layers, which is energetically favorable. These layers are occupied by rare-earth element (REE) cations, and barium cations are rejected to a layer free of oxygen vacancies. The physical properties of cationordered PrBaMn<sub>2</sub>O<sub>6</sub> manganites differ significantly from those of cation-disordered Pr<sub>0.5</sub>Ba<sub>0.5</sub>MnO<sub>3</sub> manganites and depend on the ordering of  $Pr^{3+}$  and  $Ba^{2+}$  cations. A  $PrBaMn_2O_6$  sample with the maximum degree of cation ordering is a metallic ferromagnet with a Curie temperature  $T_{FM} > 300$  K, whereas  $T_{FM}$  of a fully disordered sample does not exceed 140 K.

The temperature dependences of magnetic susceptibility, magnetization, and electrical conductivity [16] showed that a transition from a paramagnetic (PM) into an FM state occurred in ordered PrBaMn<sub>2</sub><sup>16-18</sup>O<sub>5.97</sub> manganites at temperatures below  $T_{FM} \approx 305$  K. When the temperature decreases in the range 240–200 K, the magnetic moment decreases, which points to an FM–AFM spin-reorientation transition at critical temperature  $T_c$ . The oxygen isotopic substitution of <sup>18</sup>O for <sup>16</sup>O increases critical temperature  $T_c$  by 8.4 K (negative oxygen isotope effect) and slightly decreases  $T_{FM}$  by 3 K (positive oxygen isotope

effect). The isotope exponents were  $\alpha_{T_c} = -0.31 \pm 0.025$  and  $\alpha_{T_{EM}} = 0.07 \pm 0.015$ . A magnetic field significantly widens the temperature range of FM ordering:  $T_c$  decreases by 15 K and the isotope shift  $\Delta T_c = T_c(M_0) - T_c(M_0 = 16)$  increases by approximately 30% in a magnetic field of 3.5 T [16].

The negative oxygen isotope effect detected in the ordered  $PrBaMn_2^{16-8}O_6$  manganite supports the phenomena revealed in half-doped disordered manganites  $Nd_{0.5}Sr_{0.5}Mn^{16-18}O_3$  [11],  $La_{0.5}Ca_{0.5}Mn^{16-18}O_3$  [12],  $La_{1-x}Ca_xMnO_3$ , and  $Pr_{0.5}Ca_{0.5}MnO_3$  [3, 13, 18]. The following two oxygen isotope effects were also observed in these systems: the positive effect for  $T_{FM}$  and the negative effect for  $T_{CO}$  (CO temperature). Moreover, the FM phase is stabilized when the average oxygen mass decreases or the magnetic field increases. Therefore, it is interesting to study the negative oxygen isotope effect in  $PrBaMn_2O_6$  in high magnetic fields and to plot an H-T diagram for the case of significant critical-temperature variation.

#### 2. EXPERIMENTAL

Ceramic PrBaMn<sub>2</sub>O<sub>5 97</sub> samples were prepared by chemical homogenization. Paper ashless filters were impregnated with a stoichiometric mixture of cation nitrate solutions and were then dried at 100°C. After drying the filters were burned on a gas burner and were then annealed in air at 600°C. The prepared powders were pressed into pellets and annealed at 1100°C for 20 h to synthesize the  $(Pr_{0.5}Ba_{0.5})MnO_{2.98}$  manganite without cation ordering was formed. The samples were subjected to additional annealing in a closed ampule at 1100°C and a partial oxygen pressure  $P(O_2) = 10^{-19}$  atm, which was ensured by an Fe/FeO getter located in the ampule at 800°C. According to X-ray diffraction (XRD) data, the heat-treated samples consisted of oxygen-deficient single-phase PrBaMn<sub>2</sub>O<sub>5.9-x</sub> perovskites with the double unit cell parameter due to the ordering of Pr and Ba ions (degree of ordering was higher than 95%). To fill oxygen vacancies, we performed additional annealing at 500°C in an oxygen atmosphere and prepared oxygen-saturated samples with the natural isotopic composition PrBaMn<sub>2</sub>O<sub>5.97(1)</sub> (oxygen index was supported by iodometric titration) [19].

The isotopic saturation of the prepared samples was carried out by diffusion upon long-term (more than 7 days) annealing at 750°C in an oxygen atmosphere with 90% isotopic enrichment by <sup>18</sup>O. Note that the cation sublattice was not disordered under these conditions. The <sup>18</sup>O enrichment ( $85 \pm 7$ )% was determined from the mass change. Samples with the natural isotopic composition were simultaneously prepared under the same conditions. The absence of mass change in the reference samples with <sup>16</sup>O during

isotopic enrichment indicates that the oxygen content in a sample is retained during isotopic saturation accurate to 0.2%.

The magnetization was measured in fields up to 32 T with a pulsed magnetic field device. The pulse rise time was about 3 ms and the capacitor bank energy was 30 kJ. The magnetization and the magnetic field were measured by an induction method, and a signal was recorded using a two-channel 16-bit GaGe CompuScope 1602 recorder. The background decompensation signal recorded in the absence of a sample was digitally subtracted from the measured signal. Calibration was performed using an yttrium iron garnet sample having the dimensions and the shape of the samples to be studied. The error of determining the magnetization was about 10%. Intermediate temperatures in the range from 78 to 300 K were obtained with a continuous-flow cryostat with electronic stabilization of the cooling gas flow temperature. The accuracy of temperature maintenance was 0.1 K, the sample temperature was measured by a copper-iron-copper thermocouple, and the accuracy of temperature measurements was 0.2 K.

### **3. EXPERIMENTAL RESULTS**

Figure 1 shows the field dependences of differential magnetic susceptibility  $\chi = dM/dH$  and magnetization M, which were obtained at a fixed temperature. Wellresolved peaks, which point to an AFM-FM transition, are visible in the  $\chi(H)$  dependences. As the temperature decreases, phase-transition magnetic field  $H_c$ increases and becomes more than 25 T at 110 K. The field dependence of magnetization M(H) also exhibits a transition into an ordered FM state and is saturated in high fields. The extrapolation of the  $M(H^{-2})$  dependence toward high temperatures gives the saturation magnetization  $M_{\text{sat}} = 3.2 \mu_{\text{B}}/\text{Mn}$  and  $M_{\text{sat}} = 3.4 \mu_{\text{B}}/\text{Mn}$ for the samples with <sup>16</sup>O and <sup>18</sup>O, respectively. These values are close to the value  $(3.5\mu_B/Mn)$  calculated for the half-doped manganites. This fact demonstrates that the FM phase concentration is close to 100%. The magnetization curves in the temperature range 260-300 K correspond to the magnetization of a ferromagnet.

A significant (more than 4 T) field hysteresis M(H) and an isotope shift of the AFM–FM transitions toward high fields in the samples with heavy oxygen are visible in Fig. 1c. This shift is a direct experimental evidence of the fact that the existence of the FM phase is energetically favorable in the samples with light oxygen.

Based on these data, we plotted an H-T phase diagram (see Fig. 2). Critical field  $H_c$  of the AFM–FM transition at a given temperature  $T_c$  was determined from the maximum in the  $\chi(H)$  curve in Fig. 1a. Line  $T_c(H_c)$  separates the fields of the FM and AFM states. This phase diagram is characterized by an increase in



**Fig. 1.** (Color online) Field dependences of (a) magnetic susceptibility  $\chi$  and (b) magnetization *M* in the range of increasing magnetic field for the temperature range 240–130 K at a step of 10 K for a PrBaMn<sub>2</sub><sup>18</sup>O<sub>5.97</sub> sample and (c) field dependences of magnetization of (dotted curves) PrBaMn<sub>2</sub><sup>16</sup>O<sub>5.97</sub> and (solid curves) PrBaMn<sub>2</sub><sup>18</sup>O<sub>5.97</sub> at three fixed temperatures.

the isotope shift of the critical temperature  $\Delta T_c$  with increasing magnetic field or decreasing temperature. The results obtained at low fields are close to the data obtained upon cooling the same samples in a dc magnetic field [16]. The  $T_c(H_c)$  dependence was interpolated (Fig. 2, lines), and difference isotope parameter  $\alpha$  was calculated for the forward and reverse runs of magnetization (see Eq. (1)).

The error in determining  $\alpha$  is the sum of the error of determining  $\Delta T_c$  (about 1.5 K) and the error of determining the isotope enrichment (about 7%). The total error of measuring  $\alpha$  is 12–15% at low temperatures and increases to 30% when  $T \approx 240$  K is approached.

Figure 3 shows the temperature and field dependences of  $\alpha$  for PrBaMn<sub>2</sub>O<sub>5.97</sub>. The temperature dependences  $\alpha(T_c)$  obtained for the negative isotope effect agree with exponential dependence (2) for both field sweep directions and are close to the results



**Fig. 2.** (Color online) H-T phase diagram for ( $\blacksquare$ ) PrBaMn<sub>2</sub><sup>16</sup>O<sub>5.97</sub> and ( $\bigcirc$ ) PrBaMn<sub>2</sub><sup>18</sup>O<sub>5.97</sub>. (solid curves) Interpolation of the data obtained when the magnetic field increases and (dashed curves) interpolation of the data obtained when the magnetic field decreases. (solid symbols) This work and (open symbols) data from [16].

obtained on these samples in a dc field [16]. The isotope exponent becomes high ( $\alpha \approx 2$ ) at the lowest temperatures and in high magnetic fields. Along with the data for PrBaMn<sub>2</sub>O<sub>5.97</sub>, we also present the  $\alpha(T_c)$ dependences calculated using the reported results of measuring the negative isotope effect in various disordered R<sub>0.5</sub>Ba<sub>0.5</sub>MnO<sub>3</sub> compounds. Although the results obtained by different research teams are slightly different, we can conclude that the temperature dependence  $\alpha(T_c)$  is close to an exponential function. Note that parameter  $T_0 \approx 63$  K is close for the negative and positive isotope effects and that parameter  $G_0$  is different for different manganites, as in [16]. Field dependences  $\alpha(H)$  are shown in the inset to Fig. 3. The results obtained from the ascending and descending magnetization branches are identical within the limits of experimental error accurate to a magnetic field shift of 4.7 T.  $\alpha$  exponentially depends on the magnetic field in a wide field range and has a singularity in the vicinity of  $\alpha = 0.5$ . The obtained values agree well with the results found upon dc magnetic field measurements. For comparison, we present data for two other half-doped manganites, La<sub>0.5</sub>Ca<sub>0.5</sub>MnO<sub>3</sub> and  $Nd_{0.5}Sr_{0.5}MnO_3$ . Obviously, the magnetic fields at which significant differences in  $\alpha$  take place are substantially different for different compounds; therefore, a magnetic field is not a "good" parameter for the



**Fig. 3.** (Color online) Temperature dependences  $\alpha(T_c)$ : (○) AFM-FM transition in PrBaMn<sub>2</sub>O<sub>5.97</sub> (this work); (●) AFM-FM transition in PrBaMn<sub>2</sub>O<sub>5.97</sub> [16]; (◇) CO-FM transition in La<sub>0.5</sub>Ca<sub>0.5</sub>MnO<sub>3</sub> [12]; (□) CO-FM transition in Nd<sub>0.5</sub>Sr<sub>0.5</sub>MnO<sub>3</sub> [11]; (★) CO-FM transition in La<sub>0.43</sub>Ca<sub>0.57</sub>MnO<sub>3</sub> [3]; CO-FM transition in (◆) Nd<sub>0.5</sub>Sr<sub>0.5</sub>MnO<sub>3</sub>, (▽) La<sub>0.5</sub>(CaSr)<sub>0.5</sub>MnO<sub>3</sub>, (△) La<sub>0.5</sub>Ca<sub>0.5</sub>MnO<sub>3</sub>, and (▲) Pr<sub>0.5</sub>Ca<sub>0.5</sub>MnO<sub>3</sub> [13]; and (■) CO-FM transition in Pr<sub>0.5</sub>Ca<sub>0.5</sub>MnO<sub>3</sub>

results to be compared even within one family of halfdoped (x = 0.5) manganites.

# 4. DISCUSSION OF RESULTS

Based on the new data obtained for the negative isotope effect, we can conclude that  $\alpha(T_c)$  falls in the range determined by Eq. (2) for most manganites. Using definition (1) and experimentally grounded Eq. (2), we can find reduced critical temperature  $y = T_c(m)/T_0$  as a function of reduced average oxygen mass  $m = M_0/16$  in a sample. We can easily show that

$$\mp \frac{e^{y} dy}{v} = G_0 \frac{dm}{m}.$$
 (3)

From here on, a superscript (subscript) belongs to the positive (negative) isotope effect. The solution to Eq. (3) is represented by the function

$$C \mp \left[ \ln y + \sum_{i=1}^{\infty} \frac{y^i}{i \cdot i!} \right] = G_0 \ln m, \tag{4}$$

where constant of integration C is determined from the condition m = 1 and depends only on reduced critical temperature  $y(1) = T_c(M_0 = 16)/T_0$  in the samples with the natural isotopic composition. Note that mchanges in the narrow range 1-1.125 in experiments. Figure 4 shows the dependence  $T_c(M_0)/T_c(M_0 = 16)$ calculated by Eq. (4) at fixed values of  $T_c(M_0 = 16)/T_0$ . This dependence reproduces the main tendencies of the isotope effect in manganites: at high critical temperatures  $(T_c(M_0 = 16)/T_0 > 1)$ , the  $T_c(M_0)$  dependence is almost linear and a small isotope effect occurs; as the critical temperature decreases ( $T_c(M_{\Omega} =$  $16)/T_0 \sim 1$ ), the isotope effect grows and the mass dependence becomes nonlinear.  $T_0$  is assumed to be the minimum critical temperature for a certain compound. A comparison with the experimental data in [17] demonstrates good agreement of the model and the experimental results up to the heavy-oxygeninduced transition into a nonmetallic AFM state (Fig. 4).

The double exchange model is usually applied to estimate the isotope shift of the FM transition temperature in manganites. Temperature  $T_c$  is assumed to be proportional to the band of delocalized  $e_g$  electrons. Following the designations in [20], we obtain

$$T_c \propto At$$
,

where  $A \propto z\delta$ , z is the number of nearest neighbors,  $\delta$  is the free carrier concentration, and t is the jump matrix element. The polaron narrowing of the mobile carrier band can be used to find  $T_c$  as a function of the oxygen mass,

$$T_c = A\overline{t} \equiv At \exp(-\lambda E_p/\hbar\omega), \qquad (5)$$

where  $\lambda$  is an electron-phonon coupling constant,  $E_p$  is the polaron energy, and  $\omega$  is the phonon frequency. As was noted in [5, 21], the differentiation of Eq. (5) with respect to mass yields a dependence that differs qualitatively from the experimental dependence:  $\alpha$  increases with  $T_c$ . This finding supports the conclusion from [5, 14] about the importance of the physical limitations imposed by functional dependence (2) on the models used to describe the properties of manganites.

From the general shape of the  $\alpha(T_c)$  dependences, we can conclude that the natures of the negative and positive isotope effects in manganites are the same. Thus, the models that describe the positive and negative isotope effects in manganites should contain functionally similar dependences of  $T_{FM}$  and  $T_{CO}/T_{AFM}$  on the main parameters and predict dependences for the critical temperature that, at least, do not contradict  $\alpha(T_c)$  experimental data. A simple phenomenological model, which meets these criteria, was proposed in [20]. Plakida [20] used an expression for the critical temperature in the presence of several competing exchange mechanisms in the form

$$T_c = A(\overline{t} - t^F) \tag{6}$$



**Fig. 4.** (Color online) Critical temperature  $T_c/T_c(M_0 = 16)$  vs. mass. Calculation by Eq. (4) at  $G_0 = 23$  and  $T_0 = 63$  K for the positive isotope effect  $(T_c(M_0)/T_c(M_0 = 16) < 1)$  and at  $G_0 = 11$  and  $T_0 = 63$  K for the negative isotope effect  $(T_c(M_0)/T_c(M_0 = 16) > 1)$ . Numerals at the curves are the values of parameter  $T_c(M_0 = 16)/T_0$ . ( $\circ$ ) Data on the AFM(CO)–FM transition temperature in (LaPr)<sub>0.7</sub>Ca<sub>0.3</sub>MnO<sub>3</sub> [17].

for the transition into the FM state and

$$T_c = B(t^{CO} - \overline{t}) \tag{7}$$

for the transition into the CO (AFM) state. Here,  $t^{F}$ and  $t^{CO}$  are the constants that characterize the indirect AFM exchange and the Coulomb repulsion, respectively, which weakly depend on the oxygen mass (see [20]). The functional form of Eqs. (6) and (7) reflects the common nature of the negative and positive isotope effects. The double FM exchange under the polaron narrowing of the mobile carrier band (term  $\overline{t}$ ) is the origin of the isotope effects of both signs. Being the difference between two high values, the critical temperature can be very sensitive to a small change in  $\overline{t}$  depending on external parameters, including the oxygen mass, and can vary over wide limits. This form of dependences makes it possible to obtain a high isotope effect even in terms of weak and/or intermediate electron-phonon coupling [20].

Using Eq. (6) and rather simple transformations, we obtain the following  $\alpha(T_c)$  dependence in the case of a positive isotope effect:

$$\alpha = -\frac{1}{2} \ln \left( \frac{T_c}{At} + \frac{t^F}{t} \right) \left( 1 + \frac{At}{T_c} \frac{t^F}{t} \right).$$
(8)

JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS Vol. 126 No. 3 2018

A similar expression is obtained for the negative isotope effect when a charge-ordered AFM state transforms into an FM state to within the substitution B =-A and  $t^F = t^{CO}$ . The dashed lines in Fig. 3 show the  $\alpha(T_c)$  dependence calculated by Eq. (8) at the parameters that are close to those used in [20]. Qualitative agreement with the experimental data is observed. At a high critical temperature, the calculation result corresponds to the experimental data. When the temperature decreases, the dependence predicted by the model is weaker than the experimental one, which points to an underestimated effect of the oxygen mass.

We are far from believing that Eqs. (6) and (7) can comprehensively describe the critical temperature in manganites. They are most likely to exhibit the functional dependence that can consistently describe the experimental results. Using a bipolar model, the authors of [5] (Eq. (5), p. 238) described the behavior of the critical temperature, which was functionally similar to our description. Specifically, the critical temperature is a function of the difference between two high contributions. Note that the model used in [20] is rather schematic and does not take into account many important features in the behavior of the magnetic system, which can affect the end result. One of these features is phase separation: it substantially influences the phase composition of manganites, especially when the critical temperature decreases.

# 5. CONCLUSIONS

We found the field dependences of the magnetization and the magnetic susceptibility in an isotopically oxygen-rich ordered  $PrBaMn_2O_{5.97}$  manganite in high magnetic fields up to 32 T. An H-T diagram was plotted over a wide range of the critical temperature of the spin-reorientation.

We detected a negative isotope shift of the AFM– FM spin-reorientation transitions in samples containing heavy oxygen, including the case of high magnetic fields. The FM phase field was shown to grow when the oxygen mass decreased. The H-T diagram is characterized by an increase in the isotope shift of the critical temperature  $\Delta T_c$  with increasing magnetic field or decreasing the critical transition temperature.

We determined the isotope exponent as a function the transition temperature ( $\alpha(T_c)$ ) and concluded that it was close to exponential dependence (2). A comparison of the isotope exponent in the ordered PrBaMn<sub>2</sub>O<sub>5.97</sub> manganite and other disordered A<sub>0.5</sub>B<sub>0.5</sub>MnO<sub>3</sub> compounds demonstrates that the exponential  $\alpha(T_c)$  dependence can also be applied in the case of the negative oxygen isotope effect.

A comparison of the detected negative and positive oxygen isotope effects points to their common nature in most doped manganites. As a consequence of the exponential  $\alpha(T_c)$  dependence, we found the dependence of the isotope shift of the critical temperature on the average oxygen mass, which was supported by direct measurement results. To interpret our experimental results, we used the approach [20], which allowed us to describe the oxygen isotope effect in manganites consistently.

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