

Observation of spin glass behavior in $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$

D.F. Shao¹, J. Yang^{1,a}, X.B. Zhu¹, J.M. Dai¹, Z.R. Yang¹, W.H. Song¹, and Y.P. Sun^{1,2,b}

¹ Key Laboratory of Materials Physics, Institute of Solid State Physics, Chinese Academy of Sciences, P.O. Box 1129, Hefei 230031, Anhui Province, P.R. China

² High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei 230031, P.R. China

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Abstract. The structural and magnetic properties of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{1-x}\text{Co}_x\text{O}_3$ ($0 \leq x \leq 0.2$) have been investigated. All samples show a cubic structure with the space group of $Pm\bar{3}m$ at room temperature. $\text{Ba}_{0.8}\text{La}_{0.2}\text{TiO}_3$ exhibits a carrier induced Pauli-paramagnetism and $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.9}\text{Co}_{0.1}\text{O}_3$ shows a Curie-Weiss like paramagnetism. With increasing cobalt doping, $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ seems to undergo a spin glass like transition at $T_f = 10.1$ K as evidenced by the frequency dependence of ac susceptibility measurements, aging effect measurements, memory effect measurements and magnetic relaxation measurements. The time decay of the thermoremanent magnetization can be well described with the stretched exponential function. It is worthwhile to note that the temperature dependence of relaxation characteristic time τ_r and the critical exponent n deduced from the function show opposite tendencies below and above T_f , and the possible reason has been discussed. n at T_f close to 2/3 suggests that $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ may be a three dimensional Ising spin glass.

1 Introduction

The ferroelectric ceramic material BaTiO_3 has been widely investigated since it can be used as a dielectric material for ceramic capacitors, and as a piezoelectric material for microphones and other transducers. The crystal structure of BaTiO_3 at room temperature belongs to a tetragonal structure with an empty $3d$ band of Ti^{4+} . Doping BaTiO_3 with La^{3+} will introduce Ti^{3+} with $3d^1$ configuration giving rise to a continuous filling of $3d$ band of Ti ions, and therefore a metallic phase will occur when the doping level of La exceed 0.35 [1]. $\text{Ba}_{1-x}\text{La}_x\text{TiO}_3$ as a typical filling-control metal-insulator transition system has been reported on the structure, magnetic, and transport properties [1–3]. In order to improve the dielectric properties of $\text{Ba}_{1-x}\text{La}_x\text{TiO}_3$ ($x \leq 0.2$), Parkash et al. studied $\text{Ba}_{1-x}\text{La}_x\text{Ti}_{1-x}\text{Co}_x\text{O}_3$ by doping Co^{3+} on Ti site giving rise to eliminate Ti^{3+} ions due to the effect of internal charge compensation in this system [4–7]. However, the report is not yet available on the magnetic properties of $\text{Ba}_{1-x}\text{La}_x\text{Ti}_{1-x}\text{Co}_x\text{O}_3$. In this paper, we investigated the magnetic properties of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{1-x}\text{Co}_x\text{O}_3$ ($0 \leq x \leq 0.2$). It is found that the sample $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ exhibits the different behavior compared with the samples $\text{Ba}_{0.8}\text{La}_{0.2}\text{TiO}_3$ and $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.9}\text{Co}_{0.1}\text{O}_3$. A three

dimensional (3D) Ising spin glass (SG) behavior is observed in $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ based on the data of magnetization, the frequency-dependent of ac susceptibility, aging effect measurements, memory effect measurements and the time decay of the thermoremanent magnetization (M_{TRM}).

2 Experimental

Polycrystalline samples were prepared by conventional solid state methods. Stoichiometric amount of BaTiO_3 (99.7%), La_2O_3 (99.99%), Ti_2O_3 (99.9%), Co_2O_3 (99%) were mixed and ground, and then calcined at 900 °C for 7 days. The obtained powders were ground, pelletized, and sintered at 1300 °C for 40 h with an intermediate grinding, and finally the furnace was cooled slowly down to room temperature. $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ was synthesized under air condition, whereas $\text{Ba}_{0.8}\text{La}_{0.2}\text{TiO}_3$ and $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.9}\text{Co}_{0.1}\text{O}_3$ were sealed in an evacuated quartz tube during the preparation process for the sake of the introduction of Ti^{3+} ions.

The crystal structure was determined by powder X-ray diffraction (XRD) using $\text{Cu } K_\alpha$ radiation at room temperature. The magnetic measurements were carried out with a quantum design superconducting quantum interference device (SQUID) magnetic properties measurement system in the ranges of $2 \text{ K} < T < 400 \text{ K}$, $0 \text{ T} < H < 5 \text{ T}$.

^a e-mail: jyang@issp.ac.cn

^b e-mail: ypsun@issp.ac.cn

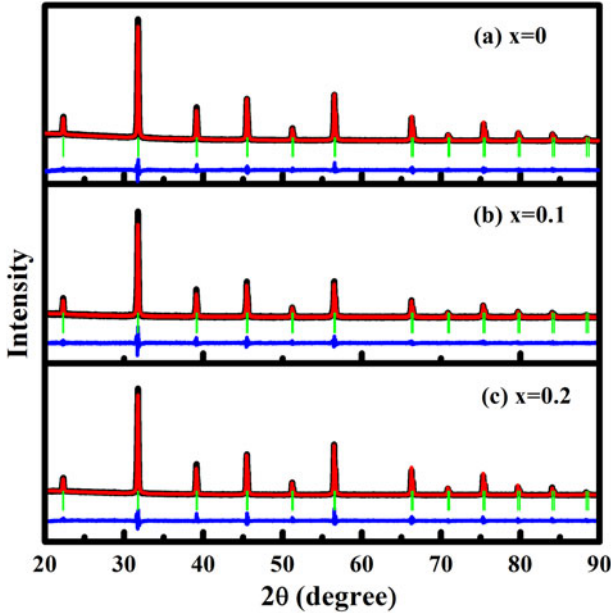


Fig. 1. (Color online) XRD patterns of the samples with $x = 0$, 0.1, and 0.2. Black line indicates the experimental data and the calculated data is the red line overlapping them. The lowest curve shows the difference between experimental and calculated patterns. The vertical bars indicate the expected reflection positions.

3 Results and discussion

The powder XRD pattern at room temperature reveals that all the samples are single phase with no detectable secondary phases. The structural parameters are refined by using the program FULLPROF and all samples can be indexed by a cubic lattice with space group $Pm\bar{3}m$ [8]. Figures 1a–1c shows the experimental and calculated XRD patterns of the samples with $x = 0$, 0.1, and 0.2, respectively. The lattice parameters turn out to be $a = 3.98504(9)$, $3.98677(1)$ and $3.98678(8)$ Å for the samples with $x = 0$, 0.1, and 0.2, respectively. The valence state of Co ions in cobalt doped samples should both be trivalent due to the following reasons. In the case of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.9}\text{Co}_{0.1}\text{O}_3$, this sample were prepared in sealed evacuated quartz tubes in order to introduce Ti^{3+} ions and prevent the Ti^{3+} ions from oxygenating. A Curie constant of $0.3296 \text{ emu K}/(\text{Oe mol})$ and a Weiss temperature of -28.0755 K can be deduced from the Curie-Weiss fit as shown in the inset of Figure 2. And thus an effective magnetic moment μ_{eff} is determined to be $1.6238\mu_B$ corresponding to the amount of ~ 0.1 high spin state (HS) Co^{3+} based on the expression of $\mu_{\text{eff}}^2 = xg^2S(S+1)\mu_B^2$ (x is the number of magnetic ions, g is Landé g factor, and S is the spin value of a magnetic ion), which is in good consistent with the stoichiometry of Co ions in $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.9}\text{Co}_{0.1}\text{O}_3$ implying that the valence state of Co ions is trivalent. The sample $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ can be regarded as the solid solution of BaTiO_3 and LaCoO_3 , i.e., $0.8\text{BaTiO}_3 + 0.2\text{LaCoO}_3$ and the valence state of LaCoO_3 prepared in air was

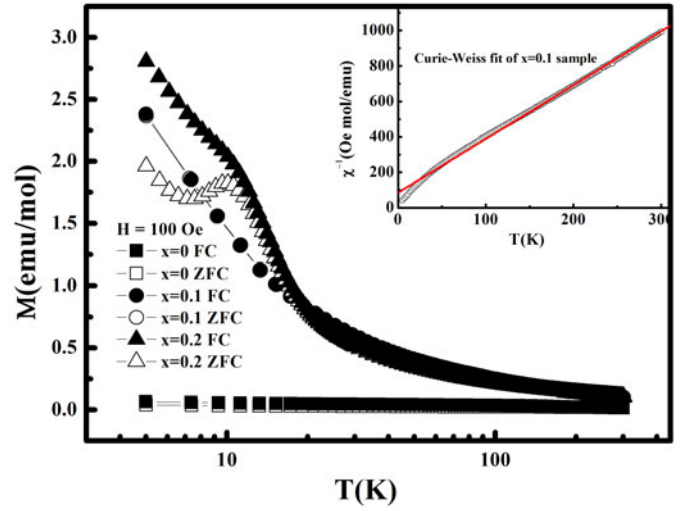


Fig. 2. (Color online) Temperature dependence of magnetization for the samples with $x = 0$, 0.1, and 0.2 in the ZFC and the FC modes measured at $H = 100 \text{ Oe}$. The inset shows the Curie-Weiss fit of $x = 0.1$ sample.

found to stabilize as $+3$. Moreover, the early studies about $\text{Ba}_{1-x}\text{La}_x\text{Ti}_{1-x}\text{Co}_x\text{O}_3$ [4–7] suggest the Co ions in the sample are trivalent, too. On the other hand, the radius of Co^{3+} ion is close to that of Ti^{4+} and the Co^{3+} ion can easily occupy the sites of Ti ions. Therefore, the valence state of the Co ions in the samples $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.9}\text{Co}_{0.1}\text{O}_3$ and $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ are trivalent.

The temperature dependence of magnetization in the zero-field-cooled (ZFC) and the field-cooled (FC) modes at an applied field of 100 Oe was measured. Figure 2 shows the temperature dependence of magnetization of the sample with $x = 0$, 0.1, and 0.2 under an applied field of 100 Oe . The doping of La^{3+} introduces carriers into the sample with $x = 0$. So the magnetization of the sample with $x = 0$ is almost temperature independent, as expected in the case of carrier induced Pauli-paramagnetism [1]. It can be found that the sample with $x = 0.1$ exhibits a Curie-Weiss like paramagnetism. Moreover, the ZFC magnetization (M_{ZFC}) and the FC magnetization (M_{FC}) curves of $\text{Ba}_{0.8}\text{La}_{0.2}\text{TiO}_3$ and $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.9}\text{Co}_{0.1}\text{O}_3$ are nearly superposed.

With further increasing the doping level of Co ions to $x = 0.2$ it is found that there is a deviation between M_{ZFC} and the M_{FC} curves below 15 K . Moreover, the M_{ZFC} curve exhibits a peak at the temperature of 10.1 K and then decreases with decreasing temperature, which implies that there are magnetic exchange interactions between the magnetic Co ions at low temperatures. In the present study, the doping level of Co^{3+} ions at the Ti sites is much fewer than that of Ti ions and it is expected that the occupancy of Co^{3+} ions is random with Ti ions. Therefore, the increase in the doping level of Co^{3+} ions will give rise to increase the probability of the occurrence of the exchange interactions between Co^{3+} ions. That is why the sample $x = 0.2$ exhibits a distinct magnetic behavior compared with the samples with $x = 0$ and 0.1. From Figure 2, it is

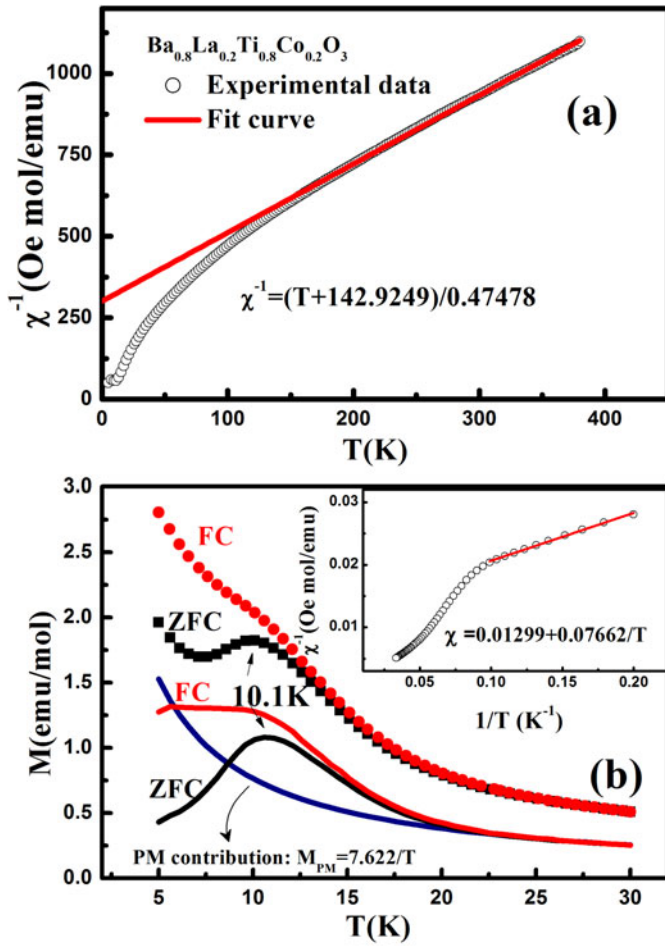


Fig. 3. (Color online) (a) Temperature dependence of the inverse of magnetic susceptibility for $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$. The solid line is the calculated curve according to the Curie-Weiss law. (b) Temperature dependence of magnetization below 30 K for $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ in the ZFC and the FC modes measured at $H = 100$ Oe, as shown by the scattered points. The lines denote the decomposed parts of the experimental M_{ZFC} and M_{FC} plots. The inset shows the magnetic susceptibility as a function of the inverse of temperature below 30 K and the line is the best fit to the paramagnetic susceptibility.

also found that a Curie-upturn is observed below 7.5 K. In the M_{FC} plot, there is a change in the slope of the plot around 10 K. Above 100 K, the inverse magnetic susceptibility follows well the Curie-Weiss law as shown in Figure 3a, giving Curie constant of 0.47478 emu K/(Oe mol) and Weiss temperature of -142.9 K. An effective magnetic moment μ_{eff} is determined to be $1.9489\mu_B$ from the Curie constant. Since the dominant exchange between Co^{3+} HS ions is antiferromagnetic, and the negative Weiss temperature and the large effective magnetic moment might indicate the Co^{3+} ions are composed of HS and low spin state (LS). The expected effective magnetic moment of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ can be expressed as $\mu_{\text{eff}}^2 = \sum \mu_{\text{eff}i}^2 = x_i g^2 S_i(S_i + 1) \mu_B^2$. It can be deduced that the ratio of HS and LS state of Co^{3+} ions is 79% : 21%

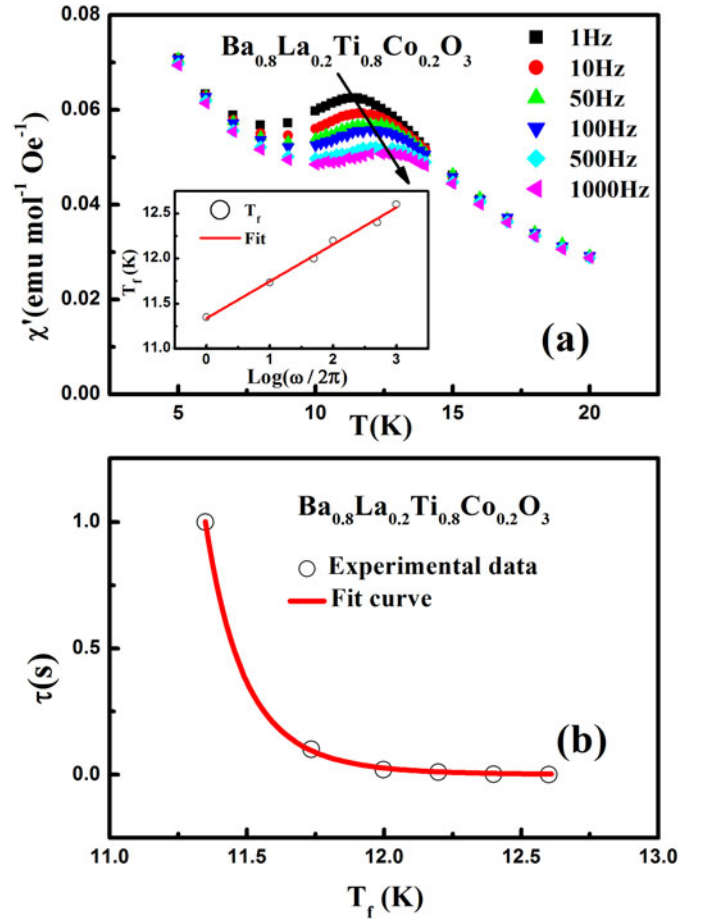


Fig. 4. (Color online) $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$: (a) temperature dependence of the real part of the ac magnetic susceptibility measured at 1, 10, 50, 100, 500, and 1000 Hz with a driving field of 3.8 Oe. The inset shows the frequency dependence of the peak position. (b) The best fit of $T_f(\omega)$ data extracted from ac magnetic susceptibility measurements based on the expression of $\tau/\tau_0 = [(T_f - T_0)/T_f]^{-z\nu}$.

in $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$. In order to make clear the nature of magnetic transition of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ below 20 K, we performed a detailed $M(T)$ measurement from 5 to 30 K and the results are shown in Figure 3b. After subtracting the paramagnetic (PM) contribution based on the Curie-Weiss law shown in the inset of Figure 3b, the plots of M_{FC} and M_{ZFC} are reminiscent of a hallmark of a SG transition [9–11].

In order to further elucidate the transition at low temperatures, we carried out the measurement of ac-susceptibility as a function of temperature in the frequency range $1 \text{ Hz} \leq f \leq 1000 \text{ Hz}$ in a field of 3.8 Oe, as shown in Figure 4a. The shift in the susceptibility peak to the higher temperatures with increasing frequency is distinct, which is one of the characteristic features of a SG transition. Moreover, the frequency shift K defined by:

$$K = \frac{1}{T_f} \frac{\Delta T_f}{\Delta \log \omega} \quad (1)$$

is calculated as 0.03, which is in agreement with the value of K ranging from 0.0045 to 0.28 for a canonical SG system [10,12].

The dynamic scaling theory [13] is generally used to characterize a SG transition [14], and this theory predicts a power law of the form:

$$\tau = \tau_0 \left(\frac{T_f - T_0}{T_f} \right)^{-zv} \quad (2)$$

where τ_0 is the microscopic attempt time available to the system, T_f is the temperature of the susceptibility cusp, T_0 is underlying SG transition temperature determined by the interactions in the system, z is the dynamic critical exponent, and v is the critical exponent of the correlation length. The best fit based on equation (2) (Fig. 4b) gives $T_0 = 10.1$ K, $zv = 9.98$, and $\tau_0 = 2.81 \times 10^{-10}$ s. The value of T_0 is very close to the temperature of the cusp in the M_{ZFC} plot, which is in good agreement with the dynamic scaling theory. One can also notice that τ_0 and zv lie within the range of typical values of SG systems: $\tau_0 = 10^{-10} \sim 10^{-12}$ s [15] and $zv = 5-10$ [14,16]. To further characterize the magnetic properties of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ at low temperatures, the magnetic-field dependence of magnetization $M(H)$ (Fig. 5) was measured. It shows that the hysteresis effect exists at the temperatures below 15 K with very small remnant magnetizations (M_r) implying the existence of short-range ferromagnetic (FM) interaction, which may be originated from the dilution of Co^{3+} HS ions. It is known that the coexistence and competition between FM and antiferromagnetic (AFM) interaction would favor the formation of a SG, which is consistent with the results shown in Figures 3 and 4. With decreasing the temperature, the coercive field H_c and M_r increase with almost the same tendency. It is due to the freezing degree together with the small thermal activation energy.

The experimental features regarding the typical irreversibility found in M_{FC} and M_{ZFC} with a cusp in the plot of M_{ZFC} at the freezing temperature T_f and a frequency-dependent shift in the peak of ac-susceptibility around T_f are found both in superparamagnets and SG systems. In order to distinguish between superparamagnets and SG systems, we performed the aging effect measurement, memory effect and magnetic relaxation measurements, since these behaviors are crucial features of the SG behavior [9,10].

The aging effect was studied at 8 K. The sample was first cooled down from room temperature to 8 K under a magnetic field of $H = 100$ Oe. After the stabilization of temperature and a certain waiting time t_w , the magnetic field was switched off. The magnetization was recorded as a function of the elapsed time. The results for different values of t_w (1000, 3000, 5000 s) are presented in Figure 6. It can be found an obvious difference between the results of $t_w = 1000$ s and $t_w = 3000$ s. But the results of $t_w = 3000$ s and 5000 s show a little difference. In fact, the time of stabilizing the temperature depends on the condition of equipment, so the actual waiting time of the middle one may be longer than 3000 s, which leads to the small

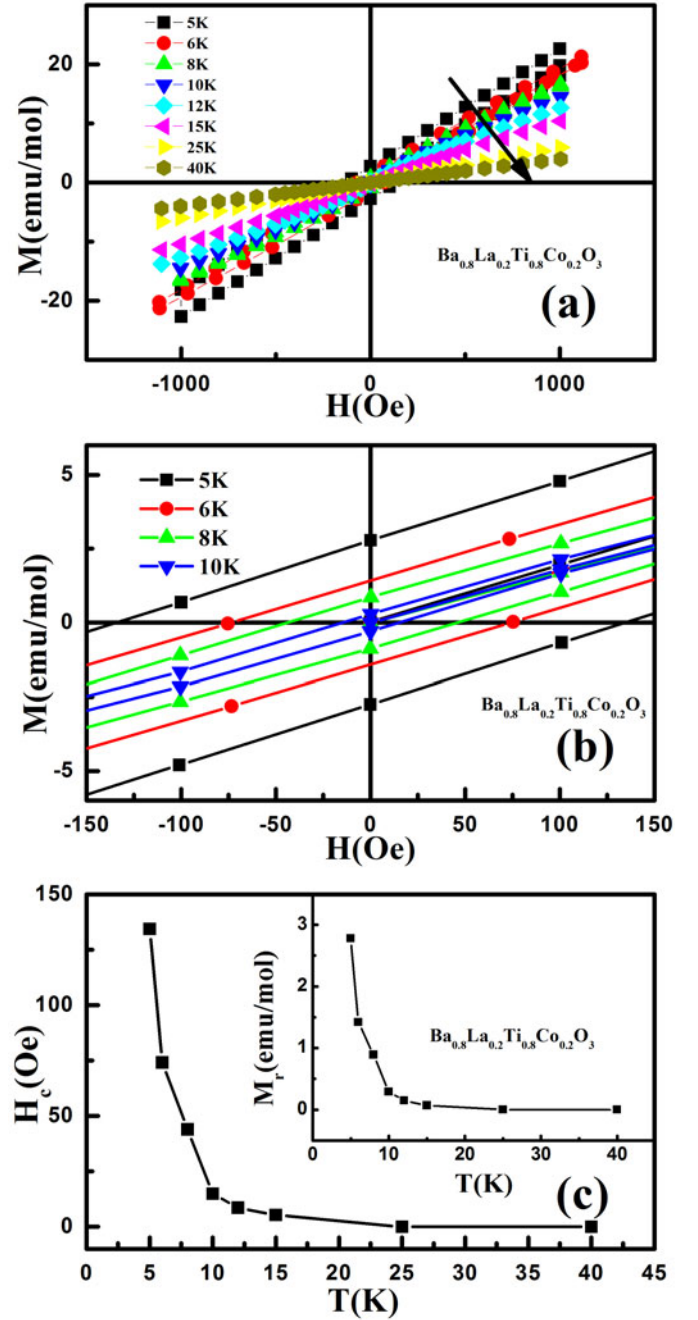


Fig. 5. (Color online) $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$: (a) magnetization as a function of field at 5, 6, 8, 10, 12, 15, 25, and 40 K. (b) Detailed information of the field dependence of magnetization at 5, 6, 8, and 10 K. (c) Coercive field as a function of temperature. The inset shows the temperature dependence of remanent magnetization.

difference. The magnetic viscosity $S(t) = \frac{1}{H} \left(\frac{\partial M}{\partial \log(t)} \right)$ was shown in the inset of Figure 6. The shifts in the minimum position of $S(t)$ with different t_w , as expected to occur for a spin-glass system, is clearly observed.

The memory effect in the temperature dependence of magnetization was measured following an unconventional procedure suggested by Sun et al. [17] (see Fig. 7).

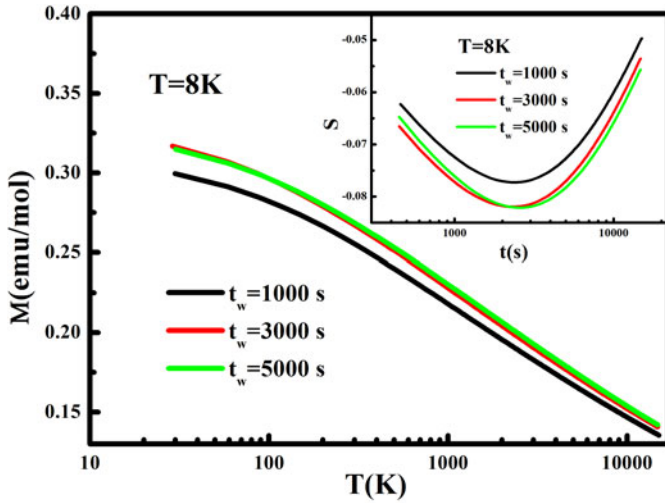


Fig. 6. (Color online) $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$: the waiting time dependence of magnetization recorded at 8 K. Inset: The waiting time dependence of magnetic viscosity $S(t) = \frac{1}{H} \left(\frac{\partial M}{\partial \log(t)} \right)$.

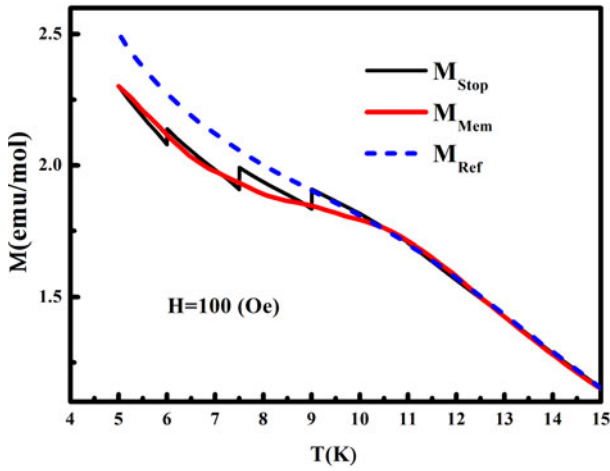


Fig. 7. (Color online) $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$: the memory effect in temperature dependence of magnetization. The curve was obtained by cooling the sample under $H = 100$ Oe with intermediate stops (M_{stop} , black solid line), and then warming the sample under the same field back to high temperature (M_{Mem} , red solid line). The reference curve (blue dashed line) was obtained by cooling the sample under same field without any stop.

Chronologically, the measurement was performed in the following steps: (i) the sample was cooled under a magnetic field $H = 100$ Oe from 100 to 5 K with intermediate stops of duration $t_w = 5000$ s each and $T_{\text{stop}} = 9, 7.5$, and 6 K. During each stop, the temperature was kept as a constant and the field was reduced to zero. After each stop, the field was reapplied, and the sample was continued cooling, which resulted in a step like M - T curve (M_{Stop}). (ii) After the temperature reached to 5 K, the sample was heated under a magnetic field of $H = 100$ Oe, which produced a so-called “memory” curve (M_{Mem}).

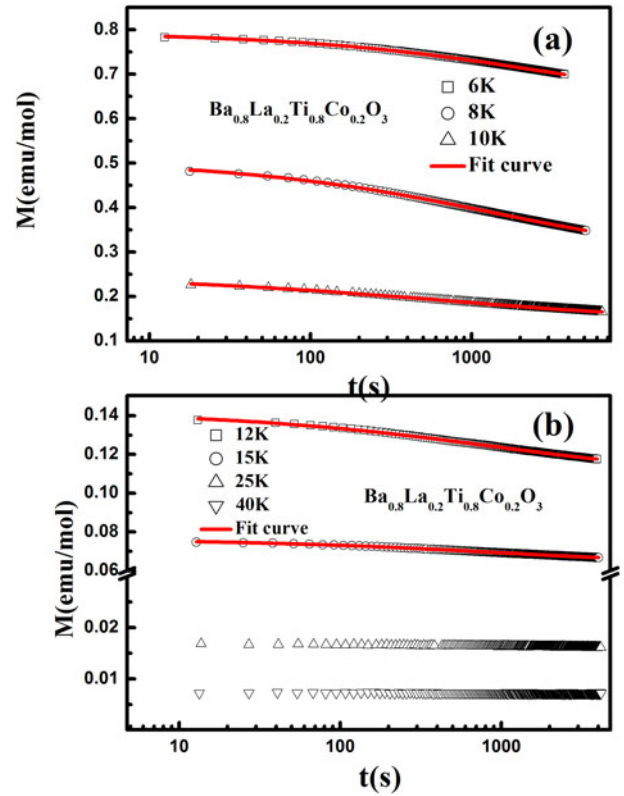


Fig. 8. (Color online) $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$: the time decay of thermoremanent magnetization at (a) 6, 8, and 10 K; (b) 12, 15, 25, and 40 K. The lines are the best fit to the data based on the stretched exponential relaxation function.

(iii) A reference curve was also produced by simply cooled the sample under the same field without any stops (M_{Ref}). A striking memory effect was observed. At each T_{stop} , the sample produces a clear upturn revealing the previous history of stops in zero field at that temperature.

The magnetic relaxation was studied at several temperatures below and above T_f . The sample was cooled in a field of 100 Oe from 300 K to the measured temperature, at which point the field is switched off and the time decay of M_{TRM} was recorded by the SQUID magnetometer. The logarithmic time dependence of $M(t)$ is presented in Figure 8. It shows that the time decay of M_{TRM} below 15 K is distinct, whereas the decay is unremarkable with further increasing temperature. It is known that the magnetic relaxation in SG systems and cluster glasses can be described by the stretched exponential relaxation function [9,18–21]:

$$M(t) = M_0 - M_{tr} \exp \left[- \left(\frac{t}{\tau_r} \right)^{1-n} \right] \quad (3)$$

where M_0 , M_{tr} , τ_r and n are the FM component, the glassy component, the relaxation characteristic time, the critical exponent, respectively. The solid lines in Figure 8 denote the best fit to the data using the expression, and the fit parameters are listed in Table 1. It can be seen from

Table 1. Fitting parameters of the time decay of thermoremanent magnetization of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$.

T (K)	M_0 (emu/mol)	M_{tr} (emu/mol)	n	τ_r (s)
6	0.6619 ± 0.00095	0.1323 ± 0.00067	0.5020 ± 0.0040	2402.656 ± 0.1029
8	0.3182 ± 0.00084	0.1913 ± 0.00082	0.5422 ± 0.0044	1375.149 ± 0.1592
10	0.1538 ± 0.00034	0.0973 ± 0.00055	0.6429 ± 0.0044	775.1938 ± 0.1152
12	0.1131 ± 0.00018	0.0295 ± 0.00019	0.5603 ± 0.0066	934.5794 ± 0.2065
15	0.065 ± 0.00009	0.0114 ± 0.00010	0.5454 ± 0.0082	1030.702 ± 0.4177

Figure 8 that the data below 15 K can be well described by equation (3). Moreover, M_0 , M_{tr} , and τ_r exhibit a large variation on T , while n shows a weak dependence on T . It should be noted that n increases from 0.5020(40) at 5 K to 0.6429(44) at 10 K and decreases with further increasing temperature, whereas the value of τ_r shows an inverse correlation to the variation of n . The inflection point at 10 K just corresponds to the freezing temperature ($T_f = 10.1$ K) of SG transition. Furthermore, the value of n implies the magnitude of magnetic relaxation. If $n = 0$, the system exhibits the exponential relaxation with the type of Debye and single time-constant, and if $n = 1$, the system does not display any relaxation at all. Therefore, based on the fit parameters shown in Table 1, it can be found that the relaxation of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ decreases with increasing temperature when $T \leq 10$ K and increases with further increasing temperature. Normally, with the temperature increasing, the freezing spins will get more thermal activation energy to overcome the energy barriers and the SG systems will eventually decay into a more stable state. Thus the relaxation of the system will decrease and disappear when the system enters the PM region, and accordingly the value of n will increase monotonically and the relaxation time will decrease with increasing temperature. These tendencies coincide with the results reported in other systems [9,19,20]. Then a salient question to ask is the following: why does the value of n in $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ decreases with increasing temperature when $T > 10$ K?

Suppose the magnetic phase above the freezing temperature of 10 K is paramagnetic, the system $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ will not display the characterization of relaxation and the value of n will approach 1. However, $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ still exhibits the relaxation behavior when temperature increases to 15 K, implying the existence of SG phases above 10 K. Therefore, there may be a characterization temperature T^* above which point the system $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ enters the PM region. Between 10 K and T^* , the microscopic magnetic structure of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ can be understood by the coexistence of a unique SG phase and a PM phase. As the temperature decreases from T^* to 10 K, SG phases start to appear and become partly frozen, whereas the PM phases are still dominant in $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$, and the dominant PM phase in $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ overwhelms the SG phase giving rise to the increase in the value of n . In a word, in the temperature region above T_f , it is a growing and percolating process of the SG phase during cooling.

The variation of the relaxation around T_f is consistent with the model that there is a critical region between a SG phase and a PM phase in the 3D Ising spin glass phase proposed by Ogielski [22]. It can also be found in some other systems, i.e., $\text{Cu}_{0.5}\text{Co}_{0.5}\text{Cl}_2\text{-FeCl}_3$ [23], $\text{Eu}_{0.4}\text{Sr}_{0.6}\text{S}$ [24]. Moreover, the value of $n = 0.6429$ at T_f close to $2/3$ corresponds to Ogielski's results [22]. Although the most reported Ising spin glass are single crystal, the behavior of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ still implies that the sample has a possibility to be a 3D Ising SG.

4 Conclusion

The magnetic properties of La^{3+} and Co^{3+} co-doped $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{1-x}\text{Co}_x\text{O}_3$ ($0 \leq x \leq 0.2$) were investigated. $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ shows a different magnetic behavior compared with the samples with $x = 0$ and 0.1. The dynamic magnetic properties of $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ were studied. The frequency dependence of ac susceptibility measurements, aging effect measurements, memory effect measurements, and the time decay of the M_{TRM} indicate that $\text{Ba}_{0.8}\text{La}_{0.2}\text{Ti}_{0.8}\text{Co}_{0.2}\text{O}_3$ undergo a SG transition at 10.1 K, which might be due to the dilution of Co^{3+} HS ions.

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