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Positive and negative exchange bias effects in the simple perovskite manganite NdMnO3

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Abstract

Exchange bias effects were studied in the simple perovskite NdMnO 3. Nd 3+ ordering is induced by the Mn 3+ ferromagnetic component, and they are antiferromagnetically coupled with each other. At 30 K, both negative and positive exchange bias effects are found, which are dependent on the cooling field. The exchange bias fields are around -2400 Oe and 1800 Oe, respectively. Positive and negative exchange bias effects were also observed at 8 K, but the exchange bias fields are only 130 Oe and -120 Oe. The coupling intensity between Nd 3+ ordering and Mn 3+ ordering, and their initial states determine the polarity of the exchange bias fields. © 2012 American Institute of Physics.

Keywords

manganite, perovskite, simple, negative, effects, positive, bias, exchange, ndmno3

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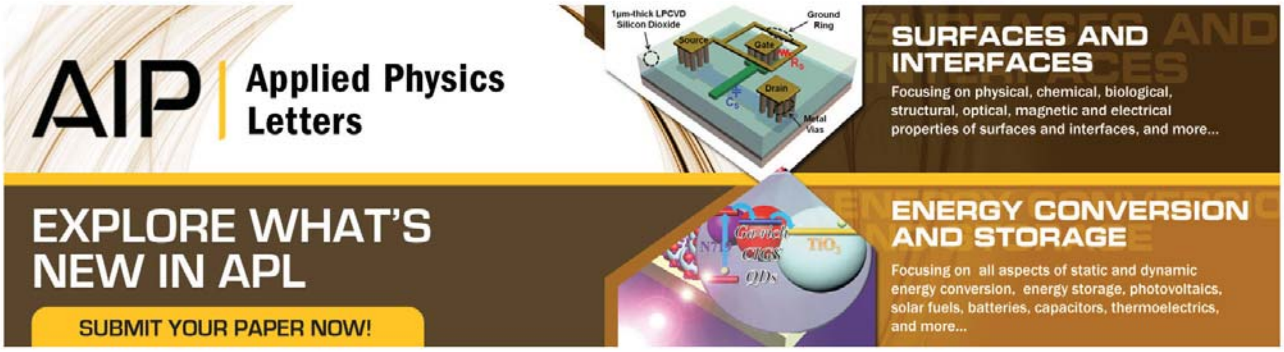

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Positive and negative exchange bias effects in the simple perovskite manganite $NdMnO_3$

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Exchange bias effects were studied in the simple perovskite $NdMnO_3$. Nd^{3+} ordering is induced by the Mn^{3+} ferromagnetic component, and they are antiferromagnetically coupled with each other. At 30 K, both negative and positive exchange bias effects are found, which are dependent on the cooling field. The exchange bias fields are around −2400 Oe and 1800 Oe, respectively. Positive and negative exchange bias effects were also observed at 8 K, but the exchange bias fields are only 130 Oe and −120 Oe. The coupling intensity between Nd^{3+} ordering and Mn^{3+} ordering, and their initial states determine the polarity of the exchange bias fields. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4751990]

The exchange bias effect usually occurs in ferromagnetic and antiferromagnetic bilayers or multilayers. In such a system, the two coercive fields of the magnetic hysteresis loop are not symmetric, and the centre of the magnetic hysteresis loop shifts to the left or right. A representative system is Co-CoO,[1,2] where Co is ferromagnetic and CoO is antiferromagnetic. In this system, exchange bias occurs at the interface between these two different magnetic materials, and the maximum exchange bias field in this system is 9500 Oe.[3] In a similar system, Fe-Fe_3O_4,[4,5] the exchange bias field is about 120 Oe, much smaller than that in Co-CoO. Materials with exchange bias effects are widely used in magnetic recording devices.[3,6] In recent years, the exchange bias effect has been found in heterostructures and artificial interfaces, in which the exchange bias effect can be adjustable. In the $Co_{0.9}Fe_{0.1}/BiFeO_3$ system, the intensity of the exchange bias interaction is found to be dependent on the properties of the ferroelectric domain walls in the $BiFeO_3$ layer,[7] which sheds light on how to control the exchange bias effect by an external electric field.[8] A similar study was also reported on the Co/$BiFeO_3$ system[9] and the $BiFeO_3/YMnO_3$ system.[10] Interface interaction may induce unique properties and change the magnetic properties of bulk materials, as in a systematic study of the exchange bias effect that was carried out on $LaNiO_3$-$LaMnO_3$ superlattices.[11] On the other hand, the exchange bias effect can also exist in compounds or composites which allow the coexistence of both a ferromagnetic component and an antiferromagnetic component. Recently, the exchange bias effect was intensively studied in $La_{1-x}Pr_xCrO_3$ and Sr_2YbRuO_6, in which both positive and negative exchange bias effects can be observed and are dependent on the cooling field and temperature.[12,13] In these two compounds, the exchange bias effect is different from what appears in bilayer and other interface structures. The coupling between the Pr^{3+} magnetic rare earth ions and the Cr^{3+} transition metal ions at different atomic sites in the ABO_3 structure determines the properties of the exchange bias effect in $La_{1-x}Pr_xCrO_3$.[12] In Sr_2YbRuO_6, however, the exchange bias effect originates from the Dzyaloshinsky–Moria interaction induced ferromagnetic component and from the antiferromagnetic coupling between the magnetic rare earth ion Yb^{3+} and the transition metal ion Ru^{3+}, which are in the same atomic site in the ABO_3 structure. Therefore, it is likely that the exchange bias effect may be observed in some other similar systems. To explore new materials with exchange bias based on this idea, we have chosen to study the simple perovskite manganite $NdMnO_3$, considering that the Nd^{3+} spins enter into ferromagnetic ordering, while Mn^{3+} is in the antiferromagnetic state at low temperature. Our results show that both a positive and a negative exchange bias effect can be observed for different magnetic states. The cooling field can affect the exchange bias field and change the polarity of the exchange bias effects. A simple scheme is proposed to explain these unique exchange bias effects.

Polycrystalline samples of $NdMnO_3$ were made by the traditional solid state reaction method from Nd_2O_3 (99.9%) and $MnCO_3$ (99.9%) powders bought from Sigma-Aldrich. Stoichiometric amounts of raw oxide powder were weighed carefully and mixed in an agate mortar, followed by pressing into pellets 15 mm in diameter at 20 MPa. Samples were calcined at 950 °C for 10 h and sintered at 1450 °C for 48 h. The crystal structures of the samples were examined by X-ray diffraction at room temperature (XRD, model: GBC MMA), using Cu Kα radiation at $\lambda = 1.54056$ Å. The Rietveld refinement calculations were conducted via FULLPROF software. The magnetic measurements were carried out using a 5 T magnetic property measurement system (MPMS) and a 14 T physical property measurement system (PPMS), equipped with a vibrating sample magnetometer (VSM), over a wide temperature range from 5 to 300 K.

The results of structural characterization of the sample by XRD are given in Figure 1. We employed Rietveld analysis to refine the diffraction patterns. The quality of the refinement is expressed by the refinement parameter $\chi^2 = 2.4$. All XRD peaks can be assigned to the single phase orthorhombic structure with space group *Pnma*, and no detectable impurity phase is present. The lattice parameters are $a = 5.7524$ Å, $b = 7.5623$ Å, and $c = 5.4068$ Å, respectively.

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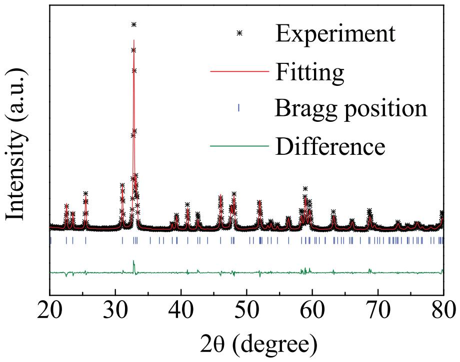

FIG. 1. XRD Rietveld refinement results for $NdMnO_3$, with $\chi^2 = 2.4$ (star symbols, experimental data, and solid red line, fitted pattern from Rietveld structural refinement, respectively). The mismatch between the measured and Rietveld refined spectra is plotted with a slight downshift for clarity. The short vertical solid lines are guides for the eyes to mark the corresponding Bragg positions.

The temperature dependence of the magnetic moment was measured under both zero field cooling (ZFC) and 5000 Oe field cooling (FC) conditions in warming up mode, and the results are given in Figure 2(a). A clear peak can be identified in the ZFC curve around 13 K, which is assigned to the occurrence of the Nd^{3+} long-range ordering. This result is consistent with the neutron diffraction results.[14] When the temperature increases, there is a sudden decrease in the ZFC moment, due to the dropping out of the Nd^{3+} long-range ordering. The bump starting at around 79 K (shown by the black arrow) is ascribed to the Mn^{3+} magnetic ordering. The Curie-Weiss law fitting over the interval from 150 K to 300 K, as shown in Figure 2(b), gives a positive Curie temperature of about 50 K, indicating that there is relatively strong ferromagnetic interaction in the Mn^{3+} sublattice. It is also true that we observe an increasing moment below 79 K, which suggests ferromagnetic behaviour. Meanwhile, the Curie-Weiss law fitting also gives a total effective moment of about 6.0 μ_B. If we calculate the theoretical moment, the high spin state will produce an effective moment of about 6.09 μ_B, while the low spin state will produce an effective moment of about 4.59 μ_B (Mn^{3+}: 2.828 μ_B/atom in the low spin state and 4.9 μ_B/atom in the high spin state; Nd^{3+}: 3.62 μ_B/atom). The close agreement between the experimental effective moment and the theoretical moment in the high spin state indicates that the Mn^{3+} is in the high spin state. This high spin state determines the relatively strong trend towards antiferromagnetic interaction among the Mn^{3+} ions, because the Mn^{3+} 3*d* orbital has four electrons. Neutron studies also confirm the antiferromagnetic property of Mn^{3+} ordering.[14] Similar to the case of $LaMnO_3$, it was reported that the Mn^{3+} ordering in $NdMnO_3$ is also A-type antiferromagnetic ordering.[14] In this case, the ferromagnetic component should originate from the canted A-type antiferromagnetic spin arrangement. The FC moment is negative at low temperature and reaches its maximum value at 13 K. This abnormal phenomenon indicates that the Nd^{3+} ordering is antiferromagnetically coupled with the Mn^{3+} ferromagnetic component. A higher measuring field, such as 5 T, can force the Nd^{3+} spins to flip below 13 K and give a positive total moment (not shown), which follows the trend of a common ZFC and FC temperature dependence of the magnetic moment. Our previous work has claimed that short-range Nd^{3+} ordering still exists above 13 K.[15] This means that the Nd^{3+} ordering is induced by the strong Mn^{3+} ferromagnetic component, which is similar to the case of $SmMnO_3$.[16] This phenomenon can also be confirmed by the magnetic hysteresis loops in Figure 3, which will be discussed later. Therefore, in $NdMnO_3$, ferromagnetic ordering and antiferromagnetic ordering coexist, and they are coupled with each other. Exchange bias may occur in such a system.

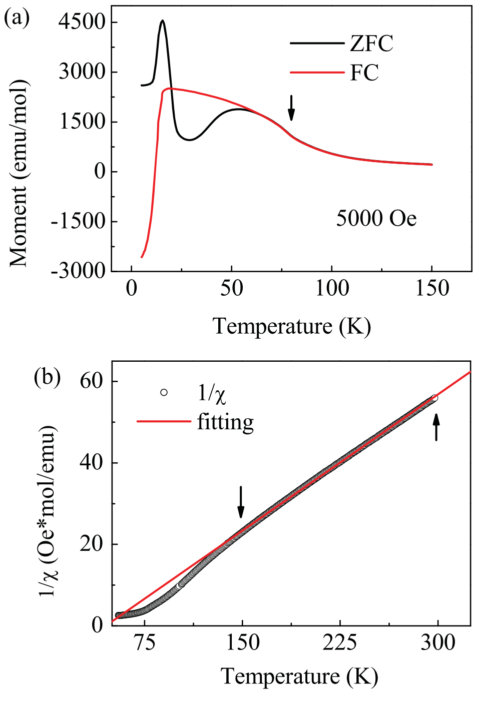

FIG. 2. (a) Zero field cooling and 5000 Oe field cooling temperature dependence of magnetic moment; (b) Curie-Weiss law fitting for spin state calculation.

To study the possible exchange bias effect, we measured the magnetic hysteresis loops when the Nd^{3+} was in the short-range ordering state at 30 K and in the long-range ordering state at 8 K. The magnetic hysteresis loops at 30 K and 8 K are presented in Figures 3 and 4, respectively. Figure 3 shows the cooling field dependence of the magnetic hysteresis loop at 30 K, after the sample was cooled down from 150 K (which is much higher than the Mn^{3+} ordering temperature) to 30 K in various positive cooling fields. The measuring fields range from −3 T to 3 T, in which Nd^{3+} spins will remain relatively still, while the Mn^{3+} spins will easily follow the external field (as will be discussed later). When the sample is cooled down to 30 K without magnetic field, a nearly symmetric hysteresis loop is obtained, and no obvious exchange bias effect is presented, because of the disordered nature of the ferromagnetic-like initial domain state, as shown in Figure 3(a). However, a significant negative exchange bias effect is observed when the cooling field is 2 T, with the exchange bias field reaching about −2400 Oe, as shown in Figure 3(b). The negative exchange bias effect will become weaker when the cooling field increases to 5 T, at which there is only a shift of about −340 Oe, as shown in Figure 3(c). On the contrary, a significant positive exchange bias effect occurs when the cooling field is 10 T, at which the

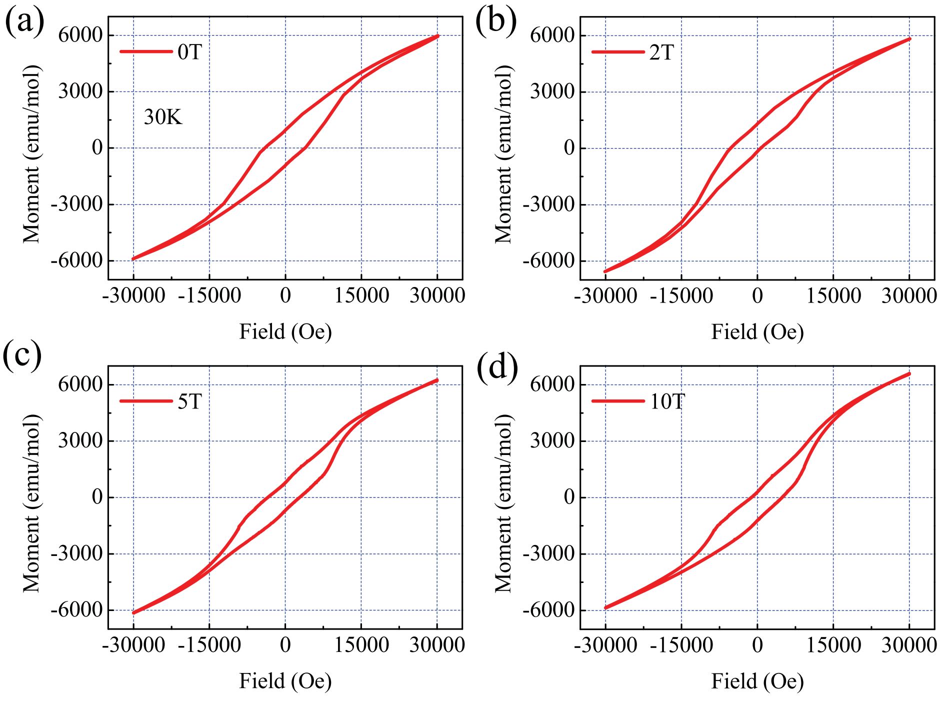

FIG. 3. (a)–(d) Magnetic hysteresis loop measured at 30 K while the Nd^{3+} is in the short range ordering state after cooling down from 150 K in various positive cooling fields: 0 T, 2 T, 5 T, and 10 T, respectively.

exchange bias field is about 1800 Oe, as shown Figure 3(d). The cooling field dependence of the exchange bias field at 30 K is presented in Figure 5(a).

On the other hand, Figure 4 presents the cooling field dependence of the magnetic hysteresis loop at 8 K. When the sample is cooled down from 150 K to 8 K in the zero field, below the Nd^{3+} ordering temperature, no obvious shift can be observed, as shown in Figure 4(a). However, a positive exchange bias effect can be observed in a 2 T cooling field, and the exchange bias field is about 130 Oe, as shown in Figure 4(b). Because of the strong Nd^{3+} ferromagnetic contribution at 8 K, the coercive fields are very strong, and the shift is not as significant as that measured above the Nd^{3+} ordering temperature. When the cooling field increases to 5 T, a negative exchange bias effect occurs with an exchange bias field of about −70 Oe, as shown in Figure 4(c). When the cooling field further increases to 10 T, the exchange bias field reaches −120 Oe, as shown in Figure 4(d). The cooling field dependence of the exchange bias field at 8 K is presented in Figure 5(b). We also measured the exchange bias effect in the vicinity of the Nd^{3+} ferromagnetic ordering temperature at 13 K and found that only a very weak exchange bias effect occurs, which can be neglected (not shown). In this case, the exchange bias effect is strongly

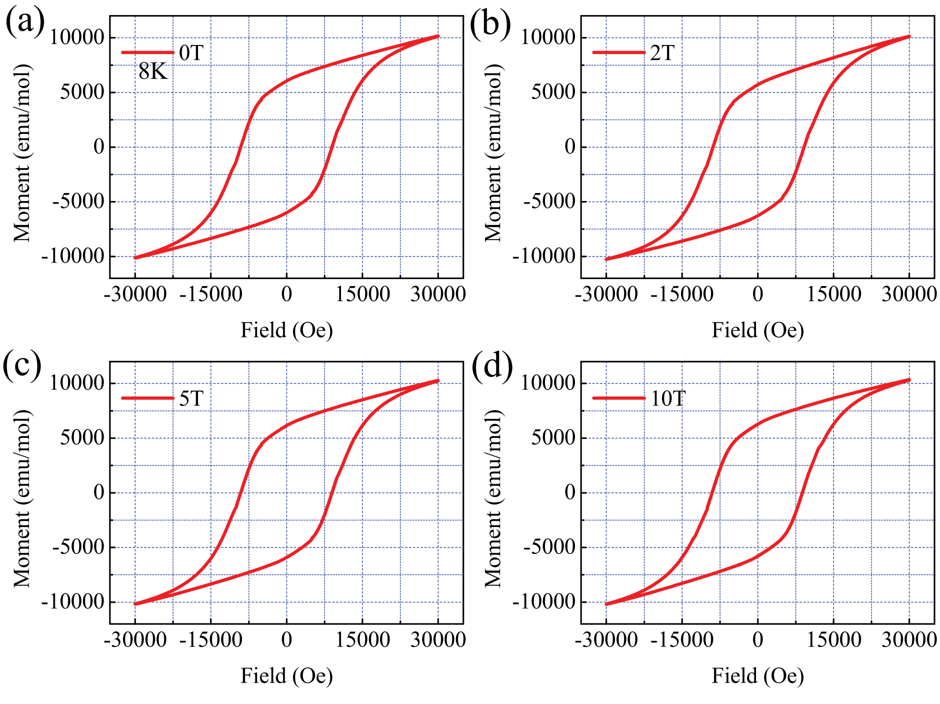

FIG. 4. (a)–(d) Magnetic hysteresis loop measured at 8 K, at which temperature the Nd^{3+} is in the long-range ordering state after cooling down from 150 K in various positive cooling fields: 0 T, 2 T, 5 T, and 10 T, respectively.

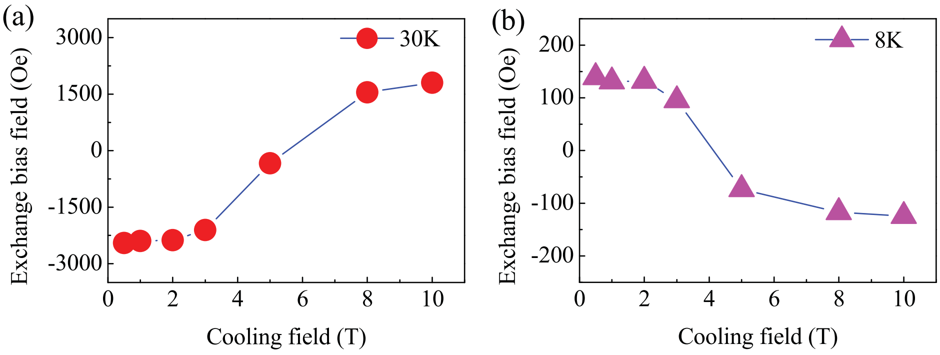

FIG. 5. (a) Cooling field dependence of the exchange bias field at 30 K (red solid circles) and (b) cooling field dependence at 8 K (pink triangles).

dependent on the coupling intensity between the Nd^{3+} ordering and the Mn^{3+} ordering, and on the initial states as well.

The positive and negative exchange bias effects take place in different magnetic states, which indicates that their mechanisms may be different. First of all, we discuss the case of the negative exchange bias observed at 30 K. When the Nd^{3+} is in the short-range ordering state, local ferromagnetic spin arrangements could form, as shown in Figure 6, which are not strictly antiferromagnetically coupled with the ferromagnetic component of Mn^{3+}. When the sample is cooled down in a relatively low cooling field, which does not exceed the exchange field (∼6 T, which can be obtained from Figure 5(a)) between Mn^{3+} and Nd^{3+}, the spin arrangement between Mn^{3+} and Nd^{3+} spins does not change too much, so that the Mn^{3+} spins will be aligned along the cooling field, and the Mn^{3+} and Nd^{3+} ions still tend to couple with each other antiferromagnetically. A positive measuring field will favour this Nd^{3+}/Mn^{3+} antiferromagnetically coupled state if the maximum field is much smaller than the exchange field. When an opposite measuring field (compared with that of the Mn^{3+} ferromagnetic component) is applied, the Mn^{3+} ferromagnetic component becomes unstable and begins to break free, which weakens the exchange interaction between Mn^{3+} and Nd^{3+}. In this case, the antiferromagnetic exchange field is not ∼6 T any longer, but begins to decrease, which further favours the switching of Mn^{3+} spins. During this process, the Nd^{3+} spins remain relatively still and offer a strong pinning force, while the Mn^{3+} spins follow the measuring field. Once Mn^{3+} spins are aligned along the negative measuring field, the Mn^{3+} and Nd^{3+} spins are ferromagnetically coupled, which is a metastable state with a ferromagnetic exchange field and could be favoured by the negative measuring field. The Nd^{3+}/Mn^{3+} antiferromagnetically coupled state, however, is more stable in terms of energy than the ferromagnetically coupled state. Therefore, it is much easier for the measuring field to achieve the antiferromagnetically coupled state than to achieve the ferromagnetically coupled state. Consequently, the negative exchange bias effect can be observed. When the cooling field is higher than the exchange field, both Nd^{3+} and Mn^{3+} ions will be aligned along the external field, and run in the same direction. The positive measuring field favours this metastable Nd^{3+}/Mn^{3+} ferromagnetically coupled state, but it is easy to go back to the more stable antiferromagnetically coupled state once the measuring field changes from positive to negative. A positive exchange bias can then be observed. As illustrated in Figure 6(a), a low positive cooling field could give a negative exchange bias effect because the Nd^{3+} spins are always opposite to the direction of the cooling field; when the positive cooling field is very high, high enough to

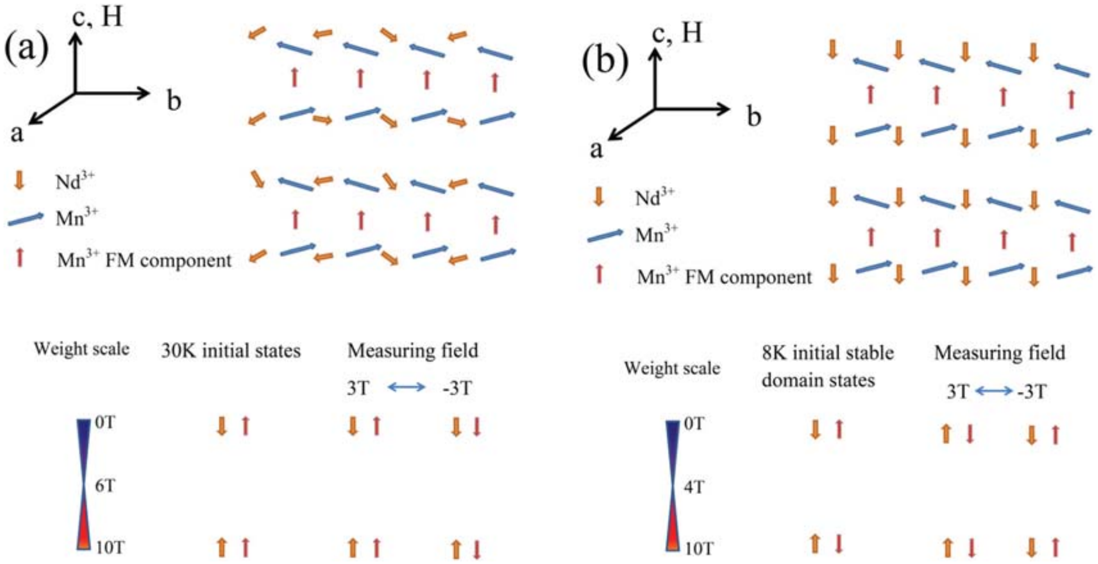

FIG. 6. (a) Scheme of the spin arrangement when Nd^{3+} is in the short-range ordering state at 30 K and (b) scheme of the spin arrangement when Nd^{3+} is in the long-range ordering state at 8 K.

align both the Nd^{3+} spins and the Mn^{3+} spins, then a positive exchange bias effect occurs, because the Nd^{3+} spins are always along the direction of the cooling field. When the cooling field is moderate, the Nd^{3+} spin arrangement will be disturbed, and the ions are unable to order along the same direction any more, but enter into a disorder-like state. In that case, the total pinning force will decrease, and the previous significant negative exchange bias effect will be suppressed.

On the other hand, when Nd^{3+} is in the long-range ordering state at 8 K, as shown in Figure 6(b), a strong ferromagnetic spin arrangement is present, which could always antiferromagnetically couple with the ferromagnetic component of the Mn^{3+} ordering, considering that the exchange field is about 10 T.[17] Then, the Nd^{3+} and Mn^{3+} spin system can be simply regards as a ferromagnetic or ferrimagnetic state at 8 K, and we could also only consider the contribution from Nd^{3+} spins because their moments are much larger than those of the Mn^{3+} spins. Therefore, when the sample is cooled down from high temperature in an external magnetic field, the ferromagnetic component of the Mn^{3+} ordering will be in the direction of the external field above the Nd^{3+} ordering temperature. Below the Nd^{3+} ordering temperature, the Mn^{3+} ions are still aligned along the external cooling field, if it is not high enough to flip all the Nd^{3+} spins. Normally, the cooling field should be no more than ∼1 T, which is the coercive field of Nd^{3+} spins, as illustrated in Figure 4. In this case, negative Nd^{3+} domains have formed before we measure the hysteresis loop. If the cooling field is higher than ∼1 T, but lower than the field which could switch all the negative domains, then there are still minority negative domains which could offer a pinning force to prevent the switching of majority domains, as illustrated in Figure 6(b). Consequently, the negative domain state is easier to achieve than the positive domain state, and a positive exchange bias effect occurs. If the cooling field is high enough to flip the Nd^{3+} below 13 K or above 13 K, positive domains will form before we measure the hysteresis loop, and then the positive domain state is easier to achieve, and a negative exchange bias effect occurs. Therefore, the exchange bias effects at 8 K stem from domain-domain interaction, which could be suppressed by a very high measuring field.[18,19]

In summary, positive and negative exchange bias effects in the simple perovskite manganite $NdMnO_3$ were studied. The temperature dependence of the magnetic moment reveals that Mn^{3+} has canted A-type antiferromagnetic ordering below 79 K. On the other hand, Nd^{3+} shows long-range ferromagnetic ordering below 13 K and short-range ordering below the Mn^{3+} ordering temperature. The ferromagnetic component of the Mn^{3+} sublattice is antiferromagnetically coupled with the ferromagnetic ordering of the Nd^{3+} sublattice, which provides the possibility for the exchange bias effect to occur. Systematic magnetic hysteresis loop measurements have confirmed the exchange bias effect. At 30 K, Nd^{3+} is in the short-range ordering state, so a significant negative exchange bias effect occurs when the cooling field is relatively small, reaching −2500 Oe when the cooling field is 1 T. Meanwhile, a positive exchange bias can also be achieved by using a big cooling field such as 10 T, in which the exchange bias field reaches 1800 Oe. In addition, a negative cooling field can also switch the negative exchange bias effect to the positive exchange effect, with almost same absolute values of the exchange bias fields. On the other hand, both positive and negative exchange bias effects can also be observed at 8 K. They can reach 130 Oe in 2 T cooling field and −120 Oe in 10 T cooling field, respectively. The polarity of the exchange bias field depends on the coupling intensity between the Nd^{3+} ordering and the Mn^{3+} ferromagnetic component, and on the initial states as well.

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