Giant anisotropic magnetostriction in Pr$_{0.5}$Sr$_{0.5}$MnO$_3$

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Abstract

Magnetic, linear thermal expansion (LTE), anisotropic ($\lambda_t$) and volume ($\omega$) magnetostriction properties of Pr$_{0.5}$Sr$_{0.5}$MnO$_3$ were investigated. The LTE decreases smoothly from 300 K without a clear anomaly either around the Curie ($T_C = 270$ K) or the Neel temperature ($T_N = 100$ K) and it exhibits hysteresis over a wide temperature range (60 K-270 K) upon warming. Isothermal magnetization study suggests that 13 % of the ferromagnetic phase coexists with 87 % of the antiferromagnetic phase at 25 K. The parallel and perpendicular magnetostricitions undergo rapid changes during the metamagnetic transition. Contrary to the isotropic giant volume magnetostriction reported in manganites so far, this compound exhibits a giant anisotropic magnetostriction ($\lambda_t \approx 10^{-3}$) and smaller volume ($\omega \approx 10^{-4}$) magnetostrictions below $T_N$. We suggest that the field induced antiferromagnetic to ferromagnetic transition is accompanied by a structural transition from
the $d_{x^2-y^2}$ orbital ordered antiferromagnetic (orthorhombic) to the orbital disordered ferromagnetic (tetragonal) phase. The metamagnetic transition proceeds through nucleation and growth of the ferromagnetic domains at the expense of the antiferromagnetic phase. The preferential orientation of the ferromagnetic (tetragonal) domains along the field direction increases the linear dimension of the sample in the field direction and decreases in the orthogonal direction leading to the observed giant anisotropic magnetostriction effect. Our study also suggests that nanodomains of the low temperature antiferromagnetic phase possibly exist in the temperature region $T_N < T < T_C$. 

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I. INTRODUCTION

Mixed valent RE$_{1-x}$A$_x$O$_3$-type manganites (RE$^{3+}$ and AE$^{2+}$ are rare earth and alkaline ions respectively) are best known for their extraordinary sensitivity of resistivity to internal molecular and external magnetic fields. The ferromagnetic ordering of the localized t$_{2g}^3$ spins at Mn$^{3+}$:t$_{2g}^3$e$_g^1$ and Mn$^{4+}$:t$_{2g}^3$e$_g^0$ sites favors the delocalization of e$_g$ carriers due to the double exchange interaction and, the antiferromagnetic ordering of the t$_{2g}^3$ spins favors the localization of the e$_g$-carriers. However, the nature of the antiferromagnetic (AF) ordering in manganites is strongly influenced by the carrier concentration, the average ionic radius $<r_A>$ of the A-site cations and the orbital degree of freedom. Hence, different types of antiferromagnetic configurations (A, pseudo CE, CE, C, and G) are found in manganites. In particular, the compound Pr$_{0.5}$Sr$_{0.5}$MnO$_3$ received much attention due to the discovery of the first order antiferromagnetic insulator-ferromagnetic metal transition under a magnetic field. The low temperature antiferromagnetic transition was earlier thought to be of CE type, but later studies showed that it is an A-type antiferromagnet with successive ferromagnetic planes coupled antiferromagnetically. Charges are itinerant within the ferromagnetic planes. The A-type antiferromagnetism in this compound is believed to be the result of the d$_{x^2-y^2}$ orbital ordering of the Mn$^{3+}$ ions. It was earlier interpreted that the low temperature insulating state in zero field is charge and CE-type antiferromagnetic ordered and, the destruction of the insulating state under a magnetic field is caused by the field induced melting of charges. However, the notion of charge ordering was later discarded. Presently, colossal magnetoresistance in this compound is believed to be the result of the field induced antiferromagnetic to ferromagnetic transition. However, it is not known whether the lattice is also affected by the magnetic field and if it is so in what manner. Studying the nature of the lattice distortion under a magnetic field could shed light on the mechanism of magnetoresistance. There are only few reports on the magnetostriction effect in the three dimensional perovskite manganites. These works mostly concentrate on the compounds which have ferromagnetic metallic or insulating ground states. Recently, the magnetostric-
tion behavior of the manganites having charge and antiferromagnetic (CE-type) orders at low temperature was investigated. \textsuperscript{7,8} It was found that the field induced transition from the charge ordered antiferromagnetic to the charge delocalized ferromagnetic transition in Nd\textsubscript{0.5}Sr\textsubscript{0.5}MnO\textsubscript{3} and La\textsubscript{0.5}Ca\textsubscript{0.5}MnO\textsubscript{3} \textsuperscript{7,8} is accompanied by a giant positive volume magnetostriction (i.e. the lattice volume increases under an external magnetic field) whereas Nd\textsubscript{0.5}Ca\textsubscript{0.5}MnO\textsubscript{3} and some other charge ordered systems exhibit a giant negative volume magnetostriction (i.e., lattice volume contracts under an external magnetic field). \textsuperscript{7,8} In this context, we investigated the magnetostriction behavior of Pr\textsubscript{0.5}Sr\textsubscript{0.5}MnO\textsubscript{3} which is neither charge ordered nor exhibits CE type antiferromagnetism.

II. EXPERIMENT

The polycrystalline Pr\textsubscript{0.5}Sr\textsubscript{0.5}MnO\textsubscript{3} sample was earlier characterized by X-ray diffraction and zero field resistivity measurements. \textsuperscript{11} The room temperature structure was found to be tetragonal (space group \textit{I4/mcm}) by neutron diffraction. \textsuperscript{11} We carried out magnetization \(M\), Linear thermal expansion (\(\Delta L/L\)) and magnetostriction on the previously characterized sample. The temperature dependence of \(M\) at \(\mu_0H = 1\) mT was measured using a Quantum Design SQUID magnetometer. We measured the isothermal magnetization up to 12 T using a vibrating sample magnetometer. The linear thermal expansion \(\Delta L/L\) by the strain gauge method in absence of a magnetic field was measured in 300 K-10 K range. The value of \(\Delta L/L\) at 300 K was taken as the reference point. Magnetostriction isotherms were measured using a pulsed magnetic field up to \(\mu_0H = 14\) T with the magnetic field parallel and perpendicular to the measuring direction. From the measured parallel (\(\lambda_{||}\)) and perpendicular (\(\lambda_{\perp}\)) magnetostrictions, we calculated the volume (\(\omega\)) and the anisotropic (\(\lambda_t\)) magnetostrictions for randomly oriented polycrystallites using the relations \(\omega = \lambda_{||}+2\lambda_{\perp}\) and \(\lambda_t = \lambda_{||} - \lambda_{\perp}\). The field dependence of the magnetostriction at selected temperatures was registered after zero field cooling the sample from 300 K to a desired temperature.
Figure 1 shows the temperature dependence of $M$ and $\Delta L/L$ of $\text{Pr}_{0.5}\text{Sr}_{0.5}\text{MnO}_3$ on the left and right scales respectively. The $M(T)$ curve suggests that the sample first undergoes a paramagnetic to ferromagnetic transition ($T_C = 270 \text{ K}$) and then from ferromagnetic to antiferromagnetic with ($T_N = 100 \text{ K}$) while cooling. The inflection point of the rapidly varying part of the $M(T)$ curve was taken as the Neel temperature. The antiferromagnetic ordering was shown to be A-type. While warming $T_N$ increases to 125 K and $M(T)$ exhibits hysteresis up to the Curie temperature. It should be noted that $M$ has not become zero at 10 K ($T<<T_N$) but exhibits a large value (1/5 of the maximum $M(T)$ while cooling and 1/2 of the maximum $M(T)$ while warming). This suggests that a fraction of the ferromagnetic phase continues to exist even below $T_N$. The presence of the ferromagnetic phase below $T_N$ is also shown up in the field dependence of the magnetization to be shown later. The structural symmetry at room temperature is tetragonal and it is unaffected by the paramagnetic-ferromagnetic transition. However, the ferromagnetic-antiferromagnetic transition is accompanied by tetragonal ($I4/mcm, \sqrt{2}a_p \times \sqrt{2}a_p \times a_p$) -orthorhombic ($Fmmm, 2a_p \times 2a_p \times 2a_p , a_p =$ lattice parameter of a pseudo cubic unit cell) structural transition. The vertical dashed lines mark the coexistence of the high and low temperature phases as found by the neutron diffraction study on a similar composition. The $\Delta L/L$ decreases rather continuously from 300 K down to 10 K without a clear anomaly either at the Curie temperature or at the Neel temperature. It should be pointed here that a clear volume contraction is observed around the Neel temperature in $\text{Nd}_{0.5}\text{Sr}_{0.5}\text{MnO}_3$ and $\text{La}_{0.5}\text{Ca}_{0.5}\text{MnO}_3$ and more recently even in the higher Sr content compound $\text{Pr}_{0.46}\text{Sr}_{0.54}\text{MnO}_3$. The $\Delta L/L$ of $\text{Pr}_{0.5}\text{Sr}_{0.5}\text{MnO}_3$ exhibits hysteresis over a wide temperature range (60 K- 270 K) similar to the $M(T)$ behavior. This behavior is strikingly different from $\text{Pr}_{0.46}\text{Sr}_{0.54}\text{MnO}_3$ which showed hysteresis only around the Neel temperature.

Figure 2(a) shows the field dependence of the magnetization at selected temperatures for $T<T_N$ and Figure 2(b) shows the $M(H)$ behavior above $T_N$. The behavior the $M(H)$
curve below $T_N$ suggests the coexistence of the ferromagnetic and the antiferromagnetic phases. The behavior of $M(H)$ below $\mu_0 H = 2 \, T$ at 25 K is dominated by the domain wall displacement and domains alignment of the ferromagnetic phase. The sudden increase of $M(H)$ just above $\mu_0 H_C = 4 \, T$ is the result of the metamagnetic transition in the antiferromagnetic phase. A rough value of the ferromagnetic phase fraction can be estimated as $y = M_0/M_{FM}$ where $M_0$ is the spontaneous magnetization and $M_{FM}$ is the saturation magnetization if the whole sample is ferromagnetic. The value of $M_0$ can be determined by plotting $M$ versus $1/H$ and extrapolating the linear part of the high field magnetization ($\mu_0 H < 2 \, T$) to 0 T which we found to be 0.46 $\mu_B$. The value of $M_{FM}$ for this composition is 3.5 $\mu_B$ and hence $y \approx 13\%$. The volume fraction of the ferromagnetic phase increases when the sample undergoes the metamagnetic transition and finally $y$ reaches 100 % at $\mu_0 H = 12 \, T$. As $T$ increases from 25 K, $\mu_0 H_C$ decreases from 4 T to 1.05 T at 100 K. The size of the ferromagnetic phase in the antiferromagnetic host appears to be dependent on the sample preparation condition. Allodi et al.\textsuperscript{15} and Jung et al.\textsuperscript{16} suggested nanoscale size ferromagnetic clusters at 10 K ($<<T_N$) whereas our results suggest rather a macroscopic (few 1000 Angstrom) size ferromagnetic phase. Very recently, Boujelben et al.\textsuperscript{17} showed that the magnetic properties of Pr$_{0.5}$Sr$_{0.5}$MnO$_3$ is sensitive to the quenching condition. The sample air quenched to room temperature from 1673 K was orthorhombic ($Imaa$) and underwent ferromagnetic-antiferromagnetic transition whereas the water quenched sample was rhombohedral ($R3c$) and did not show antiferromagnetic transition. Both the samples were found to be stoichiometric and the differences in magnetic properties were suggested to disorder effect in A-site.\textsuperscript{18} Our sample was furnace cooled (5 K/min) from 1573 K to room temperature and was found to be tetragonal.\textsuperscript{10,11} Recent theoretical model predict that the strength of disorder at A-site cations can control the size of two coexisting phases.\textsuperscript{18}

Fig. 3(a) shows the parallel magnetostriction ($\lambda_{\parallel}$) isotherms for $T \leq T_N$ and Fig. 3(c) shows $\lambda_{\parallel}$ for $T_N < T < T_C$. At 25 K, $\lambda_{\parallel}$ is small below $\mu_0 H_C = 4 \, T$ and then increases rapidly in between 4 T and 6 T. A change of slope occurs around 6.5 T and above this
field $\lambda_\parallel$ increases less rapidly without saturation up to the maximum field of 14.2 T. The value of $\lambda_\parallel$ at 14.2 T is $900 \times 10^{-6}$. A clear hysteresis is seen while reducing the field. When the field is reduced to 0 T, $\lambda_\parallel$ does not return to the original starting value but attains a higher value ($\approx 50 \times 10^{-6}$). The rapid increase of $\lambda_\parallel$ just above 4 T correlates with the metamagnetic transition found in the M(H) behavior (see Fig. 2). The metamagnetic like behavior in magnetostriction is present until 100 K and as T increases from 25 K the metamagnetic like transition occurs at lower fields which is in agreement with M(H) behavior (Fig. 2). At 125 K, 150 K and 175 K, $\lambda_\parallel$ increases rapidly at very low fields ($\mu_0H_C < 0.5$ T) due to ferromagnetic domain wall motion. However, $\lambda_\parallel$ increases without saturation up to the maximum field. We do not see any ferromagnetic contribution to the magnetostriction below the Neel temperature although such a behavior is shown in M(H) (see Fig. 2). This is possibly due to the smaller fraction of the ferromagnetic phase. Fig. 3(b) and Fig. 3(d) shows the perpendicular magnetostriction ($\lambda_\perp$) isotherms. As for $\lambda_\parallel$, $\lambda_\perp$ undergoes a rapid change during the metamagnetic transition but the sign is opposite to $\lambda_\perp$. An important difference is that the magnitude of the maximum magnetostriction value is lower in the perpendicular case ($\lambda_\perp = 600 \times 10^{-6}$, $\lambda_\parallel = 900 \times 10^{-6}$ at 14.2 T and T = 25 K) and the hysteresis, in particular the irreversibility at the origin is much larger in the perpendicular magnetostriction isotherms. For example, $\lambda_\perp = -200 \times 10^{-6}$ and $\lambda_\parallel = 50 \times 10^{-6}$ at 0 T after the field is reduced from the highest value. The irreversibility vanishes above the Neel temperature (see 125 K data in Fig. 2(b) and Fig. 2(d)).

Figs. 4(a) and 4(b) show the anisotropic magnetostriction ($\lambda_t$) isotherms calculated from the parallel and perpendicular magnetostrictions in Figs. 3(a)-(d). The anisotropic magnetostriction is nearly zero in the antiferromagnetic state but increases rapidly during the metamagnetic transition. At T = 25 K and $\mu_0H = 14.2$ the anisotropic magnetostriction reaches the maximum value of $1500 \times 10^{-6}$. It is indeed surprising since such a huge value anisotropic magnetostriction is not found in manganites so far. In a number of manganites, the anisotropic magnetostriction was found to be negligible ($\lambda_t < 60 \times 10^{-6}$) compared to
the volume magnetostriction ($\approx 10^{-2}$). What is also surprising is that the anisotropic magnetostriction even in between $T_N$ and $T_C$ (see 125 K, 150 K, and 175 K data) is at least a factor of 3-5 times larger than what is found in the ferromagnetic manganite $La_{0.7}Ca_{0.3}MnO_3$ in the same temperature range. The field dependence of $\lambda_t$ below 125 K shows a strong irreversibility at the origin which is a reflection of the behavior of the perpendicular and the parallel magnetostriction isotherms in Fig. 3. In $Pr_{0.46}Sr_{0.54}MnO_3$, the maximum $\lambda_t$ was less than $250 \times 10^{-6}$ at 14.2 T. The volume magnetostriction ($\omega$) shows a complex behavior as a function of field. The value of $\omega$ at $T = 25$ K is negligible in the antiferromagnetic state and shows a sudden decrease during the metamagnetic transition. At $T = 25$ K, $\omega$ reaches $-250 \times 10^{-6}$ at the maximum field which is about six times lower than the $\lambda_t$ value at the corresponding field. When the field is decreased from the maximum value $\omega$ decreases to reach still a lower value $-600 \times 10^{-6}$ at 1.5 T and then increases again for further decrease in H. At the origin, $\omega$ is much lower ($-500 \times 10^6$) with respect to the starting value. There is not much a big change in $\omega$ value between 25 K and 100 K but $\omega$ becomes positive above 125 K as can be clearly seen in Fig. 4(c) and Fig. 4(d). It is noteworthy to mention that the volume magnetostriction is positive and larger in value ($\omega > 1000 \times 10^{-6}$ at 25 K) below the Neel temperature in other half doped manganites $Nd_{0.5}Sr_{0.5}MnO_3$ and $La_{0.5}Ca_{0.5}MnO_3$ and also in $Pr_{0.46}Sr_{0.54}MnO_3$.

Fig. 5 shows the value of $\lambda_t$ and $\omega$ at the maximum field ($\mu_0H = 14.2$ T) as a function of the temperature. A rapid change in both $\lambda_t$ and $\omega$ occurs as the Neel temperature is approached from below. The anisotropic magnetostriction decreases rapidly and the volume magnetostriction changes the sign as $T_N$ is approached. No clear anomaly is observed at the Curie temperature in contrast to the behavior of $La_{0.7}Ca_{0.3}MnO_3$. The lack of volume anomaly at $T_C$ can be understood as a result of weak electron-phonon interaction in the paramagnetic state compared to $La_{0.7}Ca_{0.3}MnO_3$. It is worthy to note that charges are itinerant in the paramagnetic state ($d\rho/dT > 0$) of our compound whereas they are localized in $La_{0.7}Ca_{0.3}MnO_3$ ($d\rho/dT < 0$).
What is the origin of the unusual giant anisotropic magnetostriction in Pr$_{0.5}$Sr$_{0.5}$MnO$_3$? Giant anisotropic magnetostriction is generally found in rare earth intermetallic compounds like TbFe$_2$ and it is caused by the coupling of magnetic moments to the oval or pancake shaped anisotropic charge cloud of 4f orbitals of the rare earth ion. The anisotropic magnetostriction in our compounds due to spin-orbit coupling of Pr-ions can be neglected since anisotropic effect was not observed in related compounds. We have to consider other possibilities. The A-type antiferromagnetism in Pr$_{0.5}$Sr$_{0.5}$MnO$_3$ is caused by the e$_g$-d$_{x^2-y^2}$orbital ordering of Mn$^{3+}$ ions which drives the tetragonal (I4/mcm) to orthorhombic (Fmmm) structural transition. The e$_g$-orbital moment is quenched but orbital ordering creates a quadrupole moment. Since there is an unpaired electron in the d$_{x^2-y^2}$ orbital, there exists a magnetic dipole moment in addition to the quadrupole moment. The quadrupole moment (which is also assigned to pseudo spin $\tau^z = 1/2$ for d$_{3z^2-r^2}$ and $\tau^z = -1/2$ for d$_{x^2-y^2}$ orbitals) of the e$_g$-orbital can interact with the lattice through the quadrupole-strain interaction. When the spin ordering changes from the A-type antiferromagnetic to ferromagnetic, the d$_{x^2-y^2}$ orbital ordering is also expected to be destroyed. Hence, a magnetic field induced structural transition from Fmmm to I4/mcm symmetry takes place. The field induced transition is of first order with coexistence of the A-type AF domains (Fmmm) and the ferromagnetic domains (I4/mcm). At very high field (H $>>$H$_C$), only the ferromagnetic mono domain(I4/mcm) is expected. However, the orientation and perhaps the shape of the crystallographic (I4/mcm) domains just above H$_C$ depend on the direction of the applied field. When the measuring direction is parallel to the applied magnetic field, the I4/mcm domains are favorably oriented in the field direction and hence the parallel magnetostriction is positive and its value is larger. If we consider columns of the I4/mcm domains aligned in the field direction, the sign of the perpendicular magnetostriction indicates that the columns contract in the lateral direction. Hence, the anisotropic magnetostriction which is the difference between the parallel and perpendicular magnetostricitions is large. When
the field is reduced from the high value, some of the $I4/mcm$ domains do not revert back to the $Fmmm$ structure which causes the irreversibility at the origin. The rapid decrease of the anisotropic magnetostriction as $T_N$ is approached from below can be understood as a result of the decrease in the phase fraction of the $Fmmm$ phase.

The large value of the anisotropic magnetostriction (see 125 K, 150 K and 175 K data) above the Neel temperature but below the Curie temperature is intriguing. A possible scenario is that nano domains of the low temperature orbital ordered antiferromagnetic phase already exist in the high temperature ferromagnetic phase. As the temperature reduces these nanodomains grow in size and fuse into macrodomains around the Neel temperature. This can cause hysteresis in $M(T)$ and $\Delta L/L$ as we have observed. Such a scenario is not an unlikely possibility given the fact that we also observed appreciable positive volume magnetostriction in the ferromagnetic phase of Nd$_{0.5}$Sr$_{0.5}$MnO$_3$ and we have suggested the possibility of the charge-orbital ordered domains in the ferromagnetic phase\cite{7}. More recently, orbital ordered nanostructure was indeed found by X-ray diffusive scattering study in the same composition\cite{23}. Then, the contribution from the field induced structural changes of these nanodomains adds to the usual ferromagnetic contribution and hence the anisotropic magnetostriction is large. Finally, some remarks to be made about the differences between the magnetostriction behaviors of Pr$_{0.46}$Sr$_{0.54}$MnO$_3$ and Pr$_{0.5}$Sr$_{0.5}$MnO$_3$. It was shown earlier\cite{14} that Pr$_{0.46}$Sr$_{0.54}$MnO$_3$ exhibits a giant positive volume magnetostriction in contrast to the small negative volume magnetostriction effect found in Pr$_{0.5}$Sr$_{0.5}$MnO$_3$. But, the anisotropic magnetostriction in Pr$_{0.46}$Sr$_{0.54}$MnO$_3$ is an order of magnitude smaller than in Pr$_{0.5}$Sr$_{0.5}$MnO$_3$. We believe that these differences are related to the volume of differences between the orthorhombic(antiferromagnetic) and tetragonal (ferromagnetic or paramagnetic) phases. The spontaneous volume ( $H = 0$ T) shows a dramatic decrease around the Neel temperature in Pr$_{0.46}$Sr$_{0.54}$MnO$_3$ whereas it is rather smooth across the ferromagnetic-antiferromagnetic transition in Pr$_{0.5}$Sr$_{0.5}$MnO$_3$. The behavior of the $d_{x^2−y^2}$ orbital ordering due to excess electrons and the magnitude of exchange interactions will play
important role in these two compounds, but the details are yet to be understood.

V. SUMMARY

To summarize, the linear thermal expansion of Pr$_{0.5}$Sr$_{0.5}$MnO$_3$ does not show any clear anomaly either at the ferromagnetic or antiferromagnetic transition. Our isothermal magnetization study suggests that a minority ferromagnetic phase coexists with the majority antiferromagnetic phase below the Neel temperature. The ferromagnetic phase fraction is about 13\% at 25 K. The field induced antiferromagnetic to ferromagnetic transition is accompanied by a giant anisotropic magnetostriction ($\lambda_t \approx 10^{-3}$) and a smaller volume contraction ($\omega \approx 10^{-4}$). This is the first time such a large anisotropic magnetostriction is found in manganites. The value of anisotropic magnetostriction is large below the Neel temperature but its value even in the ferromagnetic temperature region is larger than found in other manganites. The anisotropic magnetostriction does not saturate even at 14.2 T in the ferromagnetic temperature region. We suggest that the metamagnetic transition in spin sector is accompanied by the creation of tetragonal ($I4/mcm$) ferromagnetic domains from the orthorhombic ($Fmmm$) antiferromagnetic matrix. The large anisotropic magnetostriction is suggested to formation of ferromagnetic domains ($I4/mcm$) in the field direction. Our magnetostriction and temperature dependence of the magnetization also suggest that nanodomains of the low temperature $Fmmm$ (antiferromagnetic phase) are possibly present in 125 K- 200 K where the sample is supposed to be a long range ferromagnet. Contrary to the large anisotropic magnetostriction, the volume magnetostriction is rather small. In view of the large anisotropic magnetostriction found it is worth to investigate anisotropic properties in magnetoresistance and magnetization as was found in the case of La$_{1-x}$Sr$_x$CoO$_3$.\textsuperscript{24}
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FIGURE CAPTIONS

Fig. 1: Temperature dependence of magnetization (left scale) and zero-field linear thermal expansion (right scale) of Pr$_{0.5}$Sr$_{0.5}$MnO$_3$ during cooling from 300 K to 10 K warming back to 300 K. M(T) was measured under $\mu_0H = 1\ mT$.

Fig. 2: Field dependence of magnetization (a) below $T_N$ and (b) above $T_N$ in Pr$_{0.5}$Sr$_{0.5}$MnO$_3$.

Fig. 3: Parallel and Perpendicular magnetostriction isotherms of Pr$_{0.5}$Sr$_{0.5}$MnO$_3$.

Fig. 4: Anisotropic and Volume magnetostriction isotherms of Pr$_{0.5}$Sr$_{0.5}$MnO$_3$.

Fig. 5: Temperature dependence of volume ($\omega$) and anisotropic ($\lambda_t$) magnetostriction at $\mu_0H = 14.2\ T$ for Pr$_{0.5}$Sr$_{0.5}$MnO$_3$. 
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