Chapter 6

Magnetic and transport behavior of Co-doped \( \text{Eu}_{0.5}\text{Sr}_{0.5}\text{MnO}_3 \)

6.1 Introduction

So far in the previous chapters we have focused on the magnetic and magneto-functional properties of several doped-MnNiGe alloys. In the present chapter we are going to investigate the magnetic and magneto-transport properties of Co-doped \( \text{Eu}_{0.5}\text{Sr}_{0.5}\text{MnO}_3 \) manganites with nominal compositions \( \text{Eu}_{0.5}\text{Sr}_{0.5}\text{Mn}_{1-x}\text{Co}_x\text{O}_3 \) \((x = 0, 0.02, 0.05, \text{and} \ 0.1)\). Among mixed-valent manganites, \( \text{Eu}_{1-p}\text{Sr}_p\text{MnO}_3 \) \((0 < p < 1)\) (ESMO) is one of the well studied systems which show AFM ground state due to the presence of smaller \( \text{Eu}^{3+} \) ions. [57, 58, 180–183] The competition between AFM and FM interactions is very strong around \( p \sim 0.5 \) and the ground state magnetic nature can easily be influenced by external \( H \). ESMO around \( p \sim 0.5 \) shows PM to AFM transition on cooling, which results insulating behavior of the compound down to the lowest temperature of measurement. On application of \( H \), the AFM insulating state transforms to a metallic FM state showing first-order insulator-metal (IM) transition on cooling. [57, 180, 181] Among transition metal doping in the Mn site of perovskite manganites, Co doping is particularly important because of the presence of differ-
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6.1 Introduction

6.2 Experimental results and discussions

6.2.1 Characterization

The room temperature XRD patterns indicate that the samples are in single phase with orthorhombic \( Pbnm \) structure (see main panel of fig. 6.1). No traces of extra phase are detected in these patterns. The orthorhombic lattice parameters of all the samples are plotted as a function of Co concentration in the inset of fig. 6.1. Lat-
Fig. 6.2: Main panels of (a), (b), (c) and (d) represent temperature ($T$) dependence of magnetization ($M$) for $x = 0, 0.02, 0.05$ and $0.1$ samples respectively in presence of $100$ Oe of applied magnetic field ($H$). Here measurements were performed in the zero-field-cooled heating (ZFCH), and field-cooled heating (FCH) protocols. Insets depict isothermal variation of $M$ as a function of external $H$ at $5$ K for the respective samples.

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peak around 45 K in ZFCH protocol. Peak in ZFCH data is also observed for all Co-doped samples (see main panels of fig. 6.2 b, c, and d). The observed peak in the ZFCH $M(T)$ data is found to be broadened and shifted towards higher $T$ with increasing Co concentration. About 20 K shift is observed for $x$ changing from 0 to 0.1. Instead of this peak like structure, a change of slope is associated with the FCH $M(T)$ data. In addition, FCH $M(T)$ data is found to deviate from the ZFCH $M(T)$ data below a certain temperature. This temperature also increases with increasing Co concentration. The nature of $M(T)$ data observed here is typical for a glassy magnetic ground state. There are several reports available in literature on the observation of glassy magnetic state at low-$T$ region in different compositions of ESMO. [58, 180] The observed glassy states in these compounds are not the conventional one, where glassy transition takes place in paramagnetic background, rather it originates from the presence of FM clusters in AFM background, which introduce frustration in long-range AFM order. Isothermal magnetization as a function of magnetic field at 5 K for all the compositions are also recorded and depicted in the insets of fig. 6.2. Clear signature of field induced metamagnetic transition (AFM to FM transition) is observed in the virgin leg (first field increasing line) for $x = 0$ and 0.02 compounds. No such transition is visible for $x = 0.05$ and 0.1 compounds within $\pm 50$ kOe. Magnetic moment in presence of 50 kOe of applied magnetic field is found to decrease with increasing Co concentration. This is clearly the effect of decrease in double exchange mechanism (ferromagnetic interaction) in presence of Co doping.

6.2.3 Magneto-transport

We have recorded $T$ variation of $\rho$ (see main panels of fig. 6.3) for all the samples in zero field as well as in presence of 50 and 150 kOe of applied $H$ in cooling and subsequent heating protocols. Zero field $\rho$ for all the samples are found to be insulating down to the lowest-$T$ of measurement. But in presence of external $H$, samples start to show metallic behavior below a certain $T$. A clear IM transition around 80 and 65 K is
Fig. 6.3: Main panels depict temperature ($T$) variation of resistivity ($\rho$) during cooling and subsequent heating protocol in presence of 0, 50, and 150 kOe of applied magnetic field ($H$) for $x = (a) 0$, (b) 0.02, (c) 0.05 and (d) 0.1 samples respectively. Inset of (a), (b), (c) and (d) shows variation of magnetoresistance (MR) as a function of $T$. Arrows in all panels indicate the direction of $T$ change.

observed for $x = 0$ and 0.02 samples respectively in presence of 50 kOe of external $H$ (see main panels fig. 6.3 (a) & (b)). A thermal hysteresis is also associated with this 50 kOe $\rho(T)$ data which confirms the first order nature of the transition. No such IM transition is visible in $x = 0.05$ and 0.1 sample in presence of 50 kOe applied $H$. But on application of higher external $H$ of 150 kOe, $x = 0.05$ sample shows IM transition around 52 K. It is to be noted that, in presence of 150 kOe of $H$, IM transition in $x = 0$ and 0.02 samples is found to be shifted towards higher $T$ at 105 and 102 K respectively. This 150 kOe magnetic field is also not high enough to induce any field induced IM transition in $x = 0.1$ sample. This type of field induced IM transition is not uncommon for ESMO. [57, 180] In presence of external $H$, the FM clusters start to grow in otherwise AFM ground state of these materials. For the presently studied
Co-doped samples, AFM interaction gets stronger with increasing Co concentration (Co doping reduces ferromagnetic double exchange interaction by reducing Mn$^{3+}$ to Mn$^{4+}$ ratio in the system) which results an increase in the critical field for AFM to FM transition (IM transition). Increase in strength of AFM interaction is also confirmed by the increase in low field PM to AFM transition temperature observed in $M(T)$ data (main panel of fig. 6.2). This AFM interaction becomes strong enough for $x = 0.1$ sample, which results absence of any IM transition even in presence of 150 kOe of applied $H$. We have calculated and plotted magnetoresistance [$MR = \frac{\rho(H) - \rho(0)}{\rho(0)}$] as a function of $T$ in field-cooled heating protocol for all the samples (see insets of fig.6.3). All the samples show negative MR ($\rho$ decreases in presence of $H$) over the measurement range. Magnitude of MR increases with decreasing temperature and found to be maximum at the lowest temperature of measurement. MR is recorded to be more than -99.9% in presence of 50 kOe of $H$ around 40 K for $x = 0$ and 0.02 samples. Whereas, for $x = 0.05$ and 0.1 samples MR is about -70% and -59% respectively at 40 K. Melting of AFM clusters into the FM state results this large negative MR, as commonly observed in CMR manganites [189].

Obervation of large negative MR well below the region of IM transition in FC state can not be explained only by the disorder driven first order phase transition from AFM insulator to FM metallic state. To shed more light on this phenomena we have recorded $\rho(T)$ data in varied conditions, such as, zero field heating after being cooled in zero field (curve i), heating in 150 kOe after zero field cooling (curve ii), and heating in 150 kOe after field cooling in 150 kOe (curve iii) (see fig. 6.4). We have performed this measurement for all the samples showing IM transition. A representative figure is shown for $x = 0.05$ sample in fig. 6.4. Nature of $\rho(T)$ curves depends strongly on the previous history of magneto-thermal cycling. Starting from the lowest $T$, curve ii remains well separated from curve iii though both of them are recorded in presence of 150 kOe of applied $H$. This is the effect of field cooling across the IM transition. This behavior is likely to be connected to the field-induced arrest
Fig. 6.4: Resistivity data for $x = 0.05$ sample recorded during heating in (i) zero field after being cooled in zero field, (ii) 150 kOe after being cooled in zero field and (iii) 150 kOe after being cooled in 150 kOe.

of the metallic FM state within the insulating AFM matrix. Application of 150 kOe of external $H$ in ZFC condition at 5 K transforms some of the AFM insulating phase to metallic FM phase. But as the $T$ and hence the thermal energy of the sample starts to increase, more AFM insulating state transforms to metallic FM state. This transition continues up to 26 K, until most of the AFM state transforms to FM state and it touches curve iii. Similar type of magneto-thermal behavior is also observed in different phase separated manganites and ferromagnetic shape memory alloys with AFM ground state. [49, 57, 92, 190, 191]

We have recorded $\rho$ as a function of $H$ at different constant $T$ as shown in fig. 6.5. All data were obtained during heating in a thermally demagnetized state. Thermally demagnetized state was obtained by cooling the sample from room temperature to 5 K and then heated back to the respective temperature of measurements in zero magnetic field. Large variation of $\rho$ is observed below and around the IM transition region. Interestingly $\rho(H)/\rho(H = 0)$ is found to be highly irreversible with respect to $H$ in the region of metastability. In this region, the virgin curve (first field increasing
Fig. 6.5: $\rho(H)/\rho(H=0)$ data at different constant temperatures are plotted as a function of external magnetic field for $x = (a) 0$, (b) 0.02, (c) 0.05 and (d) 0.1 sample. Dotted arrows indicate field increasing direction whereas solid arrows represent field decreasing direction.

line from zero field) remains well outside the subsequent field cycling paths. Initial application of $H$ below IM transition region results sharp drop in $\rho$ and the system remains arrested in the low-$\rho$ state even on removal of $H$. On further field cycling (beyond the virgin line) $\rho$ takes a completely different path forming clear hysteresis loop, however no further arrested states are observed. It is clear that on application of 150 kOe of $H$, $x = 0$, 0.02 and 0.05 samples have been arrested in a low resistive FM state and remains partially arrested in that state even when the field is removed. The virgin line effect becomes less prominent with increasing temperature and Co concentration. The $x = 0.1$ sample does not show any virgin line effect or field induced transition which agrees well with the $\rho(T)$ data, where we do not observe any field induced IM transition.
6.2.4 Magnetic relaxation and memory

The nature of the $M$ vs. $T$ data indicates that the studied samples may have glassy magnetic ground state. To investigate the spin dynamics of the magnetic ground state of studied samples we performed magnetic relaxation measurement at 5 K (see fig. 6.6). During this measurement samples were cooled from 300 K to 5 K in presence of 250 Oe of external $H$ and $M$ was measured as a function of $t$ immediately after removing the external $H$. Strong relaxation effect was observed for the undoped sample and it starts to decrease with increasing Co concentration. After 4000 s of measurement about 1.8% change in $M$ was observed for the undoped sample, where as for 10% Co-doped sample change in $M$ was found to be about 0.25%. Such a large difference in relaxation effect indicates that the landscape of energy states distributed over the spatial dimension of the sample, through which the system evolves, decreases with increasing Co concentration. Relaxation data of these samples can be well fitted by modified stretched exponential function given by
Magnetic viscosity is plotted as a function of time for $x = (a) 0$, (b) 0.02, (c) 0.05, and (d) 0.1 samples. Here the relaxation was measured in the zero-field-cooled state at $H = 250$ Oe for two different values of $t_w$.

$$M(t) = M_0 + b \exp(-t/\tau)^\beta$$  \hspace{1cm} (6.1)

This particular equation is popularly known as Kohlrausch-Williams-Watt (KWW) equation and is widely used to describe the relaxation behavior of glassy magnetic systems. [75, 144, 145, 192] Here $M_0$ stands for initial magnetization, $b$ is the contribution from glassy part, $\tau$ is the relaxation time and the exponent $\beta$ signifies the number of intermediate states through which the system evolves and its value lies between 0 and 1 for different disordered magnetic systems. As the value of $\beta$ approaches 1, number of intermediate states diminishes. [193] For the presently studied samples, $\beta$ is found to increase with increasing Co concentration (see table 6.1), which indicates that doped samples evolve through a lesser number of intermediate states than the undoped one. This is due to the fact that Co doping reduces AFM-FM competition in the sample by reducing DE and hence FM domains in otherwise AFM sample.

Distribution of local energy minima (free energy landscape), responsible for such
large relaxation effect, may occur either from a disordered magnetic state or from a SG-like ground state. To examine the exact nature of magnetic ground state, we carefully investigated aging effect for all the samples. During this measurement samples were first cooled in zero field from 300 K to 15 K and allowed to age isothermally in zero field for certain period $t_w$. Subsequently $M$ was measured as a function of time in the presence of $H = 250$ Oe. The measurement was repeated for two different values of $t_w$, e.g. 600 s and 4800 s for each sample. We have calculated and plotted magnetic viscosity $[S(t) = \frac{1}{H} \frac{\partial M}{\partial \ln t}]$ as a function of time from $M(t)$ data (see fig. 6.7). Systematic shift in the peak observed in $S(t)$ data with $t_w$ is an indication of the presence of spin glass like ground state in the sample. Peaks observed for the studied samples do not match exactly with $t_w$. This type of behavior is not uncommon among glassy magnetic materials indicating deviation from classical spin glass behavior. [194, 195]

Tempted by the observation of strong relaxation effect and aging phenomena, we performed ac susceptibility measurement at four different constant frequencies. The imaginary part ($\chi''_{ac}$) of ac susceptibility data are plotted as a function of $T$ in the main panels of fig. 6.8 (a)-(d) (real part not shown here). Clear peak-like features are associated with $\chi''_{ac}(T)$ data in all the studied compounds and the peak temperature is found to be shifted towards higher $T$ with increasing Co concentration, which agrees well with the dc magnetization data. Interestingly, the peak in the $\chi''_{ac}(T)$ data shifts to higher $T$ with increasing driving frequency $(f)$ of applied ac magnetic field. This non-ergodic behavior is a possible signature of glassy magnetic ground state in these samples. The shift in the peak temperatures $(T_f)$ for all the samples are around 1 K for $f$ changing from 19 Hz to 191 Hz. We have calculated relative shift in $T_f$ which is often expressed as $P = \frac{\Delta T_f}{T_f |\Delta \log \omega|}$, where $\omega = 2\pi f$ is the angular frequency of the ac excitation. For the present series of samples $P$ is found to be within 0.01-0.03 which lies well within the reported values for cluster glasses. [75, 196, 197]

This type of peak shift may also arise from the non-interacting superparamagnetic nanoparticles simply from the particle size distribution and associated distribution in
Fig. 6.8: Main panels of (a)-(d) depict imaginary part of the ac susceptibility as a function of \( T \) for \( x = 0, 0.02, 0.05, \) and 0.1 samples respectively. During these measurements the dc magnetic field was kept zero and the magnitude of ac field was 3 Oe. Insets show variation of relaxation time (\( \tau \)) as a function of peak temperature (\( T_f \)). Solid line in the insets indicate fitting to the experimental data in accordance with the dynamical scaling model.

To investigate the true reason behind the observation of the shift in ac susceptibility data, we have tried to fit \( T_f \) vs \( f \) data by the simple Arrhenius law (\( f = f_0 \exp[-E_a/k_B T_f] \)), expected for non-interacting superparamagnetic system. [75] Here, \( f_0 \) is a characteristic frequency of the system, \( E_a \) is the activation energy, and \( k_B \) is the Boltzmann constant. None of our experimental data (\( T_f \) vs \( f \) data) follow this equation, which indicate that the shift in the peak of \( \chi''_{ac}(T) \) data observed for the present samples may arise from the SG-like ground state and not from the magnetic relaxation of non-interacting nanoparticles.

To shed more light on the glassy magnetic ground state of the studied compounds, frequency shift in the \( \chi''_{ac}(T) \) data were investigated through dynamical scaling (DS)
**Table 6.1: Different fitting parameters**

<table>
<thead>
<tr>
<th>$x$</th>
<th>$\beta$</th>
<th>$\tau_0$ (s)</th>
<th>$z\nu$</th>
<th>$T_g$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.6072</td>
<td>$2.13 \times 10^{-11}$</td>
<td>6.93</td>
<td>40.58</td>
</tr>
<tr>
<td>0.02</td>
<td>0.6257</td>
<td>$5.11 \times 10^{-8}$</td>
<td>3.92</td>
<td>44.12</td>
</tr>
<tr>
<td>0.05</td>
<td>0.6309</td>
<td>$3.2 \times 10^{-8}$</td>
<td>2.82</td>
<td>47.03</td>
</tr>
<tr>
<td>0.10</td>
<td>0.6726</td>
<td>$2.3 \times 10^{-6}$</td>
<td>1.69</td>
<td>48.41</td>
</tr>
</tbody>
</table>

analysis (see relaxation time $\tau$ vs. $T_f$ data in the insets of fig. 6.8). In this method, relaxation time $\tau$ ($= 1/2\pi f$) (for the decay of the fluctuations to the spin correlation length) can be expressed as $\tau = \tau_0(T_f/T_g - 1)^{-z\nu}$, [198] where $z$ is the dynamic critical exponent, $\nu$ is the spin-correlation length exponent, $T_g$ is the zero frequency spin freezing temperature, and $\tau_0$ is the characteristic spin flipping time. The parameters $\tau_0$, $T_g$, and $z\nu$ obtained from the analysis are summarized in table 6.1. For canonical spin glass (CSG) systems, $\tau_0$ is reported to be about $\sim 10^{-13}$ s whereas $z\nu$ falls in the range 4-12. [75] It is clear from table 6.1, that the value of $\tau_0$ obtained for the undoped sample is a little bit larger than that of the CSG materials and it increases with increasing Co concentration. These large values of $\tau_0$ indicates slower rate of spin flipping, commonly observed for cluster glass and reentrant spin glass compounds. [75] On the other hand, $z\nu$ for the undoped sample ($z\nu = 6.93$) falls well within the reported range of CSG materials, but we observe a significant decrease in the $z\nu$ value with increasing Co concentration. For 10% Co doping, value of $z\nu$ obtained is about 1.69 which is well below the reported values for CSG materials. Recently there are several reports on the observation of low values of $z\nu$ in some systems, such as LaMn$_{0.5}$Fe$_{0.5}$O$_3$, BiFeO$_3$ and Cu$_{2.84}$Mn$_{0.44}$Al$_{0.72}$, but the reason behind the observation of such low value of $z\nu$ is not clear yet. [199–201]

To ascertain the non-ergodicity of the magnetic ground state, we performed magnetic memory measurement for all the samples in different protocols. Fig. 6.9 (a)-(d) depict field-cooled field-stop memory measurement in the $M$ vs. $T$ data. [150]
Fig. 6.9: (a), (b), (c) and (d) depict field-cooled field stop memory effect in dc magnetization vs. temperature data for $x = 0$, 0.02, 0.05 and 0.1 samples respectively. Main panels of (e), (f), (g) and (h) show relaxation memory measurement in presence of 250 Oe of applied field. Time evolution of $M$ were measured with a small negative $T$ cycling in three different segment (eg. $KL$ (20 K), $PQ$ (15 K) and $UV$ (20 K) for $x = 0$ sample) of about 8600 s each. Insets of (e), (f), (g) and (h) show rejuvenation (positive $T$ cycling) measurements of magnetic relaxation.

Protocol, samples were cooled from room temperature to 5 K in presence of 100 Oe of applied $H$ with intermediate stops for $t_w = 3600$ s at three different constant temperatures $T_{stop}$ (points $S_1$, $S_2$ and $S_3$ in curve $M_{FC}^{stop}$). During these isothermal stops, applied $H$ was reduced to zero, however, during further cooling, the field was applied again. Subsequent heating (without any stop) in 100 Oe shows clear anomalies at each $T_{stop}$, revealing the presence of magnetic memory in these samples.

To strengthen the observation of magnetic memory in $M(T)$ data, we performed relaxation memory measurements with negative $T$ cycling for all the samples (see main panels of fig. 6.9 (e)-(h)). [202, 203] During this measurement samples were first cooled in zero field from 300 K to 20 K and magnetization was measured as a function of time ($t$) in presence of 250 Oe of external $H$ in three different segments $KL$, $PQ$ and $UV$ (main panel of fig. 6.9(e)) with the sample $T$ being at 20 K, 15 K and 20
K respectively. $M$ was measured for about 8600 s in each segment. The relaxation process during UV is simply a continuation of the process during KL. This observation indicates that the sample can remember its previous state when it is cycled back to initial $T$ (here 20 K). This relaxation memory measurement was performed for all the samples and we observe a positive result. To check whether the memory in the sample can be erased or not, we performed rejuvenation measurement for all the samples (see insets of fig. 6.9 (e)-(h)). Rejuvenation measurements were performed by giving a small positive $T$ cycling, samples were heated to a higher value of $T$ for the intermediate relaxation measurement, instead of negative $T$ cycling as given in the relaxation memory measurements. Here $M$ vs. $t$ was measured consecutively at 20 K (IJ), 25 K (JN), and 20 K (YZ). The results of these measurements are found to be significantly different (not a continuation of similar $M$) from the main panels of fig. 6.9 (e)-(h), which is common for any non-ergodic system.

Signature of magnetic memory can also originate from super-paramagnetic nanoparticles. Though we ruled out this possibility by ac susceptibility analysis, we also performed zero-field-cooled memory measurements in $M$ vs. $T$ data (see fig. 6.10) for all the samples to ensure that the presence of magnetic memory is an outcome of SG-like ground state only. [78, 151, 152] In this protocol, samples were first cooled from 300 K to 5 K in absence of external $H$ with two intermediate stops of 14400s each (e.g. point $S_1^{ZFC}$ and point $S_2^{ZFC}$ in fig. 6.10(a)). The samples were then heated back to 60 K in presence of 100 Oe of applied $H$. Characteristic features are observed around the stoppage points. These features are clearer in the difference curves $\Delta M(T) = M_{ZFC}^{ref}(T) - M_{ZFC}^{mem}(T)$. Presence of zero-field-cooled memory effects indicate that the ground state of these compounds are SG-like.
Fig. 6.10: Main panels show memory measurement in zero field cooled condition in $M$ Vs. $T$ data for $x = (a) 0$, (b) 0.02, (c) 0.05, and (d) 0.1 samples respectively. The samples were first cooled in $H = 0$ with two intermediate stops (e.g., $S_1^{ZFC}$ and $S_2^{ZFC}$ for $x = 0$ sample). Samples were then reheated in presence of $H = 100$ Oe up to 60 K ($M_{ZFC}^{mem}$). Zero field cooled reference curves ($M_{ZFC}^{ref}$) with no intermediate stops during cooling were also recorded. The difference in magnetization $\Delta M = M_{ZFC}^{ref} - M_{ZFC}^{mem}$ are plotted as a function of $T$ in the insets.

### 6.3 Summary and conclusions

From our investigations we observe a systematic change in the magneto-transport behavior of $\text{Eu}_{0.5}\text{Sr}_{0.5}\text{Mn}_{1-x}\text{Co}_x\text{O}_3$ compound with $x$. This system is an interesting example where we observe metastability and field-induced arrest around IM transition. These observations are not very uncommon among the materials containing magneto-structural first order transition and is related to the existence of minima in the free energy landscape corresponding to parent (AFM insulator) and product (FM metallic) phases. [49, 57, 190, 191] On application of external $H$, the barrier height between parent and product phase decreases paving the path for field induced transition. One can also influence this barrier height by other parameters also. In the present work,
strong dependence of magneto-thermal irreversibility and field induced IM transition with Co doping indicate that it affects the free energy landscape by increasing the barrier height between the parent and product phases. This energy barrier becomes high enough for $x = 0.1$ sample and no field induced transition is observed even in presence of 150 kOe of applied $H$. The virgin line anomaly in isothermal $\rho - H$ data is also an outcome of field induced arrest. This behavior is observed in several other compounds with first order metamagnetic transition. [48, 49, 92, 159, 163, 191, 204]

Our magnetic studies on Co-doped Eu$_{0.5}$Sr$_{0.5}$MnO$_3$ compounds indicate a gradual shift from a CSG-like ground state to a CG-like ground state with increasing Co concentration. Due to the presence of smaller Eu$^{3+}$ ions, AFM interaction dominates in the parent compound (Eu$_{0.5}$Sr$_{0.5}$MnO$_3$) in spite of the presence of equal ratio of Mn$^{3+}$ and Mn$^{4+}$ ions. The competition between AFM and FM interactions is very strong for the parent compound and ground state magnetic nature can easily be influenced by external $H$. Observation of field induced IM transition confirms this strong competition between AFM and FM interactions. Co doping in Mn site, which affects the ratio of Mn$^{3+}$ and Mn$^{4+}$ ions, results decrease in the double exchange interaction (FM interaction) between Mn$^{3+}$ and Mn$^{4+}$ to some extent by strengthening ground state AFM interaction. Increase in the critical fields for IM transition with Co-doping confirms this effect. In other words, the parent compound consists of smaller size AFM and FM domains and the AFM domains start to increase in size with increasing Co concentration, which indicates an increase in the intra-domain (AFM and FM) frustrated/frozen spin regions. This increase in AFM domain size and hence frustrated/frozen spin regions results a gradual change in the magnetic ground state nature of these compound from CSG-like to CG-like.

In conclusion, we observe metastability, CMR behavior and field induced arrest around and below IM transition in Co-doped ESMO. These behaviors are primarily connected to the AFM insulator to FM metallic transition. Magneto-transport properties of these compounds depend strongly on the previous history of field cy-
The presence of the ZFC memory confirms that the glassy magnetic state is associated with cooperative spin freezing.