Reentrant spin glass behavior in a layered manganite \( \text{La}_{1.2}\text{Sr}_{1.8}\text{Mn}_2\text{O}_7 \) single crystals

S. H. Chun, Y. Lyanda-Geller, and M. B. Salamon

*Department of Physics and Materials Research Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801-3080*

R. Suryanarayanan, G. Dhalenne, and A. Revcolevschi

*Laboratoire de Physico-Chimie de l’Etat Solide, CNRS, UMR 8648, Bat.414 Université Paris-Sud, 91405 Orsay, France*

(March 21, 2022)

We report here a detailed study of AC/DC magnetization and longitudinal/transverse transport properties of \( \text{La}_{1.2}\text{Sr}_{1.8}\text{Mn}_2\text{O}_7 \) single crystals below \( T_c = 121 \) K. We find that the resistivity upturn below 40 K is related to the reentrant spin glass phase at the same temperature, accompanied by additional anomalous Hall effects. The carrier concentration from the ordinary Hall effects remains constant during the transition and is close to the nominal doping level (0.4 holes/Mn). The spin glass behavior comes from the competition between ferromagnetic double exchange and antiferromagnetic superexchange interactions, which leads to phase separation, i.e. a mixture of ferromagnetic and antiferromagnetic clusters, representing the canted antiferromagnetic state.

I. INTRODUCTION

Recent investigations of nearly-cubic doped perovskite manganites that show colossal magnetoresistance (CMR) reveal the importance of a delicate balance among charge, spin, lattice, and orbital degrees of freedom. It is also clear that effective dimensionality of a system plays an important role, as the CMR effect becomes larger in layered manganites, particularly the \( n=2 \) member of the Ruddlesden-Popper series \( \text{(La,Sr)}_{n+1}\text{Mn}_n\text{O}_{3n+1} \), compared to the \( n=\infty \) case, \( \text{La}_{1-x}\text{Sr}_x\text{MnO}_3 \). The ferromagnetic transition temperature \( T_c \), however, considerably lowers (~120 K) in the former. Because of the reduced dimensionality, the balance between ferromagnetic (FM) double exchange and antiferromagnetic (AFM) superexchange interaction between Mn ions is more subtle. Therefore, slight changes in doping lead to significantly different magnetic ground states. For example, Kubota et al. reported that the ferromagnetic easy axis changes from \( c \) axis \( (x \approx 0.32) \) to \( ab \) plane \( (x > 0.32) \) and that additional doping results in a canted antiferromagnetic state, with the canting angle increasing with doping, saturating at 180° at \( x = 0.48 \). For \( \text{La}_{1.2}\text{Sr}_{1.8}\text{Mn}_2\text{O}_7 \) \( (x = 0.4) \), neutron scattering studies show that, in the ground state, ferromagnetic and antiferromagnetic features co-exist, which can be interpreted as either a canted AFM state or phase separated clusters. We may expect, then, some related effects in bulk transport and/or magnetic properties.

Here, we report a detailed study of the magnetic and transport properties of \( \text{La}_{1.2}\text{Sr}_{1.8}\text{Mn}_2\text{O}_7 \) single crystals below \( T_c = 121 \) K. Our data show that the resistivity upturn below 40 K, typically seen in previous studies, is related to a transition in the magnetic subsystem from ferromagnetic to a “disordered canted” state. The possibility of a transition from the ferromagnetic state to one of several canted phases was discussed theoretically in the early paper by de Gennes. More recently, the phase diagram of manganites in the presence of the competition between ferromagnetic and antiferromagnetic interactions has received renewed attention. This competition can lead to phase separation into a system with FM clusters or to a canted antiferromagnetic state. Our study of AC/DC magnetization indicates that the magnetic ground state of the layered system, in the temperature range where the resistivity upturn occurs, shows characteristics of a reentrant spin glass phase. Furthermore, we observe that the transport properties in this regime are characterized by additional anomalous Hall effects.

II. EXPERIMENT

Single crystal rods of \( \text{La}_{1.2}\text{Sr}_{1.8}\text{Mn}_2\text{O}_7 \) were grown by the floating-zone method using a mirror furnace. The composition of the crystals as revealed by EDX analyses was very close to that of the starting material, used as polycrystalline seed rods in the growth furnace. For transport measurements a thin bar shaped sample was cut from one of the rods such that the surface is perpendicular to the \( c \)-axis. Contact pads were made by Au sputtering and Au wires were attached using silver paint. We adopted a low frequency ac method for the measurements. AC/DC magnetizations of the same sample were measured by SQUID magnetometers equipped with an ac susceptibility setup.

The in-plane resistivity \( \rho_{xx} \) and low field \( (H = 5 \text{ Oe} \text{ / } ab\text{-plane}) \) dc magnetization \( m \) of our crystal are shown as a function of temperature in Fig. 1. As typically seen in other studies, the resistivity drops sharply by more than two orders of magnitude at the ferromagnetic transition.
temperature ($T_c = 121$ K). Application of a magnetic field drastically reduces $\rho_{xx}$ over a wide range of temperatures both below and above $T_c$, resulting in an MR ratio $[(\rho(0 T) - \rho(7 T))/\rho(7 T)]$ as large as 14000% at $T_c$. An interesting feature is presence of a resistivity minimum at $T_{min} = 40$ K (without magnetic field). Okuda et al. ascribed this minimum to the existence of impurities or disorder in similar materials ($x = 0.35$). However, when magnetic field is applied, the resistivity minimum moves to higher temperatures compared to the resistivity minimum at zero magnetic field. Furthermore, there is a significant difference between the zero-field-cooled (ZFC) and field-cooled (FC) magnetizations (Fig. 1).\footnote{The magnetization studies imply that the ground state is not a simple ferromagnet, but in fact may indicate a possible spin-glass transition.}

In order to clarify the origin of the ZFC-FC hysteresis, we measured the ac magnetic susceptibility of our sample. The remanent DC magnetic field from the superconducting magnet was nulled below 1 mOe before the measurement. Figure 2(a) shows the temperature and the frequency dependence of the ac susceptibility ($H_{ac} = 1$ Oe). What we expect from a ferromagnet is similar to the dashed line in the figure, which is the ac susceptibility of a ferromagnetic La$_{0.7}$Ca$_{0.3}$MnO$_3$ single crystal ($T_c$ was scaled for comparison). Compared to this, our crystal shows a totally different behavior. After the ferromagnetic transition on cooling, the real part of the ac susceptibility ($\chi_{ac}^r$) decreases again below 20 K, a typical shape for a reentrant spin glass transition.\footnote{The appearance of frequency dependence only below 50 K strongly supports the glassy nature of the magnetic state in this region.}

The spin-glass phase is characterized by sluggish response to changes in external field and by slow relaxation of remanent magnetic moments. A useful method to deduce the glass transition temperature and the relaxation rate is to measure the temperature and time dependence of the thermoremanent magnetization (TRM).\footnote{The TRM is the dc magnetic moment measured after removing the field at a certain temperature. The inset of Fig. 1 shows the upturn in the temperature dependence of remanent magnetic moments. A useful method to deduce the glass transition temperature and the relaxation rate is to measure the temperature and time dependence of the normalized relaxation rate, which is the slope of relaxation divided by the initial magnetic moment $\frac{dM}{d\ln t}/M_{init}$, was 0.015 at 5 K. This value is much smaller than that found, for example, in the AuFe system\footnote{The temperature dependence of the normalized relaxation rate is required for an accurate comparison.}, which implies smaller barrier height. However, the detailed temperature dependence of the normalized relaxation rate is required for an accurate comparison.}

The temperature dependence of TRM, shown in the main panel of Fig. 2(b), is a good measure of the glass transition temperature $T_f$. The data were taken on heating the sample right after removing $H$ at 10 K from the field-cooled state. As temperature increases, the TRM drops rapidly and disappears at 40 K, which coincides with the minimum temperature of $\rho_{xx}$, $T_{min}$ (the small negative moments above $T_{min}$ are due to the remanent field of the magnet itself about 3 Oe). This confirms that the longitudinal resistivity upturn is indeed coincident with a change in the magnetic state. The correspondence between $T_f$ and $T_{min}$ is rather unusual, because in metallic spin glasses the effect of magnetic moment freezing is barely seen in resistivity measurements. It is the double-exchange interaction in this system which induces the strong correlation between magnetism and electronic transport. Application of a high magnetic field reduces $T_f$ significantly as in conventional spin glasses, and at the same time, makes the system more conductive. The MR is still large and even increases again below $T_{min}$, whereas there is nearly no MR in 3D perovskite manganites at low temperatures.

**III. MAGNETIC STATE AND TRANSPORT PROPERTIES OF THE SYSTEM.**

De Gennes in his classic paper\footnote{De Gennes in his classic paper proposed that the magnetic subsystem in the presence of double exchange interaction can undergo two transitions. One of these transitions is the usual ferromagnet-to-paramagnet transition at high temperatures while the other, from ferromagnetic to a canted ferromagnetic, a helical or a disordered spin state\footnote{A canted-like spin arrangement minimizes the sum of double-exchange energy of spins, $E_d \propto \cos \theta/2$, where $\theta$ is the angular deviation between spins, and (antiferromagnetic) superexchange energy, $E_{ex} \propto \cos \theta$. At finite temperatures orientation fluctuations of individual spins cause the mean interaction energies $\langle E_d \rangle \propto \langle \cos \theta/2 \rangle$ and $\langle E_{ex} \rangle \propto \langle \cos \theta \rangle$ to decrease at different rates. Thus, the two components in the effective local field change differently with temperature, leading to decrease of the canting angle, and eventually to ferromagnetic ordering. However, magnetic fields tend to align spins and to decrease fluctuations of their orientation, therefore leading to an increase in the temperature of the canted-state-to-ferromagnet transition.}\footnote{We now turn to the results of our resistivity measurements (Fig.1) that show the upturn in the temperature dependence of the resistivity occurring at 40 K in the absence of magnetic field. When magnetic field is applied, the upturn in the temperature dependence of the resistivity occurs at higher temperatures (Fig.1). We suggest that the temperature of the upturn in resistivity is the temperature at which the system begins to cross over to a de Gennes canted-like state. In crystals with high doping level the ferromagnet-to-canted-state transition is feasible when the hopping amplitude which determines the double-exchange interaction is sufficiently small. In layered systems, the amplitude of hopping between layers is indeed much smaller than hopping amplitude in cubic} proposed that the magnetic subsystem in the presence of double exchange interaction can undergo two transitions. One of these transitions is the usual ferromagnet-to-paramagnet transition at high temperatures while the other, from ferromagnetic to a canted ferromagnetic, a helical or a disordered spin state\footnote{The appearance of frequency dependence only below 50 K strongly supports the glassy nature of the magnetic state in this region.} occurs at lower temperatures due to competition between double exchange and direct antiferromagnetic interactions. Canted-like spin arrangements minimize the sum of double-exchange energy of spins, $E_d \propto \cos \theta/2$, where $\theta$ is the angular deviation between spins, and (antiferromagnetic) superexchange energy, $E_{ex} \propto \cos \theta$. At finite temperatures orientation fluctuations of individual spins cause the mean interaction energies $\langle E_d \rangle \propto \langle \cos \theta/2 \rangle$ and $\langle E_{ex} \rangle \propto \langle \cos \theta \rangle$ to decrease at different rates. Thus, the two components in the effective local field change differently with temperature, leading to decrease of the canting angle, and eventually to ferromagnetic ordering. However, magnetic fields tend to align spins and to decrease fluctuations of their orientation, therefore leading to an increase in the temperature of the canted-state-to-ferromagnet transition. We now turn to the results of our resistivity measurements (Fig.1) that show the upturn in the temperature dependence of the resistivity occurring at 40 K in the absence of magnetic field. When magnetic field is applied, the upturn in the temperature dependence of the resistivity occurs at higher temperatures (Fig.1). We suggest that the temperature of the upturn in resistivity is the temperature at which the system begins to cross over to a de Gennes canted-like state. In crystals with high doping level the ferromagnet-to-canted-state transition is feasible when the hopping amplitude which determines the double-exchange interaction is sufficiently small. In layered systems, the amplitude of hopping between layers is indeed much smaller than hopping amplitude in cubic.}
manganites, as demonstrated by strong anisotropy of resistivity in the whole temperature range. We believe that the resistivity minimum in La$_{1.2}$Sr$_{1.8}$Mn$_2$O$_7$ is intrinsic and is related to the change in magnetic ground state. Indeed, a transition from ferromagnetic order to canted-like states should influence the resistivity of the system. In the simple two-sublattice canted arrangement, spins are aligned within planes, but form fixed angle with spins in neighboring plane. When double exchange interaction regulates the charge carrier motion, the probability of charge carrier to propagate in the canted-like arrangement is significantly modified compared to isotropic ferromagnetic arrangement, and the character of charge carrier motion changes significantly, both because of self-trapping due to local spin distortions and because they become more confined to the two-dimensional planes. It is important to note that an increase in the resistivity in this case is essentially independent of its mechanism. On one hand, for example, a metallic system in the diffusive, low temperature regime might undergo a reentrant transition to an insulating state due to he effects of quantum interference and electron-electron interactions in the presence of disorder.[1] On the other hand, in the regime of hopping conduction between localized states,[2] charge carrier confinement to the two-dimensional planes significantly suppresses charge percolation. In this regard, we remark that similar temperature dependence has been observed for both in-plane and c-axis resistivity.

The increase in resistivity must also manifest itself if the spin-glass transition is between ferromagnetic ordering and a state exhibiting a phase separation; i.e., with coexisting ferromagnetic and antiferromagnetic regions. Such a state, in fact, is most likely to occur, as noticed in both experimental and theoretical studies.[3] In our case of layered manganites, a simple canted arrangement is less likely to manifest itself, because the system is intrinsically anisotropic, and charge carrier confinement to two-dimensional planes exists even in the absence of canted spin arrangements. However, inhomogeneity resulting from phase separation results in a pronounced resistivity increase. It is noteworthy that the magnetic field cannot simply change the relative proportions of the two regions without a decrease in the phase separation temperature. We also note, that a system with coexisting ferromagnetic and antiferromagnetic regions is quite likely to be characterized by a spin-glass like response.

Let us now turn our attention to the Hall effect. Recent studies show that anomalous Hall effects (AHE) in CMR materials depend strongly on the local magnetic moment texture, another consequence of double exchange.[4] The transition into a canted phase, or the freezing of magnetic moments should also be manifest in the AHE. Figure 3(a) shows the field dependence of the transverse (Hall) resistivity $\rho_{xy}$ at several temperatures around $T_F$ (the magnetic flux density $B$ was corrected by the sample demagnetization factor). The overall behavior is the same for all temperatures below $T_c$. As in typical ferromagnetic metals, $\rho_{xy}$ can be written as $\rho_{xy}(B, T) = R_0(T)B + \mu_0 R_S(T) M(B, T)$, where $R_0(T)$ and $R_S(T)$ are the coefficients of the OHE and the AHE, respectively.[5] Once the magnetization becomes saturated at higher field (about 2 T in this system), $\rho_{xy}$ increases linearly owing to the positive, hole-like ordinary Hall effect (OHE) $R_0$. In the free electron approximation, the effective charge carrier density per Mn ($n_{eff}$) can be calculated from $n_{eff} = V/eR_0$, where $V$ is the volume of unit cell containing one Mn atom. As we can see in Fig. 3(b), up to 75 K, $n_{eff}$ is constant, 0.36±0.02 holes/Mn, which is very close to the nominal doping level (0.4 holes/Mn) and, in particular, is insensitive to the transition at $T_F$.[6] Therefore, as concluded above, a mobility change causes the resistivity minimum. Applying a traditional metallic model for charge carrier transport in our system has to be done with caution. The reason is that estimates using a Drude-like model indicate that the resistivity of layered manganites is near or above the maximal Ioffe-Regel-Mott metallic resistivity throughout the whole range of temperatures, including the region of the resistivity minimum and the resistivity upturn, for both in-plane and, of course, c-axis resistivity. However, we observe no temperature dependence which would indicate hopping conductivity of charge carriers between localized states. Most probably, the conductivity can be qualitatively rendered as metallic, with low magnitude due to magnetic and charge inhomogeneities and strong scattering by magnetic domain boundaries. This point of view finds additional support from the temperature dependence of conductivity in the low-temperature regime (Fig. 4). Similarly to the work of Okuda et al.[7] we observe a square-root temperature dependence of the conductivity. Such a behavior in 3D metallic system at low temperatures (although significantly smaller in magnitude than we observe) would indicate electron-electron corrections to conductivity due to disorder.[8] Similar behavior may occur in layered systems.[9] However, the relative magnitude of the observed magnetoconductivity changes and low magnitude of the absolute value of the conductivity preclude any quantitative analysis.

Turning to $|R_S|$, as extracted from the low-field behavior of $\rho_{xy}$, Fig. 3b shows it to have a minimum close to $T_{min}$. One may expect this because it is known that $R_S$ correlates with $\rho_{xx}$ in other ferromagnetic metals.[10] In perovskite manganites, $R_S$ is proportional to $\rho_{xx}^2$ in the metallic region supporting the known side-jump picture.[11] However, the magneto resistance of this 2D system, large even below $T_c$, precludes a quantitative analysis based on $R_S$ only. Instead, in Fig. 5, we present the magnetic field dependence of the Hall conductivity $\sigma_{xy}$ at various temperatures. Below $T_{min}$, the temperature dependence of the Hall conductivity falls onto a single curve within the margin of experimental error. For contributions to the anomalous Hall effect at roughly temperature-independent magnetization, such a behavior can indeed be attributed to a side-jump effect. The side-jump contribution in the metallic conductivity regime,
depends on the product of the displacement of the center of gravity of the wavepacket describing charge carriers, which depends only on quantum mechanical phases, and the probability of the side jump. The latter in turn is proportional to the nonequilibrium population of carriers in the presence of electric field, governed by the momentum relaxation (transport) time. If the same mechanism, for example scattering from fluctuations of core spins, leads both to side jumps and to the transport relaxation time, then the anomalous Hall conductivity is temperature-independent. We note that the side-jump mechanism is close in its physical picture to the hopping mechanism of the anomalous Hall effect that we discussed recently. The anomalous Hall effect in the hopping regime arises from topological phases in disordered magnetic background in the presence of Dzyaloshinskii-Moriya spin-orbit interactions. The macroscopic mechanism that we proposed explains the scaling behavior of the Hall effects in La_{0.67}(Ca,Pb)_{0.33}MnO_3 single crystals near T_c. The anomalous Hall contribution due to the change in the magnetic texture in the regime of the spin glass transition in localized phase in a certain sense is similar to side-jump effects arising in the course of scattering by magnetic fluctuations in metallic regime. Both these mechanisms that are difficult to distinguish in the regime close to metal-insulator transition may cause the additional $R_S$ below $T_{min}$ that we observe.

IV. CORRESPONDENCE BETWEEN TRANSPORT STUDIES AND NEUTRON SCATTERING DATA

We now briefly discuss correspondence between our results and neutron scattering data on magnetic ordering in layered manganites. Neutron scattering data suggest that the antiferromagnetic superexchange is more pronounced in the quasi-2D layered system because of reduced dimensionality and the mixed FM and AFM features are interpreted as canted bilayer states. However, these results can be interpreted otherwise, as mentioned by Osborn et al. The first scenario, i.e. much weaker intrabilayer correlations compared to intraplanar correlation, is partially true. Chatterji et al. found that the intraplanar exchange interaction is three times larger than the intrabilayer coupling although nearest-neighbor distances are almost equal. The second possible scenario is an inhomogeneous distribution of FM and AFM regions. Monte Carlo calculations by Moreo et al. reproduced a pseudogap feature observed in the same system that we studied. Moreo et al. concluded that this was caused by the formation of metallic FM domains in an insulating AFM host. It is noteworthy that the many-body ground state of the double exchange model has local FM order without long range order. Thus, the interpretation of canted state based on neutron scattering data is inconclusive. Our observation of metastability below 40 K favors the cluster model which allows intrinsic disorder, although the system may transform to the canted state after a long time relaxation or by external field.

In any case, La_{1.2}Sr_{1.8}Mn_2O_7 is at a delicate balance between competing magnetic forces. Indeed, when La is partially substituted by Nd, the spin glass transition is more pronounced.

V. CONCLUSION

In conclusion, we studied AC/DC magnetization and longitudinal/transverse transport properties of La_{1.2}Sr_{1.8}Mn_2O_7 single crystals in detail. In the low field limit, the magnetic state changes from a ferromagnet to a spin glass at 40 K where the resistivity starts to increase. We interpret the resistivity upturn as an indication of a cross over from a ferromagnetic state to a (disordered) canted state as predicted by de Gennes. It is supported by the increase of the upturn temperature with field. This transition is accompanied by additional anomalous Hall effects due to the change in the magnetic texture while the carrier concentration deduced from ordinary Hall effects remains constant.

VI. ACKNOWLEDGMENT

The authors would like to thank M. Jaime and H. Yanagihara for helping experiments and J. P. Renard for useful comments. This work was supported in part by DOE DEFG-91ER45439.
has a secondary ferromagnetic transition at 250 K presumably due to the intergrowth. However, the relative magnetization was less than 0.6%, a too small value to account for more than the 50% reduction in ZFC magnetization at low temperatures.

12 C. D. Potter et al., Phys. Rev. B 57, 72 (1998).
13 B. R. Coles and S. B. Roy, Frontiers in Solid State Sciences: Selected Topics in Magnetism, Vol. 2, eds. L. C. Gupta and M. S. Multani, p363 (World Scientific, Singapore, 1993).
14 C. N. Guy, J. Phys. F: Metal Phys. 8, 1309 (1978).

We assume that doping corresponds to the part of the phase diagram, in which the ordered state is a ferromagnet. At a different doping, the high temperature transition can be the antiferromagnet-to-paramagnet transition, and the low temperature transition will then be the antiferromagnet-to-canted-phase transition.

15 We assume that doping corresponds to the part of the phase diagram, in which the ordered state is a ferromagnet. At a different doping, the high temperature transition can be the antiferromagnet-to-paramagnet transition, and the low temperature transition will then be the antiferromagnet-to-canted-phase transition.

16 B. L. Altshuler and A. G. Aronov, in Electron-Electron Interactions in Disordered Systems, A. L. Efros and M. Pollak, editors, North Holland, NY, 1985.

This result contrasts with what was observed in La$_{1-x}$Sr$_x$MnO$_3$, where $n_{\text{eff}}$ is several times larger than the nominal doping concentration and attributed to charge compensation effects.

19 S. H. Chun et al., Phys. Rev. B 59, 11 155 (1999) and references therein.
20 A. A. Abrikosov, Phys. Rev. B 61, 7770 (2000).
21 L. Berger, Phys. Rev. B 2, 4559 (1970).
22 S. H. Chun, M. B. Salamon, Y. Tomioka, and Y. Tokura, Phys. Rev. B 61, R9225 (2000).
23 T. G. Perring, G. Aeppli, Y. Moritomo, and Y. Tokura, Phys. Rev. Lett. 78, 3197 (1997); S. Rosenkranz et al., J. Appl. Phys. 83, 7348 (1998).
24 R. Osburn et al., Phys. Rev. Lett. 81, 3964 (1998).
25 T. Chatterji et al., Phys. Rev. B 60, R6965 (1999).
26 D. S. Dessau et al., Phys. Rev. Lett. 81, 192 (1998).
27 J. Zang, H. Röder, A. R. Bishop, and S. A. Trugman, J. Phys. Cond. Mat. 9, L157 (1997).
28 Even though single-site mean field calculation with relevant parameters points to the canted phase, the authors of Ref. 8 noted that the real system might possess more complicated spin ordering like spin glasses.
29 Y. Moritomo, Y. Maruyama, T. Akimoto, and A. Nakamura, Phys. Rev. B 56, R7057 (1997).

FIG. 1. In-plane resistivity $\rho_{xx}$ (H//c) and low field dc magnetizations (H//ab) of a La$_{1.2}$Sr$_{1.8}$Mn$_2$O$_7$ single crystal as a function of temperature.
Figure 1. Chun et al.
Figure 2. Chun et al.

(a) The figure shows the ac susceptibility ($\chi'$) as a function of temperature ($T$) for different frequencies: 1 Hz, 10 Hz, 100 Hz, and 1 kHz, with $H_{ac} = 1$ Oe // ab.

(b) The figure illustrates the magnetization ($m$) as a function of temperature ($T$) at $T = 5$ K. The inset shows the magnetization as a function of time ($t$) in minutes for $T = 5$ K.
Figure 3. Chun et al.
Figure 4. Chun et al.

\[ \sigma_{xx} \left( \frac{1}{\Omega \text{ cm}} \right) \]

vs.

\[ T^{1/2} \left( K^{1/2} \right) \]

Curves for different magnetic fields:
- \( H = 0 \text{ T} \)
- \( H = 3 \text{ T} \)
- \( H = 7 \text{ T} \)
Figure 5. Chun et al.