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IX TRIESTE WORKSHOP ON
OPEN PROBLEMS IN
STRONGLY CORRELATED SYSTEMS

14 - 25 July 1997

NEW EXPERIMENTS AND KEY ISSUES IN COLOSSAL MAGNETORESISTANCE

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These are preliminary lecture notes, intended only for distribution to participants.

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COLOSSAL MAGNETORESISTANCE OXIDES

1. Introduction
2. Theoretical ideas
3. Unusual metallic state
4. The paramagnet
5. Charge ordering and related phenomena.

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1. Introduction :-

A. $LaMnO_3$ is an insulator
[Both above and below the Neél temperature ~ 150 K]
Mott insulator

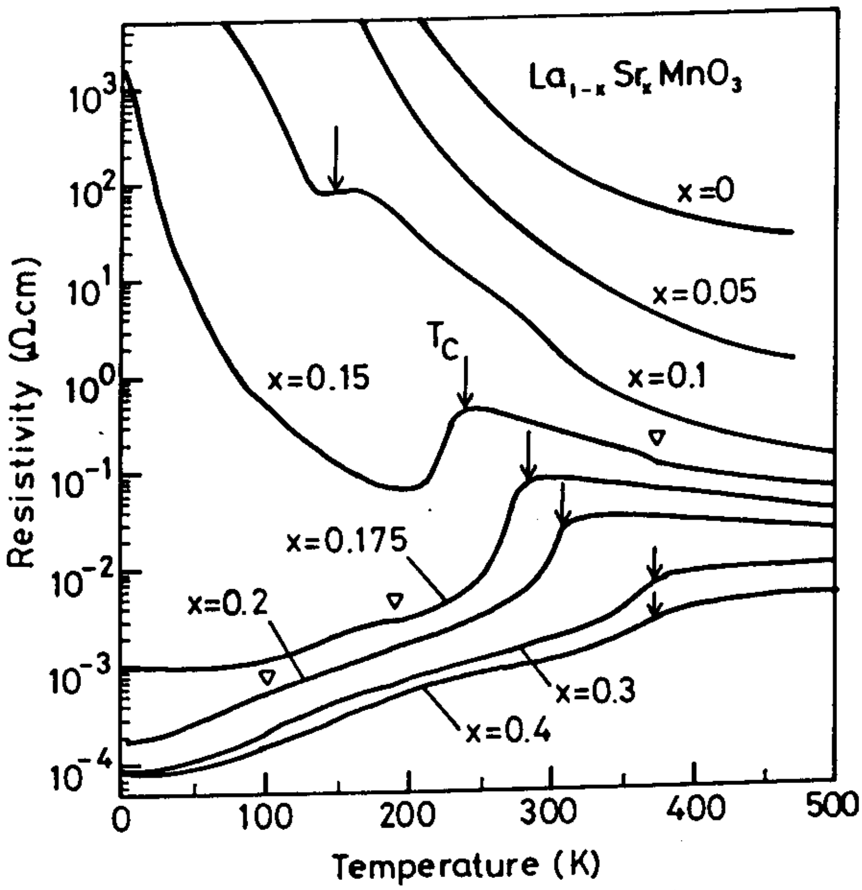
$La_{1-x} Sr_x Mn O_3$ is a metal
for $0.18 \lesssim x \lesssim 0.4$(?) and at low temperature.

Paramagnetic (bad metal? insulator?) → Ferromagnetic metal
$T_0 \sim 300K$.

The family $Re_{1-x} A_x Mn O_3$
is home to a variety of phenomen

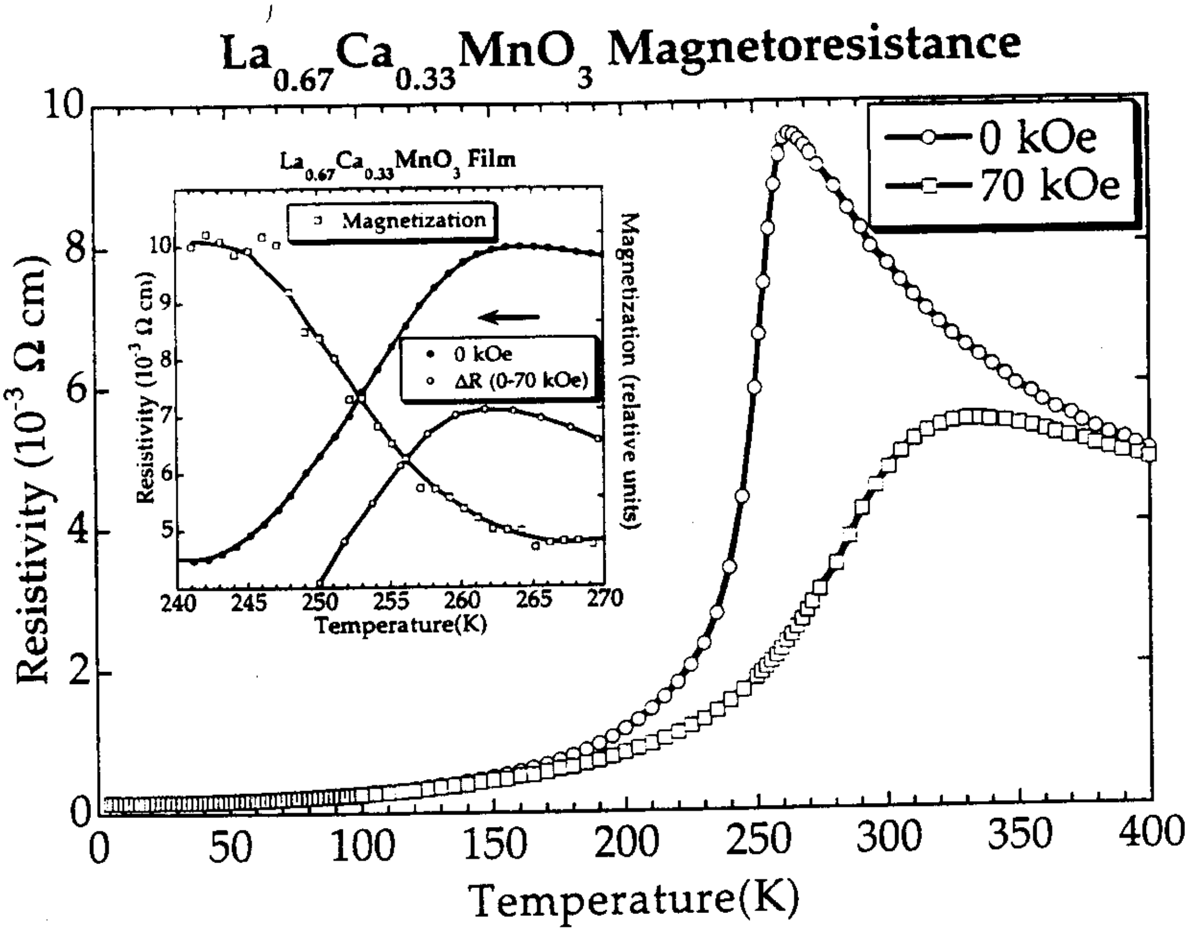
α) metal insulator transitions (as T increase)
β) colossal magnetoresistance [and other forms of hypersensitivity to magnetic fields, strain, current ....]
γ) charge ordering / melting ....

many of which are poorly understood, unusual and spectacular.



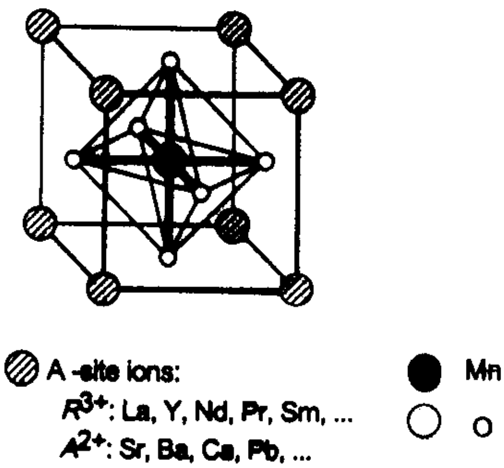
Urushibara . . . Tokura

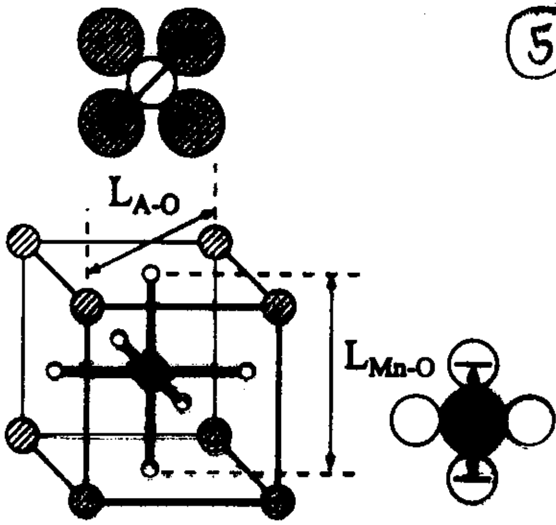
(4)



Snyder . . . Geballe

$(R,A)MnO_3$

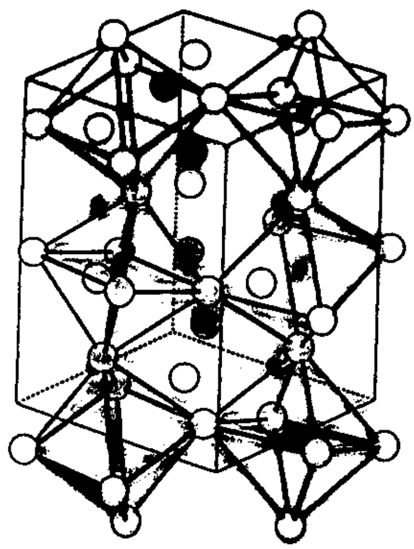


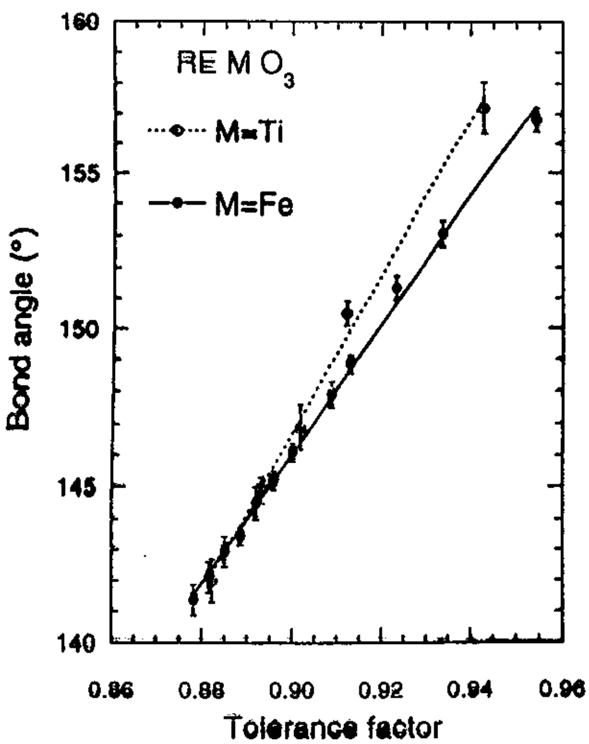


tolerance factor $t = \frac{L_{A-O}}{\sqrt{2} L_{Mn-O}}$

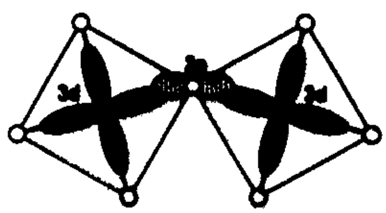
Carrier Doping

$R_{1-x}A_xMnO_3$: Mn $(3d)^{4-x}$





Tilting of octahedra reduces electron hopping.



$t_{dd} \propto (\cos\theta)^2$

Bandwidth control

Fig. 66

Ionic radii :—

La^{3+} ~ 1·22

$(Pr, Nd)^{3+}$ ~ 1·145

Sm^{3+} ~ 1·13

Ca^{2+} ~ 1·18

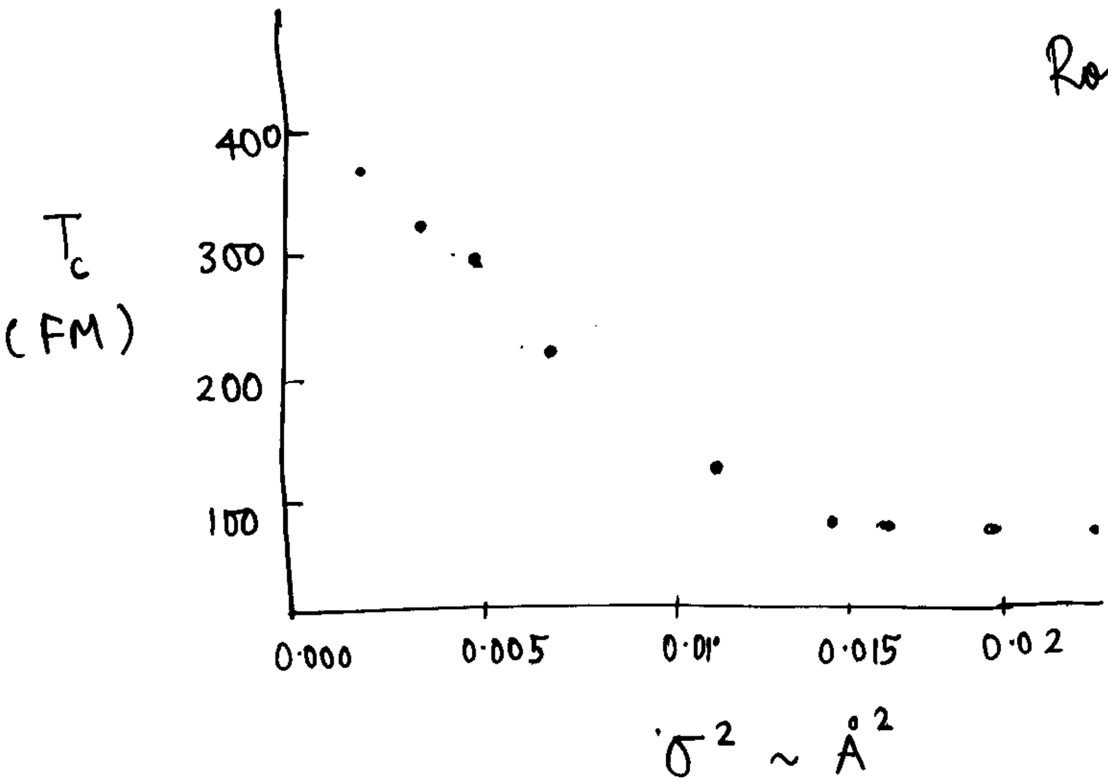
Sr^{2+} ~ 1·31

Ba^{2+} ~ 1·47

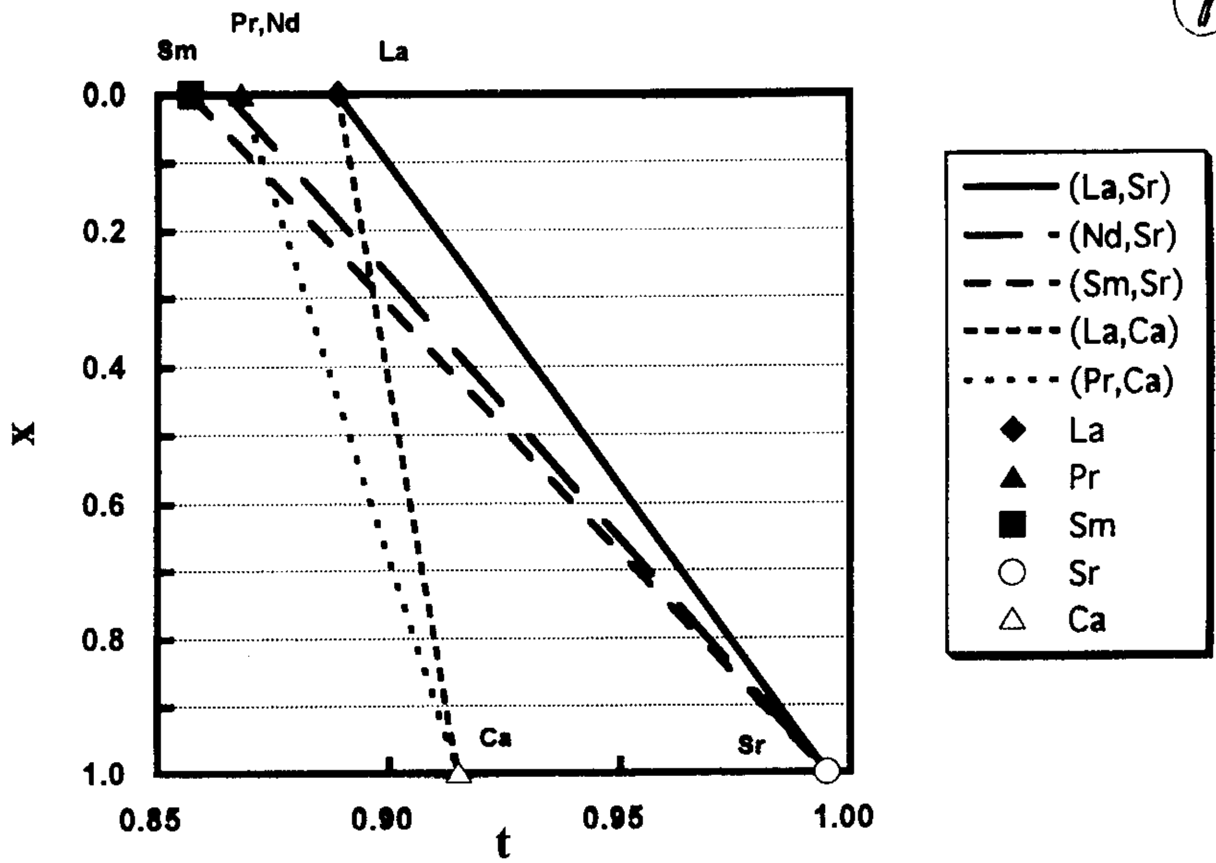
Ideal size ≃ 1·30 Å

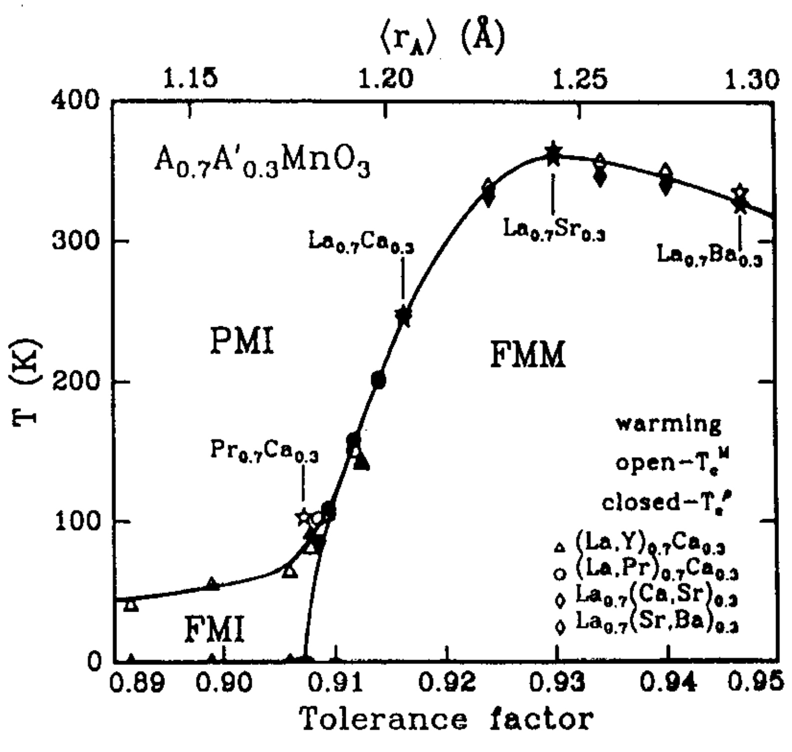
$\langle r_A \rangle$ or tolerance factor often used to organize information.

Useful, but not always.



Rodriguez-Martinez & Attfield

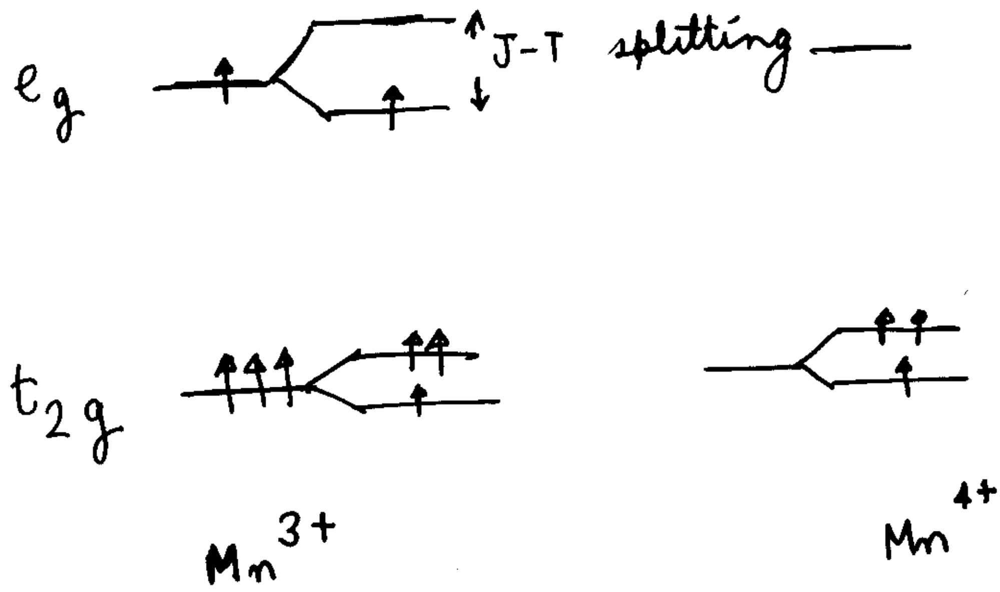




Hwang et al.

"Lattice effect"

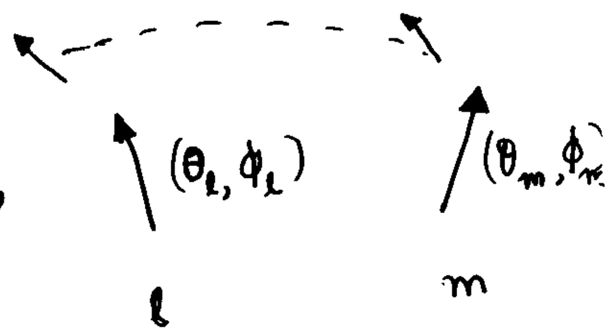
Local electronic levels :-



(i) Strong Hund's rule coupling.

[Zener, Anderson and Hasegawa, de Gennes].

$$H = -\sum_{\langle lm \rangle} \left(t_{lm}\, c_l^{\dagger} c_m + h.c \right)$$



$$c_l = \cos\left(\frac{\theta_l}{2}\right) c_{l\uparrow} + i \sin\left(\frac{\theta_l}{2}\right) e^{i\phi_l}\, c_{l\downarrow}$$

$$t_{lm} = \cos\left(\frac{\theta_l}{2}\right)\cos\left(\frac{\theta_m}{2}\right) + \sin\left(\frac{\theta_l}{2}\right)\sin\left(\frac{\theta_m}{2}\right) e^{i(\phi_l - \phi_m)}$$

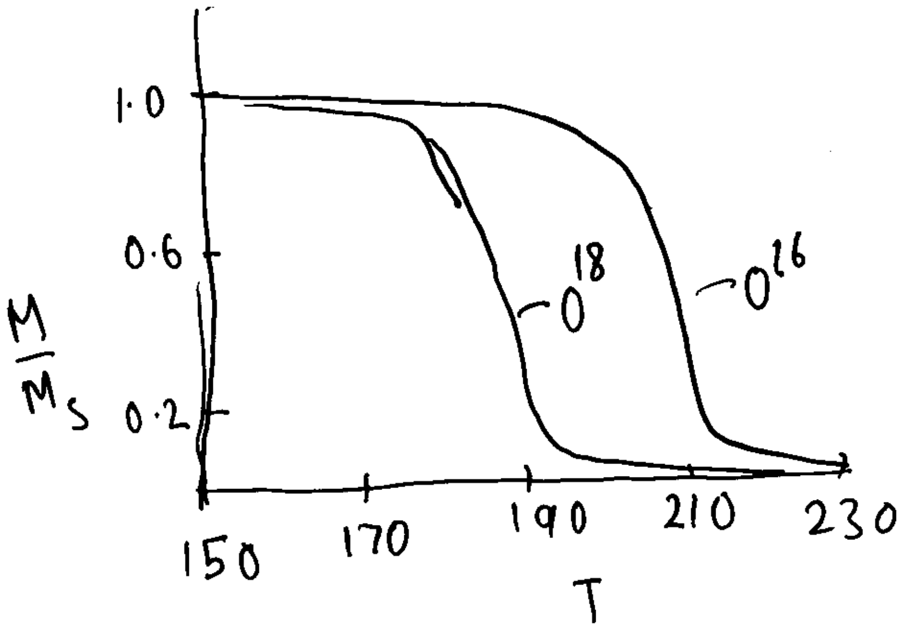
$(U = \infty, \quad J_H = \infty)$.

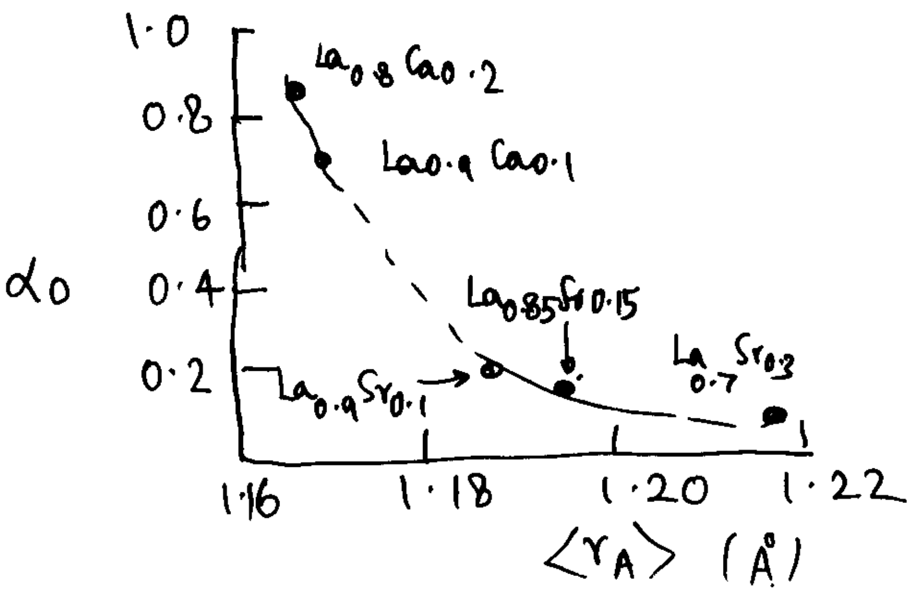
Strong electron lattice effects

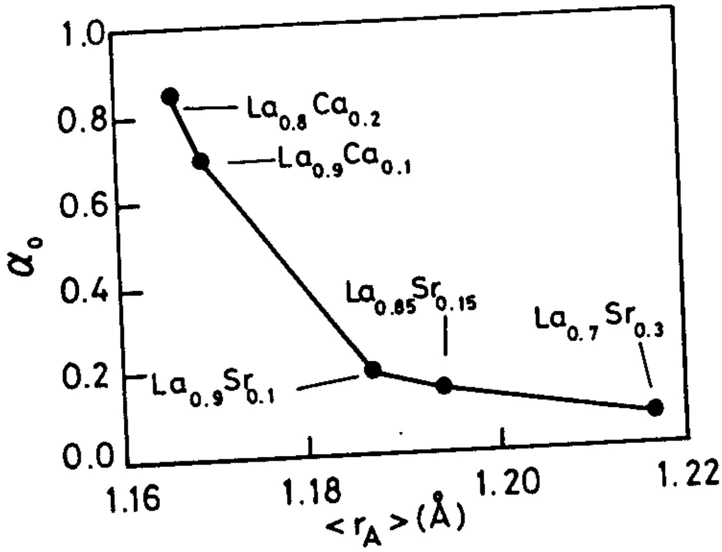
(i) Mn - O radial distribution

(ii) Debye - Waller factor

(iii) Isotope effect on T_c.






1.0
0.8
0.6
0.4
0.2
0.0
α_0
$La_{0.8}Ca_{0.2}$
$La_{0.9}Ca_{0.1}$
$La_{0.85}Sr_{0.15}$
$La_{0.7}Sr_{0.3}$
$La_{0.9}Sr_{0.1}$
1.16
1.18
1.20
1.22
$<r_A>$ (Å)

$$H_{J-T} = g \sum_{l,a,\alpha} \vec{r}_l \cdot c^{\dagger}_{la\alpha} \vec{\tau}^{ab} c_{lb\alpha}$$

a, b orbitals
α electron spin
$\vec{r}_l$ lattice displacement

Other interactions between spins ?

Mn^{4+} limit :- Ferromagnetic

Mn^{3+} limit :- Antiferromagnetic.
(in some detail)

Models explored, so far :-

$$H = H^F_{Kondo}$$ (Furukawa)

$$H^F_{Kondo} = -\sum_{\langle ij \rangle} t_{ij} c^{\dagger}_{i\sigma} c_{j\sigma} - \sum_i J_H \vec{s}_i \cdot \vec{S}_i$$

$$H = H^F_{Kondo} + H_{J-T} + H_{ph}.$$

[In $d=\infty$ dynamical mean field theory. $\Sigma_i(\omega)$, m_i, r_i]

coherent metal → incoherent metal

(ferromagnetic) (paramagnetic).

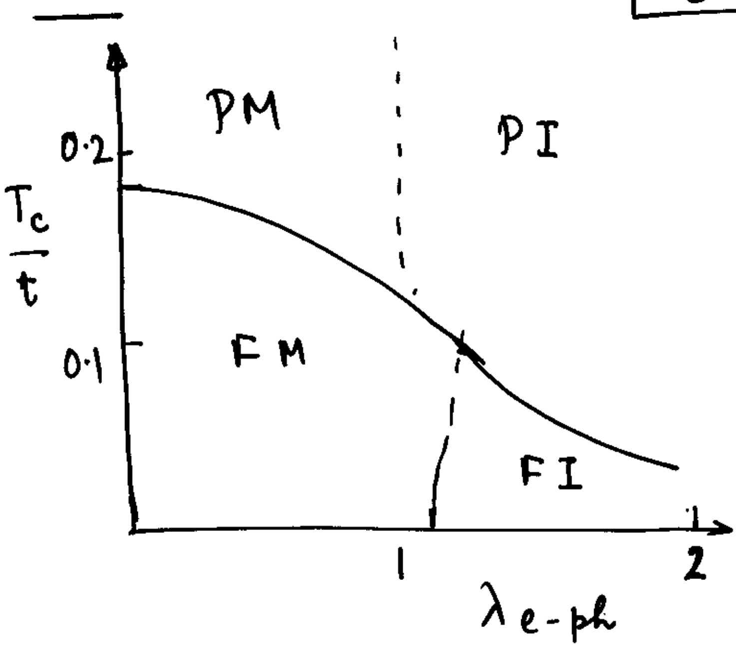
$$\rho(T) \Rightarrow \rho\left(\frac{M}{M_s}\right)$$

and similar scaling relations.

Realistic T_c ($\ll x W$).

Spin wave spectrum

$n_e = 1$ per site



Insulator due to J-T distortion, and local, bound (trapped) electron for large λ_{e-ph}

$\lambda_{e-ph} \sim (J/t)$.

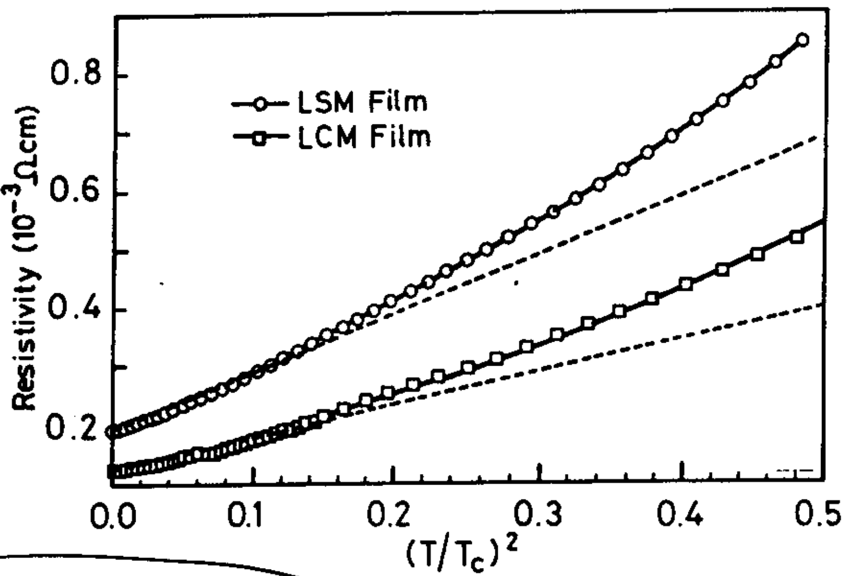
Much milder effects away from $n_e = 1$.

Broad features similar to experiment.

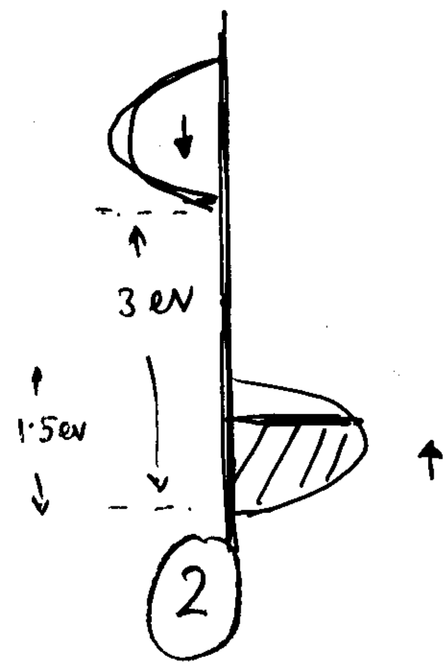
(α) Low Temperature Resistivity :

$$\rho(T) \simeq \rho(0) + A\, T^2 \qquad T \ll T_c .$$

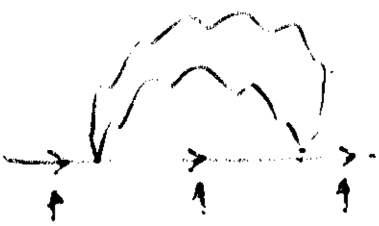
A → very large.



Snyder ... Geballe



No low energy spin flip excitations



$\Delta\rho \sim T^{9/2}$.

(β) Strong violation of Mott σ_{min} (ρ_{max})

(i) $\rho^{metal}_{max} \sim 2\ m\Omega\ cm$.

[Geometrical, i.e. related to

$\lambda_{de\ Broglie} \sim r_{interatomic}$]

Generally well obeyed, except for quantum effects at low T and near critical disorder.

(ii) Exponentially large $\rho(T=0)$.

$$\rho \sim \rho_0 \exp\left(\frac{\lambda \delta M}{M_s}\right) \quad ?$$

$T < T_c$.

(iii) Polaronic band narrowing?

a) ρ_{max} indep. of bandwidth.

$$\sigma \sim e^2 \langle \vec{v} \rangle^2 \, \underline{\rho(\epsilon_F)} \left(\frac{1}{\Gamma}\right)$$

bandwidth t

$$\sim \frac{e^2}{a^3} (a\, t)^2 \left(\frac{1}{t}\right)\left(\frac{1}{t}\right)$$

$\left[\sigma_{min} \sim \frac{e^2}{\hbar a} \right.$

(iii) classical → quantum

$$\sigma \sim \left(\frac{p_{hopping}}{k_B T} \right) \qquad p_{hopping} \sim t_{eff}$$

$k_B T >> t_{eff}$

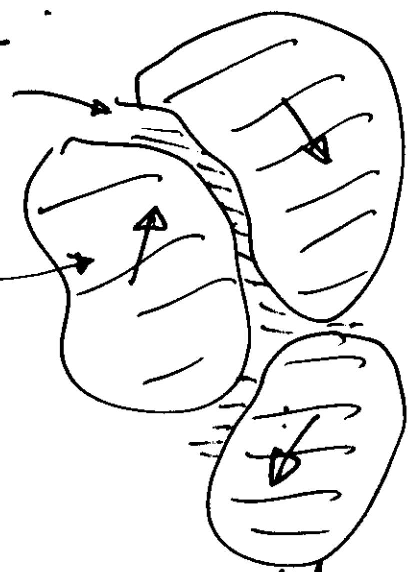
$$\sim \frac{p_{hopping}}{t_{eff}} \sim \left(\frac{e^2}{\hbar a} \right)$$

$k_B T << t_{eff}$

No signs of our being in classical regime or of such a low T crossover.

Mahesh, Raychaudhuri, Rao

(iv) <u>Grain boundary effect</u> ?



$$\rho \simeq \rho_1 + \left(\frac{L_2}{L_1} \right) \rho_2$$

(Crude effective medium picture, $L_2 << L_1$).

L_1	ρ
24 μm	10^{-2} Ω cm
3	2×10^{-1} Ω cm
·02	3×10^{2} Ω cm

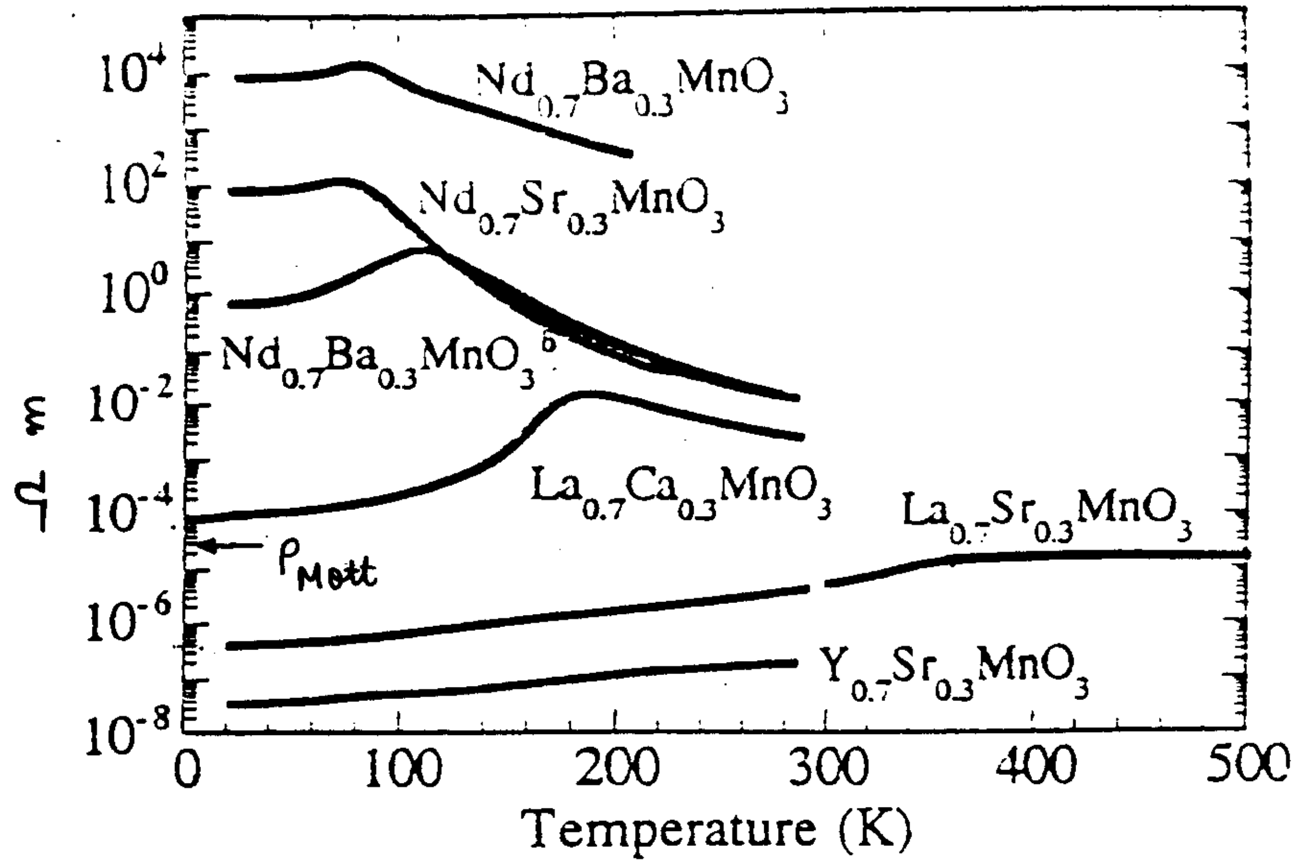
Fits above model.

$L_2^* \rho_2 \simeq 6 \times 10^{-5}$ Ω cm^2

$L_2 \simeq 10$ Å

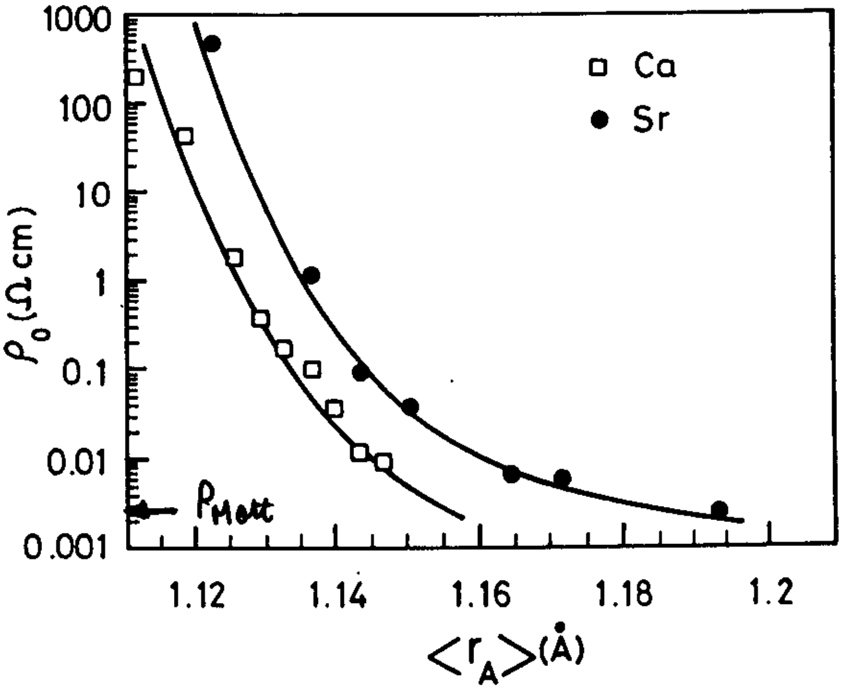
$R_2 \simeq 10^5 \, (h/e^2)$!

(14)



2. Temperature dependence of the resistivity of $_xB^{2+}_x$)MnO_3 thin films ([b] denotes a polycrystalline ic).

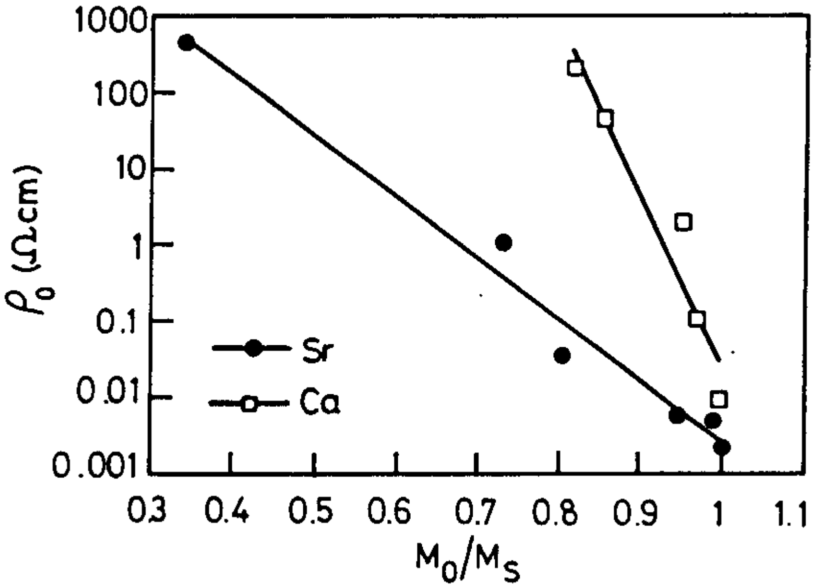
(Coey et al)



Garcia-Munoz et al

$\langle r_A \rangle$

(5)



$$\rho_0 = \rho_{Mott} \exp\left[\lambda \frac{\delta M}{M_S}\right]$$

$\rho_{Mott} \simeq 2\ m\Omega\ cm$

$\lambda \simeq 18$ for Sr

$\lambda \simeq 71$ for Ca

(6)

Garcia-Munoz et al

(17)

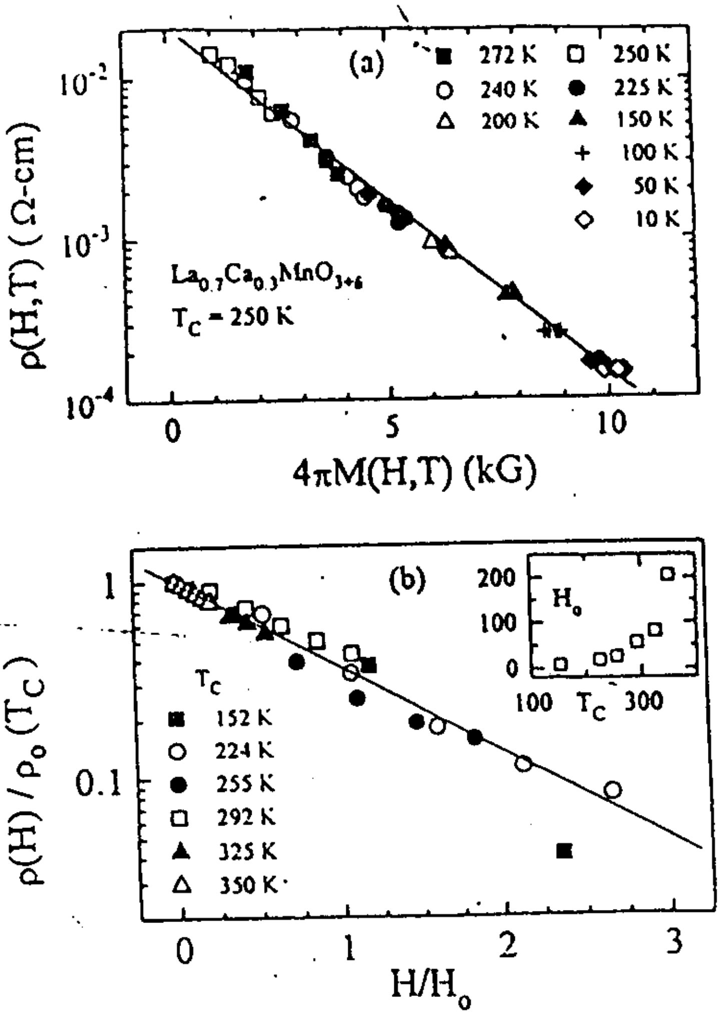


FIG. 4. (a) $\rho(H,T)$ vs. $M(H,T)$ for sample 3. At each T, points are included at $H=10$, 20, 30, 40, and 50 kOe. The solid line is a least-squares fit to the data. (b) Normalized magnetoresistance at T_c plotted vs. H/H_0 for samples 1–6; the scaling parameter H_0 (in kOe) is plotted against sample T_c in the inset.

Hundley et al

18

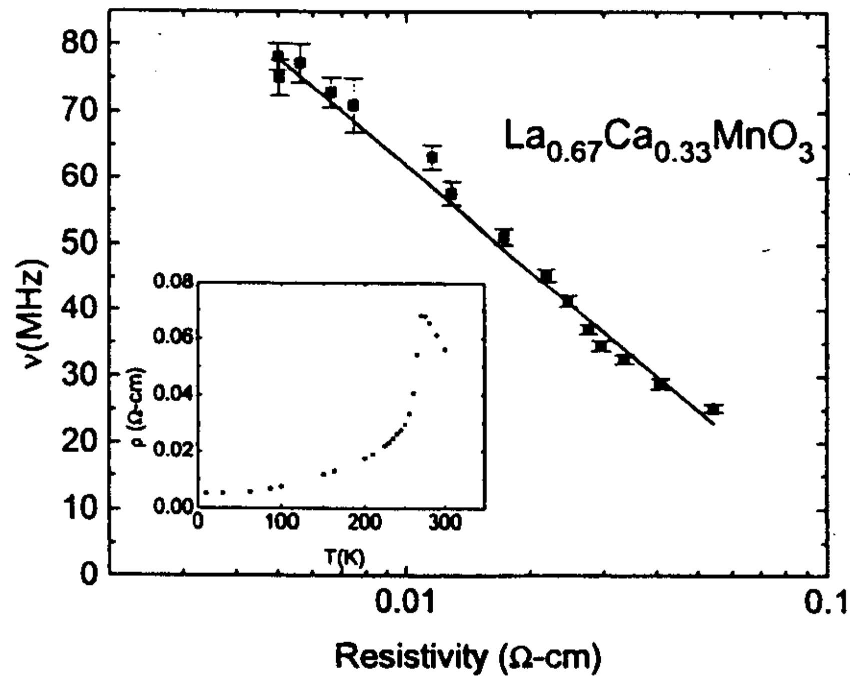


FIG. 2. Temperature dependence of $\nu_\mu(T)$ vs resistivity on a log scale. The solid line is a least squares fit showing $\nu_\mu(T) \propto -\ln[\rho(T)]$. The inset shows resistivity vs temperature.

Heffner, .. Uemura ...

(γ) Optical conductivity (19)

$n_{eff} \sim .014\ n$

m^* enhanced ?

γ (electronic heat capacity) shows no sign of it

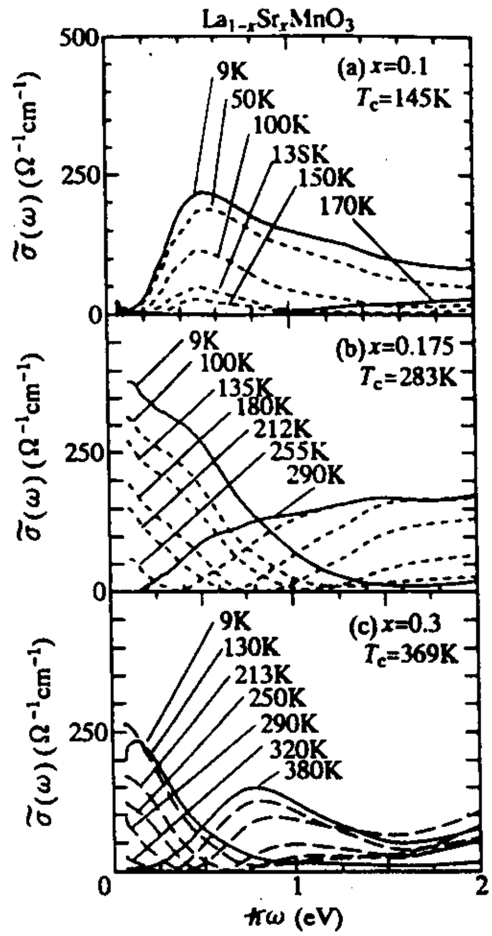


FIG. 6. Reduced optical conductivity spectra which are derived by subtracting the temperature independent part (the hatched curves in Fig. 5) at various temperatures in $La_{1-x}Sr_xMnO_3$: (a) $x=0.1$, (b) $x=0.175$, and (c) $x=0.3$. The far-infrared region dominated by the optical phonons is omitted to avoid complexity.

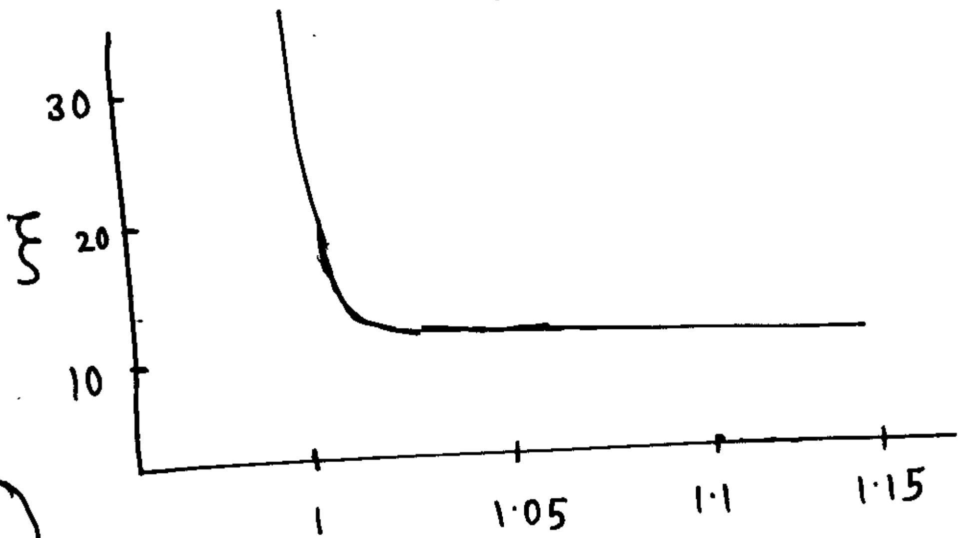
Okimoto, ... Tokura

(iv) Behaviour near and above T_c :-

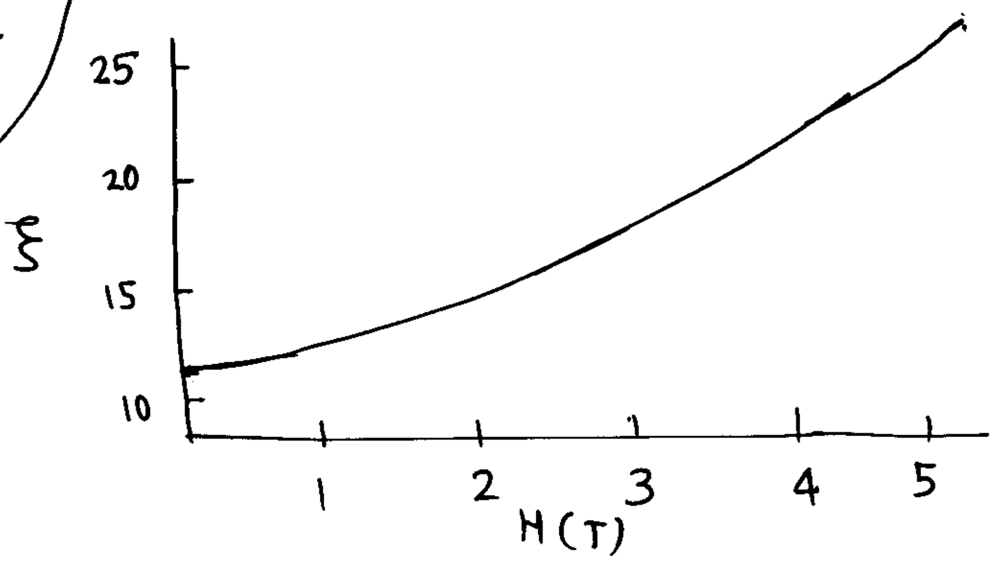
1. Considerable short range order

SANS with $\xi_{mag} \gtrsim 12$ Å

$T \simeq 1.2\, T_c$



de Teresa Ibarra et al



ξ_{mag} increases rapidly with field.

2. Carriers localize above T_c

$$\left(\frac{\mu_0 H \rho_{xx}}{\rho_{Hall}} \right) \sim \mu$$ — mobility

Use this to find n_e.

(i) mobility weakly field dependent at low H

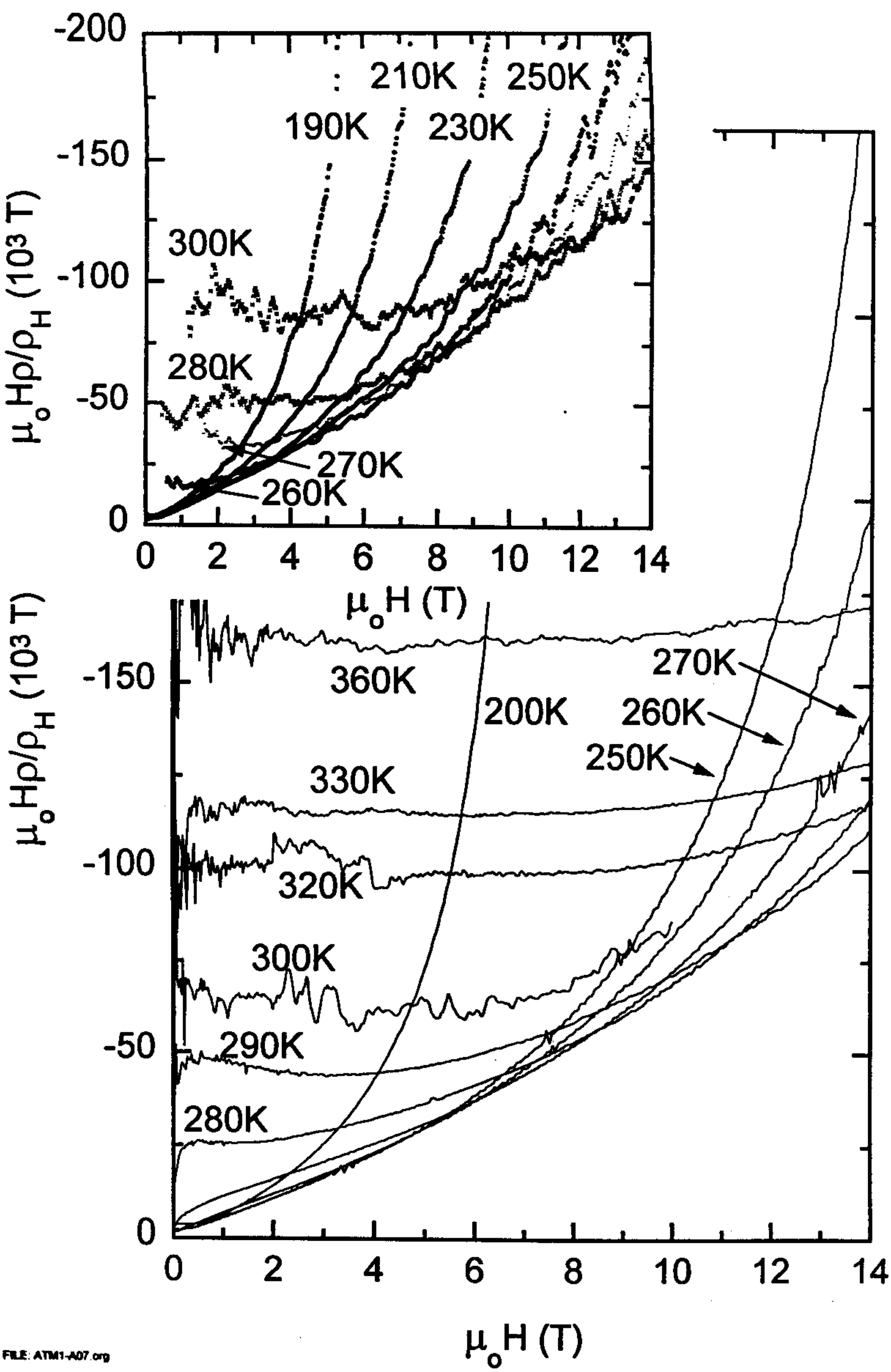
(ii) n_e strongly T dependent.

Analysis complicated due to

Anomalous Hall Effect ($\propto M$)

strong and magnetic field dependence of

ρ_{xy}, ρ_{xx} . . .



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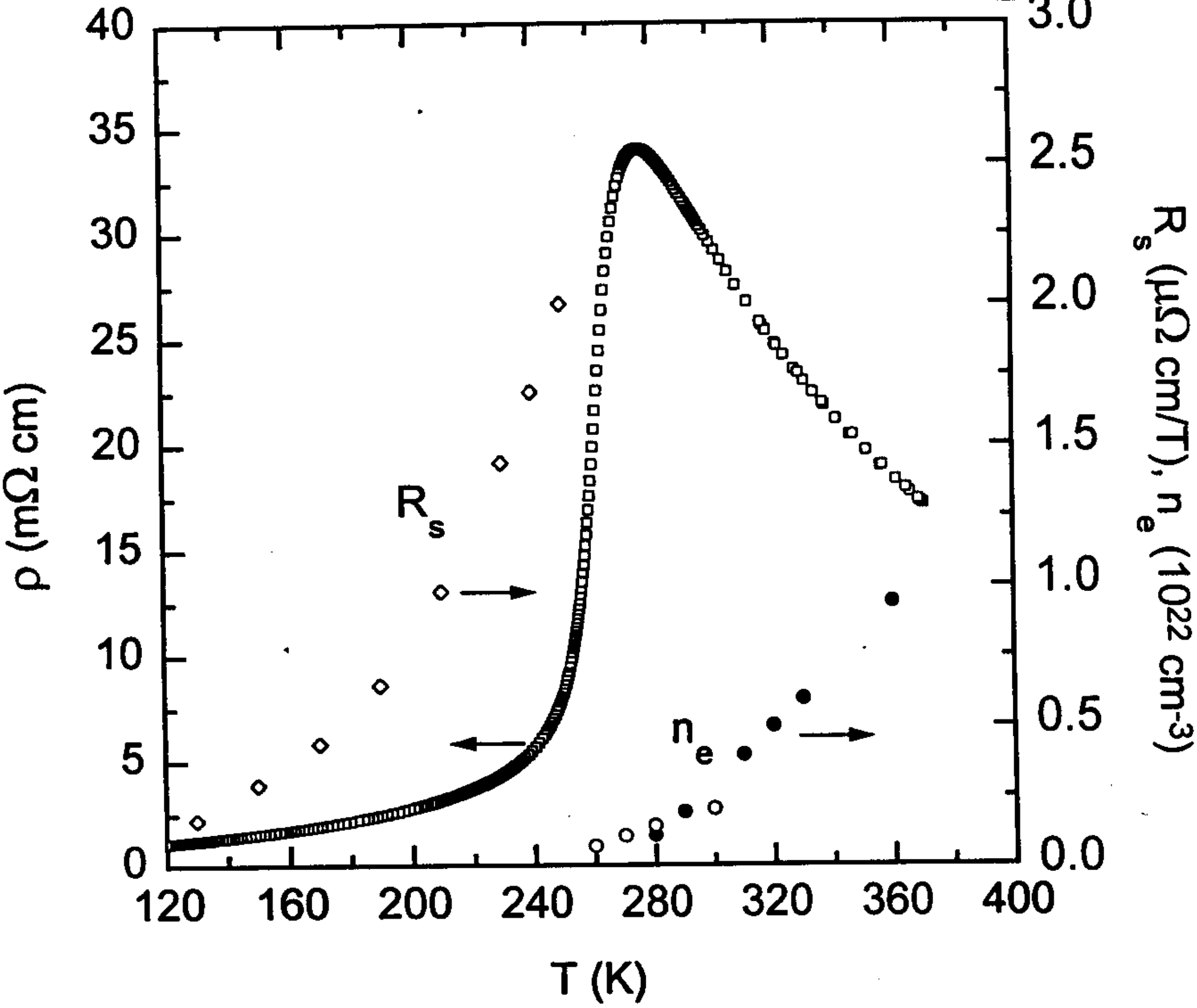
Matl FIG 4

Ong et al

Ong et al

(23)



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Matl FIG 3

V) Charge ordering :-

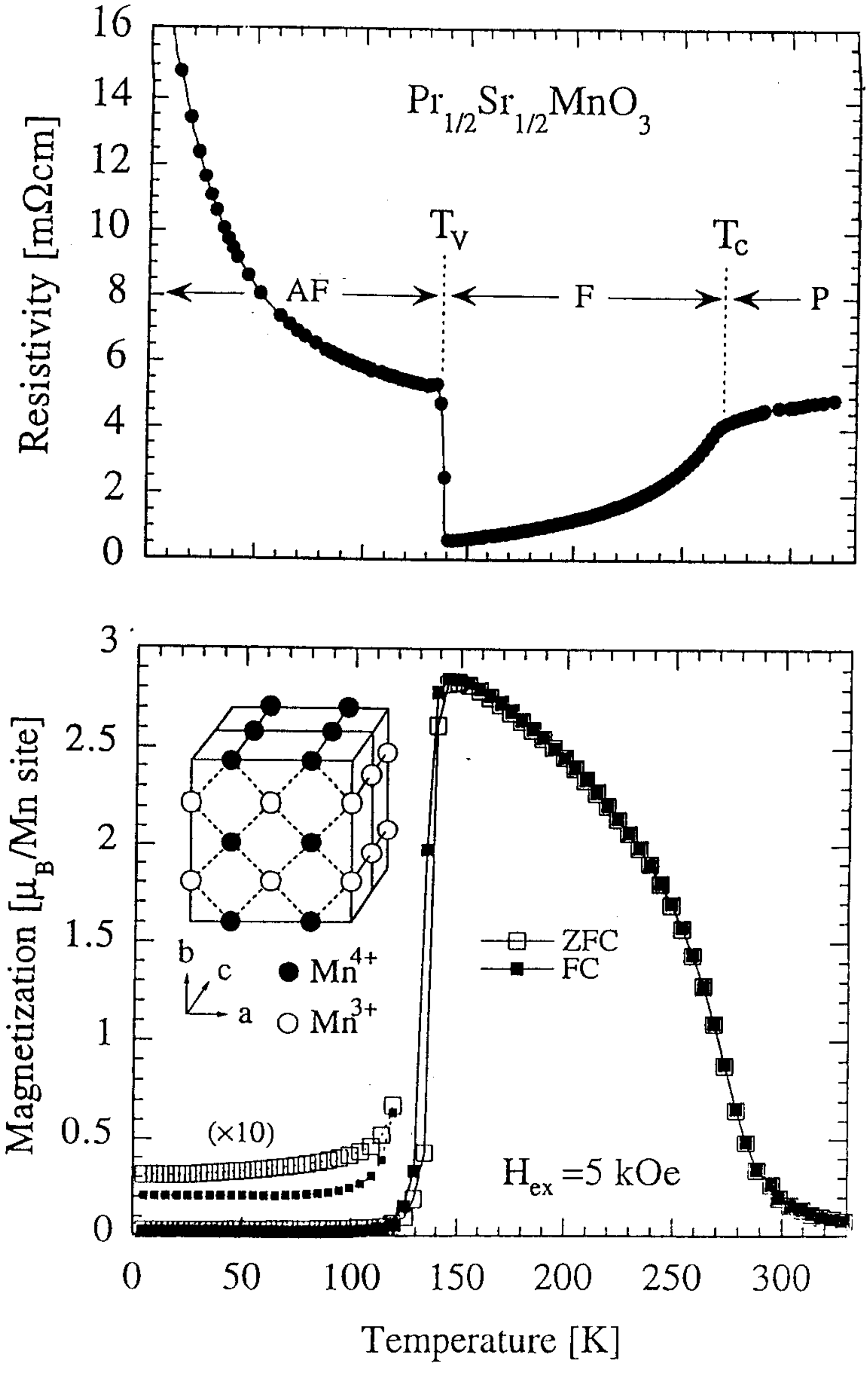
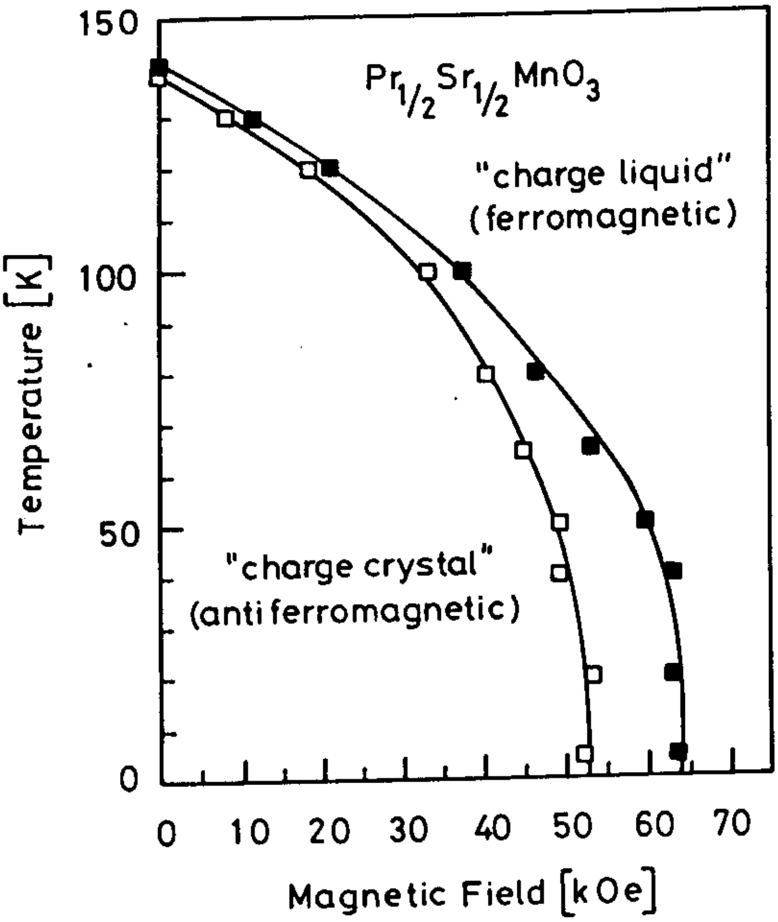


Figure 1. Y. Tomioka et al.

(25)

Tokura et al

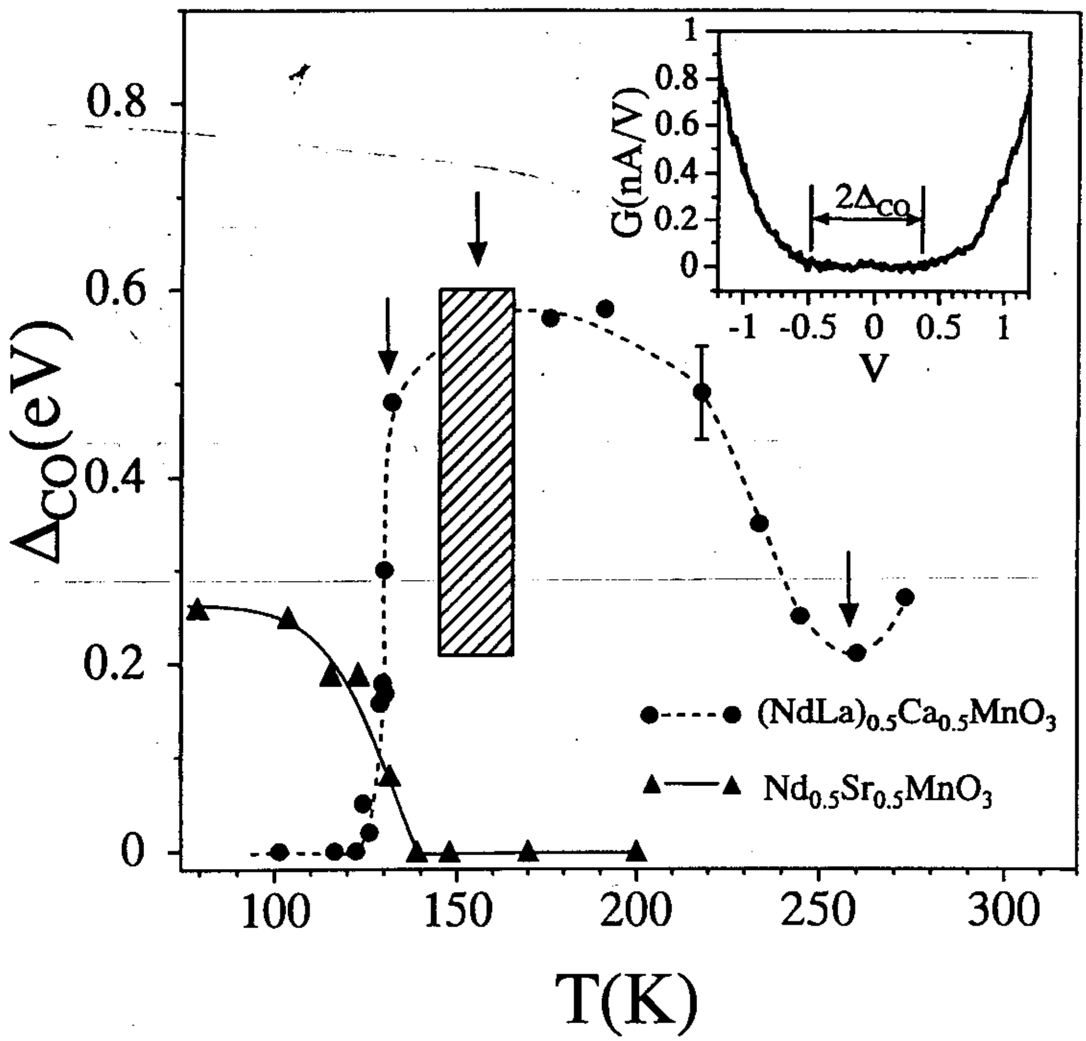


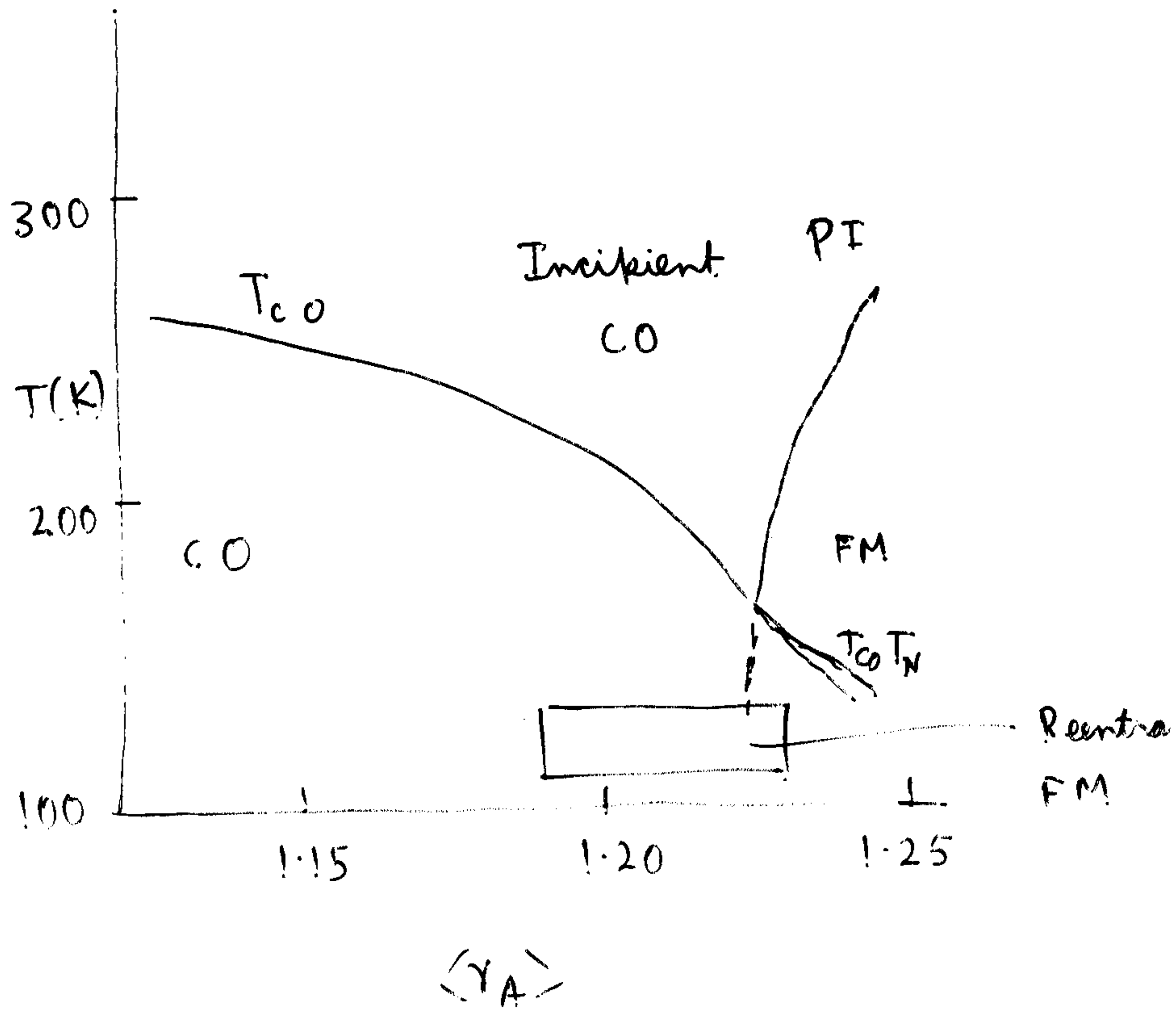
5 Tesla $\simeq 5 \times 3.5 \times \frac{2}{3}$

$\simeq 12$ K.

(9)

Raychaudhu
Rao
et al




300
200
100
T(K)
T_{CO}
Incipient
CO
PI
CO
FM
T_{CO} T_N
Reentra
FM
1·15
1·20
1·25
$\langle r_A \rangle$

Conclusion :-

(i) The ingredients are known
(basic interactions)
but we don't fully know
how to cook
(put them together so as
to describe what is seen).

(ii). There is a very effective
(exponentially effective ?)
localizing mechanism
that is poorly understood.

(iii) Because of (ii) and
competing interactions,
rich variety of phases.