Colossal Magnetoresistance

Instructor: Dr. Elbio R. Dagotto
Class: Solid State Physics 2

Nozomi Shirato

- Background
- Physics of CMR manganites
  - Structure
  - Exchange Interactions
  - Ordering
- Summary

Background

- ***Magnetoresistance (MR)***
  - Consider an electric current running in a material like iron. Placed in a strong magnetic field, its resistance drops or increases by several percent, depending on orientation.
- ***Giant Magnetoresistance (GMR).***
  - 1988, thinly layered materials were found that increased or decreased their resistivity by 20 percent or more in relatively weak magnetic fields -- hence "giant" Magnetoresistance, or GMR. The basic effect depends on the alignment of electron spins at the interface of different kinds of magnetic materials.
- ***Colossal Magnetoresistance (CMR).***
  - 1993, materials were found that could increase or decrease resistance not by a few percent but by orders of magnitude. Hence "colossal" Magnetoresistance
  - However, the effective temperature is too low for the applications.

CMR shows changes of resistance by orders of magnitude @ Tc

Background

- Discovery of huge magnetoresistance effects in the manganese oxide class of materials (such as $La_{1-x}A_xMnO_3$ (A = Sr, Ca, Ba))

- People believe CMR offers potential in a number of technologies, such as for read/write heads in magnetic recording media, sensors, and spin-polarized electronics.

- Traditional ferromagnets such as Fe, Co and Ni where the spin system is isolated from the lattice

- In CMR manganites the *charge*, *spin*, and *lattice degrees of freedom are strongly coupled together*, leading to a delicate balance of interactions that gives rise to a rich variety of physical phenomena

Strong coupling of charge, spin, lattice degrees of freedom

CMR manganites

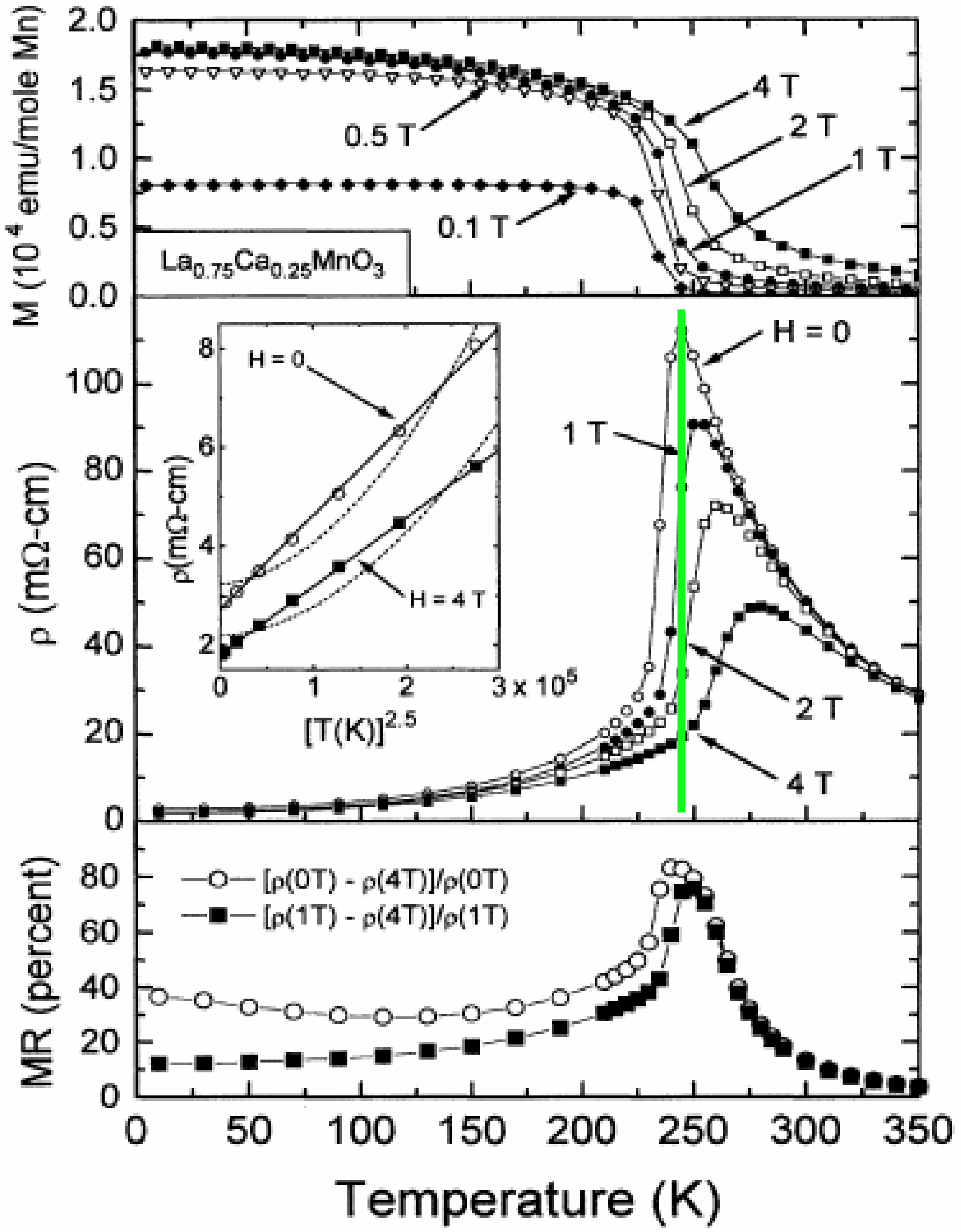
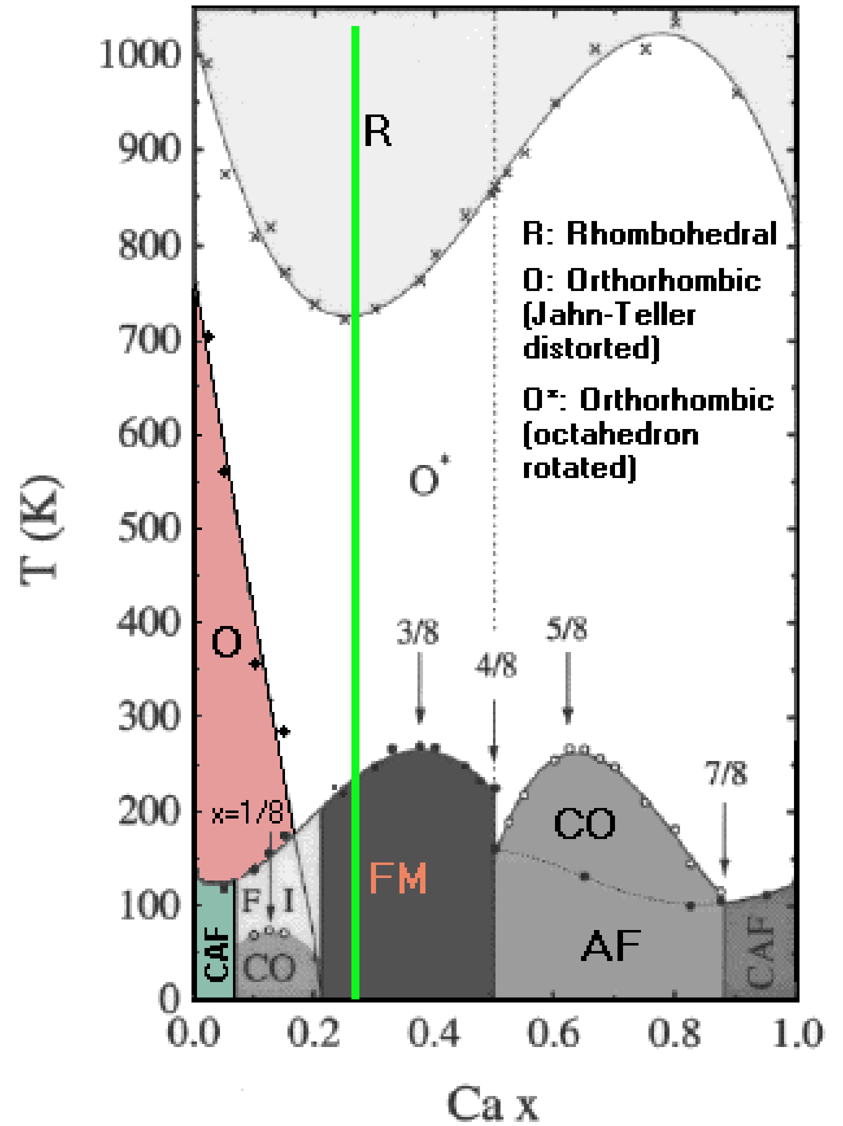


FIG. 2. The magnetization, resistivity, and magnetoresistance of $La_{0.75}Ca_{0.25}MnO_3$ as a function of temperature at various fields. The inset shows ρ at low temperatures; the lines are fits to the data as described in the text.

Shiffer PRL 75, 3336 (1995)
G. Jonker, and J. van Santen, Physica (Amsterdam) **16**, 337 (1950)



Phase Diagram of $La_{1-x}Ca_xMnO_3$

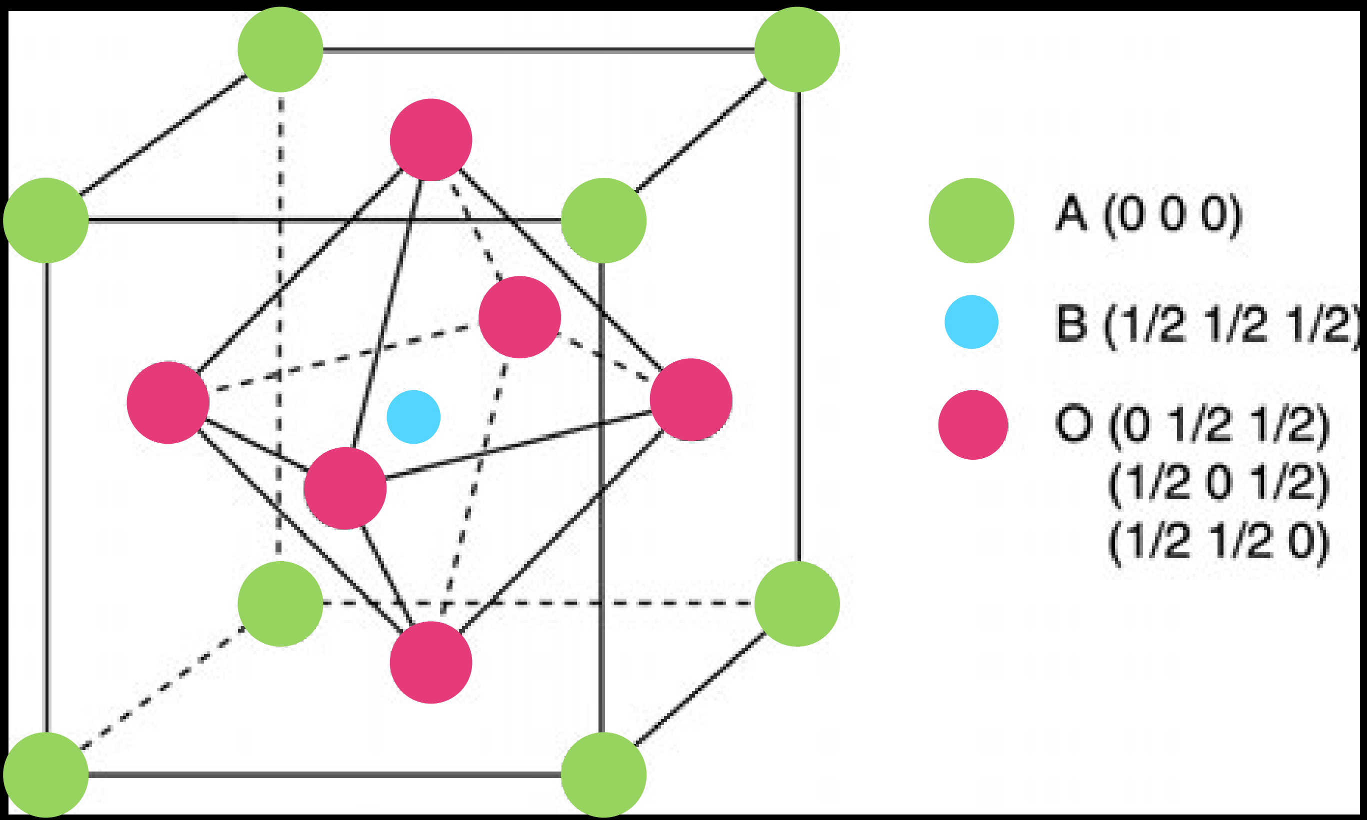
Uehara, Kim and Cheong

[5,6]

HOW can we explain different resistivity and magnetic regions ??

Physics of CMR: *Structure*

Crystallographic structure



cubic pervoskite [2]

Structure of RE(1-x)M(x)MnO_3 oxides

- Large sized RE trivalent ions and M divalent ions

  → A-site with 12-fold oxygen coordination

- Smaller Mn^{+3}, Mn^{+4} ions

  → B-site with 6-fold oxygen coordination

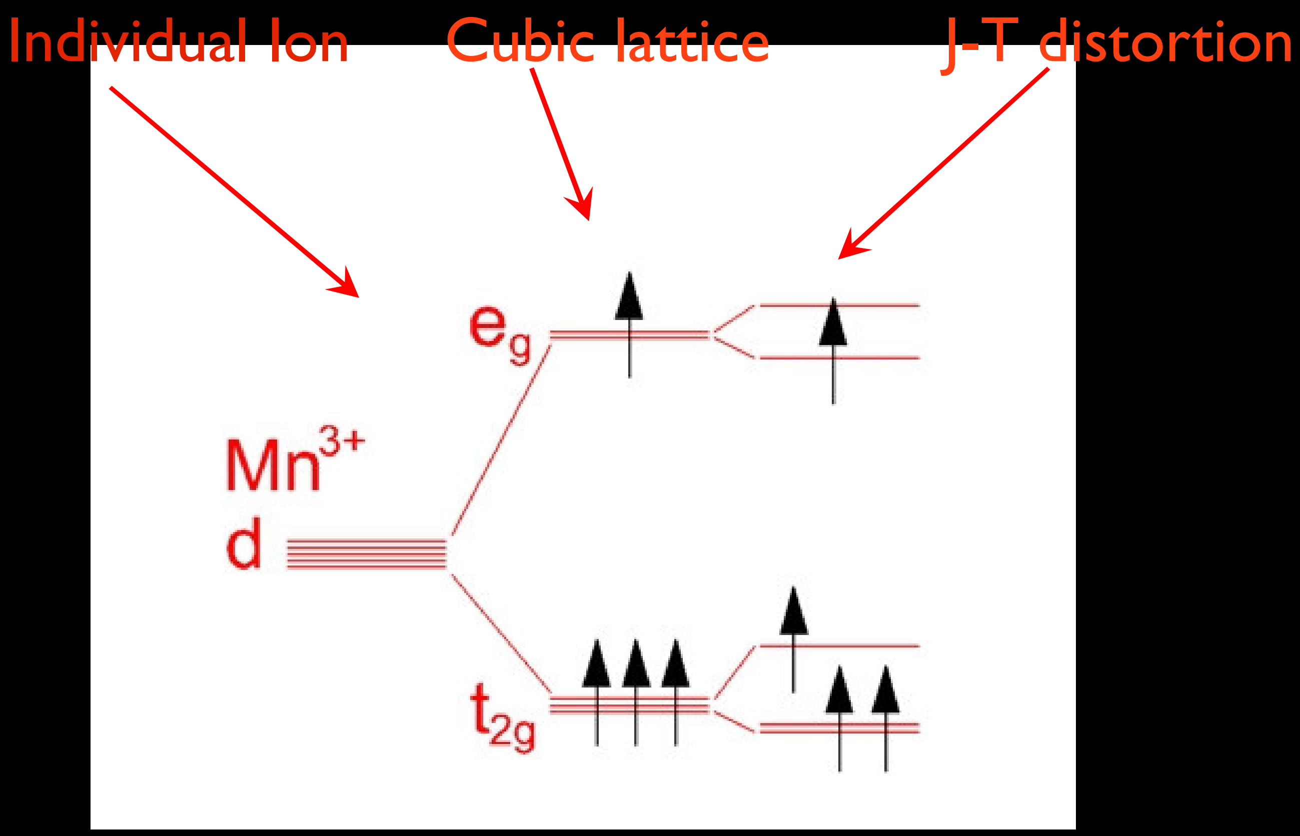
- Proportions of Mn ions in +3 and +4 1-x, x respectively

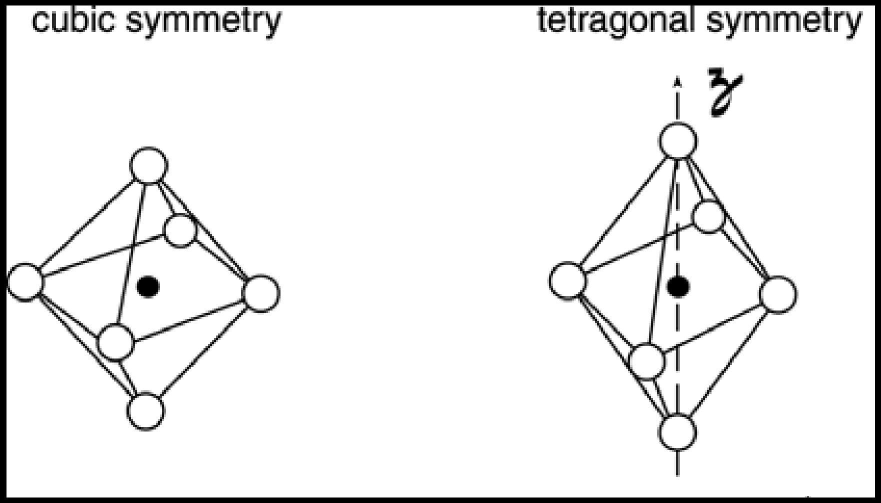
Physics of CMR: *Structure*

Electronic structure

- Cubic lattice
  ➙partly lifting degeneracy
  (5 d-orbitals—t_{2g} and e_g)

- J-T distortion
  ➙another degeneracy
  (3 t_{2g} and 2 e_g)



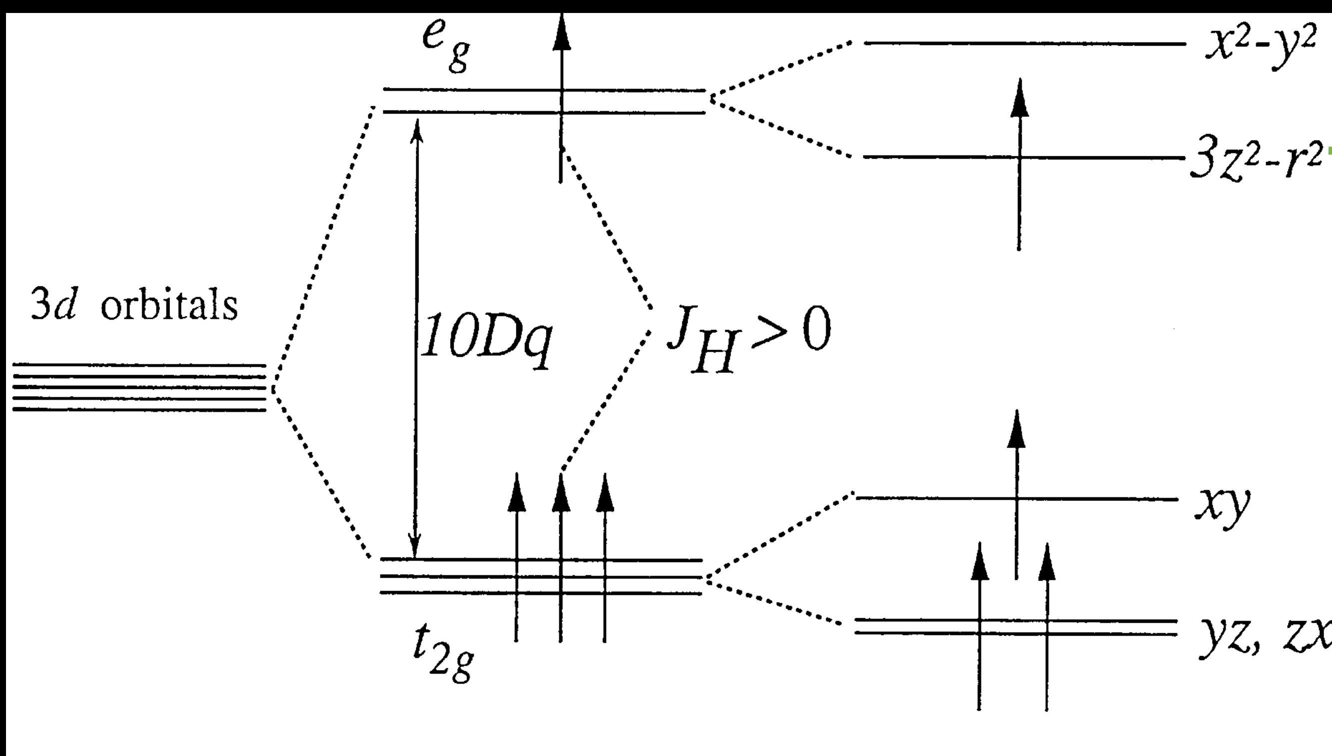


[1,7]

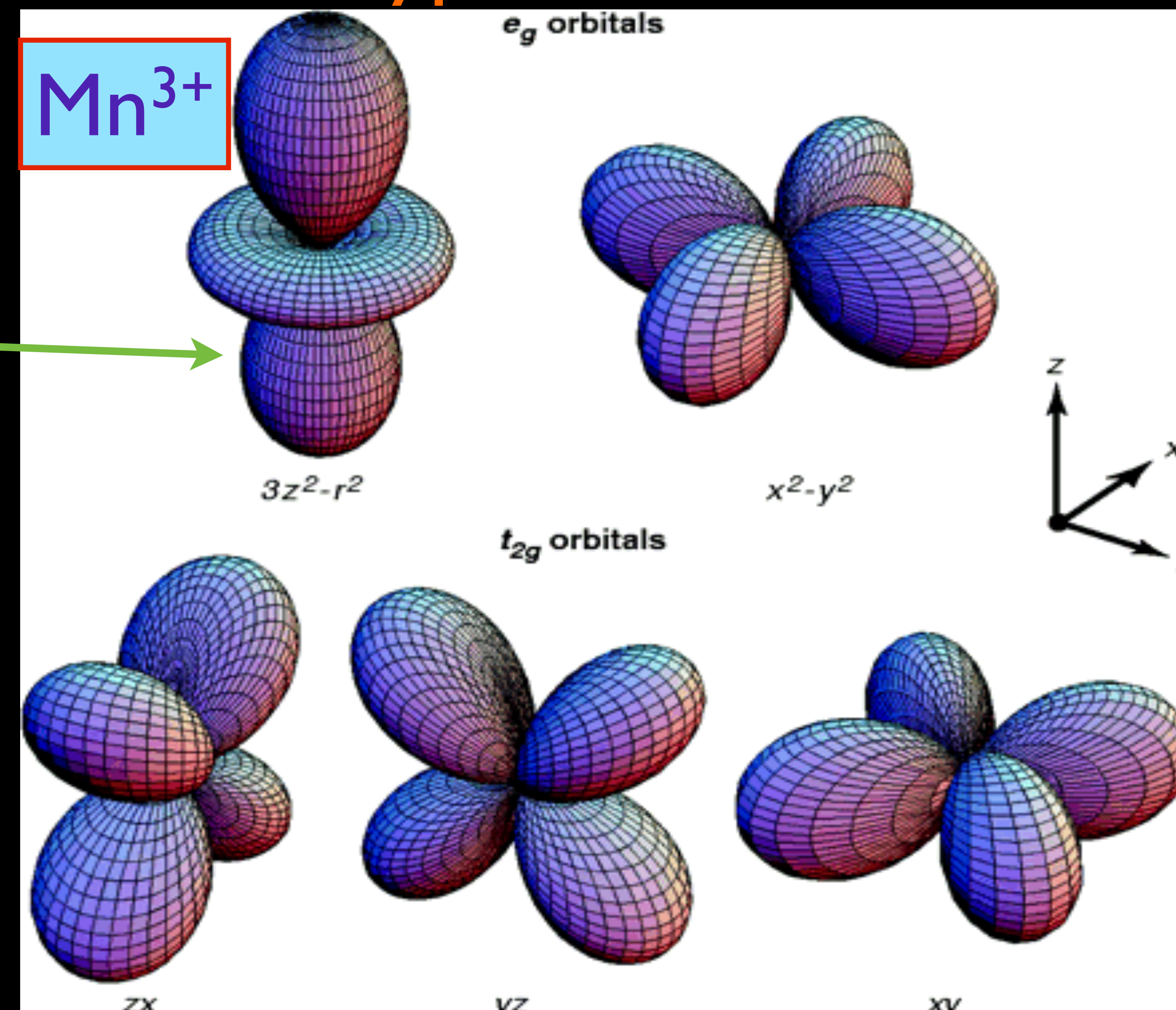
cubic lattice + J-T distortion → 3 t_{2g} and 2 e_g

Physics of CMR: *Structure*

Electronic structure



Five types of d-orbitals



[2,7]

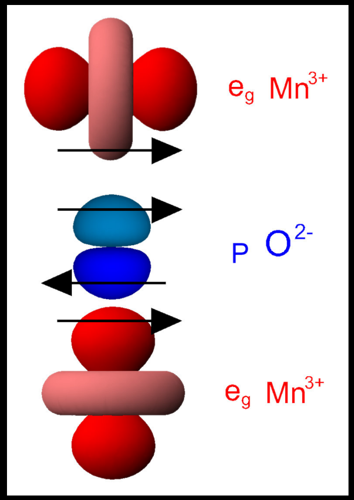
Physics of CMR: *Exchange Interactions*

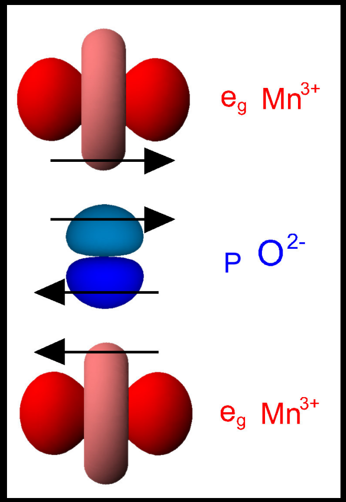
- Magnetic properties of manganites ➔ exchange interaction between Mn ion spins.
- Mn-O-Mn interaction ➔ controlled by overlap between Mn d-orbital and O p-orbitals

Super Exchange

superexchange interactions depend on orbital configuration

- M+3-O-Mn+3→ F or AF
- M+4-O-Mn+4→ AF





[7]

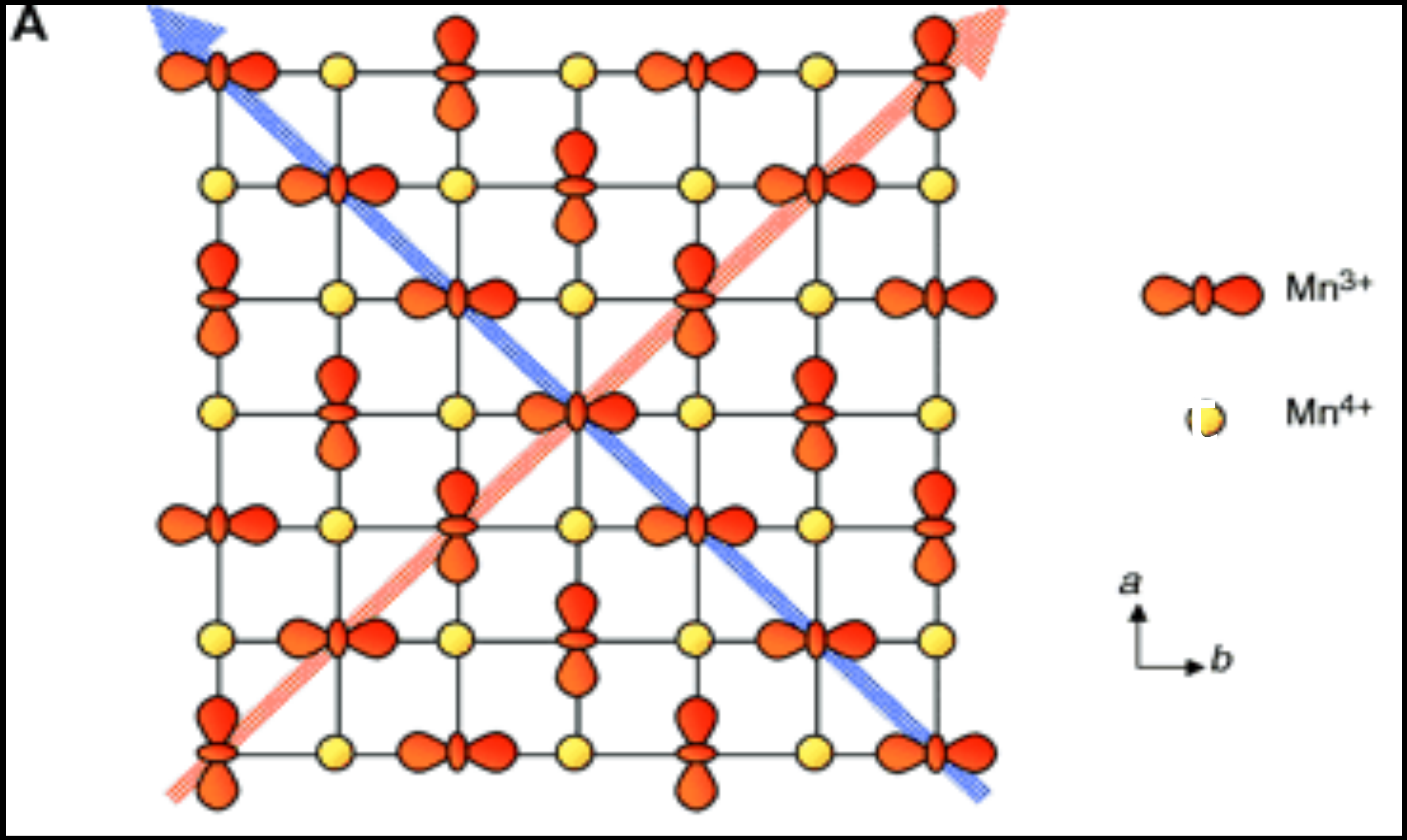
Double Exchange

Electron jumps from Mn3+ to Mn 4+

Only if other spins are properly aligned. ← the Hund coupling
Net result: ferromagnetic coupling conductivity sensitive to spin order

Physics of CMR: *Ordering*

Charge ordering



Charge ordering along ab-plane in $La_{0.5}Sr_{0.5}MnO_4$

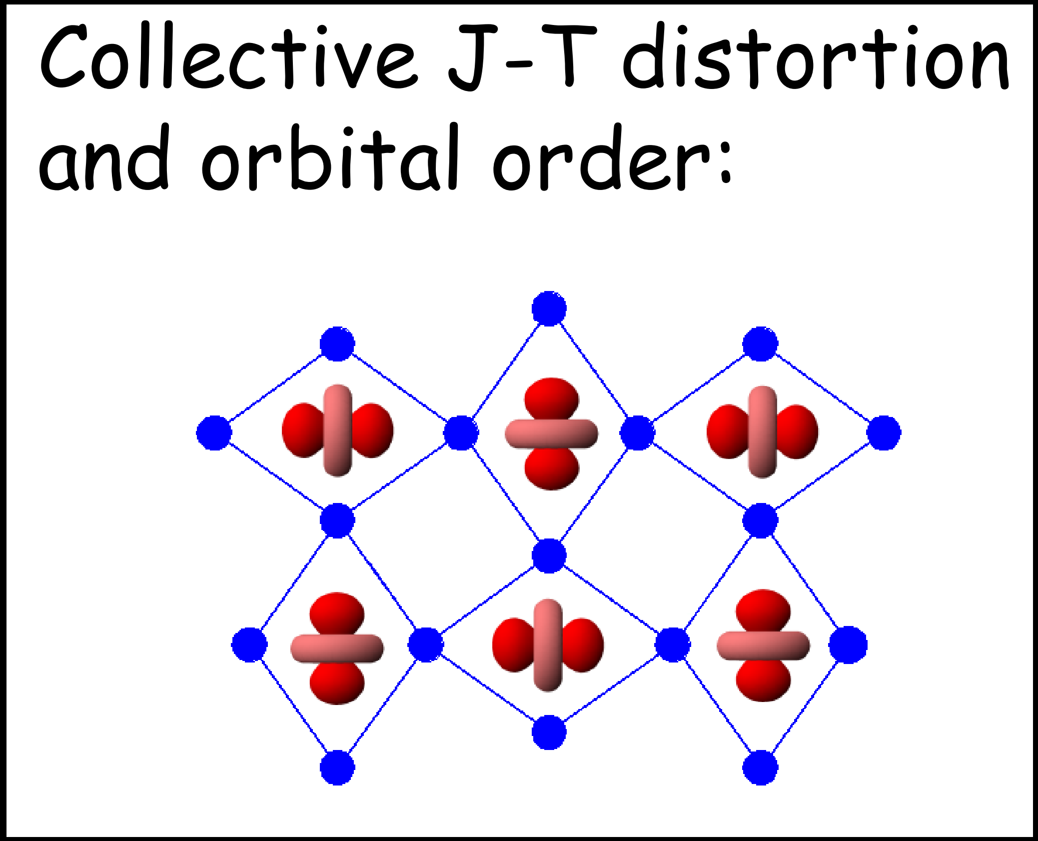
[7]

- Due to localization of charges therefore it is associated with insulating and antiferromagnetic (or paramagnetic) behavior

Physics of CMR: *Ordering*

Orbital ordering

- Orbital-ordering gives rise to the anisotropy of the electron-transfer interaction.
- This favors or disfavors the double-exchange interaction or superexchange interaction in an orbital direction-dependent manner.
- Hence gives a complex spin-orbital coupled state. The orbital-ordering is coupled with Jahn-teller distortion .



[7]

Physics of CMR: *Ordering*

Spin ordering

Interactions with neighboring atoms make the spin of electrons align in a particular fashion

Ferromagnetism →when the spins are arranged parallel to one another.
Antiferromagnetism →results when they are anti-parallel to one another.

Antiferromagnetic ordering is of three types particularly in perovskite-type oxides.

A-type: The intra-plane coupling is ferromagnetic while inter-plane coupling is antiferromagnetic.

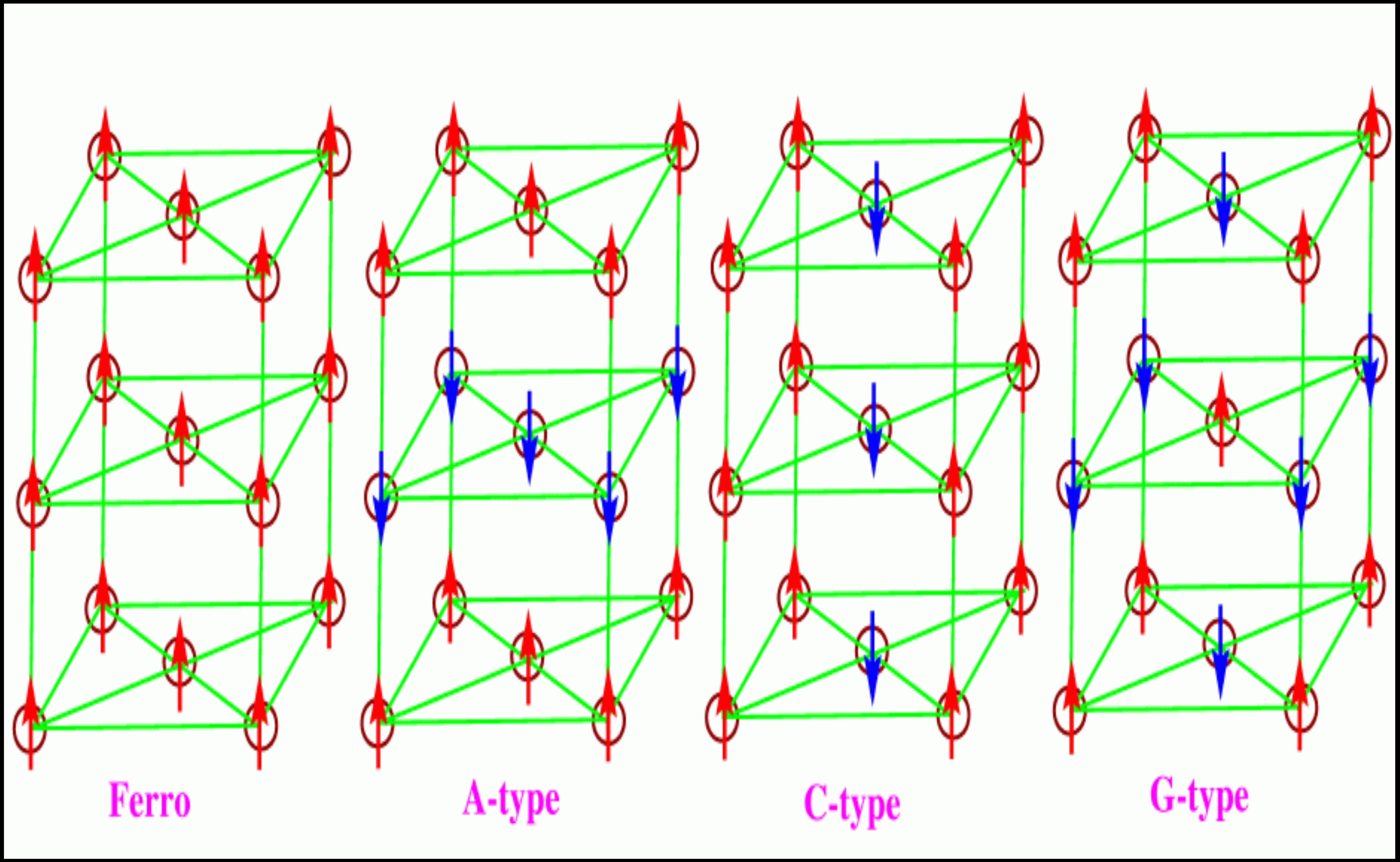
C-type: The intra-plane coupling is antiferromagnetic while inter-plane coupling is ferromagnetic.

G-type: Both intra-plane and inter-plane coupling are antiferromagnetic.

Physics of CMR: *Ordering*

Spin ordering

Types of spin ordering in perovskite oxides



[7]

- Physics of CMR manganites
    - Structure: Cubic pervoskite, t2g and 2g degeneracy
    - Exchange Interactions: Super Exchange, Double Exchange (DE)
    - Ordering: Charge, Orbital and Spin Ordering

CMR manganites

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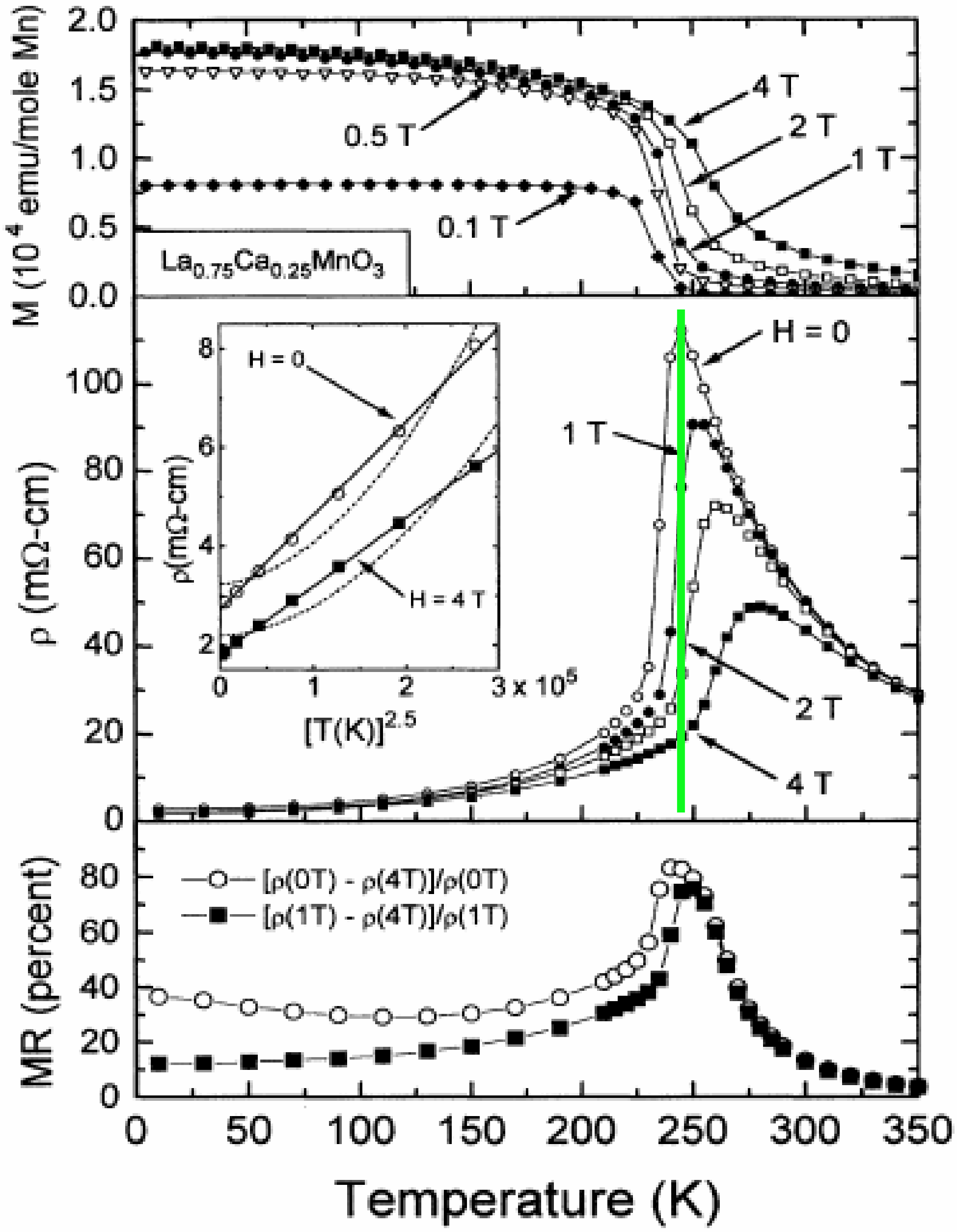

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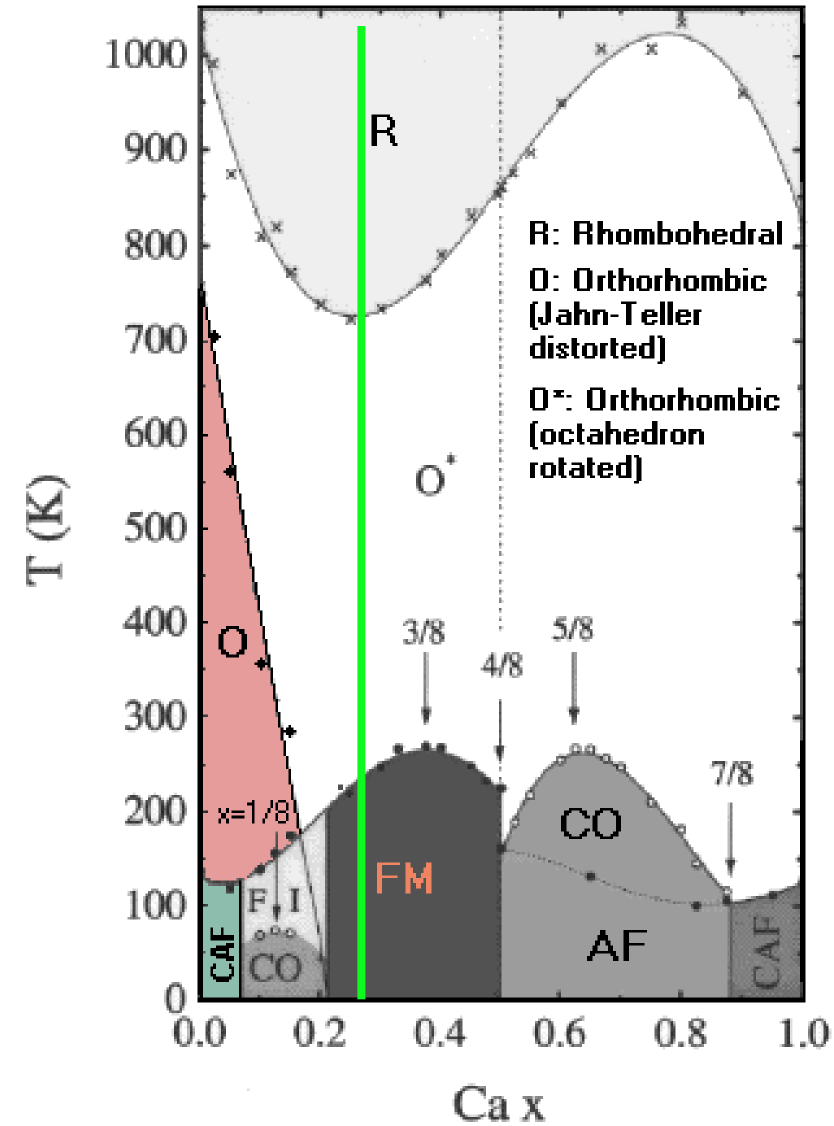

Phase Diagram of $La_{1-x}Ca_xMnO_3$

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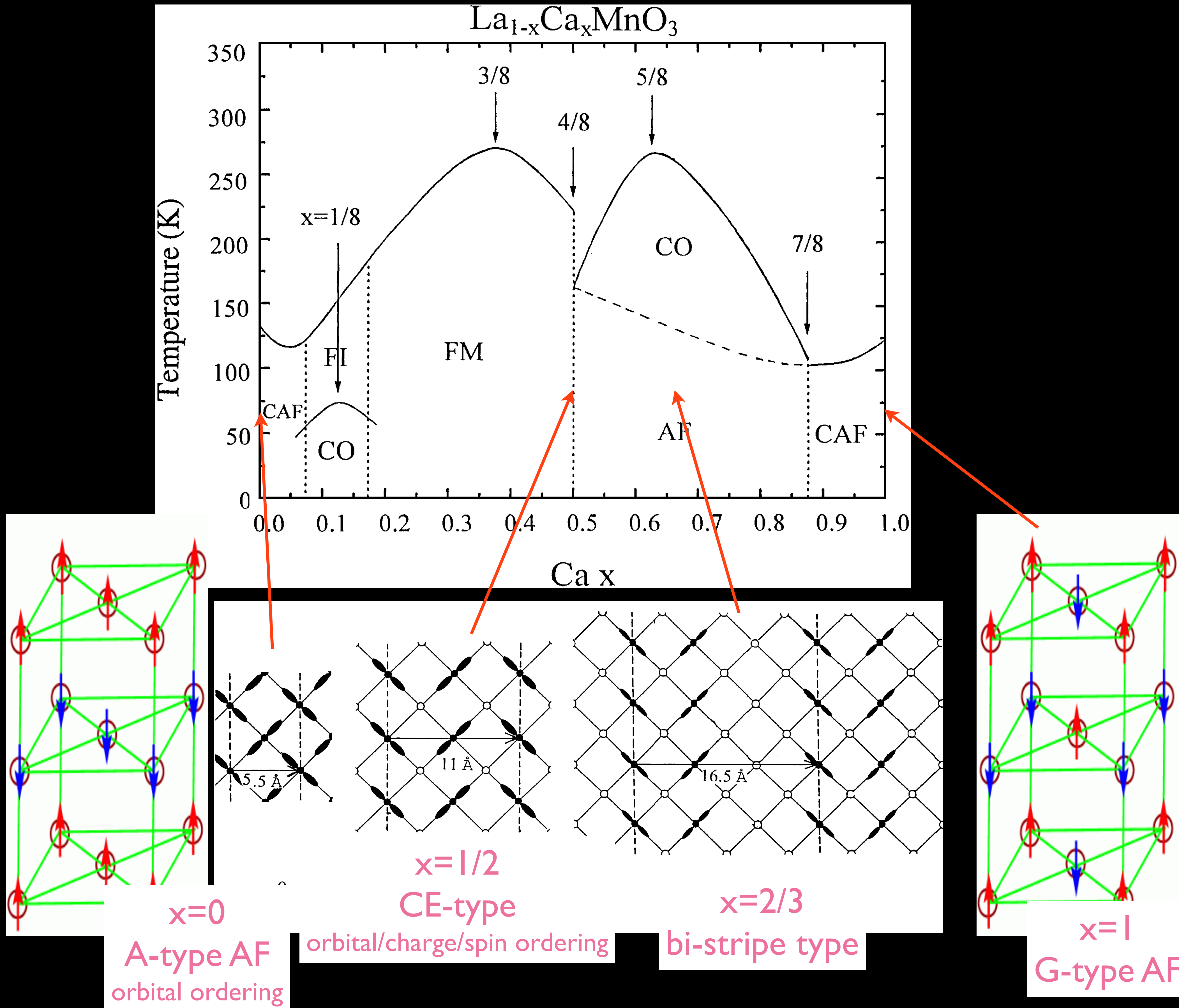
La1-xCaxMnO3
Temperature (K)
350
300
250
200
150
100
50
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Ca x
3/8
4/8
5/8
7/8
x=1/8
CO
FI
FM
CAF
CO
AF
CAF
5.5 Å
11 Å
16.5 Å
x=0
A-type AF
orbital ordering
x=1/2
CE-type
orbital/charge/spin ordering
x=2/3
bi-stripe type
x=1
G-type AF

[2,7]

Summary

- CMR shows large amount of magnetoresistance, however the operating temperature is too low for general applications.
- Spin/Charge/Lattice degrees of freedom are coupling together
- Exchange interactions, orbital ordering, Hund coupling and Jahn-Teller distortion are origins of ferromagnetism
- Still remaining unexplained mechanism

References

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5. Shiffer, PRL, 75, 3336, (1995)
6. G. Jonker, and J. van Santen, Physica, 16, 337, (1950)
7. http://folk.uio.no/ravi/activity/ordering/colossal-magnet.html