Colossal Magnetoresistance

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Outline

• Description of CMR
• Magnetic structure in manganites: early neutron scattering results
• Phase separation
• CMR vs. GMR
What is colossal magnetoresistance?

Applying a magnetic field to a material results in a significant decrease in its resistivity.

Sample is ferromagnetic at low temperatures.

Metal-insulator transition at the Curie temperature.

CMR in $\text{La}_{0.75}\text{Ca}_{0.25}\text{MnO}_3$.

P. Schiffer et al., PRL 75, 3336 (1995)
Manganese 3d shell

- Each Mn atom has a magnetic moment.
- The $e_g$ electron can easily hop between two atoms with the same magnetization direction.
- For this interaction to dominate, we need sufficient populations of $\text{Mn}^{3+}$ and $\text{Mn}^{4+}$ atoms.
- Is this the whole story?

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Early Experiments: Neutron Scattering

“The inner cryostat and sample assembly are held in accurate alignment with the beam and the pole pieces by three nylon cords held taut by banjo type string tighteners anchored to a brass box.”

The undoped cases: antiferromagnetic

E. O. Wollan and W. C. Koehler, Phys. Rev. 100, 545 (1955)
Mixed valence

**Fig. 15.** Curie and Néel temperatures vs composition. Solid circles Jonker and Van Santen ferromagnetic saturation data, open triangles ferromagnetic neutron data, open circles and squares antiferromagnetic data, square referring to CaMnO$_3$ series.

The simple conductivity model doesn’t explain everything

E. O. Wollan and W. C. Koehler, Phys. Rev. 100, 545 (1955)

S. Grenier et al., PRB 69, 134419 (2004), following J. B. Goodenough et al., Phys. Rev. 100, 564 (1955)
The plot thickens

White = charge ordered


S. Mori et al., PRL 81, 3972 (1998)
Phase Separation

Inhomogeneities in a homogeneous system!
What about the other atoms?

Tilted octahedra $\Rightarrow$ lower conductivity and smaller ferromagnetic domains

S. Grenier et al., PRB 69, 134419 (2004)
Low-bandwidth compound: (Pr,Ca)MnO$_3$

Fig. 2.3.1. Phase diagram of Pr$_{1-x}$Ca$_x$MnO$_3$. PI and FI denote the paramagnetic insulating and ferromagnetic insulating states, respectively. For hole density between 0.3 and 0.5, the antiferromagnetic insulating (AFI) state exists in the charge/orbital-ordered insulating (COI) phase. The canted antiferromagnetic insulating (CAFI) state, which may be a mixed FM$_J$AF state, also has been identified between $x \approx 0.3$ and 0.4. Reproduced from Tomioka and Tokura (1999).

Fig. 2.3.2. Temperature dependence of the resistivity of Pr$_{1-x}$Ca$_x$MnO$_3$ with $x \approx 0.3$ at various magnetic fields. The inset is the phase diagram in the temperature-magnetic field plane. The hatched region has hysteresis. Results reproduced from Tomioka and Tokura (1999).

It is interesting to observe that pressure leads to a colossal MR effect quite similar to that found upon the application of magnetic fields (see for example Fig. 2.3.3, where results at $x \approx 0.30$ from Moritomo et al. (1997) are reproduced).

The abrupt metal-insulator transition at small magnetic fields found in Pr$_{1-x}$Ca$_x$MnO$_3$ at $x \approx 0.30$ appears at other densities as well, as exemplified in Fig. 2.3.4, which shows the resistivity vs. temperature at $x = 0.35, 0.4$ and 0.5, reproduced from Tomioka et al. (1996). Fig. 2.3.5 (from Tomioka and Tokura, 1999) shows that as $x$ grows away from $x \approx 0.30$, larger fields are needed to destabilize the charge-ordered state at low temperatures (e.g., 27 T at $x = 0.50$ compared with 4 T at $x = 0.30$).

It is also interesting to observe that the replacement of Ca by Sr at $x = 0.35$ also leads to a metal-insulator transition, as shown in Fig. 2.3.6 taken from Tomioka et al. (1997).

Clearly Pr$_{1-x}$Ca$_x$MnO$_3$ presents a highly nontrivial behavior that challenges our theoretical understanding of the manganese oxide materials. The raw huge magnitude of the CMR effect in this compound highlights the relevance of the CO-FM competition.

2.4. Other perovskite manganite compounds

Another interesting perovskite manganite compound is Nd$_{1-x}$Sr$_x$MnO$_3$, and its phase diagram is reproduced in Fig. 2.4.1 (from Kajimoto et al., 1999). This material could be labeled as E. Dagotto et al. (2001)
High-bandwidth compound: (La,Sr)MnO$_3$

The whole picture for $x=0.45$
Challenges for the Future

• Full explanation of phase separation
• Growing good samples
• Measurements that give us a clear picture of what’s going on inside the materials
• Dynamics
Summary

- CMR is the result of phase separation within homogeneous systems
- A simple model of ferromagnetic metallic behavior can only take us so far
- By changing the size of the dopants, we can explore a very large phase space
So how and CMR and GMR related?
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- CMR and GMR are unrelated
- GMR: magnetic multilayer systems
- CMR: single materials