Charge Instabilities At The Metamagnetic Transition

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1 Layered Sr-Ruthenates

2 Stoner and Pomeranchuk scenarios for the metamagnetic transition

3 2D Hubbard model perspective: mechanisms?

4 Micro phase separation?

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Layered Strontium-Ruthenates $\text{Sr}_{n+1}\text{Ru}_n\text{O}_{3n+1}$
Ruddlesden-Popper Series

Single layer: $\text{Sr}_2\text{RuO}_4$
Triplet superconductor, $T_c=1.5\text{K}$,
expanding FS volume: strong increase of $\chi$

Double layer: $\text{Sr}_3\text{Ru}_2\text{O}_7$
close to ferromagnetism,
metamagnetic transition
Electronic Structure: Single Layer $\text{Sr}_2\text{RuO}_4$

- 3 $t_{2g}$ bands ($d_{xy}, d_{xz}, d_{yz}$) cross Fermi level, almost 2D band structure
- LDA, dHvA and ARPES agree on Fermi surfaces
- Van Hove singularity near Fermi level

Damasceelli et al. 
Mazin & Singh

van Hove singularities

$\text{Sr}_2\text{RuO}_4$ cleaved at 180 K
$T = 10$ K
$hv = 28$ eV

Local-density-approximation band-structure calculation
Doping La\(^{3+}\) For Sr\(^{2+}\): Pushing The FS Closer To Van Hove Points & Ferromagnetism

- \(\text{Sr}_{2-y}\text{La}_y\text{RuO}_4\): \(y > 0\) adds electrons, **expands all Fermi surfaces**
- Spin susceptibility \(\chi\) increases (FM tendencies!)
- FS pushed toward van Hove points
- Multi-layer splittings push FS closer to VH points (Sigrist)

Kikugawa et al., 2004
Double-Layer Sr$_3$Ru$_2$O$_7$: Metamagnetic Transition

- Sharp increase of magnetization in magnetic field around 7.8T

- Feature in resistivity, anomalous T-dependence:
  \[ \rho = \rho_0 + A T^x \]  with \( x \neq 2 \) in critical region.

Perry et al. PRL 2001
Stoner Picture

- Mean field theory for local repulsion $U$: metamagnetic transition near van Hove filling

\[ f_{\text{HF}}(n, m, T) = f_0(n, m, T) + U n_\uparrow n_\downarrow \]

Minimize $g(T, h, n) = f_{\text{HF}} - h m$

Binz & Sigrist 2003:
New Samples: At Least Two Jumps

- Ultraclean samples ($\rho_0=0.4$ $\mu\Omega$cm) show two or three peaks in low frequency susceptibility $\chi$
- peaks in $\text{Im } \chi$ interpreted as hysteretic signals of two 1st order transitions
Cleaner samples develop a big (×2) resistivity anomaly at the metamagnetic transition.

In anomalous B-field range: no significant increase of ρ with T → elastic scattering.

Domains of something sensitive to impurities?
**d-Pomeranchuk Scenario**

Proposal: *d*-wave ´Pomeranchuk´Fermi surface deformation

- increases magnetization
- makes domains responsible for resistivity anomaly
- should be sensitive to sample quality

Grigeira et al. 04

Kee & Kim 04
d-Wave FS Deformation In 2D Hubbard Model

- RG in Hubbard model near half filling:
  - tendencies toward d-wave FS deformation (e.g. Halboth&Metzner 2000)
  - typically not strongest instability (CH et al. 2001), but generic tendency
- Effective interaction

\[
H_{dPom}^{\text{eff}} = -g \sum_{\vec{k}, \vec{k}', s, s'} f(\vec{k}, \vec{k}') c_{\vec{k}, s}^+ c_{\vec{k}', s} c_{\vec{k}', s'}^+ c_{\vec{k}, s'}
\]

\[
f(\vec{k}, \vec{k}') = \left(\cos k_x - \cos k_y\right) \times \left(\cos k'_x - \cos k'_y\right)
\]

forward scattering needs this form with \(g > 0\)

→ calculate \(f_{kk'}\) with RG
Effective Interactions From Functional RG

- Momentum-shell RG: integrate out shell around FS at decreasing energy scale $\Lambda$
  \[ \rightarrow \text{low energy interactions} \]
- **Temperature flow**: follow flow of vertex functions down to low $T$
  \[ \rightarrow \text{effective low-T interactions} \]
- **N-Patch implementation** gives detailed $k$-dependence of effective interactions $V(k_1,k_2,k_3)$
RG: Triplet Superconductivity Near Ferromagnetism

- Temperature RG flow \textit{p-wave instability near FM regime} at van Hove filling (CH & Salmhofer 01, Katanin 03,04)
Forward Scattering In Hubbard Model

AF side: d-wave o.k.

\[ d_k = \cos k_x - \cos k_y \]

attraction!

FM side: ?

no attraction!

Sr\textsubscript{2}RuO\textsubscript{4}
Sr\textsubscript{3}Ru\textsubscript{2}O\textsubscript{7}

- RG finds contradiction: d-wave FS deformations unfavorable (no attractive coupling constant) in FM regime!
- Alternative explanations?
Similarity To Liquid-Gas Transition

Liquid gas transition:
- Jump in entropy $S$ vs. $T$ at $T_c$
- Also feature in $F$ as function of $V$
- Regions with negative curvature wrt $V$
  $\rightarrow$ phase coexistence

Analogue for metamagnetic transition?

\[
S = -\frac{dF}{dT}
\]

\[
p = -\frac{dF}{dV}
\]

\[
M = \frac{dG}{dB}
\]

Isothermal line at $T_c$

coexistence region

$V_c$
Unstable Density Regions Near MM Transition

- Gibbs potential $G(T,h,n)$ in Binz-Sigrist mean-field model has negative curvature wrt density $n$.

$\Rightarrow$ Coulomb-frustrated phase separation?

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Maxwell Destruction Of Magnetization Jump?

- Mixing parameter $p$ from Maxwell construction:
  
  **Density:** 
  
  $$n_{\text{tot}} = (1-p) n_<(h) + p n_>(h)$$
  
  ($p$ varies continuously from 0 to 1 through transition)

  **Magnetization:** 
  
  $$m_{\text{tot}} = (1-p) m_<(h) + p m_>(h)$$

- Does phase separation wipe out magnetization-step?
Coulomb & Interface Energies

Coulomb energy frustrates phase separation

→ **micro phase separation** on nanoscale

→ **interfaces** between high- and low-density phases cost additional energy $G_I$

→ not all mixing ratios $p$ energetically favorable, very thin stripes don’t pay

$$G(h,n,T)$$

$p<h$ $p>(h)$

mixing ratio $p$ grows

$n<h$ $p=0$ $n>(h)$ $p=1$
Two Jumps

Increasing $h$: two jumps
- from 0 to $p_<$ on entry into inhomogeneous phase
- from $p_>$ to 1 on exit

$G(h,n,T)$
$h$ fixed

$p_<(h)$
$p_>(h)$

$n_<(h)$
$p=0$

$n_>(h)$
$p=1$

$G_I(h)$

Grigeira et al, 04
Length Scale Of Domains

• stripes in metals (Lorenzana et al.):
  size of domains $\sim$ screening length $\sim$ lattice distance

$$l_s^2 = \varepsilon_0 / (4\pi e^2 \kappa)$$

$k = \text{compressibility}$

Is our description sensible? BUT:

• only one Fermi surface (of 6) near VH points, other FS are spectators
• mutual screening by other FS reduces effective charge of domains $\rightarrow$ screening length increases

$$l_s^2 = \varepsilon_0 / (4\pi e^2 Z^* \kappa)$$

$Z^* < 1$ charge reduction
Conclusions

• Strontium-Ruthenates are good test case for understanding of correlation effects

• Scenarios for resistivity anomaly at metamagnetic transition
  – Pomeranchuk FS deformation hard to reconcile with FM tendencies and Hubbard-type models
  – MM transition invites micro phase separation, Coulomb+interface energies might create two magnetization jumps
  – Alternative: uncharged Condon domains due to demagnetization (Binz, Sigrist et al.)

Possible experimental test: STM (Cornell group)