Non-Fermi Liquids and Bad Metals in NdNiO$_3$ Thin Films

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Acknowledgements

- Graduate students and postdocs:
  - Evgeny Mikheev
  - Adam Hauser
  - Nelson Moreno
  - Jinwoo Hwang (now at OSU)
  - Jack Zhang
  - Junwoo Son (now at Postech)

- Collaborators: Burak Himmetoglu, Chris Van de Walle (UCSB Materials)

- Funding
Quantum Criticality

- Continuous phase transition at zero-temperature
- Quantum fluctuations influence the material over a wide range of temperatures and across phase diagram

A non-thermal control parameter causing large changes in properties: metal-insulator transitions, magnetic transitions, ...
Non-Fermi liquid behavior:

- Poorly understood power laws in transport coefficients
- Non-saturating resistances that escalate past the Mott-Ioffe-Regel limit: “Strange Metals”
- Strong temperature dependence of the Hall coefficient (not reflecting a real change in Fermi surface)
Bad Metals

- **Mott-Ioffe-Regel limit**: mean free path length \( \sim \) lattice spacing
- Neither saturating nor non-saturating metals are understood


- **Saturating metals are described by**:

\[
\frac{1}{\rho} = \frac{1}{\rho_0} + \frac{1}{\rho_{\text{sat}}} + \frac{1}{\rho_{\text{MIR}}}
\]

- Electron-electron scattering: \( n \sim 2 \)
- Non-Fermi liquids: \( n < 2 \)
- \( \rho_0 \): residual resistance (disorder)
- Saturation resistance connected in parallel, serves to reduce resistance

\[
\rho_{\text{MIR}} = \frac{3\pi^2 \hbar}{q^2 k_F^2 a}
\]
Non-Fermi liquid behavior in strained NdNiO$_3$ thin films:

- NFL power law coefficients in resistivity
- Quantum critical point
- Bad metal behavior
- Vary strain and confinement (thickness): relationship to electronic structure
Metal-Insulator Transitions in \( \text{RNiO}_3 \)

- Quantum phase transition
- Size of the rare earth ion is the tuning parameter: “band-width driven metal-insulator transition”
- Expect the transition to be sensitive to strain
- Is the transition quantum critical?
- Non-Fermi liquid behavior?


Orbital Engineering in $\text{RNiO}_3$


PRL 103, 016401 (2009)

Turning a Nickelate Fermi Surface into a Cupratelike One through Heterostructuring

P. Hansmann, $^{1,2}$ Xiaoping Yang, $^1$ A. Toschi, $^{1,2}$ G. Khaliullin, $^1$ O. K. Andersen, $^1$ and K. Held$^2$
Tensile strains and confinement favor the large hole surface

Promotes a spin density wave instability and insulating state

Confinement and tensile strains have qualitatively similar effects
Epitaxial strain systematically shifts the MIT

MIT is relatively independent of deposition conditions, which affect the stoichiometry

Low-pressure films can be strained to larger strains without relaxing

Tensile strains favor the large hole surface
Promotes a spin density wave instability and the insulating state
Strain as a Tuning Parameter

Likely more complex reasons for films with insulating state at all temperature than simple band width tuning

Role of disorder?

Criterion for Anderson transition in this system?


Insulator at all temperatures

Metals at all temperatures

NNO/DSO (+2.96%) on DyScO$_3$
Metal-Insulator Transitions in NdNiO$_3$

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]
Metal-Insulator Transitions in NdNiO$_3$
MITs and Non-Fermi Liquids

\[ \rho = \rho_0 + A T^n + \rho_{\text{sat}} \]

- Metallic phase exhibits saturating resistance
- Need to take into account to get correct NFL exponent

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]
MITs and Non-Fermi Liquids

\[ R = R_0 + AT^n \]

\( n \approx 1.6 \) (NFL)

\( n = 2 \) (FL)

\( \rho_0 > \rho_{\text{sat}} \)

Anderson Insulator

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]
Non-Fermi liquid behavior only if MIT is suppressed
Same exponent (5/3) across the entire sample series
$n$ is independent of disorder
Need to take resistance saturation into account to get correct $n$
Quantum critical point shifts to more compressive strains with decreasing film thickness.

Confinement promotes $x^2-y^2$ orbital polarization, which favors spin density wave and the AFM insulator.

Suppression of MIT leads to NFL behavior.


E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]
Bad Metals

- Mott-Ioffe-Regel limit: mean free path length ~ lattice spacing
- Neither saturating nor non-saturating metals are understood


- Saturating metals are described by:

\[
\rho_{MIR} = \frac{3 \pi^2 \hbar}{q^2 k_F^2 a}
\]

- Electron-electron scattering: \( n \sim 2 \)
- Non-Fermi liquids: \( n < 2 \)
- \( \rho_0 \): residual resistance (disorder)
- Saturation resistance connected in parallel, serves to reduce resistance
Saturating Metallic Phase

In the 0-K limit:

\[
\frac{1}{\rho(0\text{ K})} = \frac{1}{\rho_0} + \frac{1}{\rho_{\text{sat}}}
\]

- \(\rho_{\text{sat}}\) and \(\rho_0\) depend on the magnitude of the mismatch strain
- \(\rho_{\text{sat}}\) is independent of thickness (confinement, disorder)
- \(\rho_0\) strongly depends on thickness

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]
Saturation and Orbital Polarization

- $\rho_{\text{sat}}$ depends on the magnitude of orbital polarization
- A parallel channel due to interband scattering
- Conversely, predict that materials with a single band at the Fermi level show no saturation (i.e., cuprates)

Consistent with theoretical predictions (modified Boltzmann transport models that account for interband scattering and QMC simulations)


- $\rho_{\text{sat}}$ is tunable by orbital polarization

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]
Criterion for the "Anderson Insulator": $\rho_{\text{sat}} \sim \rho_0$

- $\rho_{\text{sat}}$ is independent of thickness but depends on strain
- $\rho_0$ depends on thickness
- Predict that material is insulating at all temperatures when $\rho_{\text{sat}} \sim \rho_0$
- Correct to within 1 u.c.
- This Anderson insulator is strain and thickness tunable

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]
\[
\frac{1}{\rho} = \frac{1}{\rho_0} + \frac{1}{\rho_{\text{sat}}} 
\]

MITs and Non-Fermi Liquids

\( n \sim 1.6 \) (NFL)

\( n = 2 \) (FL)

\( \rho_0 \gg \rho_{\text{sat}} \)

Anderson Insulator
Phase Diagram

PM (NFL) ↔ AFI

Anderson Insulator

$\rho_{\text{sat}} \sim \rho_0$
Summary

- Single non-Fermi liquid exponent (5/3) across the entire series, if MIT is suppressed
- Non-Fermi liquid phase or quantum critical point?
- Need to take resistance saturation into account to get correct NFL exponent
- NdNiO$_3$ is a saturating metal, but Ioffe Regel Limit is exceeded
- Degree of “bad metal” behavior depends on orbital polarization (strain)
- Large orbital polarization increases $\rho_{\text{sat}}$ and makes the material increasingly “non-saturating” → resistivity escalates past the Mott-Ioffe-Regel limit
- Can be tuned by strain and confinement
- Metals with large degeneracy have large $\rho_{\text{sat}}$ and are thus non-saturating
- Quantitative understanding of the role of electronic structure in strongly correlated phenomena is desirable
- New routes to controlling MITs:
  - Confinement stabilizes spin-density wave and insulating state ⇒ modulate confinement
  - Strain can modulate transition between Anderson insulator and metal

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]
Thank you