Strong Electron Correlations in Oxide Quantum Wells

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Outline

- Quantum Criticality
- Manipulating strong electron correlations in oxide heterostructures
- Magnetism and non-Fermi liquid behavior in oxide quantum wells
- Outlook
Quantum critical points are driven by quantum fluctuations that are present even at 0 K

Quantum criticality persists to finite temperatures

Leads to new electronic behavior and novel states of matter
Introduction: Quantum Critical Points

Unconventional superconductors, heavy fermions, organics, ...

Key features (?):
- Antiferromagnetism
- Nearly 2D

Iron-based superconductors
- Tetragonal, magnetic fluctuations
- Orthorhombic, magnetic fluctuations
- Orthorhombic, antiferromagnetic

CuO-based superconductors
- Insulator and antiferromagnetic
- Strange metal
- Pseudogap phase
- Superconducting

Non-Fermi Liquid

Introduction: Quantum Critical Points

Fermi Liquid: \( R = R_0 + A T^2 \)

<table>
<thead>
<tr>
<th></th>
<th>Ferromagnetic (Q = 0)</th>
<th>Antiferromagnetic (Q ≠ 0)</th>
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</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>3D</td>
<td>2D</td>
</tr>
<tr>
<td>Resistance</td>
<td>( T^{5/3} )</td>
<td>( T^{4/3} )</td>
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- Leads to new electronic behavior and novel states of matter
Introduction: Quantum Critical Points

Key open questions:
- Roles of dimensionality and order parameter symmetry in QCPs?
- Which types of critical fluctuations mediate new ordered phases (i.e., is antiferromagnetism needed)

Limitations of bulk material studies:
- Complexity of materials systems
- Truly two-dimensional systems are difficult to obtain
- Dimensionality cannot be manipulated
- Doping as the tuning parameter changes many other parameters:
  - Disorder
  - Lattice distortions
Complex Oxide Heterostructures

Exceptional control (and simplicity):

- Precise control over **dimensionality** using layer control and electrostatic confinement
- **Electrostatic doping**: charge carriers without disorder
- Proximity effects to control lattice and introduce magnetic order
Complex Oxide Heterostructures

Design interactions from bottom-up for improved understanding and control
A high-density, two-dimensional electron system in close proximity to magnetism
Mott/Band Insulator Interfaces

GdTiO$_3$
- Mott insulator
- Ferrimagnet

SmTiO$_3$
- Mott insulator
- Antiferromagnet

Orbital order is crucial in determining the magnetic state
- Anti-ferro-orbital in ferromagnetic RTiO$_3$
- Ferro-orbital in antiferromagnetic RTiO$_3$

Requirements for the 2DEG

Conditions for Strong Electron Correlations

- High electron densities are key for strong electron correlation physics
- Short range Coulomb interactions require significant probability for two electrons to occupy the same site
- Opposite of the usual correlation regime investigated in conventional semiconductor 2DEGs
Mobile charge carrier density at the interface of $\frac{1}{2}$ electron per interface unit cell, or $\sim 3 \times 10^{14}$ cm$^{-2}$

Forms a high-density, quantum confined 2DEG at the interface

Order of magnitude higher charge density than what is achievable in conventional semiconductors

Formally analogous to LaAlO$_3$/SrTiO$_3$

MBE of Mott/Band Insulator Interfaces


Sheet carrier density (n-type) is independent of SrTiO$_3$ thickness

Conduction in a space charge layer with constant thickness

Sheet charge carrier density corresponds to the theoretical expected density of $\sim 3 \times 10^{14}$ cm$^{-2}$

- GdTiO$_3$ is insulating (p-type)
- Remarkable drop in sheet resistance even for one unit cell of SrTiO$_3$
- Sheet resistance independent of SrTiO$_3$ thickness for all thickness greater than 20 nm
- Sheet carrier density (n-type) is independent of SrTiO$_3$ thickness
- Conduction in a space charge layer with constant thickness
- Sheet charge carrier density corresponds to the theoretical expected density of $\sim 3 \times 10^{14}$ cm$^{-2}$

2DEGs at Mott/Band Insulator Interfaces

- Sheet carrier density scales with number of multilayer repeats (interfaces)
- Independent of SrTiO$_3$ or GdTiO$_3$ thickness
- Each interface contributes a constant charge carrier density $\sim 3 \times 10^{14}$ cm$^{-2}$


Extreme Carrier Density Quantum Wells

Very large 3D carrier densities in SrTiO$_3$ quantum wells
“2 SrO” quantum well: 1 electron/three Ti layers
On-site Coulomb repulsion (electron correlations)?
Quantum well in GdTiO3 become insulating at 2 SrO thickness

- Abrupt transition and orders of magnitude change in resistance
- 2D small polaron gas
- All quantum wells in SmTiO3 are metallic
- Even a single SrO layer in SmTiO3 remains metallic

Shown are the A-site displacements (deviation from 180° angle in cubic SrTiO₃)

- Sr atom displacements in the 2 SrO-thick, insulating quantum wells, consistent with octahedral tilts
- Sr atoms are NOT displaced in the metallic quantum wells
- Structural transition accompanies the transition to insulating phase
- Abrupt transition

Structural displacements are much smaller in quantum wells in SmTiO$_3$

- Explains why the quantum wells remain metallic
- Larger difference than expected from the bulk tilts in adjacent Mott insulator
Mott/Band Insulator Interfaces

- GdTiO$_3$
- Mott insulator
- Ferrimagnet

Quantum Well

- SmTiO$_3$
- Mott insulator
- Antiferromagnet

Magnetism and Dimensionality?
Mott/Band Insulator Interfaces

- GdTiO₃
- Mott insulator
- Ferrimagnet

Quantum Well

2DEG

Magnetism and Dimensionality?
Ferromagnetism in the 2DEG

- Ferromagnetic hysteresis below ~ 5 K
- Spin polarized 2DEG in narrow quantum wells

Ferromagnetism in the 2DEG

- Angle-dependent behavior consistent with anisotropic magnetoresistance (AMR)
- Spin-polarized, high-density 2DEG at an epitaxial oxide interface
- Negative AMR ($\Delta \rho_A = \rho_\parallel - \rho_\perp < 0$)
- Similar to III-V 2DHGs under compressive strain
- Indicative of spin-orbit coupling in the 2DEG

\[ \rho_{xx} = \rho_\perp + \Delta \rho_A m_x^2 \]
\[ \rho_{xy} = \Delta \rho_A m_x m_y \]
\[ m_x = \cos \alpha \cos \beta \]
\[ m_y = \sin \alpha \cos \beta \]

Ferromagnetism in SrTiO$_3$ quantum well is distinct from that of GdTiO$_3$.

- Metallic conducting is GdTiO$_3$ not magnetic.
- Onset of hysteresis in quantum well at about 5 K, vs. $T_c = 20$ K in GdTiO$_3$.
- Coercive fields are different.

Mott/Band Insulator Interfaces

SmTiO₃
Mott insulator
Antiferromagnet

Quantum Well

Magnetism and Dimensionality?
Non-Fermi liquid (NFL) behavior above cross-over temperature indicates proximity to a quantum critical point. Cross-over temperature changes with quantum well thickness. 1-SrO layer quantum wells show NFL at all temperatures. Temperature exponent of NFL = 5/3.

Temperature exponent of NFL = 5/3

Indicates three-dimensional critical fluctuations with a wave vector $Q = (0,0,0)$

Both SmTiO$_3$ and the quantum well have orthorhombic symmetry, with a unit cell that is doubled along the three cube axes $→ Q = (0, 0, 0)$

The electron system is two-dimensional

Can we reduce the dimensionality of the fluctuations and tune the exponent?

→ Reduce the thickness of the SmTiO$_3$
Magnetism and octahedral tilts are suppressed in thin GdTiO₃ films

Suppression of orbital order

Fermi-liquid behavior for SmTiO$_3$ superlattices with $x < 12$ u.c.

NFL for 16 u.c SmTiO$_3$ with temperature exponent = $4/3$

Reducing the dimensionality of the SmTiO$_3$ changes critical exponent

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Magnetic State of 1 SrO Quantum Well

- No ferromagnetic hysteresis
- Positive magnetoresistance below 4 K indicates SDW

\[ \Delta R_{xx}/R_{xx}(0) \] vs. \( B (T) \) for different temperatures:
- 2 K
- 4 K
- 6 K
- 10 K
- 20 K
- 30 K

\[ R_s (k\Omega/sq) \] vs. \( T^{5/3} (x10^3 K^{5/3}) \) for 1 SrO

- Number of SrO layers and coupling between layers are the tuning parameters for NFL
- Quantum critical point
### Comparison: $RTiO_3/SrTiO_3/RTiO_3$ ($R = \text{Gd, Sm}$)

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<tr>
<td>Electron Density in SrTiO$_3$ QW</td>
<td>$7 \times 10^{14}$ cm$^{-2}$</td>
<td>$7 \times 10^{14}$ cm$^{-2}$</td>
</tr>
<tr>
<td>Metal-insulator transition</td>
<td>✓ at 2 SrO layers; small polaron gas</td>
<td>itinerant to 1 SrO</td>
</tr>
<tr>
<td>Fermi liquid</td>
<td>✓</td>
<td>NFL below 2 SrO</td>
</tr>
<tr>
<td>Mass enhancement</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Magnetism below critical thickness</td>
<td>Ferromagnetic 2DEG</td>
<td>AFM/Spin density wave</td>
</tr>
<tr>
<td>Octahedral tilts below critical thickness</td>
<td>✓ at MIT</td>
<td>✓ small tilts</td>
</tr>
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**Precise Control and Design of Emergent Phenomena**
Theory and more sophisticated measurements are needed to better understand dimensionality of fluctuations, the ordered state, and the tuning parameter.
Electron Correlation Physics with Oxide Quantum Structures

- Spin-polarized, high-density 2DEG
- Two-dimensional antiferromagnetism
- Proximity to quantum critical point
- Conditions favoring unusual states of matter are present in these quantum wells
  - Non-centrosymmetry
  - Strong electron correlations
  - Proximate magnetism
  - Spin-orbit coupling
- Can test more complex spin states and fluctuations, and other proximity effects, such as superconductivity
Thank you