Classes of materials

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Strong - weak coupling regime
Two material classes

Metals

Semiconductors

Past and present

Present
Basic notions:
We understand well the two material classes through electrical transport measurements.

- Metals: \( \rho \sim T^n \)
  - 1- electron – phonon
  - 2- electron – electron
  - 3- s-d electron scattering
  - 5- electron - phonon
  - \( \rho(T \to 0) \to \rho_0 \)

- Insulators: \( \rho \sim e^{1/T} \)
  - \( e^{T^{-1/n}} \)
  - \( n = 2, 3, 4 \)
  - Depending on the dimensionality

\( \rho(300 \text{ K}) \) - small
- Silver - \( 1.59 \times 10^{-6} \ \Omega\text{cm} \)
- Cooper - \( 1.68 \times 10^{-6} \ \Omega\text{cm} \)

\( \rho(300 \text{ K}) \) - big
- Silicon- \( 6.4 \times 10^4 \ \Omega\text{cm} \)
- Teflon - \( 10^{24} \ \Omega\text{cm} \)
Order-disorder

![Graph showing order-disorder in Cu and Au with Cu₃Au and CuAu phases.](image)
Metals with strong disorder

Value of resistivity - very low – metallic
Slope – becomes nonmetallic

**Fig. 2** Resistivity versus temperature for Ti and TiAl alloys containing 0, 3, 6, 11, and 33% Al. Data are from Mooij, Ref. [19]. The solid line represents the temperature range where our theoretical calculation will be compared with the experimental data.
Screening of the magnetic impurity: Kondo-effect

\[ H_{Kondo} = J \sum_i \vec{S}_i \cdot \vec{S}_i \]

\[ \rho = \rho_v + c_m a \ln(\mu/T) + bT^5 \]
Where to look for novelities?

How to fill the gap?

$10^{-6} \, \Omega \text{cm} \quad 10^4 \, \Omega \text{cm}$

Metals

Semiconductors

Novel conductors

Correlated metals

Past and presence

Presence and future
A different look on the same thing

Interesting phenomena: $U \sim W$

Electrons are “strongly correlated” if
- their mutual Coulomb repulsion is more important than their energy gain due to delocatization
- their Coulomb energy dominates the kinetic energy
Narrow bands compounds

d- & f-electrons are different

strong coupling regime

graphic by P. Coleman, after Smith & Kmetko, J. Less-Common Metals 90 (1983) 83

Smith and Kmetko (1983)
\[ W (\sim k_B T) < U \]
A lattice of interacting sites

Kondo lattice - development of coherency at low temperature

Dissolution of localized, and neutral magnetic f spins into the quantum conduction sea, where they become mobile excitations. Once mobile, these free spins acquire charge and form electrons with a radically enhanced effective mass.

P. Coleman, 2012
Large $W$ ($\sim 1\text{eV}$), but even larger $U$ ($\sim 10\text{eV}$)

High-$T_c$ cuprate superconductors
Conclusions

**Resistivity** $\rho = m^*/(\rho e^2 \tau)$

**Scattering rate** $\cot(\Theta_H) = C_2 T^2 \propto 1/\tau$

Change in paradigm: Novel prospect!

**Resistivity** \( \rho = m^* / (n e^2 \tau) \)

**Scattering rate** \( \cot(\Theta_H) = C_2 T^2 \propto 1/\tau \)

Preprint, submitted to PRX 2016

Localization of the ONE
Until now – Universalities only

N. Barišić et al., Nat. Phys. 9, 761 (2013).


N. Barišić et al., PNAS 110, 12235 (2013).

• raw data
• only textbook formulas applied
3\textsuperscript{rd} topic addressed: Non universal behaviors
Evolution of carrier density near $p^* \approx 0.19$

LSCO

Evolution of carrier density near $p^* \approx 0.19$

\[ \cot(\Theta_H) \propto C_2 T^2 \]


Evolution of carrier density near $p^* \approx 0.19$

\[ \cot(\Theta_H) \propto C_2 T^2 \]


Evolution of carrier density near $p^* \approx 0.19$

\[ \cot(\Theta_H) \propto C_2 T^2 \]


Evolution of carrier density near $p^* \approx 0.19$

\[
\cot(\Theta_H) \propto C_2 T^2
\]


\[
R_H = \sigma_{xy}/(H\sigma_{xx}\sigma_{yy}), \quad \text{where } \sigma \text{ is the conductivity tensor}
\]

\[
\sigma_{xy} \to 0 \quad \rightarrow \quad R_H \to 0 \quad \rightarrow \quad C_2 \propto 1/R_H \quad \rightarrow \quad \text{diverges}
\]

\[R_H \] - ceases to be a proper measure of the carrier density!

Evolution of carrier density near $p^* \approx 0.19$

\[ \cot(\Theta_H) \propto C^2 T^2 \]


\[ n_H = 1/(eR_H) \]

If $n_H = x/V$

then $eR_H x/V = 1$

Evolution of carrier density near \( p^* \approx 0.19 \)

\[
cot(\theta_H) \propto C^2 T^2
\]


\[ n_H = 1/(eR_H) \]

If \( n_H = x/V \)

then \( eR_H x/V = 1 \)

M. Hashimoto et al.,
Evolution of carrier density near $p^* \approx 0.19$


[Graphs and equations]

$n_H = 1/(eR_H)$

If $n_H = x/V$

then $eR_Hx/V=1$

$dc$ resistivity and optical conductivity $p = x$

in the PG/FL phase
Evolution of carrier density near \( p^* \approx 0.19 \)

**LSCO - Important messages**

- \( R_H \) - ceases to be a proper measure of the carrier density!
- **Failure of the effective-mass approximation** and not of the applicability of the **Fermi Liquid** concept.
- Resistivity (and optical conductivity) reveals the correct carrier density!

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Evolution of carrier density near \( p^* \approx 0.19 \)

**LSCO - Important messages**

- \( R_H \) ceases to be a proper measure of the carrier density!
- **Failure of the effective-mass approximation** and not of the applicability of the **Fermi Liquid** concept.
- **Resistivity (and optical conductivity)** reveals the correct carrier density!

**Universal sheet resistance**

Delocalization of one carrier per planar copper is **not abrupt but gradual** (as a function of doping and temperature)


N. Barišić et al., *PNAS* 110, 12235 (2013)
YBCO & Hall number

YBCO

Nature 531, 210 (2016)

L. P. Gor’kov, G. B. Teitel’baum  

N. Barišić et al.,  

N. Barišić et al.,  
PNAS 110, 12235 (2013)
YBCO & Hall number

**YBCO**


- L. P. Gor’kov, G. B. Teitel’baum

- N. Barišić *et al.,*


- N. Barišić *et al.,*
YBCO & Hall number

**YBCO**


- **L. P. Gor’kov, G. B. Teitel’baum**

- **N. Barišić et al., arXiv:1507.07885 (2015)**

- **D. Fournier et al., Nature Phys. 6, 905 (2010)**


- **N. Barišić et al., PNAS 110, 12235 (2013)**
YBCO & Hall number

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Nature 531, 210 (2016)

L. P. Gor’kov, G. B. Teitel’baum

N. Barišić et al.,

D. Fournier et al., Nature Phys. 6, 905 (2010)

K. Segawa et al.,

N. Barišić et al.,
PNAS 110, 12235 (2013)
Conclusions

Resistivity \( \rho = m^*/(n e^2 \tau) \)

Scattering rate \( \cot(\Theta_H) = C_2 T^2 \propto 1/\tau \)

Preprint, submitted to PRX 2016

Localization of the ONE – GRADUAL!
4\textsuperscript{th} topic addressed: Quantum oscillations
Comment on the Quantum oscillations – universal property of underdoped cuprates

Arcs
- large effective $E_F$

Pockets
- small $E_F$

Comment on the Quantum oscillations – universal property of underdoped cuprates

**Arches**
- large effective $E_F$
- $v_F$ doping and compound independent

**Pockets**
- small $E_F$


arc to pocket transition expected
Resonant X-ray scattering
-Charge density wave correlations

Field induced transition expected

W. Tabis et al., Nat. Comm. 5, 5875 (2014)
Comment on the Quantum oscillations – universal property of underdoped cuprates

**Arrows**
- Large effective $E_F$
- $v_F$ doping and compound independent

**Pockets**
- Small $E_F$

---

**Hg1201**

- Charge Density Wave vector

---

**Single pocket expected**

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Comment on the Quantum oscillations – universal property of underdoped cuprates

Arches
- large effective $E_F$
- $\nu_F$ doping and compound independent

Pockets
- small $E_F$


Solid lines correspond to Lifshitz-Kosevich fit.

Fourier transform of the oscillatory part - only one peak is observed with temperature independent position.

N. Barišić et al., Nat. Phys. 9, 761 (2013)
Comment on the Quantum oscillations

– single frequency

High-resolution measurements

Los Alamos – 100T

Hall, Seebeck, and Nernst Coefficients
- Fermi-Surface Reconstruction

N. Doiron-Leyraud et al.,
6\textsuperscript{th} topic addressed:
(q=0) Magnetism
Neutron Scattering
- Triple-Axis Spectrometer

- Cross section proportional to $S(Q, \omega)$, the Fourier transform of the pair correlation function
  \[
  \frac{d^2\sigma}{d\Omega dE_f} \propto S(Q, \omega)
  \]
  Dynamic structure factor
  \[
  S(Q, \omega) \propto \int \langle \rho(r, 0)\rho(r', t) \rangle e^{i(Q\cdot(r-r')-\omega t)} \, dr dr' dt
  \]

- Momentum transfer $Q = k_i - k_f$ and energy transfer $\hbar\omega = E_i - E_f$

- Geometry for triple-axis neutron scattering:

\begin{itemize}
  \item source \hspace{1cm} monochromator \hspace{1cm} analyzer \hspace{1cm} detector
  \item $E_i, k_i$ \hspace{1cm} $E_f, k_f$
  \item sample
\end{itemize}
Neutron Scattering
- Polarized Neutrons

- Polarization analysis: magnetic vs. nuclear scattering
- \( \mathbf{Q} = \mathbf{k}_i - \mathbf{k}_f; \hbar \omega = E_i - E_f \)
- Measure moment component perpendicular to both \( \mathbf{Q} \) and polarization \( \mathbf{P} \)
- For \( \mathbf{P} \parallel \mathbf{Q} \), magnetic scattering occurs in spin-flip channel only
- Cold 3-axis instrument (4F1) at LLB used for diffraction (\( E_i = 14.7 \) meV):
Pseudogap
- “hidden” magnetic order

Nuclear Bragg peak (1 0 1)

In agreement with previous measurements on YBCO
Fauqué et al., PRL (2006)

Universal Magnetism in the Pseudogap

- Universal magnetic order associated with pseudogap


7th topic addressed: Electron doped cuprates
Phase diagram

Resistivity: underdoped regime

- **LS**CO: La$_{2-x}$Sr$_x$CuO$_4$
- **YBC**O: YBa$_2$Cu$_3$O$_{6+\delta}$
- **LYCO**: La$_{2-x}$Y$_x$CuO$_4$
- **La-Bi2201**: Bi$_2$Sr$_{2-x}$La$_x$CuO$_{6+\delta}$
- **Hg1201**: HgBa$_2$CuO$_{4+\delta}$

**NCCO**: Nd$_{2-x}$Ce$_x$CuO$_{4-\delta}$

**PCCO**: Pr$_{2-x}$Ce$_x$CuO$_{4-\delta}$

**SCCO**: Sm$_{2-x}$Ce$_x$CuO$_{4-\delta}$

**PLCCO**: Pr$_{1.3-x}$La$_{0.7}$Ce$_x$CuO$_{4-\delta}$
Resistivity: upturn

(1) Anderson (strong) localization--disorder
(2) Variable Range Hopping
    Mott VRH
    Efros-Shklovskii VRH--Coulomb interaction

(3) Weak localization--quantum interference
(4) Kondo Effect--magnetic impurities
(5) Scattering with spin/charge order
    etc.
Electron irradiation: upturns

$YBa_2Cu_3O_{6+\delta}$

Electron irradiation: upturns

\[
\rho = \rho_{\text{res}} + A_2 T^2 + \Delta \rho
\]

\[
\Delta \rho \sim -\log\left( \frac{T}{T_{\log}} \right)
\]

YBa$_2$Cu$_3$O$_{6+\delta}$

Resistivity: Novel analysis

\[ \rho = \rho_{\text{res}} + A_2 T^2 \]

Y. Li et al., PRL 117, 197001 (2016)
\[ \rho = \rho_{\text{res}} + A_2 T^2 \]

**Resistivity: Novel analysis**

\[ \rho = \rho_{\text{res}} - A \log \left( \frac{\rho}{\rho_{\text{log}}} \right) + A_2 T^2 \]

\[ \rho = \rho_{\text{res}} + A_0 \log \left( \frac{T}{1K} \right) - A \log \left( \frac{T}{1K} \right) + A_2 T^2 \]

\[ \rho = A_0 - A_0 \log \left( \frac{T}{1K} \right) + A_2 T^2 \]
Resistivity: Novel analysis

\[ \rho = \rho_{res} - A \log \log(T / T_{log}) + A_2 T^2 \]

\[ \rho = \rho_{res} + A_1 \log(T_{log} / 1K) - A \log T / 1K + A_2 T^2 \]

\[ \rho = A_0 - A \log T / 1K + A_2 T^2 \]
\[ \rho = \rho_{res} - A_{\log} \log{T / T_{log}} + A_2 T^2 \]

\[ \rho = \rho_{res} + A_{\log} \log{T_{log} / 1K} - A_{\log} \log{T / 1K} + A_2 T^2 \]

\[ \rho = A_0 - A_{\log} \log{T / 1K} + A_2 T^2 \]
Resistivity: Novel analysis

\[ \rho = A_0 - A_{\log} \log(T/1K) + A_2 T^2 \]

\[ A_0 - A_{\log} \log(T/1K) \] - black dashed lines

Y. Li et al., PRL 117, 197001 (2016)
Doping/compound dependencies

\[ A_{2\Delta} (\Omega/K^2) \propto 1/x \]

Ce concentration \( x \)

\[ A_{2\Delta} (\Omega/K^2) \propto 1/p \]

Hole concentration \( p \)

\[ A_0 = \rho_{\text{res}} + A_{\log} \log(T_{\log}/1\text{K}) \]

Y. Li et al., PRL 117, 197001 (2016)
Matthiessen's rule vs. phase separation

\[ \rho = A_0 - A \log \log(T/1K) + A_2 T^2 \]

\[ 1/\tau_{total} = 1/\tau_1 + 1/\tau_2 + .. \]

Matthiessen's rule or serial resistor network?

Kohler’s rule in LSCO:

M. K. Chan et al., PRL 113, 177005 (2014)
Hole-doped cuprates

Scattering rate \( \cot(\Theta_H) = C_2 T^2 \propto 1/\tau \)

- Fermi-liquid scattering rate across \( T^* \)
- independent of doping and compound

Barišić et al., arXiv:1507.07885
Electron-doped cuprates

\[
\cot \theta_H = \frac{\rho}{BR_H} \propto \frac{m^*}{\tau}
\]

\[
\rho = A_0 - A_{\log} \log(T / 1K) + A_2 T^2
\]

Y. Li et al., PRL 117, 197001 (2016)
Universal planar scattering rate

Scattering rate \( \cot(\Theta_h) = C_2 T^2 \propto m^*/\tau \)

Y. Li et al., PRL 117, 197001 (2016)
I do not wish to imply that the cuprates are trivial!

The observation of a protected Fermi-liquid transport scattering rate in an inherently inhomogeneous system that exhibits strong correlations with a carrier density that varies with temperature (localization of one carrier per planar copper) and results in arcs remains a challenge to capture theoretically.

Effective Fermi energy is large \((E_F >> k_B T)\).

It appears necessary to explicitly include the planar oxygen degrees of freedom.
Large $W$ small $U$

Dimensionality
(Iron pnictides, $\text{BaVS}_3$)
Fermi surface

\[ \varepsilon(\mathbf{k}) = -2t_x \cos(k_x a) - 2t_y \cos(k_y b) - 2t_z \cos(k_z c) \]

3D FS

Q2D FS

t_x:t_y:t_z = 1:1:1

t_x:t_y:t_z = 1:1:1/2

Q1D FS

t_x:t_y:t_z = 1:1:1/100

t_x:t_y:t_z = 1:1:2:1/100

t_x:t_y:t_z = 1:1/100:1/100

(TMTSF)₂ClO₄  t_x:t_y:t_z ≈ 300:25:2 meV
Nesting
electron-electron (phonon mediated) scatterings
Backward scattering
Forward scattering
Umklapp scattering - commensurability
Another forward scattering
Quasi 1d - Organic conductors

(TMTSF)$_2$ClO$_4$

ClO$_4$ anion

ac-plane

Se — Se — Se
First organic metals

Shchegolev I F 1972

Peierls transition, CDW Q-1D fluctuations

Strong interaction of electrons with the ions (lattice) leads to charge density waves

STM image of individual atoms on the NbSe$_2$ surface 96Å x 96Å. The additional 3x3 triangular structure is a collective electronic state known as a charge density wave.
Fröhlich conductivity and p-dependence

After Cooper J R and Korin-Hamzic B
1992
Phase diagram: Classical 1d conductors

Is that it?

Logical extension of physics related to the Q1D band is by introducing a narrow partially filled band.

Case of: BaVS$_3$. 
1D - Crystal structure

T > 240 K
hexagonal

l_{inter} = 6.73 Å
l_{intra} = 2.81 Å
Crystal field splitting

\[ \text{BaVS}_3 \rightarrow \text{Ba}^{2+}\text{V}^{4+}\text{S}^{2-}_3 \]

\[ \text{V}^{4+} \rightarrow 3d^1 \]

Symmetries:

Isotropic → Octahedral → Trigonal → Orthorombic

doubling of the unit cell-screw axis conserved
1D band - 1D fluctuation

\( q_c = 0.5 \, c^* \)

Optical conductivity in the infrared range

Polarized light, mosaic sample (phonons)

Results in polarized light reveal the anisotropy in the optical response.

Resistivity - 2nd set of electrons

ARPES - 2nd set of electrons

Band structure calculations

Commensurable diffusive lines $\rightarrow$ tetramerization $\rightarrow$ 1D $d_z^2$ band $\frac{1}{4}$ field

$e_g$-$d_z^2$ hybridization $\rightarrow$ isotropic conductivity

Hidden nesting $\rightarrow$ CDW and/or SDW instability


I. Kupcic et al., in preparation.
Phase transitions - Resistivity

$\rho \, [\text{m} \Omega \text{cm}]$

$T_s = 240 \, K$

$2\Delta_{ch} = 600 \, K$

$T_{MI} = 69 \, K$

Phase transitions - Susceptibility

Metallic phase:
Curie susceptibility

\[ \chi_c(T) \]

\[ T_{MI} \]

\[ d\chi_a/dT \]

\[ \chi_a \]

\[ T_X \]

\[ \chi_c(T) \] - Curie susceptibility

\[ T_{MI} \] - Metal Mott Insulator transition

\[ T_X \] - Curie-Weiss temperature

\[ \chi_a \] - aFM (0.226, 0.226, 0)

References:

Phase transitions  
Commensurate compounds

Second order:  

\[ T_S = 240 \text{ K} \]

\[ 240 \text{ K} > T > 70 \text{ K} \]

orthorhombic

\[ T_{\text{MI}} = 70 \text{ K} \]

tetramerization of the unit cell along \( c \) direction

\[ T_X = 30 \text{ K} \]

magnetic transition  

\[ \text{BaVS}_3 \]

\[ d_{z^2} - e_g \]

INTERPLAY

\[ - \frac{1}{4} \text{ filling} \]

\[ - \text{ cusp in } \chi \]

\[ - \, ? \]
High-pressure setup

Pressure range: 1 bar – 3 GPa
Temperature range: 1.5 – 300 K
Magnetic fields: 0 – 12.7 T
High-pressure setup
High-pressure setup
High-pressure setup
\[ p = \frac{F}{S} = \frac{mg}{r^2 \pi} \]

2 kbar = \(2 \times 10^8\) Pa

g \sim 10 \text{ m/s}^2

r = 3.5 \text{ mm} = 3.5 \times 10^{-3} \text{ m}

\[ r^2 \sim 10^{-5} \text{ m}^2 \]

\[ 2 \times 10^8 = \frac{10 \text{ m}}{10^{-5} \pi} = \frac{m}{\pi} 10^6 \]

m \sim 1500 \text{ kg}

1500 \text{ kg} \sim 2 \text{ kBar}
10*

1500 kg ~ 2 kBar

= 20 kBar
Following the $T_{MI}$ by: pressure

$\rho$ vs $T$ for different pressures.

$T_{MI} = 70K - 29.15K/GPa p$

At $p \sim 2.4$ GPa $T_{MI}$ extrapolates to 0 K.


Pressure dependence:
of optical conductivity in the infrared range

\[ \Delta \approx 11 T_{MI} \]
Magnetoresistance

Shift of the transition temperature:

\[
\frac{\Delta T_{\text{MI}}(H, p_0)}{T_{\text{MI}}(p_0)} = -\gamma \left( \frac{gS\mu_B H}{k_B T_{\text{MI}}(p_0)} \right)^2
\]

\( \gamma = 0.45 \) is
- pressure independent
- same value as in spin-Peierls systems


Following the T_{MI} by: pressure

Collapse of the insulating phase T_{MI} extrapolates to 0 K and T_{MI} ~ 15 K

Collapse of the insulating phase by increase of the magnetic field.

Following the $T_{MI}$ by: pressure

Is there a QCP?

Is there a NFL-FL transition?

Role of disorder?

Collapse of the insulating phase

$p \sim 1.7$ GPa and $T_{MI} \sim 15$ K

Crossover from Non-Fermi Liquid to Fermi Liquid

\[ \rho = \rho_0 + AT^n \]

\[ \rho = \rho_0 + AT^n \]

\( \rho_0 \) is by its definition describes the behavior of the system at the temperature of absolute zero.

Pressure dependence of the low temperature resistivity coefficients \( n, A, \rho_0 \) strongly suggests that at 2 GPa system is in the proximity of a QCP.
$\rho = \rho_0 + A_2(T) \cdot T^2$

$m^* \propto A_2^{\frac{1}{2}}$

NFL - FL

$p = 2.04 \text{ GPa} - 2.7 \text{ Gpa}$
Disorder and NFL behavior ($p > p_{cr}$)

- Imperfections in the crystal structure
- Sulfur deficiency
- Isovalent substitution

Theoretical prediction for $n(c)$

$\text{RRR ratio} \sim 10 - \text{low quality samples}$

$\sim 100 - \text{high quality samples}$

$n(c) \rightarrow 1$
Disorder and NFL ($p>p_{cr}$)

- Isovalent substitution

Theoretical prediction for $n(c)$

RRR ratio ~ 10 - low quality samples
~ 100 - high quality samples

$R(300\,K)/R_0 = 4.4 - 6.5$

$R = R_0 + A T^n$

$n(c): 1.5 \rightarrow 1$

New features in pure samples – Hysterisis in T

\[ T_C [K] \]

\[ QCP \]

\[ P [GPa] \]

\[ \rho [\Omega cm] \]

\[ S \]

\[ d(\log R) / d(1/T) \]

\[ \text{BaVS}_3 \]

No.00

18,65 K

1.76 GPa

0 T

1.9 GPa

0 T
New features in pure samples - Hysterisis in B

- • - 1.9GPa 4K BaVS₃ No.00

\[ \Delta \rho/\rho_0 \text{ [%]} \]

\[ B \text{ [T]} \]
Nonlinear behaviour in I

d.c. current

\[ \rho \text{ [\(\mu\Omega\text{cm}\))] vs. } T \text{ [K]} \]

- 0 T
- 6 T
- 12.7 T 20-200\(\mu\text{A}\)
- 12.7 T 500\(\mu\text{A}\)

\[ 1.9 \text{ GPa BaVS}_3 \text{ No.00} \]

a.c. current

\[ \frac{dV}{dl} \text{ [\(\mu\text{V/\muA}\])] vs. } I \text{ [\(\mu\text{A}\)]} \]

\[ 4 \text{ K} \]

- Decreasing B from 12.7 T
- Increasing B from 0 T

\[ 8.9 \text{ T} \]

\[ 12.7 \text{ T} \]
Phase diagram for pure BaVS$_3$

RRR ratio $\sim$ 60 - high quality samples

![Phase diagram for pure BaVS$_3$](image)
Disorder effects on $T_{MI}$ and $T_X$

Isovalent substitution

Due to the field change from 5 kG to 7 kG

$R(300 \text{ K}) / R_0 = 6.5$

$\Delta \chi [10^{-3} \text{ emu/mol}]$

$\text{Ba}_{0.85}\text{Sr}_{0.15}\text{VS}_3$

$T [\text{K}]$

$R [\Omega]$

$T [\text{K}]$
Disorder effects on $T_{MI}$ and $T_X$

- Imperfections in the crystal structure
- Sulfur deficiency

\begin{align*}
\chi_c^{-1} \text{ [mol/emu]} & \quad 20 \text{ K} \\
T \text{ [K]} & \\
\Delta\chi^{-1} \text{ [mol/emu]} & \quad T \text{ [K]}
\end{align*}
$T_X$ as a function of pressure?
Brings together all three discussed material classes:

- Quasi 1d conductors (quasi 1d band)
- Heavy Fermions (narrow band + broad band)
- Cuprates (d-orbital of V in the center of S octahedron)

Frustrations – triangular lattice
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