Title: Electronic Liquid Crystalline Phases of Highly Correlated Electronic Systems

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Abstract: In one extreme, where the interactions
are sufficiently weak compared to the interactions, electrons form a â€œFermi
liquidâ€• â€“ the state that accounts for the properties of simple metals. In the other extreme, where the interactions
are dominant, the electrons form various â€œMottâ€• insulating or â€œWigner
crystallineâ€• phases, often characterized by broken spatial and/or magnetic symmetries. Corresponding charge and/or magnetically
ordered insulating phases are common in nature.
Between these two extremes lie highly correlated electronic fluids, and
correspondingly a host of interesting and perplexing materials, including such
diverse systems as the cuprate and iron-based high temperature superconductors,
the failed metamagnet Sr₃Ru₂O₇, and a variety
of quantum Hall fluids. Some insight
into electron fluids in this rich intermediate coupling regime can be obtained
from viewing them as partially melted electron solids, rather than as strongly
interacting gases. Here, analogies with
the liquid crystalline phases of complex classical fluids provide useful
guidance for a new approach to this key problem in condensed matter physics.

Electronic liquid crystals

Waterloo - 2013

Strongly Interacting Electrons

$$r_s \sim V/K \sim h^{-2}\, n^{-1/3}$$

$$V \sim e^2\, n^{1/3} \qquad K \sim h^2\, n^{2/3} / 2m$$

Strongly Interacting Electrons

$r_s \sim V/K \sim h^{-2}\, n^{-1/3}$

Quantum "temperature" $\sim 1/r_s$

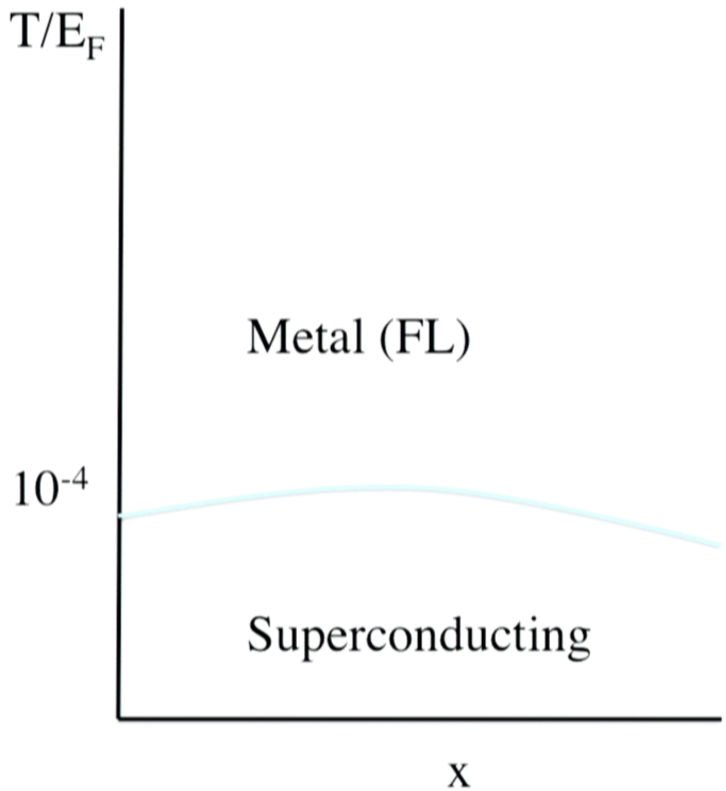
Strongly Interacting Electrons

$r_s \sim V/K \sim h^{-2}\, n^{-1/3}$

Quantum "temperature" ~ $1/r_s$

r_s = "small"	Fermi Gas (simple metal)
r_s = "very large"	Wigner-Mott Insulator
r_s = "pretty darn large"	Highly Correlated Fluid

Phase diagram of simple metals – $A_{1-x}B_x$ - with $r_s \sim 1$



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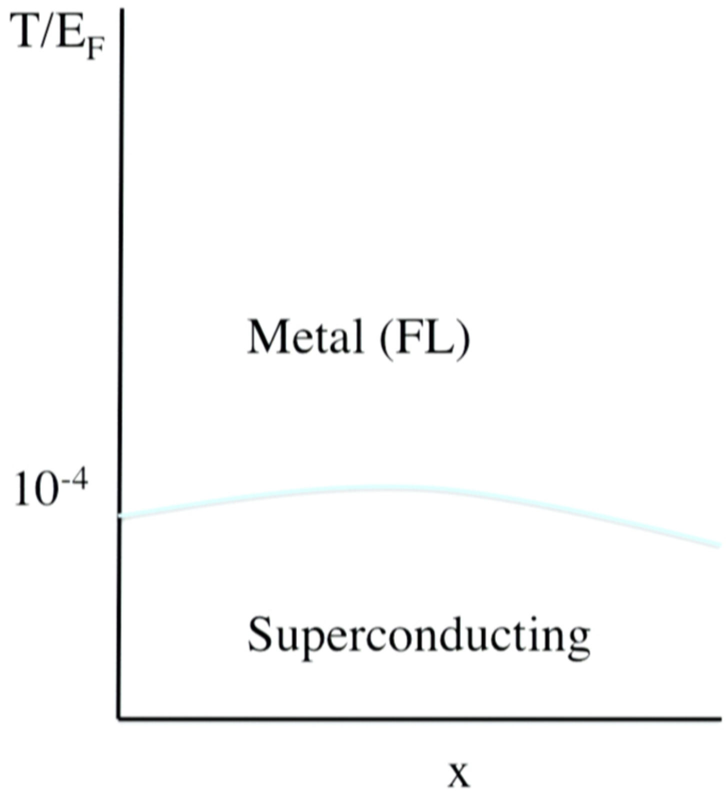


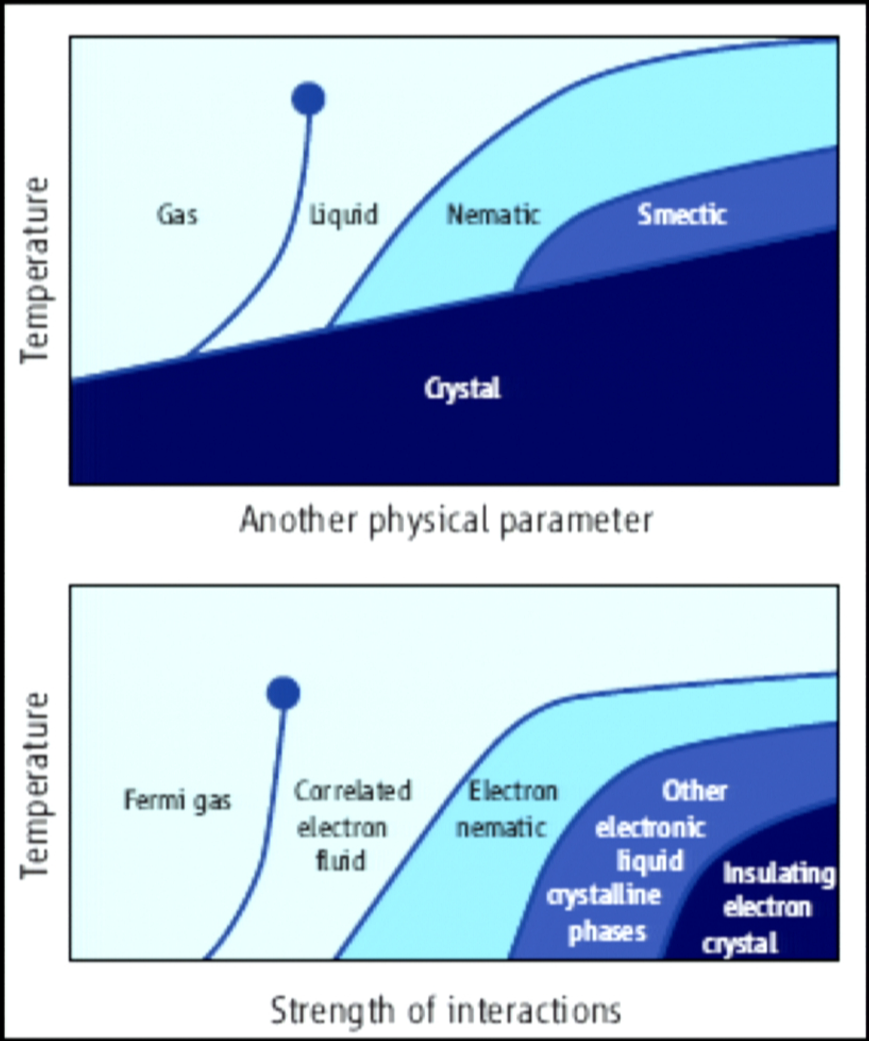
$r_s \sim 1$ is "natural"

The unnatural stability of the Fermi liquid

Anderson's theorem

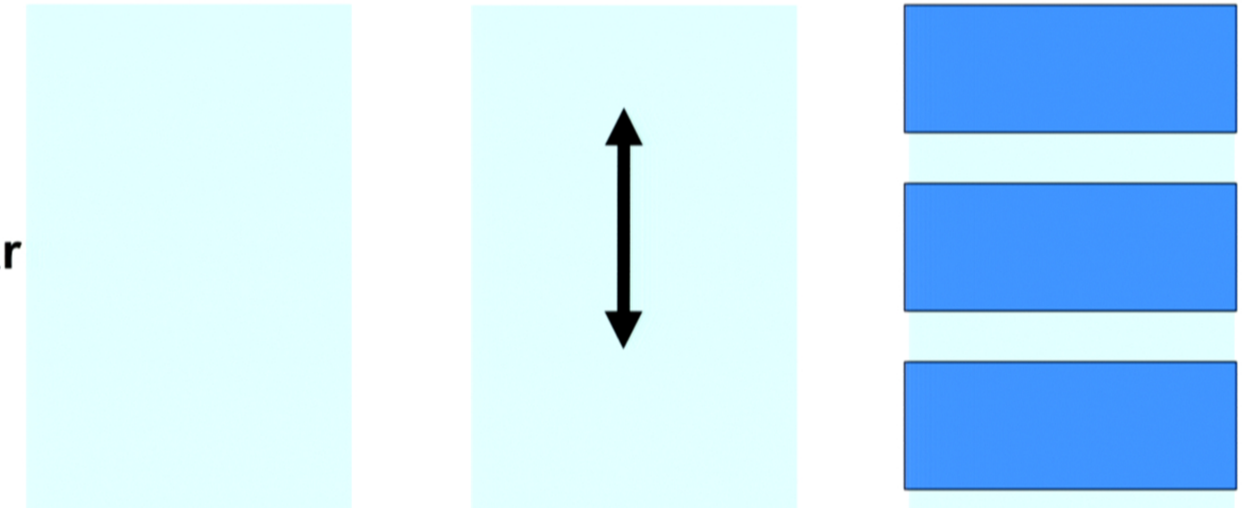
Traditional approach: View highly correlated fluid
as a strongly interacting gas,
figure out approximate ways of resumming
perturbation series,
and invoke the magic of adiabatic continuity
(*i.e.* Fermi liquid theory).

Correlated Fluids Viewed as Partially Melted Crystals



Classical Liquid Crystals: the broken symmetries

Molecular liquid



Isotropic	Nematic	Smectic
	Traceless symmetric tensor (Headless vector)	Unidirectional "density-wave"

Electronic liquid crystalline phases are “unnatural” if we start from an interacting Fermi gas.

However, electron liquid crystalline phases seem reasonable when thought of as partially quantum melted electron crystalline phases.

Spin-Stripe Crystal in a Doped Antiferromagnet

Breaks τ, T_x, T_y, $R_{\pi/2}$, mirrors, (spin-rotation)

Incommensurate or high order commensurate

Bond-centered or site centered, diagonal or vertical

Some “practical” considerations:

1) **Crystals are imperfect** … quenched disorder

In case of a broken symmetry, this can lead to the presence of “random fields:”

$$\Delta H = \int d\vec{r}\, \mathbf{h}(\vec{r}) \cdot \phi(\vec{r})$$

In 2d, and under many conditions in 3d, this spoils most macroscopic manifestations of broken symmetry, and “rounds” the phase transition.

Some “practical” considerations:

2) Often spatial symmetries are only approximate

In case of a broken symmetry, this leads to a “small” symmetry breaking field:

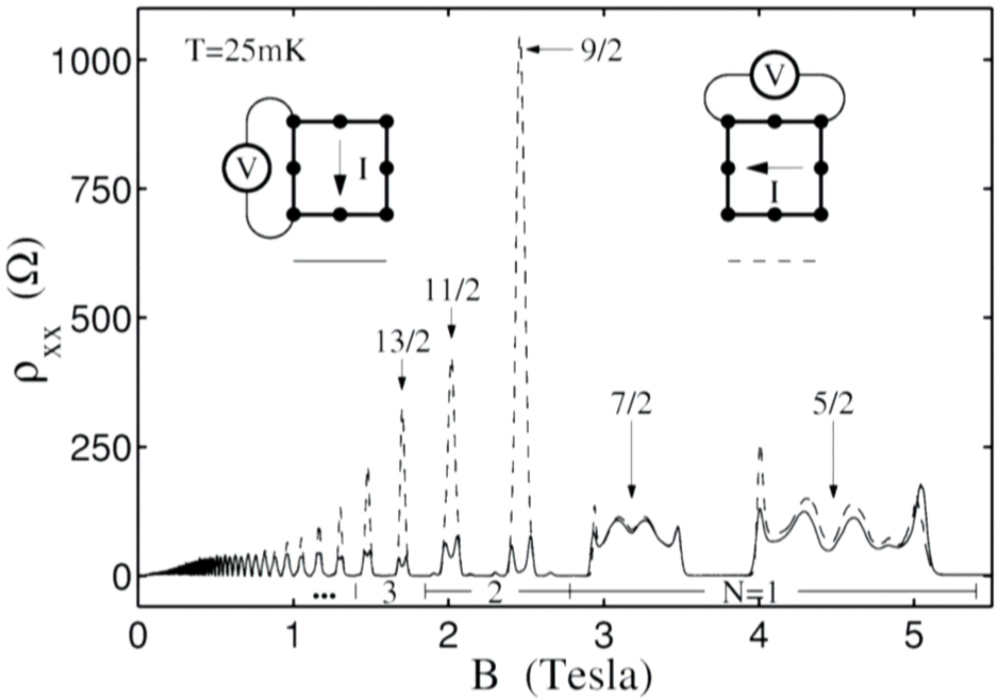
$$\Delta H = \int d\vec{r}\ \mathbf{h} \cdot \phi(\vec{r})$$

This spoils the sharp distinction between the broken symmetry state and the symmetric phase, and so “rounds” the phase transition

However, field cooling circumvents vexing non-equilibrium effects of domain formation.

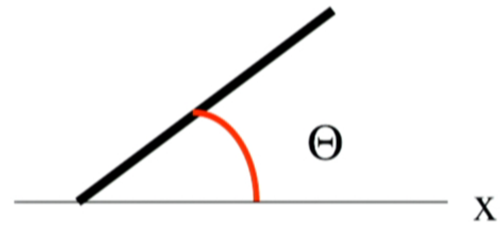
Anisotropic State in Higher Landau Levels

Eisenstein and co. PRL 1999 etc. $\nu = n_{el}\,\phi_o$



Ultra high mobility 2DEG in GaAs-GaAlAs heterostructures

Symmetry considerations:



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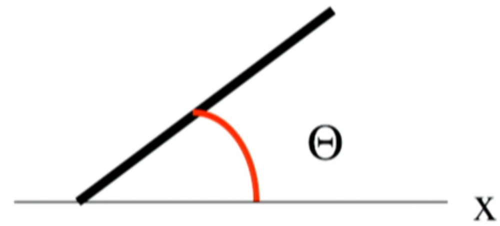


Nematic $\Theta = \pi - \Theta$

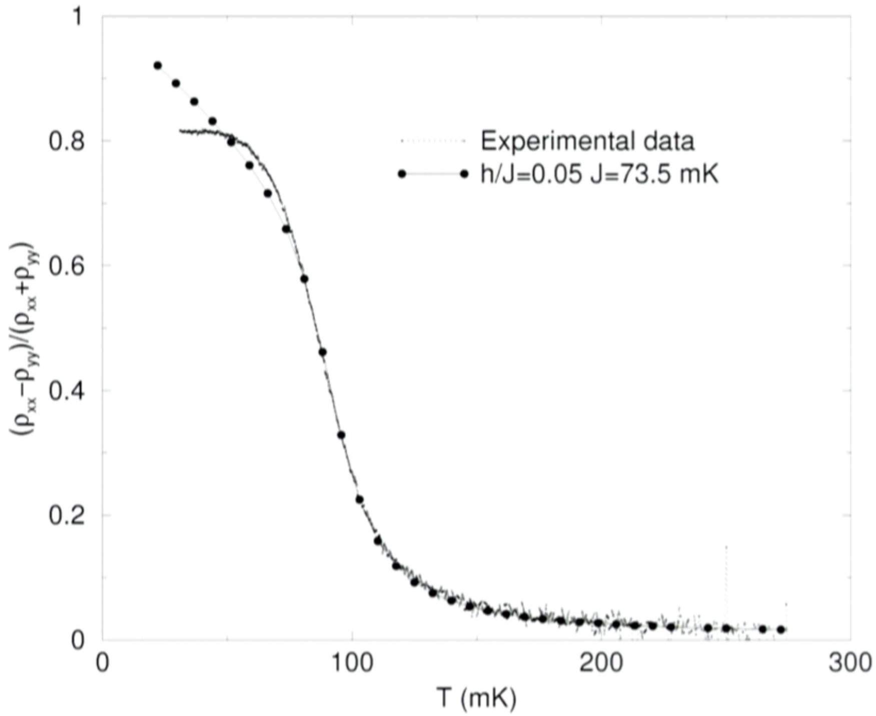
$m = < \cos(2\Theta) >$

Within effective mass approximation -
full rotational symmetry.

Crystal field effects in bulk $V_{CF} = V_4 \cos(4\Theta)$

$V_4 \sim Ry^* \, (a_B/a_B^*)^2 \sim 10^{-4} \, Ry^*$

Comparison with classical XY model of Nematic transition

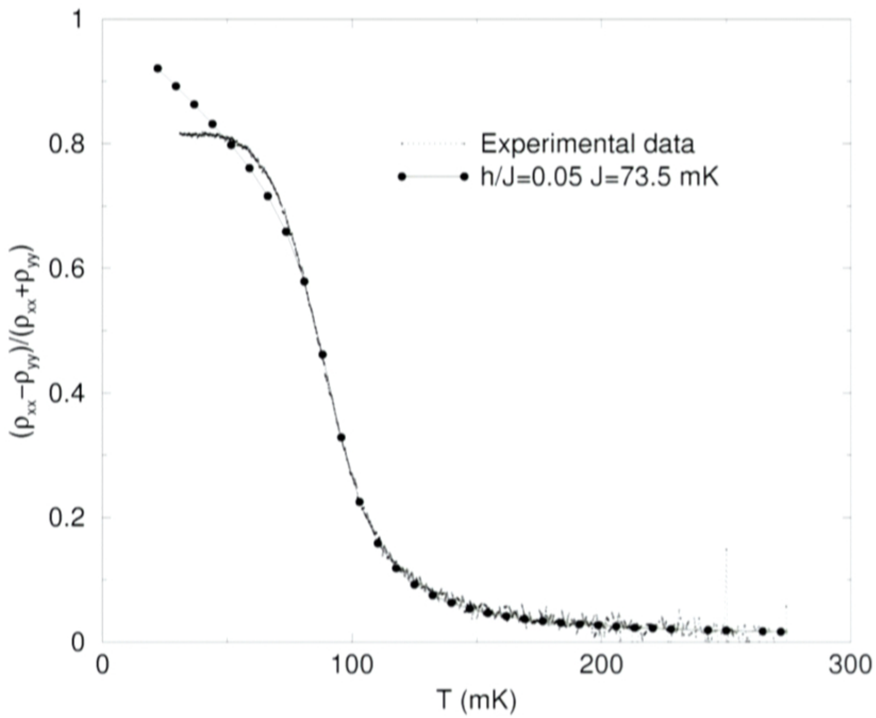


$$H = -J\cos(2\theta_i - 2\theta_j) - h\cos(2\theta_i)$$

$$\frac{\rho_{xx}-\rho_{yy}}{\rho_{xx}+\rho_{yy}} \sim \langle \cos(2\theta) \rangle$$

Fradkin and SAK (1999)

Comparison with classical XY model of Nematic transition



$$H = -J\cos(2\theta_i - 2\theta_j) - h\cos(2\theta_i)$$

$$\frac{\rho_{xx} - \rho_{yy}}{\rho_{xx} + \rho_{yy}} \sim \langle \cos(2\theta) \rangle$$

Fradkin and SAK (1999)

Quantum Hall Nematic:

Finite T phase transition to a conducting state with a large resistivity anisotropy

Transition fits well to a KT transition in a small symmetry breaking field

No depinning field or similar signatures of a CDW state in non-linear I-V's

Symmetries (available for breaking) of the square lattice electronic system

Point group symmetry including

Discrete rotations $R_{\pi/2}$, R_{π},

Reflection planes,…

Translations, T_x, T_y, …

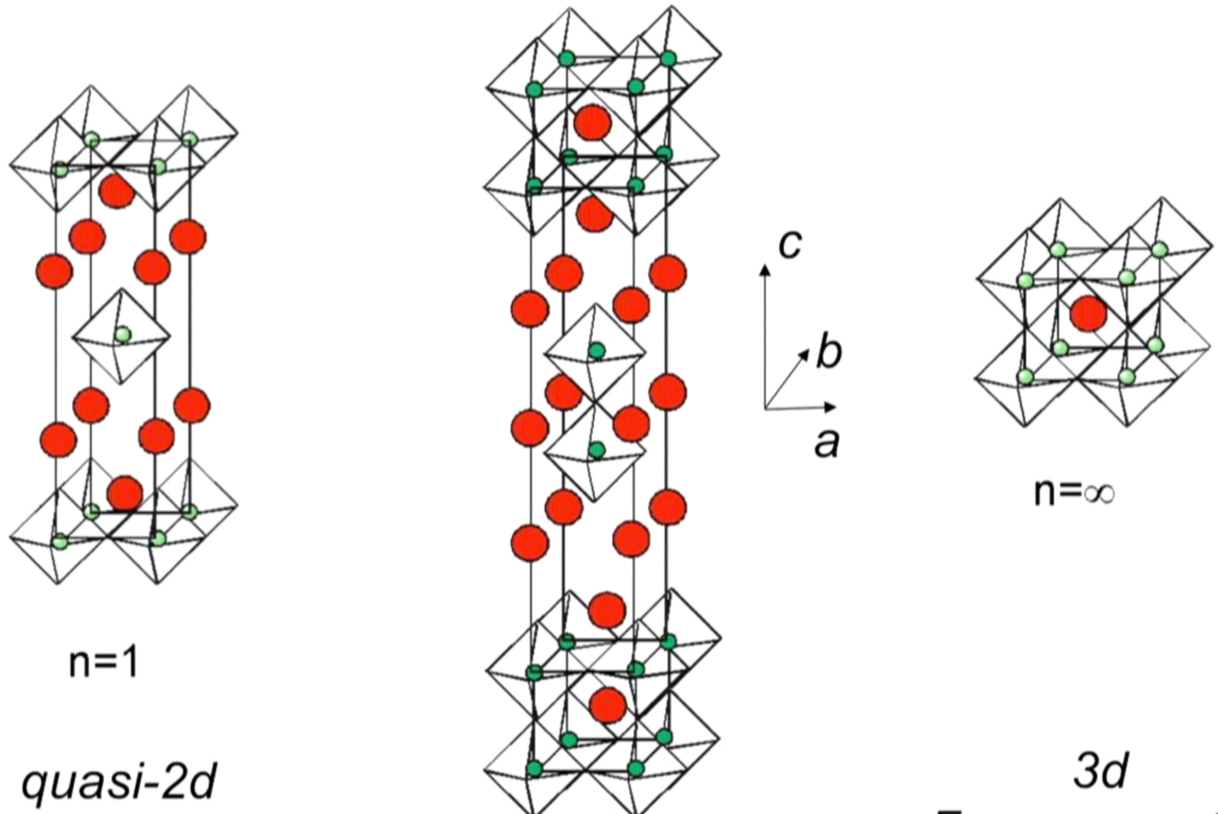
Time reversal, τ

Large scale gauge symmetry (number conservation)

An electron liquid is a conducting (or superconducting) state of the electrons in a solid.

Introduction: Materials

The Ruddlesden-Popper Series: $Sr_{1+n}Ru_nO_{1+3n}$



n=1

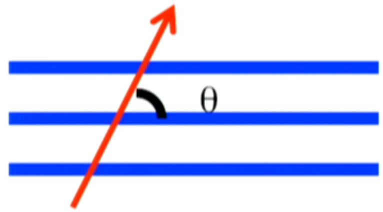
quasi-2d
Paramagnetic Fermi liquid
Triplet superconductor

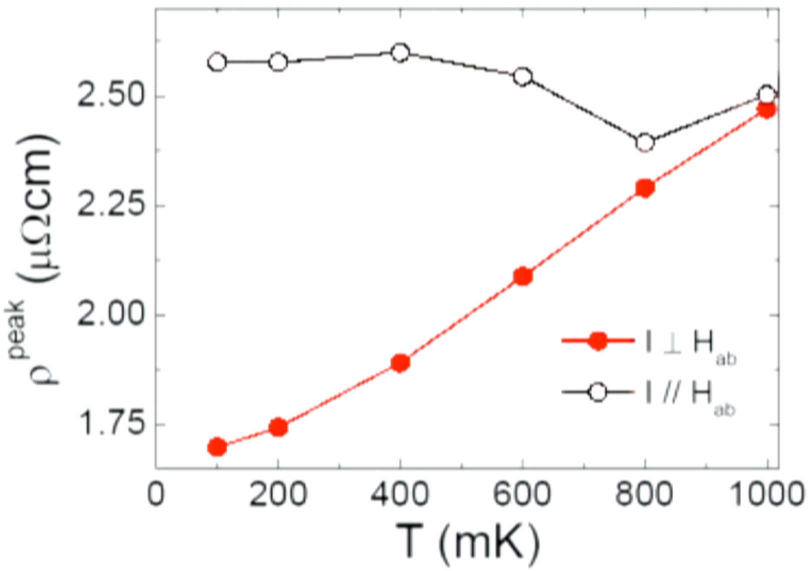
n=2

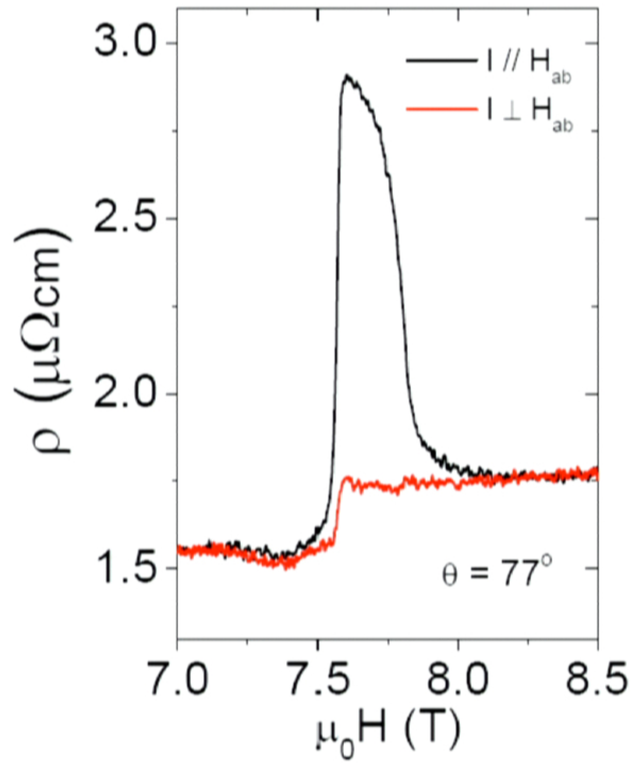
n=∞

3d
Ferromagnetic,
T_c*=160K*

Anisotropic resistivity: temperature dependence







No orthorhombicity has been detected in X-ray scattering

O(N) quantum rotor model: $\vec{S}_i \cdot \vec{S}_i = N$

$$H_{2D} = J_1 \sum_{<i,j>_1} \vec{S}_i \cdot \vec{S}_j + J_2 \sum_{<i,j>_2} \vec{S}_i \cdot \vec{S}_j - \frac{K}{N} \sum_{<i,j>_1} [\vec{S}_i \cdot \vec{S}_j]^2$$

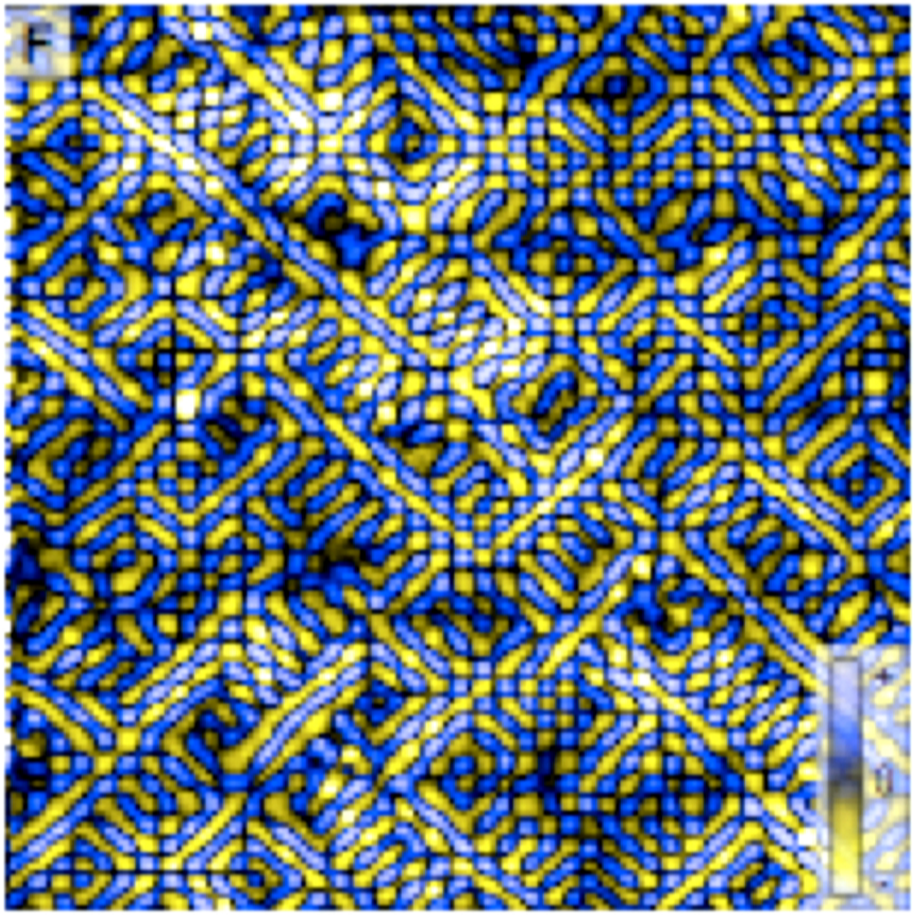
"Weak" interlayer coupling: $H_\perp = -J_\perp \sum_{<i,j>_\perp} \vec{S}_i \cdot \vec{S}_j$

Experimental "proof" of the existence of electron nematic (and other electronic liquid crystalline phases) has been adduced primarily in certain, very clean, very intensely studied materials.

Disorder is a disaster, especially in quasi 2D:

Inevitably leads to a glassy (domain) state.

STM image of a "Nematic Glass" phase on the surface of BSCCO with $T_c \sim 90K$



From Kohsaka *et al*, Nature (2007)
STM on BSCCO or NaCCOC

The End

Electronic liquid crystalline phases, with new and unexpected properties exist in a variety of materials

Both nematic and various forms of electronic smectic order appear prominently in the cuprate phase diagram