Disorder and Quantum Fluctuations in Effective Field Theories for Highly Correlated Materials

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Introduction

motivation: central aspect of many transition metal compounds: phase transitions controled by

doping

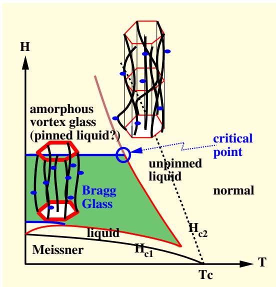
disorder effects on large length scales

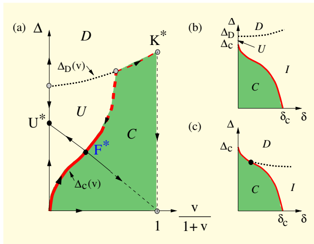
change of microscopic system parameters

so far: Classical Systems

flux-line lattice

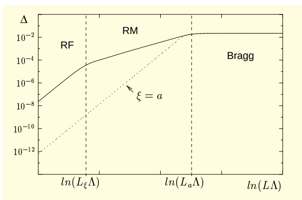
charge density waves

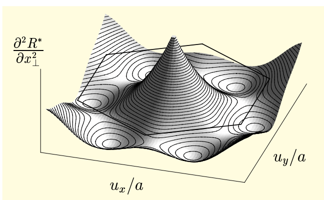




[Emig & Nattermann, PRL **79**, 5090 (1997); Emig & Nattermann, PRL **81**, 1469 (1998)]

Results: new phases and phase transitions, e.g. Bragg-Glass phase with QLRO and non-universal critical exponents



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Vortex-glass phases in type-II superconductors

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Abstract

A review is given on the theory of vortex-glass phases in impure type-II superconductors in an external field. We begin with a brief discussion of the effects of thermal fluctuations on the spontaneously broken U(1) and translation symmetries, on the global phase diagram and on the critical behaviour. Introducing disorder we restrict ourselves to the experimentally most relevant case of weak uncorrelated randomness which is known to destroy the long-ranged translational order of the Abrikosov lattice in three dimensions. Elucidating possible residual glassy ordered phases, we distinguish between *positional* and *phase-coherent vortex glasses*. The study of the behaviour of isolated vortex lines and their generalization—directed elastic manifolds—in a random potential introduces further important concepts for the characterization of glasses. The discussion of *elastic* vortex glasses, i.e. topologically ordered dislocation-free positional glasses in two and three dimensions occupy the main part of our review. In particular, in three dimensions there exists an elastic vortex-glass phase which still shows quasi-long-range translational order: the 'Bragg glass'. It is shown that this phase is stable with respect to the formation of dislocations for intermediate fields. Preliminary results suggest that the Bragg-glass phase may not show phase-coherent vortex-glass order. The latter is expected to occur in systems with weak disorder only in higher dimensions (or for strong disorder, as the example of unscreened gauge glasses shows). We further demonstrate that the linear resistivity vanishes in the vortex-glass phase. The vortex-glass transition is studied in detail for a superconducting film in a parallel field. Finally, we review some recent developments concerning driven vortex-line lattices moving in a random environment.

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[Emig, Bogner & Nattermann, PRL **83**, 400 (1999); Bogner, Emig & Nattermann, PRB **63**, 174501 (2001)]

Future: Highly Correlated Fermi-Systems with Disorder

Universal properties depend mainly on symmetries and dimensions

$\rightsquigarrow$ detailed knowledge of microscopic mechanisms and parameters is not necessary

Starting point: effective field theories

- allow to classify the mechanisms
- describe fluctuations of collective modes
- allow to deal with disorder in an appropriate way

For the present we concentrate on **effective theories** for stripe phases.

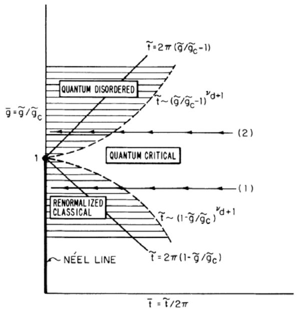
Effective Field Theories: an Example

$$\hat{\mathcal{H}}_{\text{Hubbard}} = -t \sum_{\langle i,j \rangle, \sigma} \hat{c}^{\dagger}_{i\sigma} \hat{c}_{j\sigma} + U \sum_{i} \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}$$

- for $t \ll U$ mapping on t–J–model with $J \sim \frac{t^2}{U}$
- antiferromagnetism of the Cu–layers is described by a quantum–nonlinear–σ–model

$$S_{\text{eff}}/\hbar = \frac{\rho_s^0}{2\hbar} \int_0^{\beta\hbar} d\tau \int d^d x \left[|\nabla \cdot \mathbf{\Omega}|^2 + \frac{1}{c^2} \left| \frac{\partial \mathbf{\Omega}}{\partial \tau} \right|^2 \right]$$

$\rightarrow S(\mathbf{k}, \omega)$ of La_2CuO_4

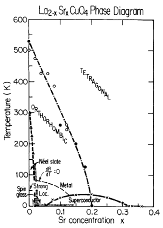


$\tilde{g} = g/g_0$
$g_0 = \hbar c/\rho_s^0$
$\rho_s^0 \sim J$
$d = 2$

[Chakravarty, Halperin & Nelson, PRL **60**, 1057 (1988)]

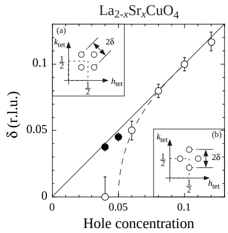
Experimental Researches

Generic
Phase-diagram:



[1]

Experimental Evidence for
Stripe Phases:



[2]

Nickelates:

La_2NiO_4 diagonal static SDW (Tranquada et al. '94, Shirane et al. '95)
$La_{2-x}Sr_xNiO_4$ for $0 < x < 1/2$ diagonal static CDW and SDW, $T^{CDW} > T^{SDW}$ (Yoshinari, Hammel, Cheong '99)

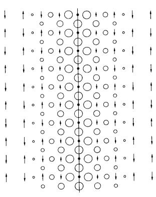
Manganates:

$La_{0.5}Ca_{0.5}MnO_3$ static CDW (Mori/Chen/Cheong '98, Uehara/Mori/Chen/Cheong '99)
$La_{1-x}Sr_{1+x}MnO_4$ static CDW for $0.5 < x < 0.65$ (Larochelle et al.)
$La_{2-2x}Sr_{1+2x}Mn_2O_7$ short range charge stripe order for $x \backsimeq 0.40$ (Vasiliu-Doloc et al.)
$La_{0.9}Sr_{0.1}Mn0_3$ static CDW (Vigliante et al.)

Cuprates:

$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ static SDW (Tranquada et al. '95, Imai, Hunt, Singer), most clear at $x = 1/8$; static CDW for $x < 0.2$ (Niemöller et al.); *strong competition with SC*
$La_{2-x-y}Eu_ySr_xCuO_4$ static stripes for $0.08 < x < 0.17$ (Kataev, Validov, Büchner, Hücker, Berg)
$La_{2-x}Sr_xCuO_4$ dynamic SDW and CDW (Cheong, Aeppli, Mason, Mook '91, Yamada et al.); *coexistence with SC*
$YBa_2Cu_3O_{6+x}$ dynamic SDW and CDW (Mook et al. '98, Egami); *coexistence with SC*

Phenomenological stripe picture: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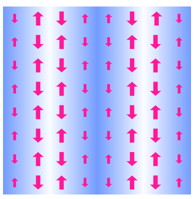
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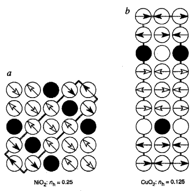
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Preparatory Work

Structure

skip competetive pinning of stripes by disorder and crystal potential
CDW- and SDW-period depend on doping:
z.B. $\frac{1}{8}$-problem lock-in phenomenon?

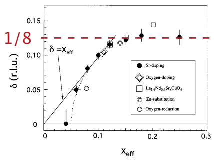
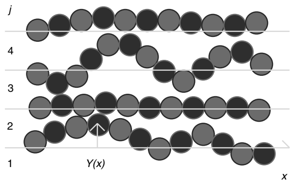


FIG. 7. Sr-doping dependence of the incommensurability of the spin fluctuations.

[6]



[7]

Model:
Stripes as lattice of fluctuating quantum strings with disorder (induced by doping) and crystal potential

$$
\begin{aligned}
\rho(\mathbf{r},\tau) &\simeq \frac{1}{a}\Big\{\sum_m e^{iQ_m[x-u(\mathbf{r},\tau)]} - \partial_x u(\mathbf{r},\tau)\Big\} \\
\mathcal{S} &= \frac{1}{\hbar}\int_0^{\hbar/T} d\tau \left\{\int d^2r\, \frac{\mu}{2}(\partial_\tau u)^2 + \mathcal{H}\right\}. \\
\mathcal{H}_{\text{el}} &= \int d^2r\, \frac{\gamma}{2}(\boldsymbol{\nabla} u)^2, \\
\mathcal{H}_U &= \int d^2r\, \rho(\mathbf{r})U(x), \\
\mathcal{H}_V &= \int d^2r\, \rho(\mathbf{r})V(x,y)
\end{aligned}
$$

Results of RG-analysis:

- disorder relevant, dominates quantum fluctuations
- implies glassy dynamics
- in 2D: disorder destroys translational order
- lock-in only possible with 3D coupling

[Bogner & Scheidl, Phys. Rev. B **64**, 054517 (2001)]

Magnetism

Motivation:
Focus on the low doping regime. Investigation of the stability of AFM against doping; Description of the AFM → spin glass transition.

Model:
Holes are located on bonds, AFM → FM exchange couplings
⇝ frustration, Heisenberg spin glass [8]

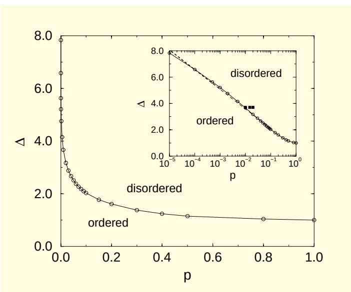
$$H = \frac{1}{2}\sum_{\mathbf{r},i} J_i(\mathbf{r})\,[\nabla_i \vec{S}(\mathbf{r})]^2 \qquad \begin{aligned} J_i(\mathbf{r}) &= [1-\Delta_i(\mathbf{r})]J \\ \Delta_i(\mathbf{r}) &= \begin{cases} \Delta & \text{with probability } p, \\ 0 & \text{with probability } 1-p. \end{cases} \end{aligned}$$

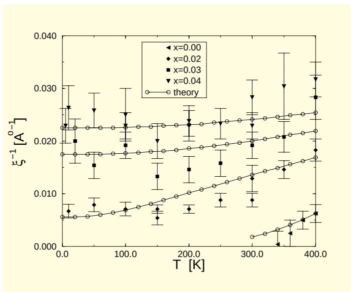
RG approach (symmetries are preserved, quenched nature of defects)

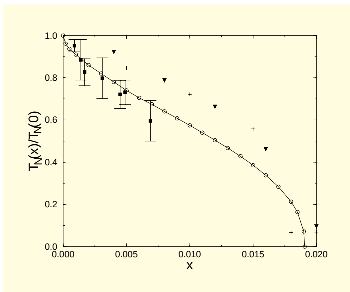
$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}\ell} j_\ell &= (d-2)j_\ell - \frac{N-2}{\Lambda^2/d}t - \frac{4\Delta^2}{j_\ell}\hat{R}''_\ell(0), \\ \frac{\mathrm{d}}{\mathrm{d}\ell}\hat{R}_\ell(\phi) &= d\hat{R}_\ell(\phi) - (2 + \frac{N-2}{\Lambda^2/d}\frac{t}{j_\ell})\phi\hat{R}'_\ell(\phi) \\ &\quad + \frac{2\Delta}{j_\ell}\phi[\hat{R}''_\ell(\phi) - \hat{R}''_\ell(0)]. \end{aligned} \qquad \begin{aligned} t &= T/J \\ \phi &= \frac{\Delta}{t}\sum_{\alpha=1}^{n}[\nabla_i \vec{S}^\alpha(\mathbf{r})]^2 \\ j_0 &= 1 - p\Delta \\ \hat{R}_0(\phi) &= \ln\left[1-p+p\,e^{\phi/2}\right] - \frac{1}{2}p\phi \end{aligned}$$

Results:

- 2D phase diagram at $T=0$
- Calculation of the $2D$ correlation-length $\xi(T, x=2p)$
- Include 2D/3D crossover → phase-boundary in qualitative agreement to experiments







[Krüger & Scheidl, cond-mat 0110061 (2001)]

Localization in coupled Luttinger liquids with impurities

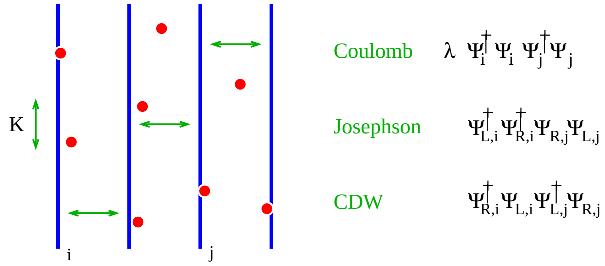
striped phases in Mott insulators:
electronic liquid crystal phases,
"smectic metal" (SM)
⇝ 2D non-Fermi liquid [7]

without disorder:

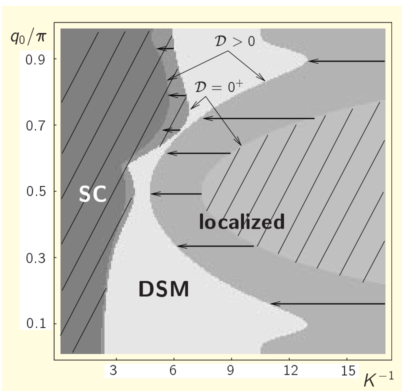
- SM phase strongly limited by inter-stripe CDW and SC [9].

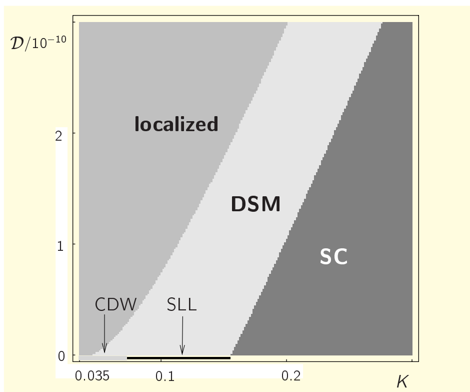
with disorder:

- weak CDW couplings between stripes irrelevant, relevance of SC couplings reduced
  ⇝ renormalized 1D system
- delocalization transition possible even for repulsive interaction
- new phase: delocalized smectic metal, DSM, Luttinger-like longitudinal transport, short-ranged longitudinal and transversal order



$$
\begin{aligned}
S^0 &= \frac{1}{2\pi}\sum_j \int_{x\tau} \Big[v_J(\partial_x\Theta_j)^2 + v_N(\partial_x\Phi_j)^2 \\
&\quad -2i\partial_\tau\Phi_j\partial_x\Theta_j + \gamma v_J^{-1}(\partial_\tau\Phi_j)^2 \Big] \\
S^{\mathrm{fw}} &= -\frac{\sqrt{2}}{\pi}\sum_j \int_{x\tau} \eta_j(x)\partial_x\Phi_j, \\
S^{\mathrm{bw}} &= \frac{1}{\pi\alpha}\sum_j \int_{x\tau} \left\{ \xi_j(x) e^{i(\sqrt{2}\Phi_j - 2k_{\mathrm{F}}x)} + \mathrm{h.c.} \right\}. \\
S^V &= \frac{1}{2\pi}\sum_{i\neq j} \int_{x\tau} \partial_x\Phi_i V_{i-j}\partial_x\Phi_j. \\
S^{\mathrm{CDW}} &= \sum_{i\neq j} \mathcal{C}_{i-j} \int_{x\tau} \cos\left[\sqrt{2}(\Phi_i - \Phi_j)\right], \\
S^{\mathrm{SC}} &= \sum_{i\neq j} \mathcal{J}_{i-j} \int_{x\tau} \cos\left[\sqrt{2}(\Theta_i - \Theta_j)\right].
\end{aligned}
$$





[Bogner, Emig & Scheidl, cond-mat 0110265 (2001)]

Low temperature behavior of one-dimensional quantum systems

CDWs, superfluids, Luttinger Liquids

$$\hat{\mathcal{H}} = \int_0^L \left\{ \frac{c}{2}\left[\left(\frac{v}{c}\right)^2 \hat{P}^2 + (\partial_x \hat{\varphi})^2\right] + U(x)\rho(x) + W\cos\left(\frac{q\pi}{\hbar}\int^x dy\, \hat{P}(y)\right)\right\}$$

dimensionless parameters

$$t = T\Lambda^{d-2}K_d/c,\;\; K = \hbar v \Lambda^{d-1}K_d/c,\;\; u^2 = U^2\Lambda^{d-4}K_d/c^2,\;\; w = WK_d/c\Lambda^2$$

disorder fluctuations

$$\frac{dK}{dl} = \left[-\frac{p^4u^2}{2}\coth\frac{K}{2t}B_0(p^2K,\frac{K}{2t})\right]K$$

$$\frac{dt}{dl} = t$$

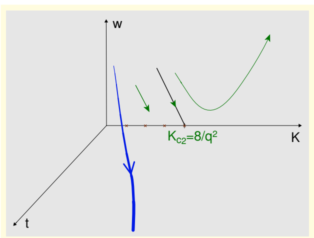
$$\frac{du^2}{dl} = \left[3 - \frac{p^2K}{2}\coth\frac{K}{2t}\right]u^2$$

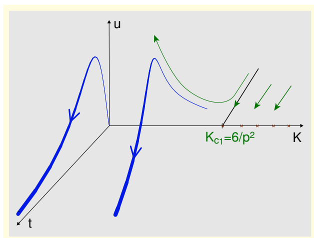
quantum phase slips

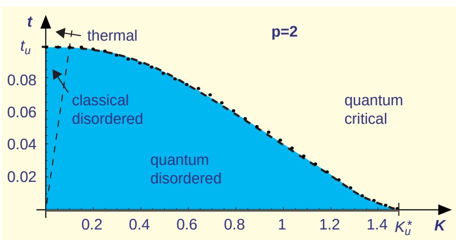
$$\frac{dK}{dl} = \left[-\frac{\pi}{2}\frac{q^2w^2}{K^4}\coth\frac{K}{2t}B_2\left(\frac{q^2}{K},\frac{K}{2t}\right)\right]K$$

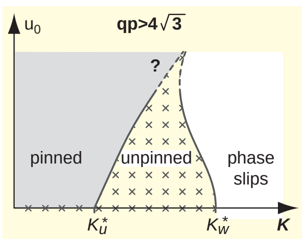
$$\frac{dt}{dl} = \left[1 - \frac{\pi}{2}\frac{q^2w^2}{K^4}\coth\frac{K}{2t}B_1\left(\frac{q^2}{K},\frac{K}{2t}\right)\right]t$$

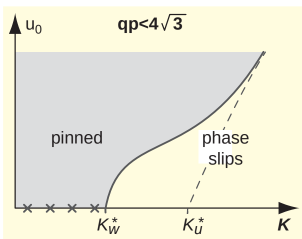
$$\frac{dw}{dl} = \left[2 - \frac{q^2}{4K}\coth\frac{K}{2t}\right]w$$











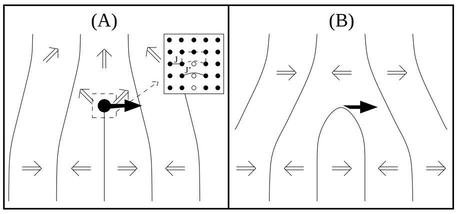
numerical calculated cross-over phase diagram for disordered 1D CDWs

combined influence of disorder and quantum phase slips ($T = 0$)

[Glatz & Nattermann, cond-mat 0202507 (2001)]

Future Projects

- analysis of disorder effects in effective models for stripe phases, in particular in coupled Luttinger-Liquids systems as electronic models for stripe phases
- interplay between charge and spin order in consideration of quantum fluctuations and planar anisotropie; spin/charge separation
- effects of topological defects [Krüger & Scheidl, cond-mat 0203354 (2002)]



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- non equilibrium properties
- methodically related projects: disordered Wigner–Crystals, vortex lattices, Quantum-Hall Stripe Phase, scattering between Quantum-Hall edges

Cooperations in SFB 608

B1: transport measurements $\rightsquigarrow$ electronic properties of stripe phases

B3: temperature dependence of transport properties
$\rightsquigarrow$ search of Non-Fermi-Liquid behavior; susceptibility measurements
$\rightsquigarrow$ magnetic order

C2: neutron scattering $\rightsquigarrow$ structural aspects of stripe phases

D1: microscopic fundamentals of effective field theories

D5: numerical studies of electronic properties

D6: gauge theoretical models of strongly fluctuating magnets

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