Correlated lattice fermions in a spin-dependent random potential

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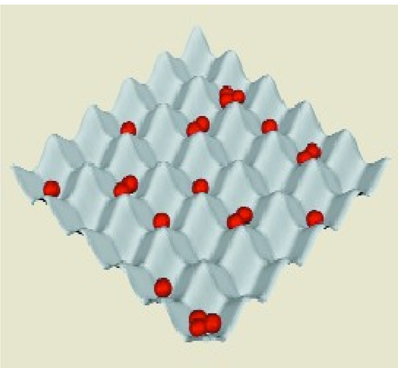
Motivation and aims

Neutral particles in optical lattices can emulate behaviour of electrons in true materials



I. Bloch, Phys. World 17, 25 (2004)

Interacting electrons in materials

Strongly correlated materials

Hubbard model (1963):

Electron correlations in narrow energy bands

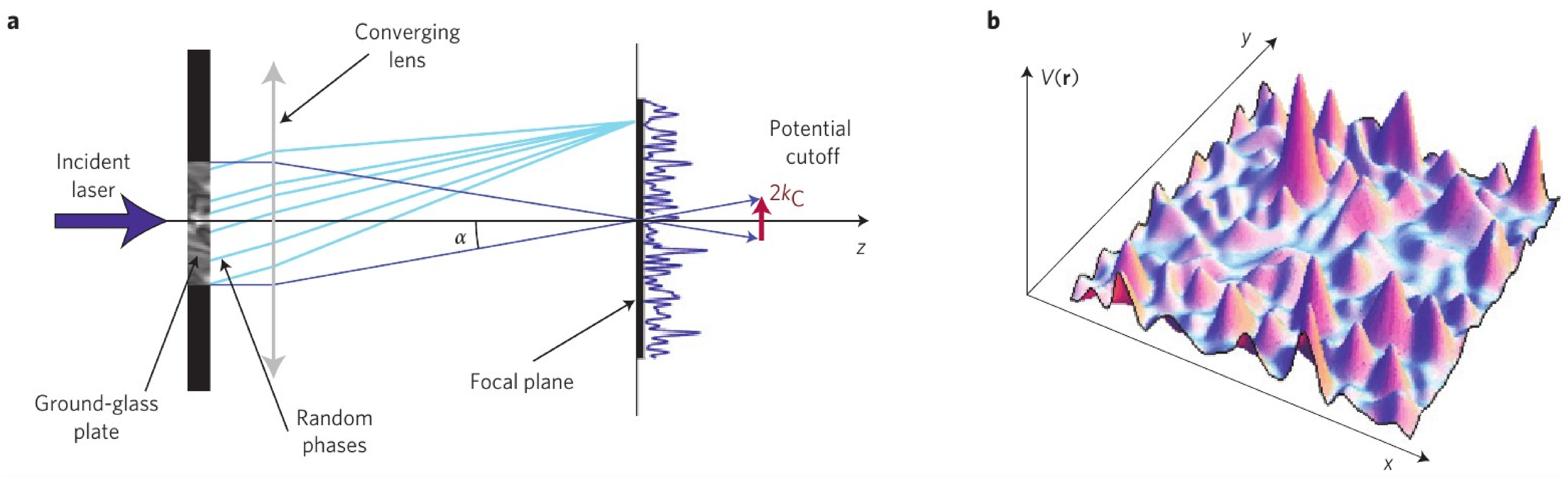
By J. Hubbard

that a possible approximation is to neglect all the integrals (8) apart from I. If this approximation, the validity of which is discussed in greater detail below, is made, then the Hamiltonian of (6) becomes

$$H = \sum_{i,j}\sum_{\sigma} T_{ij} c^{\dagger}_{i\sigma} c_{j\sigma} + \tfrac{1}{2} I \sum_{i,\sigma} n_{i\sigma} n_{i,-\sigma} - I \sum_{i,\sigma} \nu_{ii} n_{i\sigma}, \qquad (10)$$

Neutral particles in an optical lattice appeared to be a very good realization of the Hubbard model of particles in a crystal – quantum simulation of the Hubbard model.

Optical lattice with disorder



L. Sanchez-Palencia, M. Lewenstein, Nature Phys. 6, 87 (2010)

Spin-dependent lattices first proposed:

D. Jaksch, H. Briegel, J. Cirac, C. Gardiner, and P. Zoller, Phys. Rev. Lett. 82, 1975 (1999)

Spin-dependent lattices first implemented:

O. Mandel, M. Greiner, A. Widera, T. Rom, T. Hänsch, and I. Bloch, Nature (London) 425, 937 (2003)

P. Soltan-Panahi, J. Struck, P. Hauke, A. Bick, W. Plenkers, G. Meineke, C. Becker, P. Windpassinger, M. Lewenstein, and K. Sengstock, Nat. Phys. 7, 434 (2011)

also: D. McKay, B. DeMarco, New J. Phys. **12**, 055013 (2010)

- disorder in lattice realized
- spin-dependent lattice realized

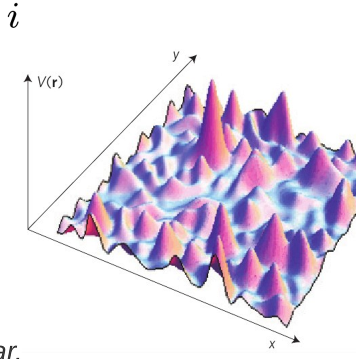
Spin-dependent disorder in optical lattice possible to realize (beyond standard solid state physics)

Comprehensive thermodynamics?

Hubbard model with spin-dependent disorder

$$H = t\sum_{(i,j)}\sum_{\sigma=\uparrow,\downarrow} \hat{c}^{\dagger}_{i\sigma}\hat{c}_{j\sigma} + \sum_{i}\sum_{\sigma=\uparrow,\downarrow} \epsilon_{i\sigma}\hat{n}_{i\sigma} + \sum_{i} U\hat{n}_{i\uparrow}\hat{n}_{i\downarrow} \qquad \hat{n}_{i\sigma} \equiv \hat{c}^{\dagger}_{i\sigma}\hat{c}_{i\sigma}$$

Disorder in the model:
- comes through diagonal terms
- quenched disorder

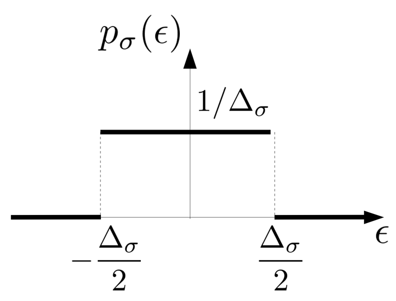


Similar model: R. Nanguneri, M. Jiang, T. Cary, G.G. Batrouni, and R.T. Scalettar, Phys. Rev. B 85, 134506 (2012)

but: U<0, Bogolubov de Gennes mean field theory

Uncorrelated rectangular probability distribution function:

$$P(\epsilon_{1\uparrow}, \epsilon_{1\downarrow}, \ldots) = \prod_i p_{\uparrow}(\epsilon_{i\uparrow}) p_{\downarrow}(\epsilon_{i\downarrow})$$



Two cases investigated here and compared:

Spin-dependent disorder:	$p_{\uparrow}(\epsilon) \neq p_{\downarrow}(\epsilon)$	$\Delta_{\uparrow} = 0; \quad \Delta_{\downarrow} \equiv \Delta$
Spin-independent disorder:	$p_{\uparrow}(\epsilon) = p_{\downarrow}(\epsilon)$	$\Delta_{\uparrow} = \Delta_{\downarrow} \equiv \Delta$

Thermodynamic properties

Magnetization: $m \equiv \lim_{N_L\to\infty} \langle\langle \sum_i \hat{m}_i \rangle\rangle_{\text{dis}}/N_L$

Double occupation: $d \equiv \lim_{N_L\to\infty} \langle\langle \sum_i \hat{n}_{i\uparrow}\hat{n}_{i\downarrow} \rangle\rangle_{\text{dis}}/N_L$

Charge susceptibility: $\chi_c = \left(\frac{\partial n}{\partial \mu}\right)_T$

Magnetic susceptibility: $\chi = \left(\frac{\partial m}{\partial h}\right)_T$

Also others: $N_\sigma(\mu), \ldots$

Method: dynamical mean field theory

- W. Metzner, D. Vollhardt, Phys. Rev. Lett. 59, 121 (1987)
- A. Georges, G. Kotliar, W. Krauth, M. J. Rozenberg, Rev. Mod. Phys. 68, 13 (1996)
- M. Ulmke, V. Janis, D. Vollhardt, Phys. Rev. B 51, 10411 (1995)

Semi elliptic DOS

$$G_{00}(i\omega_n) = \int_{-\infty}^{\infty} d\epsilon \frac{D(\epsilon)}{i\omega_n - \epsilon - \Sigma(i\omega_n) + \mu}$$

$$G_{00} = \mathcal{G}_0 + \mathcal{G}_0 \Sigma G_{00}$$

$\Sigma(\omega)$ → $G_{00}(\omega)$ → $G_{00} = \mathcal{G}_0 + \mathcal{G}_0 \Sigma G_{00}$ → $\mathcal{G}_0$ → $G_{00}(\omega)$ → $\Sigma(\omega)$

$$G_{00}(\tau,\tau') = -\langle\langle c_{0\sigma}(\tau) c^{*}_{0\sigma}(\tau')\rangle_{S_{\text{eff}}[\mathcal{G}_0]}\rangle_{dis}$$

QMC Hirsch-Fye

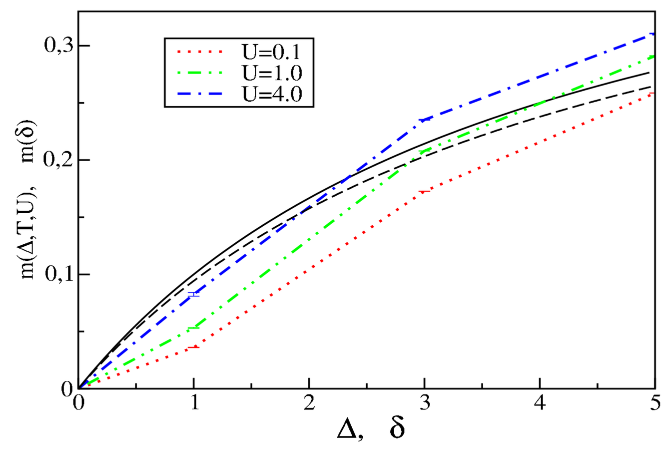
$$S_{\text{eff}} \approx \int_0^{\beta} d\tau \int_0^{\beta} d\tau' c^{*}_{0\sigma}(\tau)(\mathcal{G}_0^{-1}(\tau,\tau') - \epsilon) c_{0\sigma}(\tau') + \int_0^{\beta} d\tau U n_{0\downarrow}(\tau) n_{0\uparrow}(\tau)$$

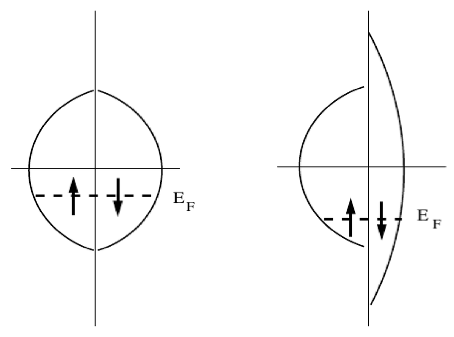
Results

Magnetization

Spin-independent disorder: $m = 0$

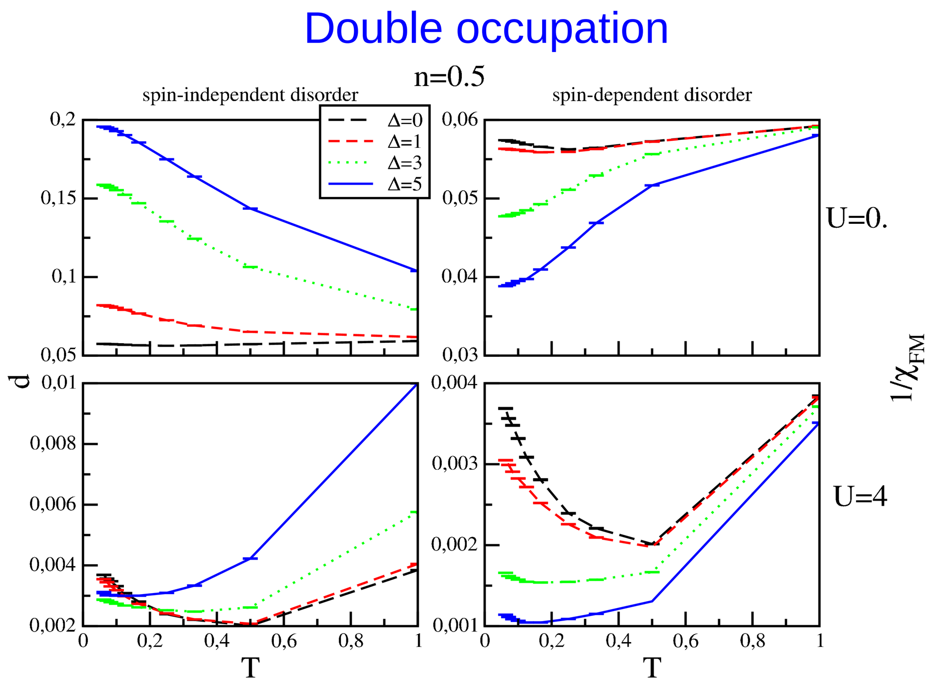
Spin-dependent disorder: n=0.5 ; T=1/16



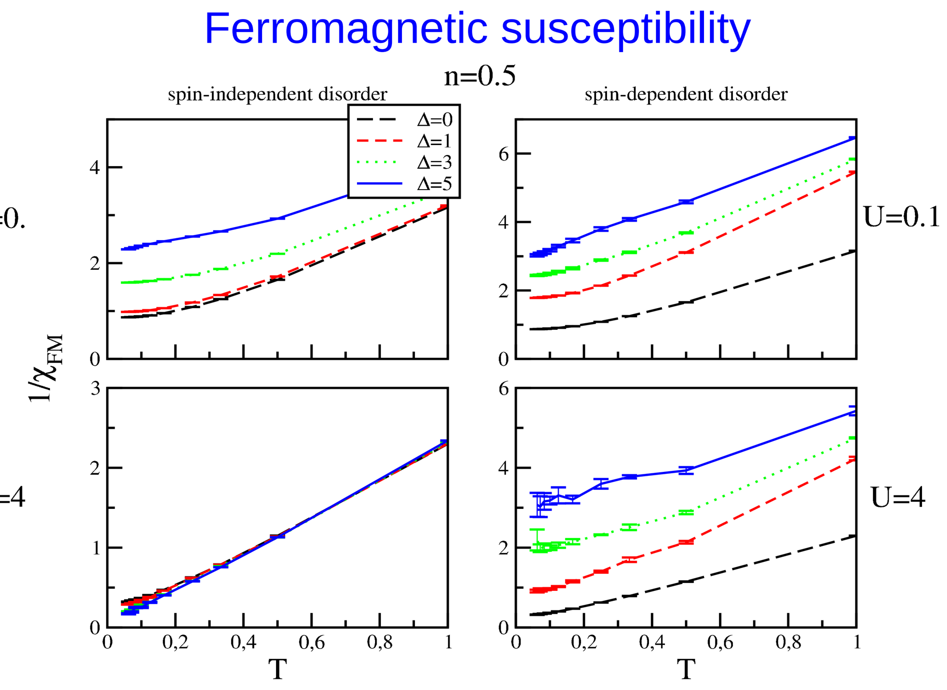


not so significant U dependence
- understanding of magnetization within non-interacting system

Double occupation



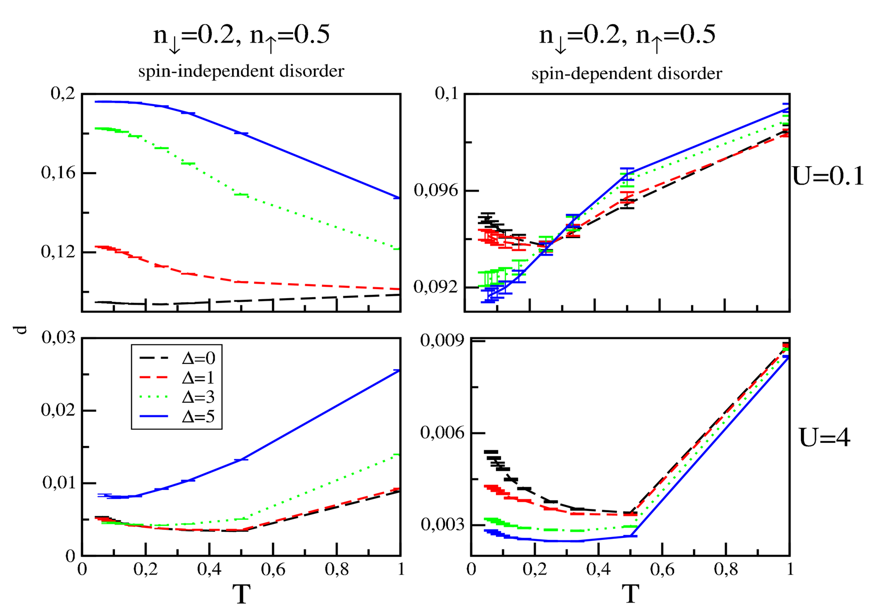
Ferromagnetic susceptibility



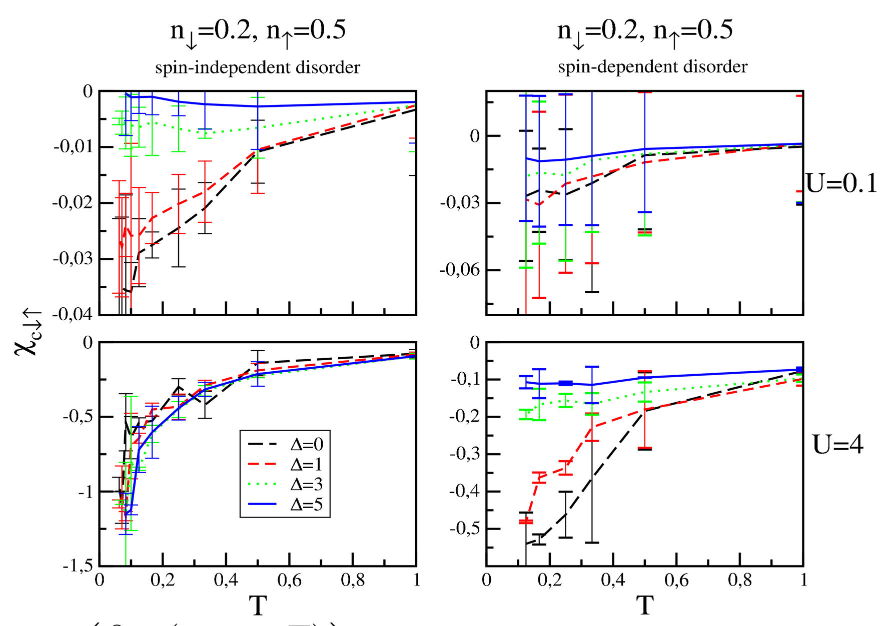
Results – spin imbalanced system

$$H = t\sum_{(i,j)}\sum_{\sigma=\uparrow,\downarrow} \hat{c}^{\dagger}_{i\sigma}\hat{c}_{j\sigma} + \sum_{i}\sum_{\sigma=\uparrow,\downarrow} \epsilon_{i\sigma}\hat{n}_{i\sigma} + \sum_i U\hat{n}_{i\uparrow}\hat{n}_{i\downarrow} - \mu_{\uparrow}\sum_i \hat{n}_{i\uparrow} - \mu_{\downarrow}\sum_i \hat{n}_{i\downarrow}$$

Double occupation



Off-diagonal compressibility



$$\chi_{c\sigma\sigma'} = \left(\frac{\partial n_\sigma(\mu_\uparrow, \mu_\downarrow, T)}{\partial \mu_{\sigma'}}\right)_T = \beta\langle\langle \hat{n}_\sigma \hat{n}_{\sigma'}\rangle - \langle \hat{n}_\sigma\rangle\langle \hat{n}_{\sigma'}\rangle\rangle_{\text{dis}}/N_L$$

Other thermodynamic properties in: K. M, J. Skolimowski, P. B. Chakraborty, K. Byczuk, D. Vollhardt, New J. Phys. **15**, 045031 (2013)

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