Quantum phases of ultracold atoms in optical lattices and magnetic microtraps

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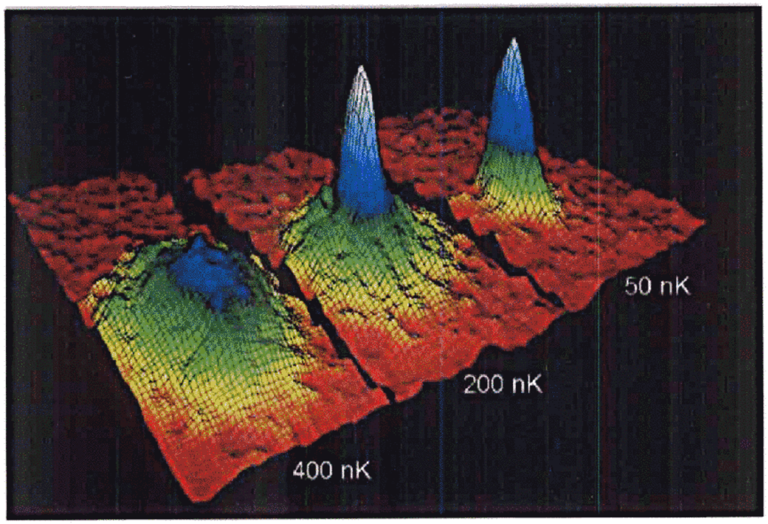
Bose-Einstein condensation of atomic gases

Anderson et.al., Science (1995)



Ultralow density condensed matter system

$n \sim 10^{14}\ cm^{-3}$

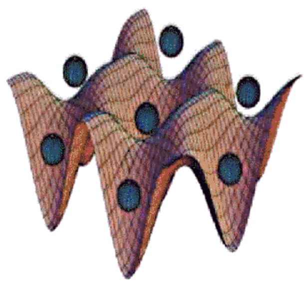
$T_{BEC} \sim 1 \mu K$

Interactions are weak and can be described theoretically from first principles

Strongly interacting bosons in optical lattices

C. Orzel et.al., Science (01); M.Greiner et.al., Nature (02)

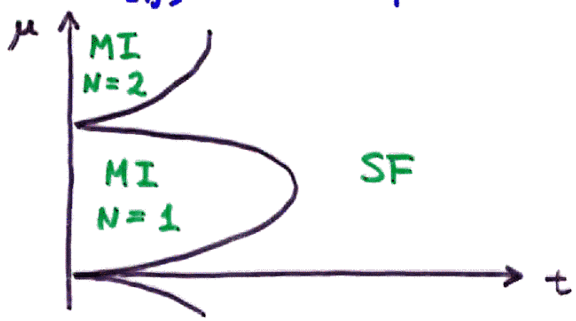
Standing wave laser fields produce
a periodic potential for atoms



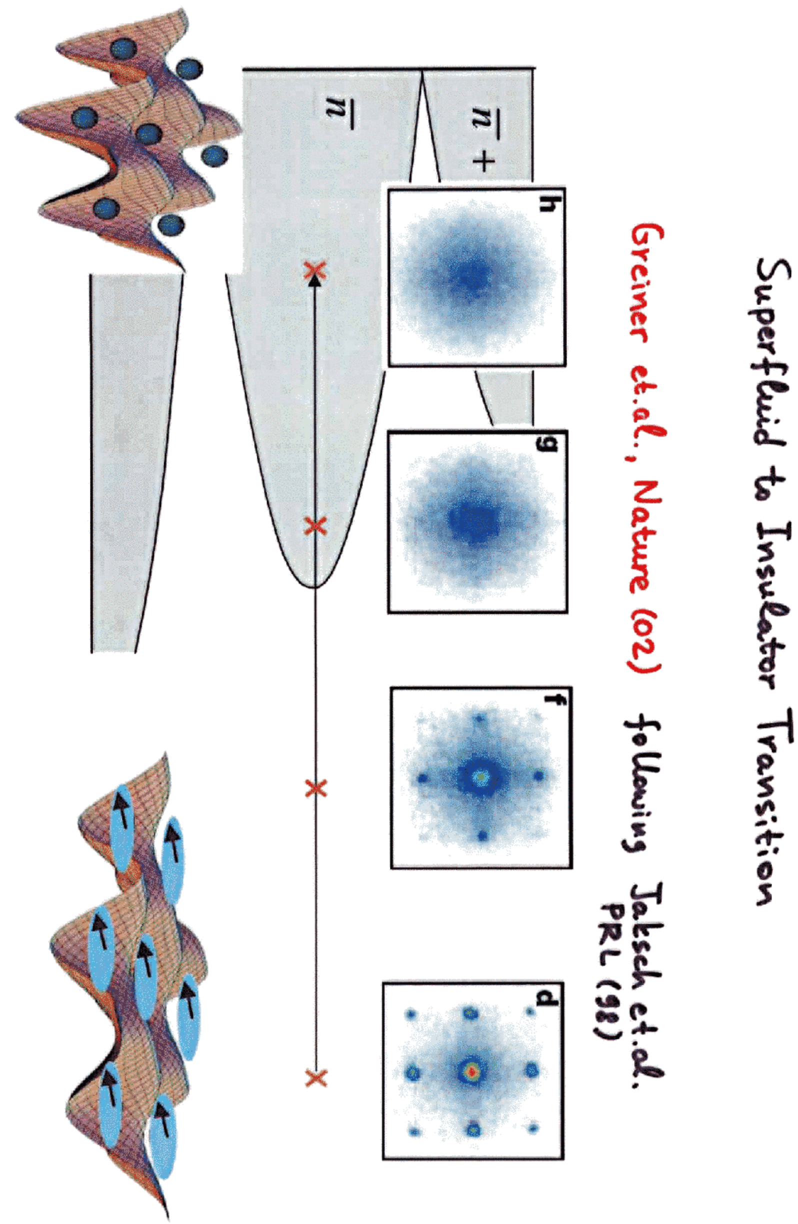
Bose Hubbard model

D. Jaksch et.al., PRL (98)

$$\mathcal{H} = -t \sum_{\langle ij \rangle} b_i^{+} b_j + U \sum_i n_i^2 - \mu \sum_i n_i$$



$Nt \gg U$ Superfluid phase
$Nt \ll U$ Mott Insulator



Outline

Two component Bose mixtures in optical lattices
Questions: Competition of several ordered phases. Fractionalized phases in $d>1$ without time reversal breaking.

Spin 1 bosons in optical lattices
Questions: Exotic spin order (nematic). Pairing in systems with repulsive interactions.

Fermions in optical lattices
Questions: Pairing of fermions with repulsive interactions. High T_c mechanism.

Boson-Fermion mixtures in 1d optical lattices
Questions: Competing orders. Polarons.

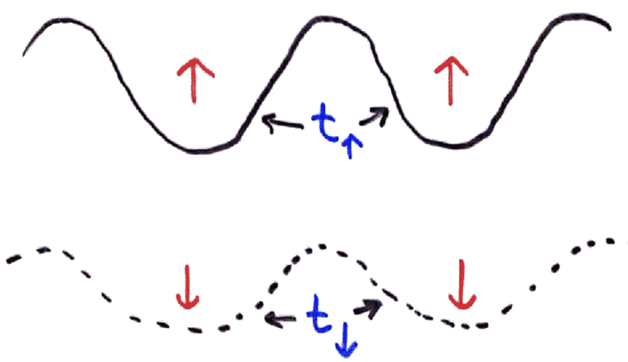
Atoms in magnetic microtraps
Questions: Interplay of disorder and interactions. Bose glass phase.

Fractional quantum Hall states of atoms in optical lattices
Questions: Charges and statistics of quasiparticles

Two component mixtures of bosonic atoms in optical lattices

Example: ^{87}Rb $\quad |\uparrow\rangle = |F=1, m_F=-1\rangle$
$|\downarrow\rangle = |F=2, m_F=-2\rangle$

Mandel et.al., Nature 2003



Two component Bose-Hubbard model

$$\mathcal{H} = -t_\uparrow \sum_{ij} a_{i\uparrow}^\dagger a_{j\uparrow} - t_\downarrow \sum a_{i\downarrow}^\dagger a_{j\downarrow}$$

$$+ U_{\uparrow\uparrow} \sum n_{i\uparrow}(n_{i\uparrow}-1) + U_{\downarrow\downarrow} \sum n_{i\downarrow}(n_{i\downarrow}-1) + U_{\uparrow\downarrow} \sum_i n_{i\uparrow} n_{i\downarrow}$$

Nature of insulating phases ?

Two component bosonic mixtures in optical lattices. Magnetic order in insulating phases

$$\mathcal{H} = -t_\uparrow \sum_{ij} a_{i\uparrow}^{+} a_{j\uparrow} - t_\downarrow \sum_{ij} a_{i\downarrow}^{+} a_{j\downarrow}$$
$$+ U_{\uparrow\uparrow} \sum_i n_{i\uparrow}(n_{i\uparrow}-1) + U_{\downarrow\downarrow} \sum n_{i\downarrow}(n_{i\downarrow}-1) + U_{\uparrow\downarrow} \sum n_{i\uparrow} n_{i\downarrow}$$

Insulating phases with $N=1$ atom per site. Average densities $n_\uparrow = n_\downarrow = 1/2$.

Easy plane ferromagnet

$$|\psi\rangle = \prod_i \left(a_{i\uparrow}^{+} + e^{i\varphi} a_{i\downarrow}^{+}\right) |0\rangle$$

Easy axis antiferromagnet

$$|\psi\rangle = \prod_{i \in A} a_{i\uparrow}^{+} \prod_{i \in B} a_{i\downarrow}^{+} |0\rangle$$

Quantum magnetism of bosons in optical lattices

XXZ magnetic systems with tunable interactions

Kuklov, Svistunov, PRL (03);

Duan, Demler, Lukin, PRL (03)

$$\mathcal{H} = J_z \sum_{ij} \sigma_i^z \sigma_j^z + J_\perp \sum_{ij} \left(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y\right)$$

$$J_z = \frac{t_\uparrow^2 + t_\downarrow^2}{2U_{\uparrow\downarrow}} - \frac{t_\uparrow^2}{U_\uparrow} - \frac{t_\downarrow^2}{U_\downarrow}$$

$$J_\perp = -\frac{t_\uparrow t_\downarrow}{U_{\uparrow\downarrow}}$$

By changing atomic and lattice properties we can manipulate

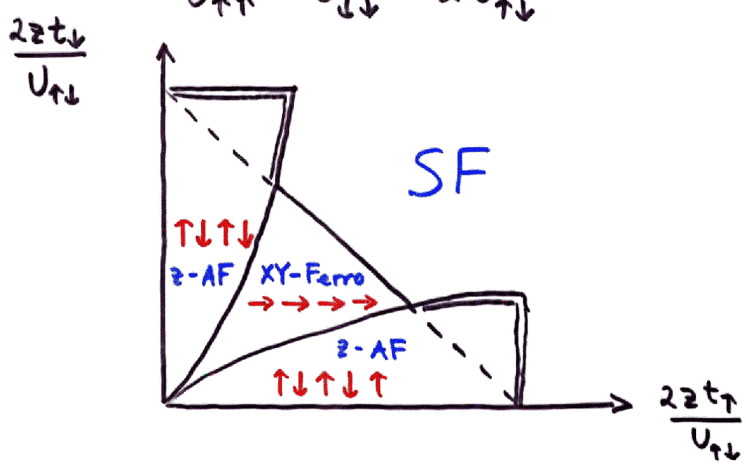
- sign of interactions
  - ferromagnetic $U_{\uparrow\downarrow} \gg U_{\uparrow\uparrow}, U_{\downarrow\downarrow}$
  - antiferromagnetic $U_{\uparrow\downarrow} \ll U_{\uparrow\uparrow}, U_{\downarrow\downarrow}$
- anisotropy
  - $|J_z / J_\perp| > 1$ easy axis
  - $|J_z / J_\perp| < 1$ easy plane

Two component mixture of Bosonic atoms in optical lattice
Phase diagram

Altman, Hofstetter, Demler, Lukin
New J. Physics (2003)

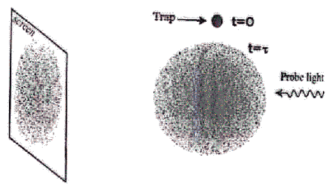
Antiferromagnetic case

$$U_{\uparrow\uparrow} = U_{\downarrow\downarrow} = 2U_{\uparrow\downarrow}$$



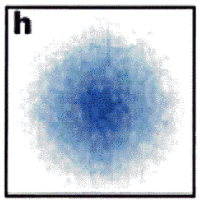
Second order coherence in the insulating state of bosons.
Hanbury-Brown-Twiss experiment for spinless bosons.

Altman, Demler, Lukin, c-m/0306226



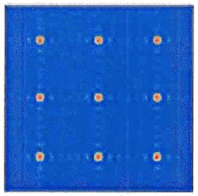
Time of flight imaging

First order coherence, $n(r)$



Second order coherence $G(r,r') = \langle n(r)\, n(r')\rangle - \langle n(r)\rangle\langle n(r')\rangle$

$$G(r,r') = A(t) \sum_G \delta\left(r - r' + \frac{\hbar t}{m} G\right)$$

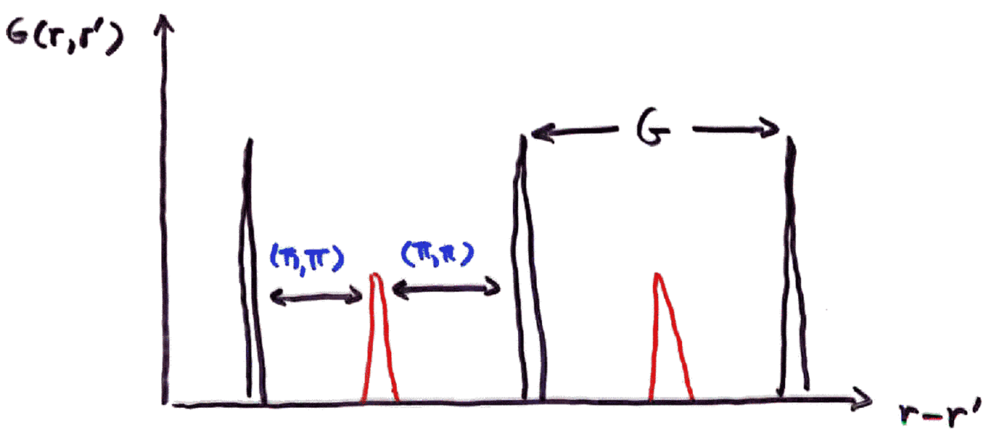


Probing spin order of bosons

Antiferromagnetic insulating state of spin-$\frac{1}{2}$ bosons

$$|\psi\rangle = \prod_{i \in A} a_{i\uparrow}^{+} \prod_{j \in B} a_{j\downarrow}^{+} |0\rangle$$

$$G(r,r') = \langle n(r)\, n(r') \rangle - \langle n(r) \rangle \langle n(r') \rangle$$

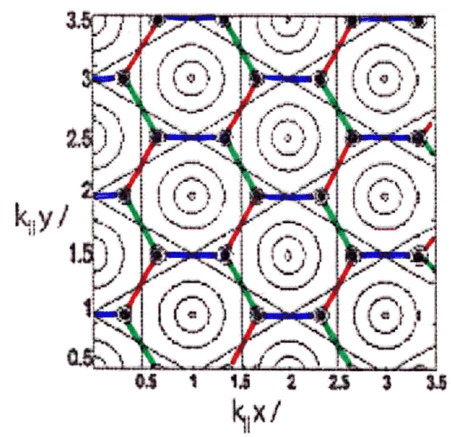


Designing exotic phases

Optical lattice in 2 or 3 dimensions:
polarization and frequencies may be different for different directions

Exactly solvable lattice model on a honeycomb lattice by Kitaev

$$\mathcal{H} = J_x \sum_{ij \in x} \sigma_i^x \sigma_j^x + J_y \sum_{ij \in y} \sigma_i^y \sigma_j^y + J_z \sum_{ij \in z} \sigma_i^z \sigma_j^z$$



- Can be created with 3 sets of standing wave light beams
- Has non-trivial topological order, anyons, ...

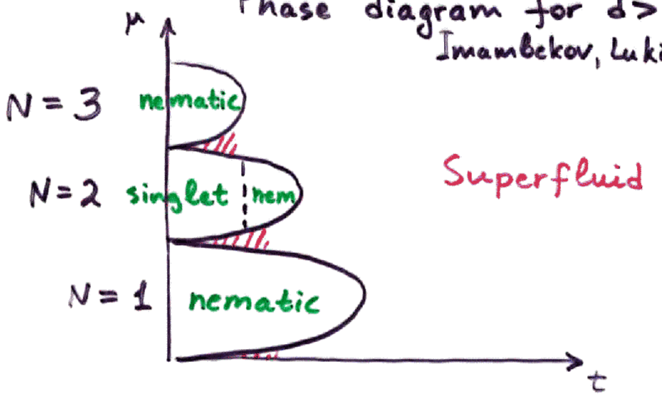
Spin F=1 atoms in optical lattices

Hubbard Hamiltonian Demler, Zhou, PRL (01)

$$\mathcal{H} = -t \sum_{ijm} a_{im}^{+} a_{jm} + U_0 \sum_i n_i^2 + U_2 \sum_i \vec{S}_i^{\,2} - \mu \sum_i n_i$$

Symmetry constraints: $N_i + S_i = \text{even}$ $\quad S_i \le N_i$

Phase diagram for $d > 1$
Imambekov, Lukin, Demler, PRA (03)



Insulating phases

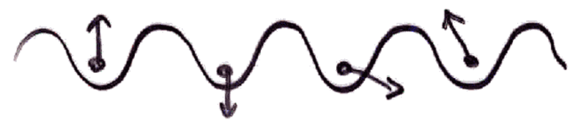
Nematic phase breaks spin rotational symmetry but not time reversal symmetry. $\langle \vec{S} \rangle = 0 \quad \langle S_a S_b \rangle \neq 0$

$$|N\rangle = \prod_i \left(n_x a_{ix}^{+} + n_y a_{iy}^{+} + n_z a_{iz}^{+} \right)^N |0\rangle$$

Spin singlet phase

$$|S\rangle = \prod_i \left(a_{ix}^{+2} + a_{iy}^{+2} + a_{iz}^{+2} \right)^{N/2} |0\rangle$$

Nematic insulating phase for N = 1



Effective S=1 spin model

$$\mathcal{H} = -J_1 \sum_{\langle ij \rangle} \vec{S}_i \vec{S}_j - J_2 \sum_{\langle ij \rangle} (\vec{S}_i \vec{S}_j)^2$$

$$J_1 = \frac{2t^2}{U_0 + U_2} \qquad J_2 = \frac{2t^2}{3(U_0+U_2)} + \frac{4t^2}{3(U_0 - 2U_2)}$$

Two site problem

S_{tot}	$\vec{S}_1 \vec{S}_2$	$(\vec{S}_1 \vec{S}_2)^2$
2	1	1
0	-2	4

Singlet state is favored when $J_2 > J_1$

Can not have singlets on neighboring bonds

Classical nematic state is a superposition of $S_{tot} = 0$ and $S_{tot} = 2$ on each bond

Singlet and nematic insulating phases for $N=2$

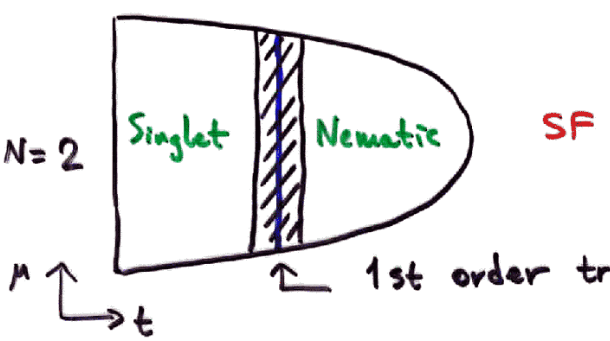
$S_i = 0$ and $S_i = 2$ states are allowed

$U_2 S_i^2$ favors $S_i = 0$

Spin exchange $(\sim t^2/U_0)$ allows "scattering"

$S_i = 0 \;\; S_j = 0 \implies S_i = 2 \;\; S_j = 2 \;\; S_i + S_j = 0$

First order singlet-nematic transition $\frac{zt^2}{U_0 U_2} \simeq \frac{1}{2}$

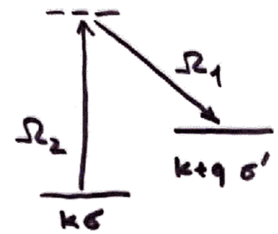


For even filling factors S-N transition

$$\frac{zN^2t^2}{U_0 U_2} \simeq 9$$

Signatures of Singlet and Nematic Phases

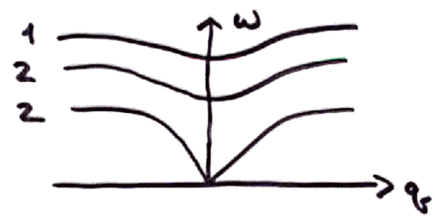
Bragg scattering from collective spin excitations



Spin singlet phase

Five-fold degenerate massive magnons

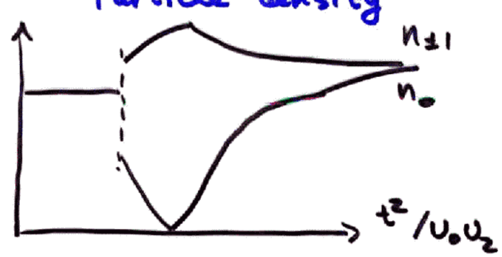
Nematic phase



Two spin waves

Three (2+1) massive amplitude modes

Particle density

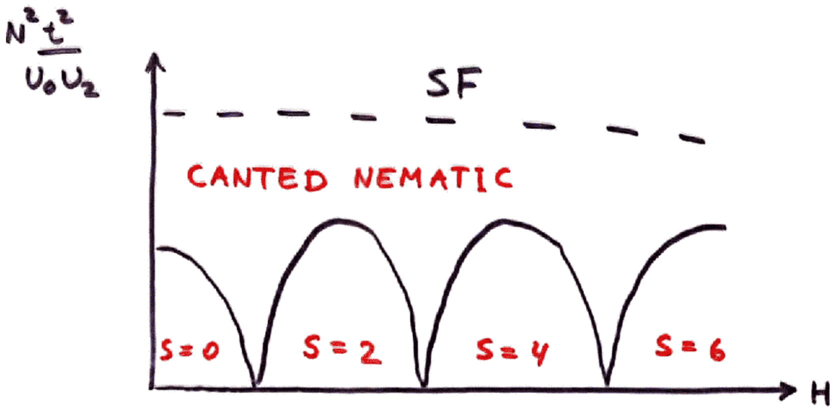


Use small mag. field to orient nematic

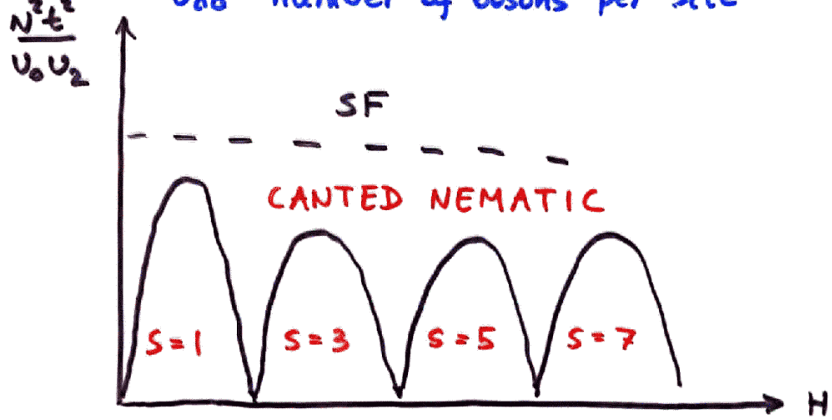
S=1 bosons in optical lattice.
Insulating phases in magnetic field

A. Imambekov, M. Lukin, E. Demler, cond-mat/0401526

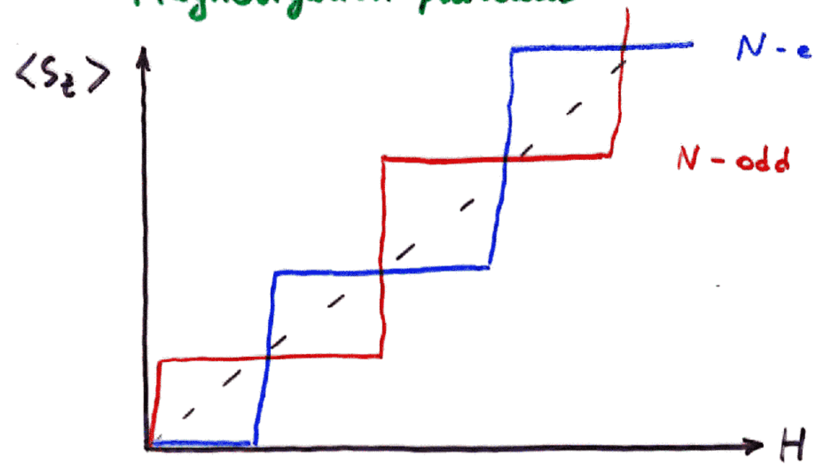
Even number of bosons per site



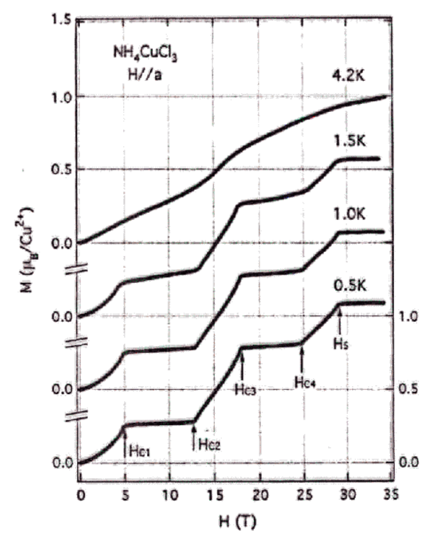
Odd number of bosons per site



S=1 bosons in optical lattice
Magnetization plateaus

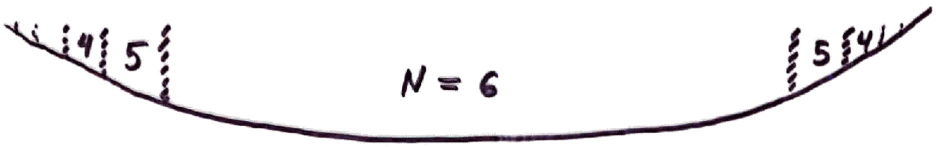


Magnetization plateaus in solid state systems

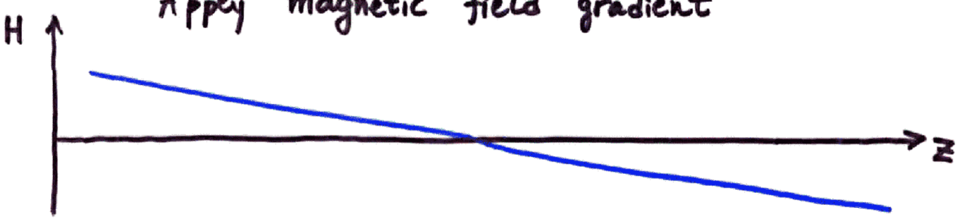


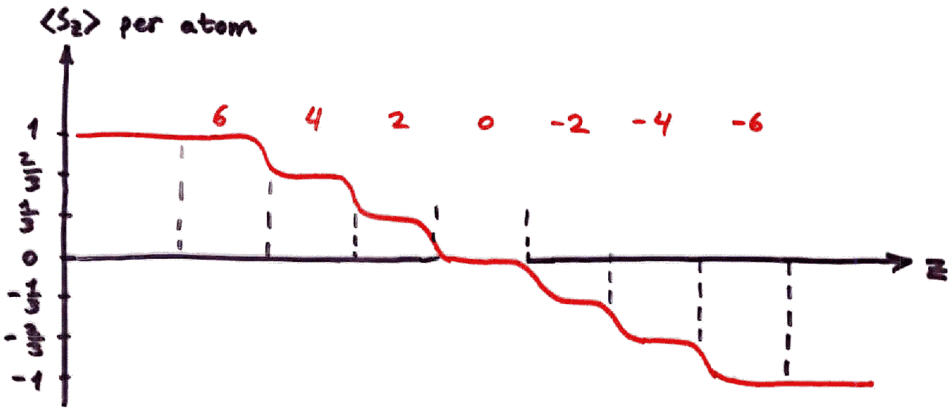
Shiramura et.al.
J. Phys. Soc. Jpn.
67 : 1549 (1998)

S=1 atoms in optical lattice
Stern-Gerlach experiments

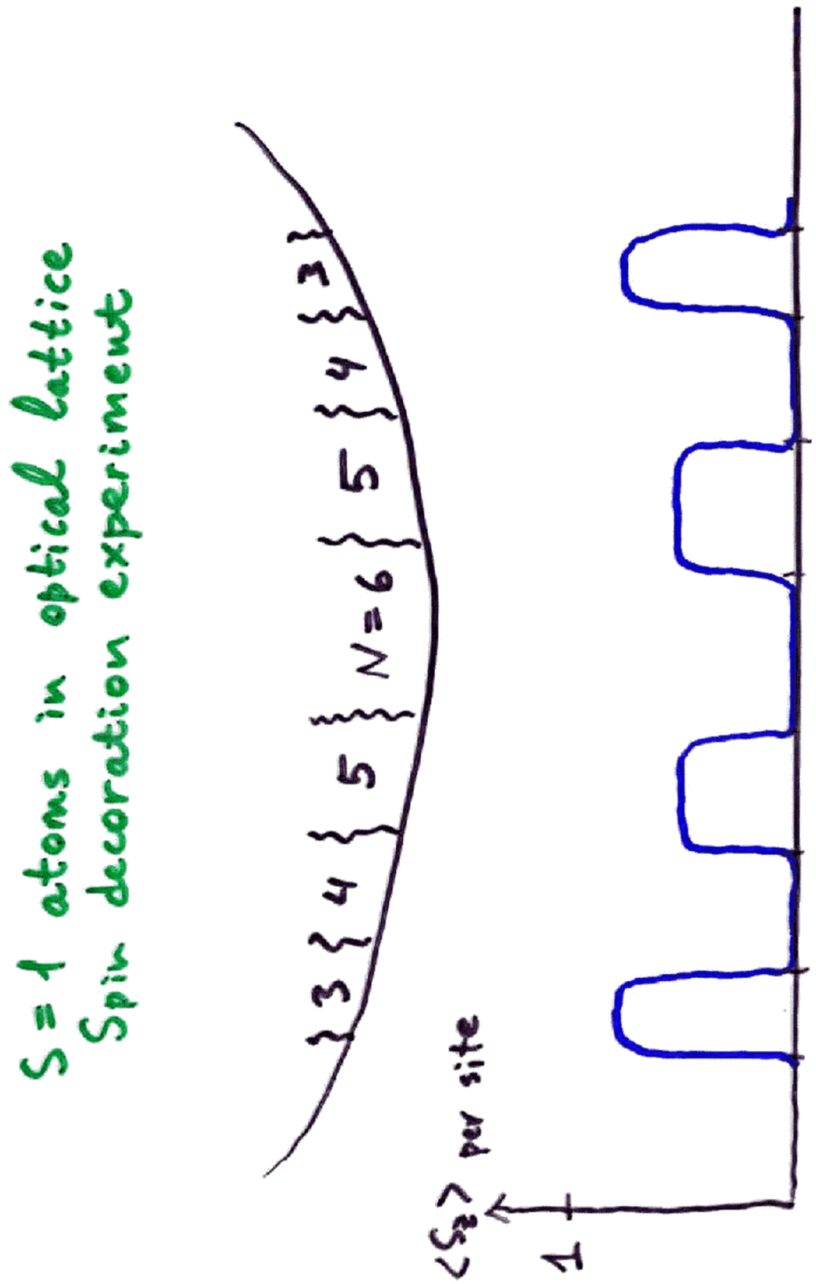


Apply magnetic field gradient





Compare to formation of spin domains for S=1 Na atoms in a single optical trap with magnetic field gradient.
Stenger et. al., Nature 1998



Enhancing superfluidity of fermionic atoms using optical lattices

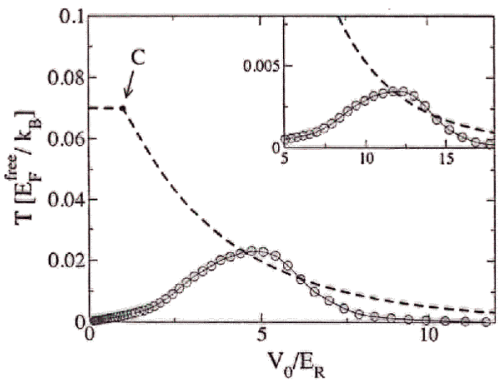
$$\mathcal{H} = -t \sum_{\langle ij \rangle \sigma} c_{i\sigma}^{+} c_{j\sigma} + U \sum n_{i\uparrow} n_{i\downarrow}$$

$t \gg |U|$ BCS regime $T_c \sim t\, e^{-7t/U}$

$t \ll |U|$ Condensation of composite Bosons $T_c \sim t^2/U$

Highest transition temperature for $t \sim U$

$$T_c^{MAX} \propto T_F^{free} \cdot \sqrt[3]{n} \ |a_s|$$



In combination with effective atomic cooling due to turning on the optical lattice

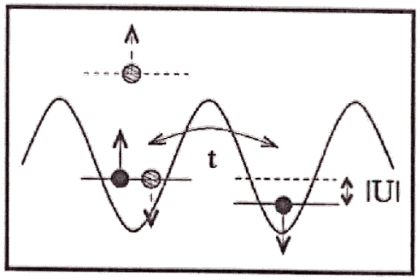
$$T_{In}^{MAX} \approx 0.1\, T_F^{free}$$

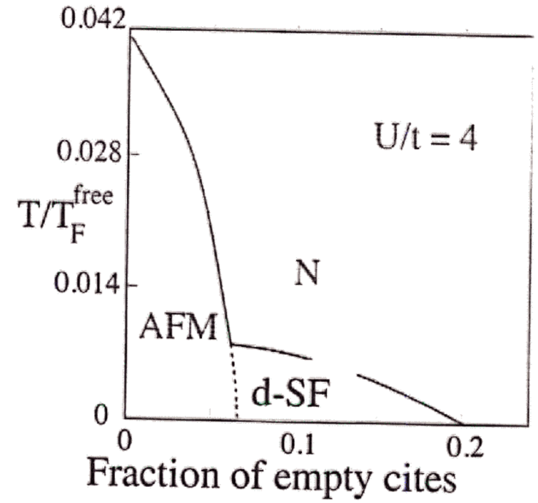
Cold atom test of high-Tc mechanism in cuprates

Cold repulsive fermions in a lattice

Effective description: Hubbard model, $U>0$

$$\mathcal{H} = -t \sum_{\langle ij \rangle \sigma} c_{i\sigma}^{+} c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$



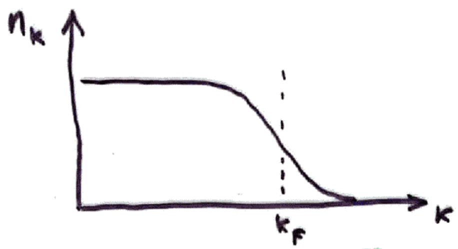


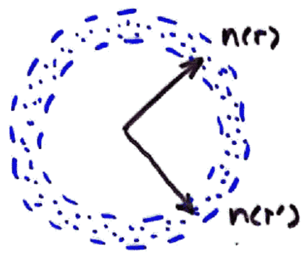
FLEX, Bickers, Scalapino '95

- Antiferromagnetic order when lattice is completely filled (1 atom per site)
- d-wave superfluidity at fractional fillings

$$(\uparrow \ \downarrow) - (\uparrow\downarrow)$$

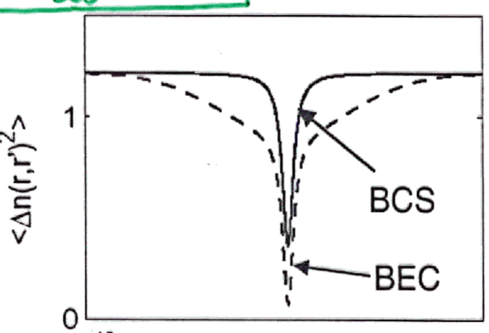
Second order interference from the BCS superfluid phase

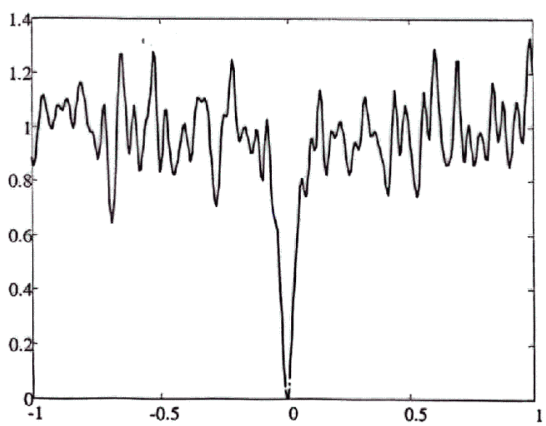




$\Delta n(r,r') = n(r) - n(r')$

$$\boxed{\Delta n(r,-r)\,|\psi_{BCS}\rangle = 0}$$





Boson-Fermion mixtures in 1d optical lattices

Mathey, Wang, Hofstetter, Lukin, Demler, quant-ph/0401151

Bosonic atoms are in the superfluid phase (high density).
They mediate interactions between fermions and provide cooling.

- spin polarized fermions
- bosons

Boson-Fermion Hubbard Hamiltonian

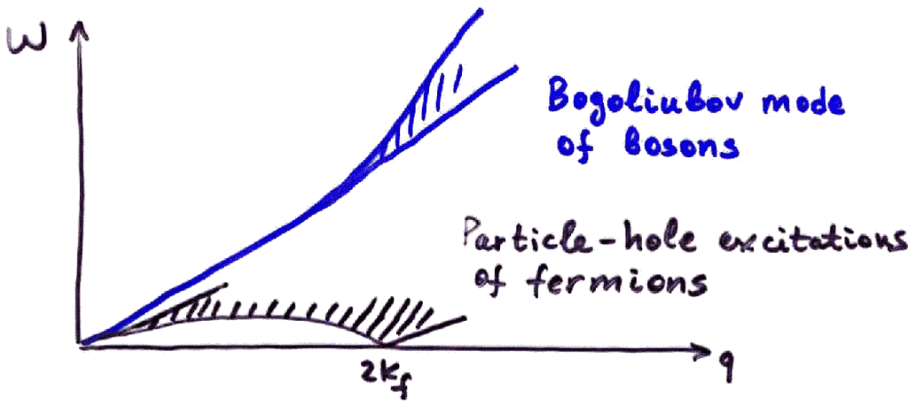
$$\mathcal{H} = -t_b \sum_{ij} b_i^\dagger b_j - t_f \sum_{ij} f_i^\dagger f_j - \mu_b \sum_i n_{bi} - \mu_f \sum_i n_{fi} + U_b \sum_i n_{bi}^2 + U_{bf} \sum_i n_{bi} n_{fi}$$

Instabilities

CDW: Periodic arrangement of fermions

Fermion pairing: Fermions bind into p-wave pairs

Polarons in Boson-Fermion mixtures

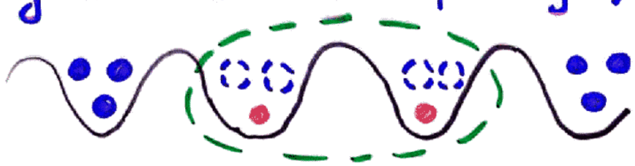


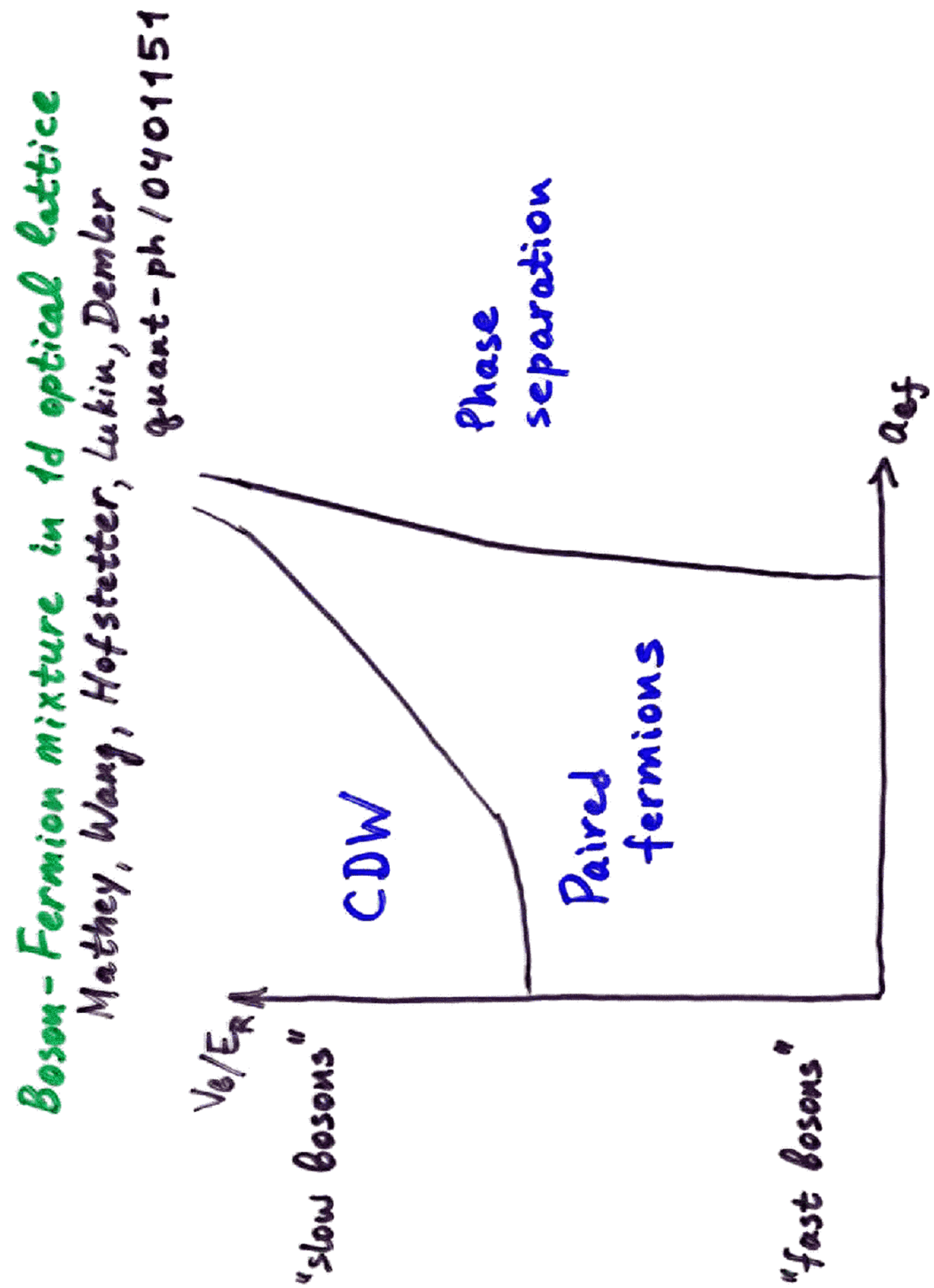
Interaction of fermions with the Bogoliubov mode of fermions is similar to electron-phonon coupling in solids.

Different order of limits $V_B \gg V_f$

Fermionic polaron:
Fermion plus a screening cloud of bosons

Pairing in BF mixtures is pairing of polarons

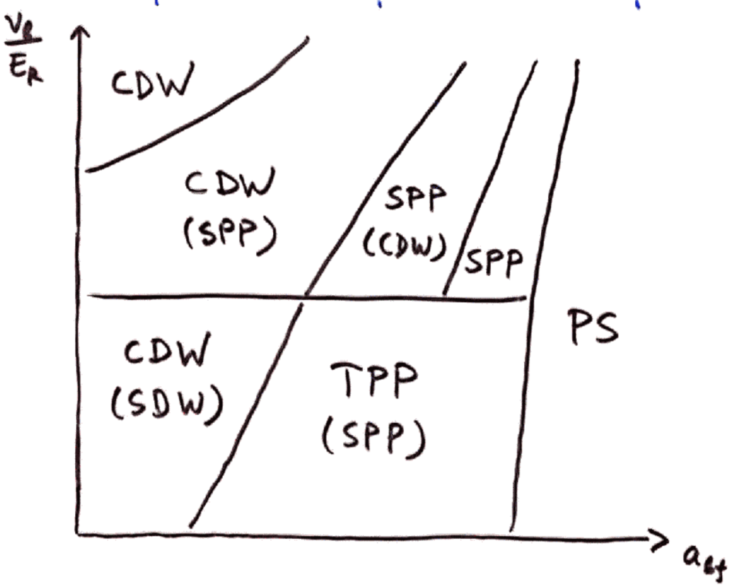




Boson-Fermion mixtures in 1d optical lattices
Spin 1/2 fermions

$$\mathcal{H} = -t_b \sum_{ij} b_i^\dagger b_j - t_f \sum_{ij\sigma} f_{i\sigma}^\dagger f_{j\sigma} - \mu_b \sum_i n_{bi} - \mu_f \sum_i n_{fi}$$

$$+ U_b \sum_i n_{bi}^2 + U_{bf} \sum_i n_{bi} n_{fi} + U_f \sum_i n_{fi\downarrow} n_{fi\uparrow}$$



PS - phase separation
SPP - singlet pairing of polarons
TPP - triplet pairing of polarons
CDW - charge density wave ($2k_f$)
SDW - spin density wave

Quantum Hall effect with ultracold atoms

Rotating condensates

N. Wilkin, J. Gunn, PRL **84**, 6 (00)
N. Cooper, N. Wilkin, PRB **60**, R16279 (99)
J. Reijnders et. al., PRL **89**, 120401 (02)

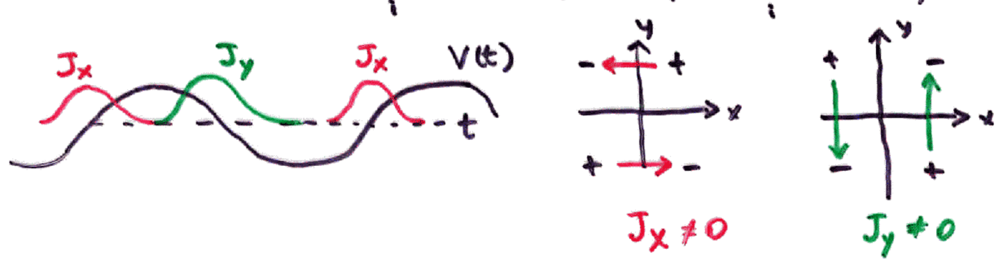
Creating effective magnetic field for neutral atoms in optical lattices

D. Jaksch, P. Zoller, New J. Phys. **5**, 56 (03)
E. Mueller, cond-mat/0404306
A. Sorensen, E. Demler, M. Lukin, cond-mat/0405079

Rotating quadrupole potential + time dependent optical lattice

$$V(x,y,t) = A \sin\omega t \cdot x \cdot y$$

$$\mathcal{H}_0 = -J_x(t) \sum_i a_i^\dagger a_{i\pm x} - J_y(t) \sum_i a_i^\dagger a_{i\pm y}$$



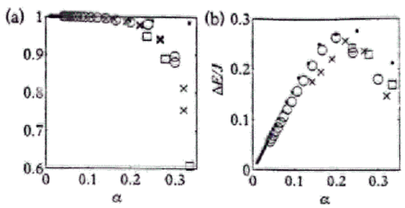
Fractional quantum Hall effect with ultracold atoms in optical lattices

Expect fractional quantum Hall phases

when $\nu = \frac{\#\text{ atoms}}{\#\text{ fluxes}} = \frac{1}{2m}$

Exact diagonalization for hard core bosons

We fix $\nu = 1/2$, α - flux density



• N = 2
o N = 3
x N = 4
□ N = 5

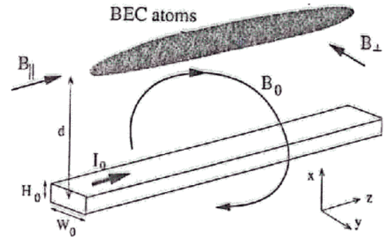
(a) - overlap with the Laughlin wavefunction

$$\psi = \prod_{i<j} (z_i - z_j)^2 \, e^{-\frac{1}{4}\sum_k |z_k|^2}$$

(b) - energy gap to the lowest excited state

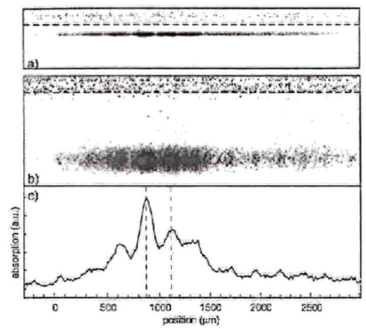
BEC in quasi one-dimensional magnetic microtrap

Thywissen et.al., Eur. Phys. J.D 7, 361 (1999)



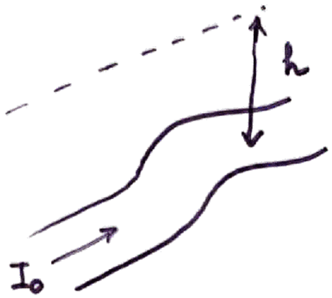
Condensate fragmentation in magnetic microtraps

Kraft et.al., J.Phys. B 35, L469 (2002)
Leanhardt et.al., PRL 89, 040401 (2002)
Fortagh et.al., PRA 66, 041604 (2002)



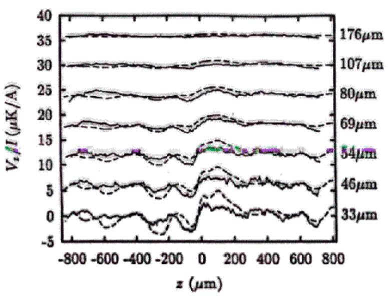
Correlated random potential in magnetic microtraps

D.W. Wang, M.Lukin, E.Demler, PRL 92, 76802 (04)



Random potential due to wire meandering

- Geometrical deformations at wavelengths smaller than h average out
- Wire width fluctuations and long wavelength deformations are not important By the Biot-Savarat law
- Lengthscale of the correlated random potential is set by the atom-wire separation, h



J. Estève et.al. physics/0403020

Probing fragmented condensates

Shaking experiments

c-m/0307402, D.W. Wang, E.D., M. Lukin

D - displacement of the confining potential

Power spectra

Summary

Two component Bose mixtures in optical lattices can be used to design spin 1/2 quantum systems. They can be used to study ferro and antiferromagnetism, fractionalized spin states.

Spin 1 Bosons in optical lattices have a rich phase diagram with several insulating and superfluid phases.

Optical lattices are an efficient tool for reaching superfluidity of fermionic atoms. Fermions with repulsive interactions can provide important insights into the origin of high temperature superconductivity (cuprates).

Boson-Fermion mixtures can be used to study formation of polarons and competition between superfluidity (BCS) and charge density wave order in 1d systems.

Fragmented condensates in magnetic microtraps can elucidate the role of disorder for interacting systems.

A combination of oscillating quadrupole potential and time dependent optical lattices can be used to create fractional quantum Hall states of ultracold atoms.