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Artificial gauge potentials for ultracold atoms in optical lattices

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Artificial gauge potential

for ultracold atoms in optical lattices

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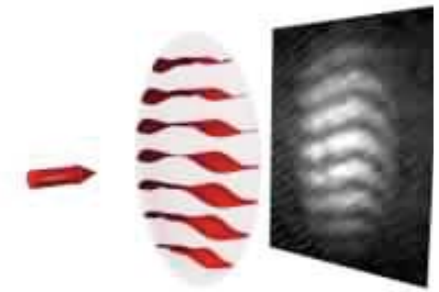
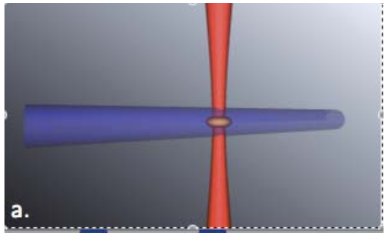
BEC group at ENS

Group leader : Jean Dalibard



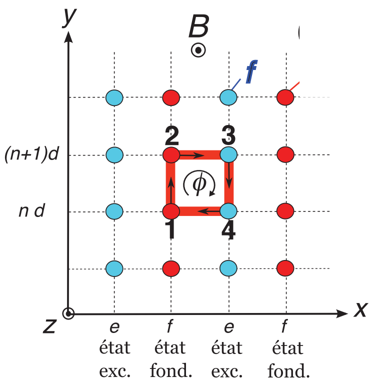
Rubidium experiment : 2D physics, vortices

L. Chomaz, R. Desbuquois, J. Leonard, C. Weitenberg, T. Yefsah, J. Beugnon, J. Dalibard



Sodium experiment : spinor condensates

V. Corre, L. DeSarlo, D. Jacob, E. Mimoun, L. Shao, J. Dalibard, F. Gerbier



Ytterbium experiment : artificial gauge fields with optical lattices condensates

A. Dareau, D. Döring, S. Krinner, J. Beugnon, J. Dalibard, F. Gerbier

Outline

1. Sodium experiment : thermodynamics of polar spinor condensates

2. Artificial gauge fields for ultracold atoms

- Quantum Hall Effect
- From rotations to laser-induced artificial magnetism
- Hofstadter regime : strong artificial fields in optical lattices
- practical implementation with Yb atoms

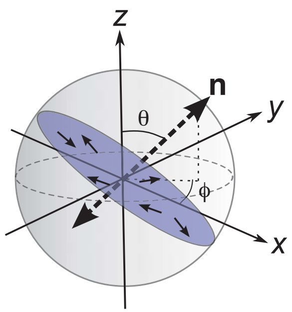
Spin F=1 polar condensates

- Spin 1 electronic ground state for Na
- All Zeeman components can be trapped in optical traps

F=1

$m_F=-1$ $m_F=0$ $m_F=+1$

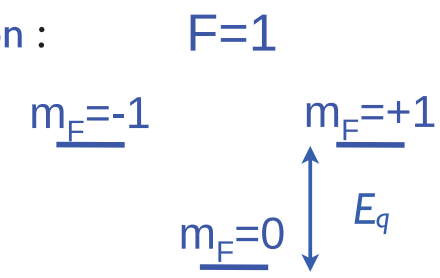
- Spin-dependent interactions : $$h_{\text{spin}} = \frac{g_s}{2}\,\mathbf{S}^2$$ g_s >0 for polar systems (Na)

Unpolarized gas : $m_z = (N_{+1}-N_{-1})/N=0$	Partially polarized gas : $m_z > 0$
 $$\vert\zeta\rangle = R(\theta,\phi)\begin{pmatrix}0\\1\\0\end{pmatrix}$$ Spins fluctuate in a plane perpendicular to a particular direction **n** (*director*)	$$\text{populations} \;:\; \begin{pmatrix}\frac{1+m_z}{2}\\0\\\frac{1-m_z}{2}\end{pmatrix}$$

T.-L. Ho, PRL 1998 T. Ohmi and K. Machida, J. Phys. Soc. Japan 1998

Magnetic field

Current experiments work in a different regime of conserved magnetization :



- Linear Zeeman shift acts only as a constant offset
- Magnetic field enters through the quadratic Zeeman shift E_q

$$h_{\rm spin} = \frac{g_s}{2}\,\mathbf{S}^2 + E_q\,\left(n_{+1}+n_{-1}\right)$$

Unpolarized gas : $m_z = (N_{+1}-N_{-1})/N=0$	Partially polarized gas : $m_z > 0$
$\text{populations} \;:\; \approx \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$	$\text{populations} \;:\; \approx \begin{pmatrix} \frac{x+m_z}{2} \\ 1-x \\ \frac{x-m_z}{2} \end{pmatrix}$ x tends to m_z for large $E_q >> g_s n$

W. Zhang, S.Yi and L.You, NJP 2003

Double condensation for ideal spin-1 gases

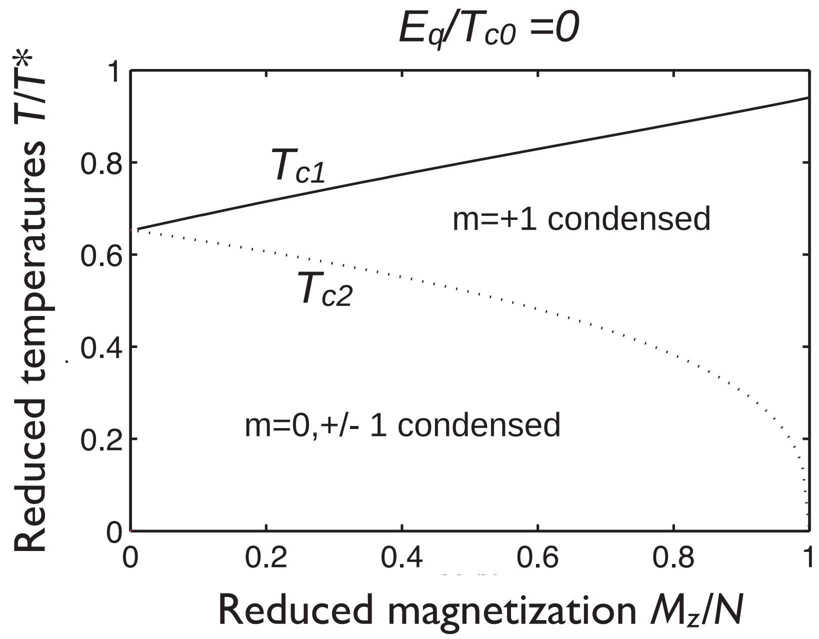
Free energy : $$G = E - \mu N - \eta M_z$$

Lagrange multiplier η to conserve M_z

$$k_B T^* = \hbar \overline{\omega} N^{1/3}$$

Chemical potentials :

$$\begin{aligned} \mu_{+1} &= \mu + \eta \\ \mu_0 &= \mu \\ \mu_{-1} &= \mu - \eta \end{aligned}$$



First critical temperature :

$$\begin{aligned} \mu_{+1} &= \mu + \eta = 0 \\ \mu_0 &= -\eta < 0 \\ \mu_{-1} &= -2\eta < 0 \end{aligned}$$

T. Isoshima, T. Ohmi and K. Machida J. Phys. Soc. Jpn. 69 (2000)

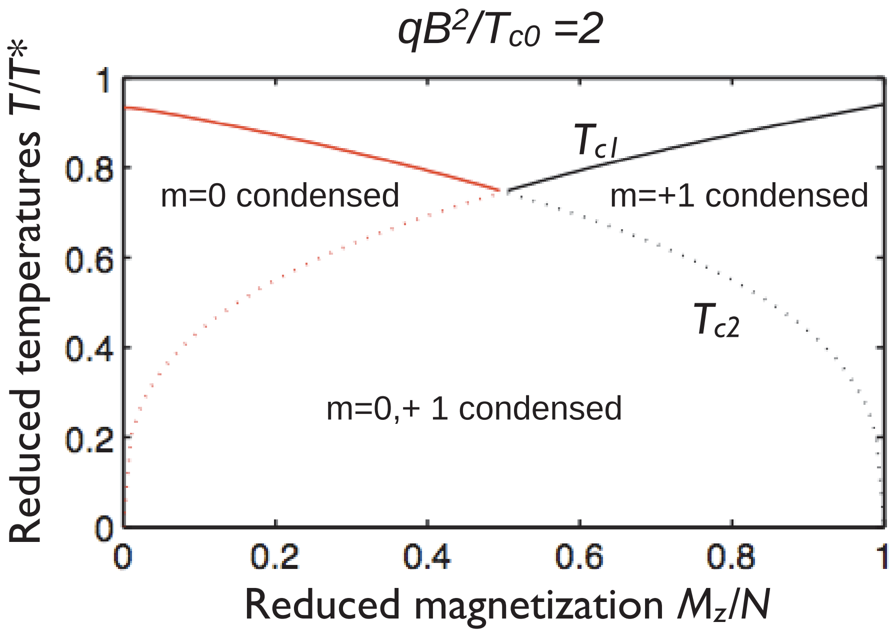
Double condensation for ideal spin-1 gases with quadratic Zeeman shift

Free energy : $$G = E - \mu N - \eta' M_z + E_q (N_{+1} + N_{-1})$$

$$k_B T^* = \hbar \overline{\omega} N^{1/3}$$

Chemical potentials :

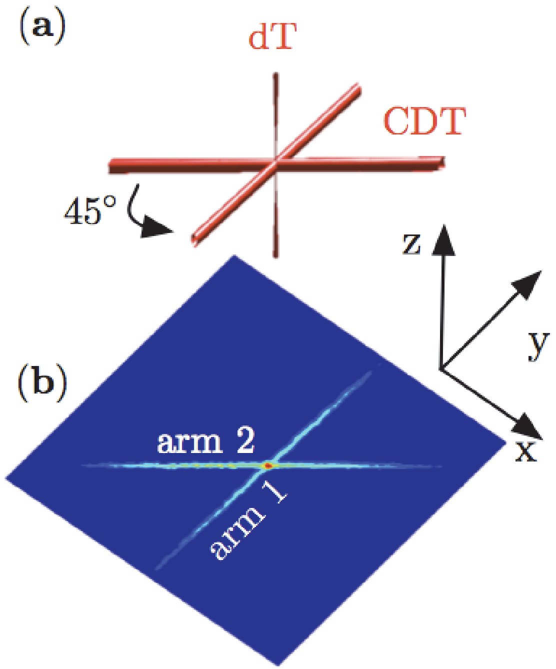
$$\begin{aligned} \mu_{+1} &= \mu + \eta - E_q \\ \mu_0 &= \mu \\ \mu_{-1} &= \mu - \eta - E_q \end{aligned}$$



Second critical temperature :

$$\begin{aligned} \mu_{+1} &= \mu + \eta - E_q = 0 \\ \mu_0 &= \mu = 0 \\ \mu_{-1} &= -2E_q < 0 \end{aligned}$$

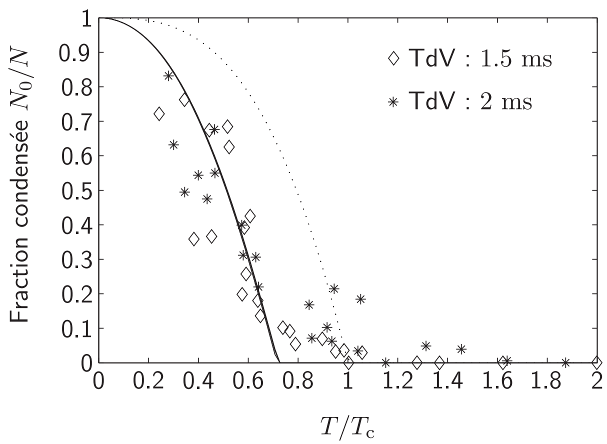
All-optical evaporation

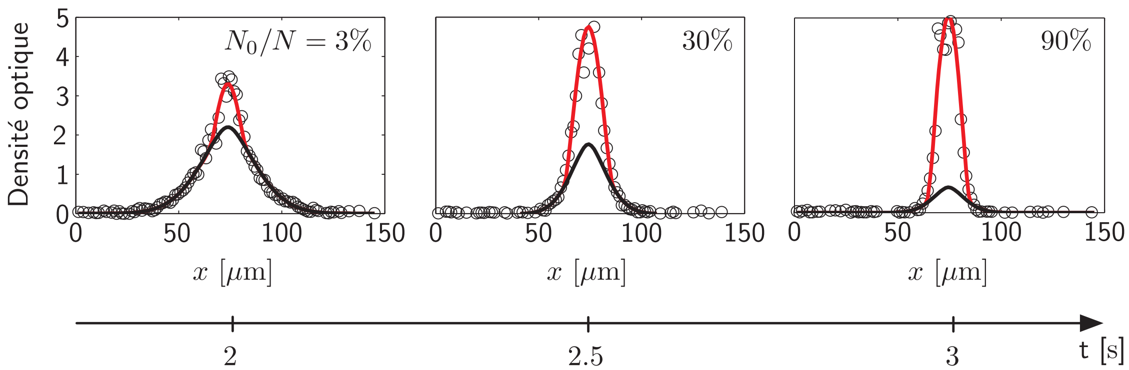


- Crossed-dipole trap (CDT) loaded from laser-cooled atoms
- Trap size ~ 8 microns

spinor BEC with ~10^4 atoms in ~3 s evaporation

- Trap frequency : $\omega/2\pi$~ *2 kHz* @ Tc
- Critical temperature : *Tc~ 2 μK*
- Chemical potential : μ~ *300 nK* @ low T
- Spin-dependent energy : $g_s n$~ *10 nK* @ low T

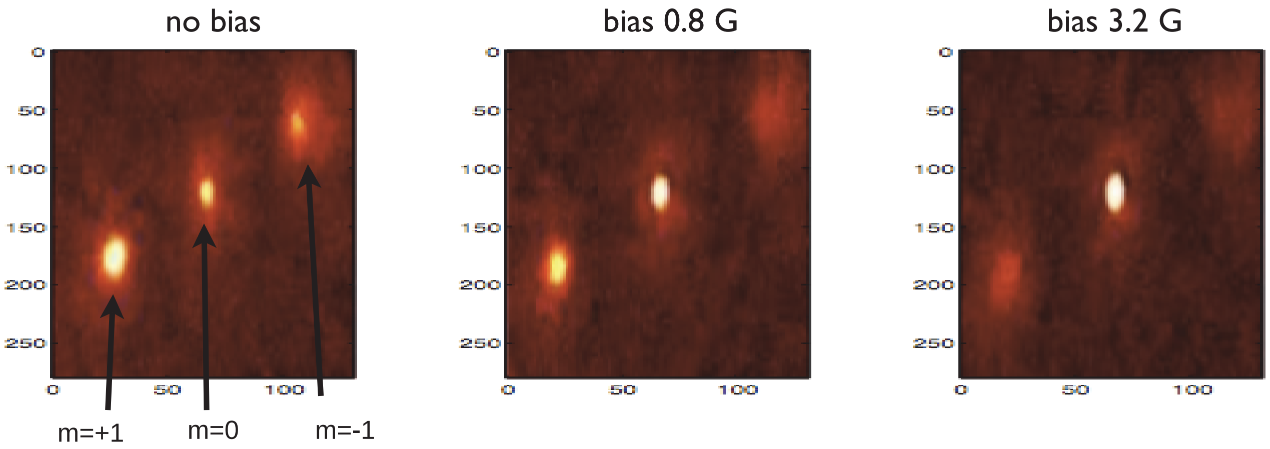




D. Jacob *et al.*, NJP 2011

Experimental procedure

- Stern-Gerlach imaging
    - release the atoms from the trap
    - apply magnetic gradient to give spin-dependent momentum kick (equivalent to Stern-Gerlach experiment)
    - take absorption picture

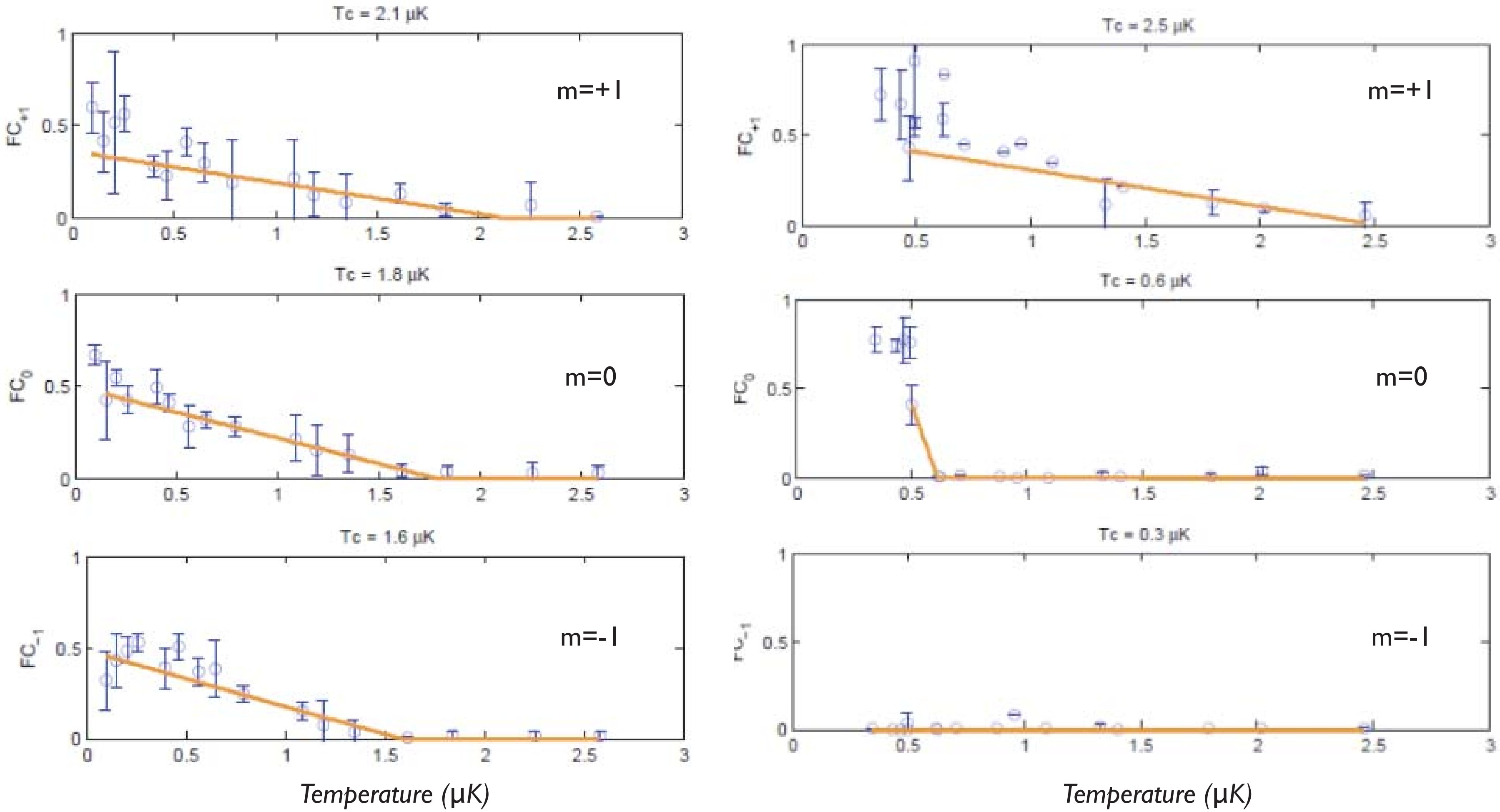


- Extract temperature, condensate fraction from bimodal fits
- Vary initial magnetization using spin-sensitive evaporation (magnetic gradient added to optical trap)

Closer look at condensed fractions (preliminary)

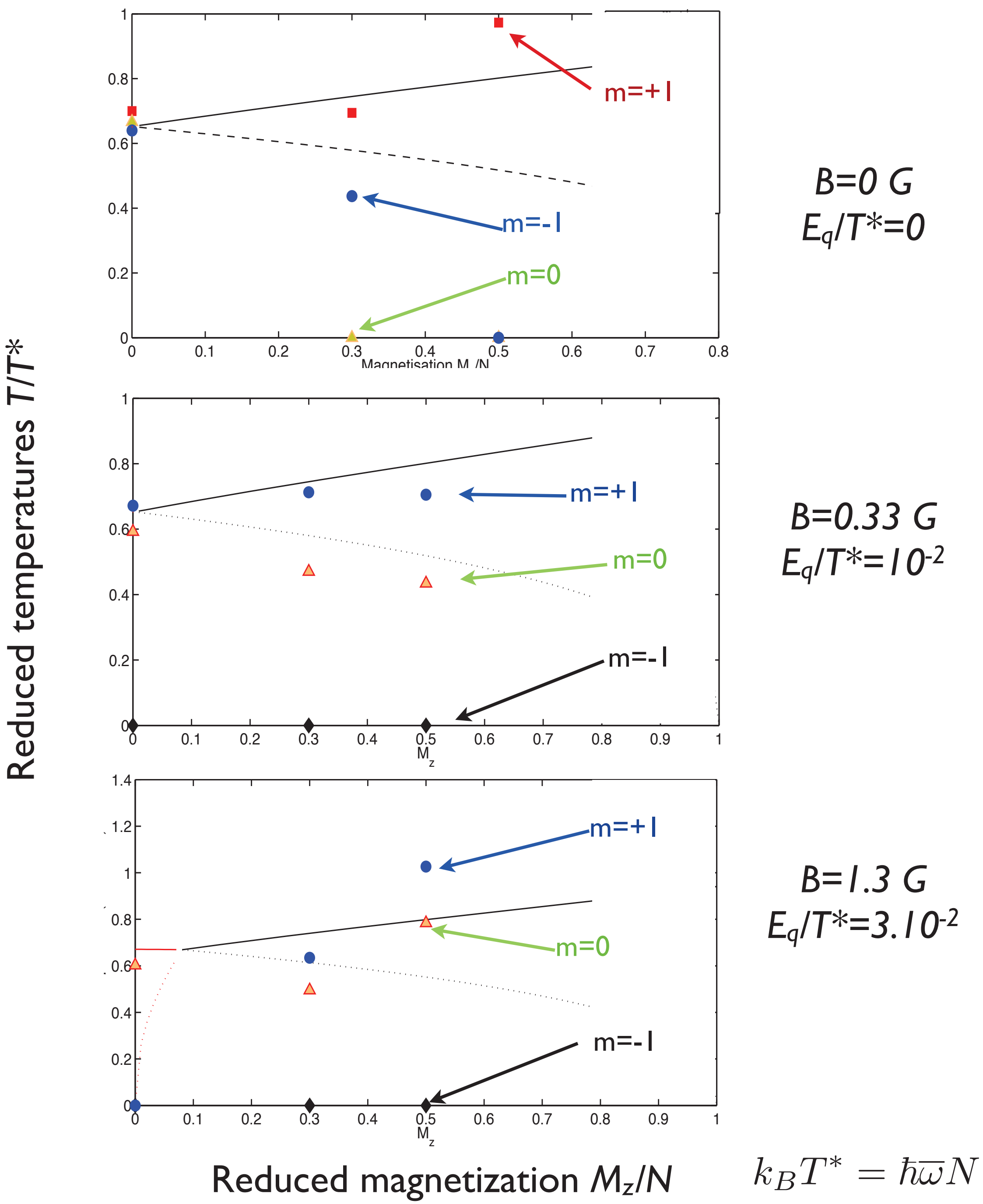
B=0 G
M_z=0.05(0.1)

B=0.33 G
M_z=0.5(0.1)



Preliminary results for T_c

- Observation of double condensation
- Qualitative behavior agrees with theory
- Currently refining data analysis and calibrations



$$k_B T^* = \hbar\overline{\omega} N^{1/3}$$

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Review article on artificial gauge potentials :

Jean Dalibard, Fabrice Gerbier, Gediminas Juzeliũnas, Patrik Öhberg, arXiv:1008.5378

Orbital magnetism for cold atoms ?

CM phenomena emerge from electronic properties: spin or charge.

- Atoms have spin: Zeeman effect, spin magnetism ...
- Atoms don't have charge: no orbital magnetism

In this talk I will present an experimentally realistic method to produce strong artificial magnetic fields for ultracold atoms in optical lattices:

- use the specific properties of Ytterbium (or alkaline earth) atoms to realized internal state dependent sublattices coherently coupled by laser beams
- optical superlattice

Possible prospects:

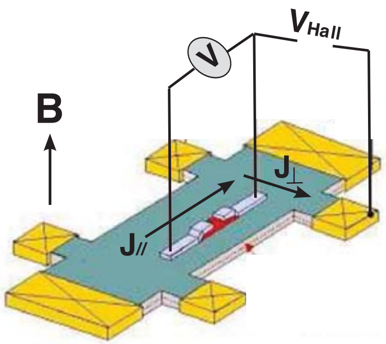
- quantum Hall states for bosons or fermions
- Josephson junction arrays (full or partial magnetic frustation)
- non-Abelian gauge fields ...

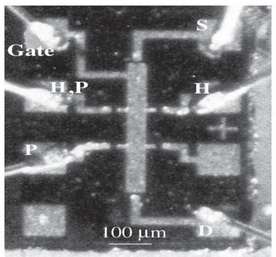
Sorensen *et al.* PRL 2005
Hafezi *et al.*, PRA 2007
Palmer & Jaksch, PRL 2006
Palmer, Klein & Jaksch, PRA 2008
Möller & Cooper, PRL 2009

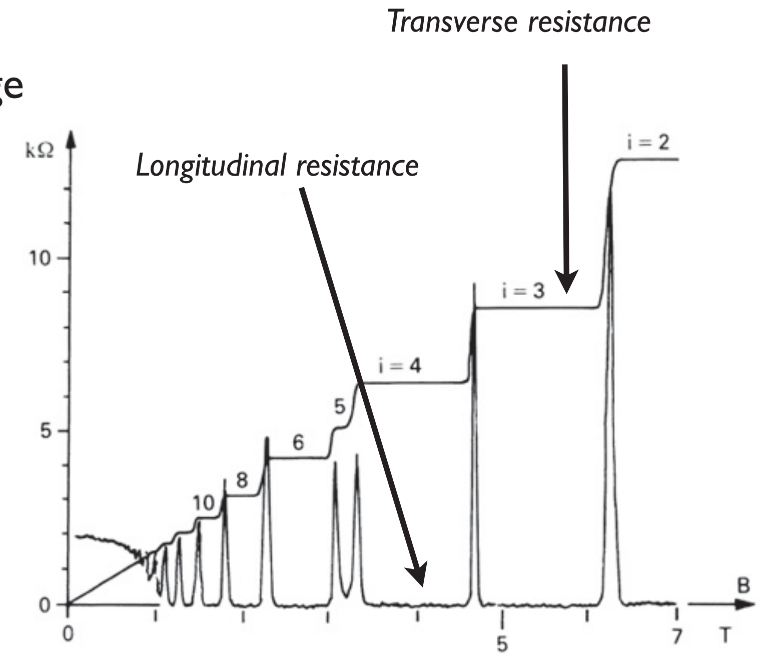
Osterloh et al. PRL 2005
Goldman, Lewenstein et al., PRA 2008

Quantum Hall effect

- 2D electron "gases" (very pure semiconductors) in Hall geometry:
  - large perpendicular magnetic field
  - Hall current perpendicular to applied voltage







- Around certain "magic" values of magnetic field (QH plateaux) :
  - Longitudinal resistance vanish (without superconductivity)
  - Hall resistance assumes quantized values $\sigma_{\rm H} = n\frac{e^2}{h}$

Fractional quantum Hall states

Filling factor : $\nu = \frac{n_{2d}}{\left(\frac{eB}{h}\right)} = \frac{N}{N_{\rm flux}}$

$$\frac{\text{\# of particles}}{\text{\# of magnetic flux quanta}}$$

➡ Integer quantum Hall effect at fractional filling factor ν =1,2,3, ...

- can be explained by a model of non-interacting electrons (filled Landau levels)

➡ Fractional quantum Hall effect at fractional filling factor ν =1/3, ...

Many-particle physics enters :

- all single-particle states (Landau levels) are degenerate
- the system is only governed by (Coulomb) interaction

- gapped, incompressible liquid
- Elementary excitations are anyons (any-ons= neither fermions nor bosons)
  - carry fractional charge νe
  - obey fractional statistics (anyons = neither fermions nor bosons)

- No order parameter as in ordinary ordered phases
- topological order : ν is robust wrt variations of the microscopic hamiltonian, provided the energy gap remains finite

key ingredients: strong electron-electron interactions and strong magnetic field

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Rotating quantum gases

Cooper, Adv . Physics (2009)

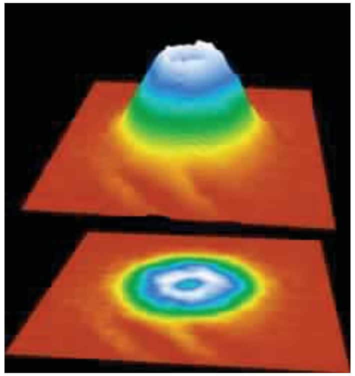
Bloch, Dalibard, Zwerger, RMP 2009

Analogy between the Coriolis and Lorentz forces

$$m\mathbf{v} \times \mathbf{\Omega} \rightarrow e\mathbf{v} \times \mathbf{B}_{\text{eff}}$$

BEC in a harmonic potential rotating at angular frequency Ω :

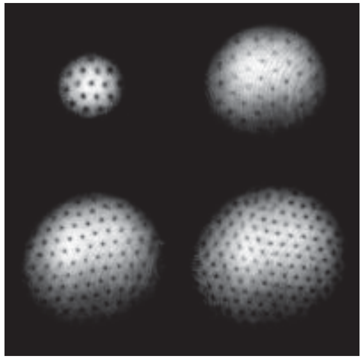
$$H = \frac{(\mathbf{p} - q\mathbf{A})^2}{2m} + \frac{1}{2}m\left(\omega_{\text{trap}}^2 - \Omega^2\right)r^2$$



ENS-
K. Madison et al., PRL 1999

Slow rotations: nucleation of vortices, vortex lattices, etc...

Vortex lattice density $n_v = \frac{m\Omega}{h}$



MIT
J. Abo-Shaeer et al., Nature 2000

JILA, ENS, MIT, Oxford, NIST, Rochester, Arizona,...

Rotating quantum gases

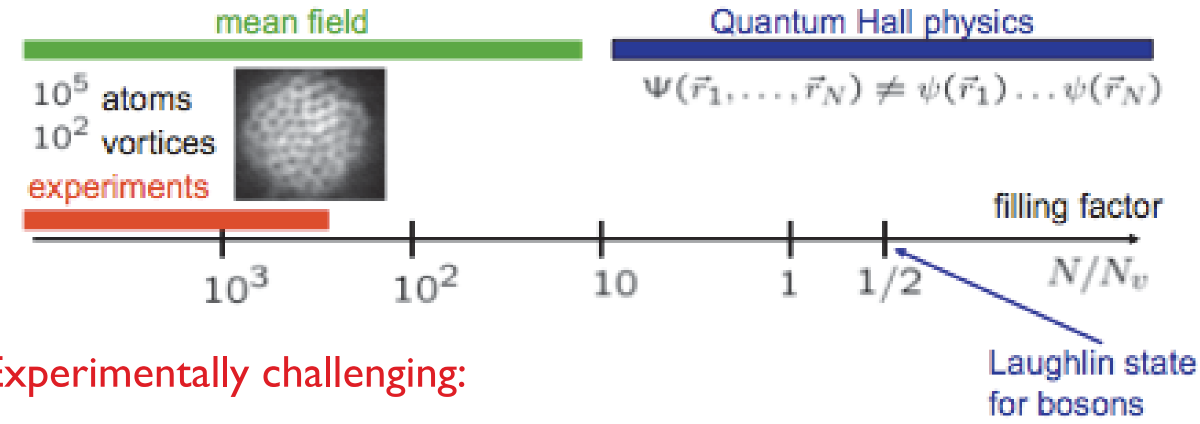
Fast rotations: $|\Omega - \omega_{\rm trap}| \ll \omega_{\rm trap}$

- vortex lattice melts: emergence of strongly correlated phases
- bosonic cousins of electronic Fractional Quantum Hall Phases

Filling fraction

$$\nu = \frac{n_{2d}}{n_v} \lesssim 6$$

Sinova et al., PRL 2003



see Cooper, Adv . Physics (2008)
Bloch, Dalibard, Zwerger, RMP 2009

Experimentally challenging:

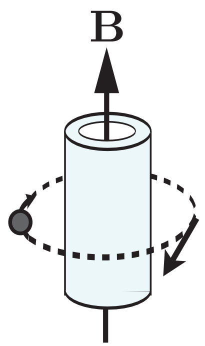
- center of mass instability for $\bar{\omega}=\omega_{trap}$
- very sensitive to residual static anisotropies of the trap (time-dependent in rotating frame)
- very small gap ~*0.05* μ (μ: chemical potential)

Aharonov-Bohm effect

- Key concept: Aharonov-Bohm phase

  Phase accumulated by a charged particle revolving around a magnetic flux tube

$$\Psi(\theta + 2\pi) = e^{i\frac{e}{\hbar}\oint \mathbf{A}\cdot\mathbf{dl}}\Psi(\theta) = e^{i\frac{e}{\hbar}\int\int \mathbf{B}\cdot\mathbf{dS}}\Psi(\theta)$$



Simulating a magnetic field is equivalent to changing the phase of the wavefunction

Condition: finite "flux" on a closed surface

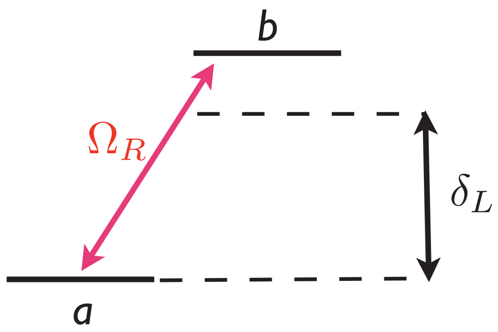
= non-zero phase around any closed contour: equivalent to Berry's geometric phase

Early ideas by Berry, Wilczek; in the context of cold atoms: Olshanii & Dum, Ho (1996)

Dressed states and geometric phases

Atom with 2 internal states *a* and *b*

Atom-laser interaction $\mathbf{d}\cdot\mathbf{E} = \frac{\hbar\Omega_R}{2} e^{i\phi}$ ← laser phase



$$H = \begin{pmatrix} -\delta_L/2 & \frac{\hbar\Omega_R}{2} e^{i\phi} \\ \frac{\hbar\Omega_R}{2} e^{-i\phi} & \delta_L/2 \end{pmatrix}$$

Dressed states = eigenstates of *H*

Lowest dressed state :

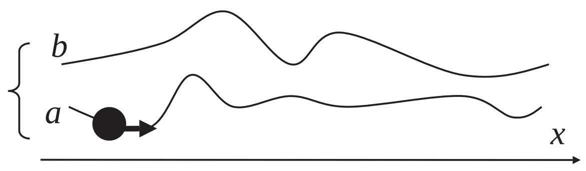
$$|-\rangle_{\mathbf{r}} \quad = \quad -\sin\left(\frac{\theta}{2}\right) e^{i\frac{\phi}{2}} |a\rangle + \cos\left(\frac{\theta}{2}\right) e^{-i\frac{\phi}{2}} |b\rangle. \qquad \cos[\theta] \quad = \quad -\frac{\delta_L}{\sqrt{\delta_L^2 + \Omega_R^2}},$$

Adiabatic or diabatic (π pulse) passage from *a* to *b* : $|\Psi\rangle = |a\rangle \rightarrow e^{-i\phi}|b\rangle$

Dressed states and geometric phases

Atom with 2 internal states in non-uniform laser field

$$H = \frac{\mathbf{p}^2}{2m} + \begin{pmatrix} -\delta_L(\mathbf{r})/2 & \frac{\hbar\Omega_R(\mathbf{r})}{2} e^{i\phi(\mathbf{r})} \\ \frac{\hbar\Omega_R(\mathbf{r})}{2} e^{-i\phi(\mathbf{r})} & \delta_L(\mathbf{r})/2 \end{pmatrix}$$



"Dressed states"= local eigenstates of atom-field coupling

$$|-\rangle_{\mathbf{r}} = -\sin\left(\frac{\theta}{2}\right) e^{i\frac{\phi}{2}}|a\rangle + \cos\left(\frac{\theta}{2}\right) e^{-i\frac{\phi}{2}}|b\rangle. \qquad \cos[\theta(\mathbf{r})] = -\frac{\delta_L(\mathbf{r})}{\sqrt{\delta_L(\mathbf{r})^2 + \Omega(\mathbf{r})^2}}$$

Assumption: The atom follows adiabatically $|-\rangle_{\mathbf{r}}$: adiabatic elimination of state $|+\rangle_{\mathbf{r}}$

$$H_- = \frac{(\mathbf{p} - \mathbf{A})^2}{2m} + V_-(\mathbf{r}) + \Phi(\mathbf{r})$$

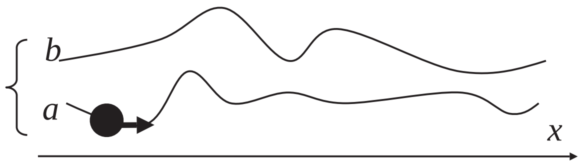
geometric scalar potential

Dutta et al., PRL 1999

geometric vector potential
(Berry connection)

$$\mathbf{A} = i\hbar\langle -|\nabla|-\rangle = \frac{\hbar\nabla\phi}{2}\cos(\theta)$$

Dressed states and geometric phases



Atom following dressed state $|-\rangle_{\mathbf{r}}$ in non-uniform laser field

$$H_- = \frac{(\mathbf{p}-\mathbf{A})^2}{2m} + V_-(\mathbf{r}) + \Phi(\mathbf{r})$$

Vector potential : $\mathbf{A} = i\hbar\langle -|\nabla|-\rangle = \frac{\hbar\nabla\phi}{2}\cos(\theta)$ $\quad \cos[\theta(\mathbf{r})] = -\frac{\delta_L(\mathbf{r})}{\sqrt{\delta_L(\mathbf{r})^2+\Omega(\mathbf{r})^2}}$

Effective magnetic field : $\mathbf{B}_{\text{eff}} = \nabla\times\mathbf{A} = \frac{\hbar}{2}\nabla\left[\cos(\theta)\right]\times\nabla\phi$

To obtain a non-zero vector potential, one needs :

- a spatially varying phase
- a spatially varying mixing angle
- with non-collinear gradients

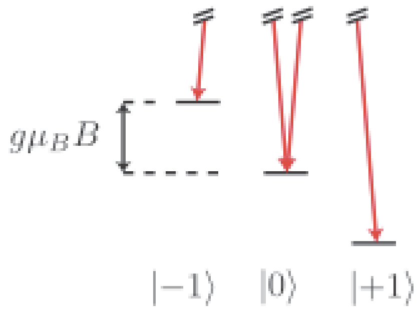
Many proposals in various geometries for realistic alkali atoms e.g.

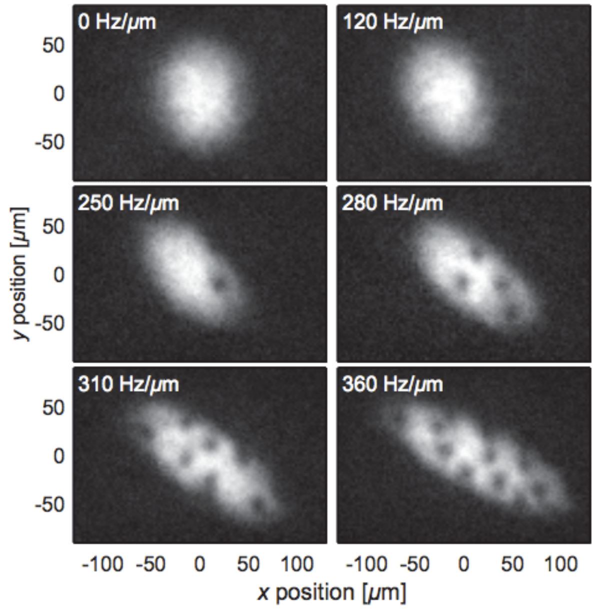
Bloch, Dalibard, Zwerger, RMP 2009
Juzeliunas et al., PRA 73 (2006); PRA 71(2005)
Cheneau et al., EPL. 83 (2008)
Günter, et al., PRA 79 (2009)
Spielman, PRA 2009

NIST experiment

- Raman coupling in F=1 manifold of Rb

Lin et al., PRL 2009; Nature 2010
Spielman, PRA 2009





- Additional magnetic field gradient along y
  - uniform Rabi frequency
  - spatially varying Raman detuning

- Observed several (~10 vortices) created in the gas
- no ordering in Abrikosov lattice (spontaneous emission limits lifetime to 1.4 s)

Strength of artificial magnetic field

Order of magnitude of vector potential: $|\mathbf{A}| \sim \hbar k_L$

Order of magnitude of magnetic field: $|\mathbf{B}_{\text{eff}}| \sim \hbar k_L |\nabla\theta|$

$$\cos[\theta(\mathbf{r})] = -\frac{\delta_L(\mathbf{r})}{\sqrt{\delta_L(\mathbf{r})^2 + |\Omega(\mathbf{r})|^2}},$$

Maximum magnetic field: $|\mathbf{B}_{\text{eff}}|_{\max} \sim \hbar k_L^2$

Achievable when laser intensity/detuning varies on the scale of an optical wavelength λ_L:

optical lattices !

Vortex density $$n_v = \frac{2B_{\text{eff}}}{h} \sim \frac{1}{\lambda_L^2}$$

Particle density ~1 atom/site $$n_{2d} \sim \frac{1}{\lambda_L^2}$$

Filling factors $n_{2d}/n_v \sim 1$ and quantum Hall states (for strong interactions) within reach !

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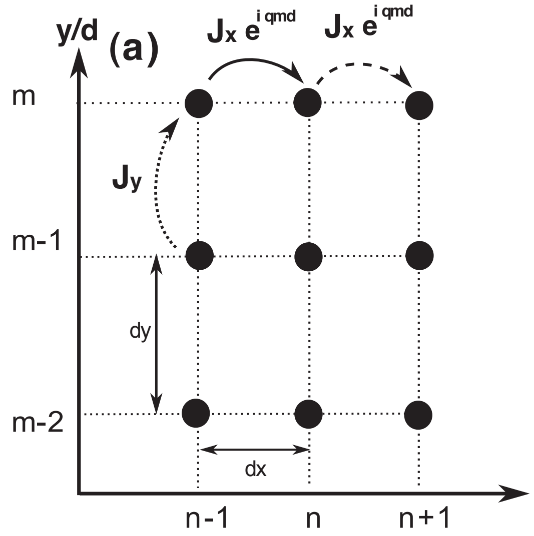
Harper hamiltonian : lattice and magnetic field

Harper hamiltonian:

$$H_{\mathrm{Harper}} = -J \sum_{\langle \mathbf{r},\mathbf{r}' \rangle} e^{i\phi_{\mathbf{r},\mathbf{r}'}} \hat{c}^{\dagger}_{\mathbf{r}'} \hat{c}_{\mathbf{r}} + \mathrm{h.c.}$$



Aharonov-Bohm phase: $\phi_{\mathbf{r},\mathbf{r}'} = \frac{e}{\hbar}\int_{\mathbf{r}}^{\mathbf{r}'} \mathbf{A}\cdot d\mathbf{l}$

Harper, 1956; Azbel 1964; Hofstadter, 1976;
Thouless et al., 1983; Kohmoto; Osadchy-Avron 2001...

Landau gauge: $\mathbf{A} = \begin{pmatrix} By \\ 0 \\ 0 \end{pmatrix}$

$$\int_x^{x+d} A_x dx = B d_x y$$

Finite flux: $\int_\square \mathbf{A}\cdot d\mathbf{l} = B d_x d_y$

$$\phi_{\mathbf{r},\mathbf{r}+d\mathbf{e}_x} = 2\pi \frac{eBd_x y}{h} = 2\pi\alpha \frac{y}{d_y}$$

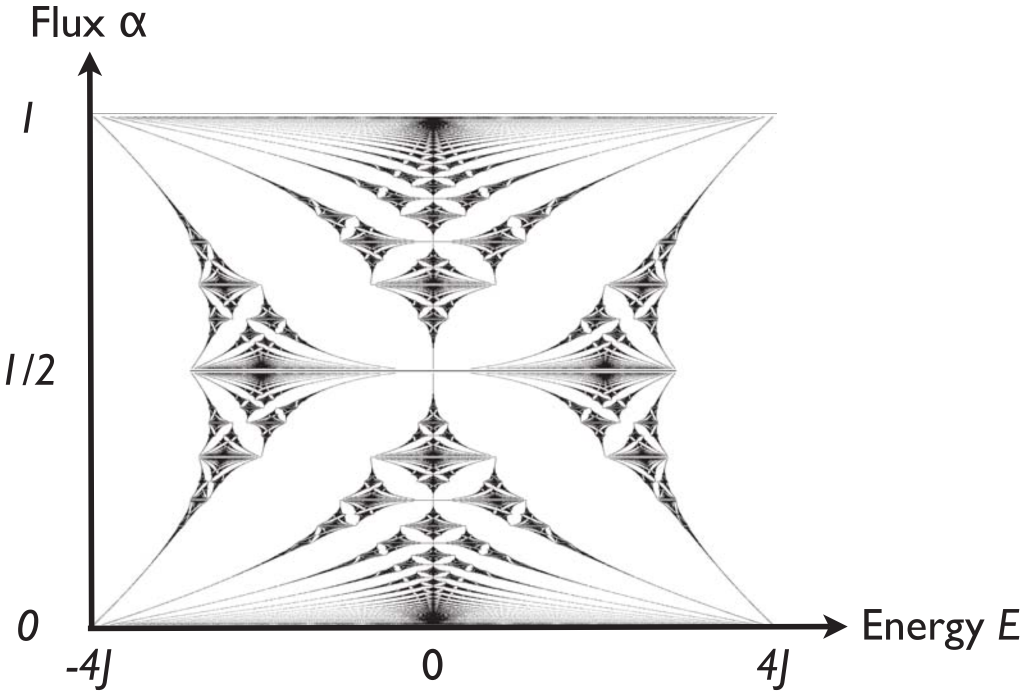
$$\sum_\square \phi_{\mathbf{r},\mathbf{r}'} = 2\pi\alpha$$

Hofstadter's butterfly: interplay between lattice and vector potentials

Harper hamiltonian:

$$H_{\text{Harper}} = -J \sum_{\langle \mathbf{r},\mathbf{r}' \rangle} e^{i\phi_{\mathbf{r},\mathbf{r}'}} \hat{c}^{\dagger}_{\mathbf{r}'} \hat{c}_{\mathbf{r}} + \text{h.c.}$$

Harper, 1956; Azbel 1964; Hofstadter, 1976;
Thouless et al., 1983; Kohmoto; Osadchy-Avron 2001...



Finite flux: $\sum_{\square} \phi_{\mathbf{r},\mathbf{r}'} = 2\pi\alpha$

Landau gauge:

$$\begin{aligned} \phi_{\mathbf{r},\mathbf{r}'} &= 2\pi\alpha y, \quad \text{for } \mathbf{r}' = \mathbf{r} + \mathbf{e}_x, \\ &= 0, \qquad \text{for } \mathbf{r}' = \mathbf{r} + \mathbf{e}_y \end{aligned}$$

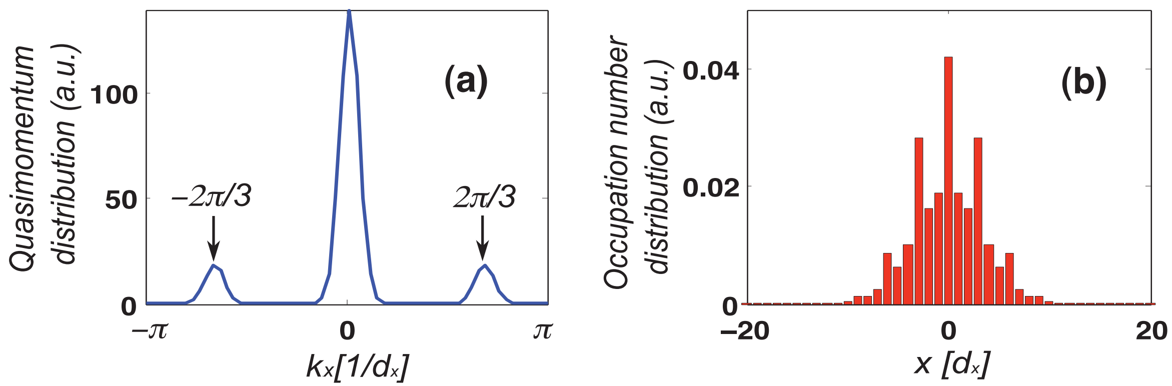
When $\alpha = p/q$ rational:

- q sub-bands, width <<8J
- Recursive structure, discovered by Azbel and Hofstadter
- Very different from Landau levels (recovered for α<<1)

Signature of the presence of a gauge potential

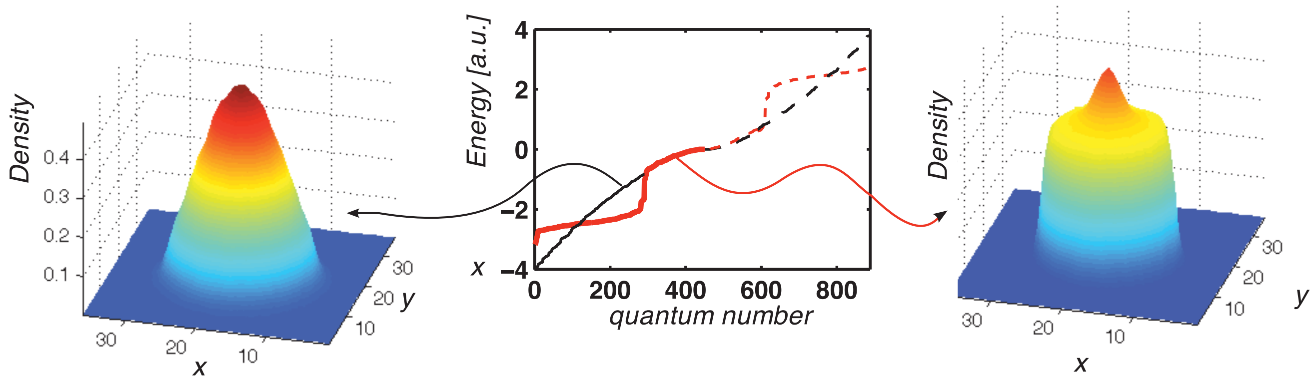
Numerical solutions including an additional harmonic trap

Non-interacting bosons: momentum distribution



α=1/3

Non-interacting fermions: spatial distribution



α=1/3, E_F=0

The Jaksch & Zoller scheme (I)

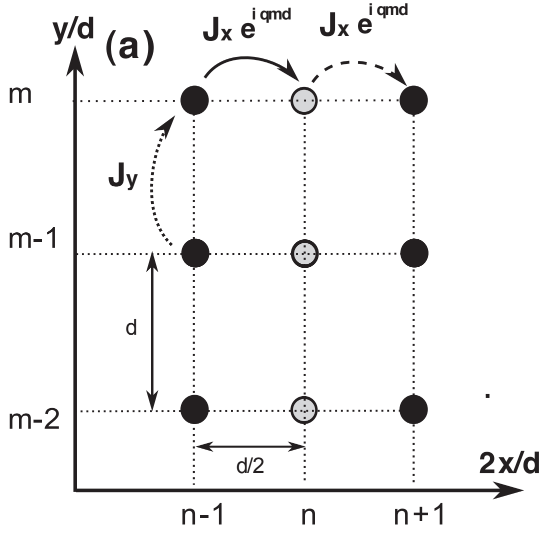
Jaksch & Zoller, NJP (2003)

also: Mueller, PRA 2004; Sorensen *et al.*, PRL 2005

optical flux lattices : Cooper, PRL 2010

Mimic the Aharonov-Bohm effect using laser-induced tunneling in an optical lattice

Spin-dependent lattice for alkalis:



- Atoms with two internal (hyperfine) states *a* and *b*

- Spin-dependent 2D lattice:
  - Lattice potential along *y* state-independent
  - Lattice potential along *x* state dependent:
    - *a* trapped at potential minima
    - *b* trapped at potential maxima
    - no free tunneling

The Jaksch & Zoller scheme (I)

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also: Mueller, PRA 2004; Sorensen *et al.*, PRL 2005

optical flux lattices : Cooper, PRL 2010

Mimic the Aharonov-Bohm effect using laser-induced tunneling in a spin-dependent optical lattice

- Atoms with two internal (hyperfine) states *a* and *b*
- Spin-dependent 2D lattice:
  - Lattice potential along *y* state-independent
    - free tunneling
  - Lattice potential along *x* state dependent:
    - *a* trapped at potential minima
    - *b* trapped at potential maxima
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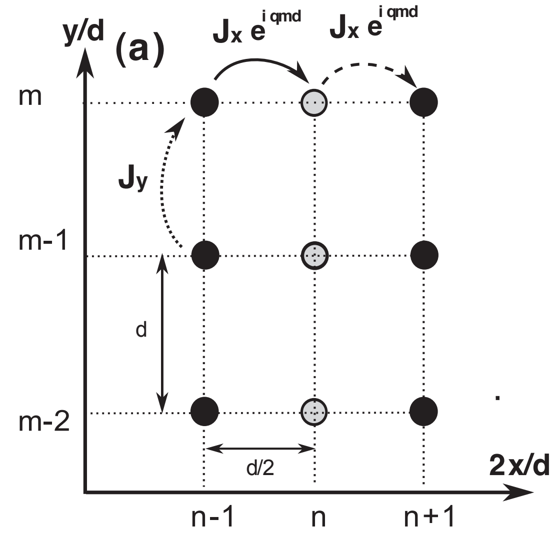


Laser-induced tunnel matrix element $\propto \hbar\Omega_L e^{iq_L y}$

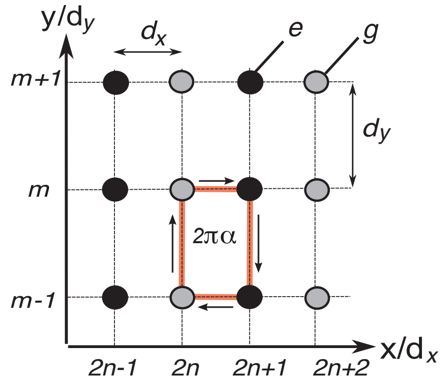
Depth V_0	$J^{(x)}_{eg}(\alpha = \frac{1}{2})$	$J^{(x)}_{gg}$
10 E_R	$h\times100$ Hz	$h\times20$ Hz
20 E_R	$h\times50$ Hz	$h\times3$ Hz
30 E_R	$h\times30$ Hz	$h\times0.5$ Hz

Single laser configuration: staggered magnetic field

Laser wavevector along y axis: $\mathbf{k}_L \cdot \mathbf{r} = 2\pi\alpha m \qquad \mathbf{r} = (n, m) \times d$

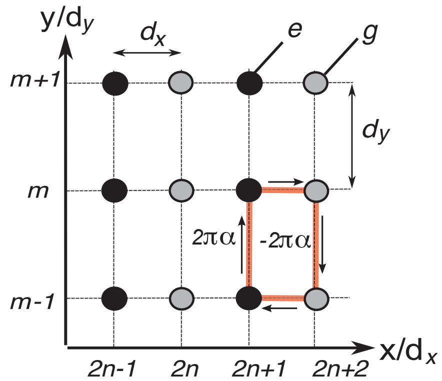
Phase factor picked around a loop:

$$|\Psi\rangle_{\rm loop} = \left(e^{i2\pi\alpha(m-1)}\right)^* e^{i2\pi\alpha m}|\Psi\rangle_0 = e^{i2\pi\alpha}|\Psi\rangle_0$$



Phase factor picked around a neighboring loop:

$$|\Psi\rangle_{\rm n-loop} = e^{i2\pi\alpha(m-1)} \left(e^{-i2\pi\alpha m}\right)^* |\Psi\rangle_0 = e^{-i2\pi\alpha}|\Psi\rangle_0$$

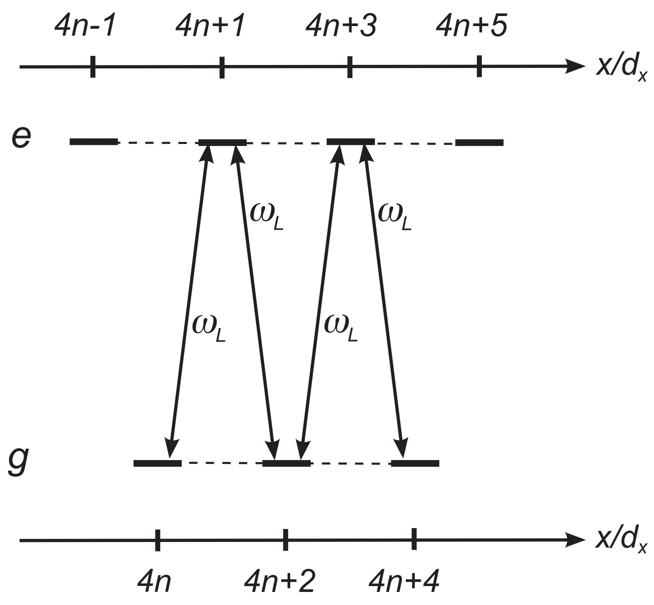


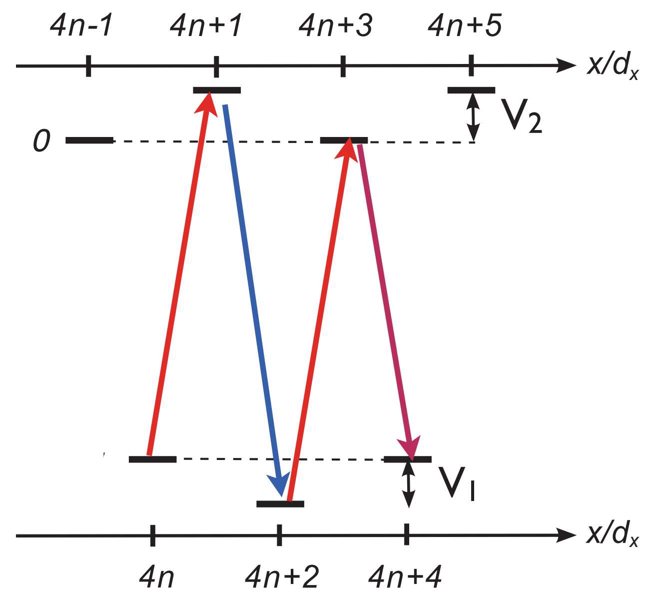
The phase per plaquette alternates from one column to the next: *staggered magnetic field*

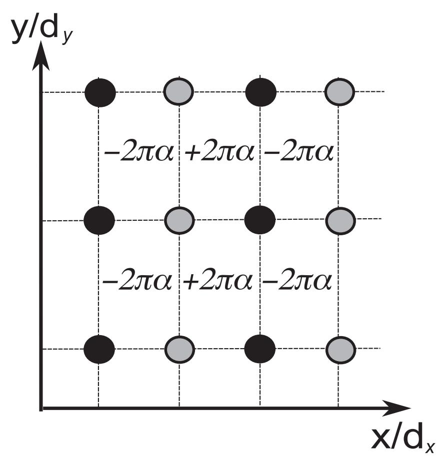
- completely different level structure than uniform field — Wang & Gong, PRB 74 (2006)
- α=1/2 ("full magnetic frustration"): Dirac point @ (π/2,π/2) — Hou, Yang, Liu, PRA 74 (2006)

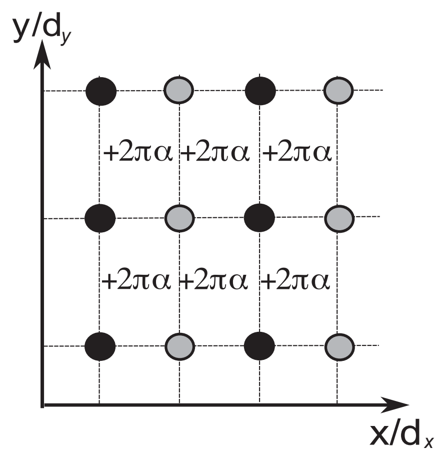
Flux rectification: uniform magnetic field

Modulate energy levels with period $2d_x$:



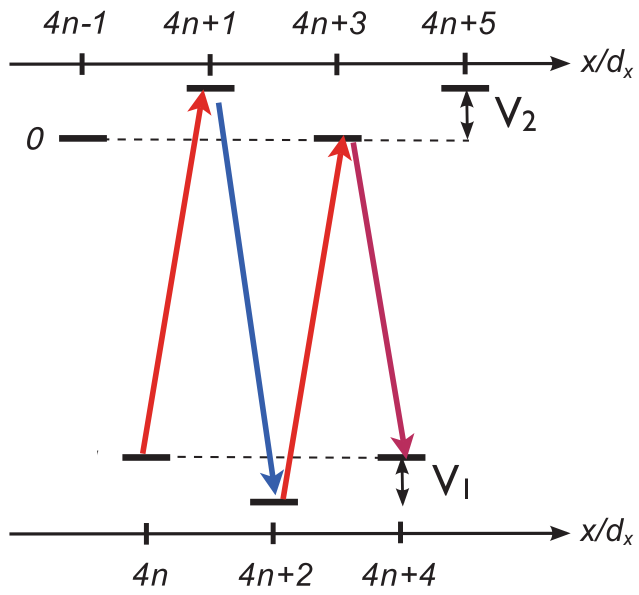


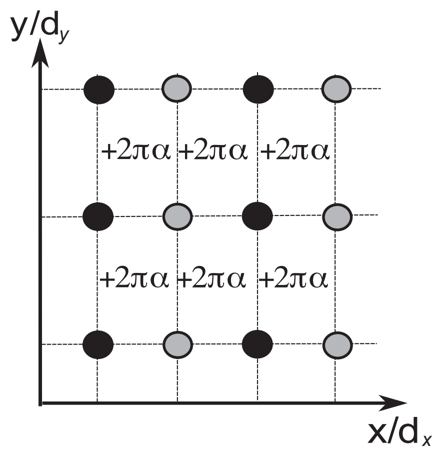




Flux rectification: uniform magnetic field

Modulate energy levels with period $2d_x$:





- Flux rectification by alternating wavevectors

- Modulation of energy levels done in practice by an additional superlattice potential:

$$V_{\rm SL}(x) = V_2 \cos(\pi x/4d_x + \varphi)^2$$

F. Gerbier & J. Dalibard, NJP (2010)

Outline

1. Sodium experiment : thermodynamics of polar spinor condensates

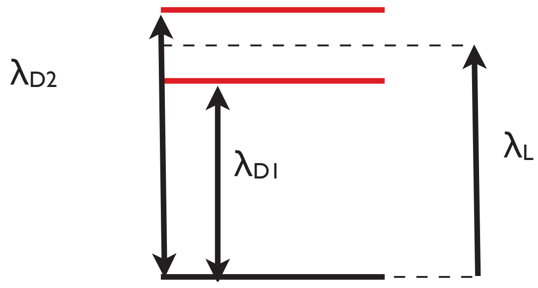
2. Artificial gauge fields for ultracold atoms

- Quantum Hall Effect
- From rotations to laser-induced artificial magnetism
- Hofstadter regime : strong artificial fields in optical lattices
- practical implementation with Yb atoms

Practical problems

Practical issues with spin-dependent lattices for alkalis:

- small detunings, entailing (relatively) large spontaneous emission
  - marginal for Rb, not feasible for other atoms (incl. fermions K, Li)



Species	λ_{D_1}	λ_{D_2}	Γ_{sp}	$\Gamma_{heating}$
Rb	795 nm	780 nm	1.5 s^{-1}	500 nK/s
K	770 nm	765 nm	...	...
Na	589.4 nm	589.0 nm	...	...
Li	671.0 nm	670.9 nm	...	...

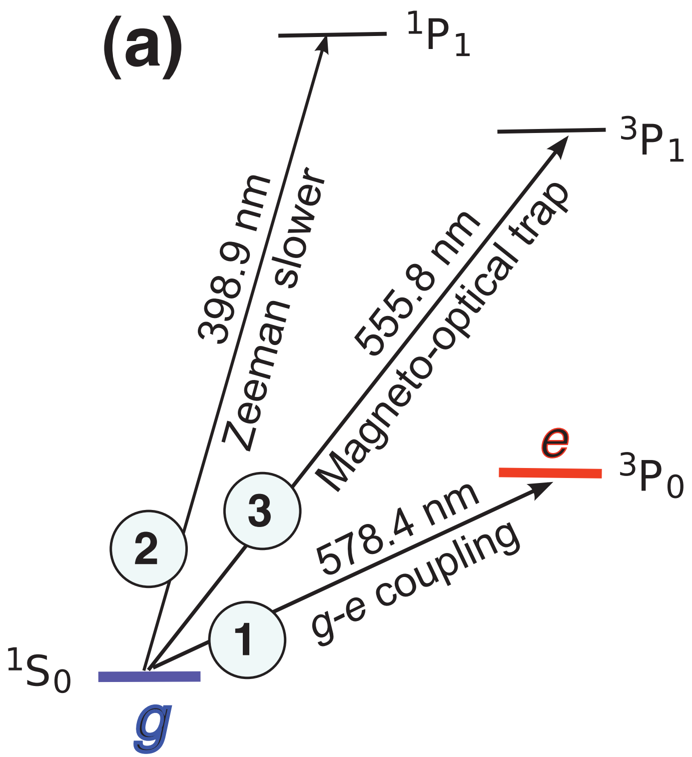
lattice depth 10 E_R $\lambda_L=(\lambda_{D1}+\lambda_{D2})/2$

- *a* and *b* must have different magnetic moments
  - high sensitivity to stray magnetic fields,
  - coherence times ~ ms

Ytterbium atoms (or alkaline-earth) allow to overcome these limitations

F. Gerbier & J. Dalibard, NJP (2010)

Ytterbium



1 Internal state manipulation using ultra-narrow (1S0-3P0) transition

- "doubly forbidden" *lifetime >20 s !*
- weak coupling in presence of hyperfine or Zeeman interactions
- optical atomic clocks

2 broad (1S0-1P1) and narrow (1S0-3P1) transitions for laser cooling

3 weak sensitivity to magnetic fields (nuclear magneton)

Bosons (spin 0): 170 Yb, 172 Yb, 174 Yb, 176 Yb

Fermions: (spin 1/2) 171 Yb, (spin 5/2) 173 Yb

quantum degeneracy reached at Kyoto University for all isotopes

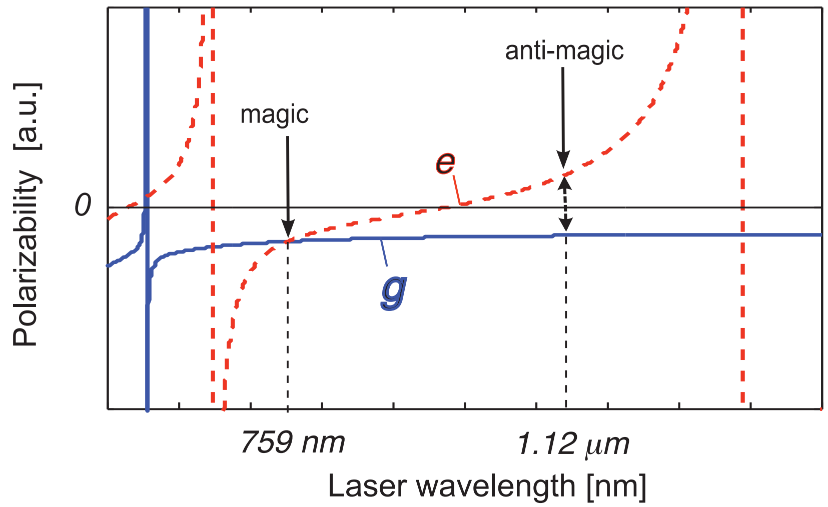
Y. Takahashi & coworkers

State-dependent lattices

- Optical trap potential:

$$V_{\rm dip} = -\frac{1}{2}\alpha(\lambda_L)|\mathbf{E}|^2$$

dynamic polarisability

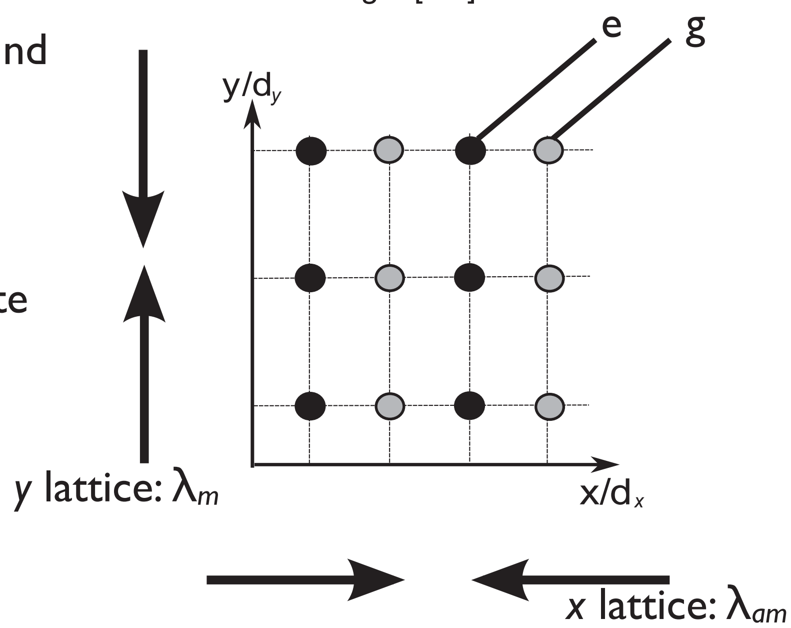


- At magic wavelength (~760 nm):

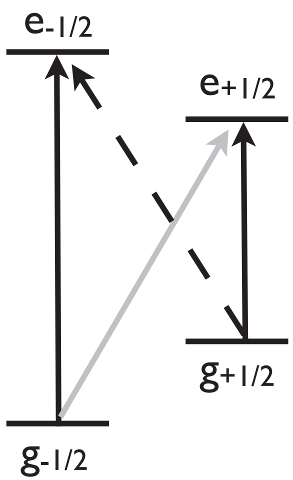
  optical potentials attractive, identical for ground and excited states (atomic clocks)

- At anti-magic wavelength (~1.1 μm):

  optical potentials is attractive for ground state atoms, repulsive for excited states atoms



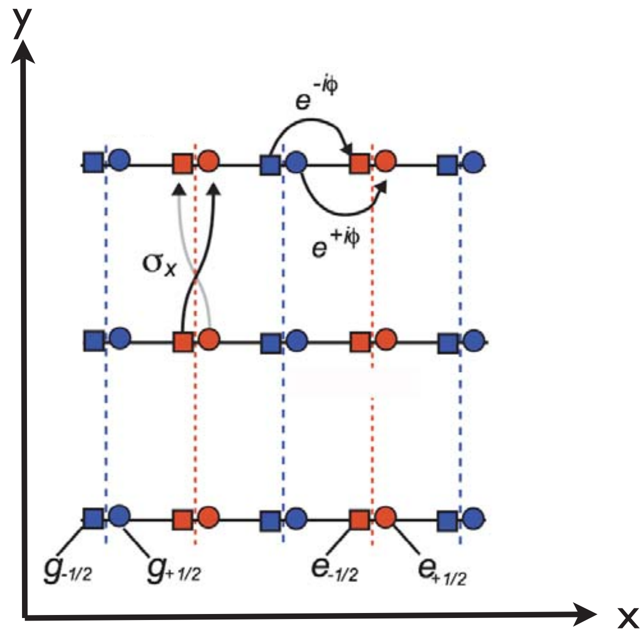
Non-abelian gauge potentials



^{171}Yb: spin=fictitious “color” charge

$$\{g_1, g_2\} \rightarrow e^{i\hat{\mathbf{M}}\cdot\mathbf{d}}\{e_1, e_2\}$$

$\hat{M}_x, \hat{M}_y$: 2×2 matrices



- Can be used to simulate spin-orbit coupling as in semiconductors (topological insulators)

- Big question : Do non-Abelian gauge fields give rise to non-Abelian anyons ?

Towards quantum Hall states

- Different methods to realize an effective artificial magnetic field for neutral atoms

  ➡ Rotation
  ➡ Space-dependent dressed states
  ➡ Laser coupling in spin-dependent optical lattices :
    - regime of strong fields and strong interactions
    - realistic experimental proposal with Yb (or alkaline earth) atoms

- Atomic fractional quantum Hall states on a lattice:

  ‣ analogue of continuum states exist

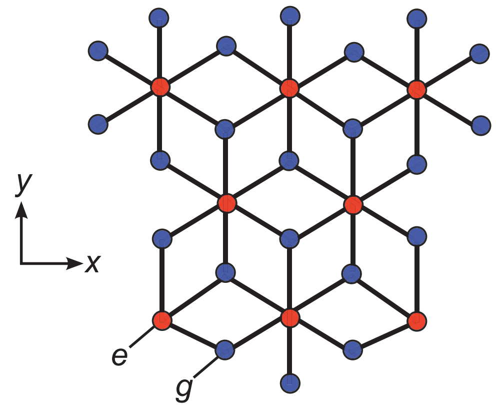
    Sorensen *et al.* PRL 2005;Hafezi *et al.*, PRA 2007
    Palmer & Jaksch, PRL 2006; Palmer, Klein & Jaksch, PRA 2008
    Möller & Cooper, PRL 2009

  ‣ completely novel quantum Hall phases that arise only on a lattice (composite fermions theory of Möller & Cooper, PRL 2009)

  ‣ Big question : how to characterize topological order if present ?

- More exotic lattices: for example T3 or "dice" lattice

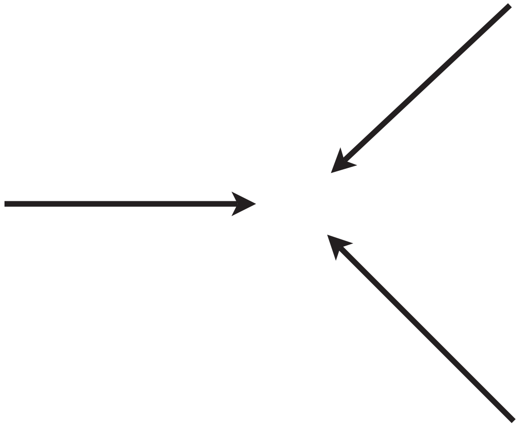
  - $\alpha=1/2$: three *flat* bands — Vidal et al. PRL 2009; Rizzi et al., PRB 2006
  - $\alpha=1/3$: exotic vortex liquids — Burkov & Demler, PRL 2006



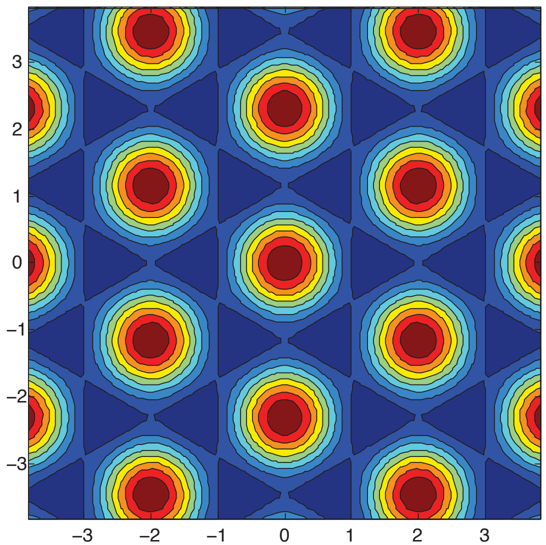
Outline

- Quantum Hall Effect
- From rotations to artificial magnetism for ultracold atoms
- Practical implementation of a strong, artificial field : Yb in optical superlattices
- Exotic geometry : T_3 lattice

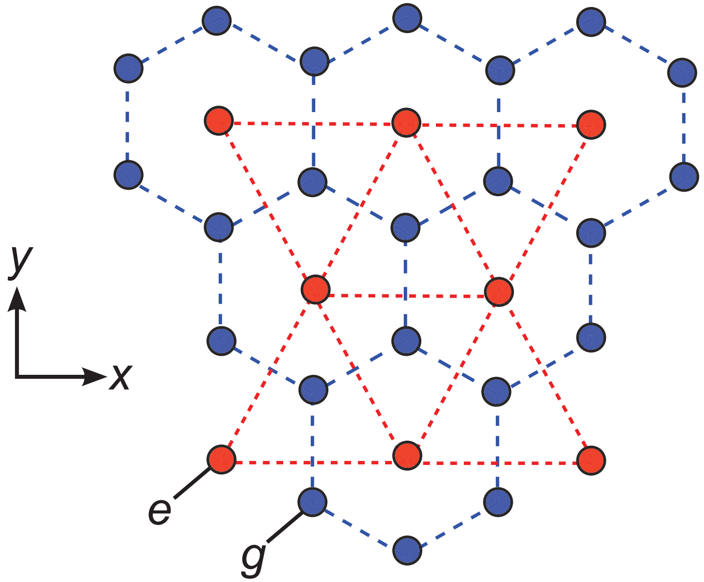
Dice lattice



3 beams at 120° in the xy plane



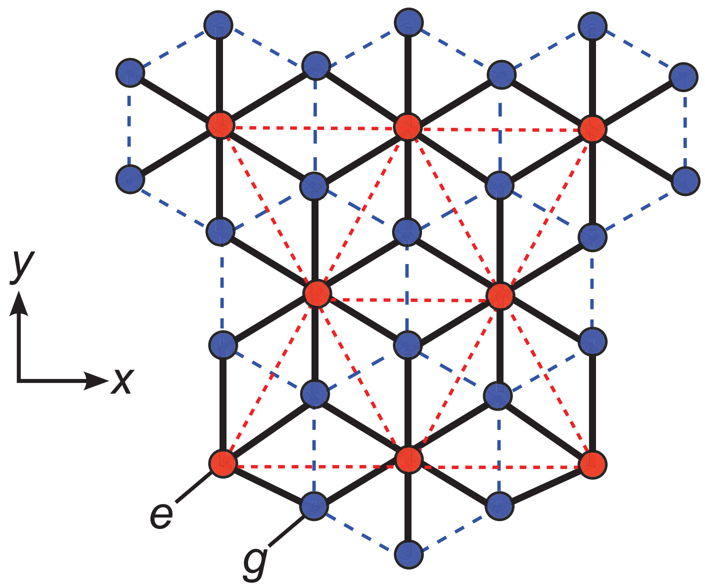
intensity map



Dice lattice

g atoms: coordination 6

e atoms: coordination 3



Dice lattice

g atoms: coordination 6

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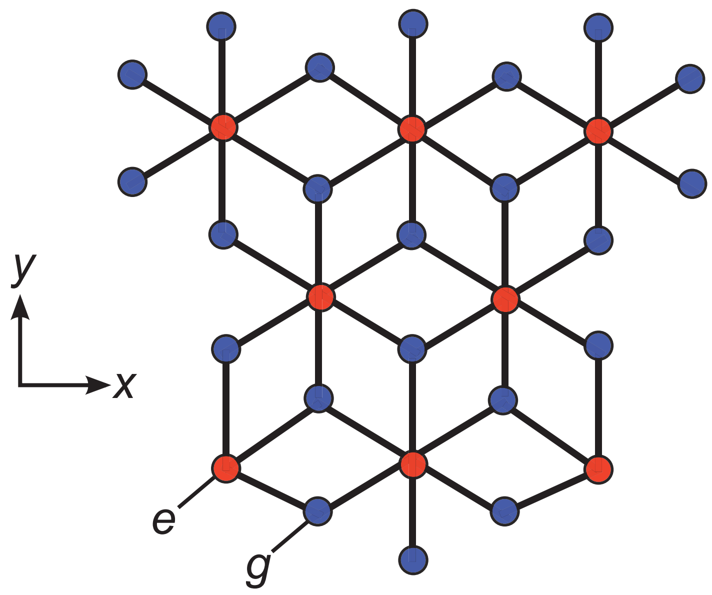
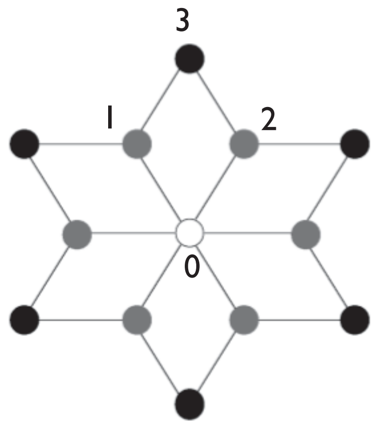


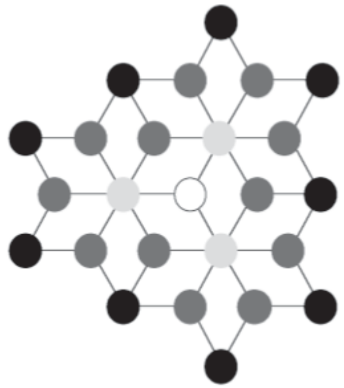
Aharonov-Bohm cages

Single-particle localisation due to destructive interferences @ α=1/2

Prediction : Vidal *et al.*, PRL 1998

Observed in Abilio *et al.*, PRL 1999 in superconducting Josephson junction arrays

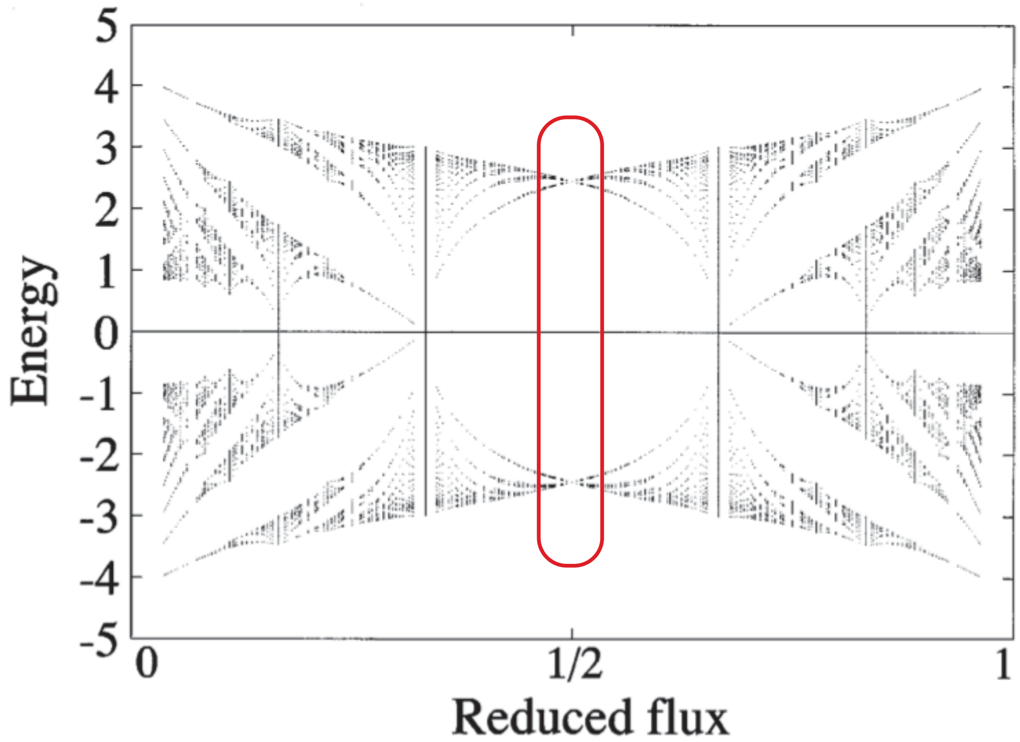




Probability amplitudes : $A_{013} = -A_{023}$

No transport (for non-interacting particles) due Aharonov-Bohm phases causing destructive interferences at "full magnetic frustration"

single-particle spectrum of the dice lattice



Three non-dispersive bands @ α =1/2: large single-particle degeneracy

Expect strongly correlated states to emerge even for (relatively weak) interactions

What to expect from the dice lattice ?

- Theory :
  - ➡ Vortex liquid @ α =1/2 (or even glassy behavior ?) — Korshunov, PRL 2001, PRB 2002; Cataudella & Fazio, EPL 2003
  - ➡ Unconventional vortex state @ α =1/3 (vortex form resonating valence bonds) — Burkov & Demler, PRL 2006
  - ➡ New insulating phase (Aharonov-Bohm insulator) ? — Rizzi *et al.*, PRA 2005

- Experiments on Josephson-junction arrays (Grenoble) : — Serret *et al.*, EPL 2003
  - ➡ Vortex liquid (?) @ α =1/2, ordered vortex lattice @ α =1/3
  - ➡ role finite range of interactions ? finite size ? glassy dynamics ?