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Coherent spectroscopy of interacting bosons using a clock transition

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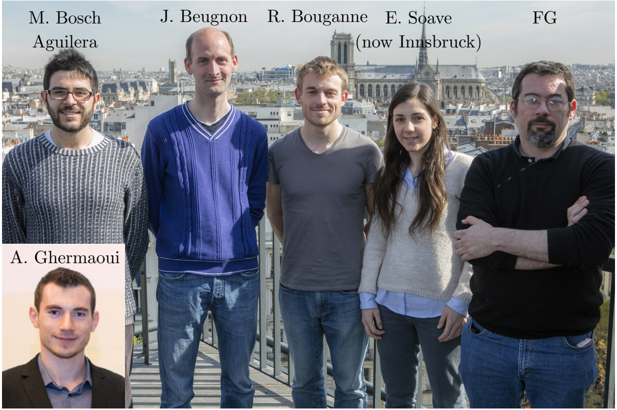
Ytterbium team at LKB



Recent work :

- Probing topology of quasicrystals with Fourier optics

  [Dareau *et al.*, arXiv:1607.00901

- Clock spectroscopy of interacting bosons in deep optical lattices

  [Bouganne *et al.*, arXiv:1707.04307

1. Orbital magnetism with ultracold atoms

2. Realizing Hofstadter optical lattices with an optical clock transition

3. Coherent spectroscopy on the clock transition

Orbital magnetism of electronic systems

Vector potential $\boldsymbol{A}$ in quantum mechanics : $\hat{H} = \frac{(\hat{\boldsymbol{p}}-q\boldsymbol{A})^2}{2m}$, $\boldsymbol{\nabla} \times \boldsymbol{A} = \boldsymbol{B}$

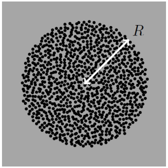
Electrons in a magnetic field exhibit many different and fascinating effects :

- Landau diamagnetism, Shubnikov-De Haas oscillations,
- Vortices in type II superconductors,
- Coherence in mesoscopic physics, ...
- Quantum Hall effect (integer and fractional)

Fractional Quantum Hall effect:

Emergence of strongly correlated phases of matter :

- incompressible liquids (gap)
- Exotic excitations with fractional charge and statistics ("anyons")
- Very similar Quantum Hall states are predicted for ultracold atomic gases [Cooper, Adv. Phys. 2008].



Laughlin state
Dubail, Read, Rezayi, PRB 2012

Key elements : flat dispersion relation and interactions

Aharonov-Bohm and geometric phases

Can we explore orbital magnetism with electrically neutral atoms ?

Vector potential $\boldsymbol{A}$ in quantum mechanics :

$$\hat{H} = \frac{(\hat{\boldsymbol{p}} - q\boldsymbol{A})^2}{2m}$$

$$\boldsymbol{\nabla} \times \boldsymbol{A} = \boldsymbol{B}$$

Aharonov-Bohm phase:

$$\phi_{\mathrm{AB}} = \frac{q}{\hbar}\int_{\mathcal{C}} \boldsymbol{A}\cdot d\boldsymbol{l} = \frac{q}{\hbar}\int_{\mathcal{S}} \boldsymbol{B}\cdot d\boldsymbol{\mathcal{S}}$$

What about neutral particles (atoms) ?

- Orbital magnetism can be simulated by generating geometric phases

$$\phi_{\mathrm{geo}} \equiv \frac{1}{\hbar}\int_{\mathcal{S}} (q\boldsymbol{B})_{\mathrm{eff}}\cdot d\boldsymbol{\mathcal{S}}$$

- Coherent atom-light coupling in quantum optics

Review articles : J. Dalibard, F. Gerbier, P. Ohberg, G. Juzeliunas, RMP 2011
N. Goldman, G. Juzeliunas, P. Ohberg, I. Spielman, Rep. Progress. Physics 2014

Harper Hamiltonian for a charged particle on a tight-binding lattice

Bulk :

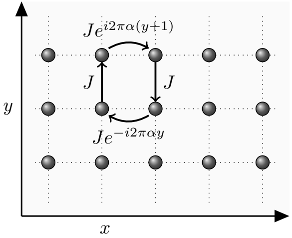
$$\hat{H} = \frac{(\hat{\boldsymbol{p}} - q\boldsymbol{A})^2}{2m}$$

$$\boldsymbol{\nabla} \times \boldsymbol{A} = \boldsymbol{B}$$

Tight-binding lattice :

$$H = -\sum_{\langle \boldsymbol{r}_i, \boldsymbol{r}_j \rangle} J e^{i\phi_{\mathrm{AB}}(\boldsymbol{r}_i \to \boldsymbol{r}_j)} \hat{a}_i^\dagger \hat{a}_j + \mathrm{h.c.}$$

J: single-particle tunnel energy



Landau gauge : $\boldsymbol{A} = -By\boldsymbol{e}_x$

Complex tunnel coefficients:

$$\phi_{\mathrm{AB}}(\boldsymbol{r}_i \to \boldsymbol{r}_j) = \frac{q}{\hbar}\int_{\boldsymbol{r}_i}^{\boldsymbol{r}_j} \boldsymbol{A} \cdot d\boldsymbol{l}$$

$$\alpha = \frac{|q|Bd^2}{h} = \frac{\text{Magnetic flux/unit cell}}{\text{Magnetic flux quantum}}$$

$$\alpha = \begin{cases} \sim 10^{-4} \text{ in usual solids with } \sim 50 \text{ T} \\ \sim 2\pi \text{ in solid-state superlattices or cold atoms.} \end{cases}$$

A quick glance at experiments

Two broad categories of experiments :

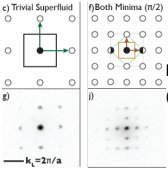
- "Quantum optics" approaches : internal states coupled by one or two-photon transitions [NIST 2008, Florence 2015]
- Floquet approach : [Pisa, Hamburg, Zürich, Chicago, Munich, MIT]

In all cases, break some symmetry of the "bare" lattice Hamiltonian and project onto a low-energy subspace.

Observation of single-particle effects

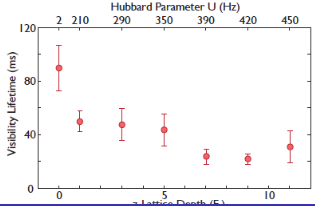
BEC reported only for $\alpha = 1/2$

- 2D : Aidelsburger *et al.*, PRL 2011, Struck *et al.*, Nature Physics 2012.
- 3D : Kennedy *et al.*, Nature Physics 2015.



Kennedy *et al.* (MIT 2015)

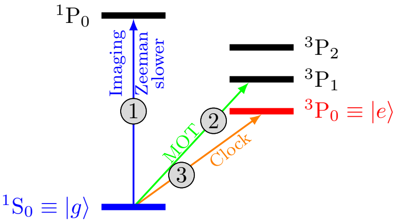
- Heating generally observed
- short BEC lifetime ($\sim 50\,$ms)



Optical atomic clock technology for many-body physics

Metastable excited state :

- "clock" transition 3 :
  $J = 0 \to J' = 0$,
- virtually no spontaneous emission $\to$ coherent manipulation,



- New generation of optical atomic clocks with frequency stability $\lesssim 10$ mHz (quality factor $\frac{\overline{\nu}}{\Delta\nu} \gtrsim 10^{17}$)

- $N-$component Fermi gases with **symmetric** interactions :
  novel many-body problems : $N \leq 6$ for ^{173}Yb, $N \leq 10$ for ^{87}Sr.

Photon recoil couples internal and external quantum states :

- spin-orbit coupling with fermions [LENS, JILA 2016]

- Artificial magnetic fields : Hofstadter optical lattices [Gerbier/Dalibard , NJP 2010].

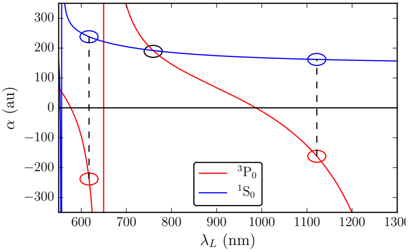
Ytterbium and clock transition

State-dependent optical potentials :

Tailored trapping potentials (without heating, unlike alkali atoms)

Potential for quantum information processing and emulation of many-body systems

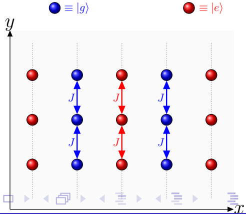
Electric polarizabilities for g and e



Dzuba, Derevianko, J. Phys. B(2010)

State-dependent 2D optical lattice :

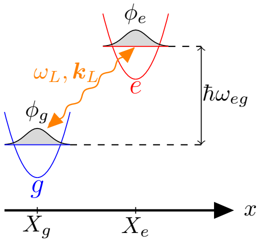
- y lattice at "magic" wavelength : $V_e(y) = V_g(y)$
- x lattice at "anti-magic" wavelength : $V_e(x) = -V_g(x)$
- regular tunneling along y



Laser-induced tunneling in a state-dependent optical lattice

Proposal for alkali atoms in [Jaksch and Zoller, NJP 2003]

- two internal states g and e
- state-dependent potential confining the atoms at **distinct places** depending on their internal state



Coupling laser $|g; \boldsymbol{R}_g\rangle \rightarrow |e; \boldsymbol{R}_e\rangle$:

- resonant $\omega_L = \omega_{eg}$
- plane wave with wavevector $\boldsymbol{k}_L$
- electric field $\boldsymbol{E}_0 e^{i\boldsymbol{k}_L\cdot\boldsymbol{r}}$

Transition matrix elements :

$$\langle e; \boldsymbol{R}_e|\hat{V}_{AL}|g; \boldsymbol{R}_g\rangle = \underbrace{\langle e| - \hat{\boldsymbol{d}}\cdot\boldsymbol{E}_0|g\rangle}_{\text{internal}}\underbrace{\langle\boldsymbol{R}_e|e^{i\boldsymbol{k}_L\cdot\hat{\boldsymbol{r}}}|\boldsymbol{R}_g\rangle}_{\text{external}} \propto e^{i\boldsymbol{k}_L\cdot\frac{\boldsymbol{R}_g+\boldsymbol{R}_e}{2}}$$

Not enough to get $\oint \boldsymbol{A}\cdot\boldsymbol{dl} \neq 0$, but good starting point !

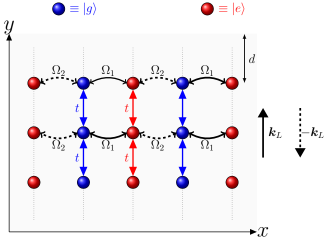
Hofstadter optical lattice for Ytterbium atoms

State-dependent optical lattice :

- regular tunneling along y
- laser-induced along x
- additional superlattice along x

$\Longrightarrow$ Harper Hamiltonian for low energies

[Gerbier/Dalibard , NJP 2010].



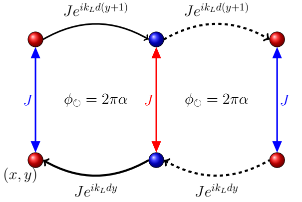
Effective Aharonov-Bohm phase :

$$\phi_{\mathrm{AB}}(\boldsymbol{r}_i \to \boldsymbol{r}_i + \boldsymbol{e}_x) = \boldsymbol{k}_L \cdot \boldsymbol{r}_i \equiv 2\pi\alpha y$$

Maximum “Flux” per unit cell:

$$2\pi\alpha_{\max} = k_L d \sim 2\pi \times 0.66$$

α can be varied between 0 and $\alpha_{\max}$ by changing the orientation of the clock laser.



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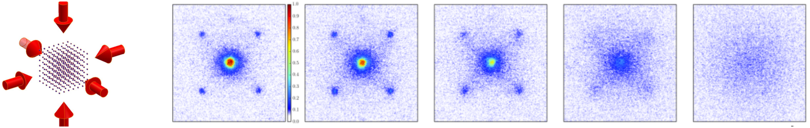
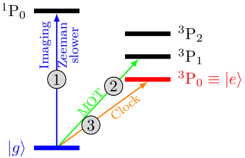
Quantum-degenerate ^{174}Yb atoms in a 3D optical lattice

Superfluid-Mott insulator transition :

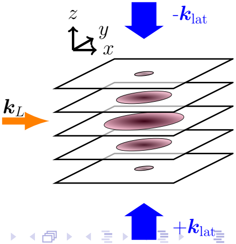


Spectroscopy on the clock transition :

- "magic" optical lattice : **identical for both internal states** g/e
- selective detection of g, e or both together

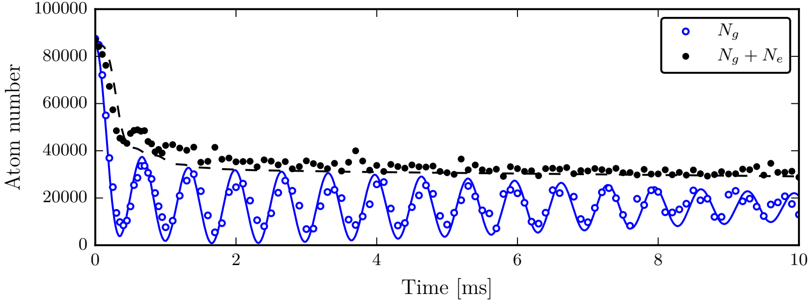


- Lattice depth $V \approx 30\,E_R$: negligible tunneling
- about 20 planes
- $N \sim 8 \cdot 10^3$ in central plane



Rabi spectroscopy on the clock transition : time domain

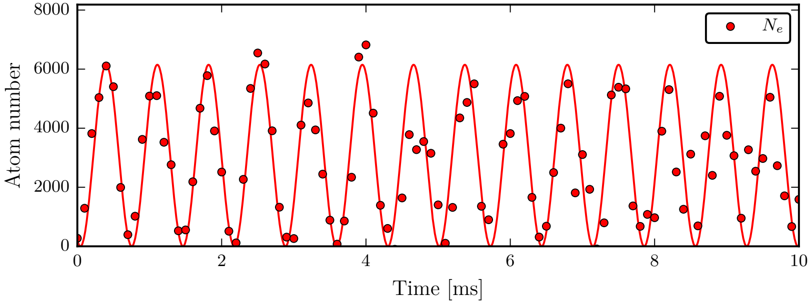
Strong driving: Rabi oscillations of a BEC in the optical domain



High initial atom number : $N \approx 8 \times 10^4$

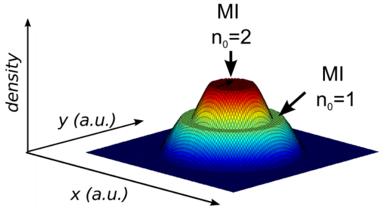
Rabi spectroscopy on the clock transition : time domain

Strong driving: Rabi oscillations of a BEC in the optical domain

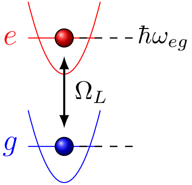


Low initial atom number : $N \approx 8 \times 10^3$

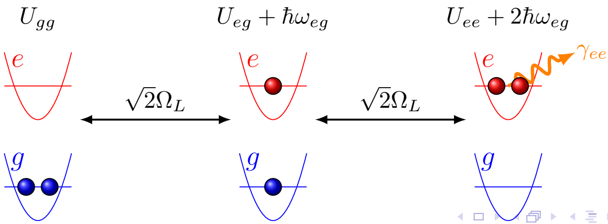
Optical spectroscopy in a Mott insulator



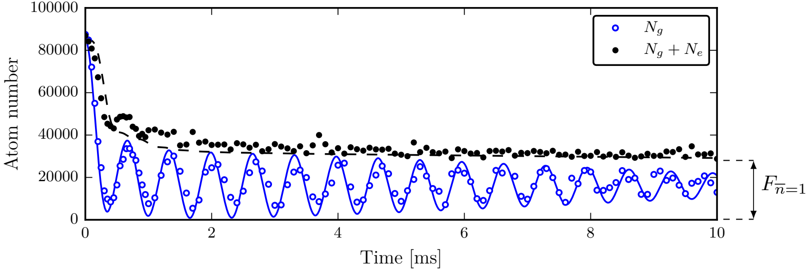
Singly-occupied sites :



Doubly-occupied sites :



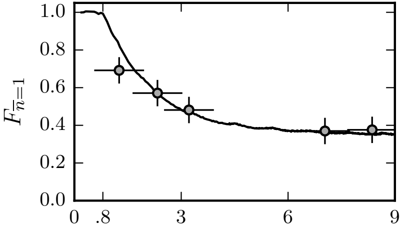
Probing the atomic distribution



Proportion of singly-occupied sites:

Solid line : model of the loading assuming

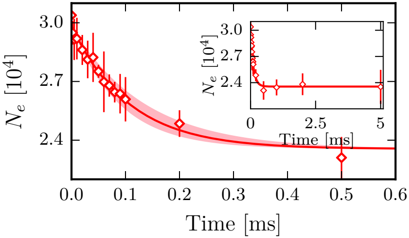
- $T = 0$
- adiabatic loading
- decay of triply-occupied sites (three-body recombination in g)



Inelastic decay and dephasing

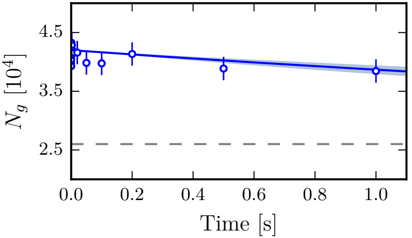
- Doubly-occupied sites decay by inelastic collisions ($\leftrightarrow$ "T_1"):

Decay of $|ee\rangle$:



$\gamma_{ee} \approx U_{gg}/\hbar$

Decay of $|eg\rangle$:



$\gamma_{ge} < 10^{-3} U_{gg}/\hbar$

- Inhomogeneous coupling $\Omega_L(\boldsymbol{r})$ ($\leftrightarrow$ "T_2"):

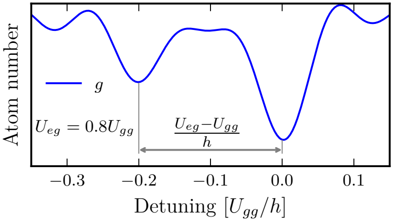
$$\frac{1}{T_{2,\mathrm{inhom.}}} \sim \Omega_L(0)\frac{R^2}{w^2}$$

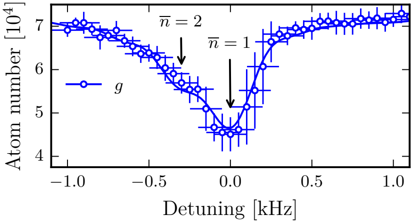
Explains dephasing for $N \approx 8 \times 10^4$: $R \approx 19\,\mu$m, $T_{2,\mathrm{inhom.}} \approx 9$ ms
Negligible for $N \approx 8 \times 10^3$: $R \approx 8\,\mu$m, $T_{2,\mathrm{inhom.}} \approx 50$ ms

- Clock laser frequency fluctuations $\delta\omega_L(\boldsymbol{r}) \lesssim 2\pi \times 100$ Hz ($\leftrightarrow$ "T_2^*")

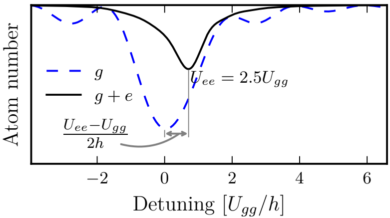
Rabi spectroscopy on the clock transition : frequency domain

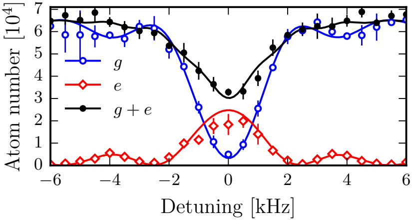
Weak-coupling resonance for doubly-occupied sites:





Strong-coupling resonance for doubly-occupied sites:





Inelastic losses in state-dependent lattice

Typical values for lattice depth $V_0 = 10\,E_R$:

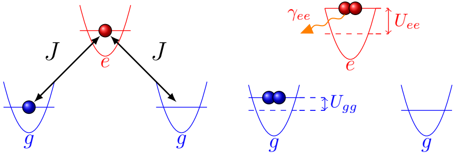
- $J/h \sim 70\,\text{Hz}$,
- $U_{gg}/h \sim 1\,\text{kHz}$,
- $\gamma_{ee}[n=2] \sim U_{gg}/\hbar$

Zeno-like supression of losses:

Three-well model, unit filling, $U_{ii} \gg J$:

Effective loss rate in the one-particle subspace

$$\gamma_{\text{eff}} \approx \frac{2J^2\gamma_{ee}}{U_{ee}^2 + \left(\frac{\hbar\gamma_{ee}}{2}\right)^2} \ll \gamma_{ee}$$



$$U_{ee} \approx \gamma_{ee} \approx U_{gg} \implies \gamma_{\text{eff}} \approx 2\frac{J^2}{\hbar U_{gg}} \ll \frac{J}{\hbar} \ll U_{ii}, \gamma_{ee}$$

Towards atomic fractional Quantum Hall states ?

Relevant parameter :

$$\nu = \frac{\text{atomic density}}{\text{flux per unit cell}} = \frac{n}{\alpha}$$

- Analogue of continuum ($\equiv$ Lowest Landau level) states exist.

Example : Laughlin states

- fermions : $\nu = \frac{1}{3}, \cdots$
- bosons : $\nu = \frac{1}{2}, \cdots$

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

- Many possible states without continuum counterparts [Möller and Cooper, PRL 2009].

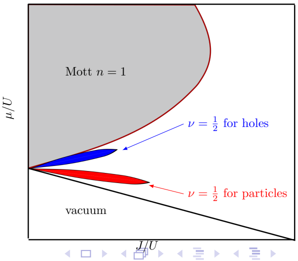
Example for $\alpha = \frac{1}{5}$:

- Laughlin state for particles at $n = \frac{1}{10}$
- Laughlin state for holes at $n = 1 - \frac{1}{10}$

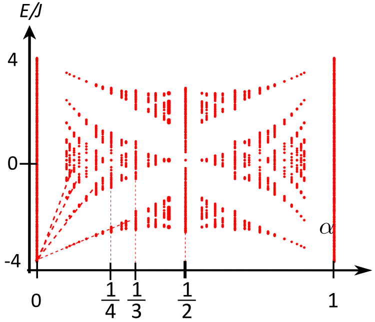
Gaps are small :

at most $\sim 0.1J$ for the $\nu = \frac{1}{2}$ bosonic Laughlin state [Hafezi et al., PRA 2007]

Narrow slices in the global phase diagram



Hofstadter butterfly



Energy spectrum vs flux :

Flux per unit cell : $2\pi\alpha$

- Fragmentation of the Bloch bands
- wide gaps, flat bands

Rational flux $\alpha = p/q$:

Magnetic unit cell $(1 \times q)$: q topological bands with Chern number $\mathcal{C} \neq 0$: