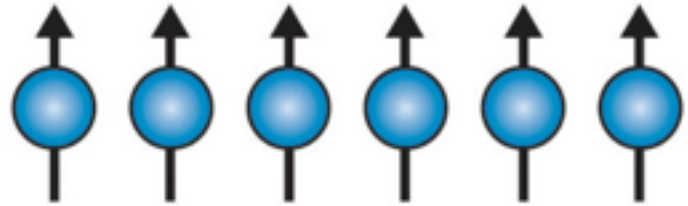

Orbital physics as a route to simulating quantum magnetism with optical lattices

Jonas Larson

Stockholm University and Universität zu Köln

SYQMA15 workshop, Dresden 4/9-2015

Motivation

1. Orbital physics is crucial for understanding transition metal oxides.
2. Spin-orbital exchanges (Kugel-Khomskii couplings) may lead to frustration.
3. KK couplings $\longrightarrow$ novel spin ordering.
4. Frustration (massive degeneracy) may prevent long range order $\longrightarrow$ spin liquids.

Outlook

1. Orbital physics with cold atoms. Introducing higher bands.
2. State-of-the-art.
3. Simulating spin models.

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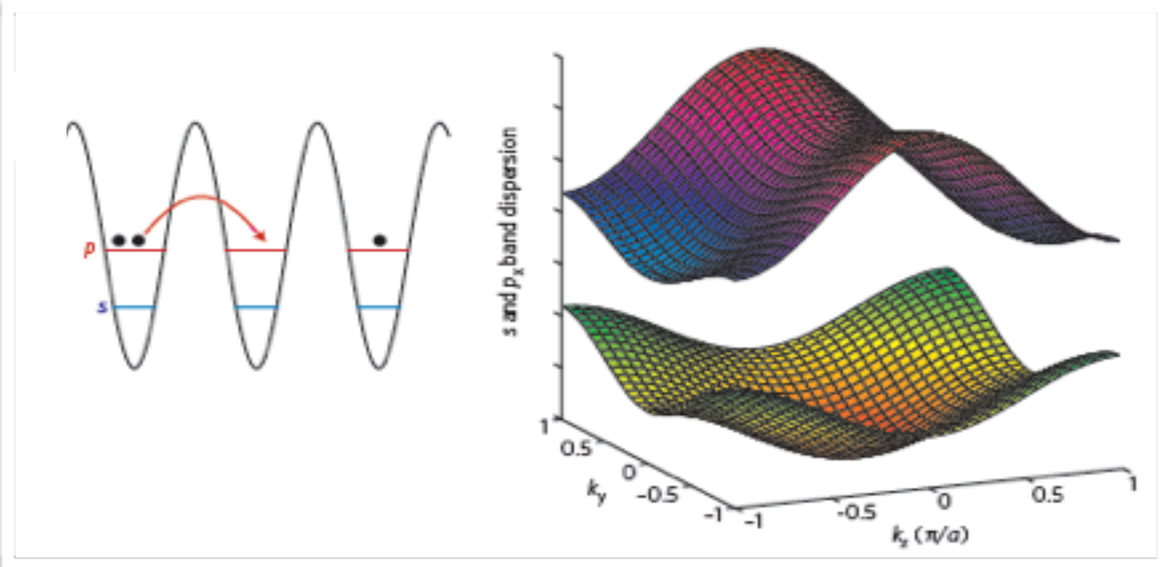
Orbital physics with cold atoms

Higher bands



Two lowest bands in a 2D square lattice.

Isotropic separable lattice ⟶ onsite states (orbitals) degenerate on higher bands.

Lowest band: s orbital, first excited bands: p_x, p_y, p_z orbitals

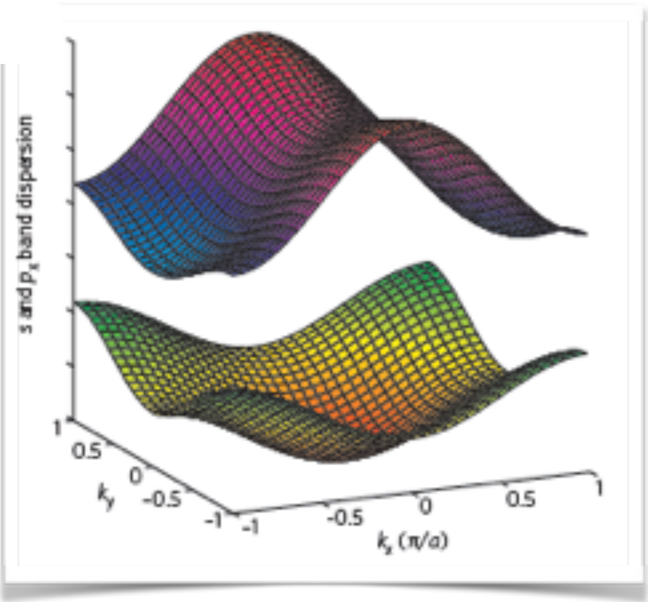
Degeneracy important ingredient

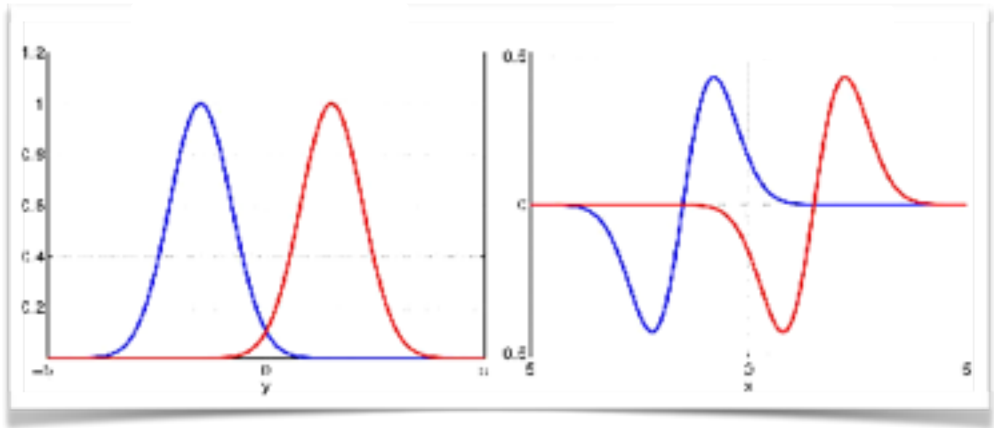
M. Lewenstein and W. V. Liu, Nat. Phys. **7**, 101 (2011); X. Li and W. V. Liu, arXiv:1508.06285.

Orbital physics with cold atoms

p-orbitals

The anomalous band-structure ⟶ orbital structure





1D Wannier functions $w_{\alpha,i}(\vec{r})$ at neighbouring sites for the s-band and p-band.

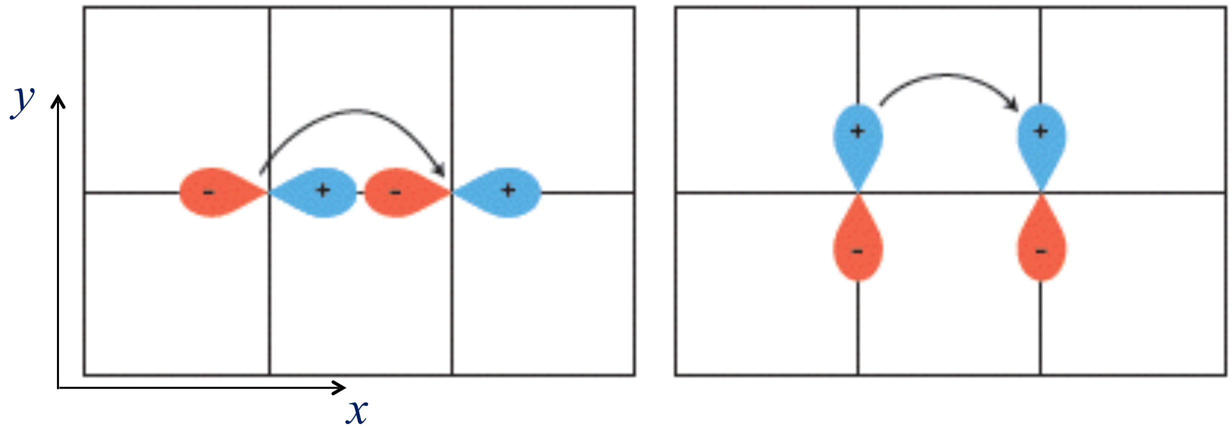
Node for the p-orbitals.

M. Lewenstein and W. V. Liu, Nat. Phys. **7**, 101 (2011); X. Li and W. V. Liu, arXiv:1508.06285.

Orbital physics with cold atoms

p-orbitals

2D isotropic square lattice; *p*-band doubly degenerate



p_x-orbital $\quad$ p_y-orbital

Tunneling anisotropic:

$$\begin{cases} t_{xx} = t_{yy} < 0, \\ |t_{xx}| > t_{xy}, \\ t_{xy} = t_{yx} > 0. \end{cases}$$

M. Lewenstein and W. V. Liu, Nat. Phys. **7**, 101 (2011); X. Li and W. V. Liu, arXiv:1508.06285.

p-orbitals

Orbital physics with cold atoms

Mean-field solution 2D

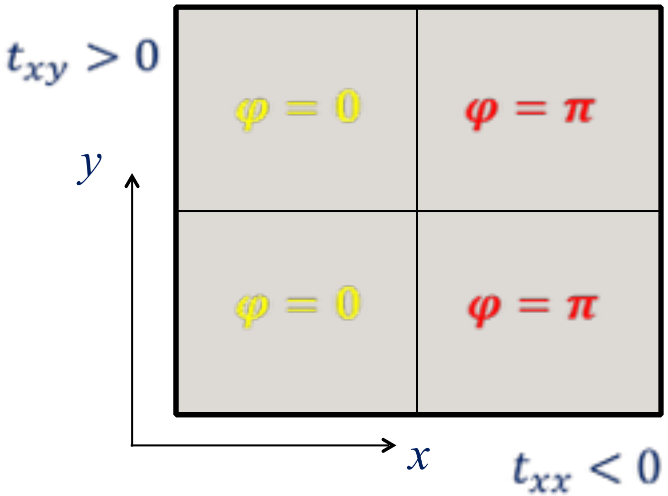
Vortex solution

Minimizing interaction energy:

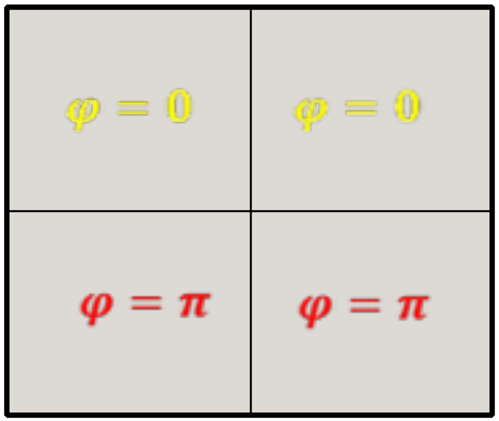
$$w_{x\mathbf{i}}(\vec{r}) \pm i w_{y\mathbf{i}}(\vec{r})$$

Minimizing kinetic energy: sign of tunneling determines phase order

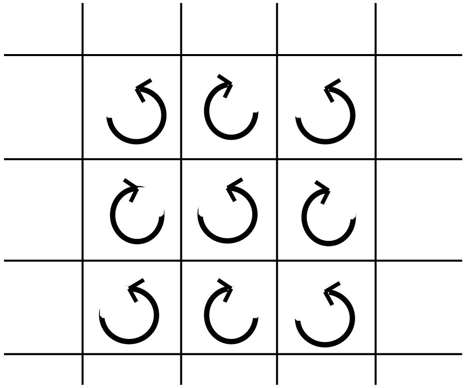
p_x-flavor



p_y-flavor



Vortex checkerboard



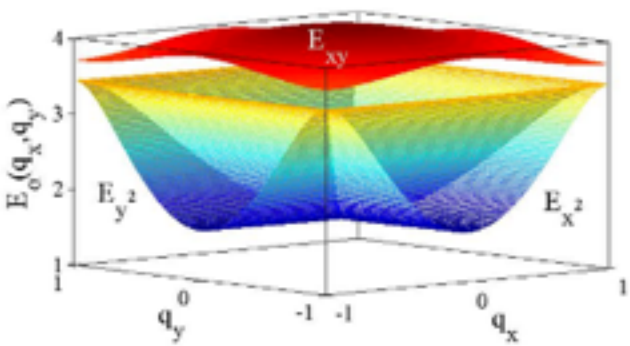
A. Collin, J. Larson, and J.-P. Martikainen, PRA **81**, 023605 (2010).

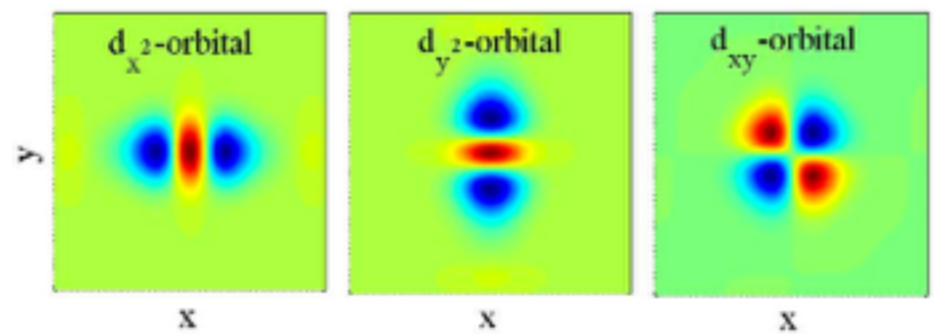
d-orbitals

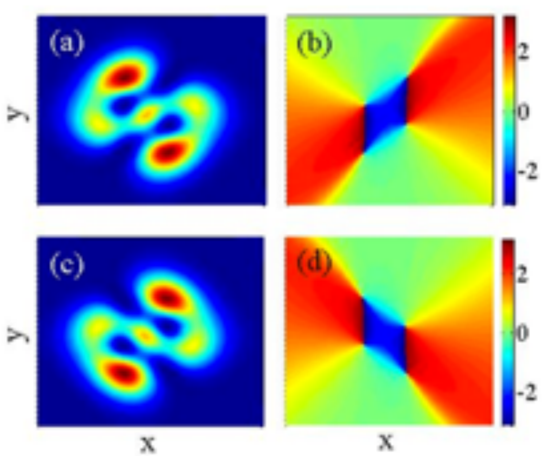
Orbital physics with cold atoms

Mean-field solution 2D

Three orbitals







Two vortex/anti-vortex pairs on every site.

Neighbouring sites, flipped ‘order’.

F. Pinheiro, J.-P. Martikainen, and J. Larson NJP **17**, 053004 (2015).

p-orbitals

Orbital physics with cold atoms

Onsite s-wave scattering interaction

Density-density, p_x-orbitals:

$$\frac{U_{xx}}{2}\hat{n}_x\left(\hat{n}_x-1\right)$$

Density-density, p_xp_y-orbitals:

$$U_{xy}\hat{n}_x\hat{n}_y$$

Flavor changing, p_xp_y-orbitals:

$$\frac{U_{xy}}{2}\left(\hat{a}_x^\dagger\hat{a}_x^\dagger\hat{a}_y\hat{a}_y+\hat{a}_y^\dagger\hat{a}_y^\dagger\hat{a}_x\hat{a}_x\right)$$

Orbital physics with cold atoms

p-orbitals

Orbital Bose-Hubbard model

$$\hat{H} = \hat{H}_{kin} + \hat{H}_{dd} + \hat{H}_{oc}$$

Kinetic term:

$$\hat{H}_{kin} = -\sum_{\alpha\beta}\sum_{\langle \mathbf{ij}\rangle} t_{\alpha\beta}\hat{a}^{\dagger}_{\alpha\mathbf{i}}\hat{a}_{\beta\mathbf{j}}$$

Density-density:

$$\hat{H}_{dd} = \sum_{\alpha}\sum_{\mathbf{i}} \frac{U_{\alpha\alpha}}{2}\hat{n}_{\alpha\mathbf{i}}\left(\hat{n}_{\alpha\mathbf{i}} - 1\right) + \sum_{\alpha\beta,\alpha\neq\beta}\sum_{\mathbf{i}} U_{\alpha\beta}\hat{n}_{\alpha\mathbf{i}}\hat{n}_{\beta\mathbf{i}}$$

Orbital changing:

$$\hat{H}_{oc} = \sum_{\alpha\beta,\alpha\neq\beta}\sum_{\mathbf{i}} \frac{U_{\alpha\beta}}{2}\left(\hat{a}^{\dagger}_{\alpha\mathbf{i}}\hat{a}^{\dagger}_{\alpha\mathbf{i}}\hat{a}_{\beta\mathbf{i}}\hat{a}_{\beta\mathbf{i}} + h.c.\right)$$

A. Isacsson and S. M. Girvin, PRA **72**, 053604 (2005).

Outlook

1. Orbital physics with cold atoms. Introducing higher bands.
2. State-of-the-art.
3. Simulating spin models.

State-of-the-art

PRL 99, 200405 (2007) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2007

State Preparation and Dynamics of Ultracold Atoms in Higher Lattice Orbitals

Torben Müller,[1,2] Simon Fölling,[1] Artur Widera,[1] and Immanuel Bloch[1,*]
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(Received 22 March 2007; published 16 November 2007)

We report on the realization of a multiorbital system with ultracold atoms in the excited bands of a 3D optical lattice by selectively controlling the band population along a given lattice direction. The lifetime of the atoms in the excited band is found to be considerably longer (10–100 times) than the characteristic time scale for intersite tunneling, thus opening the path for orbital selective many-body physic[s with] ultracold atoms. Upon exciting the atoms from an initial lowest band Mott-insulating state to highe[r] bands, we observe the dynamical emergence of coherence in 1D (and 2D), compatible with Bose-E[instein] condensation to a nonzero momentum state.

nature physics

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NATURE PHYSICS | ARTICLE

Evidence for orbital superfluidity in the *P*-band of a bipartite optical square lattice

Georg Wirth, Matthias Ölschläger & Andreas Hemmerich

...s | Corresponding author

...3 (2011) | doi:10.1038/nphys1857
... | Accepted 21 October 2010 | Published online 12 December 2010

Effective preparation and collisional decay of atomic condensate in excited bands of an optical lattice

Yueyang Zhai,[1] Xuguang Yue,[1] Yanjiang Wu,[2] Xuzong Chen,[1] Peng Zhang,[2,*] and Xiaoji Zhou[1,†]
[1]*School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, China*
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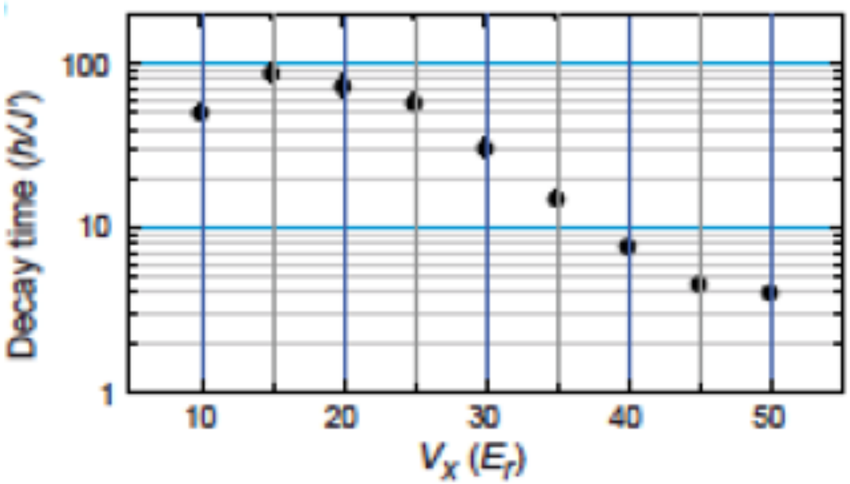
We present a method for the effective preparation of a Bose-Einstein condensate (BEC) into the excited bands of an optical lattice via a standing-wave pulse sequence. With our method, the BEC can be prepared in either a single Bloch state in a excited-band, or a coherent superposition of states

State-of-the-art

Bloch square/cubic preparation

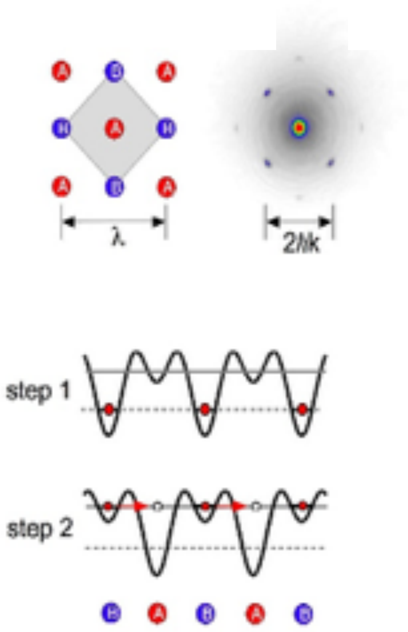


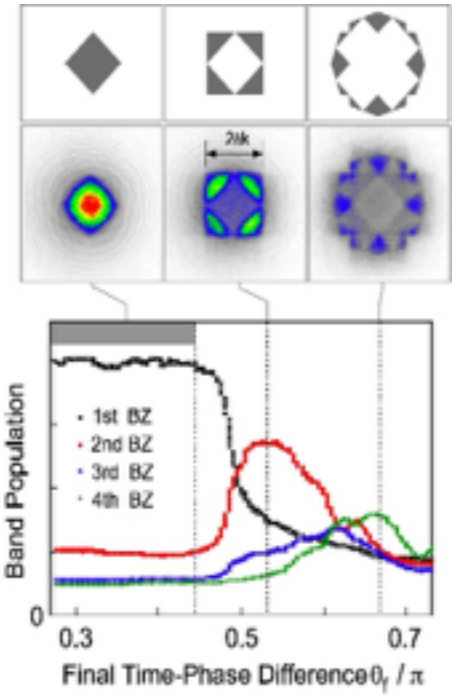
- Raman coupling between s to p_x or $p_x + p_y$.
- Lifetime $\leq$100*t*.
- Coherence in 2D and 3D.
- Decay from scattering $2p \to s + d$.
- Up to 5 times longer lifetime for $n = 1$

T. Müller *et al*. Phys. Rev. Lett **99**, 200405 (2007).

State-of-the-art

Hemmerich superlattice quench





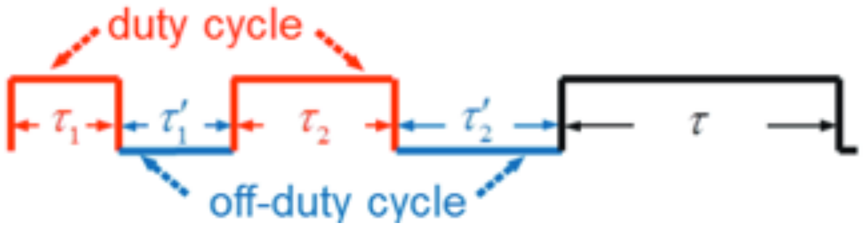
- Superlattice.
- Quench ⟶ hybridising *s*- and *p*-orbitals.
- Coherence.
- Complex order parameter.

G. Wirth *et al*. Nature Phys. **7**, 147 (2011).

State-of-the-art

Zhou non-adiabatic d-band loading

- On/off an optical lattice, optimising the pulse sequence to reach a target state.



- 1D, 98% fidelity of preparing the *d*-band!
- Coherent dynamics.
- Decay rate ~100 μs.

Y. Zhai *et al*. Phys. Rev A **87**, 063638 (2013).

Outlook

1. Orbital physics with cold atoms. Introducing higher bands.
2. State-of-the-art.
3. Simulating spin models.

Simulating spin models

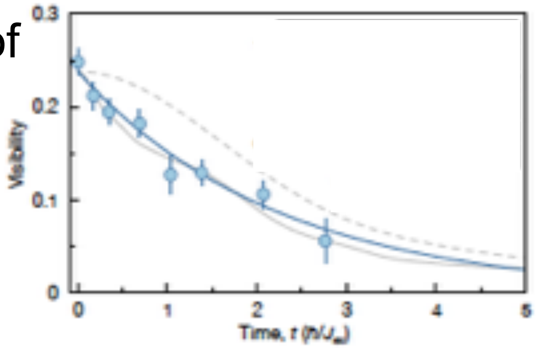
- Duan, Demler, and Lukin: Multi-component atoms, *n*=1 Mott.

$$\hat{H} = -\sum_{\langle ij\rangle\sigma} t_\sigma \left(\hat{a}^\dagger_{\sigma i}\hat{a}_{\sigma i} + h.c.\right) + \sum_{i\sigma}\frac{U_\sigma}{2}\hat{n}_{\sigma i}\left(\hat{n}_{\sigma i}-1\right) + U_{\uparrow\downarrow}\sum_i \hat{n}_{\uparrow i}\hat{n}_{\downarrow i}$$

⇒ *XXZ* Heisenberg spin model.

PRL **91**, 090402 (2003).

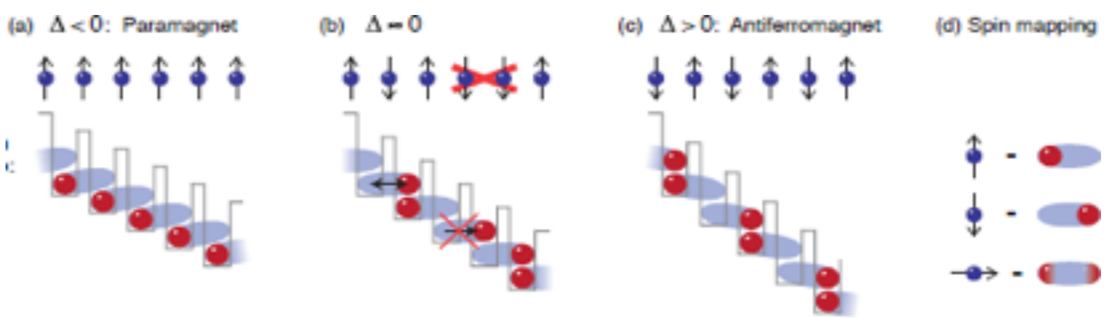
- Bloch *et al.* Mott $n=1$, decay of spin order.



⇒ *XXZ* Heisenberg spin model.

PRL **113**, 147205 (2014).

- Greiner *et al.* Tilted lattice - balance between onsite/interaction energy.



⇒ Transverse Ising model.

Nature **472**, 307 (2011).

Simulating spin models

- Mott insulator n=1 ⇨ *Strong coupling expansion,* $\mathcal{O}\left(t^2/U^2\right)$, superexchange interaction.
- Schwinger mapping ⇨ orbital to spin degrees of freedom.
- Fermion/boson statistics ⇨ ferro/anti-ferromagnetic models.
- Orbital changing interaction

$$\hat{H}_{oc}=\sum_{\alpha\beta,\alpha\neq\beta}\sum_{\mathbf{i}}\frac{U_{\alpha\beta}}{2}\left(\hat{a}_{\alpha\mathbf{i}}^{\dagger}\hat{a}_{\alpha\mathbf{i}}^{\dagger}\hat{a}_{\beta\mathbf{i}}\hat{a}_{\beta\mathbf{i}}+h.c.\right)$$

breaking continuous symmetry (possibly integrability), richer phase diagrams.

X. Li, Z. Zhang, and W. V. Liu, PRL **108**, 175302 (2012).
F. Pinheiro, G. M. Bruun, J.-P. Martikainen, and J. Larson, PRL **111**, 205302 (2013).

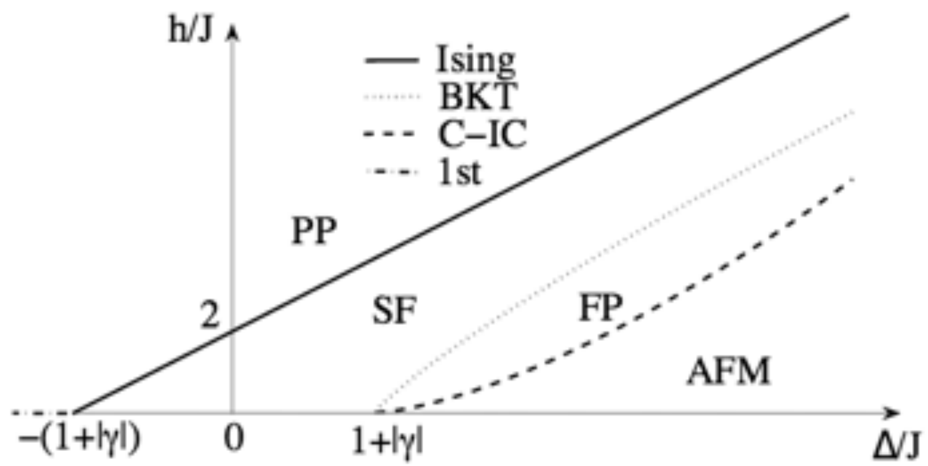
Simulating spin models

1D/2D square lattice, p-band

- Two orbitals, p_x and p_y ⟹ Heisenberg XYZ spin-1/2

$$\hat{H}_{XYZ}/J = \sum_{\langle ij \rangle} \left[(1+\gamma)\hat{S}_i^x \hat{S}_j^x + (1-\gamma)\hat{S}_i^y \hat{S}_j^y \right] + \Delta \hat{S}_i^z \hat{S}_j^z + h \sum_i \hat{S}_i^z$$

- 1D phase diagram
- Trapped ion techniques:
    - Parameter control
    - Preparation
    - Single-site addressing.



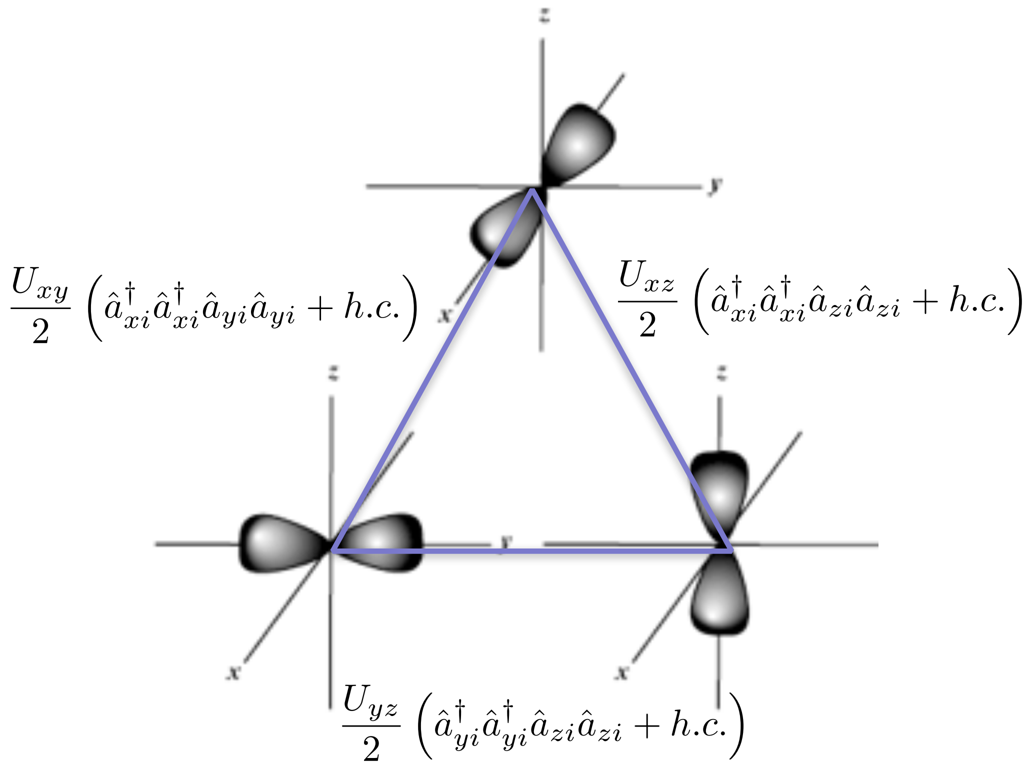
PP = polarized phase, SF = spin flop phase
FP = floating phase, AFM = anti-ferromagnetic.

F. Pinheiro, G. M. Bruun, J.-P. Martikainen, and J. Larson, PRL **111**, 205302 (2013).

Simulating spin models

3D cubic lattice, p-band

- Three orbitals, p_x, p_y and p_z ⇨ "*XYZ*" $SU(3)$ model, Gell-Mann matrices.
- Frustrated.
- Striped orders.
- Spiral spin order.



T. A. Toth *et al.*, PRL **105**, 265301 (2010); T. Grass *et al.*, PRB **90**, 195127 (2014); F. Pinheiro, arXiv:1410.7828.

Simulating spin models

2D square lattice, d-band

- Three orbitals, d_{x^2}, d_{y^2} and d_{xy}.
- Low filling, only d_{x^2} and d_{y^2} populated ⇨ *XYZ* model.

$$\hat{H}_{XYZ}/J = \sum_{\langle ij \rangle} \left[(1+\gamma)\hat{S}_i^x \hat{S}_j^x + (1-\gamma)\hat{S}_i^y \hat{S}_j^y \right] + \Delta \hat{S}_i^z \hat{S}_j^z + \sum_i h\hat{S}_i^z + \Gamma \hat{S}_i^x$$

- $\mathbb{Z}_2$ symmetry broken.
- $h=0$, "new" $\mathbb{Z}_2$ symmetry.

F. Pinheiro, J.-P. Martikainen, and J. Larson, NJP **17**, 053004 (2015).

Simulating spin models

Non-seperable lattices, p-band

- In the basis of natural orbits, p_x, p_y and p_z tunnelling terms

$$-\sum_{\alpha\beta,\alpha\neq\beta}\sum_{\langle ij\rangle} t_{\alpha\beta}\hat{a}^{\dagger}_{\alpha i}\hat{a}_{\beta j}$$

- Simulating spin-orbit couplings, $SU(2)$ and $SU(3)$.

- Spin language, *Dzyaloshinskii-Moriya* interactions. *Spin canting effect*?

A. Gagge and J. Larson, in preparation.

Open questions

- Not perfect loading, atoms remain on the *s*-band. Glass phases? Localized phases?
- Stabilize the states. Non-trivial orbital states the lowest energy states.
- Finite temperature across the Mott-SF transition.
- Spinor atoms, $SU(N) \times SU(M)$ models.


Thanks!