Spontaneous breaking of the time-reversal symmetry in optical lattices

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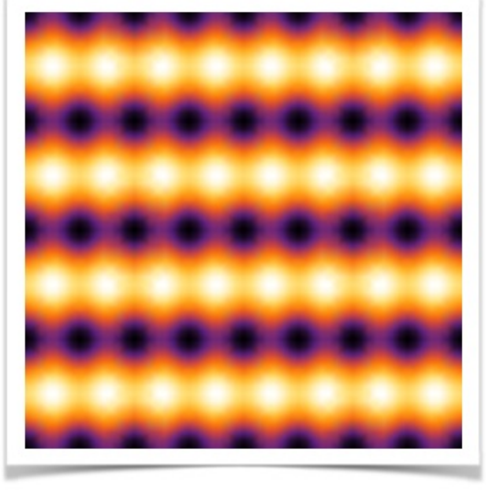
1D optical chain (with p-band degeneracy)

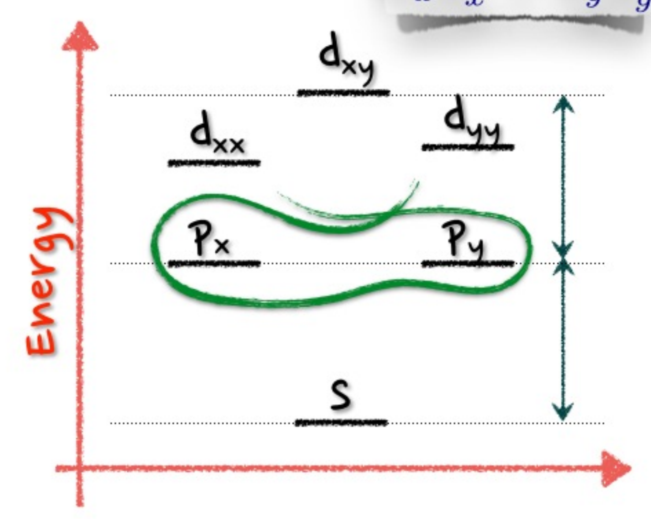
$$V(x,y) = V_x \sin^2(k_x x) + V_y \sin^2(k_y y)$$

in non-symmetric rectangular optical lattice
it is possible to obtain the degeneracy between
single-particle orbitals in p-band
by a proper adjustment of the lattice parameters

in harmonic approximation

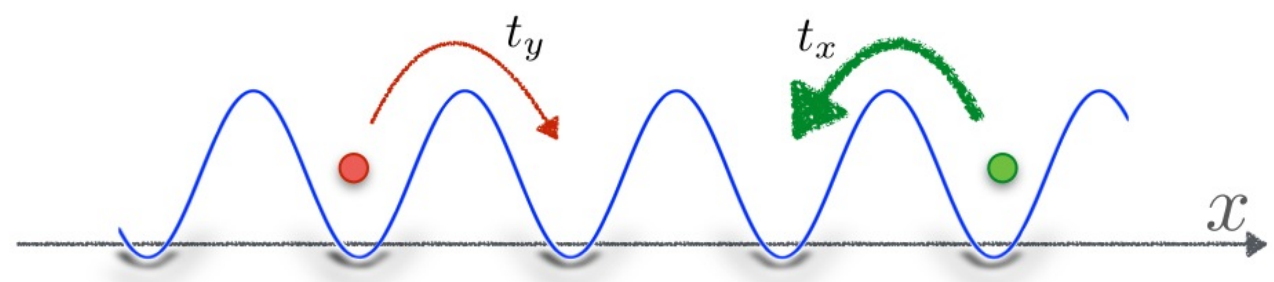
$$V_x k_x^2 = V_y k_y^2$$





single-particle tunnelings

$$\hat{\mathcal{H}} = \sum_i \hat{H}(i) - \sum_{\langle ij \rangle} \left[t_x \hat{a}^\dagger_x(i)\hat{a}_x(j) + t_y \hat{a}^\dagger_y(i)\hat{a}_y(j) + h.c.\right]$$



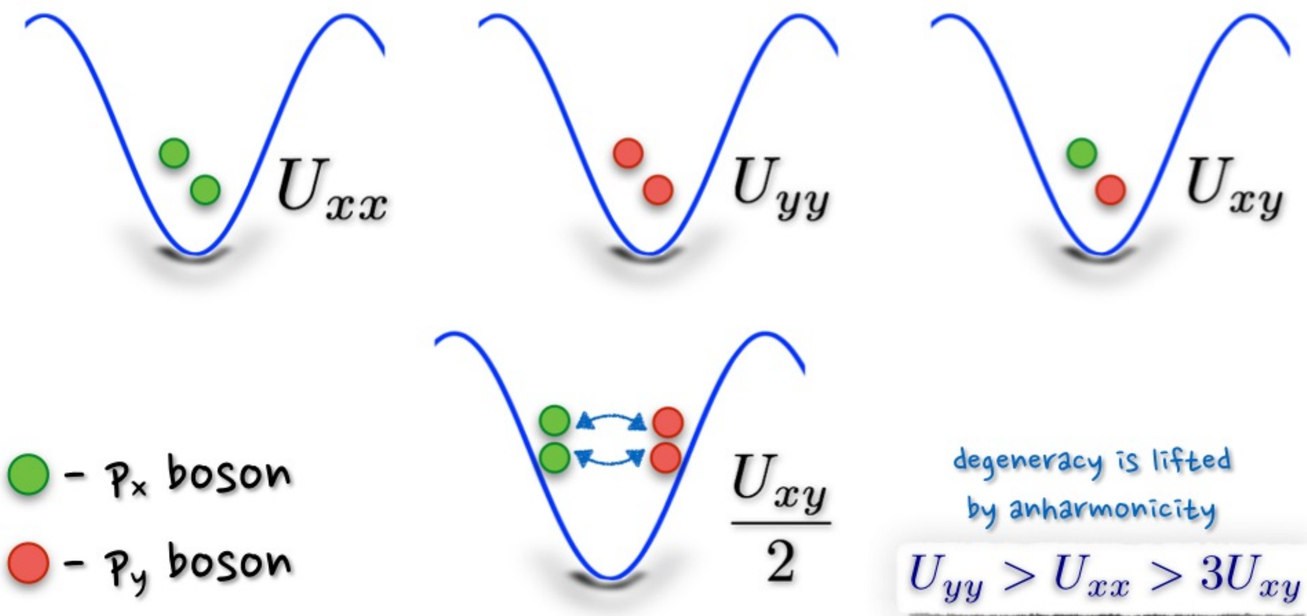
$$|t_x| > |t_y|$$

- p_x boson
- p_y boson

two-particle interactions

$$\hat{H}(i) = \frac{U_{xx}}{2}\hat{n}_x(i)(\hat{n}_x(i)-1) + \frac{U_{yy}}{2}\hat{n}_y(i)(\hat{n}_y(i)-1) + \frac{U_{xy}}{2}\left[4\hat{n}_x(i)\hat{n}_y(i) + \hat{a}^\dagger_x(i)^2\hat{a}_y(i)^2 + \hat{a}^\dagger_y(i)^2\hat{a}_x(i)^2\right]$$

local Hamiltonian



- p_x boson
- p_y boson

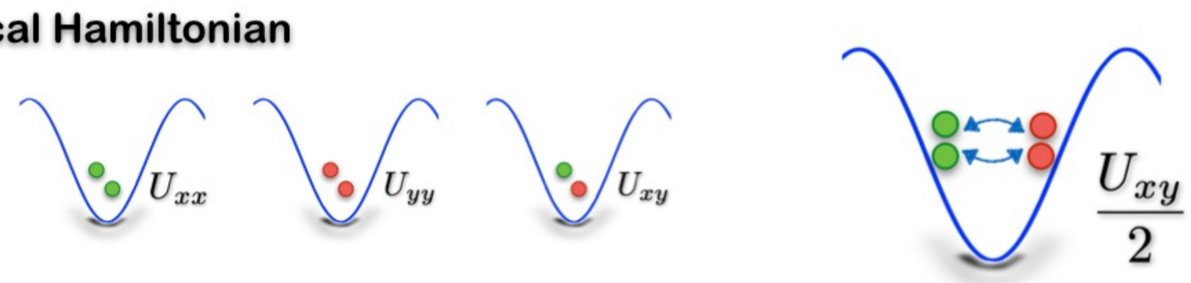
degeneracy is lifted
by anharmonicity

$$U_{yy} > U_{xx} > 3U_{xy}$$

p-orbital physics

$$\hat{\mathcal{H}} = \sum_i \hat{H}(i) - \sum_{\langle ij \rangle} \left[t_x \hat{a}^\dagger_x(i)\hat{a}_x(j) + t_y \hat{a}^\dagger_y(i)\hat{a}_y(j) + h.c.\right]$$

local Hamiltonian



total number of particles is conserved

$$\left[\hat{\mathcal{H}}, \hat{N}_x + \hat{N}_y\right] = 0$$

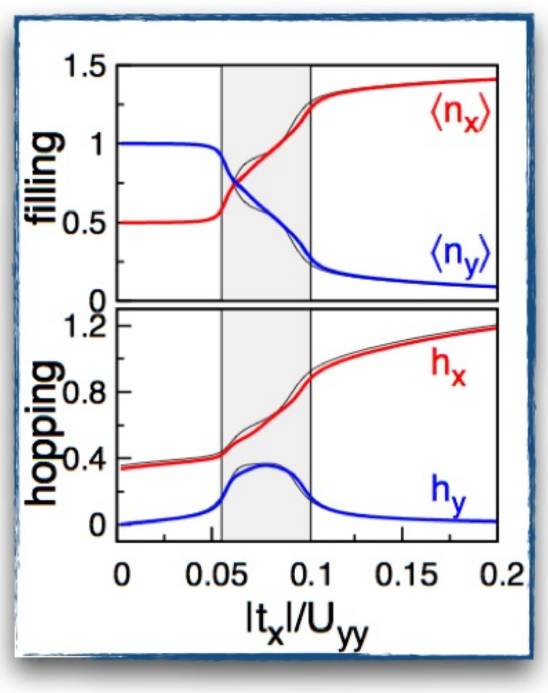
$$\hat{N}_x = \sum_i \hat{n}_x(i) \qquad \hat{N}_y = \sum_i \hat{n}_y(i)$$

additional symmetry of the system

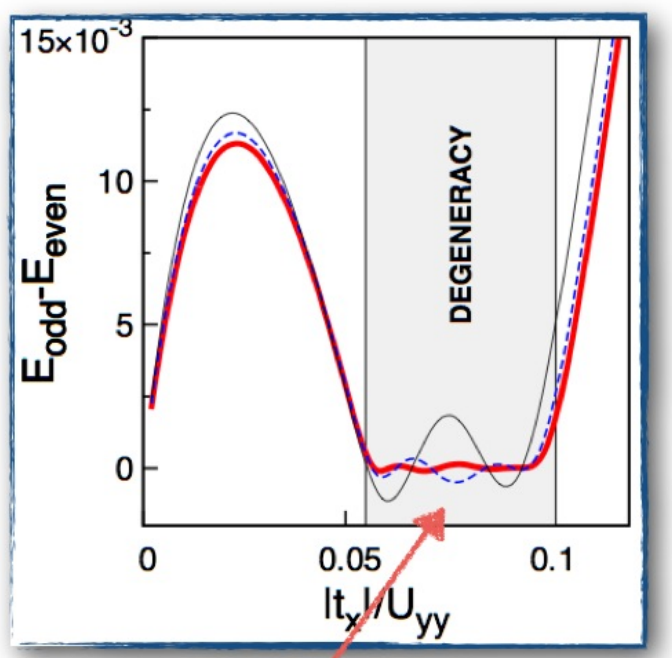
$$\hat{\mathcal{S}} = \exp(i\pi\hat{N}_y)$$

p-orbital physics

3/2 filling



$$h_x = \langle G|\hat{a}^\dagger_x(i)\hat{a}^\dagger_x(i+1)|G\rangle$$
$$h_y = \langle G|\hat{a}^\dagger_y(i)\hat{a}^\dagger_y(i+1)|G\rangle$$



two-fold degeneracy
of the many-body ground state

$|G_{odd}\rangle$ $|G_{even}\rangle$

region of restored degeneracy

two-fold degeneracy
of the many-body ground state

$$|G\rangle = \cos\theta|G_{odd}\rangle + \sin\theta e^{i\varphi}|G_{even}\rangle$$

many-body ground state
in the thermodynamic limit

Chosen ground state should be as close
to the product state as possible

Einselection principle
W. H. Żurek, Rev. Mod. Phys. 75, 715 (2003)

entanglement entropy for single lattice site

$$S(\theta,\varphi) = \sum_i \lambda_i \log\lambda_i$$

eigenvalues of the single-site
reduced density matrix

$$|G_\pm\rangle = \frac{|G_{odd}\rangle \pm i|G_{even}\rangle}{\sqrt{2}}$$

properties of the ground-state

$$|G_\pm\rangle = \frac{|G_{odd}\rangle \pm i|G_{even}\rangle}{\sqrt{2}}$$

non-trivial correlations

$$\mathcal{C}_{\alpha\beta}(j) = \langle\hat{a}^\dagger_\alpha(j)\hat{a}_\beta(j)\rangle \neq 0 \qquad \mathcal{C}_{\alpha\beta}(j) = -\mathcal{C}_{\beta\alpha}(j)$$

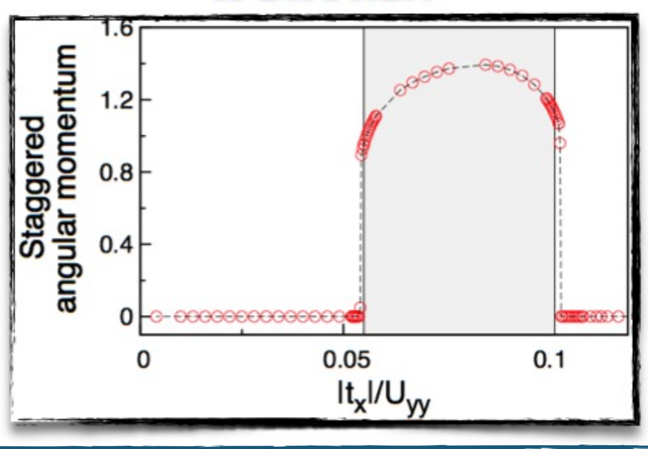
local quasi-angular
momentum operator

$$\hat{L}_z(j) = i\left[\hat{a}^\dagger_x(j)\hat{a}_y(j) - \hat{a}^\dagger_y(j)\hat{a}_x(j)\right]$$

staggered angular
momentum operator

$$\hat{\mathcal{L}}_z = \sum_j (-1)^j \hat{L}_z(j)$$

time-reversal symmetry
is BROKEN



conclusions

in asymmetric lattices it is possible to obtain
degeneracy between the single-particle energies
in given orbital (p-orbital)

this degeneracy is lifted by an anharmonicity
when contact interactions are taken into account

BUT

the degeneracy between orbitals
is dynamically restored due to tunneling

In this region an additional symmetry
of the system is spontaneously broken

The state which breaks the time-reversal symmetry
becomes the true ground state of the system

references

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Tunneling-Induced Restoration of the Degeneracy and the Time-Reversal Symmetry Breaking in Optical Lattices

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We study the ground-state properties of bosons loaded into the *p* band of a one-dimensional optical lattice. We show that the phase diagram of the system is substantially affected by the anharmonicity of the lattice potential. In particular, for a certain range of tunneling strength, the full many-body ground state of the system becomes degenerate. In this region, an additional symmetry of the system, namely, the parity of the occupation number of the chosen orbital, is spontaneously broken. The state with a nonvanishing staggered angular momentum, which breaks the time-reversal symmetry, becomes the true ground state of the system.