Presentation for Bachelor Thesis

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Introduction

- Materials with certain properties $\rightarrow$ How do we find them?
  - Naïve approach: Dig for it in the earth
  - More systematic: Create them ourselves
- Need to understand underlying physical processes better $\rightarrow$ Simulate a solid
  - Analog: Arrange atoms in lattice in the lab $\rightarrow$ Most promising for now
  - Digital: On a computer $\rightarrow$ Limitations of classical computers, quantum computers won't be there in the near future

Introduction

- Before any experiment: Theoretical model needed

Our goal:

- Establish a theoretical model arranging atoms in a lattice
- Check validity of that model with simulations

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Creating an artificial solid

How do we make atoms arrange in a lattice pattern?

- Two counter-propagating laser beams, $\omega_{\mathsf{l}} << \omega_{\mathsf{a}}$
- Optical cavities: Coerce atoms into creating their own trapping potential
- Light and atoms: Composite system $\psi_{\text{total}} = \psi_{\text{light}} \otimes \psi_{\text{atom}}$

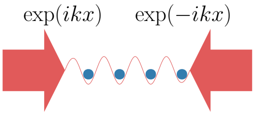

Figure 1: Counter-propagating lasers.

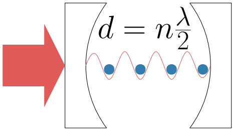

Figure 2: Optical cavity.

Cold atoms in cavities

- Problem: Motion of one atom affects cooling of another
- Solution: Transversal pumping

Paper: Collective Cooling and Self-Organization of Atoms in a Cavity [1]

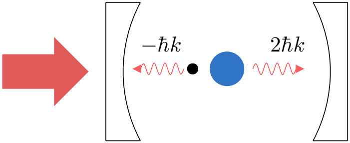

Figure 3: Longitudinal pump.

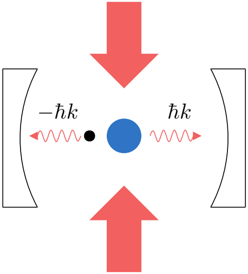

Figure 4: Transversal pump.

The Hamiltonians

Longitudinal pump ($\lambda/2$-periodic):

$$H_{\mathsf{long}} = \frac{p^2}{2m} + V_{\mathsf{ext}}(x) - \hbar\Delta_{\mathsf{c}} a^\dagger a + \hbar\eta(a + a^\dagger) + \hbar U_0 \cos(kx)^2 a^\dagger a \tag{1}$$

Transversal pump (λ-periodic):

$$\begin{aligned} H_{\mathsf{transv}} = \frac{p^2}{2m} + V_{\mathsf{ext}}(x) - \hbar\Delta_c a^\dagger a + \hbar\eta \cos(kx)(a + a^\dagger) + \\ + \hbar U_0 \cos(kx)^2 a^\dagger a \end{aligned} \tag{2}$$

Transversal pump: Superposition

When we do simulations we obtain a superposition of two symmetric states

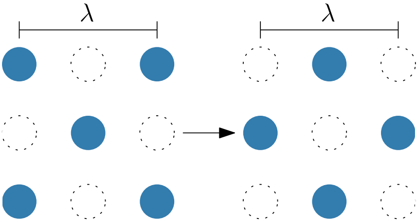

Figure 5: Lattice.

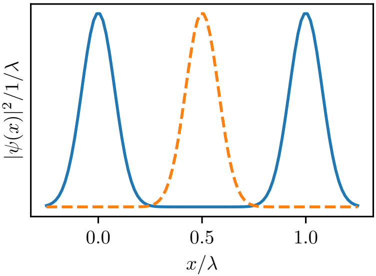

Figure 6: Wave function densities.

Our expectations

Paper: Self-organization of a Bose-Einstein condensate in an optical cavity [2]

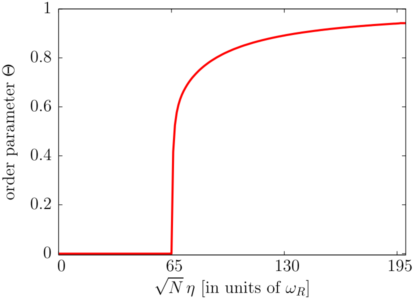

Figure 7: Order parameter.

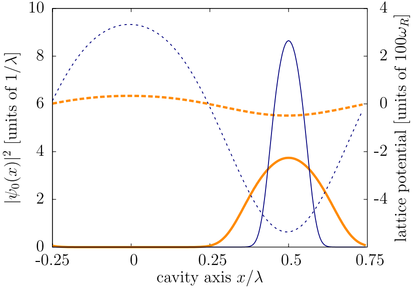

Figure 8: Lattice potential.

Our expectations

- Atoms are localized in "valleys" of optical potential
- Momenta:
  - Longitudinal: $p = 2n\hbar k$
  - Transversal: $p = n\hbar k$
- The more we pump, the more photons we will get
- Abrupt self-organization with transversal pumping

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The Julia language and QuantumOptics.jl

- High-performance languages like C, Fortran cumbersome to program
- Julia: high level convenience, low-level performance [3]
- How to program it into computer?
  - Starting from scratch: redundant
  - More convenient: QuantumOptics.jl: Quantum optics simulation framework [4]

Code snippet: Longitudinal pump

```
using QuantumOptics

η = 10 * ωr
b_position = PositionBasis(0, 1, 32)
b_fock = FockBasis(16)
p = momentum(b_position)
a = destroy(b_fock) ⊗ one(b_position)
ad = dagger(a)

potential = x -> U0*cos(k*x)^2
H_int = (one(b_fock) ⊗ potentialoperator(b_position, potential)) * ad * a
H_kin = (one(b_fock) ⊗ p^2) / k^2
H_cavity = -Δc*ad*a
H_pump = η*(a + ad)
H = H_int + H_kin + H_cavity + H_pump

E, ψ_states = eigenstates((H + dagger(H))/2, 3)
```

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Position wave function densities

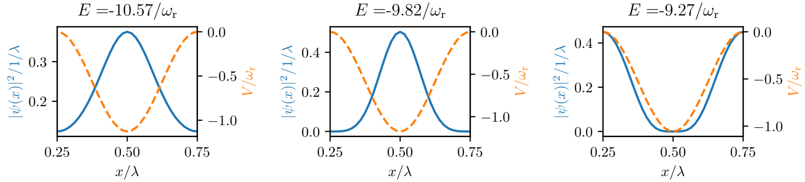

Figure 9: Longitudinal.

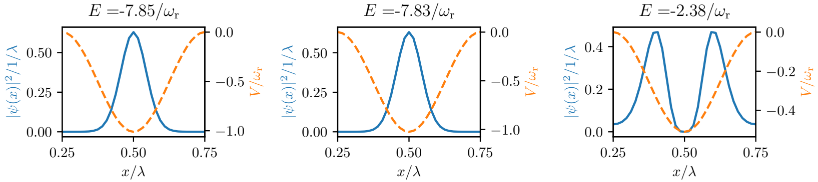

Figure 10: Transversal.

Components of the wave function

$$\psi(k) = \frac{1}{N}\sum_l c_l \exp(likx) = \tag{3}$$
$$= \frac{1}{N}\Big(c_0 + c_{\pm 1}\exp(ikx) + c_{\pm 2}\exp(2ikx) + \dots\Big)$$

c_l	wave number	momentum
c_0	0	0
$c_{\pm 1}$	$k \rightarrow \exp(ikx)$	$\hbar k$
$c_{\pm 2}$	$2k \rightarrow \exp(2ikx)$	$2\hbar k$
$c_{\pm 3}$	$3k \rightarrow \exp(3ikx)$	$3\hbar k$
$\vdots$		

Table 1: Wave function coefficients.

Momentum distribution

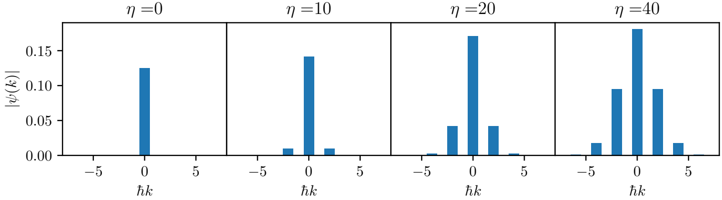

Figure 11: Longitudinal.

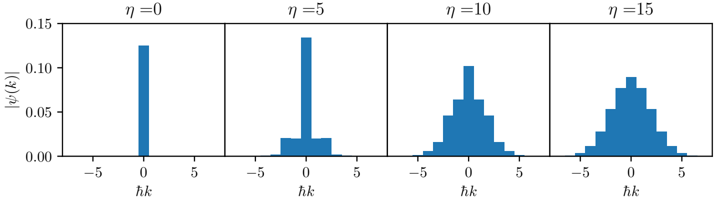

Figure 12: Transversal.

Photon number distribution

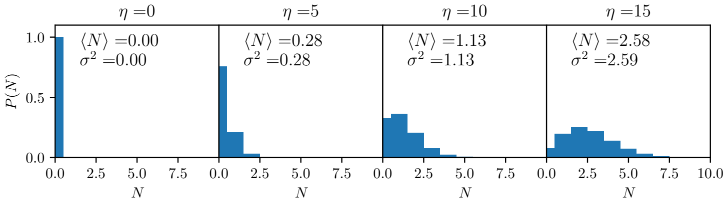

Figure 13: Longitudinal.

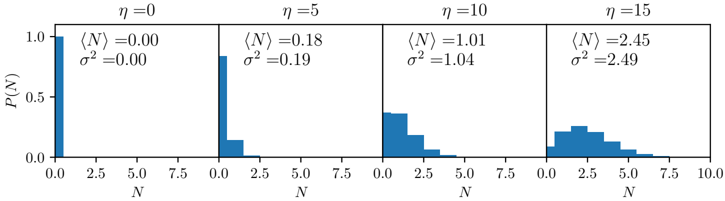

Figure 14: Transversal.

Husimi Q representation

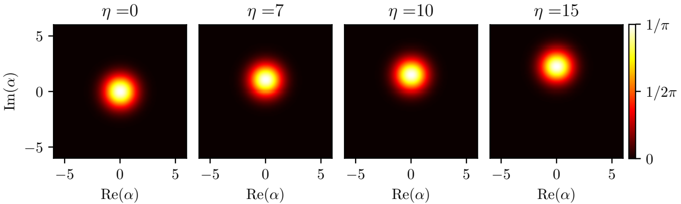

Figure 15: Longitudinal.

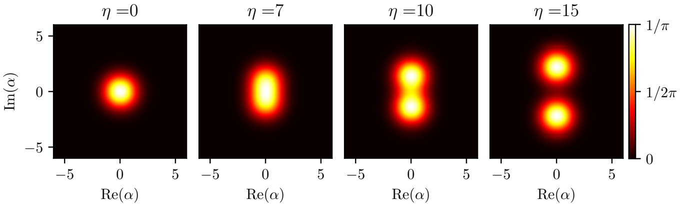

Figure 16: Transversal.

Breaking the symmetry

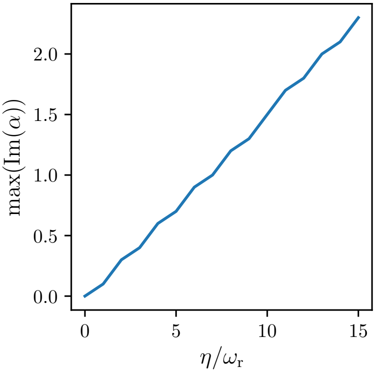

Figure 17: Longitudinal.

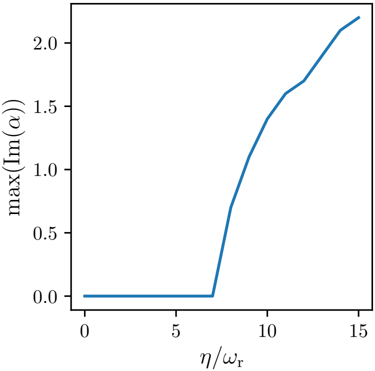

Figure 18: Transversal.

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Recap

What we discussed in this presentation...

- Why are we doing quantum simulations and how
  - Most promising for now: Analog quantum simulations
- Arrange atoms in lattice to simulate solid
  - Use laser to trap atoms
  - Make use of cavity
  - Transversal pumping
- Does our theoretical model make sense $\rightarrow$ Simulations
  - Atoms localized in "valleys" of potential
  - Specific momenta with longitudinal, transversal pump
  - More pumping $\rightarrow$ More photons
  - Abrupt self-organization with transversal pumping

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Special Thanks

Helmut Ritsch

for Opportunity, Subject

Stefan Ostermann

for Guidance, Discussion

Thank You!

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