Artificial gauge fields in extra dimensions

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Outline

Motivation

Artificial magnetic fields in optical lattices

Optical lattices involving extra dimension

- Ways of producing
- Edge states
- Closed boundaries

Summary

Quantum simulation

- Classical computer simulation of quantum system takes exponential time
- Hypothetical quantum computer does not
- Universal quantum computer still far away
- Dedicated quantum simulator possible
- Good candidate: Cold atoms

Quantum simulation

- Quantum simulation with ultracold atoms:
- Hubbard model (superfluid-Mott insulator transition)
- synthetic gauge fields (relativistic dispersion)
- strongly-correlated states (quantum Hall, spin liquids)

Edge states

- In 2D-lattice systems magnetic field induces a band structure and topologically protected states with well-defined conduction properties, called edge-states.
- The edge-states are still elusive and not experimentally demonstrated yet.

Question

Quantum simulation of edge states?

The main idea

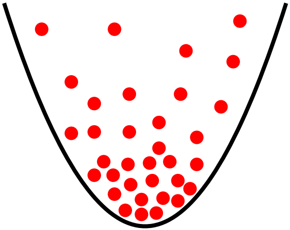
- Use a system with D spatial dimensions
- Encode the $D+1$-th dimension in a different degree of freedom (e.g., spin)

Extra dimensions

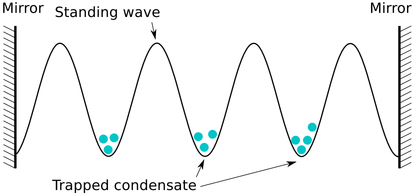
- Extra (non-spatial) dimensions:
- attempts to unify gravitation with electro-weak forces (Kaluza-Klein, Yang Mills,. . .)
- Quantum simulation of an extra dimension?

Ultracold atoms are trapped using

- Parabolic trapping potential produced by magnetic or optical means

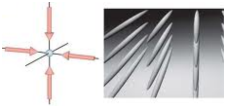


- Optical lattice – periodic potential

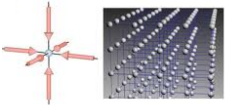


Optical lattices

- A set of counter-propagating light beams off resonance to the atomic transitions
- Atoms are trapped at intensity minima or intensity maxima of the interference pattern, depending on the sign of atomic polarisability
- Optical lattices can be state-dependent, atoms in different internal states trapped at different lattice sites – intensity minima or maxima.
- Optical lattices can be:
  - 2D



  - 3D



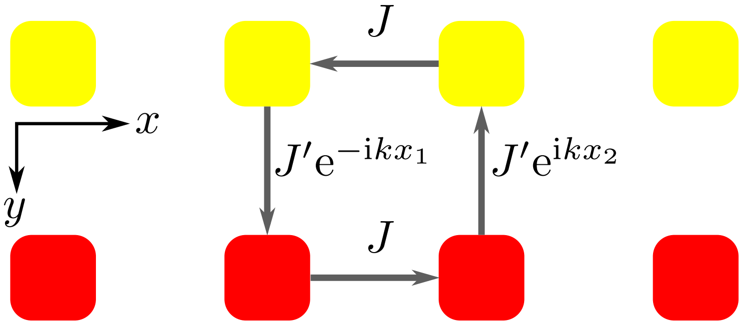
Trapped atoms – electrically neutral species

- No direct analogy with magnetic phenomena by electrons in solids, such as the Quantum Hall Effect, no Lorentz force
- A possible method to create an artificial magnetic field or artificial magnetic flux.
- Unconventional optical lattices

Artificial magnetic fields in optical lattices

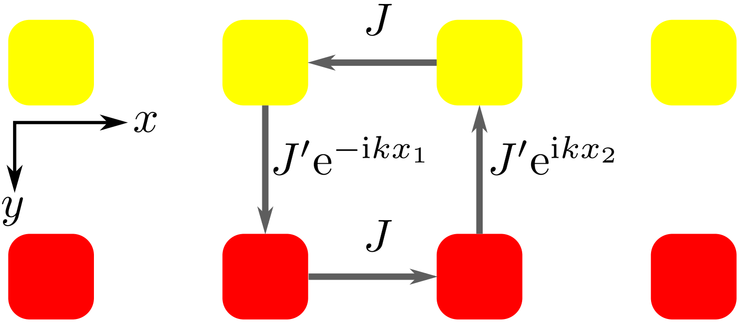
- Optical square lattices
  - D. Jaksch and P. Zoller, New J. Phys. **5**, 56 (2003).
  - J. Dalibard and F. Gerbier, New J. Phys. **12**, 033007 (2010).
- See also:
  - J. Ruostekoski, G. V. Dunne, and J. Javanainen, Phys. Rev. Lett. **88**, 180401 (2002).
  - J. Dalibard, F. Gerbier, G. Juzeliūnas and P. Öhberg, Rev. Mod. Phys. **83**, 1523 (2011).

Artificial magnetic fields in optical lattices



- Atoms in different internal states trapped at different lattice sites.
- Ordinary tunneling along x direction.
- Laser-assisted tunneling between atoms in different internal states (red or yellow) along y axis, with recoil along x.

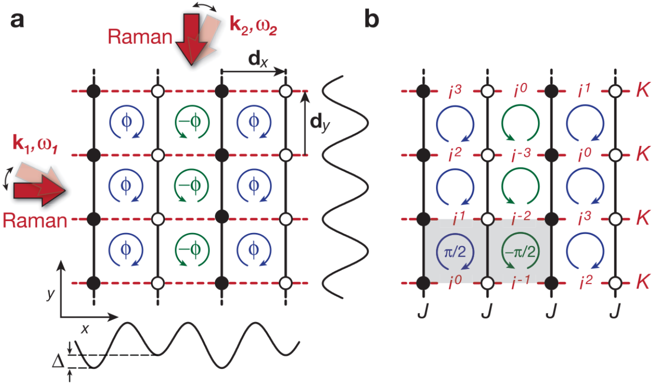
Artificial magnetic fields in optical lattices



- Non-vanishing phase for the atoms moving over a plaquette: $S = k(x_2 - x_1) = ka$
- Simulates non-zero magnetic flux over plaquette.
- Staggered flux!

Artificial magnetic fields in optical lattices

- Optical square lattices
- Experiment: M. Aidelsburger, M. Atala, S. Nascimbène, S. Trotzky,Yu-Ao Chen and I. Bloch, Phys. Rev. Lett. **107**, 255301 (2011).



Question

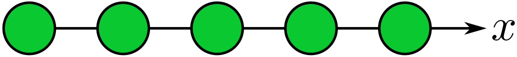
How to create non-staggered magnetic flux?

Artificial magnetic fields in optical lattices

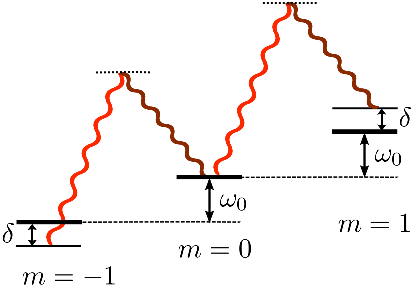
- How to create non-staggered magnetic flux?
- Different strategies by J&Z and D&G
- Quite complicated, not yet experimentally realized
- Our poposal: using optical lattices with
  extra dimension
- Can be experimentally realized with current setups

Optical lattices in extra dimensions

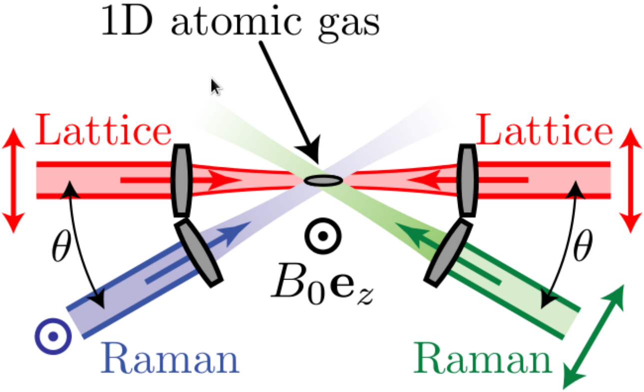
- 1D chain of atoms in real dimension



- Raman transitions between magnetic sublevels m – extra dimension

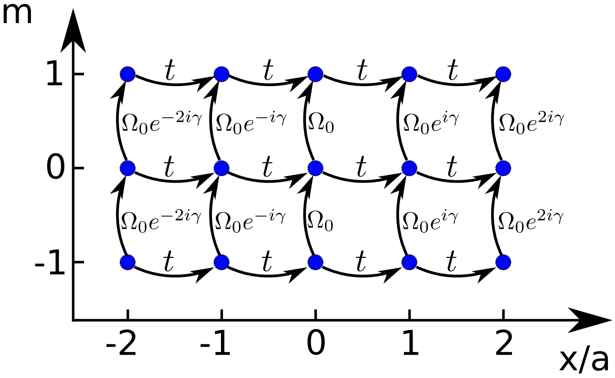


Experimental layout



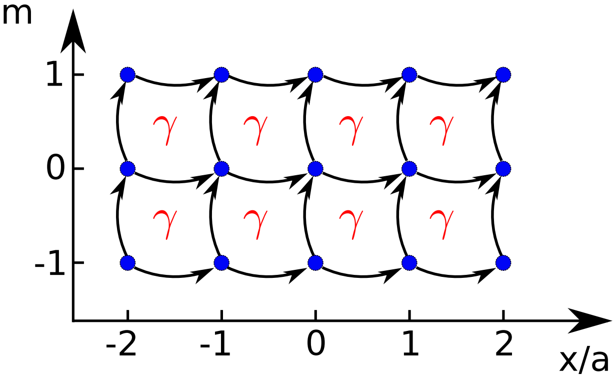
Optical lattices in extra dimensions

- Tunneling in real dimension and Raman transitions in the extra dimension yield a 2D lattice involving real and extra dimensions



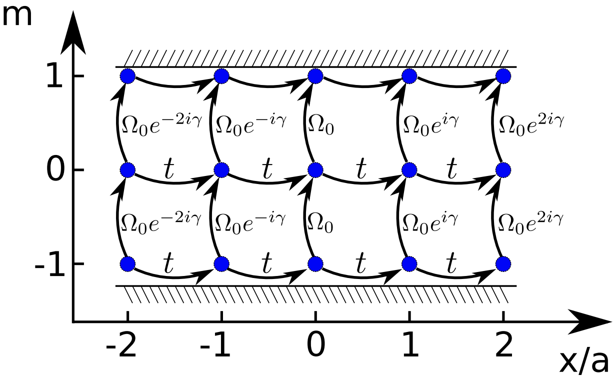
Optical lattices in extra dimensions

- Combination of real and extra dimensions yields strong and non-staggered magnetic flux $\gamma = ka$ per 2D plaquette



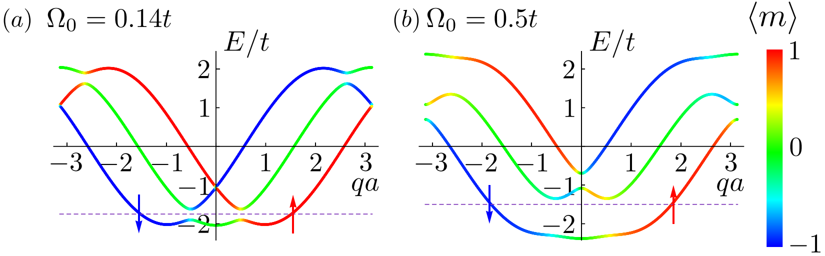
Optical lattices in extra dimensions

- Sharp boundaries in extra dimension
- Conducting edge states in extra dimension



Edge states

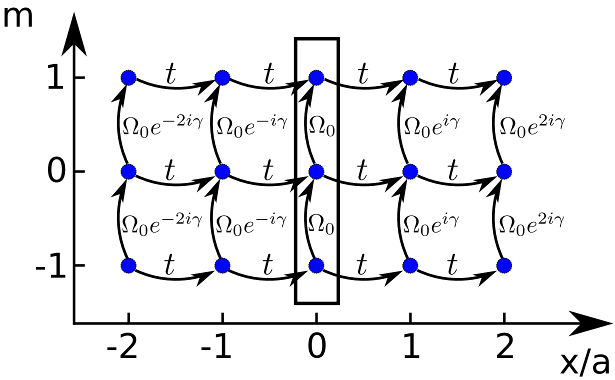
- Dispersion branches



- Atoms with opposite spins move in opposite directions

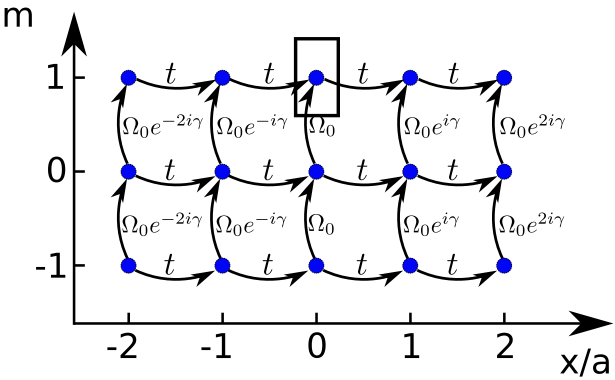
Scattering of edge states

Spin-independent potential (road block)



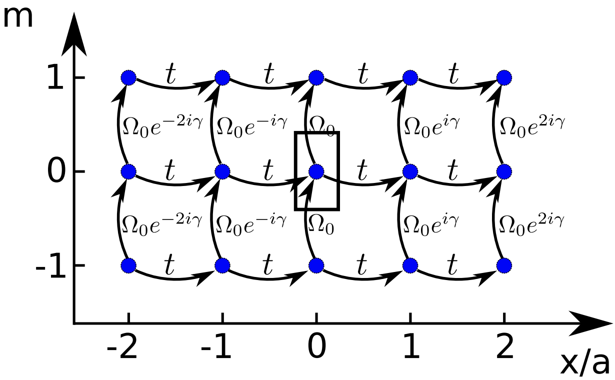
Scattering of edge states

Spin-dependent potential (perturbation for $m = 1$)



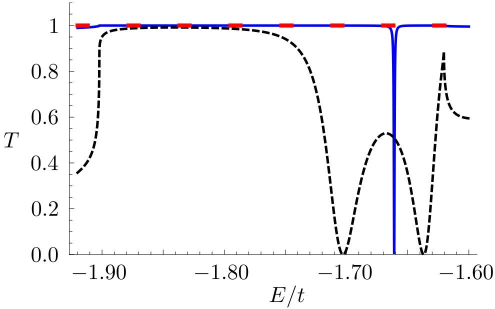
Scattering of edge states

Spin-dependent potential (perturbation for $m = 0$)



Scattering of edge states

Scattering of edge state atoms by a short-range potential:

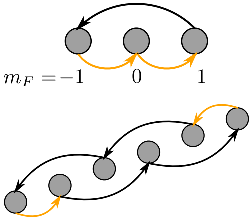


Black dashed line – spin-independent perturbation (road block). Red dashed line – perturbation for $m = \pm 1$. Blue line – perturbation for $m = 0$.

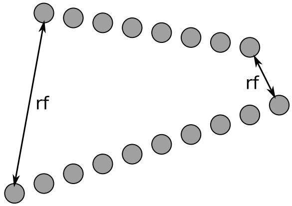
Closed boundary along the extra dimension

Various possibilities:

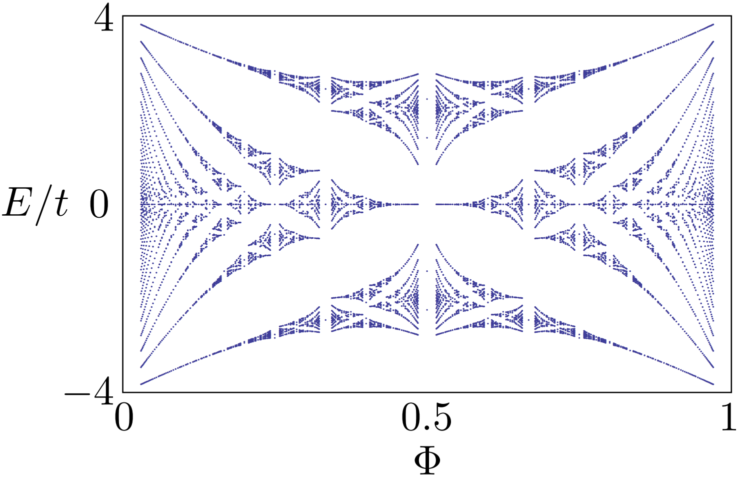
- Combination of Raman and two-photon IR transitions



- Connecting different F manifolds via rf fields



Energy spectrum of spin-1 atoms



Formation of Hofstadter butterfly using artificial dimensions

Summary

- Artificial magnetic field can be created in 1D optical lattices:
  - The atomic internal states serve as an extra dimension.
  - This makes a synthetic 2D lattice (involving real and extra dimensions) affected by a non-staggered magnetic flux.
- The artificial dimension has sharp boundaries at which the conducting edge states are formed.
- The edge states are immune to a short range scattering potential in a wide range of energies (or at least for lower energies).
- By closing the boundaries one can get the Hofstadter butterfly spectrum in a remarkably simple manner.

Thank you for your attention!