Synthetic gauge fields in synthetic dimensions

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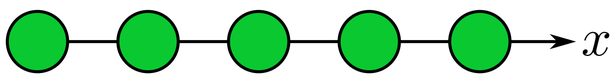
Abstract

Recently it was suggested to extend the dimension of optical lattices by using atomic internal degrees of freedom as an extra dimension [1]. Here we demonstrate that one can engineer a two-dimensional lattice with nonzero synthetic magnetic flux using atoms in a standard one-dimensional optical lattice [2]. The additional dimension appears due to laser-assisted transitions between the atomic sub-levels in the ground state manifold. The synthetic magnetic flux is generated by a combination of an ordinary tunnelling in the real space and laser-assisted transitions characterised by the complex amplitudes in the extra dimension. A distinctive feature of the proposed scheme is the sharp boundaries in the extra dimension, a feature that is difficult to implement for the atoms in optical lattices in the real-space. The boundaries of the extra dimension can be closed down using additional laser-assisted transitions. Closing the boundaries of the extra dimensions leads to a remarkably simple realisation of the fractional (Hofstadter butterfly-type) spectrum.

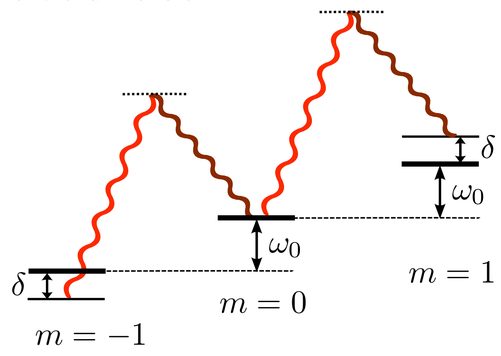
1. O. Boada, A. Celi, J. I. Latorre, and M. Lewenstein, Phys. Rev. Lett. **108**, 133001 (2012).
2. A. Celi, P. Massignan, J. Ruseckas, N. Goldman, I. B. Spielman, G. Juzeliūnas, and M. Lewenstein, Phys. Rev. Lett. **112**, 043001 (2014).

Optical lattices in extra dimensions

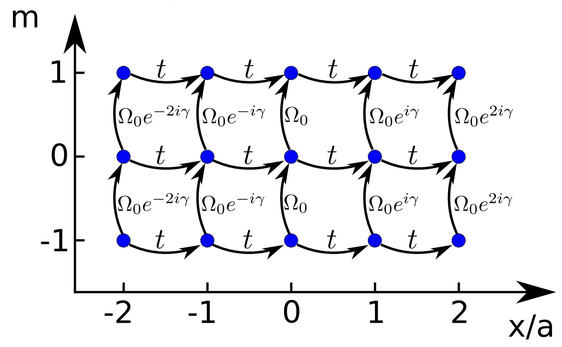
1D chain of atoms in real dimension



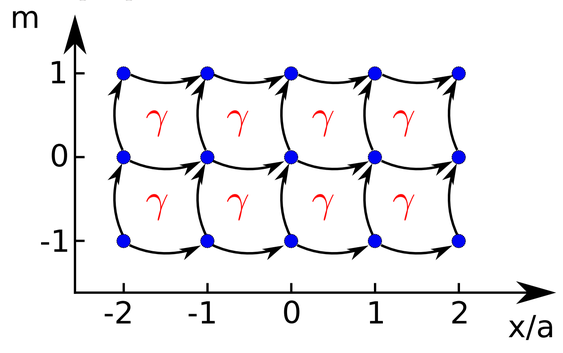
Raman transitions between magnetic sublevels
m – extra dimension



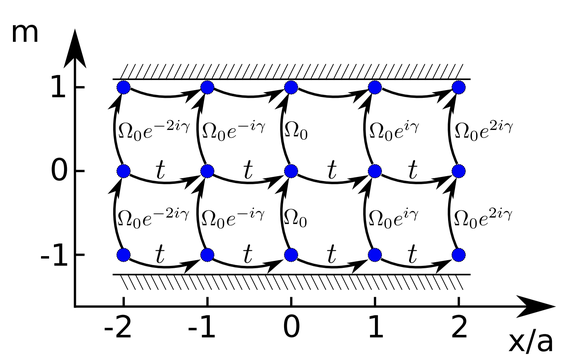
Tunneling in real dimension and Raman transitions in the extra dimension yield a 2D lattice involving real and extra dimensions



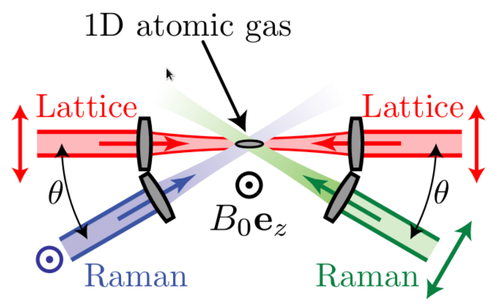
Combination of real and extra dimensions yields strong and non-staggered magnetic flux $\gamma = ka$ per 2D plaquette



Sharp boundaries in extra dimension
Conducting edge states in extra dimension

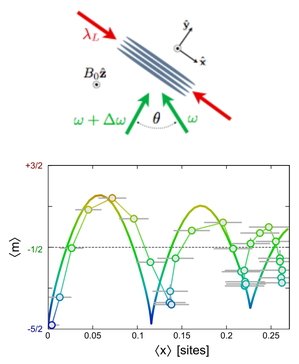


Experiments



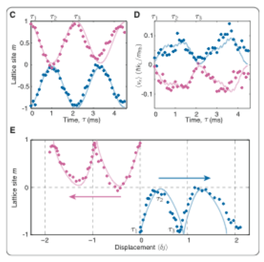
M. Mancini *et al*, arXiv:**1502.02495** [cond-mat.quant-gas] (2015).

- alkaline-earth-like ^{173}Yb atoms
- synthetic dimension encoded in a subset of the $I = 5/2$ nuclear spin manifold
- Existence of edge states detected
- Observed edge-cyclotron orbits



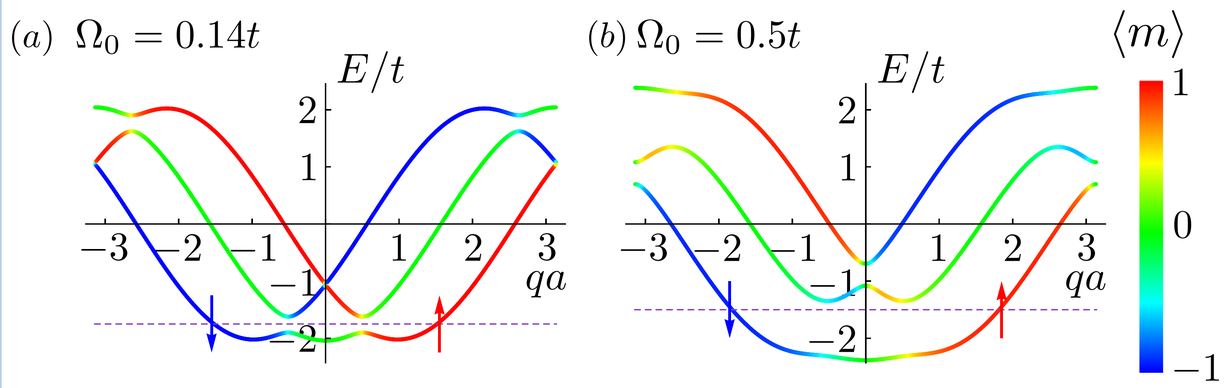
B. K. Stuhl *et al*, arXiv:**1502.02496** [cond-mat.quant-gas] (2015).

- ^{87}Rb BECs in the $F = 1$ ground state hyperfine manifold
- Directly imaged individual bulk and edge eigenstates
- Experimental observation of their edge localization and transverse skipping motion



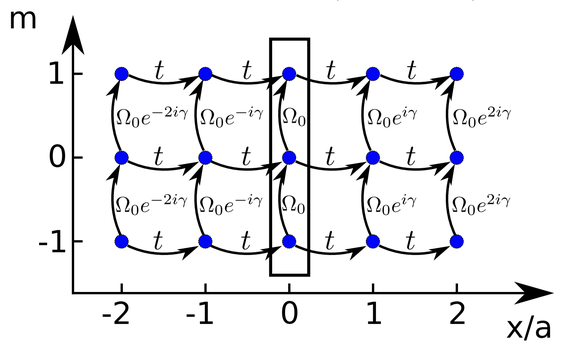
Edge states

Dispersion branches

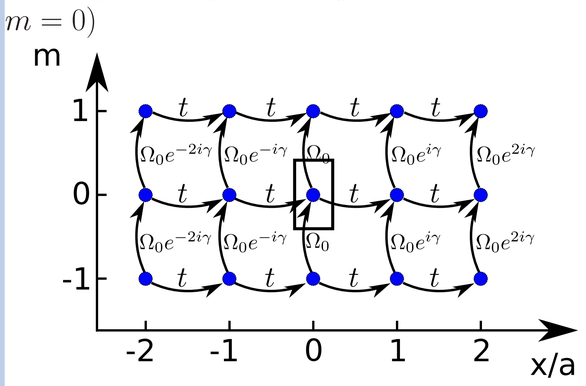


Atoms with opposite spins move in opposite directions

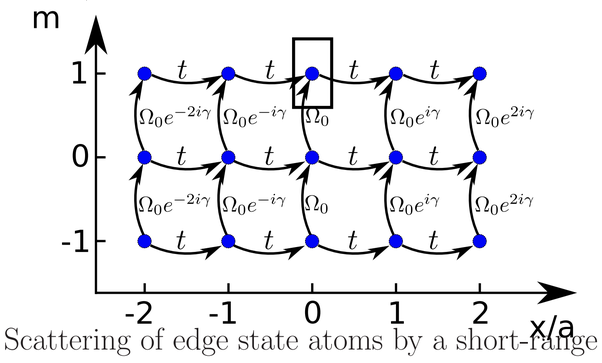
Spin-independent potential (road block)



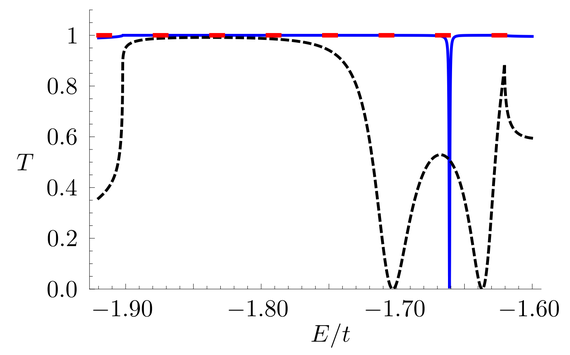
Spin-dependent potential (perturbation for $m = 0$)



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



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

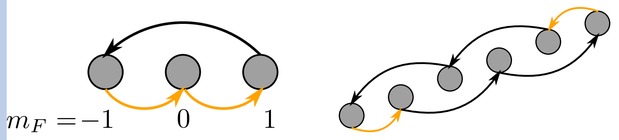


Black dashed line – spin-independent perturbation (road block).
Red dashed line – perturbation for $m = \pm 1$.
Blue line – perturbation for $m = 0$.

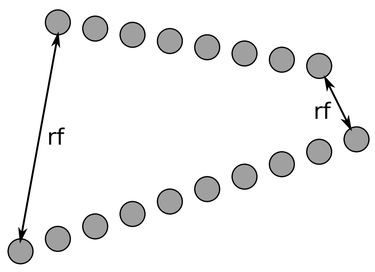
Closed boundaries

Various possibilities:

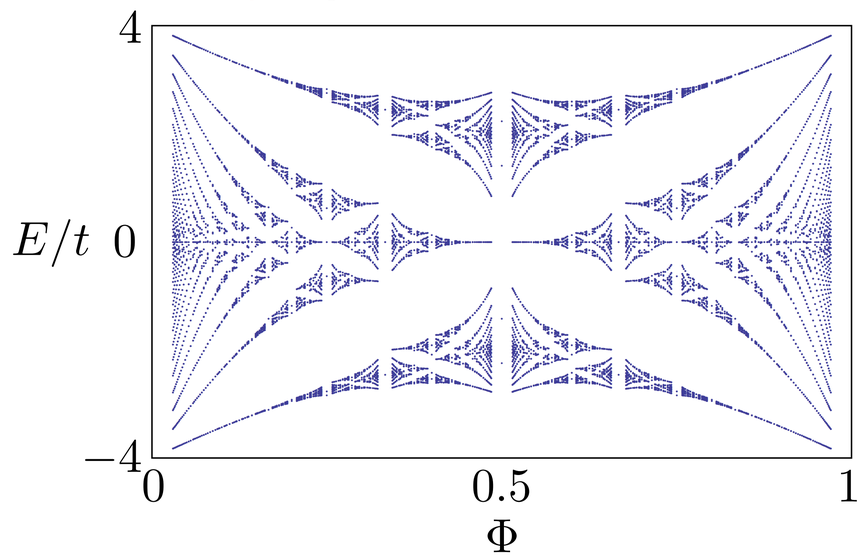
Combination of Raman and two-photon IR transitions



Connecting different F manifolds via rf fields



Formation of Hofstadter butterfly using artificial dimensions



Acknowledgements
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