Topological Charge Pumping and Artificial Gauge Fields With Ultracold Atoms in Optical Superlattices

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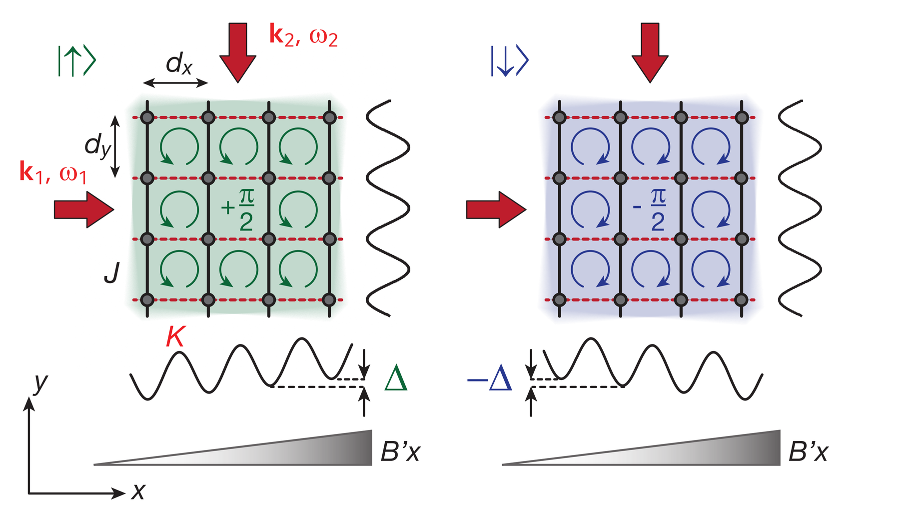
Introduction

- Motivation: Probe **topological phases of matter** in the presence of large magnetic fields (e.g. quantum Hall effect)
- Ultracold atoms in optical lattices as a **clean** and **well controlled model system** to study physics in regimes not accessible in typical condensed matter systems
- Implement **artificial magnetic fields** for ultracold neutral atoms
- **Topological charge pumping** as a tool to study higher dimensional quantum Hall physics

Artificial Gauge Fields

- **Charge neutrality** prevents direct application of Lorentz force in an external magnetic field
- Implementation of artificial gauge potentials by engineering of **position-dependent complex tunneling amplitudes** $|K|e^{i\phi}$ (Aharonov-Bohm phase) using laser-assisted tunneling in a tilted optical potential



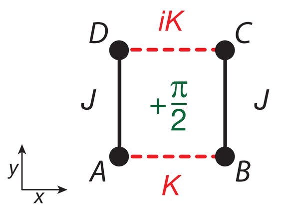
On-site modulation with position-dependent phases
$\varphi_{mn} = \mathbf{q}\cdot\mathbf{R}$

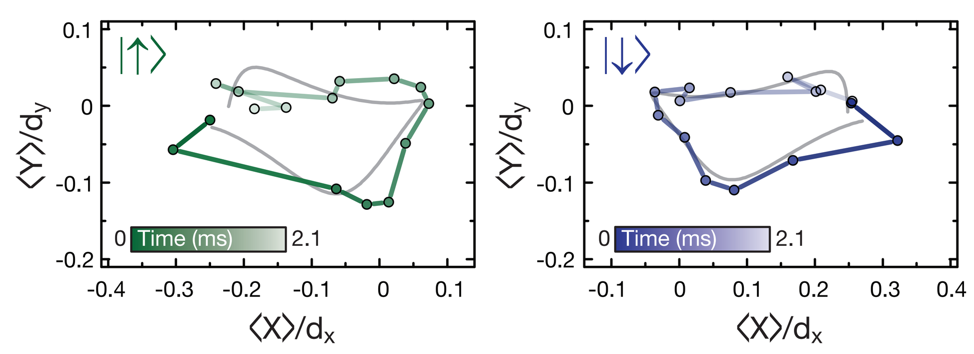
- Effective time-averaged Hamiltonian in high-frequency limit $\hbar\omega \gg J_{x/y}$:

$$\hat{H} = -\sum_{m,n}\left(Ke^{i\varphi_{m,n}}\ \hat{a}^\dagger_{m+1,n}\hat{a}_{m,n} + J\ \hat{a}^\dagger_{m,n+1}\hat{a}_{m,n}\right) + \mathrm{h.c.}$$

Uniform effective magnetic flux per 2x2 plaquette

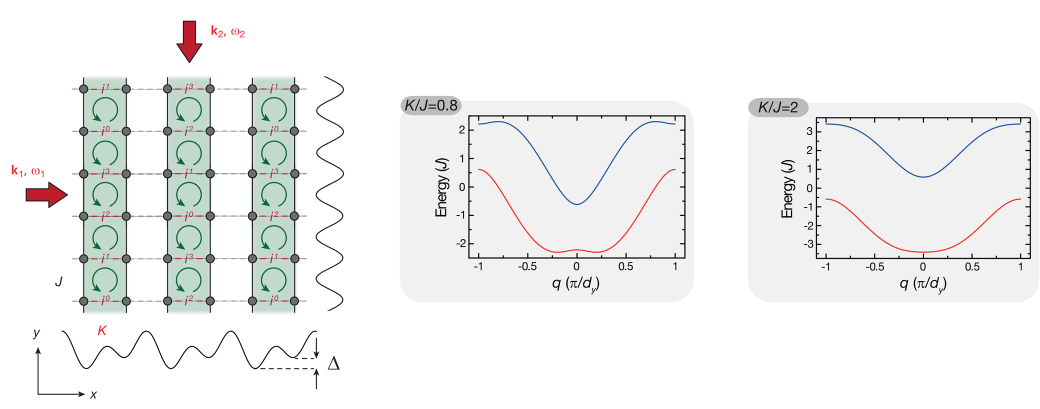
- Cyclotron orbits of single atoms in isolated 2x2 plaquettes





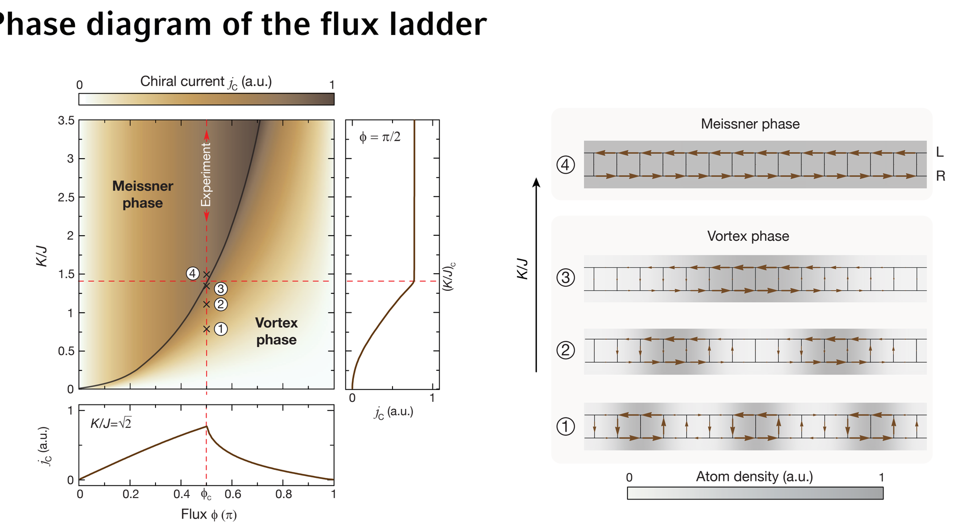
Meissner Effect in Bosonic Ladders

- **Quasi-1D ladder systems** in the presence of a uniform artificial gauge field

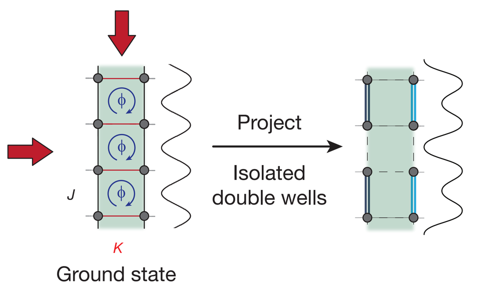


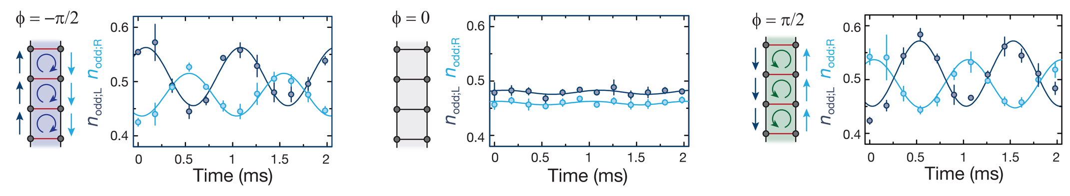
- Ground state exhibits **chiral current** in analogy to the Meissner effect in a type-II superconductor

Phase diagram of the flux ladder



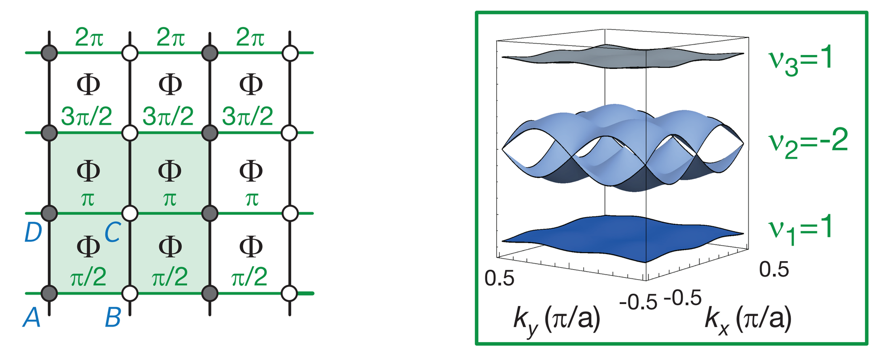
- Measurement of currents: **Projection onto isolated double wells**
- Oscillation between even and odd sites with amplitude proportional to current





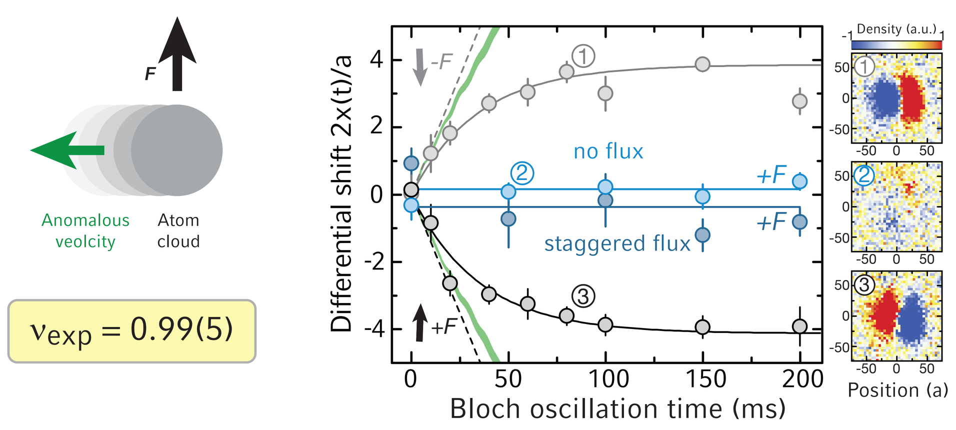
Harper-Hofstadter Model

- 2D square lattice in a uniform artificial magnetic field
- **Magnetic unit cell** contains multiple sites and the lowest Bloch band splits into **separate sub-bands** which are **topologically non-trivial**



- Measurement of the **transverse Hall response** by applying a longitudinal gradient
- Atoms perform Bloch oscillations and acquire anomalous velocity in the orthogonal direction which is proportional to the Berry curvature
- Quantized transport for filled/uniformly populated bands characterized by Chern number

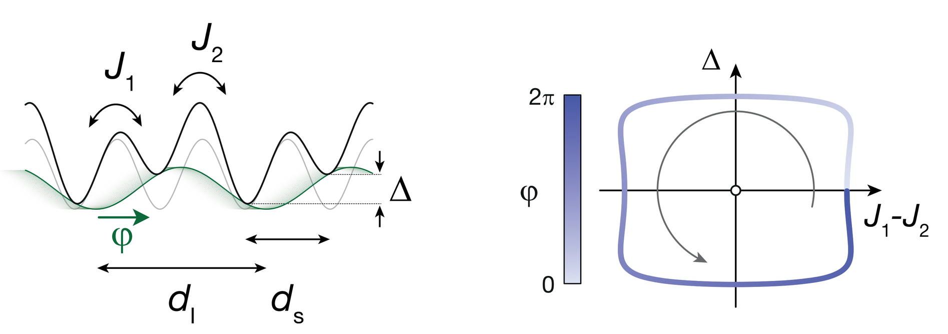
$$x_\mu(t) = -\frac{4a^2F}{h}\nu_\mu\, t \quad \text{with} \quad \nu_\mu = (1/2\pi)\int_{\mathrm{FBZ}}\Omega_\mu \mathrm{d}^2\mathrm{k}$$



$\nu_{\mathrm{exp}} = 0.99(5)$

Topological Charge Pumping

- **Transport of charge** through **adiabatic periodic variation** of the underlying Hamiltonian (even in insulating systems)
- For filled bands, the transported charge is **quantized** and related to a **topological invariant**, the Chern number, of the pumping process
- The transported charge is purely determined by the **topology of the pump cycle** and **robust against perturbations**
- n=1/2 Mott insulator in a 1D superlattice potential: pumping by adiabatic variation of the superlattice phase φ



$$\hat{H}(\varphi) = -\sum_m\left(J_1(\varphi)\hat{b}^\dagger_m\hat{a}_m + J_2(\varphi)\hat{a}^\dagger_{m+1}\hat{b}_m + \mathrm{h.c.}\right) + \frac{\Delta(\varphi)}{2}\sum_m\left(\hat{a}^\dagger_m\hat{a}_m - \hat{b}^\dagger_m\hat{b}_m\right)$$

- **Adiabatic evolution** of eigenstate

$$|u_n\rangle - i\hbar\sum_{n'\neq n}\frac{|u_{n'}\rangle\langle u_{n'}|\partial_t u_n\rangle}{\epsilon_n - \epsilon_{n'}}$$

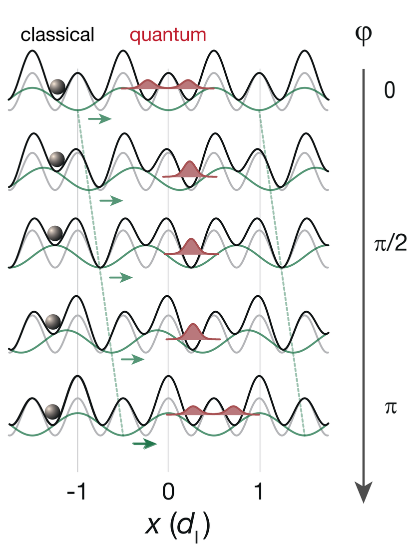
→ **anomalous velocity**

$$\underbrace{\frac{\partial\epsilon_n(k_x)}{\hbar\,\partial k_x}}_{v_{\mathrm{gr}}} - i\underbrace{\left[\left\langle\frac{\partial u_n}{\partial k_x}\middle|\frac{\partial u_n}{\partial\phi}\right\rangle - \left\langle\frac{\partial u_n}{\partial\phi}\middle|\frac{\partial u_n}{\partial k_x}\right\rangle\right]}_{\Omega(k_x,\phi)}\frac{\partial\phi}{\partial t}$$

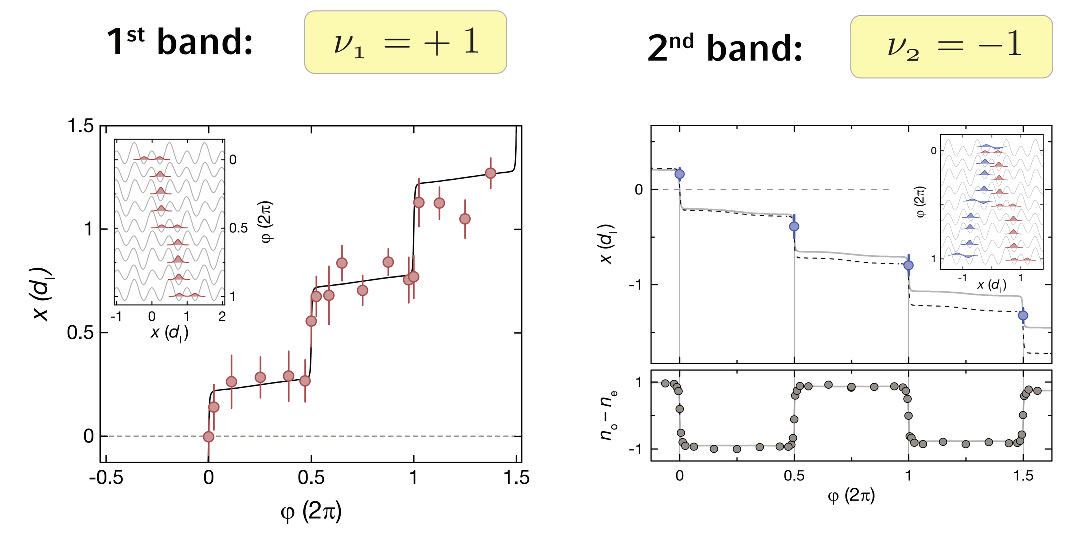
- **Homogeneously populated band**

Quantized displacement
$x = \nu_n d_l$

with $\nu_n = \frac{1}{2\pi}\int_{\mathrm{FBZ}}\int_0^{2\pi}\Omega_n(k_x,\varphi)\,\mathrm{d}\varphi\mathrm{d}k_x$



1st band: $\nu_1 = +1$ 2nd band: $\nu_2 = -1$



- Charge pumping in 1D superlattice → **dynamical version** of the **2D integer quantum Hall effect**: variation of φ equivalent to perpendicular electric field

Spin Pumping

- Pumping with **spin-dependent modulation**: transport of spins without charge transport
- Hardcore bosons in two hyperfine states: **spin chain** with **dimerized superexchange coupling** and **spin-dependent tilt**

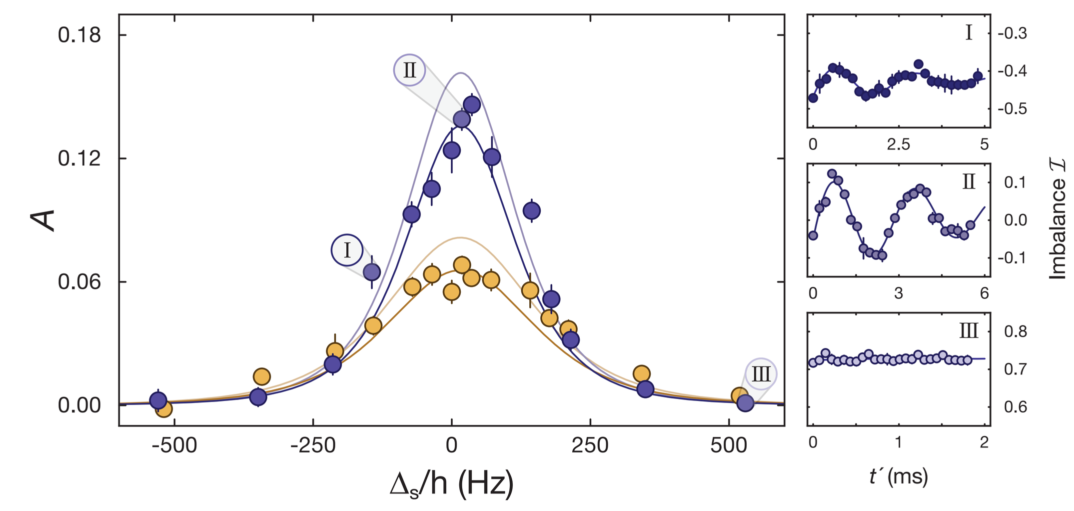
$$\hat{\mathcal{H}} = -\frac{1}{4}\sum_m\left(J_{\mathrm{ex}} + (-1)^m\delta J_{\mathrm{ex}}\right)\left(\hat{S}^+_m\hat{S}^-_{m+1} + \mathrm{h.c.}\right) + \frac{\Delta}{2}\sum_m(-1)^m\hat{S}^z_m$$

- Realization of a similar model with a **global magnetic field gradient** that is **topologically equivalent** in the limit of **isolated double wells**
- Direct measurement of spin currents in optical lattices by projection onto static double wells

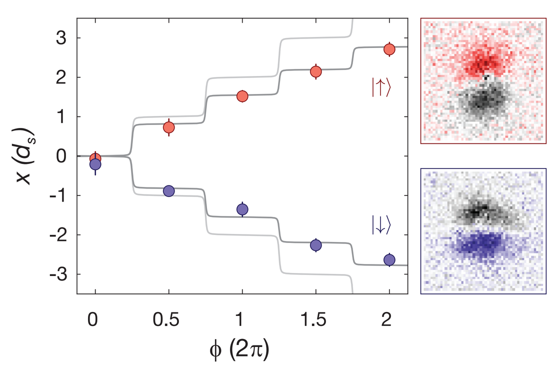
→ oscillations of the spin imbalance

$$\mathcal{I}(t') = A\sin\left(\frac{E_2(t_{\mathrm{s}}) - E_1(t_{\mathrm{s}})}{\hbar}\,t'\right) + \mathcal{I}_{\mathrm{s}}$$

with $A = -2\,a_2(t_{\mathrm{s}})\,\langle 1_{t_{\mathrm{s}}}|\hat{\mathcal{I}}|2_{t_{\mathrm{s}}}\rangle = \frac{2\hbar}{E_2(t_{\mathrm{s}}) - E_1(t_{\mathrm{s}})}\,\mathrm{j}(t_{\mathrm{s}})$



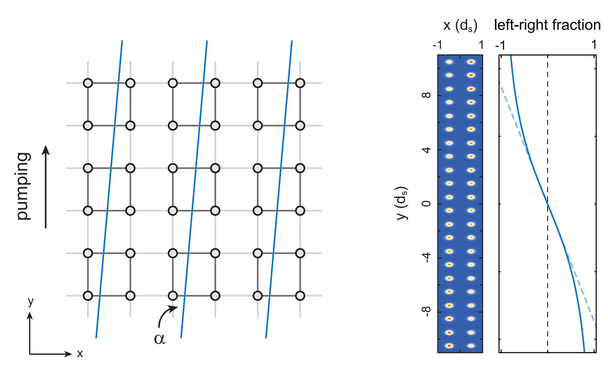
- Integrated spin current independent of exchange coupling unlike instantaneous current
- Separation of the spins' **center-of-mass position** without charge transport



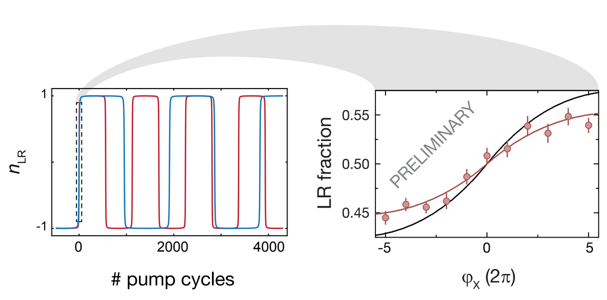
Outlook: Charge Pumping in 2D

- Simulate **4D quantum Hall effect** by charge pumping in a tilted 2D superlattice

→ non-linear Hall response characterized by 2nd Chern number



- Small atom cloud as local probe of charge transport
- Measure transverse response when pumping along orthogonal direction



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