Artificial gauge fields for ultracold atoms

- Rotating gases
- Raman-induced gauge fields
- Laser-assisted tunneling / shaking
- Synthetic lattices
- ...

Fallani group, LENS

Cornell group, JILA
Artificial gauge fields for ultracold atoms

Some really interesting physics associated with charged particles coupled to electromagnetic gauge potentials

\[ \vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) \]

Kosmos, 1986
Artificial gauge fields for ultracold atoms

Some really interesting physics associated with charged particles coupled to electromagnetic gauge potentials

Quantization, IQHE:

$$R_K = \frac{h}{e^2} = 25812.807557(18) \, \Omega$$

von Klitzing
Artificial gauge fields for ultracold atoms

Some really interesting physics associated with charged particles coupled to electromagnetic gauge potentials

Tsui, Störmer, et al.
Emergent Topological Order

Frustration + Interactions = ???

Landau levels = high degeneracy

Flat energy bands in lattices

Hofstadter model – charged particle in magnetic field

Energy spectrum

APS/Cheng Chin and Erich Mueller

Goldman, Juzeliūnas, Öhberg, Spielman (2014)

How do interacting particles arrange themselves?
Neutral atoms are neutral $\Rightarrow$ no natural Lorentz force

$$q = 0 \quad \vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) = 0$$

Need some tricks to engineer “effective” gauge fields
Rotating atomic gases

Uniform rotation can mimic a $B$-field

$\Omega_{\text{rot}} = \Omega_{\text{rot}} e_z$

Goldman, Juzeliūnas, Öhberg, Spielman (2014)
Uniform rotation can mimic a $B$-field

\[ \Omega_{\text{rot}} = \Omega_{\text{rot}} e_z \]

\[ \mathcal{A} = m\Omega_{\text{rot}} \times r \]

\[ \mathcal{B} = \nabla \times \mathcal{A} = 2m\Omega_{\text{rot}} e_z \]

Goldman, Juzeliūnas, Öhberg, Spielman (2014)
Uniform rotation can mimic a $B$-field

$\Omega_{\text{rot}} = \Omega_{\text{rot}} e_z$

Cornell group, JILA
(also, Ketterle group, MIT & Dalibard group, ENS)

Dalibard group, ENS

Goldman, Juzeliūnas, Öhberg, Spielman (2014)
Uniform rotation can mimic a $B$-field
Rotating atomic gases

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Dalibard group, ENS (also, Ketterle group, MIT & Dalibard group, ENS)
Raman-induced artificial gauge fields

a. Geometry

b. 2 Level

c. 3 Level

Spielman, JQI
Raman-induced artificial gauge fields

Spielman, JQI
Raman-induced artificial gauge fields

Geometric phases from internal degrees of freedom

"dressed" eigenstates can be superpositions of $|1\rangle$ and $|2\rangle$

$$|g\rangle = \sin \theta |1\rangle + e^{i\phi} \cos \theta |2\rangle$$

Dum & Olshanii, PRL (1994)
Higbie & Stamper-Kurn, PRA (2002)
Spielman, PRA (2009)
Raman-induced artificial gauge fields

Geometric phases from internal degrees of freedom

Suppose $\theta$ or $\varphi$ depend on position.

If our particle follows a closed path in space...

\[ |g\rangle = \sin \theta |1\rangle + e^{i\phi} \cos \theta |2\rangle \]

Dum & Olshanii, PRL (1994)
Higbie & Stamper-Kurn, PRA (2002)
Spielman, PRA (2009)
Raman spin-orbit coupling

Raman-induced artificial gauge fields

Ultimately also limited to weak effective fields due to heating (off-resonant Rayleigh scattering)
Laser-assisted tunneling

$H_{\text{tight-binding}} = -t \sum_n \left( c_n^\dagger c_{n+1} + \text{h.c.} \right)$
Laser-assisted tunneling

Turn off (off-resonant) tunneling with linear gradient

Raman transition
“turns it back on”

+ tunneling phase!

Aidelsburger, et al., PRL (2013)
Miyake, et al., PRL (2013)
Laser-assisted tunneling

Turn off (off-resonant) tunneling with linear gradient

Raman transition “turns it back on”

+ tunneling phase!

\[ t_n e^{i\phi_n} = \frac{1}{2} \int dx w^* (x-x_n) \left[ \frac{\Omega_0 \Omega_1}{2\Delta_0} e^{i2kx} e^{i(\phi_0-\phi_1)} \right] w(x-x_{n+1}) \]

Aidelsburger, et al., PRL (2013)
Miyake, et al., PRL (2013)
Laser-assisted tunneling

In 2D, with well chosen $\hat{q}$

Some control over the flux by choice of laser beam alignment
Laser-assisted tunneling

In 2D, with well chosen $\tilde{q}$

Some control over the flux by choice of laser beam alignment

Significant effects of heating remain – outstanding challenge to the field of how to stabilize against heating with interactions present

Aidelsburger, et al., PRL (2013)
Miyake, et al., PRL (2013)
Laser-assisted tunneling

Recently combined with quantum gas microscopes!

Greiner group
Nature, 2017
A stripe phase with supersolid properties in spin–orbit–coupled Bose–Einstein condensates

Jun-Ru Li\textsuperscript{1*}, Jeongwon Lee\textsuperscript{1*}, Wuje Huang\textsuperscript{1}, Sean Burchesky\textsuperscript{1}, Boris Shteynas\textsuperscript{1}, Furkan Çağrı Top\textsuperscript{1}, Alan O. Jamison\textsuperscript{1} & Wolfgang Ketterle\textsuperscript{1}

Moving density modulation from Raman potential
Floquet Hamiltonians

topological Haldane model

related “shaking” techniques

Sengstock group, Hamburg
Esslinger group, ETH Zürich
others...
Floquet driven lattices

Gemelke, et al. PRL 2005

Periodic modulation leads to coupling of bands / modification of the band structure
Alternative schemes / synthetic lattices

For some problems, one has to go to heroic efforts to engineer certain effects in real space lattices – often at a price

Examples:

- Mimicking the coupling of electrons to electromagnetic gauge fields
- Realizing hard-wall boundary conditions / periodic boundary conditions
- Realizing generic types/forms of disorder
- Realizing higher-dimensional ($d \geq 4$) physics

Some of these problems become much easier (even trivial) if one of the “dimensions” to a system is represented by discrete quantum states, such as internal states

Boada, et al. PRL (2012)
Celi, et al. PRL (2013)
and now many more
Partially synthetic chiral ladders

Celi, et al. PRL (2013)

Fallani group / Spielman group (2015)
Partially synthetic chiral ladders

Celi, et al. PRL (2013)

Fallani group / Spielman group (2015)
Partially synthetic chiral ladders


Fallani group / Spielman group (2015)
Fully synthetic lattices

- Real-valued tunneling
- Limited by finite temperature

Field-driven transitions between states – form a “synthetic lattice”

\[ H_{s.p.} = -t \sum_{n} (c_{n}\dagger c_{n+1} + \text{h.c.}) \]
Synthetic lattice engineering

Full local & temporal control of single-particle Hamiltonian

analogous to photonic simulators (Szameit, Hafezi, Silberhorn, Segev, etc.)
Chiral currents on 2D flux ladders

“shearing” ≡ \( \langle n \rangle_{m=0} - \langle n \rangle_{m=1} \)

\[
\phi = +\pi/2
\]

Images taken at 500 μs (1.05 h/t)

\[
\phi = -\pi/2
\]

F. A. An, E. J. Meier, and BG. (Science Advances)
Inhomogeneous flux - topological reflection

Quantum reflection from a potential dip

The site-potentials are completely flat in our case

But still a boundary condition to match

F. A. An, E. J. Meier, and BG. (Science Advances)