Advanced ERC Grant:
QUAGATUA

Ultracold Atoms in Artificial Non-Abelian Gauge Fields

Maciej Lewenstein, Barcelona

AvH
Senior
Research
Grant
+
Feodor
Lynen

ICFO Institut de Ciències Fotòniques

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

*icrea

QT Quantum Optical Information Technology

EU IP
AQUTE

EU STREP
NAMEQUAM

Why gauge?

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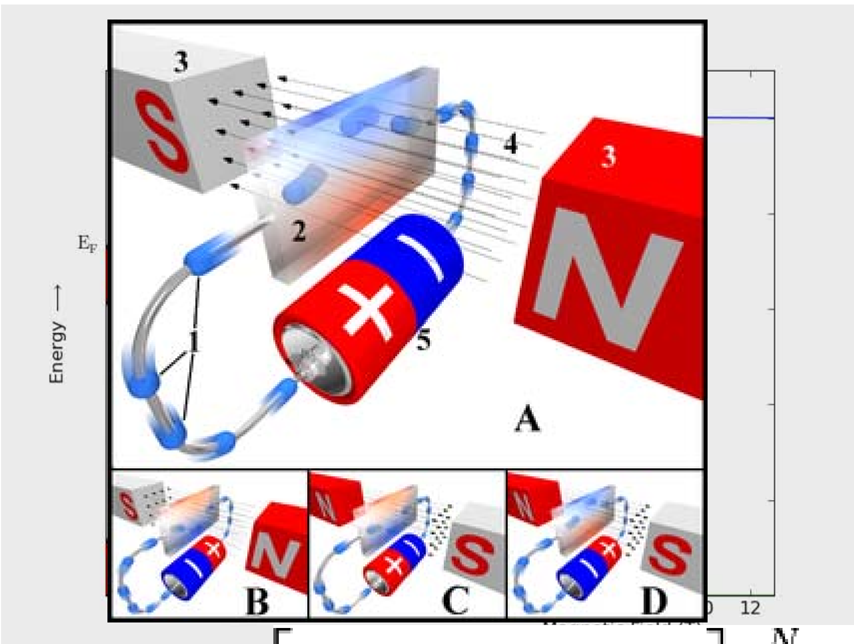
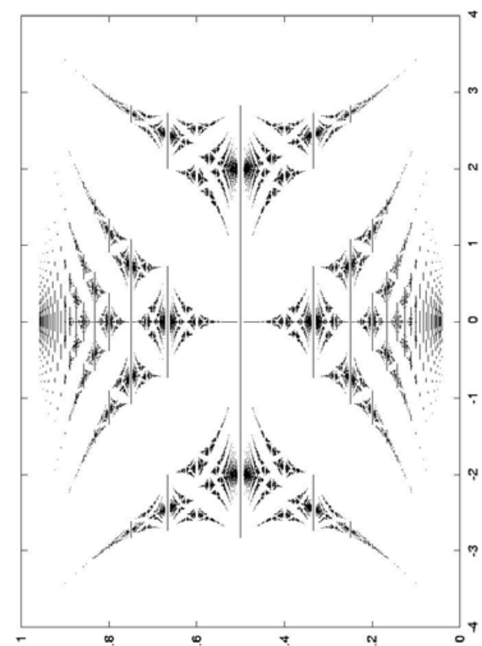
- Integer Quantum Hall effect $\sigma = \nu \dfrac{e^2}{h},$



$$\left[\prod_{N\geqslant i\geqslant j\geqslant 1}(z_i-z_j)^n\right]\prod_{k=1}^{N}\psi(z_k)$$

- Hofstadter butterfly



e
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Magnetic flux α

- Fractional Quantum Hall Effect

Why artificial?

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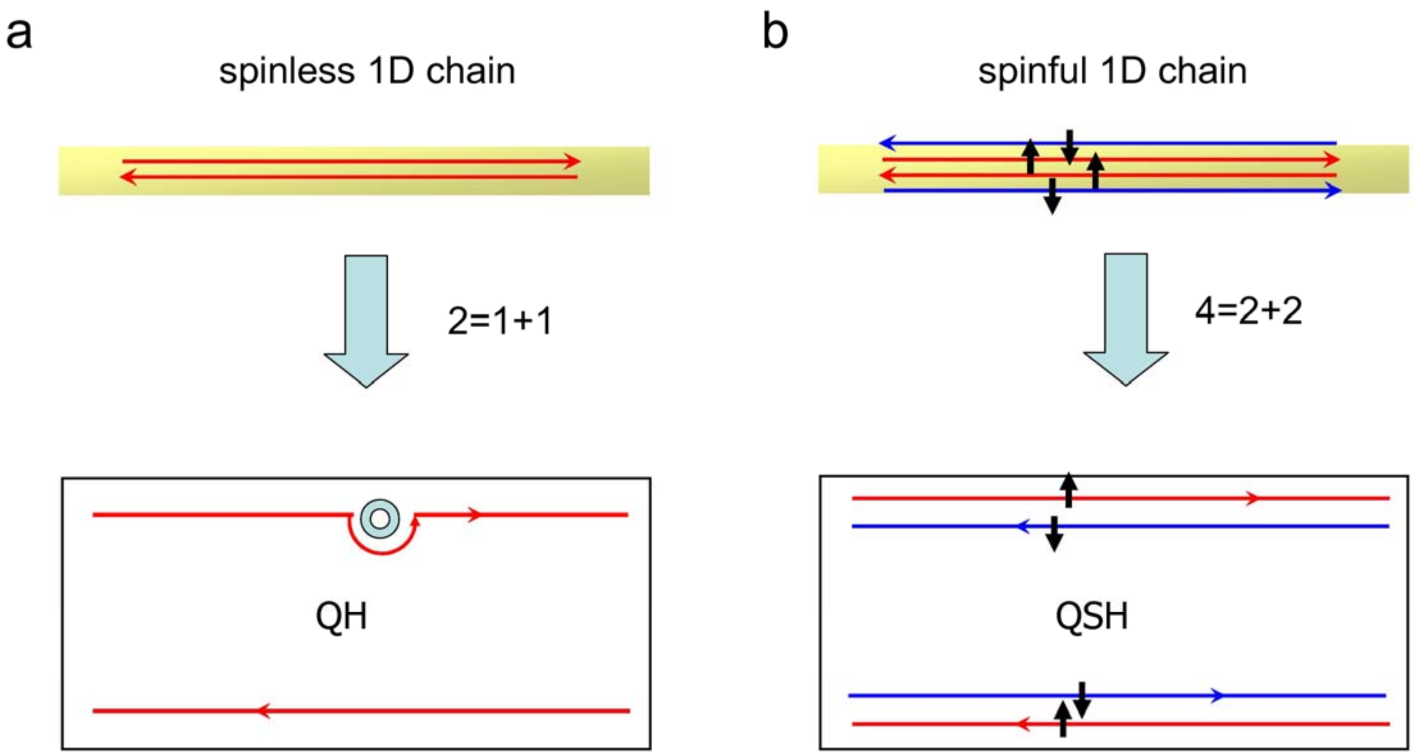
- We want to mimic effects of the Lorenz force !!!

- Ions are heavy !!!

- Atoms are neutral !!!

Why non-Abelian?

- We want to mimic Quantum Spin Hall (QSH) effect (spin-orbit, Rashba, Dresselhaus couplings and more…)



(from Physics Today, Xiao-Liang Qi and Shou-Cheng Zhang)

Why non-Abelian?

- **We want to mimic graphene and emergence of Dirac fermions…**

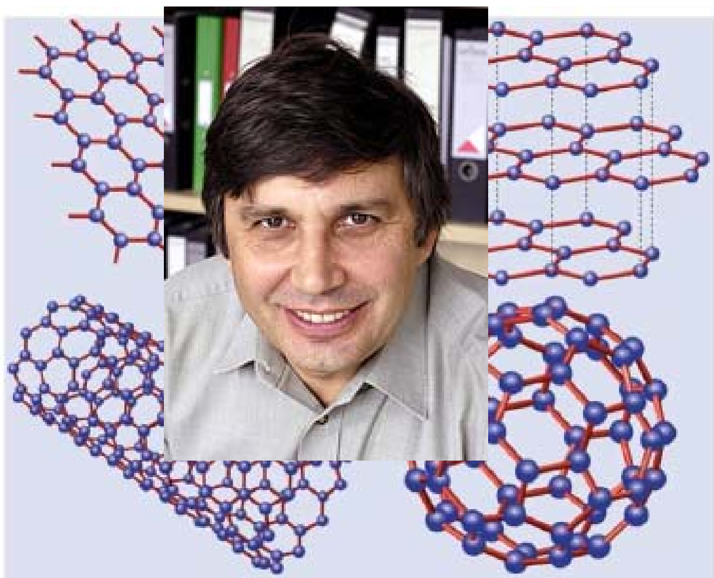


Figure 1 (Color online) Graphene (top left) is a honeycomb lattice of carbon atoms. Graphite (top right) can be viewed [illegible] 2006a).

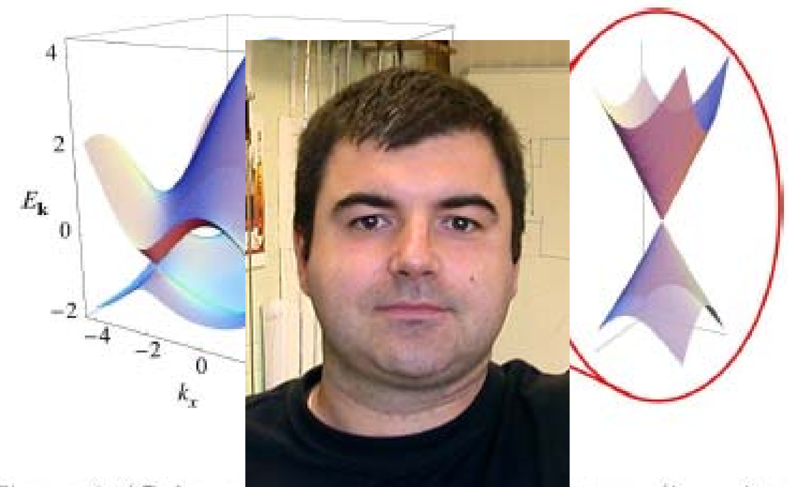


Figure 3 (Color online) Left: Energy spectrum (in units of t) for finite values of t and t', with t =2.7 eV and t' = 0.2t. Right: zoom-in of the energy bands close to one of the Dirac points.

The Nobel Prize in Physics 2010 was awarded jointly to Andrei Geim and Konstantin Novoselov *"for groundbreaking experiments regarding the two-dimensional material graphene"*

Why non-Abelian?

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- We want to mimic all possible topological insulators…

Periodic table for topological insulators and superconductors

Alexei Kitaev

California Institute of Technology, Pasadena, CA 91125, U.S.A.

TABLE 1. Classification of free-fermion phases with all possible combinations of the particle number conservation (Q) and time-reversal symmetry (T). The $\pi_0(C_q)$ and $\pi_0(R_q)$ columns indicate the range of topological invariant. Examples of *topologically nontrivial* phases are shown in parentheses.

q	$\pi_0(C_q)$	$d=1$	$d=2$	$d=3$
0	$\mathbb{Z}$		(IQHE)	
1	0			

Above: insulators without time-reversal symmetry (i.e., systems with Q symmetry only) are classified using complex K-theory.

Right: superconductors/superfluids (systems with no symmetry or T-symmetry only) and time-reversal invariant insulators (systems with both T and Q) are classified using real K-theory.

q	$\pi_0(R_q)$	$d=1$	$d=2$	$d=3$
0	$\mathbb{Z}$		no symmetry (p_x+ip_y, e.g., SrRu)	T only (^{3}He-B)
1	$\mathbb{Z}_2$	no symmetry (Majorana chain)	T only ($(p_x+ip_y)\uparrow+(p_x-ip_y)\downarrow$)	T and Q (BiSb)
2	$\mathbb{Z}_2$	T only ($(\mathrm{TMTSF})_2\mathrm{X}$)	T and Q (HgTe)	
3	0	T and Q		
4	$\mathbb{Z}$			
5	0			
6	0			
7	0			no symmetry

Also: Alex Altland + Martin Zirnbauer, Andreas Schnyder + Shinsei Ryu + Akira Furasaki + Andreas W.W. Ludwig, Xiao-Liang Qi + Taylor L. Hughes + Shou-Cheng Zhang …

Outline

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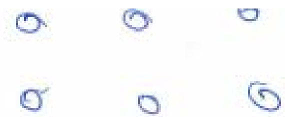
- Gauge fields in optical lattices
  - ✓ Crash course on lattice gauge fields
- Laser-induced gauge fields
  - ✓Proposal Jaksch-Zoller
  - ✓Proposal Mazza-Rizzi
  - ✓Proposal Spielman-On-A-Chip
- Physics in artificial gauge fields ("free" fermions)
  - o Hofstadter "butterflies and zebras and moonbeams and fairy tales" (Jimi Hendrix)
  - ✓ Integer Quantum Hall Effect
  - ✓ Dirac physics, topological phase transitions
  - ✓ Topological insulators and Quantum Spin Hall effect
  - ✓ Wilson fermions and axion QED

MVPs: I. Spielman, T. Porto, W. Phillips, E. Cornell, J. Dalibard, F. Gerbier, I. Bloch, A. Hemmerich, K. Sengstock (exp.), … N. Goldman, A. Bermudez, M.A. Martin-Delgado, P. Zoller, G. Juzeliūnas, J. Ruseckas, E. Demler, L. Santos, M. Fleischhauer, E. Mueller, H. Grabert, S. Das Sarma, Ch. Clark, I. Satija, D. Jaksch, L.-M. Duan, J.I. Cirac, P. Öhberg, H-P. Büchler, M. Rizzi, L. Mazza, P. Nikolić, A. Trombettoni, C. Morais Smith, J. Pachos, D. Bercieux, Y. Meurice (th.) …

Crash course on lattice gauge fields

Lattice:



2D square

<u>Bulk</u>

$$E(k) = \frac{\hbar^2 \hat{k}_x^2}{2m} + \frac{\hbar^2 \hat{k}_y^2}{2m},$$

<u>Lattice (square in 2D)</u>

$$E(k) = J\left(2 - \cos(\hat{k}_x a) - \cos(\hat{k}_y a)\right)$$

Peierls' substitution:

<u>Minimal coupling</u>

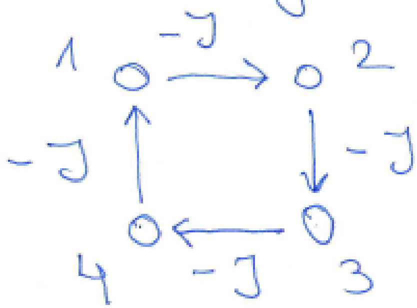
$$E(\hat{k}) = \frac{\hbar^2}{2m}\left(\hat{k} - \frac{e}{\hbar c}\hat{A}(\hat{r})\right)^2$$

$$\hat{k} \rightarrow \hat{k} - \frac{e}{c\hbar}\hat{A}$$

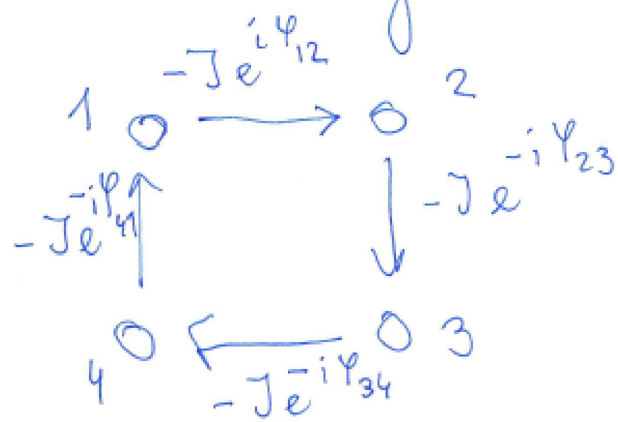
$$\cos(k_x a) \rightarrow \cos\left(k_x - A_x \frac{ea}{c\hbar}\right)$$

Crash course on lattice gauge fields

Tunneling (no field)



Tunneling (with field)



$$\frac{ea^2}{c\hbar}B = \varphi_{12}+\varphi_{23}+\varphi_{34}+\varphi_{41} \neq 0$$

↖ „magnetic" flux per plaquette (in „quantum" units)

Crash course on lattice gauge fields

Note: In experiments we design and control potentials.

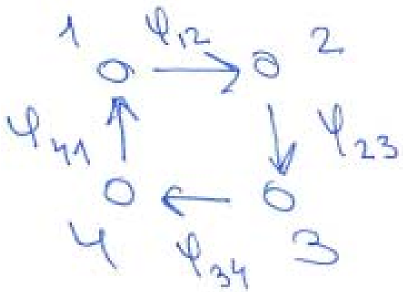
But, resulting Hamiltonians are gauge

... ccess

... quantities

Gauge dependent
freaks of all countries, unite!!!
Your time has come!!!

We can change phases locally



$$\varphi_{12} \to \varphi_{12} + \varphi_1 - \varphi_2$$
$$\varphi_{23} \to \varphi_{23} + \varphi_2 - \varphi_3$$
$$\varphi_{34} \to \varphi_{34} + \varphi_3 - \varphi_4$$
$$\varphi_{41} \to \varphi_{41} + \varphi_4 - \varphi_1$$

but $\Rightarrow \varphi_{12} + \varphi_{23} + \varphi_{34} + \varphi_{41} = \text{const}$

Crash course on lattice gauge fields

Non-Abelian fields: particles have "colors" (internal states)

Bulk

$$E(\bar{k}) = \frac{\hbar^2}{2m}\left(\bar{k} - \frac{e}{\hbar c}\hat{A}(\bar{r})\right)^2$$

If gauge fields $SU(N)$

then $\hat{A} \in su(N)$

$\hat{A}$ – hermitian matrix,

such that

$$e^{i\hat{A}} \in SU(N)$$

Lattice

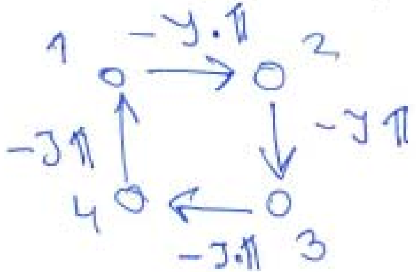
Tunnelings become unitary operations:

$$\cos(k_x a) \to \left(\cos\left(k_x - \hat{A}_x \frac{ea}{\hbar c}\right)\right)$$

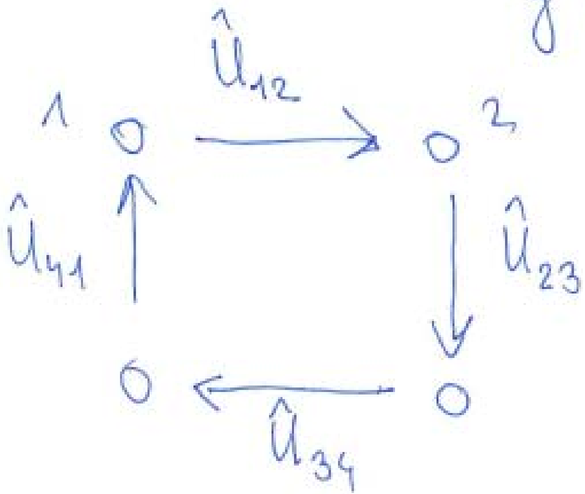
⋮

Crash course on lattice gauge fields

Tunneling (no field)



Tunneling (SU(2) field)



$U_{ij} \in SU(2)$

Wilson loop operator

(non-Abelian Aharonov-Bohm)

$W_\square = \hat{U}_{12}\hat{U}_{23}\hat{U}_{34}\hat{U}_{41}$

Wilson loop:

$\mathrm{Tr}\, W_\square = \mathrm{Tr}\left(\hat{U}_{12}\hat{U}_{23}\hat{U}_{34}\hat{U}_{41}\right)$

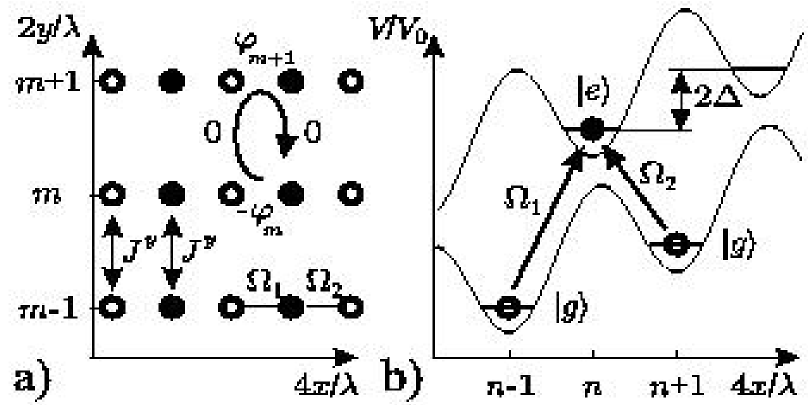
Wilson loop is gauge invariant!

Proposal Jaksch-Zoller (Abelian)

$U_y = 1$

$U_x = \exp(i\alpha m)$

$y = \lambda m/2$



The scheme = combination of laser assisted tunneling, lattice tilting, employing of internal states

D. Jaksch and P. Zoller, New J. Phys. 5, 56 (2003).

Proposal Mazza-Rizzi (non-Abelian)

U_x , U_y , U_z = "anything you want"

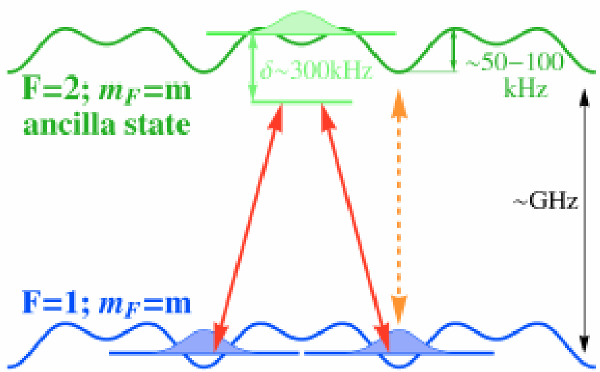


FIG. 3: Sketch of the scheme we propose to induce hopping between the levels of the $F = 1$ manifold, i.e. the adiabatic elimination of one $F = 2$ state trapped in the intermediate minimum (red non-dashed arrows). Because of orthogonality properties of wannier functions, the coupling cannot be realised with microwave fields. Optical Raman transitions through an excited state carry non-negligible momentum and can therefore be a solution. In Appendix A we also discuss

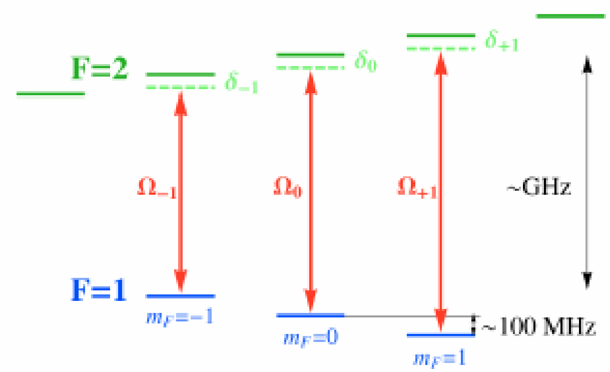


FIG. 4: Splittings of the levels of the $F = 1$ and $F = 2$ hyperfine manifolds in ^{87}Rb due to an external magnetic field. The splitting between the two manifolds is not in scale. Red arrows describe the effective couplings we want to engineer via Raman transitions, δs and Ωs are the effective parameters describing these transitions.

Emerging Bosons with Three-Body Interactions from Spin-1 Atoms in Optical Lattices
L. Mazza, M. Rizzi, M. Lewenstein, J.I. Cirac, in print PRA.

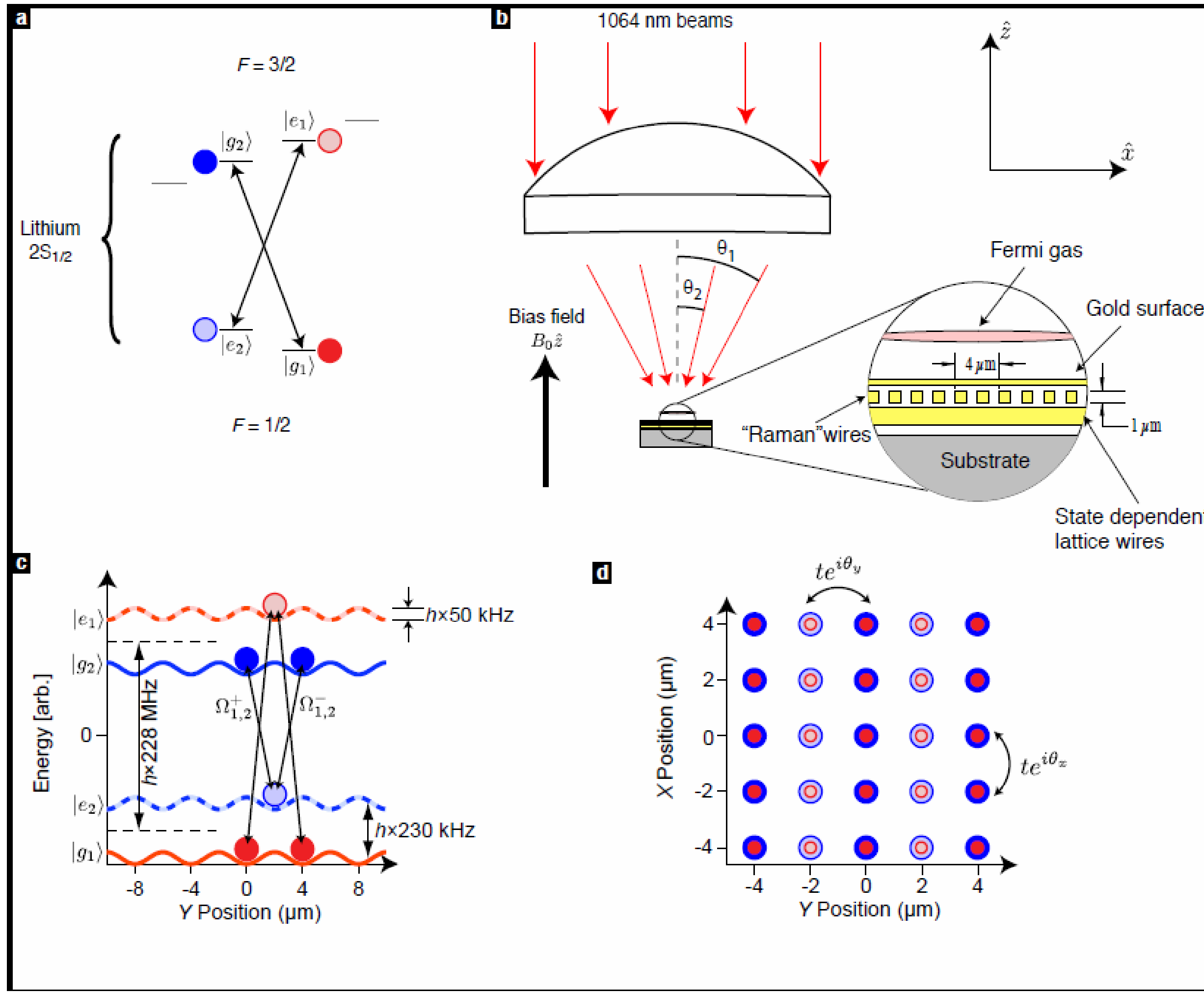
Proposal Spielman-On-A-Chip

$$U_x = \exp(i\gamma\sigma_x)$$

$$U_y = \exp(im\alpha\sigma_z)$$

$$x = m/2$$

$$H = H_{hopping} + \lambda_{stag}\sum(-1)^m c^\dagger_{mn} c_{mn}$$



Realistic Time-Reversal Invariant Topological Insulators With Neutral Atoms, N. Goldman, I. Satija, P. Nikolić, A. Bermudez, M.A. Martin-Delgado, M. Lewenstein, and I.B. Spielman, pending in PRL.

Physics with artificial gauge fields (non-Abelian U(1)xSU(2), constant Wilson loop)

$U_x = \exp(i\alpha\sigma_x)$

$U_y = \exp(im\Phi + i\beta\sigma_y)$

$x = \lambda m/2$

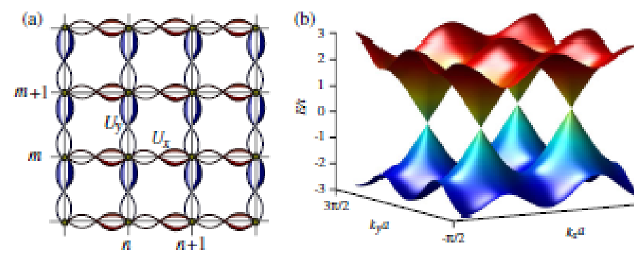


FIG. 1 (color online). (a) Square lattice subjected to a non-Abelian gauge potential. This external field induces state-dependent hoppings described by the U(2) operators U_x and U_y. (b) Energy bands close to the π-flux regime ($\Phi_\alpha = \pi/2 + 0.1$, $\Phi_\beta = \pi/2 - 0.1$), with vanishing Abelian flux $\Phi = 0$. The bands touch at four Dirac points inside the first Brillouin zone (BZ), where the energy scales linearly with momenta $E \sim k$.

When |W| = |Tr(Product of U's along the perimeter of a plaquette)| < 2, then the field is genuine non-Abelian!

Integer Quantum Hall Efect (lattices)

PHYSICAL REVIEW A **79**, 023624 (2009)

Ultracold atomic gases in non-Abelian gauge potentials: The case of constant Wilson loop

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[2]*ICFO-Institut de Ciències Fotòniques, Parc Mediterrani de la Tecnologia, E-08860 Castelldefels, Barcelona, Spain*
[3]*Marian Smoluchowski Institute of Physics, Jagiellonian University, Reymonta 4, 30059 Kraków, Poland*
[4]*Instituciò Catalana de Ricerca i Estudis Avançats, 08010 Barcelona, Spain*
(Received 21 December 2007; revised manuscript received 2 December 2008; published 26 February 2009)

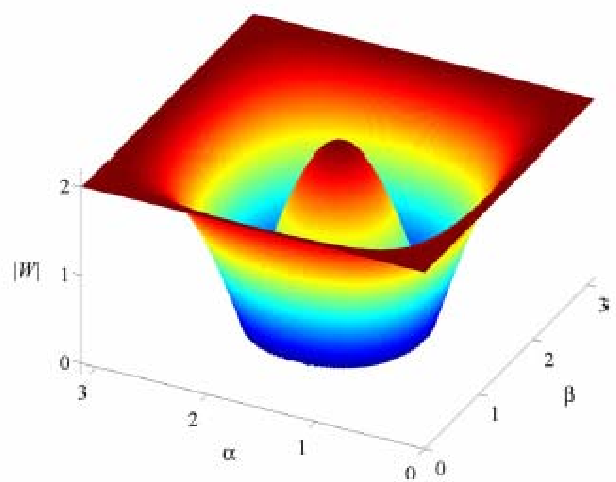

FIG. 2. (Color online) Wilson loop's magnitude as a function of the parameters $|W|=|W(\alpha,\beta)|$. The Abelian regime is determined by the criterion $|W|=2$: In the range $\alpha,\beta\in[0,\pi]$, the system is equiva-

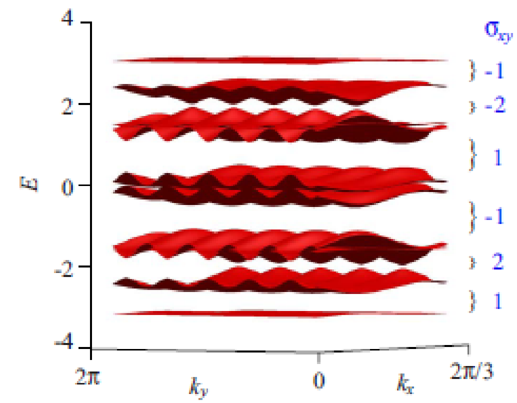

FIG. 3. (Color online) Spectrum $E=E(k_x,k_y)$ for $\alpha=1$, $\beta=2$, and $\Phi=0.2$. While the degeneracy of some of the bands is lifted, the three central bands remain doubly degenerate. Blue integers repre-

Integer Quantum Hall Efect (lattices)

Ref. [19], one can generalize the well-known Thouless-Kohmoto-Nightingale-Nijs (TKNN) expression [32] to the present non-Abelian framework, yielding

$$\sigma_{xy} = \frac{1}{2\pi i h} \sum_{E_\lambda < E_F} \int_{\mathrm{T}^2} \sum_j \left(\langle \partial_{k_x} u_{\lambda j} | \partial_{k_y} u_{\lambda j} \rangle - \langle \partial_{k_y} u_{\lambda j} | \partial_{k_x} u_{\lambda j} \rangle \right) dk, \tag{8}$$

ULTRACOLD ATOMIC GASES IN NON-ABELIAN GAUGE … PHYSICAL REVIEW A **79**, 023624 (2009)

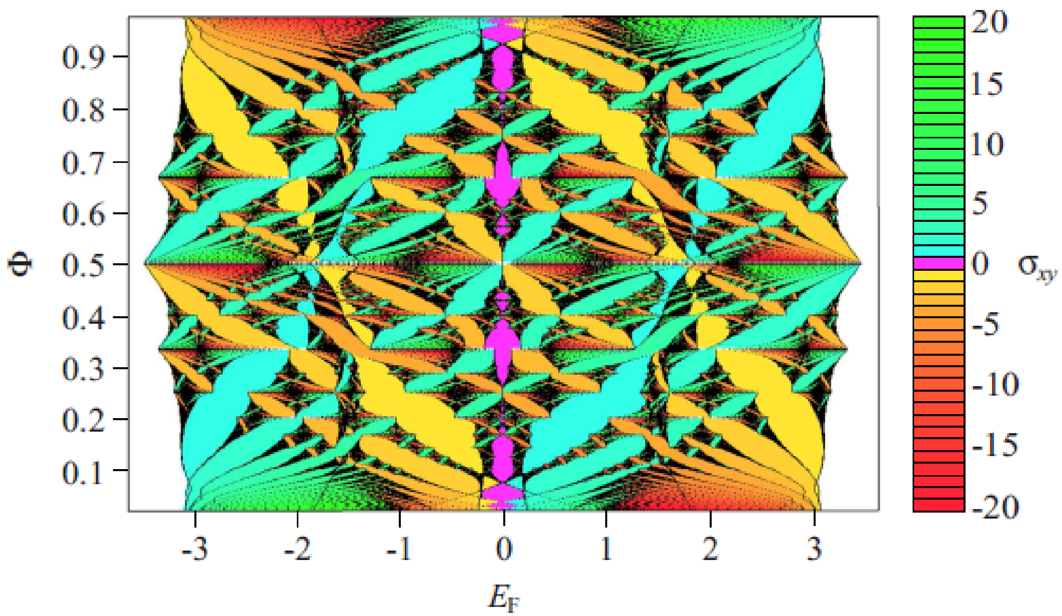

FIG. 5. (Color online) Spectrum $E=E(\Phi)$ and phase diagram for $\alpha=1$, $\beta=2$, and $\Phi=\frac{p}{q}$ with $q<97$. Cold (respectively, warm) colors correspond to positive (respectively, negative) values of the quantized conductivity. Purple corresponds to a null transverse conductivity. For $\Phi \ll 1$, the quantized conductivity evolves monotonically but suddenly changes sign around the van Hove singularities located at $E \simeq \pm 1$ (see the alternation of cold and warm colors). The Fermi energy is expressed in units of the hopping parameter t and the transverse conductivity is expressed in units of $1/h$.

Dirac physics in non-Abelian gauge fields

PRL 103, 035301 (2009) PHYSICAL REVIEW LETTERS week ending 17 JULY 2009

Non-Abelian Optical Lattices: Anomalous Quantum Hall Effect and Dirac Fermions

N. Goldman,[1] A. Kubasiak,[2,3] A. Bermudez,[4] P. Gaspard,[1] M. Lewenstein,[2,5] and M. A. Martin-Delgado[4]
[1]Center for Nonlinear Phenomena and Complex Systems - Université Libre de Bruxelles (U.L.B.), Code Postal 231, Campus Plaine, B-1050 Brussels, Belgium
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[3]Marian Smoluchowski Institute of Physics Jagiellonian University, Reymonta 4, 30059 Kraków, Poland
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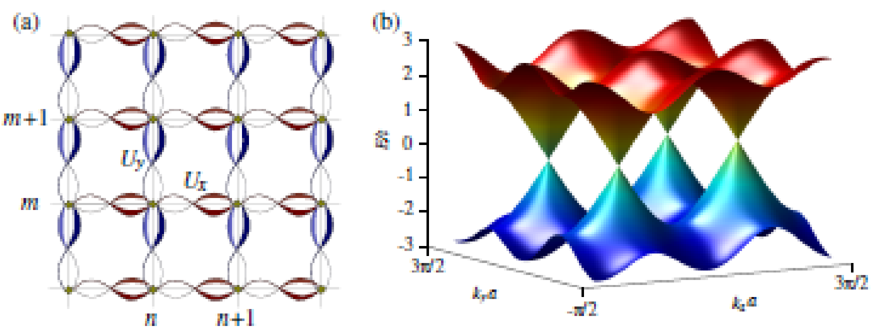


Figure 1: (a) Square lattice subjected to a non-Abelian gauge potential. This external field induces state-dependent hoppings described by the U(2) operators U_x and U_y. (b) Energy bands close to the π-flux regime ($\Phi_\alpha = \pi/2 + 0.1$,

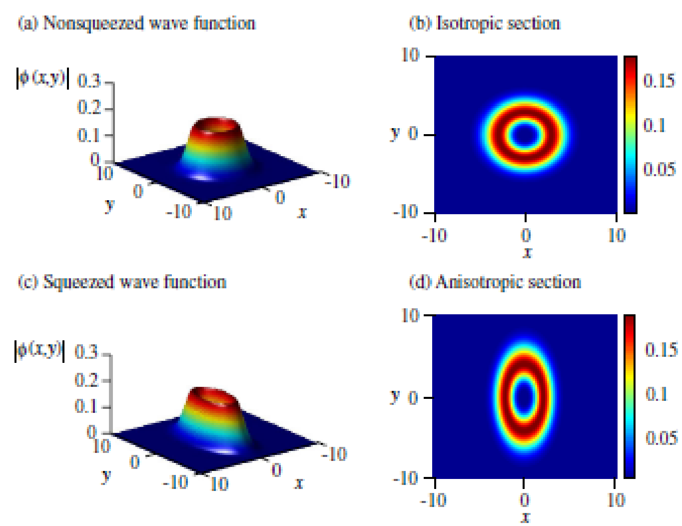
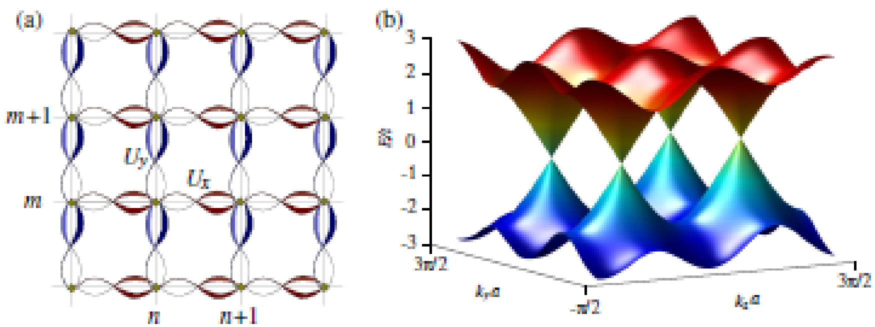


FIG. 3 (color online). Vortex-like single-particle wave functions of the LLL $\phi^m_{\rm LLL}(x, y)$ for $m = 4$. (a), (b) Isotropic limit $c_x = c_y$. (c), (d) Anisotropic regime $c_y = 2c_x$. Note that distances are measured in units of the magnetic length l_B.

Why Dirac physics in in non-Abelian gauge fields?



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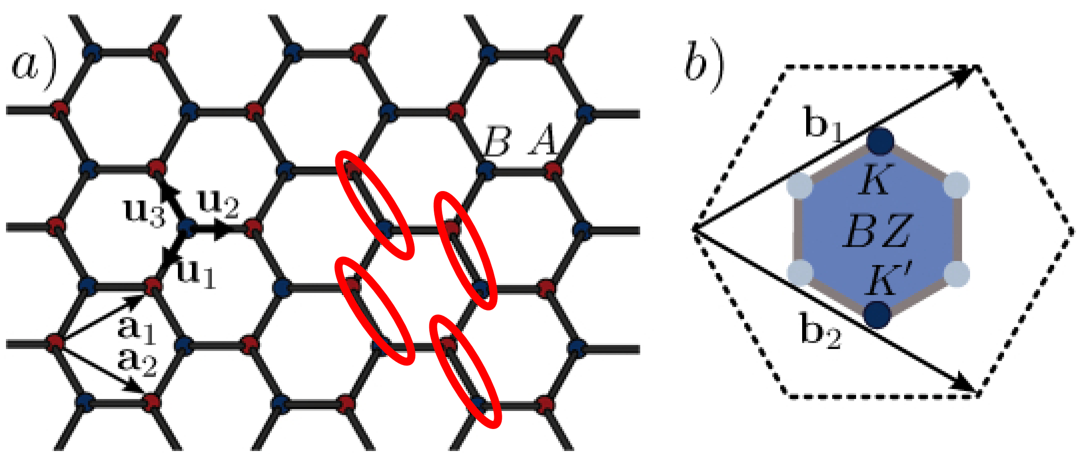
In 2D square lattice SU(2) gauge fields include spin-orbit, Rashba and Dresselhaus couplings, and more…



Topological phase transitions

New Journal of Physics
The open-access journal for physics

Topological phase transitions in the non-Abelian honeycomb lattice

New Journal of Physics **12** (2010) 033041 (38pp)
Received 8 October 2009
Published 24 March 2010

A Bermudez[1,6], N Goldman[2], A Kubasiak[3,4], M Lewenstein[3,5] and M A Martin-Delgado[1]

$U_1 = \exp(i\alpha\sigma_x)$
$U_2 = 1$
$U_3 = \exp(i\beta\sigma_y)$

Pure SU(2)

IOP Institute of Physics · DEUTSCHE PHYSIKALISCHE GESELLSCHAFT

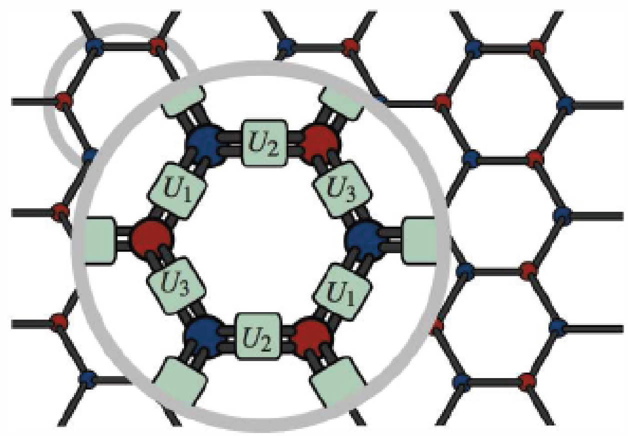
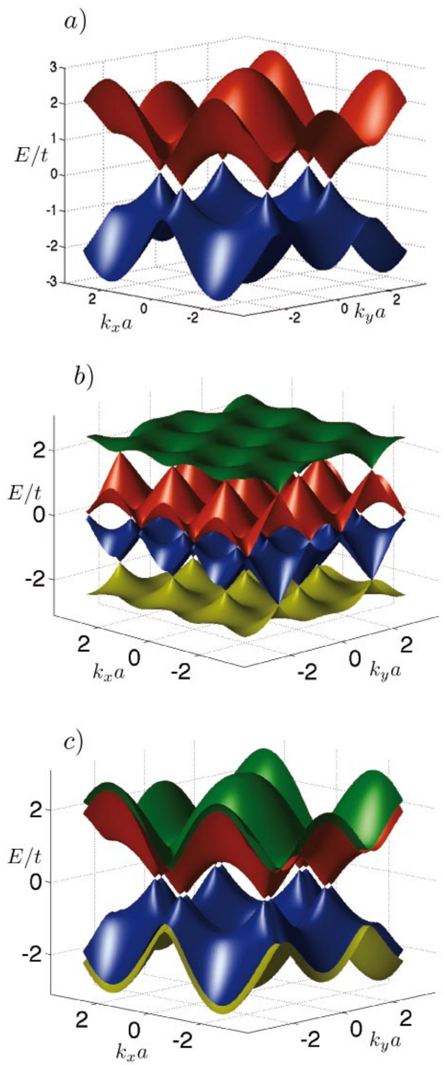


Figure 5. Scheme for the fermionic honeycomb lattice subjected to SU(2) gauge fields, where each hopping is dressed by $U_1 = e^{i\alpha\tau_x}$, $U_2 = \mathbb{I}$ and $U_3 = e^{i\beta\tau_y}$. We

Topological phase transitions



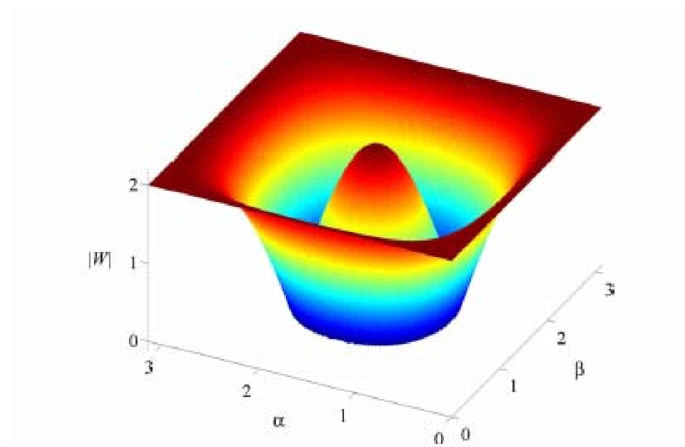


FIG. 2. (Color online) Wilson loop's magnitude as a function of the parameters $|W|=|W(\alpha,\beta)|$. The Abelian regime is determined by the criterion $|W|=2$: In the range $\alpha,\beta\in[0,\pi]$, the system is equiva-

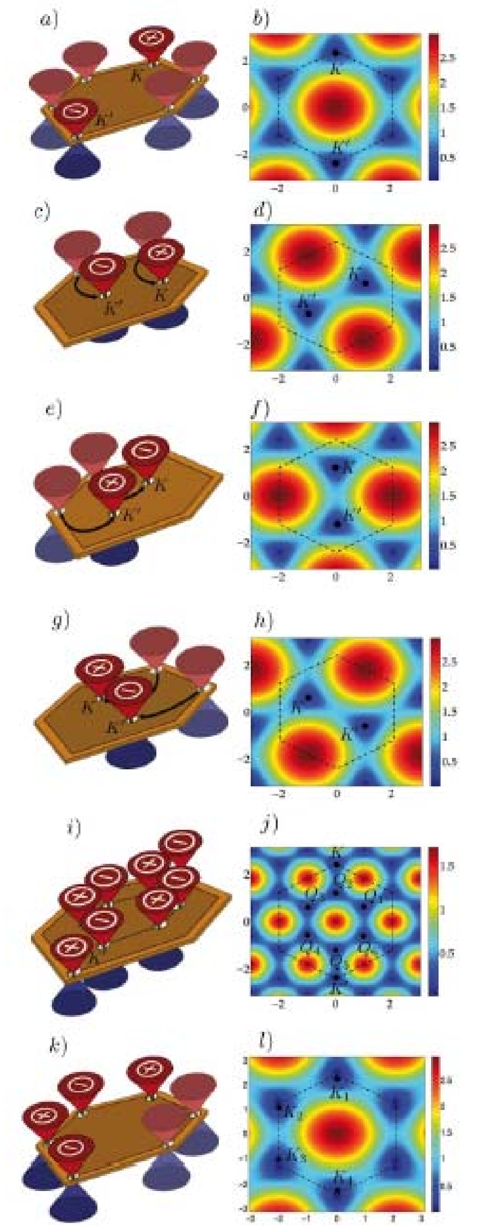
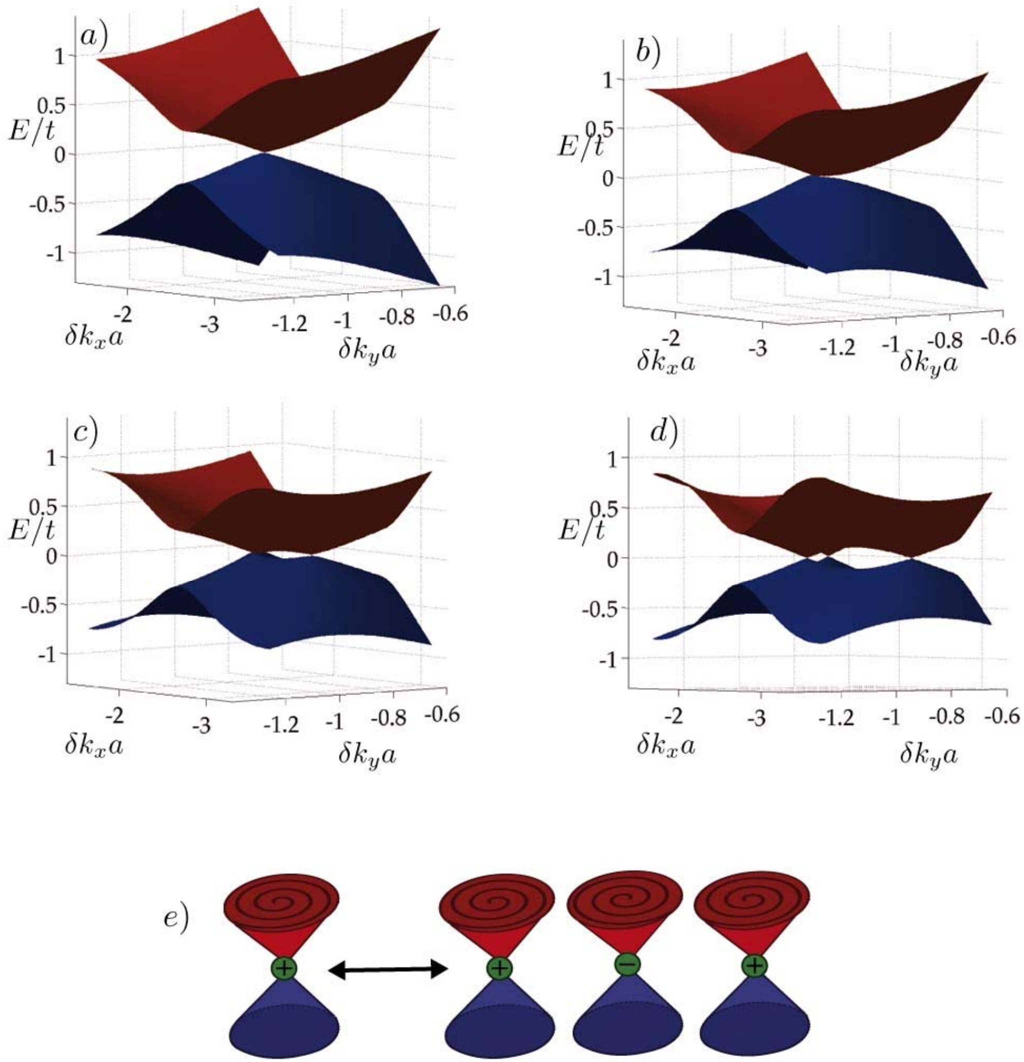


Figure 3: Distribution of Dirac points with their associated topological charges along the first Brillouin zone for (a) Graphene P_1,

Emergence of relativisitic fermions



annihilation (time-reversed event).

Topological insulators and QSH effect

$U_x = \exp(i\gamma\sigma_x)$

$U_y = \exp(im\alpha\sigma_z)$

$x = m/2$

$H = H_{hopping} + \lambda_{stag}\Sigma(-1)^m c^\dagger_{mn} c_{mn}$

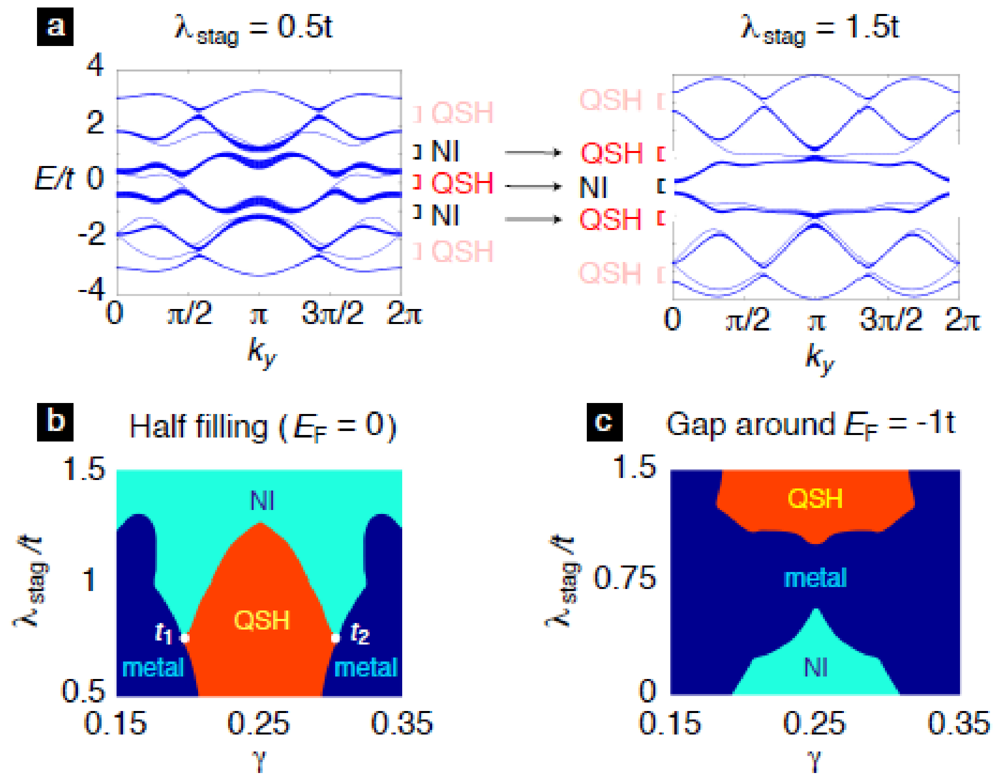


Figure 3: (a) Energy bands $E(k_y)$ for $\gamma = 0.25$ and $\alpha = 1/6$, with an external staggered potential $\lambda_{stag} = 0.5t$ and $1.5t$. The topological phases associated to the bulk gaps are indicated. (b)-(c) Phase diagrams in the (γ, λ_{stag})-plane in the vicinity of the maximally coupled case $\gamma = 0.25$ for (b) $E_F = 0$ and (c) $E_F = -1$.

Realistic Time-Reversal Invariant Topological Insulators With Neutral Atoms, N. Goldman, I. Satija, P. Nikolić, A. Bermudez, M.A. Martin-Delgado, M. Lewenstein, and I.B. Spielman, pending in PRL.

Wilson fermions and axion QED

Wilson Fermions and Axion Electrodynamics in Optical Lattices

A. Bermudez,[1] L. Mazza,[2] M. Rizzi,[2] N. Goldman,[3] M. Lewenstein,[4,5] and M.A. Martin-Delgado[1]

in print in PRL

Naive massless fermions:

$U_{rx}=\exp(-i\psi_x\alpha_x)$

$U_{ry}=\exp(-i\psi_y\alpha_y)$

$U_{rx}=\exp(-i\psi_z\alpha_z)$

$\alpha_k=\sigma_z\otimes\sigma_k$

Add on site Raman to make them all massive.

Then dd $V_{rk}=-i\exp[-i\pi\beta/2]$, $\beta=\sigma_x\otimes 1$, k-dependent strength, to make one m~0

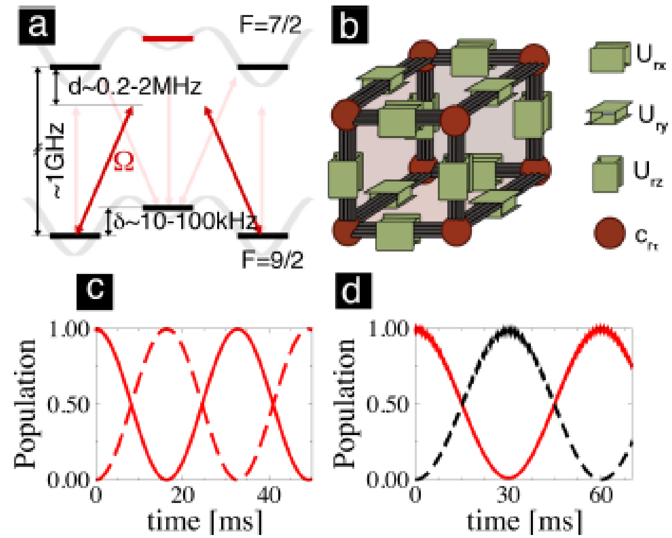


Figure 1: a) Superlattice potential (grey lines) trapping ^{40}K atoms in the main and secondary minima. The hopping between $F=9/2$ levels (in black) is laser-assisted via an intermediate $F=7/2$ state (in red). The coupling, detuned by $d+\delta$, is induced by an off-resonant Raman transition with Rabi frequency Ω. b) Scheme of the four states of the $F=9/2$ manifold (red vertices), connected by laser-induced hoppings (green boxes). (c) Time-evolution of the populations of the neighboring $m_F=9/2$ levels for the spin-preserving hopping. The solid (dashed) line is used for site i $(i+1)$. A clear spin-preserving Rabi oscillation between neighboring sites is present. The numerical simulation is an exact Runge-Kutta time-evolution of the complete model involving all the couplings and the levels in Fig 1a. (d) The same as before for a spin-flipping hopping. Notice the need for a superlattice staggering (10-20 kHz) in order to avoid on-site spin-flipping. Exact time-evolution shows oscillations between neighboring sites with a different spin.

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Wilson fermion is invariant under $U_{anti} = i(1 \otimes \sigma_y)K$

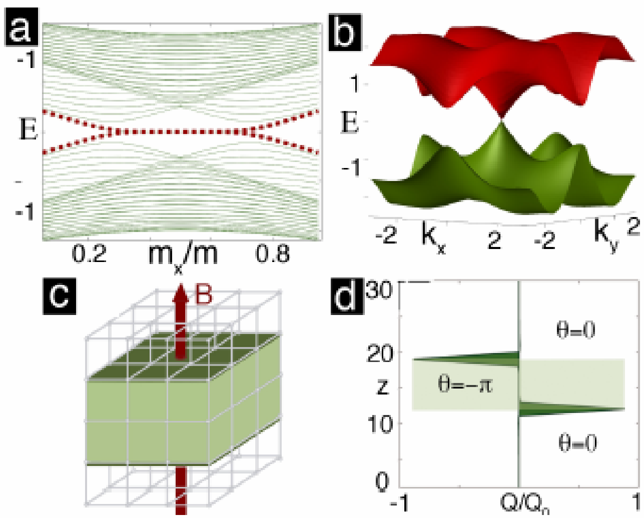


Figure 2: a) In-gap zero-energy modes (dashed red lines) for $\boldsymbol{q} = (k_x, k_y) = \boldsymbol{0}$, $m/4 \leq m_x \leq 3m/4$, and $m_y = m/2, m_z = m/4$, for a lattice with $N = 40^3$ sites and open boundaries at $z = 0, L$. b) Boundary massless Dirac fermion at $z = 0$, $\boldsymbol{q} = \boldsymbol{0}$, and $m_x = m_y = m_z = m/2$. c) Scheme for a fractional magnetic capacitor consisting of an axion well: $\theta(\boldsymbol{r}, t) = -\pi$ if $z \in [z_l, z_r]$, and $\theta(\boldsymbol{r}, t) = 0$ elsewhere, pierced by a magnetic field $\boldsymbol{B} = B\hat{\mathbf{z}}$. This is designed by tuning $m_x = m_y = m_z/2 = m/4$ globally, whereas $\tilde{m} \gg m$ is only applied to $z_l < z < z_r$. d) Accumulated charge on the "plates" of the capacitor, for a lattice of $N = 30^3$ sites, $m_x = m_y = m_z/2 = m/4$, $\tilde{m} = 10m$ (leading to $\theta = -\pi$ for $12 < z < 18$), and flux $\phi/\phi_0 = 2\pi/15$.

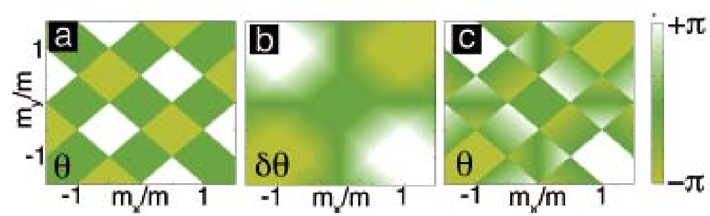
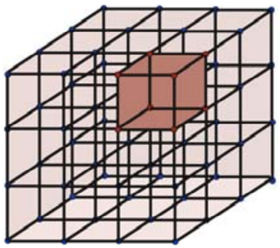
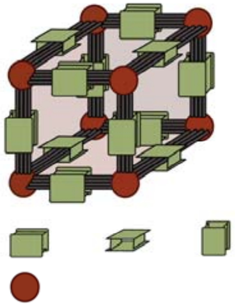


Figure 3: a) Axion index as a function of the masses $m_y/m, m_x/m$, and setting $m_z = m/2$. In the $\mathscr{U}_a$ invariant regime, only fixed values of the axion $\theta = \{0, \pi\}$ are allowed. b) Perturbations to the axion term $\delta\theta$ in the $\mathscr{U}_a$-breaking regime. d) Total axion term θ in the $\mathscr{U}_a$-breaking regime..

Outlook

- Other groups (SU(N), discrete, Heisenberg-Weyl…)
- Dirac physics in curved space





- Spin Hall Effect
  - Atoms on a atom-chip (I. Spielman)
  - Multiband scenario with spin currents (edge states)
  - Novel type of topological insulators
- Artificial Gauge Fields in 3+1 Dimensions
  - Experiment: Proposals by us and J. Dalibard/F. Gerbier
  - Artificial SU(4) lattice gauge fields
  - Emergence of massless/massive Dirac fermions
  - Laboratory for Wilson fermions, axion QED, "neutrino oscillations", …
- Interacting systems: Superfluidity and FQHE
- Toward quantum simulators of lattice gauge theories?

Frog levitation in an artificial non-Abelian “magnetic” field

- http://www.youtube.com/watch?v=A1vyB-O5i6E

QUAntum Gauge Theories and Ultracold Atoms

Collaborations: Theory

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Indu Satija, Predrag Nikolić (GMU, Fairfax, VI and NIST)
Ryan Barnett (UMD and NIST, KITP collaboration!!!)

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Collaborations: Experiments

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Klaus Sengstock + (Uni Hamburg)