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ARTICLES

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# Direct measurement of the Zak phase in topological Bloch bands

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**Geometric phases that characterize the topological properties of Bloch bands play a fundamental role in the band theory of solids. Here we report on the measurement of the geometric phase acquired by cold atoms moving in one-dimensional optical lattices. Using a combination of Bloch oscillations and Ramsey interferometry, we extract the Zak phase—the Berry phase gained during the adiabatic motion of a particle across the Brillouin zone—which can be viewed as an invariant characterizing the topological properties of the band. For a dimerized lattice, which models polyacetylene, we measure a difference of the Zak phase $\delta\varphi_{\mathrm{Zak}} = 0.97(2)\pi$ for the two possible polyacetylene phases with different dimerization. The two dimerized phases therefore belong to different topological classes, such that for a filled band, domain walls have fractional quantum numbers. Our work establishes a new general approach for probing the topological structure of Bloch bands in optical lattices.**

Franziska Maier

Dec 17, 2013

# Introduction

Topological phenomena:

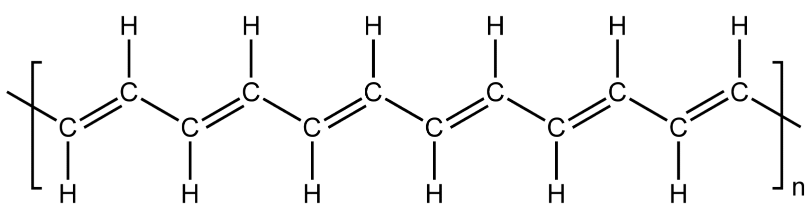
- Fermion number fractionalization
- Integer Quantum Hall effect
- Protected surface states

Topological invariants:

- (2D) Chern number – related to Berry's phase
- (1D) e.g. Zak phase to define invariants

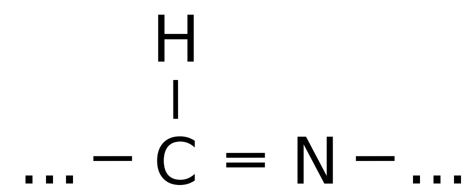
Systems with non-trivial Zak phase:

Polyacetylene (Su-Schrieffer-Heeger model)



en.wikipedia.org

Linearly conjugated diatomic polymers




Idea:

Measure Zak phase using Bloch oscillations and Ramsey interferometry in 1D optical lattices

# Definition Zak phase

$$\varphi_{\mathrm{Zak}} = i \int_{-G/2}^{G/2} \langle u_k | \, \partial_k \, | u_k \rangle \, \mathrm{d}k$$

Cell periodic Bloch function:

$$u_k(x) = e^{-ikx} \psi_k(x)$$

Reciprocal lattice vector:

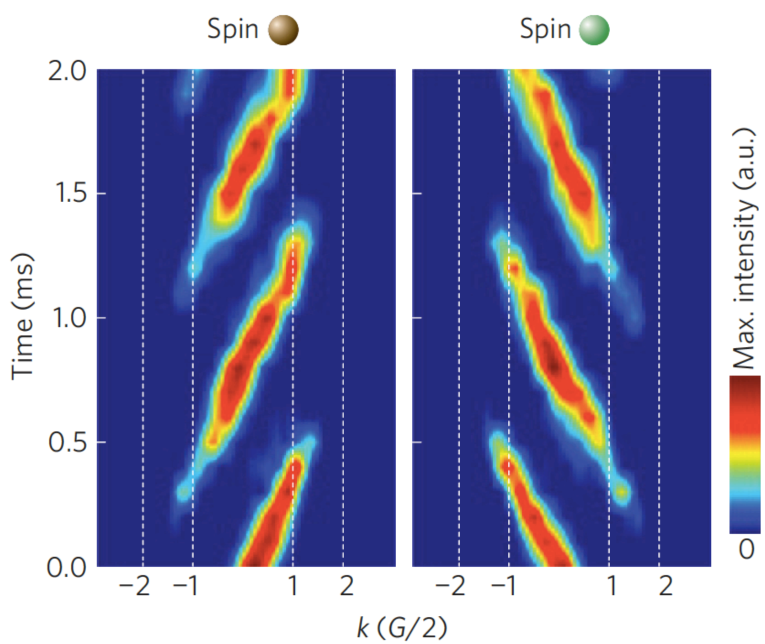
$$G = 2\pi / d$$

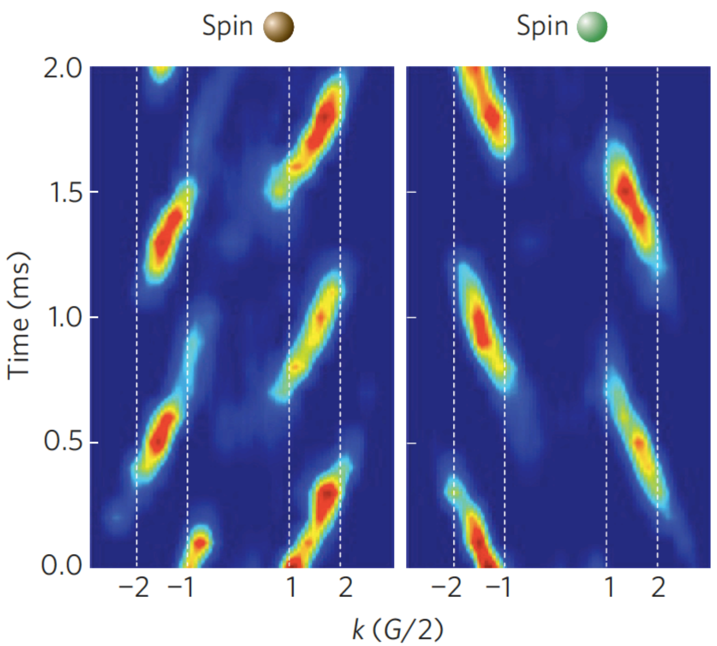
Depends on choice of unit cell, relative phase is well defined

J. Zak, PRL 62, 2747 (1989)

# Bloch oscillations - TOF distributions

Move particles adiabatically through Brillouin zone using Bloch oscillations.




Lower band

Upper band

$$\tau_{\text{Bloch osc.}} \sim 850\mu s$$

# Dimerized optical lattice

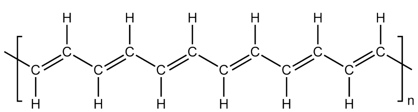
Rice-Mele Hamiltonian

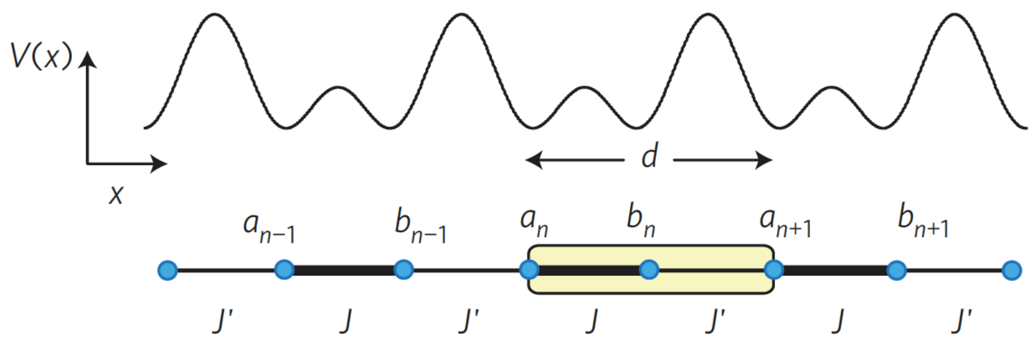
$$\hat{H} = -\sum_n (J\hat{a}_n^\dagger \hat{b}_n + J'\hat{a}_n^\dagger \hat{b}_{n-1} + \mathrm{h.c.}) + \Delta \sum_n (\hat{a}_n^\dagger \hat{a}_n - \hat{b}_n^\dagger \hat{b}_n)$$

PRL 49, 1455 (1982)

$\Delta = 0$

Polyacetlyene





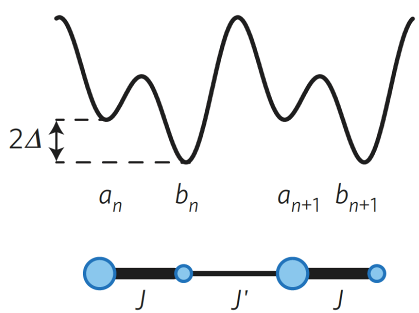

$D1,\ J > J'$

$D2,\ J < J'$

$\Delta \neq 0$

Linearly conjugated diatomic polymer

H
|
... − C = N − ...



# Realizing the lattice

Load Bose-Einstein condensate of ~5 x $10^4$ $^{87}Rb$ atoms
in 1D optical superlattice defined by

$$V(x) = V_l \sin^2(k_l x + \phi/2) + V_s \sin^2(2k_l x + \pi/2)$$

$$\phi = 0 \rightarrow D1$$
$$\phi = \pi \rightarrow D2$$
$$\phi \neq 0, \pi \rightarrow \text{control } \Delta$$

$$\lambda_s = \lambda_l/2 = 767 \text{ nm}$$
$$k_l = 2\pi/\lambda_l$$

# Eigenstates of *H*

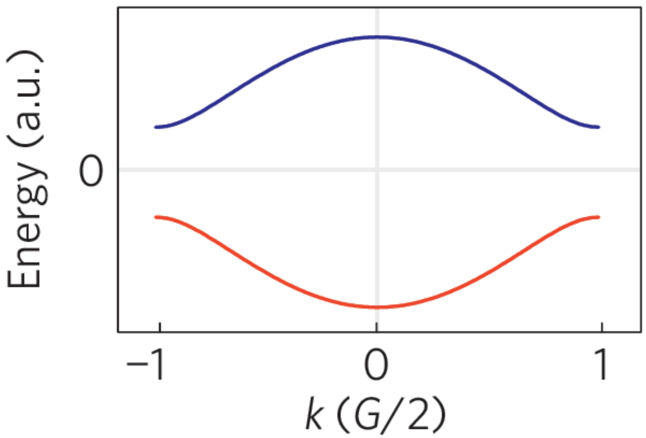
Wannier functions

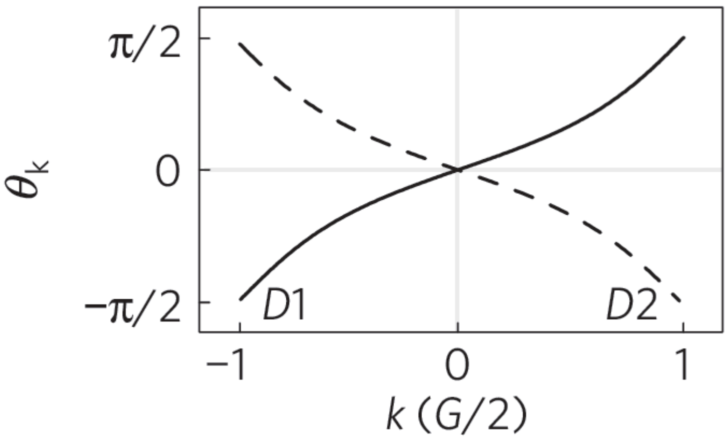
$$\psi_k(x) = \sum_n \alpha_k e^{ikx_n} w_a(x - x_n) + \beta_k e^{ik(x_n + d/2)} w_b(x - x_n - d/2)$$

Pseudospin vektor $\quad \boldsymbol{u}_k = (\alpha_k, \beta_k)$

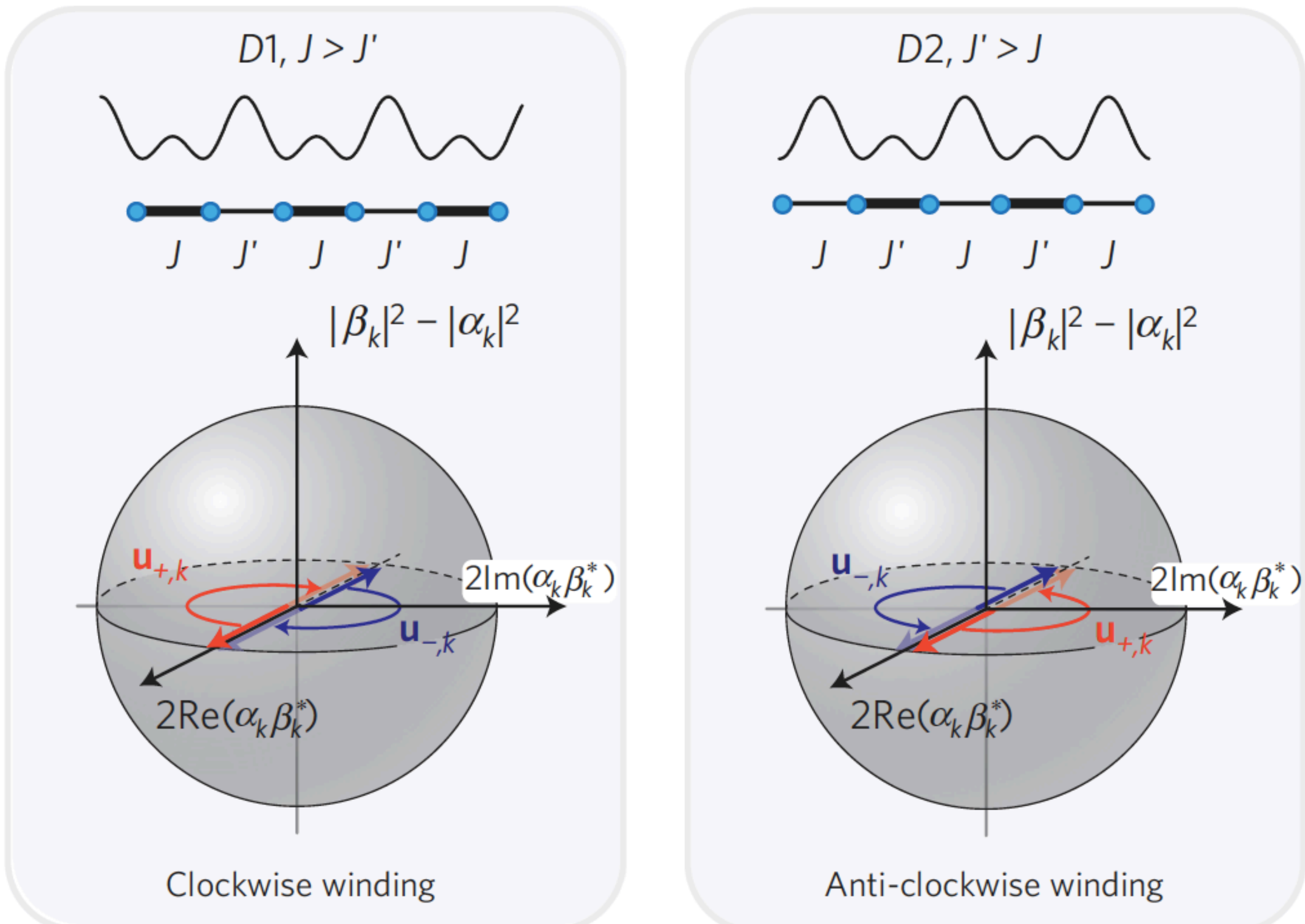
$$\Delta = 0 \qquad \boldsymbol{u}_{\mp,k} = \frac{1}{\sqrt{2}} \begin{pmatrix} \pm 1 \\ e^{-i\theta_k} \end{pmatrix}$$

$$J e^{ikd/2} + J' e^{-ikd/2} = |\epsilon_k| e^{i\theta_k}$$



# Pseudospin representation $\Delta = 0$




$$\varphi_{\mathrm{Zak}}^{D1} = \pi/2 \qquad \varphi_{\mathrm{Zak}}^{D2} = -\pi/2$$

Phase dependent winding direction of **u**

# Phase Shift - 3Step Sequence I

Phase due to adiabatic movement in Brillouin zone:

$$\varphi_{\mathrm{tot}} = \varphi_{\mathrm{Zak}} + \varphi_{\mathrm{dyn}} + \varphi_{\mathrm{Zeeman}}$$

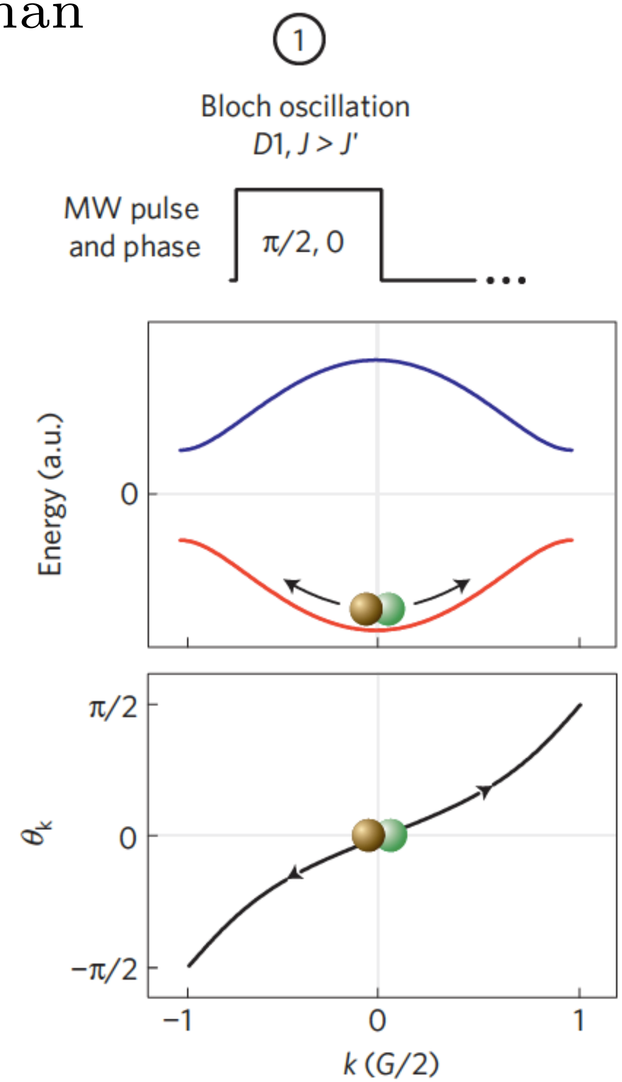
3step sequence to isolate $\delta\varphi_{\mathrm{Zak}}$
(one atom)

1) $|\downarrow, k = 0\rangle$

MW pulse $\xrightarrow{\pi/2}$ $1/\sqrt{2}(|\downarrow, k = 0\rangle + |\uparrow, k = 0\rangle)$

Bloch oscillations due to a **B**-field gradient

$$1/\sqrt{2}(e^{i\delta\varphi}\,|\downarrow, -k\rangle + |\uparrow, k\rangle)$$



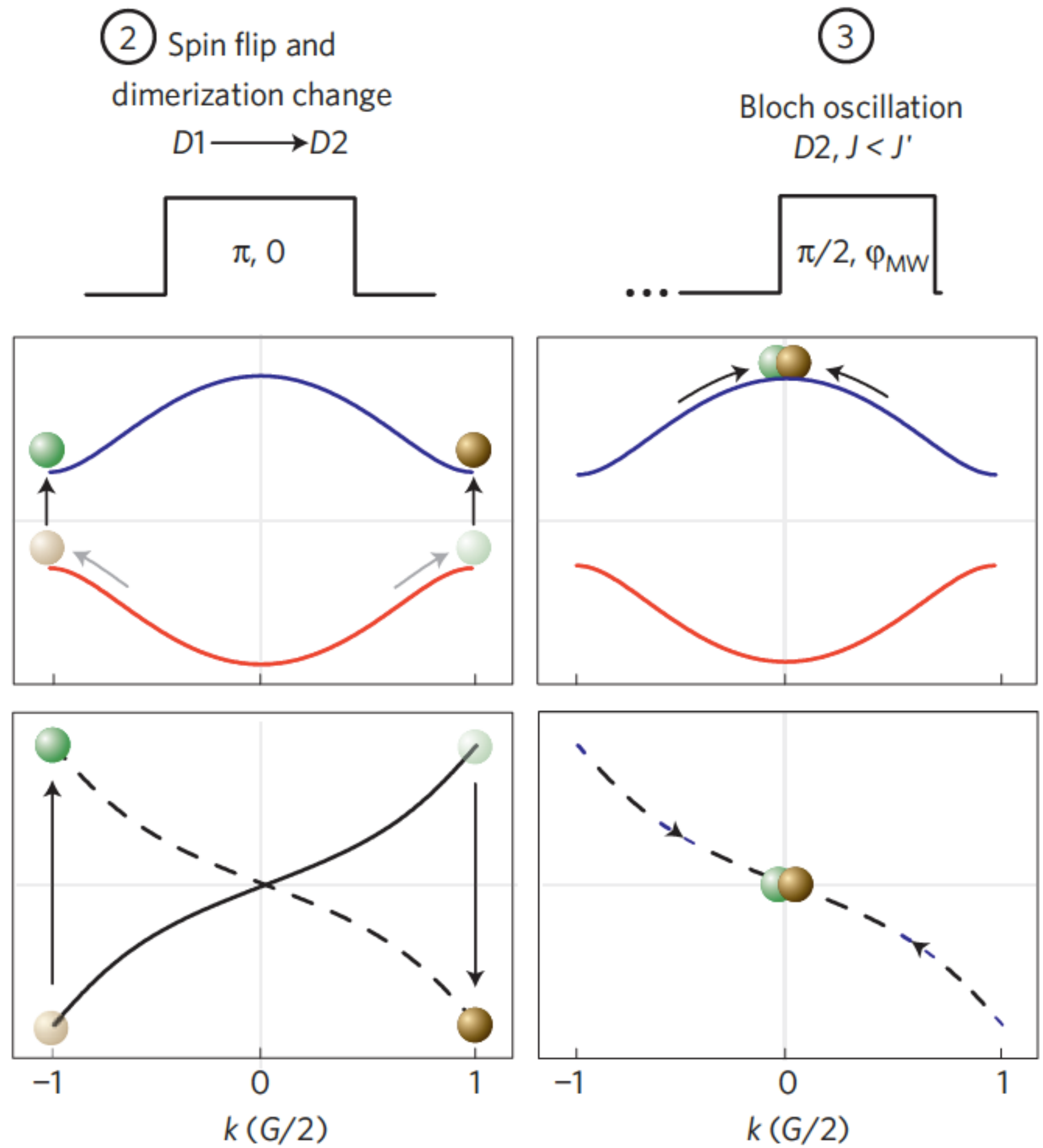
# Phase Shift - 3Step Sequence II

2) Eliminate $\delta\varphi_{\text{Zeeman}}$
by a spin echo $\pi$ pulse
and add a non-adiabatic
dimerization swap
$D1 \rightarrow D2$

3) Evolutions via
Bloch oscillations back to
$k = 0$
Interference of the two spin
components with MW $\pi/2$ pulse

TOF measurements with Stern-Gerlach setup separates spin states an reveals

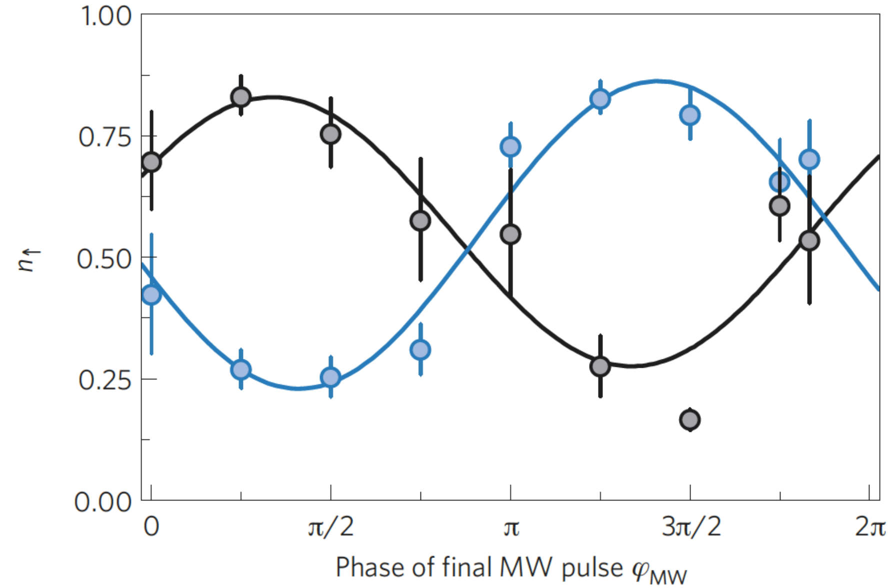
$$\delta\varphi = \varphi_{\text{Zak}}^{D1} - \varphi_{\text{Zak}}^{D2}$$



# Measured Ramsey Fringes

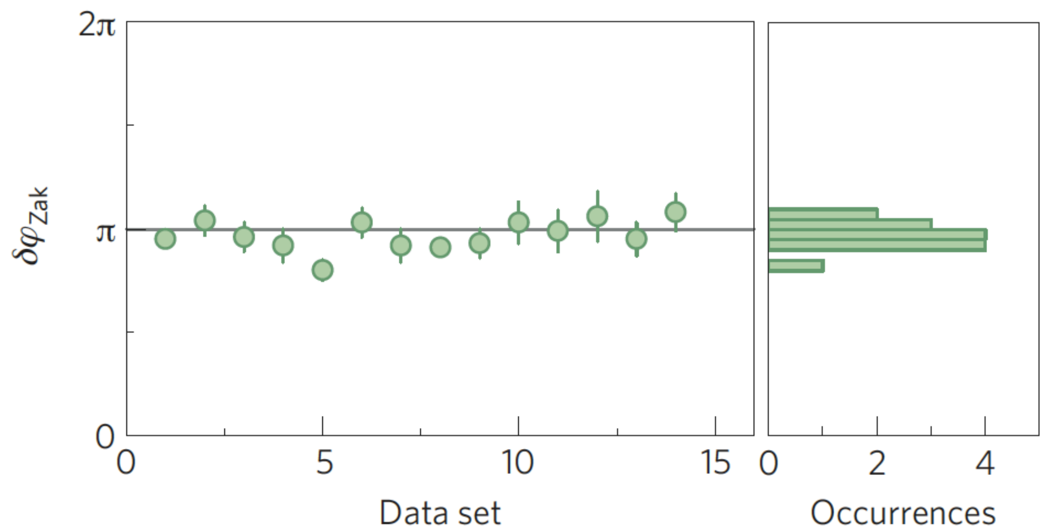
$$n_\uparrow = N_\uparrow / N_{\text{total}}$$

Blue – dimerization swapped
Black – dimerization not swapped

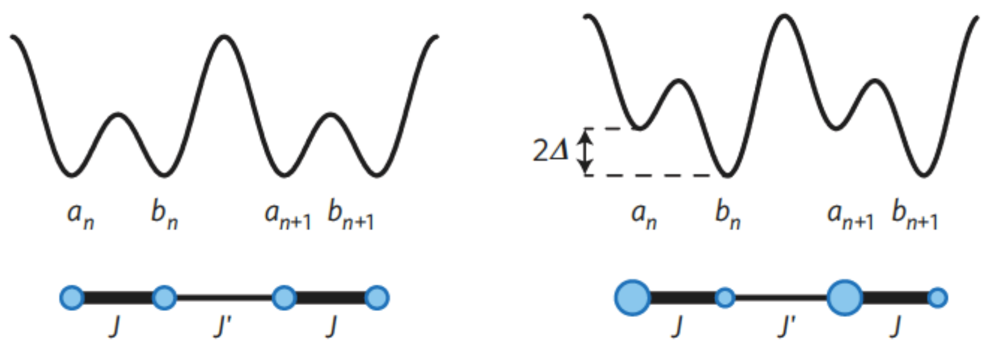


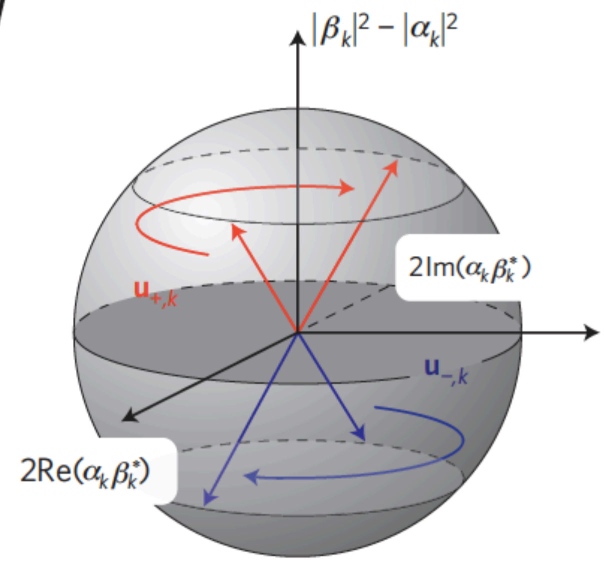

Histogram of
14 measurements

$$\delta\varphi_{\text{Zak}} = 0.97(2)\pi$$



# Fractional Zak phase $\Delta \neq 0$



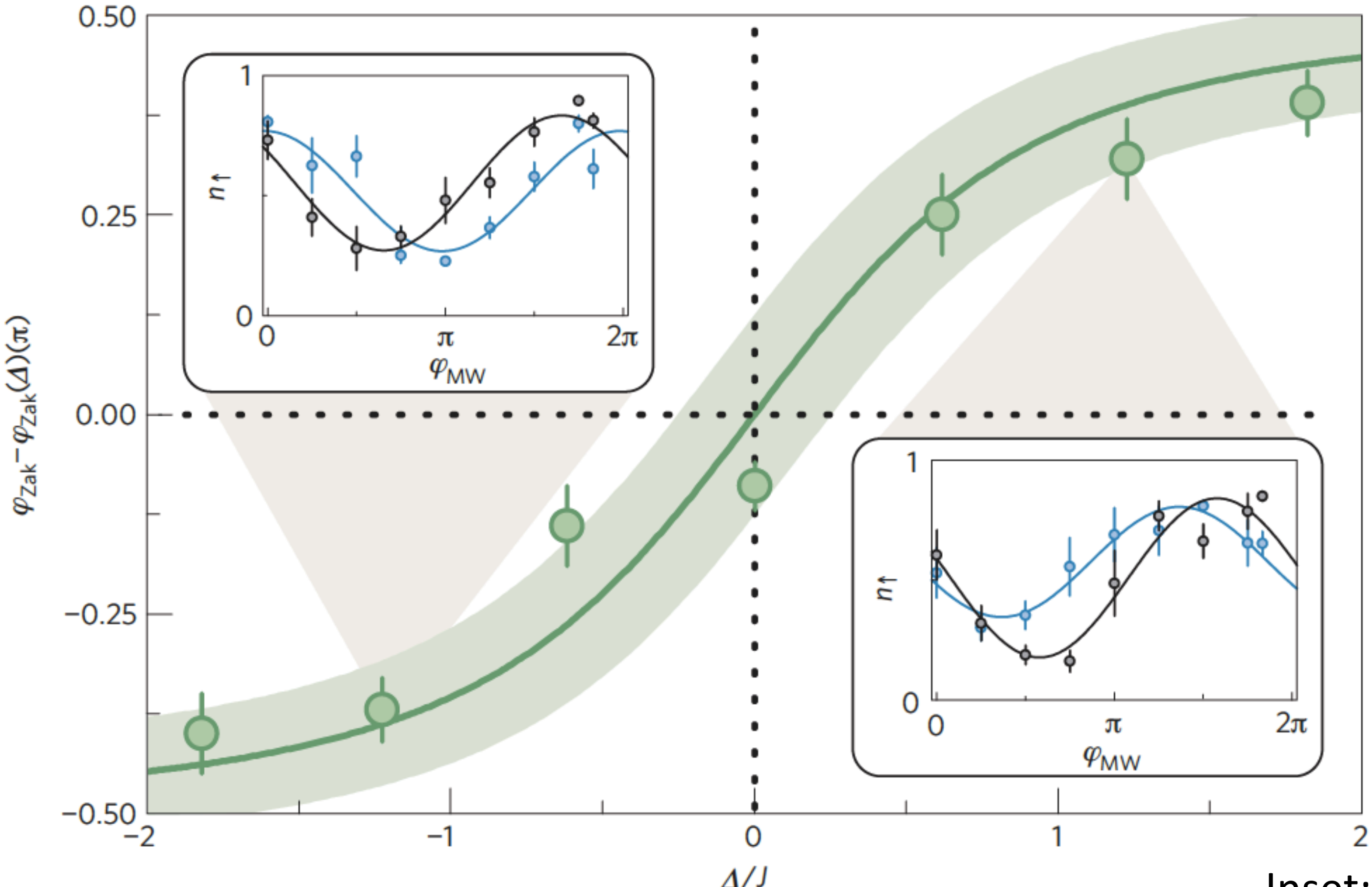




Modified 3step sequence:

$$\Delta = 0 \to |\Delta| < 2J$$

$$\varphi_{\mathrm{Zak}} = \pi/2 \to \varphi_{\mathrm{Zak}}(\Delta)$$

# Fractional Zak phase




Inset:

Ramsey Fringes

Blue – staggered

Black – not staggered

# Conclusions

- Approa
predict
- Extend
- Next st
Introdu