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Evidence for a Quantum-to-Classical Transition in a Pair of Coupled Quantum Rotors

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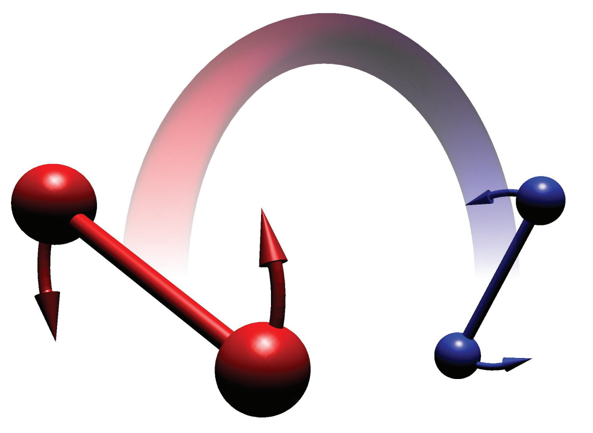
Motivation



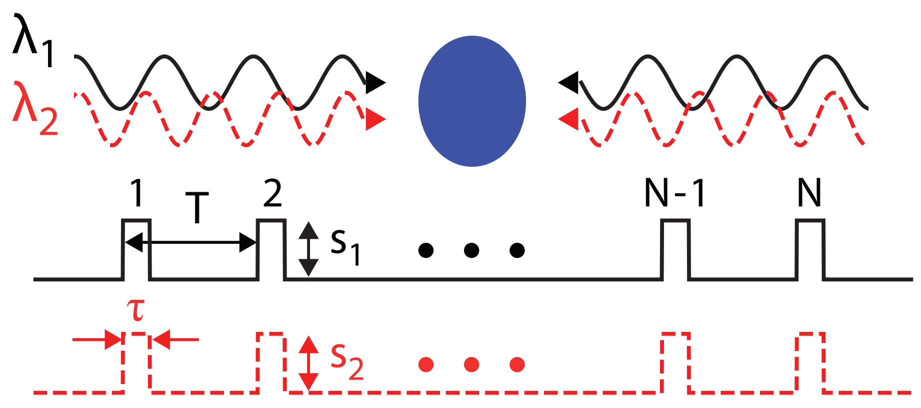
We study the dynamical response of matter-waves to a pulsed incommensurate lattice.

This system realizes a variant of the δ-kicked rotor model [Casati, *et al.* (1979) ; Moore, *et al.* (1995)] , that of *coupled* kicked quantum rotors

A quantum-to-classical transition is predicted to occur in this system [S. *Adachi, M. Toda, K. Ikeda, PRL 61, 659 (1988)*]

- quantum-to-classical transition in simple closed system with unitary, time-reversible dynamics
- classical physics emerges naturally without coupling to reservoir & decoherence
- new light on nature of localization in 2D systems

BEC in a pulsed, incommensurate optical lattice



Wavelengths ($\lambda_1 = \eta\lambda_2$; $\eta \sim 1.36$)
$\lambda_1 = 1064$ nm
$\lambda_2 = 782$ nm
Depths
$V_{1,2} = s_{1,2} E_R$
($E_R = h^2/2M\lambda_1^2$)

For short δ-like pulses, the system is described by

$$\hat{H} = \frac{-\hbar^2 \partial_z^2}{2M} + \left[\frac{s_1 E_R \tau}{2}\cos(2k_1 z) + \frac{s_2 E_R \tau}{2}\cos(2\eta k_1 z)\right]\sum_{j=1}^{N}\delta(t - jT)$$

For irrational η, with no intersection between sets of states coupled by the two lattices, we can write an effective 2D Hamiltonian in the basis of plane-wave states $|m,n\rangle$ with momentum $p_{mn} = (m+\eta n)2\hbar k_1$

$$\hat{H} = \hat{H}_0 + \hbar(\hat{\phi}_{V_1} + \hat{\phi}_{V_2})\sum_{j=1}^{N}\delta(t - jT)$$

momentum-mode-dependent quasi-energies (phase-accruals)

pseudo-random for $\kappa \neq 4\pi$ and $\eta^2\kappa \neq 4\pi$

$$\hat{H}_0 = \frac{\hbar}{T}\sum_{m,n}\frac{\kappa m^2 + \eta^2\kappa n^2 + 2\eta\kappa m n}{2}\hat{n}_{m,n}$$

$\frac{\kappa}{4\pi} = \frac{4E_R T}{h}$ controls depth of "disorder"

$\eta\kappa mn$ cross-dimensional ***coupling*** term

$$\phi_{V_2} = \frac{K_2}{\kappa}\sum_{m,n}(\hat{a}^\dagger_{m,n-1}\hat{a}_{m,n} + \hat{a}^\dagger_{m,n+1}\hat{a}_{m,n})$$

tunneling between modes separated by $2\eta\hbar k_1$

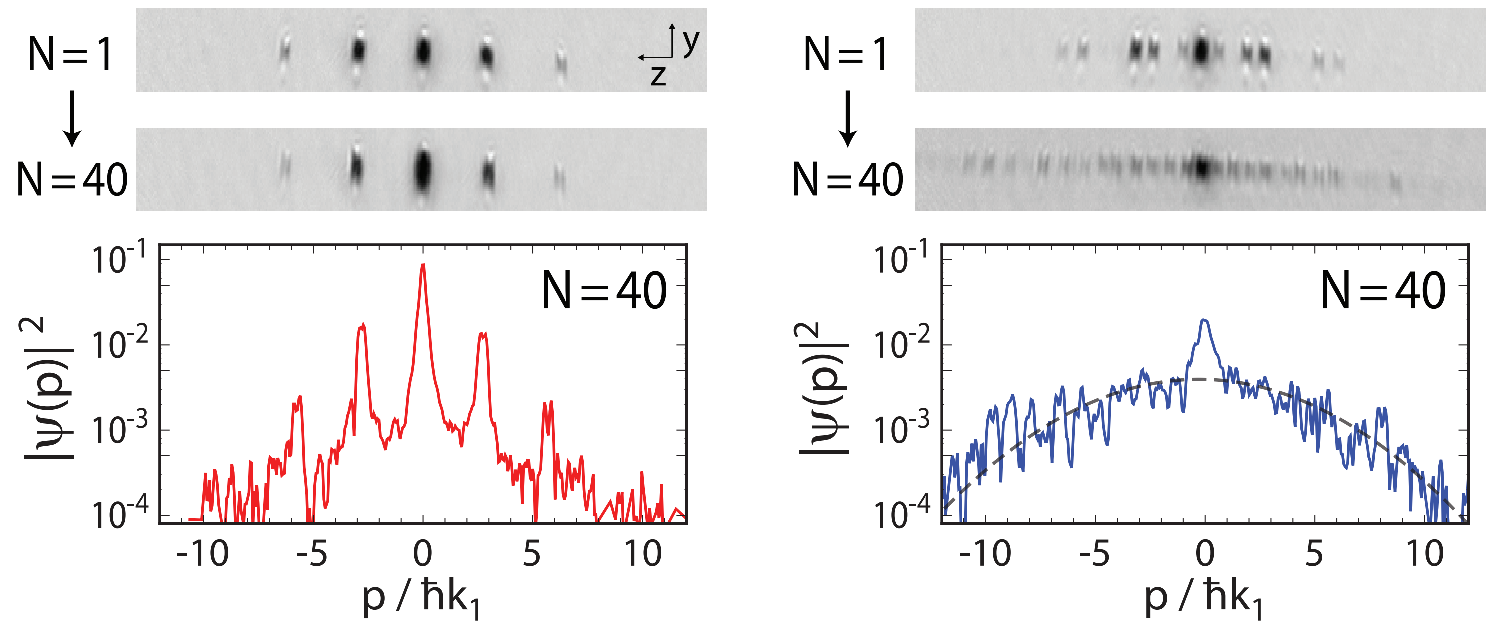
$\frac{K_{1,2}}{\kappa} = \frac{s_{1,2}E_R\tau}{2\hbar}$ controls strength of tunneling

$$\phi_{V_1} = \frac{K_1}{\kappa}\sum_{m,n}(\hat{a}^\dagger_{m-1,n}\hat{a}_{m,n} + \hat{a}^\dagger_{m+1,n}\hat{a}_{m,n})$$

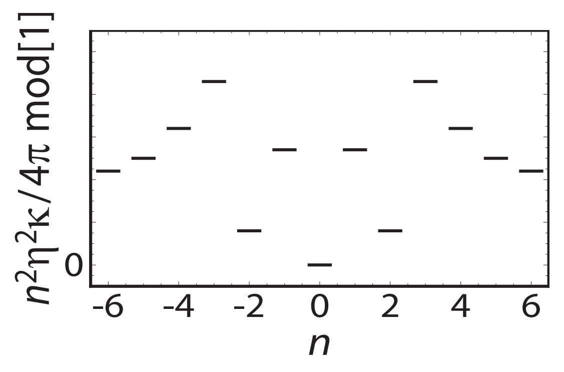
discrete-time tunneling in momentum-space between modes separated by $2\hbar k_1$

Off-Resonant Kicking ($\kappa/4\pi \neq 0$)

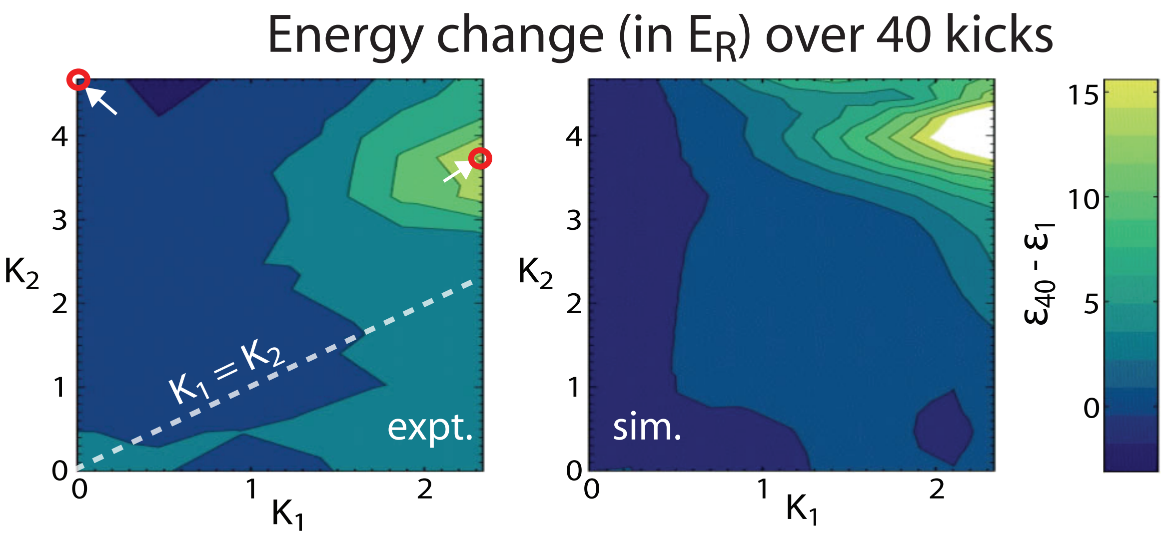
($T = 36\ \mu$s) $\kappa/4\pi = 0.29$ $\eta^2\kappa/4\pi = 0.54$

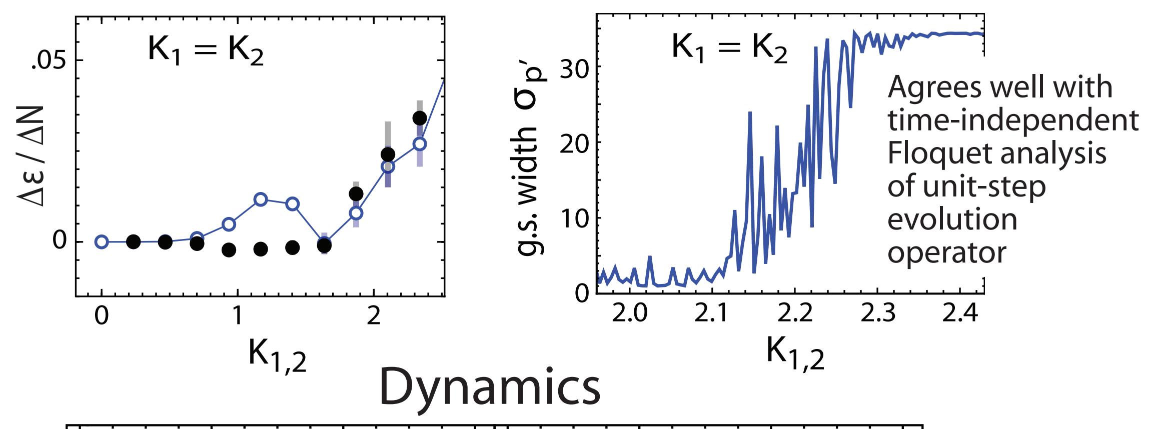


- Dynamical localization due to pseudo-random quasi-energies
- Coupling leads to classical diffusion

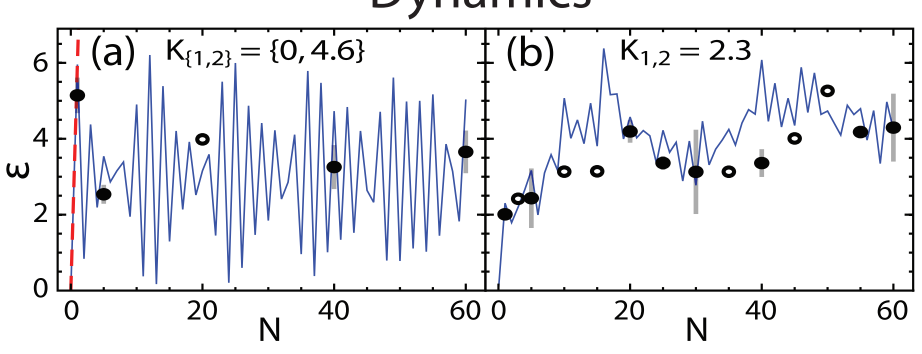


Energy change (in E_R) over 40 kicks

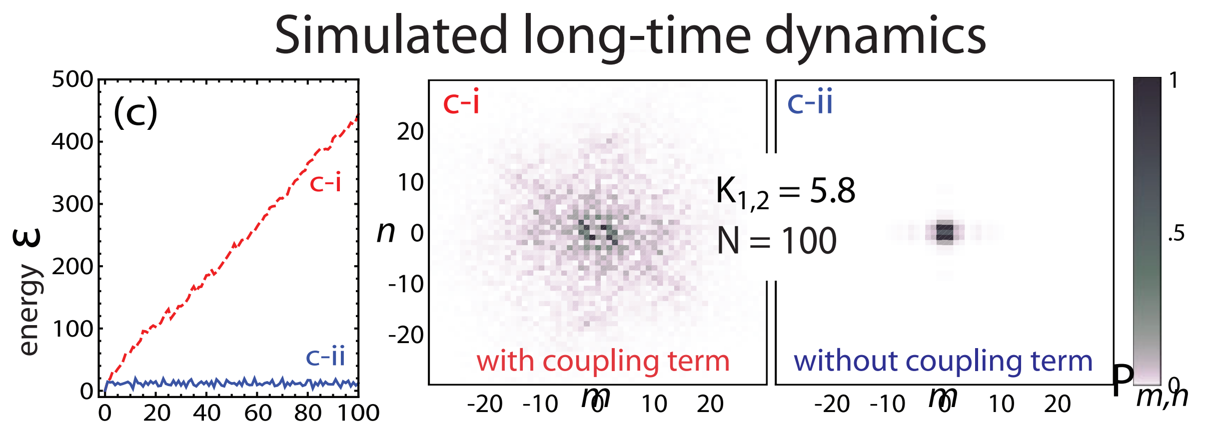




Dynamics



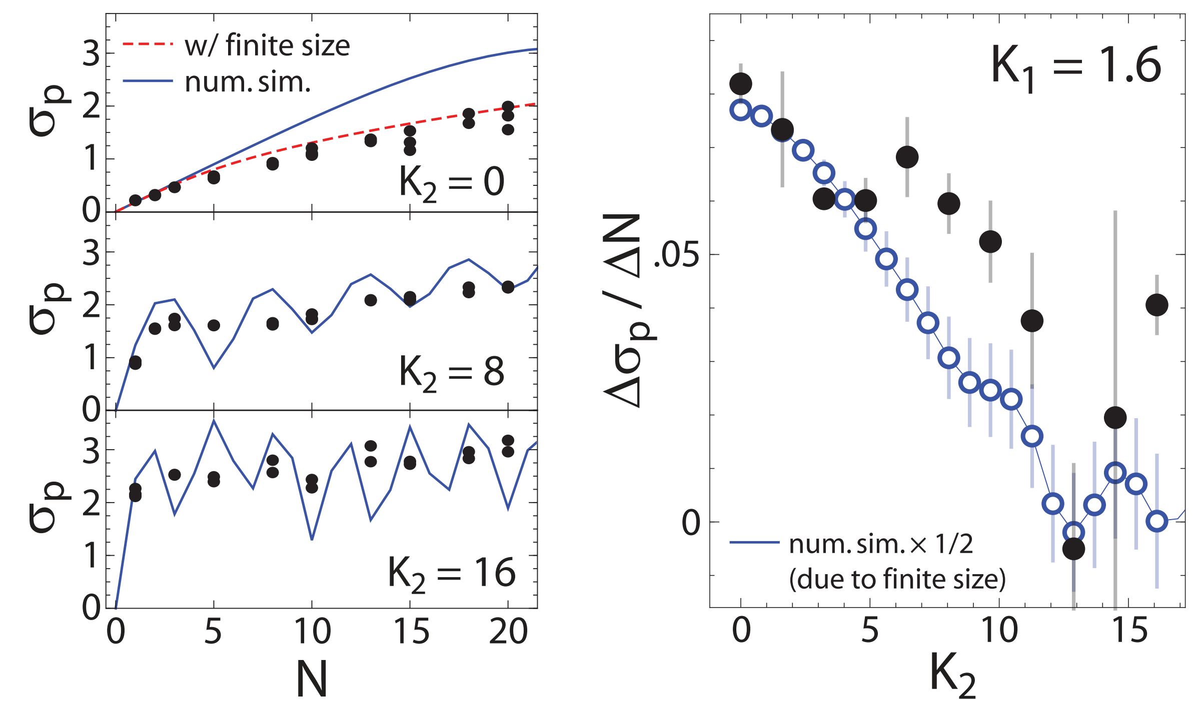
Simulated long-time dynamics



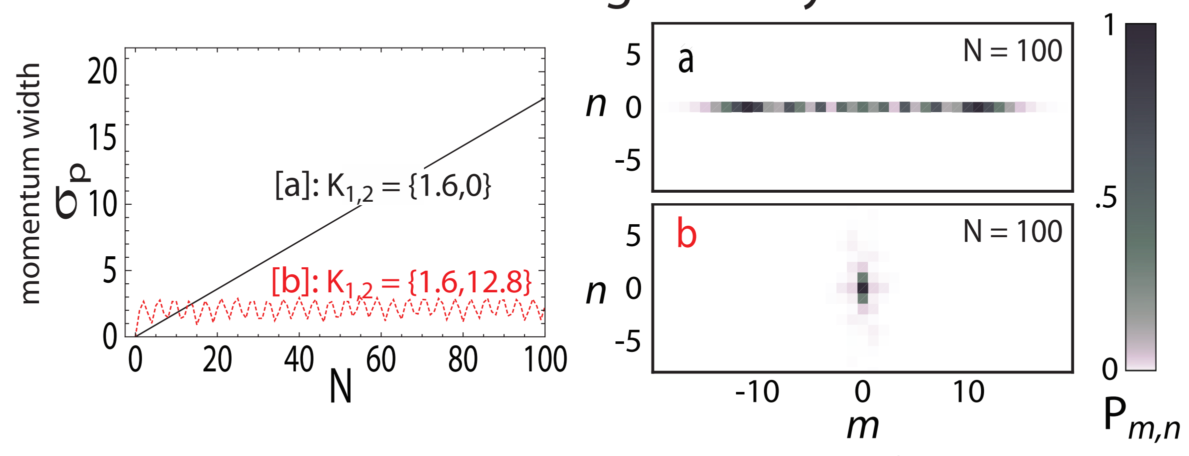
On-Resonant Kicking ($\kappa/4\pi \approx 0$)

Resonant, ballistic momentum spreading along modes of lattice 1(with $K_1 = 1.6$) is suppressed by strong off-resonant kicking with K_2

($T = 124\ \mu$s) $\kappa/4\pi \approx 1$ $\eta^2\kappa/4\pi = 1.86$



Simulated long-time dynamics



- Coupling $\eta\kappa mn$ destroys resonance for modes $n \neq 0$. However, nearly 1/2 time spent in $n = 0$ subspace
- Suppression of transport reminiscent of Kapitza pendulum / ponderomotive potentials