ac-driven quantum systems: cold atom ratchets and beyond

Theory

S. Denisov, A. Ponomarev, S. Kohler & P. Hänggi
S. Flach, F. Renzoni, L. Morales - Molina, Y. Zolotaryuk, O. Yevtushenko

Experiments

universität bonn Arbeitsgruppe Quantenoptik

UCL LaserCoolingGroup

Ratchet Idea

- driving force of zero mean
- nonlinearity
- asymmetry

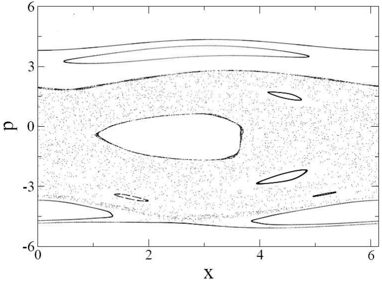
Classic Period

The model

$$m\ddot{x} = \dot{p} = \sin(x) + E(t)$$

$$E(t+T) = E(t), \quad \langle E(t) \rangle_T = 0$$

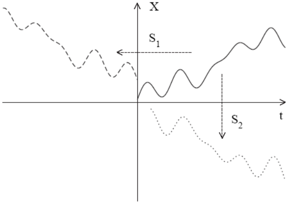
Mixed phase space



Classic Period

Symmetries

$$m\ddot{x} = \dot{p} = \sin(x) + E(t), \quad J = \lim_{t\to\infty} x(t)/t = \frac{1}{m}\langle p(t)\rangle$$



$$S_1 : (x, p, t) \to (x, -p, -t)$$
$$E(-t) = E(t)$$

$$S_2 : (x, p, t) \to (-x, -p, t + T/2)$$
$$E(t + T/2) = -E(t)$$

S. Flach, O. Yevtushenko, & Y. Zolotaryuk, PRL 84, 2358 (2000)

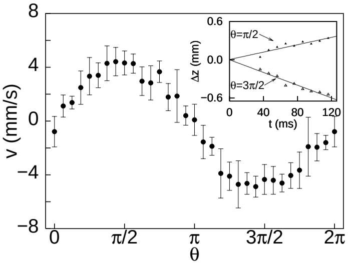
S. Denisov, *et al.*, PRE 66, 041104 (2002)

Classic Period

$$E(t) = E_1 \cos(\omega t) + E_2 \cos(2\omega t + \theta)$$

$$J(\theta) = -J(-\theta) = -J(\theta + \pi), \quad J(\theta) \sim \sin(\theta)$$

Ratchet with cold atoms

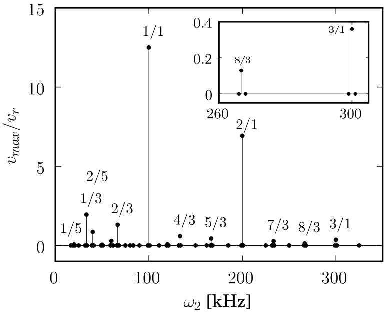


M. Schiavoni, L. Sanchez-Palencia, & F. Renzoni, PRL 90, 094101 (2003)

Classic Period

Peculiar driving: experiment with cold atoms

$$E(t) = \omega_2 \sin(\omega_2 t)[a \sin(\omega_1 t) + b \sin(2\omega_1 t)] + \omega_1 \cos(\omega_2 t)[a \cos(\omega_1 t) + 2b \cos(2\omega_1 t)]$$



$\omega_2 = (p/q)\omega_1$: $E(t) = -E(t + T/2)$ if q is even and p is odd

R. Gommers, S. Denisov, & F. Renzoni, PRL 96, 240604 (2006)

Quantum Ratchets

Schrödinger equation

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle = H(x,\hat{p},t;t_0)|\psi(t)\rangle$$

$$H(x,\hat{p},t;t_0) = \frac{\hat{p}^2}{2} + U_0(1+\cos(x)) - xE(t;t_0)$$

$$E(t;t_0) = E(t), \quad if \quad t \geq t_0, \qquad E(t;t_0) = 0 \quad otherwise$$

Floquet states

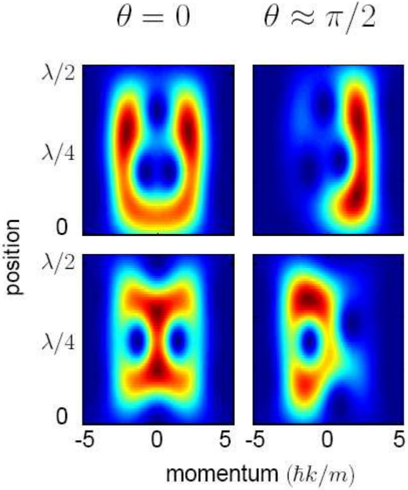
$$|\phi_\alpha(x,t_0+T)\rangle = e^{-iE_\alpha T/\hbar}|\phi_\alpha(x,t_0)\rangle, \qquad \alpha = 1,2,3,...$$

$$|\psi(x,t_0)\rangle = \sum_\alpha C_\alpha(t_0)|\phi_\alpha(x,t_0)\rangle$$

S. Denisov, L. Morales-Molina, S. Flach, & P. Hänggi, PRA 75, 063424 (2007)

Quantum Ratchets

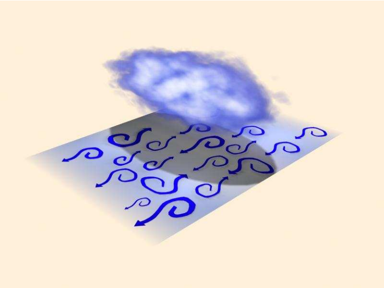
Floquet state polarization



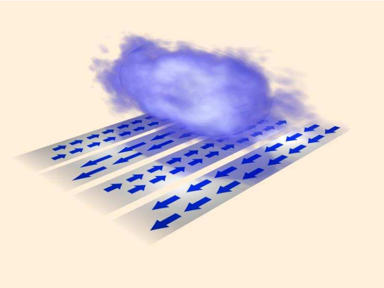
T. Salger *et al.*, Science 326, 1241 (2009)

Quantum Ratchets

Classical ratchet



Quantum ratchet



$J = J_{chaotic}$

$J = \sum_{\alpha} C_{\alpha}(t_0) \cdot v_{\alpha}$

P. Hänggi and S. Denisov, Physik Journal 9, 18 (2010)

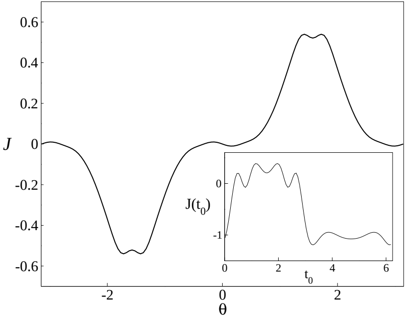
Quantum Ratchets

Flashing ratchet

$$U(x,t) = E(t)\cdot\tilde{U}(x)$$

$$E(t) = E_0(1+\epsilon_1\cos(\omega t)+\epsilon_2\cos(2\omega t+\theta))$$

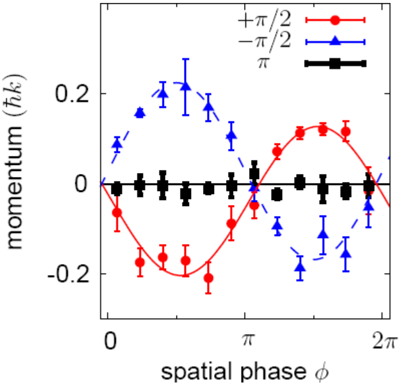
$$\tilde{U}(x) = U_1\cos(x)+U_2\cos(2x+\psi)$$



S. Denisov, L. Morales-Molina, S. Flach, & P. Hänggi, PRA 75, 063424 (2007)

Quantum Ratchets with Utracold Atoms

Ratchet current

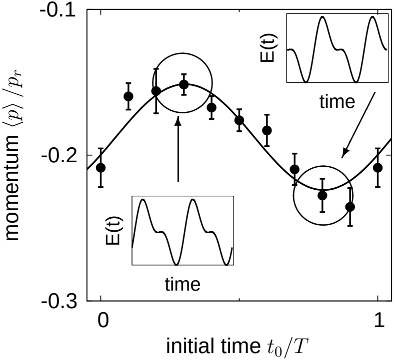


T. Salger *et al.*, Science 326, 1241 (2009)

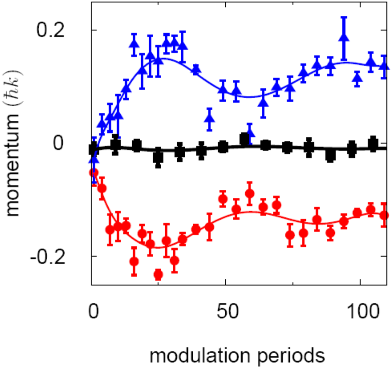
Quantum Ratchets with Utracold Atoms

Quantum features

Dependence on the start time



Quantum beating



T. Salger *et al.*, Science 326, 1241 (2009)

Quantum Ratchets in the Presence of Decoherence

Density matrix instead of wave function

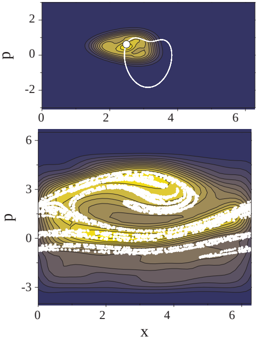
$$\dot{\varrho}_{\alpha\beta} = -\frac{\mathrm{i}}{\hbar}(\epsilon_\alpha - \epsilon_\beta)\varrho_{\alpha\beta} + \sum_{\alpha'\beta'} \mathcal{L}_{\alpha\beta,\alpha'\beta'}\, \varrho_{\alpha'\beta'},$$

$$J = \sum_{\alpha\beta} \varrho^{a}_{\alpha\beta} \bar{p}_{\alpha\beta}; \quad \bar{p}_{\alpha\beta} = \langle\langle \phi_\alpha(t)|\hat{p}|\phi_\beta(t)\rangle\rangle_T.$$

S. Denisov, S. Kohler, & P. Hänggi, EPL 85, 40003 (2009)

Quantum Ratchets in the Presence of Decoherence

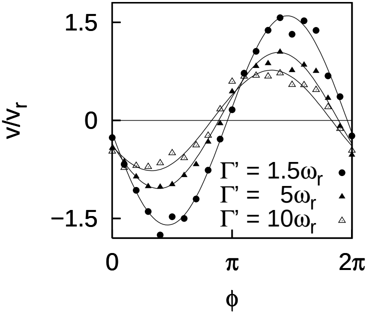
Strong decoherence



S. Denisov, S. Kohler, & P. Hänggi, EPL 85, 40003 (2009)

Underdamped ratchets

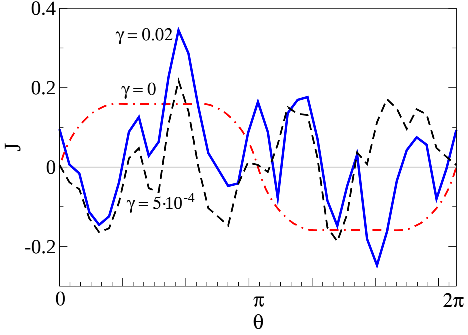
O. Yevtushenko *et al.*, EPL 54, 141 (2001)



R. Gommers, S. Bergamini, F. Renzoni, PRL 95, 073003 (2005)

Quantum Ratchets in the Presence of Decoherence

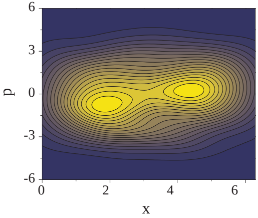
Weak decoherence



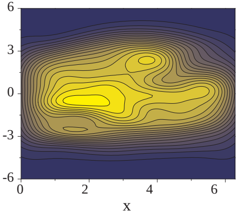
S. Denisov, S. Kohler, & P. Hänggi, EPL 85, 40003 (2009)

Quantum Ratchets in the Presence of Decoherence

Superweak decoherence



Weak decoherence

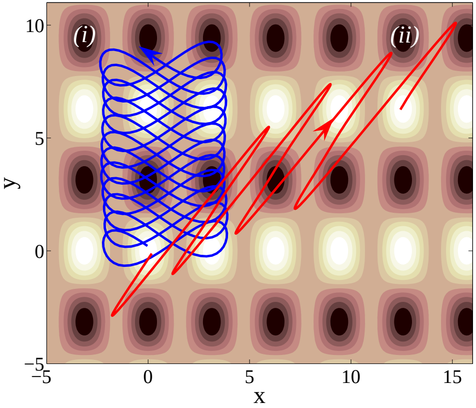


$$J = \sum_{\alpha\beta} \varrho^{a}_{\alpha\beta} \bar{p}_{\alpha\beta}; \quad \bar{p}_{\alpha\beta} = \langle\langle \phi_\alpha(t)|\hat{p}|\phi_\beta(t)\rangle\rangle_T .$$

S. Denisov, S. Kohler, & P. Hänggi, EPL 85, 40003 (2009)

... and beyond

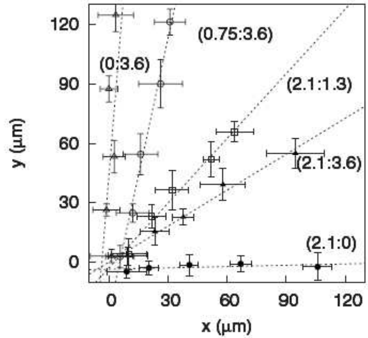
2d ratchets



S. Denisov, Y. Zolotaryuk, S. Flach, & O. Yevtushenko, PRL 100, 224102 (2008)

… and beyond

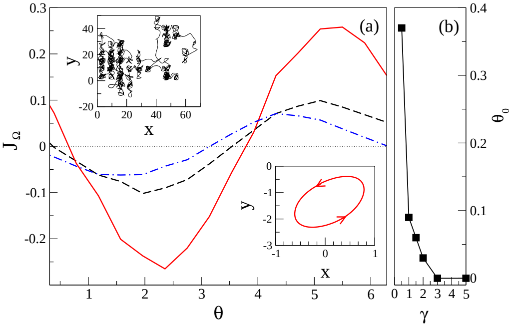
2d ratchets with cold atoms



V. Lebedev & F. Renzoni, PRA 80, 023422 (2009)

... and beyond

Creation of 2d vortices



S. Denisov, Y. Zolotaryuk, S. Flach, & O. Yevtushenko, PRL 100, 224102 (2008)

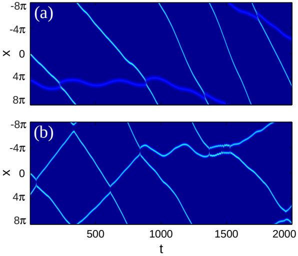
Trends & Perspectives

Many-body/nonlinearity effects:

- BEC: nonlinear effects

  D. Poletti, G. Benenti, G. Casati, P. Hänggi, & B. Li, PRL 102, 130604 (2009)

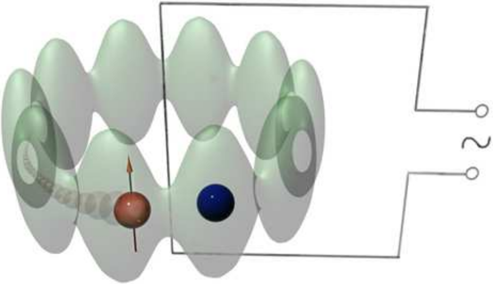
- BEC: matter-wave solitions



D. Poletti *et al.*, PRL 101, 150403 (2008)

Trends & Perspectives

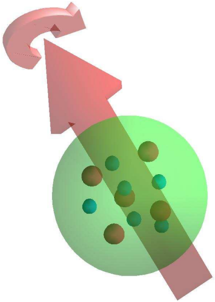
- Many (so far, two)-body ratchets



A. Ponomarev, S. Denisov, & P. Hänggi, PRL 102, 230601 (2009)

Trends & Perspectives

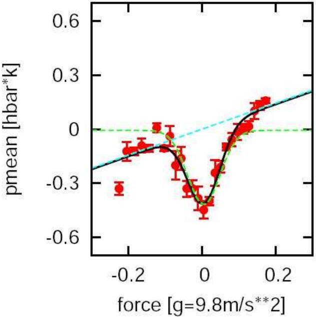
- Quantum gears

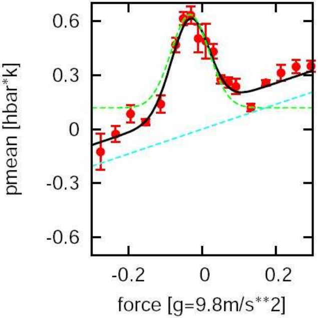


- Quantum ratchets in 2d & 3d

Quantum Ratchet Performance Under Constant Load

Ultracold atom ratchet + bias





T. Salger & M. Weitz ©

0