Chaos-assisted long-range hopping for quantum simulation

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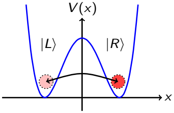
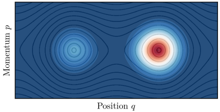
Regular tunneling in integrable systems

Oscillations of probability between two states $|L/R\rangle = \frac{1}{\sqrt{2}}(|+\rangle \pm |-\rangle)$ localized in the bottom of potential wells.



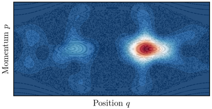


Semiclassical picture: states $|L/R\rangle$ are exponentially localized near **symmetric tori in phase space**.

$$\nu \propto |\varepsilon_+ - \varepsilon_-| \propto \exp\left(-\int_{q_1}^{q_2} p(q)\,\mathrm{d}q\,/\hbar\right).$$

Smooth variation of the tunneling rate.

Chaos-assisted tunneling in mixed systems



In most of non-integrable systems: coexistence of **regular islands** and **chaotic sea** in phase space.

Tunneling between islands is **assisted by the chaotic sea** where transport is classically possible [1].

Avoided crossings with ergodic chaotic states

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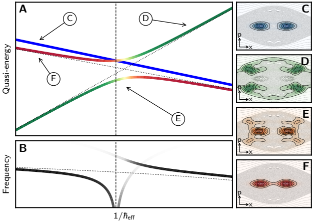
Resonances of the tunneling rate with any parameter.

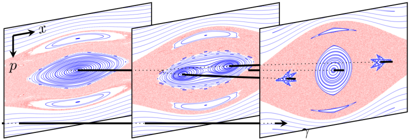


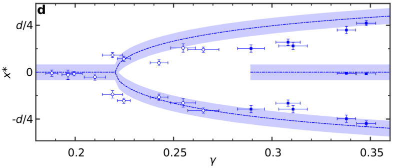
Classical phase space engineering with cold atom in modulated optical lattices

Stroboscopic mixed dynamics in the semiclassical regime can be **generically** obtained in an **intermediate regime of modulation of deep optical lattices**, e.g.

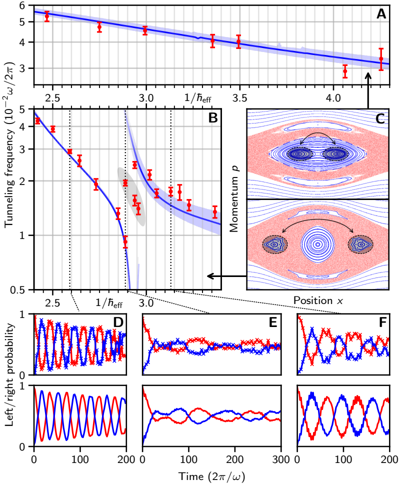
$$H(x,p,t) = \frac{p^2}{2} - \gamma(1+\varepsilon\cos t)\cos x,$$

with $\varepsilon \sim 0.2 - 0.5$, $s \sim 10 - 30\ E_L$ and $\hbar_{\text{eff}} = 2\omega_L/\omega \sim 0.2 - 0.4 \approx \mathcal{A}_{\text{island}}$.



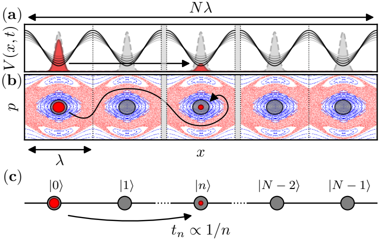


1st observation of chaos-assisted tunneling resonances with cold atom



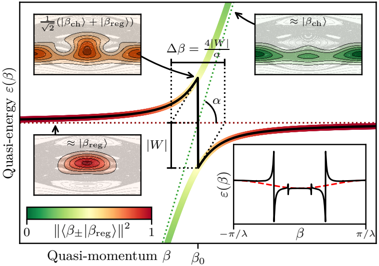
Discrepancy near the resonance can be explained by the initial finite distribution of atoms in the lattice → evidence of **long-range tunneling**?

Chaos-assisted long-range hopping

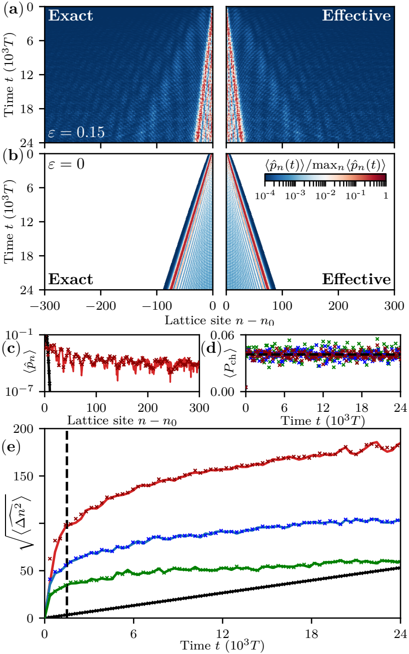


Resonances in the band structure induce effective **long-range hoppings mediated by delocalized ergodic chaotic states**

$$t_n^{\mathrm{eff}} = \frac{\lambda}{2\pi}\int_{-\pi/\lambda}^{\pi/\lambda} \varepsilon(\beta)\mathrm{e}^{i\beta\lambda n}\,\mathrm{d}\beta.$$



Dynamics of a wavepacket, initially located on a single regular site n_0.



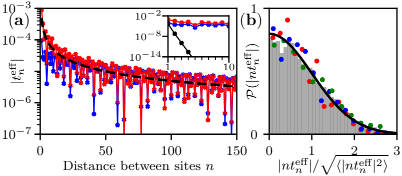
Statistical features

Analytical prediction for the hopping law

$$t_n^{\text{eff}} \approx \frac{i}{\pi n} \sum_{\text{resonances}} \text{sgn}(\alpha)|W|\mathrm{e}^{i\beta_0\lambda n}.$$

$\mathrm{e}^{i\beta_0\lambda n} \approx$ random number (for $n \gg 1$),
$|W| \approx$ gaussian random number (RMT)

$\rightarrow$ Universal **gaussian random fluctuations** of t_n^{eff} around the algebraic law $1/n$.



Why chaos-assisted tunneling opens new possibilities for quantum simulation?

Dynamics in lattices is governed by two processes: **interactions** (Feshbach resonances, vacuum modes...) versus **hoppings** (hard to engineer).
⋆ CAT allows to easily engineer hoppings.

It is **species independent** and a **generic feature** of mixed systems: appears with both phase and amplitude modulation and even in periodically kicked systems.
⋆ Accessible with state of the art experiments.

Long-range hoppings play a key role in **glassy physics**, **many-body localization** and **quantum multifractality**.
⋆ New rich physics within the reach of experiments.

[1] Chaos-assisted tunneling, *S. Tomsovic and D. Ullmo*, Phys. Rev. E **50**, 145 (1994)
[2] Chaos-assisted tunneling resonances in a synthetic Floquet superlattice, *M. Arnal, G. Chatelain, M. Martinez, N. Dupont, O. Giraud, D. Ullmo, B. Georgeot, G. Lemarié, J. Billy and D. Guéry-Odelin*, Science Advances **6**, eabc4886 (2020)
[3] Chaos-assisted long-range hopping for quantum simulation, *M. Martinez, O. Giraud, D. Ullmo, J. Billy, D. Guéry-Odelin, B. Georgeot and G. Lemarié*, arxiv :2011.02557 (2020)