Experimental observation of chaos-assisted tunneling resonances on dynamically stable islands

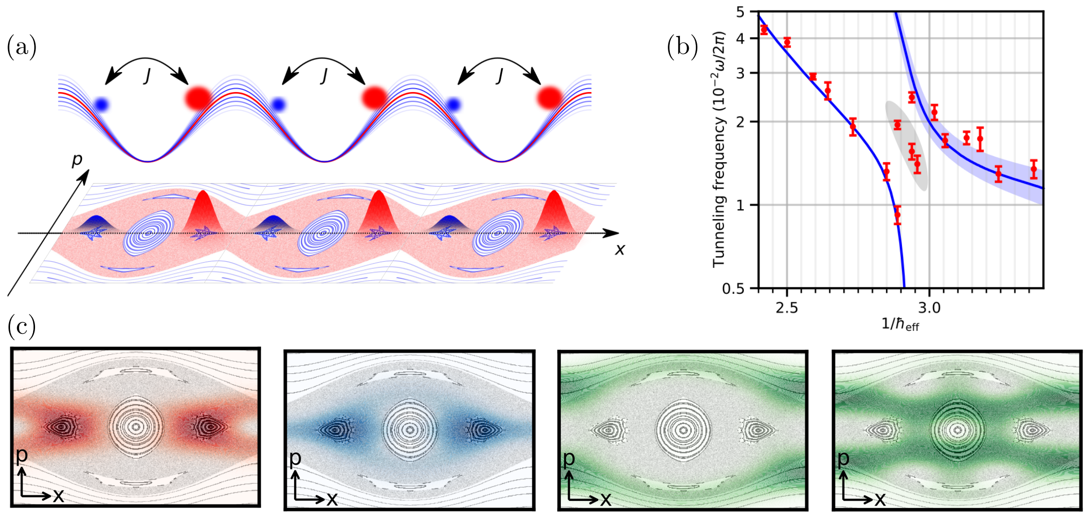
Maxime Arnal, Gabriel Chatelain, Nathan Dupont, Juliette Billy and David Guéry-Odelin
LCAR, IRSAMC, Université de Toulouse, CNRS, UPS, 31062 Toulouse, France

Maxime Martinez, Bertrand Georgeot and Gabriel Lemarié
LPT, IRSAMC, Université de Toulouse, CNRS, UPS, 31062 Toulouse, France

Olivier Giraud and Denis Ullmo
LPTMS, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

In the field of quantum simulation, where a well-controlled quantum system is used to emulate another one [1], cold atoms are a platform of ever-growing importance [2,3]. In this domain, most experiments are performed on systems with either a fully integrable or chaotic dynamics. We have developed an alternative path in an intermediate regime of mixed phase space [4]. Such a configuration allows a wave packet to tunnel between two stable islands embedded in a chaotic sea. In this case, the transport can be mediated by a delocalized state from the chaotic sea, leading to chaos-assisted tunneling [5,6,7]. This phenomenon permits a new type of control in quantum simulation through complexity.

Using a Bose Einstein condensate (BEC) placed in a deep optical lattice whose amplitude is strongly modulated, we experimentally demonstrate for the first time quantum tunneling resonances between regular islands that are symmetric in position space. These resonances are characterized by a large variation of the tunneling rate when a parameter of the system is varied. The detailed analysis of tunneling resonances reveal the intermediate states that mediate the transport through the chaotic sea. We also show how the diffraction pattern of our BEC initially placed at different positions in phase space enables us to reconstruct the classical phase space, namely realizing a phase space cartography. As we consider islands that are symmetric in position, the resulting system is a tunable superlattice with chaos-assisted hoppings. This work paves the way to a new type of quantum simulation involving long-range hoppings.



Experimental observation of chaos-assisted tunneling resonances. (a) Sketch of the CAT mechanism with BECs in a strongly modulated optical lattice. (b) Tunneling frequencies experimentally measured (red dots) as $1/\hbar_{\text{eff}}$ (proportional to the modulation frequency) is varied. Numerical simulations considering an infinite lattice without quasi-momentum distribution are shown with blue lines. The grey area corresponds to simulations when a quasi-momentum distribution is taken into account. (c) Husimis of the states involved in the tunneling dynamics at the CAT resonance.

References

[1] I. M. Georgescu, S. Ashhab, and F. Nori, *Quantum simulation*, Rev. Mod. Phys. **86**, 153 (2014).
[2] I. Bloch, J. Dalibard, and S. Nascimbène, *Quantum simulations with ultracold quantum gases*, Nature Phys **8**, 267 (2012).
[3] E. Michon *et al.*, *Phase transition kinetics for a Bose Einstein condensate in a periodically driven band systems*, NJP **20**, 053035 (2018).
[4] R. Dubertrand *et al.*, *Routes towards the experimental observation of the large fluctuations due to chaos assisted tunneling effects with cold atoms*, Phys. Rev. A **94**, 043621 (2016).
[5] S. Tomsovic and D. Ullmo, *Chaos-assisted tunneling*, Phys. Rev. E **50**, 145 (1994).
[6] D. A. Steck, W. H. Oskay and M. G. Raizen, *Observation of chaos-assisted tunneling between islands of stability*, Science **293**, 5528 (2001).
[7] W. K. Hensinger *et al*, *Dynamical tunnelling of ultracold atoms*, Nature **412**, 52 (2001).