Master 2 Internship Proposal:
Coherent processes in matter waves with engineered symmetries and interactions

Classical particles subjected to disorder or chaotic dynamics typically exhibit diffusive behavior, leading to *ergodicity*, where the configuration space is uniformly explored. However, in the quantum realm, the wave nature of matter can lead to the inhibition of diffusion due to interference effects (a phenomenon known as localization), and to the associated ergodicity-breaking phenomena of coherent forward and backward scattering. The specific *symmetries* of the system play a key role in the nature of the ergodicity breaking. Furthermore, the fate of localization and ergodicity in the many-body regime (in the presence of *interactions*) is a topic of intense ongoing research worldwide.

At the Cold Atoms team at LCAR, we experimentally investigate quantum chaos using rubidium atoms placed in an optical lattice trap. A tailored modulation of the trap allows us to engineer specific quantum states [1], or produce effective dynamics that realize models of quantum chaos with unique properties. We previously characterized the phenomenon of chaos-assisted dynamical tunnelling [2], and recently performed direct measurements of coherent scattering peaks with matter waves (see Figure 1).

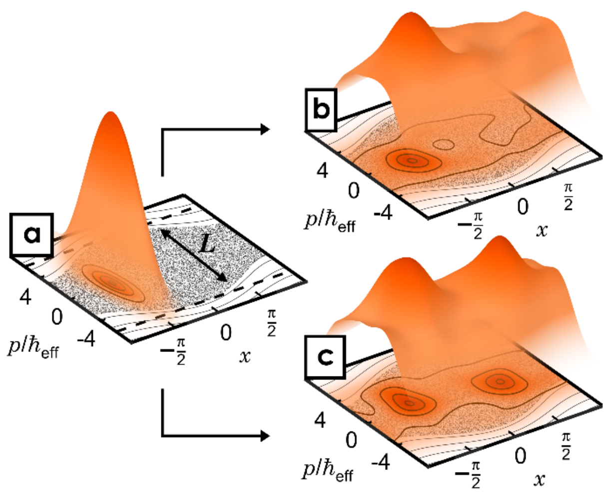

Figure 1: Cold atoms, placed in a shaken sinusoidal potential, experience chaotic dynamics: classically, an initially peaked distribution over the phase space x-p ***(a)*** *should evolve to uniformly cover the region of chaotic trajectories (grey area). Instead, a coherent process leads to a reappearance of a peak at the initial position (Coherent Forward Scattering)* ***(b)****, and for dynamics with parity-time-reversal symmetry, at the opposite position (Coherent Backwards Scattering)* ***(c).*** *Represented are the measured quasi-probability distributions over phase space from our recent experiments (manuscript in preparation).*

The ***proposed internship***, with the possibility of continuation into a PhD, aims at ***developing new engineered dynamics with cold atoms, through numerical modelling and experiments, with***

the goal of further exploring the interplay between symmetries, interactions, and chaotic dynamics.

Engineered symmetries on a synthetic lattice

We have recently developed analytical methods to engineer dynamics on an effective lattice in momentum space (a momentum ladder). The tunability of that system enables the exact realization of the Anderson model, by choosing quasi-random tunnelling amplitudes between sites, leading to localization. However, introducing parity symmetry into the system is expected to dramatically alter this behaviour, resulting in Josephson oscillations driven by small energy differences between pairs of states of opposite symmetry.

Interactions and tunnelling dynamics

As dynamical tunnelling is sensitive to small energy differences, it will be influenced by the presence of interactions, which in our dilute system introduce a mean-field energy contribution. We plan to first study this impact in a simple two-level system undergoing momentum tunnelling, and then in disordered momentum ladders, where direct control over energy spacings is possible.

A new experimental setup for many-body quantum chaos

The team is developing a new experimental setup in a state-of-the-art laboratory, designed for enhanced performance, stability, and optical access. This setup will enable the manipulation of matter waves in various optical potentials with different dimensionalities and confinements beyond 1D, allowing in particular the exploration of the strongly interacting regime. Improved optical access will facilitate the application of optical potentials and the in-situ characterization of the atomic cloud.

Beyond the Master internship, and as part of a potential PhD project, the candidate will play a key role in finalizing and operating this setup, investigating quantum chaos in these new regimes.

References
[1] *Quantum state control of a Bose-Einstein condensate in an optical lattice*
N. Dupont, G. Chatelain, L. Gabardos *et al.*, PRX Quantum **2**, 040303 (2021).
[2] *Chaos-assisted tunneling resonances in a synthetic Floquet superlattice*
M. Arnal, G. Chatelain, M. Martinez, *et al.*, Science Advances **6**, eabc4486 (2020).

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