Out-of-Equilibrium Quantum Field Dynamics in Coherently-Coupled Superfluid Mixtures

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We experimentally investigate **out-of-equilibrium dynamics** in a **coherently-coupled superfluid mixture** of sodium atoms, which realizes a ferromagnetic-like system supporting both **first-** and **second-order quantum phase transitions**. These transitions manifest in the local population imbalance, which acts as an effective magnetization.

The first-order phase transition exhibits hysteresis properties, enabling the study of field metastability, also known as **False Vacuum Decay**[1, 2]. Due to the stochastic nature of this phenomenon, it is inherently difficult to study its dynamics. To overcome this, we prepare the system in a homogeneous metastable state and seed a bubble, i.e. a region locally in the ground state, allowing us to directly observe its evolution in real time [Fig. 1(a)].

In parallel, the second-order paramagnetic-to-ferromagnetic phase transition allows us to probe the **Kibble–Zurek mechanism**, observing stochastic domain formation and defect density scaling with the quench rate [Fig. 1(b)].

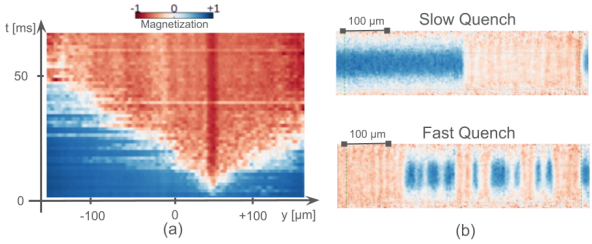

FIG. 1. (a) Seeded bubble expansion (b) Examples of domain formation through the Kibble-Zurek mechanism for slow and fast quenches.

[1] A. Zenesini *et al.*, *Nature Physics* **20**, 558 (2024).
[2] R. Cominotti, C. Baroni *et al.*, *Physical Review Letters* **18** 135 (2025).

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