Non-equilibrium Dynamics of S-wave Superconductivity and Charge Order in a Quenched Attractive Hubbard Model on a Square Lattice

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The non-equilibrium dynamics of superconducting (SC) systems are often studied within a self-consistent mean-field framework[1,2]. Previous studies have identified two key dynamical regimes based on the characteristic timescales of quasiparticle relaxation (τ_{qp}) and the superconducting order parameter (τ_{Δ}). The collisionless limit corresponds to $\tau_{qp} \gg \tau_{\Delta}$, whereas the adiabatic limit is defined by $\tau_{qp} \ll \tau_{\Delta}$. While many studies in the collisionless regime focus on momentum-space dynamics, they often overlook spatial variations that may arise in non-equilibrium conditions. Some recent works have addressed this gap by employing lattice-based models to explore real-space fluctuations.

Motivated by these considerations, we investigate the effects of a quench on the superconducting order parameter, with a particular emphasis on the behavior of the non-equilibrium quasiparticle population. Specifically, we explore (i) how this population modifies the energy landscape of the SC order parameter and (ii) its role in the system's thermalization process. Our approach is based on a mean-field description of the attractive Hubbard model on a square lattice, which captures the crossover from BCS to BEC pairing and is not restricted to the collisionless limit. Most of our analysis focuses on the half-filled case, where the system exhibits an emergent $O(3)$ symmetry, leading to a degenerate ground state between SC and charge-density wave (CDW) order. Upon doping, this degeneracy is lifted, and SC becomes the preferred ground state.

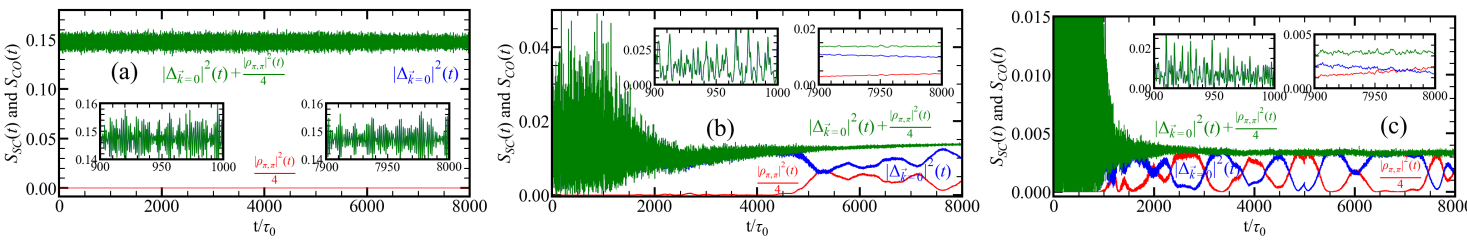
Our key findings[3] reveal distinct non-equilibrium regimes emerging as a function of quench strength. Following the quench, a non-equilibrium quasiparticle population forms and relaxes to a steady state within a characteristic time τ_{relax}. This population is well described by a Fermi distribution with an effective temperatureT_{qp}. However, the SC pairing field Δ_i exhibits a significantly lower effective temperature T_{Δ}, indicating a non-thermal steady state within this framework. Given this non-thermal state, we classify three distinct dynamical regimes at half-filling as the quench strength increases:

(i) The SC order parameter amplitude, $\Delta_{\text{amp}}=\frac{1}{N}\sum_{i}|\Delta_i|$, oscillates around a slightly reduced value.

(ii) Δ_{amp} exhibits a decaying envelope and saturates at a steady-state value.

(iii) Δ_{amp} fully decays to zero.

We provide an explanation for these results based on the non-equilibrium quasiparticle population and its influence on the SC order parameter dynamics.



Weak Quench   Intermediate Quench   Strong Quench

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2. **Yuzbashyan, E. A., Tsyplyatyev, O., & Altshuler, B. L. (2006).** "Relaxation and persistent oscillations of the order parameter in fermionic condensates." *Physical Review Letters, 96*(9), 097005. DOI:10.1103/PhysRevLett.96.097005.
3. Manuscript under process.