Phase crystals: a class of non-uniform superconducting ground states

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Superconductivity is characterized by the phase of the electron pair condensate, that breaks the *U(1)*-symmetry. Usually, the phase is uniform and rigid, but external fields can render the normal state unstable towards non-uniform superconducting states: the Abrikosov-vortex state and the FFLO state. We show that even in the absence of external fields, the superconducting state can go into a fundamentally different and more ordered non-uniform ground state, referred to as a *"phase crystal"* [1]-[6]. This state breaks translational invariance via a spatially periodic phase, non-locally driving currents and magnetic fields, breaking time-reversal symmetry.

This phase is analytically modelled using quasiclassics and Ginzburg-Landau theory [1], and crucially relies on the fact that the superfluid density is not generally a local or constant scalar, but rather a non-local and non-uniform tensor. Based on this non-local response theory, the general conditions for the instability to occur are presented, with different possible superflow patterns depending on the underlying system symmetries. As a concrete example of realization, we consider [110]-interfaces of unconventional d-wave superconductors and p-wave superfluids, and conventional S-I-F junctions. In these environments, resonant Andreev reflection breaks superconductivity and leads to zero-energy flat bands. Phase crystallization arises spontaneously to remove the flat bands, consequently healing the broken superconductivity.

The analytic results are compared with self-consistent numerics, using both quasiclassical theory [2]-[4] and several different tight-binding approaches [5]-[6]. These methods show qualitative agreement, and the state shows robustness against a number of competing orders and perturbations. The transition into the phase-crystal state is of second order and occurs at roughly 20% of Tc.

Phase crystals offer a possible explanation to the long-standing controversy of experimental detection of spontaneous currents in the cuprates, and more generally extends the paradigm of non-uniform superconducting ground states.

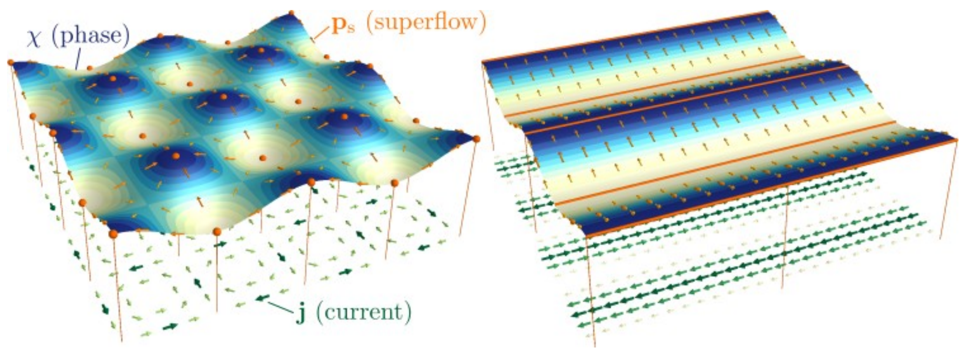

Figure 1: Spontaneous appearance of periodic phase gradients, driving current loops (left), and sheets (right).

References

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