Pis'ma v ZhETF, vol. 123, iss. 7, pp. 479 – 481

Spatial modulation of the Fulde–Ferrell–Larkin–Ovchinnikov state in *d*-wave superconductors with antiferromagnetic order

N. Liu[+*], *T. Zhou*[×○1)]

[+] *College of Physics, Nanjing University of Aeronautics and Astronautics, 210016 Nanjing, China*

[*] *School of Mathematics and Physics, Nanjing Institute of Technology, 211167 Nanjing, China*

[×] *Guangdong Basic Research Center of Excellence for Structure and Fundamental Interactions of Matter, Guangdong Provincial Key Laboratory of Quantum Engineering and Quantum Materials, School of Physics, South China Normal University, 510006 Guangzhou, China*

[○] *Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Frontier Research Institute for Physics, South China Normal University, 510006 Guangzhou, China*

Submitted 9 December 2025
Resubmitted 5 February 2026
Accepted 18 February 2026

By employing a model of a two-dimensional *d*-wave superconductor, we investigate the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) state under the influence of a Zeeman field and antiferromagnetic order. Through self-consistent solutions to the Bogoliubov–de Gennes equations, we derive the spatial distributions of the superconducting order parameter and magnetization, thereby revealing the interplay between antiferromagnetic and superconducting orders. The local density of states is computed to characterize low-energy excitations and the formation mechanism of the FFLO state. Our results show that the coexistence of antiferromagnetic and superconducting orders gives rise to a spatially modulated FFLO state, where the competition between these two orders significantly influences the spatial patterns of the order parameters and magnetic properties. These findings offer insights into the complex interplay between magnetism and superconductivity in strongly correlated systems, emphasizing the role of external fields and magnetic order in stabilizing exotic superconducting phases.

DOI: 10.7868/S3034576626040051

The Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) state, characterized by a spatially modulated superconducting order parameter, was theoretically predicted in the mid-1960s by Fulde and Ferrell [1], and independently by Larkin and Ovchinnikov [2]. While originally predicted for three-dimensional superconductors, the realization of the FFLO state requires rigorous conditions: the system must be in the clean limit with a long mean free path, and the Pauli paramagnetic limit must be exceeded while orbital depairing effects are suppressed [3]. Consequently, low-dimensional systems, such as layered quasi-two-dimensional (2D) superconductors subjected to an in-plane magnetic field, are considered the most promising candidates for observing this exotic phase, as geometric confinement strongly suppresses the orbital pair-breaking effects dominant in bulk materials.

Among candidate materials, the heavy fermion superconductor $CeCoIn_5$ has attracted significant attention as a prime candidate for hosting the FFLO state. $CeCoIn_5$ is a clean, quasi-2D *d*-wave superconductor with a large Maki parameter, satisfying the key prerequisites for the formation of a spatially modulated order parameter [4]. In clean 2D *d*-wave superconductors at low temperatures, the order parameter is expected to adopt the Larkin–Ovchinnikov (LO) form, characterized by a real, spatially oscillating standing wave, rather than the plane-wave phase factor of the Fulde–Ferrell (FF) state. While recent experiments have provided accumulating evidence for the FFLO state in various systems, $CeCoIn_5$ remains a central platform for studying the interplay between strong correlations and unconventional superconductivity.

Theoretically, the spatial structure of the FFLO state has been extensively investigated using the Bogoliubov–de Gennes (BdG) equations and Eilenberger equations. A critical theoretical issue concerns the dimensionality and geometry of the order parameter modulation. For *d*-wave pairing in square lattices, studies have suggested a competition between 1D stripe patterns and 2D checkerboard patterns, depending on the magnetic field strength and temperature [5–8].

1) e-mail: tzhou@scnu.edu.cn

And lattice structure and impurities have been shown to drive transitions between these dimensional configurations [9, 10]. Furthermore, Houzet and Mineev investigated the stability of FFLO states in the presence of paramagnetic and orbital effects, revealing a complex phase diagram [11].

Despite these advances, the interplay between the FFLO state and antiferromagnetic (AF) order in realistic lattice models remains less explored. This is a crucial omission, as AF order frequently coexists or competes with superconductivity in strongly correlated systems, such as electron-doped cuprates [12] and the high-field Q-phase of heavy fermions. The presence of onsite Coulomb interactions (U) and the resulting tendency toward magnetic ordering can fundamentally alter the energy landscape, potentially reshaping the gap structure of the FFLO state. Systematic studies on the gap structure of realistic 2D d-wave square lattice systems that account for both finite-temperature effects and the "back-action" of magnetic ordering are still scarce.

In this paper, we investigate the FFLO state in a two-dimensional d-wave superconductor under the influence of a Zeeman field and AF order. By employing a self-consistent solution to the BdG equations on a square lattice, we derive the spatial distributions of the superconducting order parameter and magnetization. Our study explicitly considers the competition between the onsite Coulomb interaction U and the superconducting pairing. The main results have been summarized in the H–U phase diagram (Fig. 1). As is presented, we reveal a reentrant dimensionality crossover in the FFLO state: as the magnetic correlation strength increases, the modulation pattern transitions from a 1D stripe phase to a 2D checkerboard phase, and surprisingly returns to a 1D phase at higher interaction strengths. These findings offer new insights into the complex interplay between magnetism and superconductivity in strongly correlated systems.

Funding. This work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

Conflict of interest. The authors of this work declare that they have no conflicts of interest.

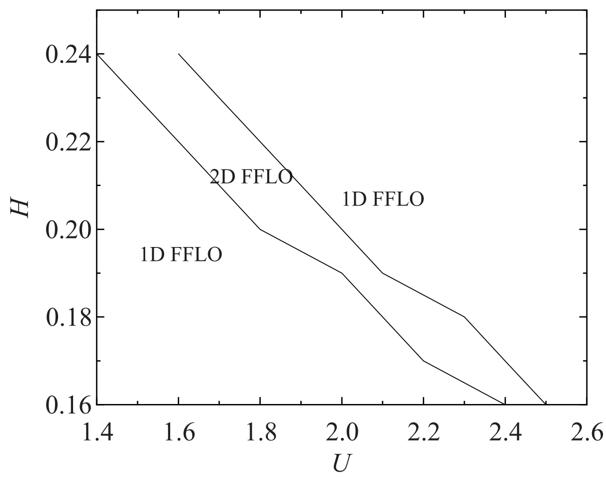

Fig. 1. H–U phase diagram of the 2D d-wave superconductor in the parallel magnetic field

1. P. Fulde and R. A. Ferrell, "Superconductivity in a strong spin-exchange field", Phys. Rev. **135**, A550 (1964).
2. A.I. Larkin and Yu.N. Ovchinnikov, "Nonuniform state of superconductors", ZhETF **47**, 1136 (1964) [A. I. Larkin and Yu. N. Ovchinnikov, "Nonuniform state of superconductors", Sov. Phys. JETP **20**, 762 (1965)].
3. L. G. Aslamazov, "Influence of impurities on the existence of an inhomogeneous state in a ferromagnetic superconductor", ZhETF **55**, 1477 (1968) [L. G. Aslamazov, "Influence of impurities on the existence of an inhomogeneous state in a ferromagnetic superconductor", Sov. Phys. JETP **28**, 773 (1969)].
4. H. A. Radovan, N. A. Fortune, T. P. Murphy, S. T. Hannahs, E. C. Palm, S. W. Tozer, and D. Hall, Nature (London) **425**, 51 (2003).
5. K. Maki and H. Won, "Fulde-Ferrell–Larkin–Ovchinnikov state in d-wave superconductors", Physica B (Amsterdam) **322**, 315 (2002).
6. Q. Wang, H. Y. Chen, C. R. Hu, and C. S. Ting, "Local Tunneling Spectroscopy as a Signature of the Fulde–Ferrell–Larkin–Ovchinnikov State in s- and d-Wave Superconductors", Phys. Rev. Lett. **96**, 117006 (2006).
7. Q. Cui and K. Yang, "Fulde–Ferrell–Larkin-Ovchinnikov state in disordered s-wave superconductors", Phys. Rev. B **78**, 054501 (2008).
8. T. Zhou and C. S. Ting, "Phase diagram and local tunneling spectroscopy of the Fulde–Ferrell–Larkin–Ovchinnikov states of a two-dimensional square-lattice d-wave superconductor", Phys. Rev. B **80**, 224515 (2009).
9. Q. Wang, C. R. Hu, and C. S. Ting, "Impurity-induced configuration-transition in the Fulde–Ferrell–Larkin–Ovchinnikov state of a d-wave superconductor", Phys. Rev. B **75**, 184515 (2007).
10. T. Kim, C.-Chun Chien and S-Zeng Lin, "Reentrant Fulde–Ferrell–Larkin–Ovchinnikov state in small-sized superconductors", Phys. Rev. B **99**, 054509 (2019).
11. M. Houzet and V. P. Mineev, "Interplay of paramagnetic, orbital, and impurity effects on the phase transition of a normal metal to the superconducting state", Phys. Rev. B **74**, 144522 (2006).
12. N. P. Armitage, P. Fournier, and R. L. Greene, "Progress and perspectives on electron-doped cuprates", Rev. Mod. Phys. **82**, 2421(2010).