WIKIPEDIA

Fulde–Ferrell–Larkin–Ovchinnikov phase

The **Fulde–Ferrell–Larkin–Ovchinnikov** (**FFLO**) **phase** (also occasionally called the **Larkin–Ovchinnikov–Fulde–Ferrell phase**, or **LOFF**)[1] can arise in a superconductor in large magnetic field. Among its characteristics are Cooper pairs with nonzero total momentum and a spatially non-uniform order parameter, leading to normal conducting areas in the superconductor.

Contents

History

Theory

Experiment

- Heavy-fermion superconductors
- Organic superconductors

References

History

Two independent publications in 1964, one by Peter Fulde and Richard A. Ferrell [2] and the other by Anatoly Larkin and Yuri Ovchinnikov,[3][4] theoretically predicted a new state appearing in a certain regime of superconductors at low temperatures and in high magnetic fields. This particular superconducting state is nowadays known as the Fulde–Ferrell–Larkin–Ovchinnikov state, abbreviated FFLO state (also LOFF state). Since then, experimental observations of the FFLO state have been searched for in different classes of superconducting materials, first in thin films and later in exotic superconductors such as heavy-fermion [5] and organic [6] superconductors. Good evidence for the existence of the FFLO state was found in organic superconductors using Nuclear Magnetic Resonance (NMR) [7][8][9] and heat capacity.[10] [11] [12] In recent years, the concept of the FFLO state was taken up in the field of atomic physics and experiments to detect the FFLO state in atomic ensembles in optical lattices. [13] [14]

Theory

If a BCS superconductor with a ground state consisting of Cooper pair singlets (and center-of-mass momentum $\mathbf{q}=\mathbf{0}$) is subjected to an applied magnetic field, then the spin structure is not affected until the Zeeman energy is strong enough to flip one spin of the singlet and break the Cooper pair, thus destroying superconductivity (paramagnetic or Pauli pair breaking). If instead one considers the normal, metallic state at the same finite magnetic field, then the Zeeman energy leads to different Fermi surfaces for spin-up and spin-down electrons, which can lead to superconducting pairing where Cooper pair singlets are formed with a finite center-of-mass momentum $\mathbf{q}$, corresponding to the displacement of the two Fermi surfaces. A non-vanishing pairing momentum leads to a spatially modulated order parameter with wave vector $\mathbf{q}$.[6]

Experiment

For the FFLO phase to appear, it is required that Pauli paramagnetic pair-breaking is the relevant mechanism to suppress superconductivity (Pauli limiting field, also Chandrasekhar-Clogston limit). In particular, orbital pair breaking (when the vortices induced by the magnetic field overlap in space) has to be weaker, which is not the case for most conventional superconductors. Certain unusual superconductors, on the other hand, may favor Pauli pair breaking: materials with large effective electron mass or layered materials (with quasi-two-dimensional electrical conduction).[5]

Heavy-fermion superconductors

Heavy-fermion superconductivity is caused by electrons with a drastically enhanced effective mass (the heavy fermions, also heavy quasiparticles), which suppresses orbital pair breaking. Furthermore, certain heavy-fermion superconductors, such as $CeCoIn_5$, have a layered crystal structure, with somewhat two-dimensional electronic transport properties.[5] Indeed, in $CeCoIn_5$ there is thermodynamic evidence for the existence of an unconventional low temperature phase within the superconducting state.[15] Subsequently, the neutron-diffraction experiments showed that this phase exhibits also incommensurate anti-ferromagnetic order[16] and that the superconducting and magnetic ordering phenomena are coupled with each other.[17]

Organic superconductors

Most organic superconductors are strongly anisotropic, in particular there are charge-transfer salts based on the molecule ET (or BEDT-TTF, "bisethylendithiotetrathiofulvalene") or BETS ("bisethylendithiotetraselenafulvalene") that are highly two dimensional. In one plane, the electric conductivity is high compared to a direction perpendicular to the plane. When applying large magnetic fields exactly parallel to the ET layers in this planes clear evidence for the existence of the FFLO state was found in the specific heat of two different ET-based superconductors. This finding was corroborated by NMR data that proved the existence of an inhomogeneous superconducting state, most probable the FFLO state.

References

1. Casalbuoni, Roberto; Nardulli, Giuseppe (26 February 2004). "Inhomogeneous superconductivity in condensed matter and QCD" (https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.76.263). *Rev. Mod. Phys*. **76**: 263. doi:10.1103/RevModPhys.76.263 (https://doi.org/10.1103%2FRevModPhys.76.263). Retrieved 27 June 2019.
2. Fulde, Peter; Ferrell, Richard A. (1964). "Superconductivity in a Strong Spin-Exchange Field". *Phys. Rev*. **135**: A550. Bibcode:1964PhRv..135..550F (http://adsabs.harvard.edu/abs/1964PhRv..135..550F). doi:10.1103/PhysRev.135.A550 (https://doi.org/10.1103%2FPhysRev.135.A550).
3. Larkin, A.I.; Ovchinnikov, Yu.N. (1964). *Zh. Eksp. Teor. Fiz*. **47**: 1136. Missing or empty `|title=` (help)
4. Larkin, A.I.; Ovchinnikov, Yu.N. (1965). "Inhomogeneous State of Superconductors". *Sov. Phys. JETP*. **20**: 762.
5. Matsuda, Yuji; Shimahara, Hiroshi (2007). "Fulde-Ferrell-Larkin-Ovchinnikov State in Heavy Fermion Superconductors". *J. Phys. Soc. Jpn*. **76**: 051005. arXiv:cond-mat/0702481 (https://arxiv.org/abs/cond-mat/0702481). Bibcode:2007JPSJ...76e1005M (http://adsabs.harvard.edu/abs/2007JPSJ...76e1005M). doi:10.1143/JPSJ.76.051005 (https://doi.org/10.1143%2FJPSJ.76.051005).
6. H. Shimahara: Theory of the Fulde-Ferrell-Larkin-Ovchinnikov State and Application to Quasi-Low-Dimensional Organic Superconductors, in: A.G. Lebed (ed.): The Physics of Organic Superconductors and Conductors, Springer, Berlin (2008).
7. Wright, J. A.; Green, E.; Kuhns, P.; Reyes, A.; Brooks, J.; Schlueter, J.; Kato, R.; Yamamoto, H.; Kobayashi, M.; Brown, S. E. (2011-08-16). "Zeeman-Driven Phase Transition within the Superconducting State of $\kappa\text{-}(\mathrm{BEDT\text{-}TTF})_2\mathrm{Cu(NCS)}_2$ " (http://link.aps.org/doi/10.1103/PhysRevLett.107.087002). *Physical Review Letters*. **107**: 087002. Bibcode:2011PhRvL.107h7002W (http://adsabs.harvard.edu/abs/2011PhRvL.107h7002W). doi:10.1103/PhysRevLett.107.087002 (https://doi.org/10.1103%2FPhysRevLett.107.087002).
8. Mayaffre, H.; Krämer, S.; Horvatić, M.; Berthier, C.; Miyagawa, K.; Kanoda, K.; Mitrović, V. F. (2014-10-26). "Evidence of Andreev bound states as a hallmark of the FFLO phase in $\kappa\text{-}(\mathrm{BEDT\text{-}TTF})_2\mathrm{Cu(NCS)}_2$ " (https://www.nature.com/nphys/journal/v10/n12/full/nphys3121.html). *Nature Physics*. **10**: 928–932. arXiv:1409.0786 (https://arxiv.org/abs/1409.0786). Bibcode:2014NatPh..10..928M (http://adsabs.harvard.edu/abs/2014NatPh..10..928M). doi:10.1038/nphys3121 (https://doi.org/10.1038%2Fnphys3121).

9. Koutroulakis, G.; Kühne, H.; Schlueter, J. A.; Wosnitza, J.; Brown, S. E. (2016-02-12). "Microscopic Study of the Fulde-Ferrell-Larkin-Ovchinnikov State in an All-Organic Superconductor" (http://link.aps.org/doi/10.1103/PhysRevLett.116.067003). *Physical Review Letters*. **116** (6): 067003. arXiv:1511.03758 (https://arxiv.org/abs/1511.03758). Bibcode:2016PhRvL.116f7003K (http://adsabs.harvard.edu/abs/2016PhRvL.116f7003K). doi:10.1103/PhysRevLett.116.067003 (https://doi.org/10.1103%2FPhysRevLett.116.067003). PMID 26919012 (https://www.ncbi.nlm.nih.gov/pubmed/26919012).
10. Lortz, R.; Wang, Y.; Demuer, A.; Böttger, P. H. M.; Bergk, B.; Zwicknagl, G.; Nakazawa, Y.; Wosnitza, J. (2007-10-30). "Calorimetric Evidence for a Fulde-Ferrell-Larkin-Ovchinnikov Superconducting State in the Layered Organic Superconductor $\kappa\text{-}(\mathrm{BEDT\text{-}TTF})_2\mathrm{Cu}(\mathrm{NCS})_2$ " (http://link.aps.org/doi/10.1103/PhysRevLett.99.187002). *Physical Review Letters*. **99** (18): 187002. arXiv:0706.3584 (https://arxiv.org/abs/0706.3584). Bibcode:2007PhRvL..99r7002L (http://adsabs.harvard.edu/abs/2007PhRvL..99r7002L). doi:10.1103/PhysRevLett.99.187002 (https://doi.org/10.1103%2FPhysRevLett.99.187002).
11. Beyer, R.; Bergk, B.; Yasin, S.; Schlueter, J. A.; Wosnitza, J. (2012-07-11). "Angle-Dependent Evolution of the Fulde-Ferrell-Larkin-Ovchinnikov State in an Organic Superconductor" (http://link.aps.org/doi/10.1103/PhysRevLett.109.027003). *Physical Review Letters*. **109** (2): 027003. Bibcode:2012PhRvL.109b7003B (http://adsabs.harvard.edu/abs/2012PhRvL.109b7003B). doi:10.1103/PhysRevLett.109.027003 (https://doi.org/10.1103%2FPhysRevLett.109.027003). PMID 23030197 (https://www.ncbi.nlm.nih.gov/pubmed/23030197).
12. Agosta, C. C.; Fortune, N. A.; Hannash, S. T.; Gu, S.; Liang, L.; Park, J.-H.; Schlueter, J. A. (2017-06-28). "Calorimetric Measurements of Magnetic-Field-Induced Inhomogeneous Superconductivity Above the Paramagnetic Limit" (http://link.aps.org/doi/10.1103/PhysRevLett.118.267001). *Physical Review Letters*. **118**: 267001. arXiv:1602.06496 (https://arxiv.org/abs/1602.06496). Bibcode:2017PhRvL.118z7001A (http://adsabs.harvard.edu/abs/2017PhRvL.118z7001A). doi:10.1103/PhysRevLett.118.267001 (https://doi.org/10.1103%2FPhysRevLett.118.267001).
13. Zwierlein, Martin W.; Schirotzek, André; Schunck, Christian H.; Ketterle, Wolfgang (2006). "Fermionic Superfluidity with Imbalanced Spin Populations". *Science*. **311**: 492. arXiv:cond-mat/0511197 (https://arxiv.org/abs/cond-mat/0511197). Bibcode:2006Sci...311..492Z (http://adsabs.harvard.edu/abs/2006Sci...311..492Z). doi:10.1126/science.1122318 (https://doi.org/10.1126%2Fscience.1122318).
14. Liao, Y. A.; Rittner, A. S. C.; Paprotta, T.; Li, W.; Partridge, G. B.; Hulet, R. G.; Baur, S. K.; Mueller, E. J. (2010). "Spin-imbalance in a one-dimensional Fermi gas". *Nature*. **467**: 567–9. arXiv:0912.0092 (https://arxiv.org/abs/0912.0092). Bibcode:2010Natur.467..567L (http://adsabs.harvard.edu/abs/2010Natur.467..567L). doi:10.1038/nature09393 (https://doi.org/10.1038%2Fnature09393).
15. Bianchi, A.; Movshovich, R.; Capan, C.; Pagliuso, P.G.; Sarrao, J.L. (2003). "Possible Fulde-Ferrell-Larkin-Ovchinnikov State in $CeCoIn_5$" (https://zenodo.org/record/1233945/files/article.pdf) (PDF). *Phys. Rev. Lett*. **91**: 187004. arXiv:cond-mat/0304420 (https://arxiv.org/abs/cond-mat/0304420). Bibcode:2003PhRvL..91r7004B (http://adsabs.harvard.edu/abs/2003PhRvL..91r7004B). doi:10.1103/PhysRevLett.91.187004 (https://doi.org/10.1103%2FPhysRevLett.91.187004).
16. Kenzelmann, M.; Strässle, Th; Niedermayer, C.; Sigrist, M.; Padmanabhan, B.; Zolliker, M.; Bianchi, A. D.; Movshovich, R.; Bauer, E. D. (2008-09-19). "Coupled Superconducting and Magnetic Order in CeCoIn5" (http://science.sciencemag.org/content/321/5896/1652). *Science*. **321** (5896): 1652–1654. Bibcode:2008Sci...321.1652K (http://adsabs.harvard.edu/abs/2008Sci...321.1652K). doi:10.1126/science.1161818 (https://doi.org/10.1126%2Fscience.1161818). ISSN 0036-8075 (https://www.worldcat.org/issn/0036-8075). PMID 18719250 (https://www.ncbi.nlm.nih.gov/pubmed/18719250).
17. Kumagai, K.; Shishido, H.; Shibauchi, T.; Matsuda, Y. (2011-03-30). "Evolution of Paramagnetic Quasiparticle Excitations Emerged in the High-Field Superconducting Phase of $\mathrm{CeCoIn_5}$" (http://link.aps.org/doi/10.1103/PhysRevLett.106.137004). *Physical Review Letters*. **106** (13): 137004. arXiv:1103.1440 (https://arxiv.org/abs/1103.1440). Bibcode:2011PhRvL.106m7004K (http://adsabs.harvard.edu/abs/2011PhRvL.106m7004K). doi:10.1103/PhysRevLett.106.137004 (https://doi.org/10.1103%2FPhysRevLett.106.137004).