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Fulde–Ferrell–Larkin–Ovchinnikov state in d-wave superconductors ☆

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Abstract

Recent reports of anomalous low-temperature properties at high magnetic fields of κ-(BEDT-TFF)$_2$Cu(NCS)$_2$ and λ-(BEDTS)$_2$GaCl$_4$ have sparked a renewed interest in possible Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) states in d-wave superconductors. In contrast to conventional three-dimensional s-wave superconductors, there is evidence that FFLO states are realizable for quasi-two-dimensional anisotropic superconductors in a magnetic field parallel to the conducting plane. In this paper, the quasiparticle density of states $N(E)$ are studied in two-dimensional d_{xy}-wave and $d_{x^2-y^2}$-wave superconductors. The energy dependence of $N(E)$ provides clear signatures of the FFLO state.

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In 1964 a possible new phase in superconductors was discussed by Fulde and Ferrell [1] and by Ovchinnikov and Larkin [2]. This Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) state was predicted to occur at small temperatures and large magnetic fields when the Pauli paramagnetism dominates the orbital effect. However, in the following decades its experimental realization appeared to be impossible for two reasons. First, a very large Ginzburg–Landau parameter $\kappa \sim 10$–100 would be required to guarantee the dominance of the Pauli term. Second, the sample would have to be extremely clean, such that the effects of impurity scattering are completely negligible.

The discovery of new classes of superconductors, such as the high-T_c cuprates, the organic conductor κ-(ET)$_2$ salts, and the heavy fermion compounds, has changed the situation dramatically. These materials intrinsically have large values of κ. Moreover, some of these samples can be synthesized in an extremely clean limit. Therefore, the above two conditions can be met by single crystals of high-quality high-T_c cuprates, κ-(ET)$_2$ salts, and CeCoIn$_5$. Furthermore, in theoretical studies it was found that the stability region of the FFLO state in two-dimensional d-wave superconductors is much more extended than the one in three-dimensional s-wave superconductors [3–5]. On the other hand, the orbital effect is typically not negligible in realistic situations. Nevertheless, there are recent reports of possible observations of FFLO states in the organic superconductors κ-(BEDT-TFF)$_2$Cu(NCS)$_2$ and λ-(BEDTS)$_2$GaCl$_4$ [6,7].

In this paper, we first consider the FFLO state in d-wave superconductors in the presence of the Pauli and the orbital term [8]. In order to incorporate the orbital effect we follow the formalism suggested by Gruenberg and Gunther [9]. This naturally gives $\Delta(\mathbf{r})$, which has a periodic spatial modulation along the direction of the applied magnetic field. Therefore FFLO state is regards as 3D crystal, while usual vortex state as 2D Crystal. It is found that in the low-temperature regime $H_{c2}(T)$ decreases almost linearly in T with increasing temperature. This quasi-linear temperature dependence has recently been observed in κ-(BEDT-TFF)$_2$Cu(NCS)$_2$,

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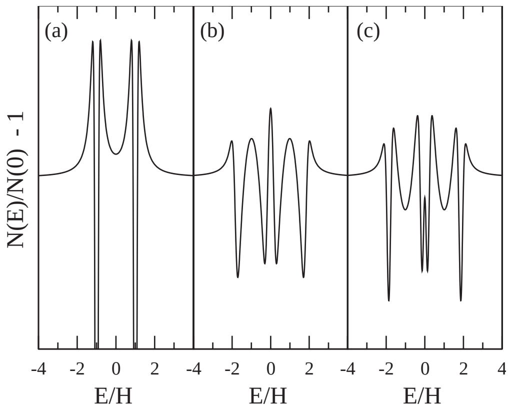

Fig. 1. Quasiparticle density of states of d-wave superconductors in a magnetic field. (a) In the absence of the FFLO state ($p = 0$), $N(E)$ is identical for $d_{x^2-y^2}$-wave and d_{xy}-wave superconductors. In the FFLO state, there is a distinctly different respone for (b) d_{xy}-wave and (c) $d_{x^2-y^2}$-wave systems.

λ-$(BEDTS)_2GaCl_4$, and $CeCoIn_5$. Furthermore, we compute the quasiparticle density of states in the vicinity of $H = H_{c2}$, which provides a clear signature of the FFLO state.

In the immediate vicinity of $H = H_{c2}$, the quasiparticle density of states can be expanded in powers of $|\Delta|^2$, which gives in leading order

$$\frac{N(E)}{N_0} - 1 = \frac{\Delta^2}{4\sqrt{\pi}} \sum_{\pm} \times \left\langle \int_{-\infty}^{\infty} \frac{\mathrm{d}u \exp(-u^2) f^2(\phi)}{[E \pm \tilde{H}(1 - p\cos\phi) - \varepsilon|s|u|]^2} \right\rangle,$$

where $p = 0$ corresponds to the absence of a FFLO state, $p \neq 0$ and $f(\phi) = \cos(2\phi)$ to a FFLO state in a $d_{x^2-y^2}$-wave superconductor, and $p \neq 0$ and $f(\phi) = \sin(2\phi)$ to a FFLO state in a d_{xy}-wave superconductor. Furthermore, we have rescaled $\tilde{H} \equiv (\mu_B g H)/2$ and $\varepsilon \equiv \sqrt{v v_c e H}$. Results for the density of states are shown in Fig. 1. For the parameters, we have chosen $p = 0.9$ and $\varepsilon/h = 0.2$, appropriate for $CeCoIn_5$ in the temperature regime T is 0.1 K. In the absence of the FFLO state, there are two sharp resonances close to $E = \pm H$. In the presence of the FFLO state, more structure appears in the spectral response, as shown in Figs. 1(b) and (c). Roughly speaking, the peaks and dips of the FFLO density of states in the $d_{x^2-y^2}$-wave system are inverted into dips and peaks for the d_{xy}-wave system. Therefore, precision measurements of the quasiparticle density of states can provide a clear signal for the presence of FFLO states and the symmetry of the underlying superconducting order parameter.

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References

[1] P. Fulde, R.A. Ferrell, Phys. Rev. 135 A (1964) 550.
[2] A.I. Larkin, Y.N. Ovchinnikov, Sov. Phys. JETP 20 (1965) 762.
[3] K. Maki, H. Won, Czech. J. Phys. 46 (1996) 1035.
[4] K. Yang, S.L. Sondhi, Phys. Rev. B 57 (1998) 8566.
[5] H. Shimahara, J. Phys. Soc. Jpn. 67 (1998) 1872.
[6] J. Singleton, et al., J. Phys.: Condens. Matter 12 (2000) L641.
[7] M.A. Tanatar, et al., Phys. Rev. B 66 (2002) 134506.
[8] H. Won, S. Haas, K. Maki, P. Gegenwart, N. Oeschler, in preparation.
[9] L.W. Gruenberg, L. Gunther, Phys. Rev. Lett. 16 (1966) 996.