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Electromagnetic Response of d-wave Superconductors

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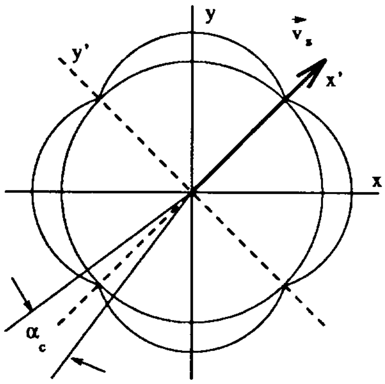
Recent theories of superconductivity based on the exchange of AFM spin-fluctuations argue for an unconventional spin-singlet order parameter with $d_{x^2-y^2}$ symmetry. One important feature of this state is that the excitation gap has nodal lines on the Fermi surface. We show that the low-energy quasiparticle states near the nodes give rise to characteristic anomalies in the surface impedance which can be used to locate the positions of the nodes of an unconventional gap in momentum space.

Theories of superconductivity for the oxide superconductors based on the Hubbard model or AFM spin-fluctuations generally predict the superconducting state to have $d_{x^2-y^2}$ symmetry (*c.f.* Ref.[1] and references therein). An important feature of the quasiparticle excitation spectrum (required by symmetry) is that the excitation gap vanishes along four lines ('nodal lines') located at the positions $|\hat{k}_x| = |\hat{k}_y|$ in the 2D plane and running along the length of the Fermi tube [see Fig. 1]. These nodal lines imply low-energy excitations, at all temperatures, and give rise to linear temperature dependence of the penetration depth for $T \ll T_c$. There is no consensus on whether or not this low temperature behavior is observed. However, Hardy, *et al.* recently reported a linear temperature dependence of $\lambda(T)$ [2].

We point out that the field-dependence of the supercurrent may be used to locate the ***positions*** of the nodal lines (or points) of an unconventional gap in momentum space, and thus provide evidence 'for' or 'against' a $d_{x^2-y^2}$ order parameter in the CuO superconductors. The origin of this field dependence can be understood by considering a clean $d_{x^2-y^2}$ superconductor at zero temperature. In the presence of the condensate flow field, $\vec{v}_s = \frac{1}{2}(\vec{\partial}\phi + \frac{2e}{c}\vec{A})$, the energy of a quasiparticle at point s on the Fermi surface is given by $E + \sigma_v(s)$, where $\sigma_v = \vec{v}_f(s) \cdot \vec{v}_s$ is the shift in the quasiparticle energy due to the superflow, $E = \sqrt{\epsilon^2 + |\Delta(s)|^2}$, ϵ is the quasiparticle energy in the normal state. The equilibrium distribution of quasiparticles is therefore $f(E + \sigma_v(s))$. Now consider the case where the velocity is directed along the nodal line $\hat{k}_x = \hat{k}_y$, *i.e.* $\vec{v}_s = v_s\hat{x}'$ as shown in Fig. 1.



1. Phase space for $\vec{v}_s \parallel$ a node.

For any non-zero $\vec{v}_s$ there is a wedge of occupied states near the node opposite to the flow velocity. Thus, the supercurrent is reduced from the ideal value for pure condensate flow by a backflow correction of order $(\frac{v_f v_s}{2\Delta_o})$. The net supercurrent becomes [3],

$$\vec{j}_s = (-\frac{e}{2}N_f v_f^2)\, \vec{v}_s \left\{1 - \frac{|\vec{v}_s|}{2\Delta_o/v_f}\right\} , \qquad (1)$$

for $\vec{v}_s$ directed along any of the four nodes. Here Δ_o is defined by the rate at which the gap opens up at the nodes; we assumed $\Delta(s) = \Delta_o(\hat{k}_x^2 - \hat{k}_y^2)$ near the nodes. Along a high symmetry direction the current is parallel to the velocity, although this is not true for general flow directions. The velocity dependence of the superfluid density,

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$\rho_s = \rho_o\{1 - \frac{|\vec{v}_s|}{2\Delta_o/v_f}\}$, is linear and non-analytic, in contrast to the quadratic behavior expected for a conventional gap. The nonlinear correction to the current is also anisotropic with respect to the direction of $\vec{v}_s$ in the ab-plane. For example, if the velocity is along an antinodal direction then

$$\vec{j}_s = (-\frac{e}{2}N_f v_f^2)\,\vec{v}_s\,\left\{1 - \frac{1}{\sqrt{2}}\frac{|\vec{v}_s|}{2\Delta_o/v_f}\right\}, \qquad (2)$$

which is again parallel to the velocity, but, the magnitude of the correction term to ρ_s is reduced by $1/\sqrt{2}$. This anisotropy is due to the relative positions of the nodal lines and is insensitive to the anisotropy of the normal state properties. The quasiparticle states that contribute to the backflow current, for any orientation of the velocity, are located in a narrow angle, $\alpha \leq \alpha_c \simeq (v_s/v_o) \ll 1$, near the nodal lines. Because the Fermi velocity and density of states are identical at the nodal positions, it is the relative occupation of the states that changes with direction and accounts for the anisotropy of the nonlinear current.

This anisotropy in the current implies a similar anisotropy in the field dependence of the penetration length, which can be calculated from eqs.(1)-(2) and Maxwell's equation [3]. To leading order in H,

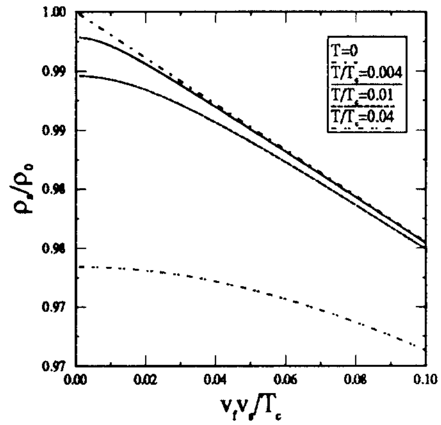
$$\frac{1}{\lambda_{eff}} = \frac{1}{\lambda}\left(1 - \frac{H}{H_o}\right), \quad \vec{H}\,||\text{ node} \qquad (3)$$

$$\frac{1}{\lambda_{eff}} = \frac{1}{\lambda}\left(1 - \frac{1}{\sqrt{2}}\frac{H}{H_o}\right), \quad \vec{H}\,||\text{ antinode} \qquad (4)$$

where $H_o = \frac{3}{2}(v_o/\lambda)(c/e) \sim \phi_o/(\lambda\xi) \sim H_c$. For YBCO where $\lambda \simeq 1400\AA$ and $\xi \simeq 15\AA$, we estimate that $H_o \simeq 3\,\text{Tesla}$.

The anisotropy of the nonlinear correction to the current also results in an anisotropic magnetic field energy as the applied field is rotated within the basal plane. The magnetic energy is a minimum for screening currents that are along the nodes, and is a maximum for currents parallel to the antinodes. For YBCO the resulting maximum in-plane torque is $\tau \simeq (1/4\sqrt{3}\pi)H^2(H/H_o)A\lambda \sim 10^{-4}dyne - cm/rad$, for $H \approx 400\ G$, area $A = (2,000\ \mu m)^2$. The precision required to observe this torque appears to have been achieved [4].

At non-zero temperatures a low-field cross-over occurs as a result of the redistribution of thermal quasiparticles in the flow field. Below this cross-over λ_{eff} becomes quadratic in H. The cross-over field is estimated by equating the excitation energy of a thermal quasiparticle with the shift in the quasiparticle energy associated with the superflow, $\pi T \simeq v_f v_s \simeq 3\Delta_o(H_x/H_o)$; *i.e.* $H_x \simeq \frac{2}{3}H_o(T/T_c)$. The numerical calculations confirm this behavior (see Fig. 2). At $100mK$ the effective penetration depth is calculated to be linear over the field range $20G \lesssim H \leq H_{c1}$. In this same field range λ_{eff} increases by approximately $20\AA$, which should be measurable. Finally, we emphasize that if the linear temperature dependence of $\lambda(T)$ at $H = 0$ is correctly interpreted in terms of a $d_{x^2-y^2}$ state the anisotropic, linear field dependence of $\lambda_{eff}(H,T)$ will be present at low temperatures, $T \lesssim 100\,mK$, and its observation would provide strong confirmation of unconventional BCS pairing.



2. Velocity and temperature dependence of ρ_s.

REFERENCES

1. N. E. Bickers, *et al.*, Phys. Rev. Lett. **62**, 961 (1989).
2. W. Hardy *et al.*, preprint.
3. S. K. Yip and J. A. Sauls, Phys. Rev. Lett. 69, 2264 (1992).
4. D. E. Farrell, Bull. Am. Phys. Soc. 38, 276 (1993).