New symmetry breaking in high Tc superconductors

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Abstract

We study a nearly square 2D Fermi surface with strong nesting properties and a Van Hove singularity at the Fermi level, as a model for high Tc superconductors, such as Bi$_2$Sr$_2$CaCu$_2$O$_{8}$ (Bi2212). Such a model is consistent with recent photoemission data. We assume an effective (phenomenological) attractive coupling between electrons as well as an exchange coupling. The (\[ln(kT/\Theta)\]^2) behaviour of the superconducting response favours a d-wave superconducting instability. When a magnetic field is applied perpendicularly to the electron plane, an orbital effect restores a 1D behaviour for the magnetic response, with an effective exchange constant rapidly increasing with the field. Therefore, we expect, above a critical field, a coexistence of superconductivity and spin density wave (SDW). This new symmetry breaking should open a gap on the whole Fermi surface. We propose to ascribe to this effect the anomalies observed in the thermal conductivity of Bi2212 and the apparent disappearance of the quasi-particles in an applied field.

Keywords: Superconducting phase transitions - Magnetic Phase transitions

1. Introduction

Recent experimental results have revealed interesting quasi-particle behaviour in a magnetic field. In fact, Krishana et al. [1] have reported a series of high-resolution measurements of thermal conductivity \( k \) in the cuprate Bi$_2$Sr$_2$CaCu$_2$O$_{8}$ that reveal a surprising feature of quasi-particles' heat current. These measurements exhibit a phase transition induced by a magnetic field and characterised by a kink in the thermal conductivity as a function of field strength, followed by a flat plateau. In the high-field state, the quasi-particle current is still zero which means that the superconducting order parameter still exists. However, the new state is necessarily characterised by a new order parameter. Let us note that K. Behnia et al. [3] have argued that recent heat conductivity data imply the presence of quasi-particles, but these data were restricted to low-T-low-field part of the phase diagram.

In order to extract which aspects of the new phenomena are due to qualitatively new physics, one needs first to understand the real effect of the applied field.

2. The model

We study a nearly square 2D Fermi surface with strong nesting properties and a Van Hove singularity at the Fermi level, as a model for high Tc superconductors. We consider a mean-field hamiltonian with SDW term (\( H_{SDW} \)) and superconductivity term (\( H_{s} \)) given by:

\[
H = H_0 + H_s + H_{SDW}
\]

where \( B \) is the magnetic field, \( c_{k}^{\dagger} \) indicates electron annihilation operator, \( g_s \) and \( g_m \) are respectively superconductivity and SDW coupling constant which are approximated by the following expressions:

\[
g_s(\mathbf{k}, \mathbf{k}') = g_{0s}(\cos k_x - \cos k'_x)(\cos k_y - \cos k'_y)
\]

Indeed, the Fermi surface of Bi2212 displays a good nesting property so that, at a threshold field, a field-induced SDW occurs and the SDW order parameter adds to the superconducting order parameter. So, we propose that the new high-field state is a mixed state in which coexist superconductivity and SDW.

We have proposed a mean-field theory model in order to show the coexistence of superconductivity and spin density wave (SDW). This new symmetry breaking should open a gap on the whole Fermi surface.
The field dependence of \( g_{\text{m}} \) is due to orbital effect of the field, responsible for quantum interference effects analysed in details in reference 2. This effect induces better nesting properties and, therefore, an effective coupling constant increasing with the field. In the present model, the coupled gap equations may be written as follows:

\[
\begin{align*}
1 &= g_{\text{m}} \sum_k \left( \cos k_x - \cos k_y \right)^2 \frac{\tanh \left( \frac{E_k}{2kT} \right)}{2E_k} \\
1 &= g_{\text{m}}(B) \sum_k \left( A + \cos k_x - \cos k_y \right)^2 \frac{\tanh \left( \frac{E_k}{2kT} \right)}{2E_k}
\end{align*}
\]

(3a)

(3b)

where:

\[
E_k = \sqrt{\xi^2 + \Delta^2(k) + \Delta^2_{\text{SDW}}(k)}
\]

\[
\xi_k = -2t \left( \cos k_x + \cos k_y \right)
\]

\[
\Delta_s(k) = \Delta_{\text{os}} \left( \cos k_x - \cos k_y \right)
\]

\[
\Delta_{\text{SDW}}(k) = \Delta_{\text{OSDW}} \left( A + \cos k_x - \cos k_y \right)
\]

So the new mixed state is characterised by coexistence of the superconducting \( \Delta_s \) and SDW \( \Delta_{\text{SDW}} \) gaps.

3. Results

We have calculated the gap values for different temperatures. In figure 1, we show the temperature dependence of \( \Delta_s \) and \( \Delta_{\text{SDW}} \).

\[\text{fig.1. Temperature dependence of superconducting } \Delta_s \text{ and SDW } \Delta_{\text{SDW}} \text{ gaps in eV, with } g_{\text{m}} = 0.12 \text{ eV, } g_{\text{m}} = 0.06 \text{ eV, } A = 2 \text{ and } t = 0.4 \text{ eV.}\]

In order to find the most stable state as a function of the SDW coupling constant \( g_{\text{m}} \), we have calculated the free energy for the possible states which are: d-wave superconducting state alone, SDW state alone and mixed state alone. We find, with varying \( g_{\text{m}} \), that the mixed state becomes more stable for a given threshold value of \( g_{\text{m}} \). For \( g_{\text{m}} = 0.04 \text{ eV} \), the mixed state has its free energy lower than the pure SDW state but higher than the pure superconducting state. As \( g_{\text{m}} \) increases from this value, the free energies of the three states vary, but the mixed state free energy decreases much faster, so that this state becomes stable above a critical field defined by \( g_{\text{m}}(B) = 0.043 \text{ eV} \), for such a field, we therefore expect a first order phase transition from a d-wave superconducting phase to a mixed phase with a finite value of \( \Delta_{\text{SDW}} \).

Therefore, our results are in good agreement with the experiments. Indeed, we show a phase transition from superconducting state to a new state where coexist superconductivity and SDW.

4. Conclusion

We have shown that above a critical field corresponding to a critical value of \( g_{\text{m}} \), a coexistence of superconductivity and SDW occurs. This new symmetry breaking opens a gap on the whole Fermi surface. We ascribe to this effect the anomaly observed in the heat conductivity in Bi2212.

5. References

[3] K. Behnia et al., to be published.