Doping dependence of the superconducting leading edge gap in Bi2212

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Abstract

The paper compares the K-dependence of the superconducting gap in different doping ranges. The fine behavior of the leading edge gap indicates that the pairing susceptibility is peaked at special regions on the Fermi surface. These hot regions are found to be centered away from nominal "hot spots". This behavior is attributed to a feedback effect on the pairing boson. Identification is made through comparison with neutron diffraction results.

1. Text

The mechanism of high temperature superconductivity is one of the most important current problems of condensed matter physics, and a detailed description of the interaction which leads to pairing is still lacking. In common with most metals, the cuprate normal state exhibits a Fermi surface\textsuperscript{1}. Phase sensitive experiments\textsuperscript{2,3} indicate that the superconducting order parameter exhibits a change of sign around the Fermi surface\textsuperscript{4}. Ding et. al. have shown that for nearly optimally doped Bi2212, the energy gap, determined from the peak position of the spectral function at the Fermi level, varies with angle around the Fermi surface as $\Delta(\phi) = \Delta(0)\cos(2\phi)$ (first order d-wave)\textsuperscript{5} where $\phi$ is the Fermi surface angle measured from the Y-M direction of the Brillouin zone. In this report, the energy gap is determined from the measured Leading Edge Gap (LEG), for reasons to be detailed below. The doping dependence of the LEG results indicates a pattern of behavior that provides
insight into the superconducting pairing mechanism.

A general discussion on the electronic structure of the cuprates was given by Shen and Schrieffer. They have stressed the difference in the line shape and doping dependence of the spectral function along the $\Gamma - M$ direction (parallel to the Cu-O bond) vs. along the $\Gamma - Y$ direction (parallel to the Cu-Cu direction). They suggested that such behavior could arise from electronic scattering peaked at $Q = (\pi, \pi)$. They further suggested this scattering mechanism to evolve into pairing susceptibility peaked at $Q = (\pi, \pi)$ at low temperatures. This work provides an evidence for a similar general behavior with some differences.

Figure 1 is a comparison between the leading edge of a spectrum taken on the Fermi surface of Bi2212 well below $T_C$ and the Fermi edge obtained from a freshly evaporated Ag film. The zero line denotes the Fermi level. The experimental details are published elsewhere.

While the peak position method of determining the gap value is considered rigorous at the Fermi surface and allows for inclusion of energy and k-resolution, the LEG is chosen here on purpose as a measure of the superconducting gap for the following reasons: 1. The fitting procedure increases the error bars to a value of $\pm 3$ meV, while the LEG method allows to push the measurement to its current technological limit of $\pm 1$ meV as was shown by Ding et. al. Figure 3 there demonstrates two points that are important for our discussion: the ability to distinguish such small shifts of the LEG and the rigidity of the LEG value to the fit. This is easily understood by comparison of the sharp leading edge and the shallow maximum (see Fig. 1). (The sharp feature at the peak is a result of noise, and the peak position is determined by fitting the spectrum to a given spectral function). 2. The LEG method allows for direct comparison of the superconducting gap and the pseudogap where the peak position method is inapplicable. 3. The case of the high $T_C$ cuprates is special since below $T_C$ appears a narrow energy region close to the chemical potential where the imaginary part of the self energy is substantially reduced and the spectral features
approach resolution limit. The leading edge is definitely in that region. The observed peak is at higher binding energy where it is more likely to be affected by renormalization (due to the finite energy resolution). 4. We are not interested in this study in the absolute value of the superconducting gap (the LEG value is numerically different than the nominal gap value), but in the relative value at different points on the Fermi surface. (Thus in Fig.2 energy gap values for different doping ranges are normalized to the maximum gap value). In conclusion, It is not claimed here that any of the methods is wrong, but that the larger error bars resulting from the peak fitting procedure may screen finer details revealed by the shift of the leading edge.

Fig. 2 presents the angular dependence of the superconducting LEG in different doping regions. Zero degrees correspond to the $(\pi, \pi) - (0, \pi)$ direction of the Brillouin zone. The data is presented in this unusual way to focus on the region of high gap value. This region will be called the hot region. Results are reflected w.r.t. the $(\pi, \pi) - (0, \pi)$ direction (Y-M). The open diamonds are the results of Gatt et. al. The filled diamonds are the LEG results of Ding et. al. on 87K slightly overdoped samples. The open circles are LEG values for underdoped 75K samples. There are three regions to distinguish. The hot region close to Y-M displays a flat behavior of the LEG. To avoid any connection to a specific model we draw a straight line through the points in this region. With increasing Fermi surface angle the LEG value drops sharply towards the node. Again, we draw a straight line through the points in that region. The third region is the region close to the node at 45 degrees. Here the gap drops less sharply with decreasing slope as function of reduced doping.

We try to use this data to identify the pairing boson. While phonons and lattice anomalies correlate somewhat with the transition temperature, spin fluctuations and other electronic excitations measured by inelastic neutron diffraction display a clear behavior that correlates well with $T_C$. We are looking for a correlation between the gap spectrum and the spectrum of a given boson. Spin fluctuations are characterized by a spin susceptibility spectrum peaked at $Q = (\pi, \pi)$. The width of this spectrum is a function of doping.
with (increasing width with increasing doping) in accordance with the decrease of the magnetic correlation length. Several theoretical efforts were done to correlate this behavior with superconductivity \[19\]–\[21\]. Within this approach it was suggested by Abanov et. al. \[22\] that the angular dependence of the gap will reflect the q-dependence of the spin susceptibility with the magnetic correlation length as a parameter. The set of data in the overdoped range indeed follows that behavior \[7\]. The doping dependence displays different behavior. At reduced doping the k dependence is different due to the presence of a transition to a pseudogap state in addition to the superconducting transition and a magnetic correlation length cannot be extracted in the same way as in the overdoped case \[22\]. To avoid any connection to a specific model, only straight lines are used in the regions of flat behavior and rapid increase as explained above. We take the intersection of the straight lines as a measure of the extension of the hot regions. We see that indeed the hot regions expand with increasing doping in accordance with the decrease of the magnetic correlation length. Normalized to the extension of the hot regions at optimal doping (OD87K) the extension in the other doping regions is about 1.6 for the OD65K samples and 0.3 for the UD75K samples, in good agreement with the variation of the magnetic correlation length with doping. Looking at the qualitative behavior, we realize two important facts: 1. The extension of the hot regions decreases continuously with decreased doping. 2. At all doping ranges the hot regions are centered at $\phi = 0$.

Fig. 3 sketches the Fermi surface \[7\] of overdoped Bi2212 \[23\]. The location of hot spots ($K_{hs}$) is given by the intersection of the square with Q as its side and the Fermi surface \[24\]. The intersection of the straight lines in figure 2 is designated $K_{co}$, the cutoff vector for the hot regions. The data of Fig. 2 indicate that the hot regions are centered at the intersection of Y-M and the Fermi surface and NOT at hot spots. These points are designated $K_{pc}$ (pairing centers) since they appear as pairing centers below $T_C$. The arrow on the Fermi surface denotes the direction of movement of $K_{co}$ with decreasing doping towards the pairing center. The Fermi surface itself changes of course in that region but slowly \[25\] (fig. 3 there). This affects the position of the hot spot so that $K_{hs}$ and $K_{co}$ move in opposite directions.
with the latter moving more rapidly. The UD75K data is very illuminating in that respect: \( K_{eo} \) has passed already the hot spot and the hot region doesn’t include the hot spot at all. This is impossible within the spin fluctuation mechanism unless there is a feedback effect in the superconducting state\(^{26-28}\): the scattering which is responsible for pairing should be peaked now at two values along the \((\pi, \pi)\) direction. This supplies a simple test which doesn’t require any fitting procedure (note that the data of Fig. 2 indicate unambiguously the center of symmetry): If indeed the pairing bosons are spin fluctuations then the split mentioned above into two different scattering vectors below \( T_C \), should be evident in the spin susceptibility spectrum. The inset to Fig. 3. are the neutron diffraction results of Mook et. al. on Bi2212.\(^{18}\) It is clearly seen that two different peaks appear below \( T_C \). The values, (as measured from the figure), of 0.88Q and 1.14Q for the spin susceptibility peaks should be compared with the Fermi surface scattering vectors. Mook et al. report \( T_c \) of 84K. The Fermi surface scattering vectors obtained from the measured Fermi surface of 87K Bi2212 give 0.83Q and 1.16Q Correspondingly. It shows less than 5 percents difference between the scattering vectors obtained from the energy gap spectrum and the position of the peaks in the bosonic spectrum.

An important question is how to interpret the commensurate resonance observed at higher energy in Bi2212 as well as in YBCO. Brinkmann and Lee\(^{26}\) have recently analyzed the energy and q-dependence of spin fluctuations observed by inelastic neutron diffraction. Their conclusion is that the resonance is pushed into the gap region due to the presence of van Hove singularity in the imaginary part of the bare spin susceptibility induced by a nearly flat particle-hole excitation energy spectrum for fermions with relative wave vector \( Q = (\pi, \pi) \). They stress that setting \( t' = 0 \) in their dispersion relation causes the rersonance to be severely broadened. We therefore consider the \textit{commensurate} resonance as representing the high energy part of the spin fluctuation spectrum which may be related but not directly to the low energy pairing boson.

Complementary information can be found in the effect of high energy electron irradiation...
tion on superconductivity. While the maximum gap hardly changes after irradiation, $T_c$ is reduced substantially and $K_{\infty}$ shifts toward the pairing center as can be seen from the measured LEG before and after irradiation (Fig. 4 there).

As was mentioned above, the LEG method allows for direct comparison of the gap below and above $T_C$ in underdoped cuprates. Since the feedback effect is expected to occur below $T_C$, it would be instructive to check whether the recovery of the symmetric $(\pi, \pi)$ scattering above $T_C$ is reflected in the $k$ dependence of the gap. Such unusual opportunity is supplied in the pseudogap state. $k$-dependence measurements of the gap were published by Ding et. al. Fig 3 there displays gap values in the superconducting and pseudogap states. Unfortunately the error bars are large. Still, from the data points it seems that the two samples in the superconducting state display flat behavior of the hot regions, centered at a pairing center, while the 10K sample, which is in the pseudogap state shows a kink very close to a hot spot location as can be verified from the published Fermi surface of 15K Bi2212.

Detailed measurements at the superconducting and pseudogap states are needed to clarify that point.

Unfortunately there are no published data on the detailed angular dependence of the gap in other materials, but a similar split below $T_c$ is observed in YBCO. The Fermi surface of YBCO was only partially measured but it was found to be very close to that of Bi2212. The pairing centers on Bi2212 are at high symmetry points. Therefore they are probably at the same points in YBCO. This implies that the locations of the incommensurate peaks along the $(\pi, \pi)$ direction in YBCO should be close to those in Bi2212 as indeed measured by Mook et. al. More ARPES measurements on YBCO are needed to allow for a quantitative comparison.

While a sharp resonance at $(\pi, \pi)$ is not observed in La214, the incommensurate peaks are observed with a very similar displacement. The fact that the incommensurate peaks are observed in all of these materials at very similar $q$-points, that their appearance coincide with $T_C$ and that the Fermi surfaces are similar, indicate that the spin fluctuations are major
pairing bosons in all of these materials.

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FIGURES

Fig. 1. Comparison of the spectrum from over-doped Bi2212 and freshly evaporated silver film. The Leading Edge Gap (LEG) is the distance between the curves at the point of half maximum. The inset shows the two edges in an expanded scale. It demonstrates that differences smaller than 1 meV can be measured. This fine behavior is the subject of the paper.

Fig. 2. Angular dependence of the LEG in different doping ranges of Bi2212. Open diamonds: over-doped 65K. Filled diamonds: over-doped 87K. Open circles: under-doped 75K. Straight lines are linear fits to data at the regions of flat and rapid change. The intersections of lines give the location of $K_{co}$ in the different doping ranges. The pairing center is the point of zero degrees on the horizontal line.

Fig. 3. The Brillouin zone and the Fermi surface of Bi2212. The vector Q is the magnetic scattering vector. $K_{co}, K_{hs}$ and $K_{pc}$ are the locations of the cut-off vector, the hot spot vector and the pairing center vector. See the text. The transition from the square with corners at M to the rectangle with corners at $K_{pc}$ is the feedback effect described in the text. The inset are the results of Mook et. al. displaying the incommensurate neutron diffraction peaks observed at low temperature in Bi2212.
LEG=1meV
Fig. 3