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ARPES STUDIES IN THE NORMAL AND SUPERCONDUCTING STATE OF $Bi_2Sr_2CaCu_2O_8$

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High resolution ARPES measurements were carried out on Bi2212 samples [T_c=87 K]. Most of the results have either appeared in print or will appear soon; here we briefly summarize the various points together with the relevent references.

Due to the low cross sections in Bi2212, we set the energy resolution in this experiment to a FWHM=18.8 meV, equivalent to a gaussian of σ= 8 meV, and the angular resolution was $\pm 1°$, equivalent to 1/22nd of the Brillouin zone edge, or 1/32nd of the zone diagonal. Normal state spectra [1,2] show only one peak corresponding to the CuO_2 planar band; no resolvable bi-layer splitting is seen above T_c. All other spectral features can be attributed to umklapp bands corresponding to a superlattice with $Q = (0.21, 0.21)\pi$ which has been independently seen in structural studies. We also find some evidence for "shadow bands" which are (π, π) fold-backs of the main bands; details will be presented elsewhere [2].

The main CuO_2 Fermi surface corresponds to a doping of 0.17 holes per Cu atom. While the Fermi surfaces and the dispersion of the peak positions appear to be like that in band theory, the spectra themselves are anomalously broad in the normal state.

With decreasing T the spectra sharpen up enormously [3]. We have carried out careful studies of the lineshape, and by studying sum rules, came to the conclusion that our ARPES data can be interpreted simply in terms of the one-particle spectral function $A(\boldsymbol{k}, \omega)$. Thus the intensity can be expressed as $I(\boldsymbol{k}, \omega) = I_0(\boldsymbol{k}) f(\omega) A(\boldsymbol{k}, \omega)$ where $f(\omega)$ is the Fermi function and I_0 includes all the matrix element effects. Even though the lineshape changes a lot with temperature, the integrated intensity at $\boldsymbol{k}_F$ does not. We note that the sharpening up of the spectra below T_c is not due to a pile-up of states below the gap, as previously interpreted in the photoemission literature, since ARPES measures the spectral function, and not the density of states. The sharpening of the spectra is due instead to a dramatic increase of the quasiparticle lifetime in the superconducting state, as observed in optical experiments. As the lifetime increases, $\Sigma''(\boldsymbol{k}, \omega)$ decreases, decreasing the width of the spectrum. Using the sum rule $\int_{-\infty}^{+\infty} f(\omega) A(\boldsymbol{k}, \omega) = n(\boldsymbol{k})$ where $n(\boldsymbol{k})$ is the momentum distribution, together with the fact that $n(\boldsymbol{k}_F)$ is independent of temperature, we find that the peak intensity must increase. We note in passing that the energy-integrated ARPES intensity can be used to experimentally measure the momentum distribution $n(\boldsymbol{k})$ [3].

We now turn to the extraction of the momentum dependence of the gap $|\Delta(\boldsymbol{k})|$. Since the intrinsic linewidth deep in the superconducting state is much smaller than the energy resolution, we can make BCS spectral function fits to the leading edge of the Energy Distribution Curves (EDC's) to extract $|\Delta(\boldsymbol{k})|$ at T=13 K; see ref. [1]. We find that the excitation gap is strongly $\boldsymbol{k}$-dependent, being largest near the $\bar{M} = (\pi, 0)$ point and much smaller at the Fermi surface crossing along the $(0, 0) \rightarrow (\pi, \pi)$ direction, as seen in earlier work. Unlike the earlier work, we find a highly non-trivial momentum dependence of the gap in the vicinity of the diagonal direction, where d-wave would have predicted a simple node.

We find limited evidence for a non-zero gap along the diagonal direction in the Y quadrant. However in the X quadrant the gap is quite sizable along the diagonal, 7 ± 2 meV, and vanishes 10° on either side of it.

A simple d-wave gap of the form $\Delta(\boldsymbol{k}) = \Delta_0(\cos(k_x a) - \cos(k_y a))$ is ruled out. Various possible interpretations are discussed in detail in ref. [4]. The simplest interpretation is in terms of an anisotropic s-wave gap which has two nodes per quadrant. Potential complications arising from the superlattice are pointed out in [1] and discussed in detail in [4] which can apply to data in the X quadrant.

In conclusion, we have shown that ARPES is a very useful probe of quasi-2D materials where one can study spectral functions, their $\boldsymbol{k}$- dispersion, the effect of the many-body physics on the line shapes, the momentum distribution, and the detailed $\boldsymbol{k}$-variation of the superconducting gap.

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