k-space Microscopy of Bi2Sr2CaCu2O8+ :Fermiology and Many-body Effects
Santoso, I.

Citation for published version (APA):

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It is now some 22 years since the discovery of superconductivity in cuprates, and the origin of its microscopic mechanism still not agreed upon. The superconductivity occurs due to pairing of the electrons, forming what are known as Cooper pairs, whereby the effective attraction is mediated by virtual exchange of a bosonic degree of freedom. Two main interpretations are emerging considering the microscopic origin of superconductivity in cuprates, in which the Cooper pairs are formed either due to the interaction between the electrons via phonons or via magnetic spin fluctuations. This thesis is one part of many efforts carried out in order to resolve this exciting issue in condensed matter physics.

In this thesis, we have presented our experimental study of the fermiology and many-body effects seen in superconducting cuprate materials, namely in Bi$_2$Sr$_2$CaCuO$_{8+\delta}$, using the angle resolved photoemission (ARPES) technique, a leading tool in probing the electronic states of solids. We summarise the main results presented in this thesis in the following paragraphs.

In Chapter 3, we investigated the origin of the shadow Fermi surface, one of the primary features in the fermiology of these systems besides the main Fermi surface. By applying a symmetry argument on the ARPES measurements geometry, we can distinguish between initial and final state effects in the photoemission from the main and shadow bands. Our polarisation dependent data, along with low energy electron diffraction (LEED) results, have proved convincingly that the shadow bands and their associated shadow Fermi surface that occur in Bi$_2$Sr$_2$CaCuO$_{8+\delta}$ and related systems are due to orthorhombic displacements of atoms from the initial tetragonal symmetry. We remarked that as a consequence of our proof that the shadow Fermi surface is of bulk, structural origin, we should formally change our paradigm for 2D Brillouin zone from tetragonal to orthorhombic and thus depart from the simple picture of the ($\pi$, $\pi$)-centered
"barrels" as the basal plane projection of the Fermi surfaces of the Bi-based HTSC.

In Chapter 4, we investigated the momentum and temperature dependence of the many-body effects in overdoped (Pb,Bi)$_2$Sr$_2$Ca-Cu$_2$O$_{8+\delta}$ with $T_C$ of 84K. We paid particular attention to avoid photon-beam-induced sample aging, since this effect was found to be pronounced at temperatures above $T_C$ and it leads to a reduction in the size of superconducting gap, a quantity required in the analysis of the renormalisation of the electronic states.

Based on a simple analysis of the dispersion relations, we have shown that the normal state dispersion of the bonding CuO$_2$-derived band for cuts crossing the Fermi surface at positions corresponding to the antinode through towards the node is quite linear. It is found that the dimensionless coupling parameter, $\lambda_N$, derived from the dispersion, is isotropic in $k$-space and has a value of 0.5. On entering the superconducting state, a dramatic change in the spectra takes place. A significant renormalisation in the dispersion relation cuts in; the combined effect of the superconducting gap and strong coupling to a bosonic degree of freedom, with a $\lambda_{SC}$ value of 2.0 for the antinodal bonding band data. This clear signature of strong coupling in the superconducting state is also anisotropic in $k$-space, with $\lambda_{SC}$ decreasing from 2.0 (FSA = 0°, antinode region) to 1.6 at a FSA of 17° (one third of the way to the node). The energy scale of the strong renormalisation effects is of order 40-50 meV.

Taking these points together, we arrived at a strong argument in favour of a further examination of these and related data in terms of the coupling of the electronic system to the spin-1 resonance mode seen at ca. 40 meV in inelastic neutron scattering data of the same system. The $k$-dependence seen clearly in our data fits nicely with the location of the spin-1 mode at Q=(π, π), as this Q-vector is highly effective for scattering fermions between the antinodal regions of Fermi surface.

In Chapter 5, we have reported a detailed study of many-body effects observed in ARPES measurements of overdoped (Pb,Bi)$_2$Sr$_2$CaCuO$_{8+\delta}$ compound with $T_C$’s of 78 K and 80 K in the superconducting state. The measurements have been performed at different locations on the Fermi surface of this system and have used multiple polarisations of the synchrotron radiation. The polarisation dependence of measured data enables us to carry out a highly robust determination of the quantities related to many-body effects, such as the dispersion (related to the renormalisation of the band) and the linewidth (related
to the lifetime of the quasiparticles). Based on the temperature dependent data discussed in the previous chapter, we chose to analyse the data presented in this chapter within a model of the self-energy comprising a Fermi liquid term, an impurity scattering term, as well as the terms dealing with the coupling of the electronic system to spin degrees of freedom. Specifically, the latter contribution contains a term related to the spin-1 resonance mode seen in inelastic neutron scattering data and coupling to a spin fluctuation continuum.

On the qualitative level, the model self-energy we adopted agrees well with the main trends in the data, offering a natural explanation for the temperature and \( k \)-dependence seen in the strong coupling effects. For Fermi surface cuts between the nodal and antinodal regions, the model is also able to provide excellent quantitative agreement with the experiment data. Surprisingly, it is near and at the antinode (the \( k \)-space region for which the model self-energy - \textit{a priori} - is the most appropriate) that a significant quantitative disagreement with the experimental data comes to light. The model self-energy footprint is most prominent at an energy scale which is the sum of the superconducting gap and the bosonic mode energy under consideration (\textit{i.e.} at \( \Delta_{SC} + \Omega_0 \)). The salient structure in the experimentally determined self-energy near the antinode is found to be at considerably lower energy than \( \Delta_{SC} + \Omega_0 \) if the mode energy is taken from inelastic neutron scattering results from BSCCO based superconductors.

We are not able, at present, to offer a complete resolution of this issue, although we note that new inelastic neutron scattering data for the La\(_2\)CuO\(_4\)-based HTSC [153] show that the spin response for \( Q=(\pi, \pi) \) is less simple than has been seen for BSCCO to date, with a very clear structure at energies of order of one half of the ‘traditional’ values for \( \Omega_0 \). It remains to be seen whether this low energy spin susceptibility with \( Q=(\pi, \pi) \) is the answer to the puzzle presented in Chapter 5 for the BSCCO based systems, or whether we need to search for a new source of strong coupling to fermionic sector close to the antinode.