Low-Dimensionality Effects in Photoemission and their Links to High-Temperature Superconductors

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The discovery of high-temperature superconductors has made it possible to study superconductivity with photoemission spectroscopy, and stimulated at the same time a complete re-analysis of the Fermi-Einstein picture of the photoelectric effect in the case of low-dimensionality and highly correlated systems. Experimental evidence has not been obtained, however, for the many exotic phenomena that have been predicted. Some of them, on the other hand, have been detected in other kinds of low-dimensionality systems. The most relevant case is the suppression of the photoemission intensity near the Fermi edge for quasi-one-dimensional structures. This phenomenon has been systematically observed for different types of systems, with the only possible exception of chemisorbed gold lines on semiconductor substrates, and correlation effects remain as their most plausible if not only possible cause. The issue of phenomenon in the same general class remains open for high-temperature superconductors, for which ultrahigh resolution experiments have revealed not only the creation of the superconductivity gap, but also structures that are not explained by BCS-like theories.

Photoelectron spectroscopy of high temperature superconductors is, at the same time, a very exciting and a very frustrating field - and the gateway to new physical phenomena in low-dimensional materials. The main point is that very little is known about the photoelectric process in collective states like the superconducting state. One does not have, therefore, the elementary guidelines to the interpretation of photoelectron data that are a big factor in the success of photoemission for essentially one-particle systems [1, 2].

The essential framework for such an elementary interpretation is the Einstein-Fermi model [1], that makes it possible the measured kinetic energy of photoelectron with, essentially, the one-particle ground-state energy - thereby making it possible to extract very valuable electronic and chemical information. Is this picture, however, even approximately valid for a superconducting state?

A partial answer was provided by the classic work of Dave Huber [3]. If one can adopt a quasi-particle framework, then a photoemission spectrum does primarily reflect the quasi-particle density of states. This has made it possible to extensively use high-resolution photoemission and study the superconducting transition in the energy neighborhood of

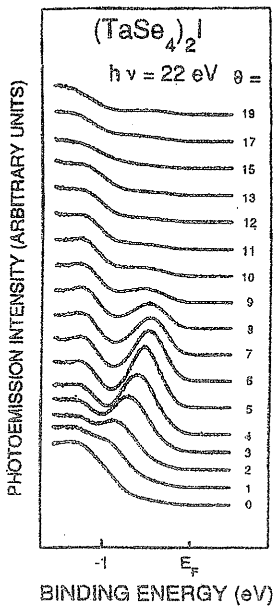

Figure 4. A series of high-energy-resolution angle-resolved photoemission spectra from Y.Hwu et al (Ref.6), taken along the direction of a nearly-one-dimensional $(TaSe_4)_2I$ sample and for different values of the azimuthal angle. They show the suppression of the photoemission intensity near the Fermi level.

near the Fermi level, which has been consistently found for a series of one-dimensional materials, re-opens in our opinion the issue of low-dimensionality in photoemission, which had somewhat frustrated the scientists because of the series of negative results on high-temperature superconductors. The search for similar phenomena in higher-dimensionality system is currently underway.

Acknoledgements

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[1] G.Margaritondo, *Introduction to Synchrotron Radiation*, (Oxford, New York, 1988).

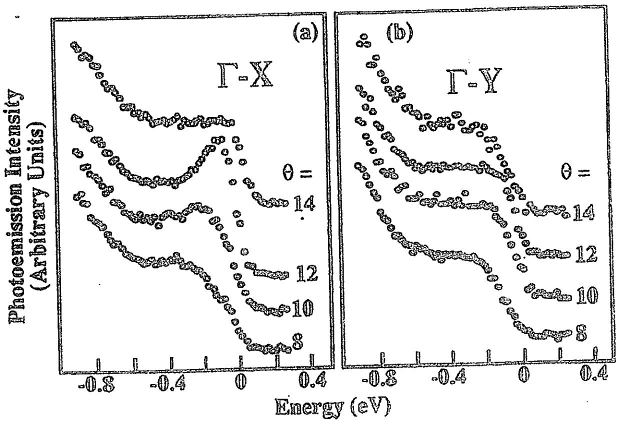

Figure 3. Normal-state photoemission spectra from Ref.15 demonstrates the asymmetric dispersion properties of BCSCO.

This result was alternatively considered with great excitement as the possible hint of new physics, or with disdain as evidence for poor quality of the people's data. We believe [15]. it is neither: the evidence for asymmetric superconductivity in this material offers a much simple solution. The lack dispersion in one direction could simply reflect the multiple folding of the Brillouin zone due to superperiodicity.

This rather negative series of facts lives, on one hand, some disappointment for the people who would like to see radical departures from classic frameworks. On the other hand, it strengthens the weight of simple and straightforward selection-rule studies like that Kelly et al [4] with the consequent symmetry information.

In the past two years, one of the types of effects that were predicted for two-dimensional high-temperature superconductors has been observed [5–7] for lower-dimensionality materials: the suppression of the photoemission signal at the Fermi level. Figure 4 provides a goon example: one sees a nice dispersion in the $(TaSe_4)_2I$ photoemission spectra up to the region near the Fermi level, then no signal at all - sharp contrast with the clear metallic nature of the material.

Several phenomena were examined [5–7] as possible explanations for the observed signal suppression: trivial final-state effects, photon polarization effects, a very low density of states near the Fermi level, fluctuation effect, the excitation of phonons and the consequent shift of the spectral weight towards higher binding energies. All of these hypotheses, however, were found to disagree with the experimental evidence.

The attention could be explained by correlation effects leading to an infrared catastrophe [15, 16]. In three dimensions, the spectral function would be given by the density of states multiplied by the renormalization factor, that leads to attenuation. For one-dimensional systems, the attenuation is expected [18] to be more drastic; instability with respect to the emission of electron-hole pairs leads to a breakdown of the quasiparticle picture, and to a vanishing spectral intensity at the Fermi level. This picture agrees quite well with what was observed.

Whatever its cause, the one-dimensional suppression of the photoemission intensity

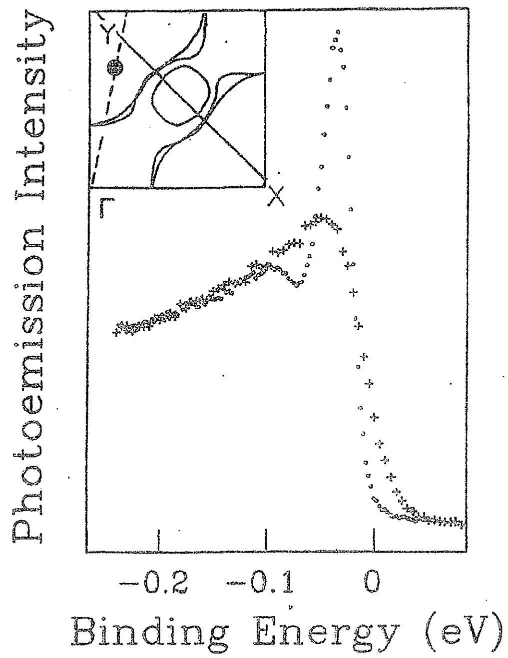

Figure 2. A high-resolved photoemission spectra of BCSCO by Y.Hwu et al (Ref.13). for the normal state (crosses) and for the superconducting state (dots), this last showing a minimum close to the main maximum.

the affected energy region being linked to the maximum spinon energy. A very careful search [3] for this effect in BCSCO, however, failed to provide any evidence, setting an unrealistic upper limit for the spinon energies. The Fermi-liquid issue was subsequently re-opened by the indication that the broadening of the high-resolution photoemission features for the normal state of BCSCO did not follow the Fermi-liquid quadratic law but a different power law [10]. The excitement produced by this result was,however, short-lived: Hwu et al [10] discovered much more severe deviations in the case of classic metals like silver and of two-dimensional crystals, with even a qualitative reversal of the energy dependence of the line width. The issue was settled by the work of Thiry, Petroff and Smith [11, 12] who pointed out that the broadening mechanism includes at the same time initial-state and final-state phenomena and cannot, therefore, be reduced to the quadratic law except in the limit case of pure two-dimensionality.

Another BCSCO photoemission feature has attracted much attention as possible evidence of deviations from the Fermi-liquid framework: the minimum that is quite evident in the superconducting-state spectrum of Fig.2, by Hwu et al [13]. This dip was, for example, proposed as possible evidence of a quasi-Fermi-liquid [14]. Unfortunately, too many theories seem able to account for this feature, so that it is no longer clear if it can be used for evidence of any specific model.

In order to complete this short series of examples, we would like to mention the data of Fig3, which show a clear dispersion asymmetry for the normal state of BCSCO [15].

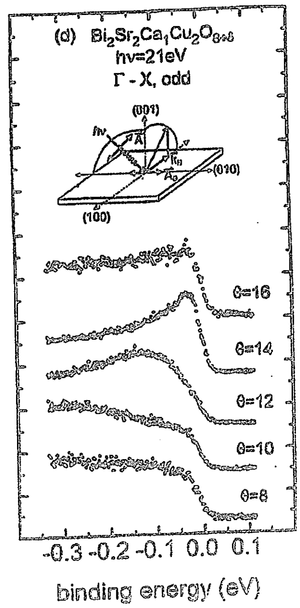

Figure 1. High-resolution angle-resolved photoemission data from Kelly et al (Ref.4). The extensive set of data of this kind was used to rule out s-wave superconductivity for BCSCO.

the superconducting gap. Figure 1 shows, for example, a series of angle-resolved photoemission spectra of BCSCO taken by Kelly et al [4]. An extensive analysis of the characteristic peak's intensity has enable these authors to rule out an s-wave symmetry for the superconducting state.

In turn, small deviation from the predictable behavior in the above framework have been taken as evidence if deviation from the Fermi-Einstein picture of the photoelectron effects. and in many cases from the Fermi-liquid framework. In light of extensive experimental data, however, one can in our opinion conclude that no clear evidence exists today for such deviations, so that both the Fermi-Einstein picture and the Fermi-liquid framework still hold.

Amazingly, however, some of the predicted phenomena have been discovered. But they seem confined to lower-dimensionality systems, notably one-dimensional crystal [5-7]. We shall briefly review here both the envisioned effects for the two-dimensional effects in high-temperature superconductors and the recently observed one-dimensionality effects.

The first hint of such effects in the case of high-temperature superconductors was the absence of signal near the Fermi level for YBCO [8]. As it turned out, however, this was a trivial stoichiometry problem related to the instability of cleaved surfaces against the loss of oxygen. The first observation of the photoemission Fermi edge for BCSCO [9] definitely ruled out *large* effects of this kind.

Subsequently, however, Dave Huber [3] predicted that a radical departure from the Fermi liquid framework, with the elementary excitation being independent holons and spinons, would also suppress the photoemission signal at the Fermi level - the width of