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The deviation in the d-wave behaviour of the gaps in Cuprate high-temperature superconductors

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ABSTRACT

The (Cuprate) High Temperature Superconductors (CHTSCs) are characterised by a d-wave gap of the $\cos(2\phi)$ form. In some systems, deviations from this canonical behaviour are observed in ARPES experiments. In this note ARPES experiments on the gaps of the one layer systems Bi2201 and LSCO are inspected and analysed. The available data give for optimal doping a superconducting gap of (9 ± 2) meV, and a pseudogap, which originates from the preformed pairs, of (15 ± 3) meV. A second pseudogap, (35 ± 5) meV, with a shorter wave vector is observed in many experiments and is ascribed to an additional ordered structure. The existence of the two pseudogaps is responsible for the deviation from the canonical $\cos(2\phi)$ behaviour. Thus the question whether the pseudogap observed in the CHTSC by ARPES is due to preformed pairs or due to additional order does not really exist at least in the one layer compounds. There are two pseudogaps present in the one layer CHTSC, one due to preformed pairs, which become superconducting below T_c, and a second one, reflecting an additional order, which is most likely the checkerboard structure.

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1. Introduction

Ordinary superconductors show a gap below T_c [1–3], which results from the lowering of the energy of the system in going from the normal conducting to the superconducting state. In contrast, (Cuprate) High Temperature Superconductors (CHTSCs) exhibit two gaps [4–7], namely a superconducting gap and a pseudogap, with the latter extending into the normal state. The nature of this pseudogap is still under discussion [5–9]. Some researchers consider the pseudogap as the signature of so-called preformed pairs, which condense into the superconducting state below T_c [5,10]. In another view, the pseudogap has nothing in common with superconductivity and is the expression of a competing order [11]. Experiments can be interpreted with both approaches. There is however agreement on the fact, that in the CHTSC the gaps are of a d-wave type, leading to a $\cos(2\phi)$ behaviour for the gap as measured from the antinodal ($\pi/0$) to the nodal ($\pi/2/\pi/2$) direction in the Brilloin zone (see inserts in Fig. 1c for the definition of ϕ).

However, deviations from the $\cos(2\phi)$ behaviour have been observed in ARPES experiments. The situation is complicated by the fact, that for the same system and the same doping, some authors find such a deviation from the $\cos(2\phi)$ function, while others do not.

In this note, primarily these deviations observed from the $\cos(2\phi)$ behaviour for the one layer compounds Bi2201 and LSCO with an approximately optimal doping will be analysed. The principle result of the analysis is, that only samples with a non-disordered

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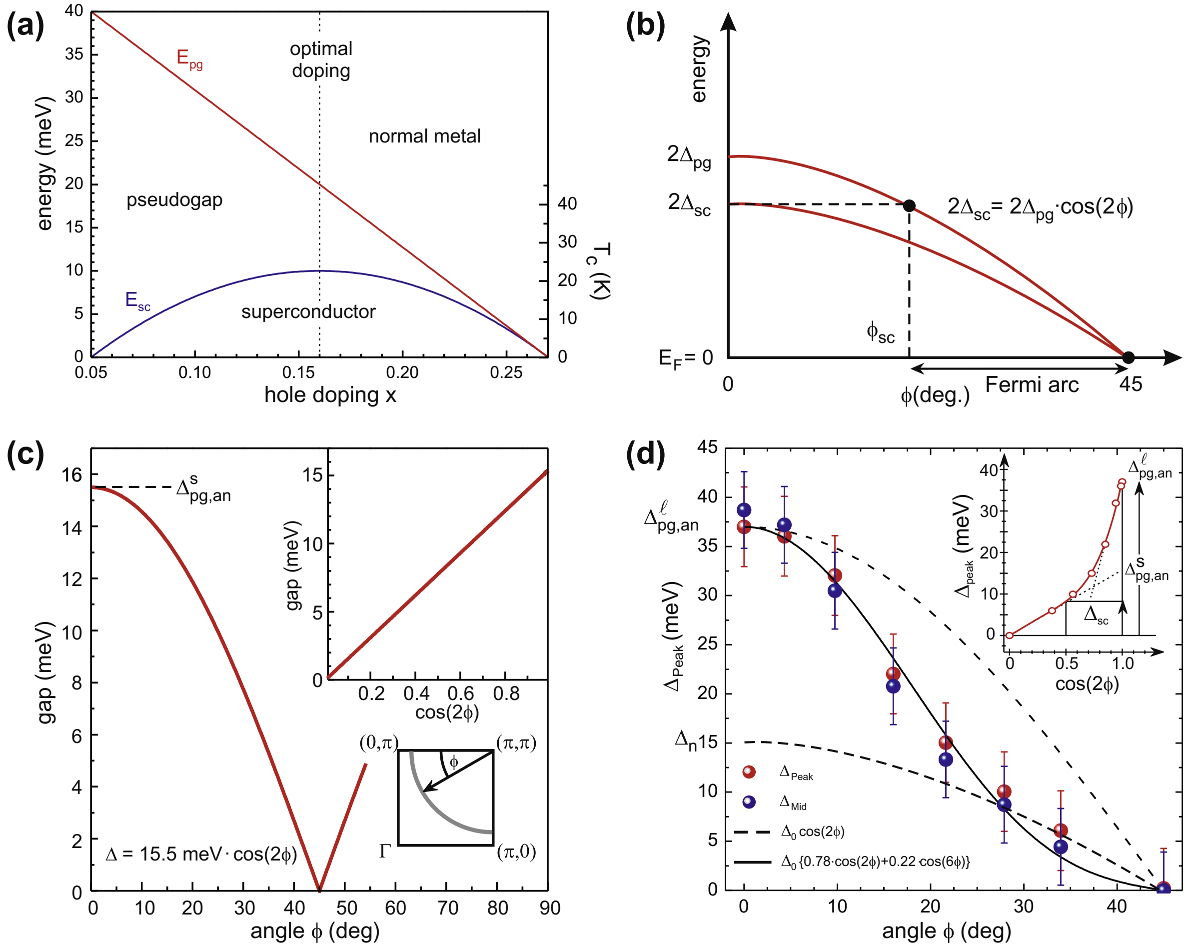

Fig. 1. Excitation energies for Cuprate High Temperature Superconductors. (a) doping dependence of the superconducting energy and the pseudogap energy [5], (b) angular dependence of the superconducting gap and the pseudogap energy between the antinodal and the nodal direction [13], (c) experimental measured pseudogap for an OP Bi2201 sample, represented by the fitting results from Ref. [16]. The upper inset shows the data below T_c as a function of $\cos(2\phi)$, the lower inset shows the definition of ϕ, and (d) experimental measured pseudogap for an OP Bi2201 sample as taken from Ref. [17]. Note in particular the large gap value at the antinode (38 meV); for the nominally identical sample, the data in (c) give 15.5 meV for this gap. The inset shows the data as a function of $\cos(2\phi)$.

structure show a one gap behaviour in the ARPES experiment. If the sample has a doping induced disorder a two gap behaviour is found, where one gap is the pseudogap representing the preformed pairs, while the second one, larger in energy, but having a smaller wave vector is derived from the additional order, which is most likely the checkerboard order [12].

Fig. 1 sketches the gap situation in the CHTSC [5]. Fig. 1a shows the well known doping dependence of the pseudogap energy (responsible for the superconductivity) and the superconducting energy. The $\cos(2\phi)$ momentum dependence of the two energies is shown in Fig. 1b. In that figure it is also indicated, how the superconducting gap and the pseudogap are related to the Fermi arc [13]. This diagram has recently been used to determine superconducting gaps from ARPES data [14,15]. The superconducting gap and the pseudogap are related by the relation, $2\Delta_{pg,an}\cdot\cos(2\phi_{FermiArc}) = 2\cdot\Delta_{sc}$.

While the doping dependence of the gaps seems undisputed, the momentum dependence is still under debate, since there are experiments that show the $\cos(2\phi)$ form as in Fig. 1c [16], while others on the same system, Bi2201 OP, show a two leg behaviour (Fig. 1d) [17]. It is interesting, that the experiment with the one leg behaviour in Fig. 1c gives a pseudogap at the antinode of 15 meV ($\Delta^s_{pg,an}$, s stands for small), while the experiment of Fig. 1d gives a pseudogap of 37 meV at the antinode ($\Delta^\ell_{pg,an}$, ℓ stands for large). The data in Fig. 1d can be analysed by two gaps of magnitude 37 meV and 15 meV, as shown in the inset, by plotting them as a function of $\cos(2\phi)$, which results approximately in two straight lines. Starting at the node, the smaller pseudogap extrapolates to the same value at the antinode (15 ± 3 meV) as observed for samples which show the one pseudogap behaviour as in Fig. 1c. The extrapolated gap is often called the nodal gap (Δ_n), because it starts near the node as a straight line as a function of $\cos(2\phi)$. The large pseudogap, if extrapolated from the antinode goes to zero around $\cos(2\phi) \sim 0.6$, indicating a wave vector for its excitation of ½ of the Brilloin zone or less. This points to a relation of this second pseudogap to an additional order like the checkerboard order as suggested previously [12].

The data in Fig. 1 demonstrate, that in the CHTSC at least three gaps are observed: the pseudogap, which measures the pairing strength ($\Delta^s_{pg,an}$), the superconducting gap (Δ_{sc}) and a second pseudogap, which measures the excitation in the additional order ($\Delta^\ell_{pg,an}$). Actually there is a fourth gap namely the so-called nodal gap, which agrees with the small pseudogap ($\Delta^s_{pg,an}$) at optimal doping, but shows no doping dependence for dopings smaller than optimal, thus deviating from the pairing gap as one moves away from optimal doping towards lower doping [18].

2. The one layer compounds Bi2201 and LSCO at optimal doping

Data from the literature on the one layer compounds Bi2201 [15,16,19–27]and LSCO [24,28–35] at (or near) optimal doping