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Multiple energy scales in the cuprate

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Abstract

We argue that the detection of a number of high, moderately high, and lower energy (temperature) scales, combined with diverse other data, for the *nonstoichiometrically doped* cuprate is strongly supportive of the hypothesis of multichannel Kondo effect in them. This hypothesis is theoretically sound, and is in excellent agreement with data.

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Keywords: Cuprate superconductors; Two channel Kondo effect

1. Introduction

A recent preprint [1] has reported that high energy ARPES reveals two hitherto unrecognised high energy(temperature) scales in four diverse 'nonstoichiometrically doped high-T_c cuprates' (HTC). They are given by a low energy kink anomaly at, say, $E1 = 0.03$–0.09 eV ≈ 350–1000 K, and by the high energy anomaly at $E2 = 0.3$–0.5 eV ≈ 3500–5500 K, quantified in a particular way, that manifest in ARPES in the characteristic 'waterfall effect' discussed often in the literature and explained below. $E1$ and $E2$ are identified by us, respectively, with $\widetilde{T}_K$ and T_K, Section 2. There is an anomalous enhancement of the LDA conduction bandwidth of the CuO_2 plane upto about 2 eV $\approx 22\,000$ K at high energy. The discrepancy between the LDA and ARPES bandwidths reduces with higher doping. $E1$ reduces upon increased doping. $E2$, if defined as the energy at which the waterfall effect occurs, would be almost indifferent to doping level. These dispersion anomalies have universality properties across the four families investigated, and have clear (in-)dependence on doping as above. A general indifference of the above scales to the superconducting transition at T_c and to superconductivity in general is an important aspect of the data. Likely explanation of these findings has been stated [1] to be along the lines of polaronic effect and the in-plane plasmon or two-magnon interaction with the carriers; the belief has been expressed that the anomalous data is the result of some unknown Mott–Hubbard physics.

It has been our conclusion [2–7] on a study of the data and theories published since 1986 that overcompensated two channel Kondo effect [8] rather than the Mott–Hubbard physics is capable of giving a simple, unified, consistent and convincing explanation of a very large volume of diverse data. Though there is no completely rigorous understanding of the two channel effect, and in particular, of the likelihood of instability of the corresponding two channel Kondo fixed point (KFP), on the basis of simple arguments an important conclusion may be reached. It is that in real nonstoichiometrically doped crystals with moderate disorder the two channel KFP is reasonably stabilised, see below. There was existing evidence for a high energy scale [9] as well as the comparatively low energy scales that have already indicated Kondo effect.

There are other recent detection [10–17] of a multiplicity of scales which though done mainly via ARPES studies has

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also been done by other techniques. The recent improvements in ARPES techniques has enabled the detection of the high energy scales. Of the data mentioned above Ref. [13] that found a plasmon ~1 eV in energy interacting with the carrier gives a direct evidence for the presence of a scale of this magnitude, T_K, which being larger than E_F here leads to the boson, a plasmon here, the dominant excitation of the crystal. Ref. [14] has detected scales of magnitude about 1 eV and 1500 meV which are the temperatures T_K and $\widetilde{T}_K$ for the relevant crystal. Not all the experiments have detected the scale ~1 eV and not even all of the other four Kondo-related scales. Not all the experiments have been, either due to planning or performance, adequate for the purpose. In sum, we consider the evidence to be sufficient in order to ascribe the presence of the multiple scales to multichannel Kondo effect in the nonstoichiometric HTC.

This work is meant to explain the origin of, and discuss the other evidence for, the multichannel Kondo effect in this case.

2. Multichannel Kondo hypothesis, and the evidence

In order to explain and analyse the above and voluminous other relevant data our working hypothesis has been that the Kondo impurity undergoes at high temperature a single-site two channel transition from a paramagnetic phase to the overcompensated two channel KFP at T_K. Kondo effect is mainly concentrated along the Cu–O bond; hence T_K as well as other Kondo temperatures have a periodic variation around the basal plane.

Simultaneously with the single-site transition, the lattice undergoes a coherent transition at a lower temperature [18] $\widetilde{T}_K$. The two channel KFP by a channel transition [8] at $\widetilde{T}_{KC}$ shifts to the one channel KFP. For higher doping when $\widetilde{T}_{KC}$ reduces it bifurcates [19] into two curves $\widetilde{T}^{\mathrm{I}}_{KC}$ and $\widetilde{T}^{\mathrm{II}}_{KC}$ corresponding, respectively, to the dominant ground level hybrid and the subdominant axial hybrid. The former occurs due to the weak mixing of the Cu3d$_{xy}$ orbital of the Cu3d crystal field (CF) multiplet with the ground level orbital Cu3d$_{x^2-y^2}$. On Kondo delocalisation at $\widetilde{T}_K$ it forms the d-wave band [20], $\mathrm{d}_{x^2-y^2} + \mathrm{id}_{xy}$ [21] that becomes superconducting at, say, T_d, Fig. 1, with the same gap symmetry. The axial hybrid [22] situated at about 1.3 eV above the ground is made up of the levels 3d$_{3z^2-r^2}$, 2p^a_z, 4 s, and the metallic orbital from the insulating layer. The 4s orbital belongs to the Cu(2) atom. On full Kondo delocalisation at $\widetilde{T}^{\mathrm{II}}_{KC}$ the resulting s-wave band undergoes s-wave superconducting transition at a lower temperature T_c. We name the fermi surface of the d-wave(s-wave) band as FS1(FS2). At the low temperature end the parent compound is believed to undergo a two channel Kondo transition at T_M.

The question arises as to why the doped HTC should undergo [18,23–25] a Kondo transition rather than the usual metal-nonmetal Mott transition at T_M. The reason [25] is that this happens in order to quench the nonzero

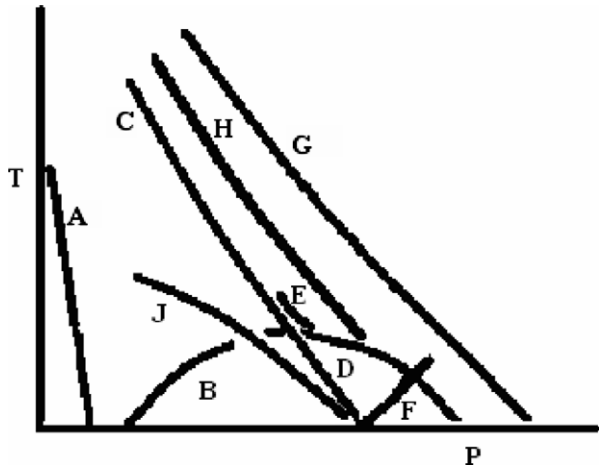

Fig. 1. This schematic p–T phase diagram (not to scale) above shows all the transition lines, fixed points, and QCPs. The symbols A...J have the following meanings: $A \equiv T_M$, $B \equiv T_C$, $C \equiv \widetilde{T}_{KC}$, $D \equiv \widetilde{T}^{\mathrm{I}}_{KC}$, $E \equiv \widetilde{T}^{\mathrm{II}}_{KC}$, $F \equiv T_f$, $G \equiv \widetilde{T}_K$, $H \equiv T_d$, $J \equiv T_{dyn}$. The unusual temperatures are mostly defined in the text; T_f is the temperature at which the two channel KFP fully terminates. The direct evidence for the various transition temperatures other than the common ones are the following publications: (i) Q. Si, et al., 42 (1990) 1033: T_K. (ii) T. Ito, et al., Phys. Rev. Lett. 70 (1993) 3995: $\widetilde{T}^{\mathrm{I}}_{KC}$. (iii) Present paper: T_K, $\widetilde{T}_K$. (iv) H. Ding et al., Nature 51 (1996) 382: $\widetilde{T}^{\mathrm{I}}_{KC}$. It is understood that in this early ARPES work the d-wave superconductivity could be detected only after the Kondo scattering is largely suppressed below $\widetilde{T}^{\mathrm{I}}_{KC}$. (v) B. Batlogg, V.J. Emery, Nature 382 (1996) 20: T_d and $\widetilde{T}^{\mathrm{II}}_{KC}$. (vi) Y. Wang et al., Phys. Rev. B 73 (2006) 24510: $\widetilde{T}_K$, $\widetilde{T}^{\mathrm{I}}_{KC}$ and T_d. (vii) H. Fukuyama, H. Kohno, Czech J. Phys. 46 (suppl. S6) (1996) 3146: $\widetilde{T}_K$, $\widetilde{T}^{\mathrm{I}}_{KC}$ and T_d. (viii) J.L. Tallon, J.W. Loram, Physica C 349 (2001) 53: $\widetilde{T}^{\mathrm{I}}_{KC}$, $\widetilde{T}^{\mathrm{II}}_{KC}$ and T_{dyn}. (ix) Y.J. Uemura, Solid State Commun. 126 (2003) 23: T_{dyn} and $\widetilde{T}^{\mathrm{I}}_{KC}$. (x) G. Deutscher, Rev. Mod. Phys.77 (2005) 109: T_f. There has not been explicit description and complete delineation of all the transition lines; we have sometimes used our judgement, in the light of data, to complete the particulars of such lines.

entropy [26,27] of the parent compound. We may mention that the Kondo transition referred to here is the conventional one channel Kondo transition only which has been detected by numerical simulation until now. The two channel transition that is fundamental to the understanding of the doped HTC has not been detected by this method yet. It is our understanding that the current simulation method is able to treat only the stoichiometrically doped crystal, e.g., YBCO:124. To our knowledge, for the nonstoichiometric crystal with moderate disorder, e.g., YBCO:123, which supports the two channel KFP, there is no appropriate simulation done to date [28]. However, we shall discuss the experimental evidence, in addition to those mentioned already, that strongly point to the presence of the two channel effect in the moderately disordered nonstoichiometric crystal.

There are apparently weighty arguments against the two channel KFP; some of them are:

(i) The expectation is that the symmetric two channel KFP undergoes a fast decay [8b] to the asymmetric one channel KFP rendering the former unstable. It is noted that that the symmetry-breaking term [8b]