ISSN 1330–0008
CODEN FIZAE4

LETTER TO THE EDITOR

PROPERTIES OF HIGH-T_c CUPRATES: SOME RECENT RESULTS AND OPEN QUESTIONS

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Dedicated to Professor Boran Leontić on the occasion of his 70th birthday

Received 9 November 1999; revised manuscript received 22 March 2000
Accepted 3 April 2000

Thirteen years ago, late in 1986, several groups confirmed striking claims of the famous paper by Bednorz and Müller [Z Phys. B **64** (1986) 189] that announced the discovery of high-T_c superconductivity in cuprates. Some 60,000 papers later, we are still struggling to understand the high-T_c oxide superconductivity. Here we present some of the most relevant recent experiments and discuss some open questions across rather complex electronic phase diagram; we also note an important role of un-intentional and intentional disorder in these layered, high-T_c oxides.

PACS numbers: 74.25.-g, 74.72 UDC 538.945

Keywords: superconductivity, high-T_c cuprates

Applications. Due to the present, rather negative view of our field by the media, we begin with applications and make an important point. Although many of the "leaders" of the semiconductor industry or analysts from the Wall Street consider the field of high-T_c superconductivity an investment risk, the applications are advancing successfully and may even dominate some technologies of the 21st century. Note that the successful Si-based technology has so far acumulated more than 10^7 men-years of know-how, III-V (Ga-As) optoelectronics technology 10^6 men-years, while all superconductivity hasn't even reached the 10^5 mark. We clearly need at least another decade of intensive R & D before giving any definite conclusions to the popular media. Especially so, as there is no doubt that the in-depth understanding of the fundamentals [1,2] of our field (superfluidity included) will certainly be relevant to many branches of advanced science and technology in the 3rd millenium [3,2].

Electronic phase diagram. True understanding of properties of high-T_c cuprates and their electronic phase diagram (Fig. 1) still presents a major challenge, despite of a remarkable progress in both, sample preparation and advanced experimental techniques [1]. One of the reasons for this is that as we dope these layered oxides, we do not only encounter rather complex electronic phases; the underlying crystallographic (structural) and "metallurgical" phase diagrams of these quaternary solids are often even more complex [3] and the disorder clearly plays an important role.

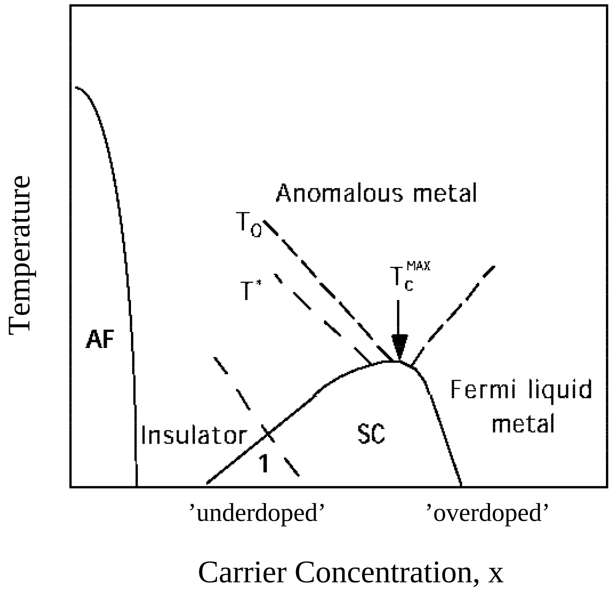

Fig. 1. Schematic phase diagram of cuprate superconductors [1]. Various authors give different name or significance to various observed lines: the "pseudogap", T^*, the 'spin-correlations' line, T_0, or the metallic Fermi-liquid region in the overdoped regime. Note the anomalous behaviour in the region 1 where the superconductor directly transits into the insulating state in very high magnetic field [7].

Normal state. We all seem to agree that at the left-hand side we have a 2D antiferromagnetic insulator and that at the right-hand side, the highly overdoped 3D perovskites exhibit more Fermi–liquid-like properties. There is an agreement on the existence of the Fermi surface in the optimally doped and overdoped samples [4] (see Fig. 2). Still, many details remain to be clarified, especially in the underdoped and overdoped samples. There is now also well established evidence, shown by all experiments, of the existence of two transition lines in the electronic phase diagram of HTSC cuprates [1]: the "pseudogap", T^*, and the "end of the spin correlations", T_0. The exact role of T_0 is discussed at length by Pines [1], while the notion of "pseudogap" was originally proposed already in 1988 by Friedel [5], in a totally different context from the present dominant idea of a pre-formed pairs in the N-state. In a recent paper [6], Deutscher has compared the gap energies, measured by different experimental techniques and has shown that these reveal the existence of two distinct energy scales: p and c. The first, determined either by angle-resolved photoemission spectroscopy or by tunnelling, is the single-particle excitation energy - the energy (per particle) required to split the paired charge-carriers that are required for superconductivity. The second energy scale is determined by Andreev reflection experiments, and Deutscher associates it with the coherence energy range of the superconducting state: the macroscopic quantum condensate of the paired charges. In the overdoped regime, p and c converge to approximately the same value, as would be the case for a BCS superconductor where pairs form and condense simultaneously. In the underdoped regime, where the pseudogap is measured, the two values diverge and p(T^*) is larger than c (T_c) [6]. This indeed corresponds to the schematic phase diagram given in Fig. 1.

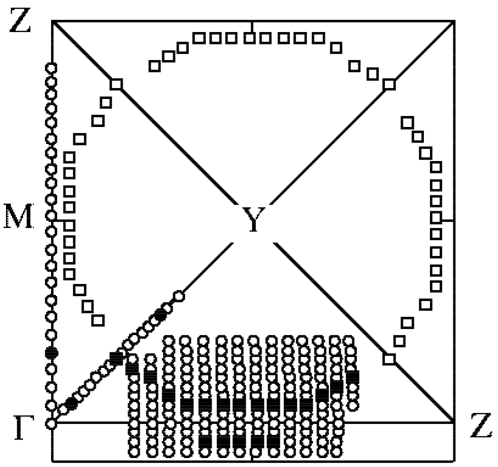

Fig. 2. Experimentally determined Fermi surface [4]: filled squares - experimental Fermi surface locations; open squares - Fermi surface obtained by symmetry operations; closed circles - superlattice band crossings along the Γ-*M*-*Z* *and* Γ-*Y* *high symmetry directions; open circles - locations in the Brillouin zone where the ARPES spectra were taken.*

Metal-insulator transition. MI transition is not understood even in simpler solids like Si:P so it is not surprising that it remains a highly disputed topic in high-T_c oxides, where anomalous behaviour was reported by Boebinger et al. [7]: deep in the underdoped regime, LSCO samples directly transit from superconducting into the insulating state in very high magnetic field [7]. However, this may be due to granularity of the sample. We also note that the measured bandwidth (obtained by ARPES) on $Sr_2CuO_2Cl_2$ – the parent antiferromagnetic insulator, is consistent with the t-J model calculations, while the overall dispersion does not completely agree with this theoretical prediction [4].

Stripes. There is evidence for formation of stripes in many weakly doped perovskites [8], yet the role of stripes in the overall HTSC-scenario is still unclear: while some authors consider them vital for the mechanism, other consider them only as a stabilizing, special phase within a low- dimensional system and almost a nuisance to high-T_c.

Superconducting state. In highly doped samples, measured properties tend to appear as BCS-like [2], yet this is also highly disputed by some researchers. In the underdoped regime, the disagreement is complete and more research is needed to clarify the controversies. In the underdoped to optimally doped samples, majority of experiments indicate a dominant d-wave symmetry [1]. There seem to be, however, some notable exceptions [1,9]: there is no evidence for d-wave component in the electron doped cuprates (Maryland Center), Sharvin experiments on LSCO give a finite minimum gap (Deutscher et al. [1]) and electronic Raman experiment on Hg-2201 compound (Sacuto et al. [10]) is not compatible with d-wave but rather with extended s-wave (with nodes). Only few experiments were performed systematically in the overdoped regime [1]. Photoemission results by Vobornik et al. are also consistent with the d-wave behaviour in highly overdoped samples [4]. Photoemission, however, cannot measure the phase of the order parameter, and therefore cannot on its own distinguish between the d-wave and anisotropic s-wave symmetry.

New materials. A recent report [11] on possible nucleation of a 2D (surface) superconducting phase (with $T_c \approx 90$ K) on WO_3 single crystals surface doped with Na^+ seems to be a genuine effect [12]. The report on the aparent coexistance of superconductivity [13] (at 30 K) and magnetism (at 120 K) in $GdBa_2RuCu_2O_{7-y}$ seems to be along the line of experiments [8,12] reported by Felner et al. in 1998. We also note that striking results were reported by J. P. Locquet et al.: they have doubled T_c (up to ≈ 50 K) of LSCO films by inducing the strain into the quasi-2D matrix (by growing films on different substrates) [14]. Such strain-induced T_c-enhancement, toghether with coexistence with magnetism [13], opens numerous creative options to the artificial nanoengineering [3] of layered oxides, especially if coupled ladder-compounds eventually also exhibit superconductivity [15].

Anomalous transport. While the main characteristics of the (anomalous) transport in cuprates seem to be well established [16], several recent results by Forró et al. [17,18] pose a challenge to our understanding of the transport. The resistivity of slightly underdoped Sr_2RuO_{4-y} superconducting ($T_c = 0.9$ K) perovskite is linear [17] over three decades of temperatures, up to 1050 K, yet the temperature dependence of the Hall coefficient is similar to what was measured in cuprates. This suggests that the linear temperature dependence of resistivity is not an exclusive signature of the anomalous normal state of high-T_c cuprates, but rather of layered oxides in general, especially single layer perovskites, possibly independently of the magnitude of the superconducting temperature [17]. Furthermore, in single crystals of Tl-2212 [$T_c = 111$ K ($\rho_c/\rho_{ab} \approx 1000$)], $\rho_{ab}(T)$ exhibits "usual" linear behaviour and $\rho_c(T)$ follows generally metallic-like, positive slope. However, there is a clear crossover of $\rho_c(T)$ to semiconductor-like behaviour close to T_c and, for the first time, above 500 K. Under high pressures (< 15 kbar), the magnitude of ρ_c strongly decreases, yet $\rho_c(T)$ slope *does not* change [18]. That suggests pressure-independent out-of-plane mechanism like in resonant tunneling in quasi-one-dimensional organic conductors proposed by Weger [19]. Above 500 K the hopping is activated, hence the measured crossover in $\rho_c(T)$ [18].

Photoemission spectroscopy. In addition to our ARPES studies on BSCCO single crystals [20] we note the first report on the change of spectral signature caused by the intentional disorder in a Bi-2212 high-T_c cuprate [21,4]. We also note that recent ARPES experiments, with 33 eV and 21eV photons produced somewhat different electronic features [22]. As this has been independently confirmed [23], it poses several profound new challenges to theorists.

In summary, there are clearly many more puzzling results and open questions in high-T_c superconductivity, so we argue that in order to resolve numerous remaining controversies, we still need many more systematic experiments on very carefully prepared and characterised samples of both, under- and over-doped, films and crystals of high-T_c oxides and related solids.

Acknowledgements

We gratefully acknowledge numerous contributions of all our colleagues at the EPFL, especially of all co-authors listed in Ref. [21]. We also acknowledge the support by the EPFL and Swiss FNRS (Bern). Davor Pavuna is profoundly grateful to Professor Boran Leontić, whose enlightening influence encouraged him to choose physics as a profession.

References

1) *The Gap Symmetry and Fluctuations in High-T_c Superconductors*, eds: J. Bok, G. Deutscher, D. Pavuna, S.A. Wolf, NATO-ASI B371, Kluwer-Plenum (1998);

2) M. Cyrot and D. Pavuna, *Introduction to Superconductivity and High-T_c Materials*, World Scientific, London, Singapore, New Jersey (1992);

3) *Oxide Superconductor Physics and Nano-engineering I, II III & IV*, eds. D. Pavuna and I. Bozovic, no. 2058, 2697, 3481, 4058 SPIE, Bellingham, USA (1994, 1996, 1998, 2000);

4) I. Vobornik, "Investigation of the Electronic Properties and Correlation Effects in the Cuprates and in Related Transition Metal Oxides", D. Sci. Thesis, École Polytechnique Fédérale de Lausanne (1999);

5) J. Friedel, Physica C **153-155** (1988) 1610;

6) G. Deutscher, Nature **397** (1999) 410;

7) G. S. Boebinger et al., Phys. Rev. Lett. **77** (1996) 5417:

8) *Stripes I & II*, ed A. Bianconi, special issue of J. of Supercond. (1997 and 2000);

9) *High Temperature Superconductivity*, eds. S. Barnes et al., CP483, American Institute of Physics (1999) (see article by R.A. Klemm et al., p. 259);

10) A. Sacuto et al., Ref. [1], p.291;

11) S. Reich and Y. Tsabba, Eur. Phys. J. B **9** (1999) 1;

12) J. C. Phillips (Lucent Bell Labs), private communication (2000);

13) R. Weht et al., in Ref. [9], p. 141;
14) J. P. Locquet et al., Nature **394** (1998) 453; also J. P Locquet et al. in Ref. 3;
15) B. Normand, D. F. Agterberg and T. M. Rice, Phys. Rev. Lett. **82** (1999) 4296;
16) N. P. Ong, Science **273** (1996) 321, and references therein;
17) H. Berger, L. Forró and D. Pavuna, Europhys. Lett. **41** (1998) 531;
18) J. P. Salvetat et al., unpublished (1999); L. Forró, Int. J. Mod. Phys. **8** (1994) 829:
19) M. Weger, J. Phys. (Colloq.) C **6** (1978) 1456;
20) S. La Rosa et al., Phys. Rev. B **56** (1997) R525;
21) I. Vobornik, H. Berger, D. Pavuna, M. Onellion, G. Margaritondo, F. Rullier-Albenque, L. Forró and M. Grioni, Phys. Rev. Lett. **82** (1999) 3128; see I. Vobornik et al., Festchrift to B. Leontić, Fizika A (Zagreb) **8** (1999) 107;
22) Y. D. Chuang et al., cond-mat/9904050 preprint (1999);
23) M. Onellion (U. Wisconsin) and S. Rast (EPFL), private communication (1999);

SVOJSTVA KUPRATA VISOKOG T_c: NEKI NOVIJI REZULTATI I OTVORENA PITANJA

Prije trinaest godina, u kasnu jesen 1986 nekoliko je istraživačkih grupa potvrdilo rezultate članka Bednorza i Müllera koji je najavio epohalno otkriće visokotemperaturne supravodljivosti u kupratima. Skoro 60.000 članaka kasnije, mi se svi jos uvijek uvelike trudimo razumjeti visokotemperaturnu supravodljivost. U ovom članku prikazujemo poneke od najvažnijih nedavnih eksperimenata i diskutiramo neke neriješene probleme u vrlo složenom elektronskom faznom dijagramu, te posebno naglašavamo važnu ulogu nenamjerne (intrinsične) i namjerno inducirane neuređenosti u tim ploškastim oksidnim supravodičima.