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Interplay between charge-density-wave gapping and *d*-wave superconductivity in high-T_c oxides

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ABSTRACT

A new theory describing the coexistence of *d*-wave superconductivity and charge density waves (CDWs) has been developed. Calculations were carried out for cuprates, in the case when the CDW gap Σ emerges on the nested antinodal sections of two-dimensional Fermi surface. It is shown that $\Sigma(T)$ is temperature (T)-reentrant for certain ranges of model parameters. The superconducting energy gap $\Delta(T)$ deviates substantially from the canonical $d_{x^2-y^2}$-one. The values of $2\Delta(0)/T_c$ are shown to fall into the range from 5 to 8 and even more, which is well-known for high-T_c oxides and has not been explained yet.

A competition and a possible coexistence between various kinds of long-range ordering in solids (e.g., magnetism and ferroelectricity, magnetism and superconductivity) are very interesting from the principal point of view, being also important because of numerous applications. A struggle between the charge-density-wave (CDW) instability and the Cooper pairing for a Fermi surface (FS) is another example of competition between different interactions. However, in this case, CDWs and accompanying periodic crystal lattice distortions are unequivocally detrimental to superconductivity and constrain the maximal critical temperature, T_c [1]. This is true for many classes of superconductors, including high-T_c oxides, where CDWs reveal themselves as pseudogaps and dip-hump structures in tunnel spectra.

A self-consistent theory of interplay between CDWs and superconductivity has been developed, so that the thermodynamic characteristics of CDW superconductors, as well as tunnel currents through junctions involving such materials, were modelled and calculated [2–4]. In that studies, the *s*-wave symmetry of the superconducting order parameter, Δ, was assumed. At the same time, it is widely recognized that cuprates show a predominately $d_{x^2-y^2}$-wave type of superconductivity [5]. This evidence stimulated us to build a self-consistent theory of coexisting *d*-wave superconductivity and CDW dielectric gapping on the nested FS sections. In the two-dimensional momentum space, we have a four-lobe *d*-wave superconducting-gap function $\Delta(T)\cos^2 2\theta$ spanning the whole FS and a CDW energy gap, $\Sigma(T)$, which in agreement with the experiment [6] is assumed to appear only on the nested FS sections in the cones 2α. The corresponding geometrical scheme is shown in Fig. 1.

We have solved a system of two coupled integral equations for the indicated order parameters [7]. The quantity $\mu = 4\alpha/\pi$ serves as a natural control parameter (the FS gapping level) of the problem. The results are shown in Fig. 2. Since the reduced dependences $\Delta(T)/\Delta(0)$ and $\Sigma(T)/\Sigma(0)$ are different, their interplay demonstrate new features as compared to the case of two competing *s*-wave gap functions [2]. As is readily seen, the superconducting gap is suppressed by its CDW rival, preserving, however, its monotonic character. On the other hand, $\Sigma(T)$ becomes reentrant for large enough ratios between the strengths of Cooper and CDW (electron-hole) interactions. It leads to the situation, in which pseudogaps manifest themselves above T_c, swiftly tending to zero far below T_c. Therefore, although the two-gap scenario (coexisting Δ and Σ) is valid, the temperature behavior of the effective tunnel gap shows an apparent smooth transition from a pseudogap into a superconducting gap, when crossing T_c. Such an evolution of the tunnel spectra imitates the one-gap scenario with a precursor psedudogap transforming into a true mean-field gap.

Despite the $\Delta(T)$ dependences in CDW *d*-wave superconductors look similar to those for conventional *d*-wave superconductors, CDWs significantly influence one of the specific features of the Bardeen–Cooper–Schrieffer (BCS) model. Namely, we mean the ratio $2\Delta(T)/T_c$, which takes exact values $(2\Delta_0/T_{c0})_s = 2\pi/\gamma$ and $(2\Delta_0/T_{c0})_d = 4\pi/\gamma\sqrt{e}$ in the weak-coupling *s*-wave and *d*-wave particular cases, respectively. Here Δ_0 and T_{c0} are the values of $\Delta(0)$ and T_c, if the competing electron-hole pairing is switched off, and e is the base of the natural logarithm. It turns out that CDWs suppress T_c of *d*-wave superconductors more vigorously than the corresponding $\Delta(0)$, due to the weakness of CDWs themselves at low T.

In Fig. 3a, the dependences of $2\Delta(0)/T_c$ and T_c/Δ_0 on Σ_0 are shown. Here, Σ_0 is the CDW gap when superconductivity is absent.

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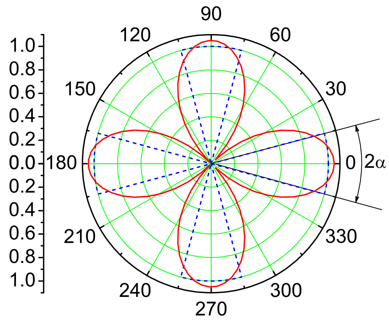

Fig. 1. (Color online) Order parameter maps for a conventional *d*-wave superconductor (Δ, solid curve) and a partially gapped CDW metal (Σ, dashed curve).

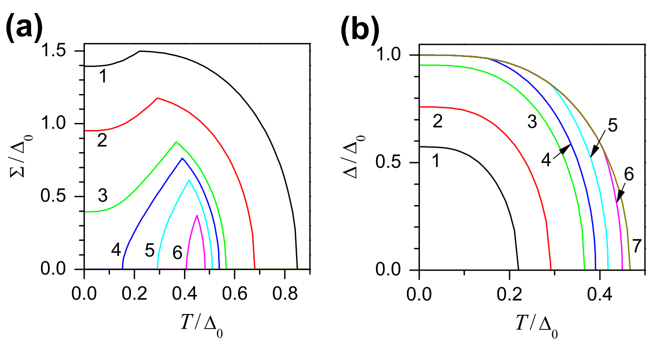

Fig. 2. (Color online) Temperature, *T*, dependences of the normalized (a) CDW Σ and (b) superconducting Δ gap functions. Δ_0 equal to $\Delta(T=0)$ when CDWs are absent is 1. The values of Σ_0 equal to $\Sigma(T=0)$ in the absence of superconductivity are 1.5 (1), 1.2 (2), 1 (3), 0.95 (4), 0.9 (5), 0.85 (6), and 0.8 (7); the control parameter μ of the CDW gapping is 0.3.

One sees that $2\Delta(0)/T_c$ sharply increases with Σ_0 for $\Sigma_0 \leqslant 1$ and swiftly saturates for larger Σ_0, whereas T_c/Δ_0 decreases almost evenly. The saturation value proves to be 5.2 for $\mu = 0.3$. We stress that such large enhancement of $2\Delta(0)/T_c$ agrees well with experimental data [8] for cuprates and *cannot* be achieved taking into account only strong-coupling electron–boson interaction effects for reasonable relationships between T_c and effective boson frequencies ω_E. At the same time, our weak-coupling model is *sufficient* to explain large $2\Delta(0)/T_c$ in cuprates. The μ-dependences of $2\Delta(0)/T_c$ and T_c/Δ_0 are shown in Fig. 3b. They illustrate that $2\Delta(0)/T_c$ can reach rather large values, if the dielectric gapping sector is wide enough. This growth is however limited by a drastic drop of T_c leading to a quick disappearance of superconductivity. We think that it is exactly the case of underdoped cuprates, when the decrease of T_c is accompanied by a conspicuous broadening of Δ. For instance, such a scenario was clearly observed in break-junction experiments for $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples in a wide doping range [9].

It should be noted that the coexistence of *d*-wave superconductivity with either *d*-like charge density waves [10] or staggered magnetization [11,12] was considered earlier. Nevertheless, our results are fundamentally different from those due to the suggested partial character of the dielectric FS gapping in our case. Such a character is dictated by the observed distinction between hot- and cold-spot behavior in cuprates.

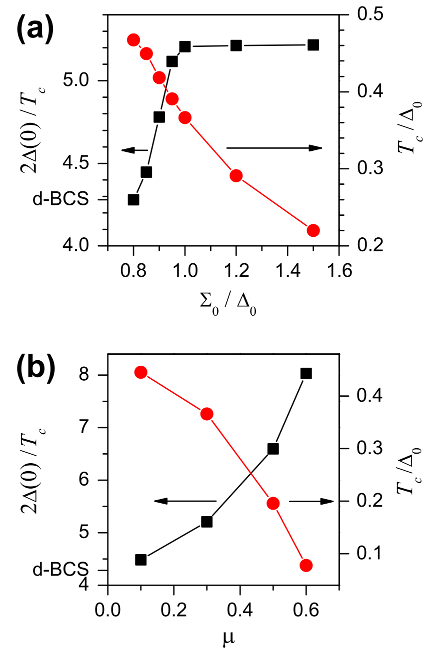

Fig. 3. (Color online) Dependences of $2\Delta(0)/T_c$ (squares) and T_c/Δ_0 (circles) on Σ_0/Δ_0 (panel a, $\Delta_0 = 1$, and $\mu = 0.3$) and μ (panel b, $\Delta_0 = 1$ and $\Sigma_0 = 1$). T_c is the superconducting critical temperature, *d*-BCS ≈ 4.28 is a value for a "pure" superconductor with *d*-wave symmetry of the order parameter.

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