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V.3

SUPERCONDUCTIVITY VERSUS ANTIFERERROMAGNETIC SDW ORDER IN THE CUPRATES AND RELATED SYSTEMS

Inhomogeneities and Electron Correlation

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Abstract: It is demonstrated that in the cuprates a dynamical, itinerant antiferromagnetic (AF)SDW state (with SDW/CDW stripe structure and d-wave SDW-gap (pseudogap)) is an additional, underlying order for the s-wave Cooper pairing (due to electron-phonon interaction) to appear at higher temperatures. The possible treatment of the nature of AF ordering observed in resistive state in recent neutron scattering experiments on the cuprates is presented. The effects in SC/SDW heterostructures with subnanolayers are discussed.

Key words: Stripe Structure, Spin Density Wave, Pseudogap, Electron-phonon Interaction, s-wave Symmetry, Spin Fluctuations

1. ANTIFERROMAGNETIC SDW PHASE TRANSITION BEFORE SUPERCONDUCTIVITY ONE IN THE CUPRATES

The problem of antiferromagnetic (AF) ordering in applied magnetic field observed at low temperatures in the high-T_c cuprates from neutron scattering [1] (and supporting picture from STM measurements [2]) is intensively discussed now. This AF ordering (spin density wave (SDW)) is considered as induced by applied magnetic field, and some theories for explanation of such phenomena was recently forwarded (see, e.g. [3]).

In this work it is demonstrated that itinerant AF SDW in the cuprates is not only competing with superconductivity (SC) order but it is an additional, underlying order which stimulates the SC to appear at higher temperature. The magnetic H-T phase diagram for the cuprates is formed : at low temperatures the SC coexists with SDW/CDW state while above $H_{c2}(T)$-boundary (with increasing T at given H [4] or with increasing H at given T [1,2]) the system enters the pure (non-superconducting) SDW/CDW state.

1.1 The phonon and magnetic contributions in electrical resistivity of the cuprates.

In fig.1 there are presented results of detailed analysis of resistive behavior for YBCO single crystal in the model where total resistivity ρ_{tot} is

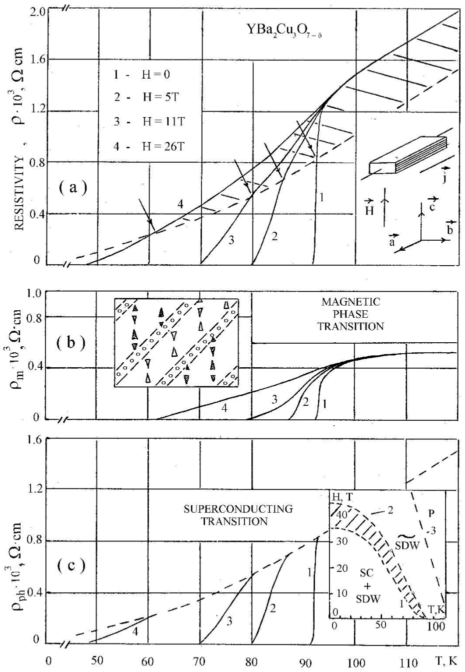

Figure V:3:1. Temperature dependence of the in-plane resistivity for YBCO single crystal [4] considered as sum of phonon contribution ρ_{ph} and magnetic (due to scattering by AF spin fluctuations) one ρ_m (usual model for magnetic metals) [5]. Phonon contribution $\rho_{ph}(T)$ (dashed curve in fig.1a and 1c) is well fitted by Bloch-Gruneisen curve with Debye temperature $\Theta_D \approx 400K$. The magnetic contribution $\rho_m(T)$ (shaded area in fig.1a) is temperature independent well in the normal state but with decreasing temperature it disappears at the "shoulder" temperature T_k (marked by arrows in fig.1a). Such disappearence is, in fact, evidence for modulated magnetic structure in the system. As it was noted before (see, e.g. [4]), such structure corresponds to SDW/CDW state with stripe structure with alternating spin and charge stripes in CuO_2-plane.

So, from analysis of $\rho_m(T)$- dependence ($\rho_m \approx const$ well in the normal state and $\rho_m = 0$ below shoulder temperature $T_k(H)$) it follows that there is a magnetic (AF SDW) phase transition before SC one in the cuprates (for details, see [4]). With decreasing temperature itinerant SDW/CDW state appears in the HTSC system with onset temperature $T_{SDW} \sim 120-150K$, depending on the family of compounds. At $T = T_{SDW}$ there appear both the stripe structure in CuO_2-plane with alternating spin and charge stripes and SDW-gap at symmetrical parts of the Fermi surface (treated usually as pseudogap (with $d_{x^2-y^2}-$wave symmetry)). In this temperature region, the spin-fluctuation scattering magnitude is high enough (transverse components in the fluctuation of local spin density, see e.g. [4]). At "shoulder" temperature spin-fluctuation scattering disappears and magnetically ordered state is completed and persists to zero temperature (SC + SDW/CDW state).

It must be noted that the slope of the linear region of the Bloch-Gruneisen curve is here considered as corresponding to the intermediate-temperature linear region (0.22 < T/θ_D < 0.43), which is universal for conventional metals [6]. Note, that the temperature dependence of this linear region of the $\rho_{ph}(T)$ curve for most metals may be described via approximative expression $\rho_{ph}(T)/\rho_1 \approx 0.275(T/\Theta_D) - 0.039$ and it steepness is somewhat higher than that for usually regarded high-temperature region of $\rho_{ph}(T)$ curve with $\rho_{ph}(T)/\rho_1 \approx 0.25(T/\Theta_D)$. (Here ρ_1 is a scaling parameter [4]). It is necessary to emphasize here that the linear dependence of $\rho_{ph}(T)$ for the intermediate-temperature region being extrapolated to $T = 0$ intersects the ρ axis in the point with negative ordinate in contrast to high-temperature one which, in fact, comes through the coordinate origin. It, in fact , denotes that the linear experimental ($\rho(T) \sim T$) dependence in the normal state, regarded now as characteristic for "good" single crystalline samples of HTSC, is not ruled out the presence of some temperature-independent contribution ρ_m in the total resistivity. It should be underlined that even at $H = 26\ T$ the onset point of SC transition (at $T_k(H)$) also falls in the Bloch-Gruneisen curve (though this curve already deviates from linearity, dashed curve in fig.1c) which fact evidents about applicability of the Bloch-Gruneisen theory to analysis of the HTSC system at $T < \Theta_D / 5$, too.

1.2 The magnetic phase H-T diagram for the cuprates.

Such a picture is supported by the magnetic phase *H-T* diagram for HTSC (see, insert in fig. 1c) formed from the data of fig. 1a. The abscisses of "shoulder" points at different values of applied magnetic field H plotted at the (*H,T*)-plane fall in a straight line (open circles at the lower part of dashed curve 2 in the insert of fig.1c) and considered as corresponding to the onset of the SC transition ($T_c^{onset}(H)$) form, in fact, temperature dependence of the upper critical magnetic field $H_{c2}(T)$. It is essential that there are no problem of the "upward curvature" usually discussed in literature but the dependence of $H_{c2}(T)$ appears to be linear in T near $T_c(0)$ as in the BSC and GL theories. (The "upward curvature" appears in the "$H_{c2}(T)$" dependences obtained, e.g. by "zero-point" methods (curve 1 in the insert of fig.1c). This curve does not correspond to the definition of the term "the upper critical magnetic field" in the type-II superconductors theory and may be considered as boundary between e.g. "vortex lattice" and "vortex liquid" phases). This linearity permits us to estimate the actual value of $H_{c2}(0)$. From the well-known relation: $H_{c2}(T) = H_{c2}(0)(1-(T/T_c)^2)$ it follows that this value is equal to $H_{c2}(0) = 45T$ (see curve 2 (corresponding to this formula) in the inset of fig.1c) what is well coincident with the data of direct measurements in the pulsed magnetic field of $H_{c2}(T \to 0) \approx 42T$ for H along c-axis (see, e.g. [4]). Note here, that from detailed analysis of the data on measurements of the magnetization in the reversible region it follows, in fact the same value for $H_{c2}(0)$ (for details, see [4]). This value of the upper critical magnetic field $H_{c2}(0)$ corresponds to the in-plane coherence length equal to $\xi_{ab} \approx 25\,\mathring{A}$.

On the other hand, the dependence of $T_k\ (H)$ is, in fact , $T_m^{order}\ (H)$ curve ($\rho_m = 0$), see fig.1b. In this sense, curve 2 and curve 3 (which corresponds to the onset of magnetic phase transition) form the magnetic phase $H-T$ diagram for the given HTCS system. So, below the $T_k\ (H)$ curve the HTSC system appears to be in the coexistence phase: SC and SDW, while above this $H_{c2}\ (T)$ curve the system is in the non-superconducting phase of SDW (modulated magnetic structure which wave number of modulation depends on both H and T (cf. with [4])). Above curve 3 corresponding to the pseudogap (SDW-gap in present treatment) onset temperature $T^*(H)$ (at $H > 60\ T$ at $T \to 0$ (see, e.g. [7]) or at $T >$ *120-150 K* in zero-field case) the system enters the spin-disordered, paramagnetic state.

2. ON THE SYMMETRY OF SC AND SDW/CDW ORDER PARAMETERS IN THE CUPRATES

The above picture is in a good agreement with the theory of itinerant electron systems with interplay between superconductivity and magnetism [8]. In that theory, an itinerant SDW gap may appear at the Fermi surface only before an SC gap, i.e. in the normal state. This SDW gap is highly anisotropic since it is only formed at symmetric parts of the Fermi surface [8] (see, fig.2). Its width Δ_{SDW} being unusually large for an SC gap , well conforms to that for an SDW gap because of inequality $\Delta_{SC} < \Delta_{SDW}$

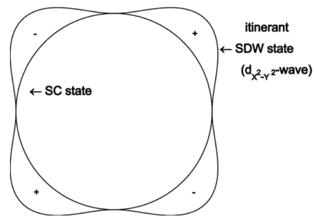

Figure V:3:2. Schematical sketch for coexistence of itinerant SDW and SC states in HTCS

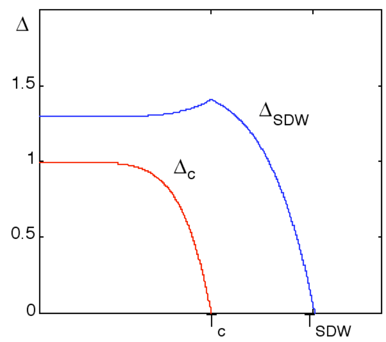

Figure V:3:3. Temperature dependence of SC and SDW order parameters in HTSC cuprates

which is peculiar for the coexistence phase in that model (fig.3). In such a case, the temperature T_c^{onset} (see, fig.1c) may be related to the appearance of the SC gap which begin develop at the Fermi surface only when the transition of the HTSC system to a magnetically- ordered state is over. Then, interrelations : $T_c^{onset} < T_{SDW}^{onset}$ (see, fig.3) and $T_c^{onset} = T_m^{order}$ (see, fig.1a) may be a natural consequence of the equality of magnetic ordering energy ε_m^{order} and the condensation pair one ε_c^{pair} considered as characteristic for such itinerant electron system with an interplay between SC and magnetism. Note here that namely such a picture was recently reported from elastic neutron scattering experiments [9] when in La-based cuprate both the SC and static magnetic order appear at the same temperature.

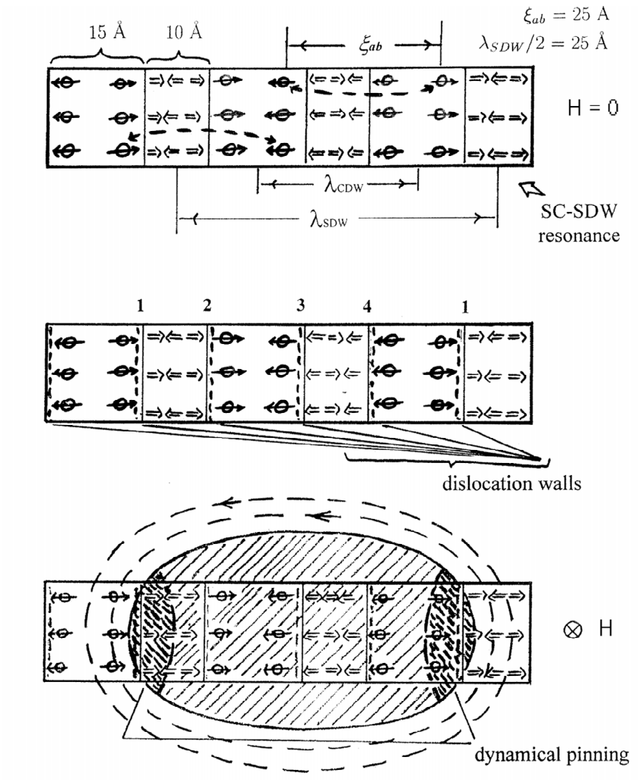

Figure V:3:4. Schematical stripe structure in the CuO_2 -plane

Then, from fig.1c it is seen that SC transition onset points $T_c^{onset}(H)(=T_k(H))$ are at the Bloch-Gruneisen curve (dashed curve). On the other hand, such a picture is characteristic for low temperature superconductors described by s-wave BCS theory. From this analogy it may be concluded that in the cuprates the SC order parameter is of s-wave symmetry, also. Moreover, as seen from magnetic phase *H-T* diagram, the

$H_{c2}(T)$-dependence (formed from SC transition onset points ("shoulder" points)) is linear in T near $T_c(H=0)$, which fact is also characteristic for s-wave BCS and GL theory. Note that such a conclusion about s-wave symmetry of the SC order parameter was supported by a new phase-sensitive test of the order parameter symmetry on the $Bi_2Sr_2CaCuO_{8+\delta}$ bicrystal c-axis twist Josephson junction, the experiment [10] which is considered the strongest one up to date.

The same conclusion follows from analysis of schematical stripe picture in the CuO_2-plane (see fig.4). According to numerical simulation in the Habbard model on a two-dimensional square lattice [11], the arrangement of each spin stripe is antiferromagnetic but two adjacent spin stripes are alternate so that in the CuO_2-plane it is formed SDW with wavelength $\lambda_{SDW} = 50$ Å. The width of stripes corresponds to those measured by Bianconi et al. [12]. This SDW is accompanied by CDW with wavelength equal to one half of that for SDW: $\lambda_{CDW} = \lambda_{SDW}/2 = 25Å$. Then, as it was obtained from insert in fig.1c, the in-plane coherence length $\xi_{ab} = 25$ Å (see above), so that there is SC-SDW resonance [13].

As it's seen from fig.3 (upper panel), for given stripe structure electrons in charge stripes (arrows with circles) are oriented by spin stripes (double arrows) in such a manner that two electrons at distance equal to coherence length $\xi_{ab} = 25Å$ can have only opposite directions of spin, which picture is characteristic for the Cooper pairing, i.e. in the s-wave BSC theory. The same result is for other electrons in given charge stripes. This orienting action of spin stripes to stabilize electrons (motion) in charge stripes provide condition for the Cooper pairing at higher temperature. In other words, the SDW ordering is an additional, underlying order for high-T_c superconductivity. In the absence of the SDW order at given temperature thermal fluctuations will destruct the coherent motion of pairing electrons so that pure phonon mechanism (BSC theory) is not able to provide s-wave Cooper pairing at this temperature.

In this concept, the observation of antiferromagnetic (SDW) order in applied magnetic field [1,2] is a direct consequence of restoring (or exposing) of underlying SDW order. In magnetic *H-T* phase diagram this observation corresponds to motion of (T,H) phase point along H axis (instead of motion along T axis in above resistive measurements (see, fig.1c).

In fig.3 (lower panel) it is schematically presented the structure of the SC vortex in the SDW/CDW + SC state. Since arising of the CDW results in the lattice modulation so that wave of dislocation walls is formed (fig.3 (middle panel)). As known, such dislocation walls are effective centers for pinning of SC vortices. Note that in such a structure every fifth wall is equivalent to first one ($c_{n+4} = c_n$). In this a model a vortex core has AF SDW structure which is also outside a core too. Because of equivalence of c_n and c_{n+4} dislocation walls vortex core becames to be two part in form fluctuating in space (cf. with [14]).

As for the SDW state, then according to the general theory of the SDW (see, e.g. [15]) such modulated state appears as due to the electron-hole pairing in the model of nesting electron and hole Fermi surfaces shifted by vector $\boldsymbol{q} = \boldsymbol{Q}$ in the reciprocal space, i.e. under translation at the nesting vector $\boldsymbol{Q}$ electron and hole surfaces appears to be superimposed. With nesting of the Fermi surfaces the system undergoes the magnetic phase transition in the SDW state with the SDW wave vector $\boldsymbol{Q}$ which appears to be incommensurate with lattice period. If nesting is total (for the whole Fermi surface), then the SDW system appears to be an AFM insulator but when only portion of the surfaces are nested then conductivity of the system is determined by other available for conduction (non-nested) parts of the Fermi surfaces. The condensation of electron-hole pairs with decreasing temperature results in the increase in resistivity but an additional decrease of the scattering rate for noncondensing carriers with decreasing temperature provides a further decrease of the total resistivity. These two opposite processes developing in the SDW system with decreasing temperature may lead to the appearance of a minimum or a shoulder at $\rho(T)$ curve under the SDW phase transition. The description of the SDW system (triplet electron-hole pairing) is in fact similar to that of superconducting system (singlet electron-electron Cooper pairing) in the BCS theory, so that temperature dependence of the SDW and SC gaps are in fact identical (see, fig. 3).

However, the influence of magnetic and nonmagnetic impurities appears to be opposite for the SC and SDW critical temperatures (T_c^{onset} and T_m^{order}, respectively). While influence of nonmagnetic impurities at depression of T_c^{onset} in the SC system is only negligible but in the SDW system normal impurities (say, *Zn*) produce the pair-breaking effect (for electron-hole pairs), the effect well known in excitonic semimetals. Such behavior is in fact analogous with the pair-breaking effect for magnetic impurities in the SC system. And vise versa, it is known that the depression of the ordering temperature in AFM metals with magnetic impurities (say, Fe) is only gradual. In the theory of the SDW (see, e.g. [15]) it is supposed that at low substitution level a single Fe atom may be coupled to the SDW (cf. with [4]) so that depression of T_c will be not so large. It is interesting to note that namely such (characteristic for the SDW) an effect of magnetic and nonmagnetic impurities is observed in the cuprates (cf. e.g. with [4]).

Then, note also that recently it was introduced a concept of so-called hidden order in the cuprates (see, e.g. [16]). Such an order is attributed to d-density wave (DDW) order. However, in their statement the type of this DDW order is not concrete but it is only considered as competing (not vital) order for SC one, moreover it is considered as corresponding to the superconductivity with $d_{x^2-y^2}$-wave pairing symmetry. As follows from above this concept may be described in terms of the (spin) density wave (S) (DW) with a $d_{x^2-y^2}$-wave symmetry accompanied by (charge) density wave (C) (DW) with $\lambda_{CDW} = \lambda_{SDW}/2$ (see above). The effects of these density waves (DW) are well known and the “hiddenness” of these (DW) in the cuprates may be of natural consequence of the dynamical nature of these (S) and (C) (DW) so that only fast and local probe (including resistivity measurements) permits to detect these (DW) concretely. Moreover, note that the picture of coexistence of triplet electron-hole pairing with SC one and possibility of arising of SC in the spin (DW) state below magnetic (SDW) ordering temperature was discussed before (see, e.g. [4] and fig.1).

It should be noted here that the conclusion about s-wave nature of the SC order parameter is consistent with conclusion about s-wave symmetry of the SC order parameter in the bulk and d-wave symmetry at the surface of the sample of the cuprates [17]. It was noted in [17] that most conclusions about d-wave symmetry was obtained in experiments (e.g. ARPES ones) on the cuprates in which mainly surface phenomena have been used. In this sense, the resistive measurements on the cuprates (see, e.g.[4]) are essentially bulk in the nature. In addition, the electron scattering (in resistivity measurements) is sensitive to the spin disorder in the system (magnetic contribution in the electrical resistivity appears, see Sec.1). Moreover, the electron scattering permits probe not only static magnetic order but dynamical (short-lived) ones because of short characteristic times as compared e.g. with usual neutron scattering.

3. ARTIFICIAL HETEROSTRUCTURES WITH SUBNANOLAYERS TO MODEL THE EFFECTS OF STRIPE STRUCTURE IN THE CUPRATES

Further, if the model is correct then artificial structures with nanolayers of metal and AFM insulator to model high-T_c superconductivity in the CuO_2 layer (fig.4) can be studied. Of course, such a structure is a 3D object

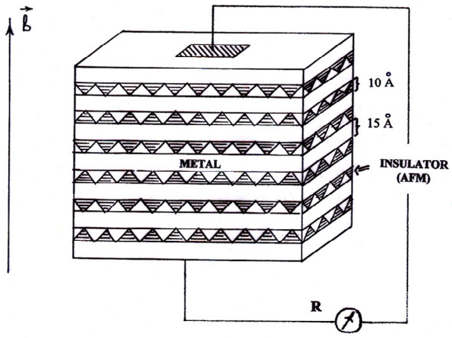

Figure V:3:5. Artificial nanostructure with SDW to model stripe structure in the cuprates

but it has a stripe structure in cross section. The study of temperature dependence of transverse resistivity in a magnetic field can give a contribution to the problem of high-T_c superconductivity. It is essential that such multilayered nanostructures are now available (X –ray mirrors, GMR-structures etc.).

On the other hand, it may be used a secondary effect, namely creation of deformation (distortion) wave in the copper oxide sample, which because of above should lead to the formation of CDW (and hence SDW) state in the volume of a sample with corresponding increase in T_c . It seems likely that namely such methods was used in [18] where thin (15 nm) film of LSCO was grown with block-by-block molecular epitaxy (defect-free growth process) on $SrLaAlO_4$ substrate which lattice period is only somewhat different from that of grown film. Such "incommensurability" results in corresponding deformation (distortion) within thin film and in twofold amplification of T_c ($T_c = 49.1K$) compared with the T_c of bulk compound ($T_c = 25K$). It is essential that in [18] it was noted the change in the $\rho(T)$ dependence in the normal state, characteristic for pseudogap (SDW gap in present treatment) and onset temperature for the pseudogap was noted.

Then, because of dynamical nature of stripe structure in CuO_2 planes there may be used the methods characteristic for solid-state plasma physics, e.g. formation of standing wave along $\vec{b}$ direction with using of, say, spin waves or another ones.

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