High-field evidence for the Bloch-Gruneisen curve in the cuprates

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A clear evidence for the Bloch-Gruneisen curve in the cuprates is obtained on the basis of recent resistive measurements in a transverse magnetic field $H=60T$. It is demonstrated that such magnetic field suppresses not only superconducting (SC), but also spin-density-wave (SDW) phase transition, preceding the SC one in the cuprates. This picture is consistent with the Fermi-liquid behavior of the electron system in the cuprates and thus with the *s*-wave BCS theory.

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A possible role of electron–phonon interaction (EPI) in the cuprates has been discussed since the discovery of high-T_c superconductivity (for review, see e.g., Refs. 1 and 2). As known, in conventional (LTSC) superconductors this interaction results in the electrical resistivity $\rho(T)$ in the normal state ($\rho \sim T$, at high temperatures) and provides Cooper pairing at low temperatures ($\rho \sim T^5$) in accordance with the *s*-wave BCS model.

However, already the first calculations[3] have demonstrated that phonon scattering (calculated for parameters of the cuprates) although providing the observed linearity of the normal-state $\rho(T)$-dependence in the optimally doped cuprates but the magnitude of the calculated phonon resistivity $\rho_{\rm ph}(T)$ is "much smaller than anything seen experimentally so far." Moreover, in the $Bi_{2+x}Sr_{2-y}CuO_{6\pm\delta}$ (BSCO) compound a strikingly linear $\rho_{ab}(T)$-dependence down to $T_c = 7$ K was claimed.[4] Such behavior is now considered as anomalous one and the EPI role in the cuprates remains to be open (for review, see e.g., Refs. 1, 2, and 5).

In the present work, it is demonstrated that recent experimental findings in a high magnetic field[6] certainly indicate to the Bloch-Gruneisen (BG) character of the normal-state behavior of resistivity (and dominant role of EPI) in the optimally doped cuprates down to near zero temperatures.

Figures 1 and 2 show a $\rho_{ab}(T)$-dependence for $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ and $La_{2-y}Sr_yCuO_4$ single crystals with optimal doping, respectively, in the transverse magnetic field $H=60T$ (symbols) as compared with the zero-field case (solid line).[6] As seen from Figs. 1 and 2, well above $T = T_c(0)$ the normal-state $\rho_{ab}(T)$ dependencies in both cases ($H=0$ and $H=60T$) are practically linear in T and coincide with each other [negligible (negative in sign) magnetoresistance (MR) effect]. But at some $T=T^*$ the $\rho_{ab}(T)$ dependencies at $H=0$ and at $H=60T$ begin to diverge: the zero-field $\rho_{ab}(T)$ dependence decreases with decreasing T down to $\rho_{ab}(T,0)=0$ (the SC transition), while the $\rho_{ab}(T,H=60T)$ dependence tends to be saturated at low T with a residual resistivity $\rho_m = \rho_{ab}(T\to 0, H=60T)$.

There are two main issues in such a picture. First, it was noted in Ref. 6 that "because the MR in the normal state is negligible," the $\rho_{ab}(T,H=60T)$ curve "represents the normal-state behavior at temperatures below T_c." If so, then the $\rho_m = \text{const}$ contribution in the total $\rho_{ab}(T,H=60T)$ resistivity is present in the entire T-range under consideration, so that its subtraction from ρ_{ab} yields the $\rho_{\rm ph}(T) = \rho_{ab}(T,H=60T) - \rho_m(H=60T)$ contribution (dashed curves in Figs. 1 and 2).

The second issue is that deviation of the $\rho_{ab}(T,H=60T)$ dependence from the zero-field $\rho_{ab}(T,0)$ one (see Figs. 1 and 2) begins in the region of $T=T^*$ corresponding to the onset T of formation of a pseudogap and a stripe structure in the CuO_2 plane observed in the cuprates.

Then, from Figs. 1 and 2 it follows that the $\rho_{\rm ph}(T)$ behavior (dashed curve in Figs. 1 and 2) can be fitted by the well known BG relation,[9]

$$\rho_{\rm ph} = \rho_1 \left(\frac{T}{\Theta_D}\right)^5 \int_0^{\Theta_D/T} \frac{x^5 dx}{(\exp(x)-1)(1-\exp(-x))}. \quad (1)$$

Here the scaling parameter ρ_1 is determined by the slope of the normal-state linear part of the $\rho_{ab}(T)$ dependence. It is essential to note here that in (1), in addition to the high-T linear region ($\rho_{\rm ph} \approx 0.25\rho_1 T/\Theta_D$), there exists an intermediate-T linear region ($0.22 \leqslant T/\Theta_D \leqslant 0.43$) with $\rho_{\rm ph} \approx 0.275\rho_1 T/\Theta_D - 0.039$, characteristic for most metals (including magnetic ones).[9] Namely, the latter, linear in T (not proportional to T), region corresponds to the normal state of the cuprates.[2–4,12] Note that (1) perfectly describes the $\rho_{\rm ph}(T)$-dependence of most metals at $T/\Theta_D \leqslant 0.22$ also, while at high temperatures it can be an essential contribution to resistivity from Umklapp processes (see, e.g., Ref. 9).

The characteristic Debye temperature (fitted by us from intermediate- and low-T parts of (1)) is $\Theta_D \approx 360$ K for

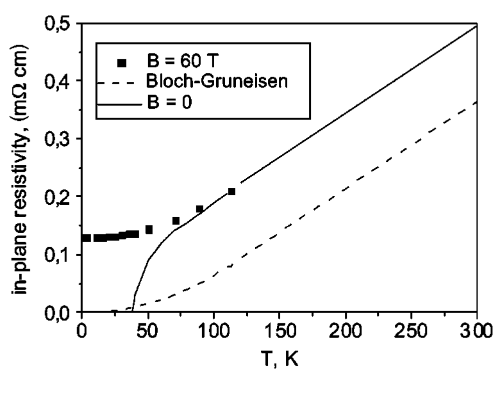

FIG. 1. Temperature dependence of ρ_{ab} for the BSLCO single crystal with optimal doping (after Ref. 6).

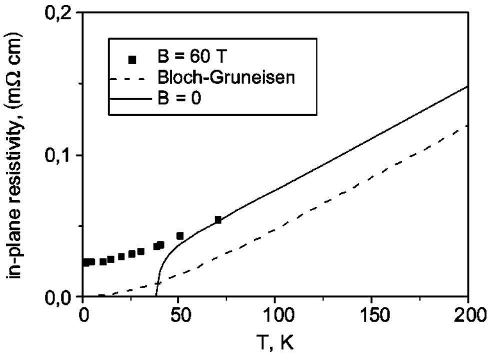

FIG. 2. Temperature dependence of ρ_{ab} in the LSCO single crystal with optimal doping (after Ref. 6).

BSLCO and $\Theta_D \approx 270$ K for LSCO single crystals whose values agree within ±5% accuracy (cf. with Ref. 4) with the available data from specific heat measurements for these compounds (see, e.g., Ref. 13).

In addition to the above procedure, it can be noted that, e.g., in transition metals, at very low temperatures, as known, it is observed T^2-contribution in resistivity which can include contributions from both *s-d* exchange and *s-d* transitions as well as contribution due to electron–electron scattering and it is very difficult to estimate their relative importance. Of course, this T^2-term being mixed with T^5-term leads to somewhat another temperature dependence of $\rho(T)$ but since magnitude of these contributions in zero-temperature region is small compared with that of normal-state "magnetic residual resistivity" (so, e.g., for Ni such T^2-term in the resistivity at $T=1$ K is of the order of $10^{-11}\ \Omega$ cm, see, e.g., Ref. 10) then their effect is out of accuracy frames of given phenomenological analysis (cf. with scale of ρ-axis in Figs. 1 and 2). (Of course, the very low temperature resistivity effects are the field of special interest but this field is beyond the scope of the present investigation.)

As an additional argument for such a picture in the cuprates it can be considered the appearance of SC (due to EPI in present treatment) in the system well above zero temperature at $H=0$ (see solid lines in Figs. 1 and 2). Such behavior is consistent with that in Ref. 11 where it was demonstrated that "the residual electron–electron interaction is of quite short range, so that an independent-particle treatment is rather well justified." Because of this "the effects of Coulomb correlations on SC" (due to EPI) "are small, so that the neglect of Coulomb interactions in the formulation of the SC problem is justified."

Then, in our earlier work[7] it was suggested that the ρ_m contribution in the normal-state resistivity ρ_{ab} has a magnetic nature (cf. with Ref. 3): parent compounds for SC cuprates are antiferromagnetic (AFM) insulators, and under doping the AF spin fluctuations persist in the SC compounds providing an effective channel for scattering of mobile charge carriers in the normal state. Note that the above decomposition procedure $(\rho_{\mathrm{tot}}(T)=\rho_{\mathrm{ph}}(T)+\rho_m(T))$ is usual for magnetic metals.[10]

As seen from Figs. 1 and 2, well above $T=T_c(0)$ the magnitude of ρ_m is high enough and nearly T-independent [cf. with Fig. 3(b)]. This behavior is consistent with the

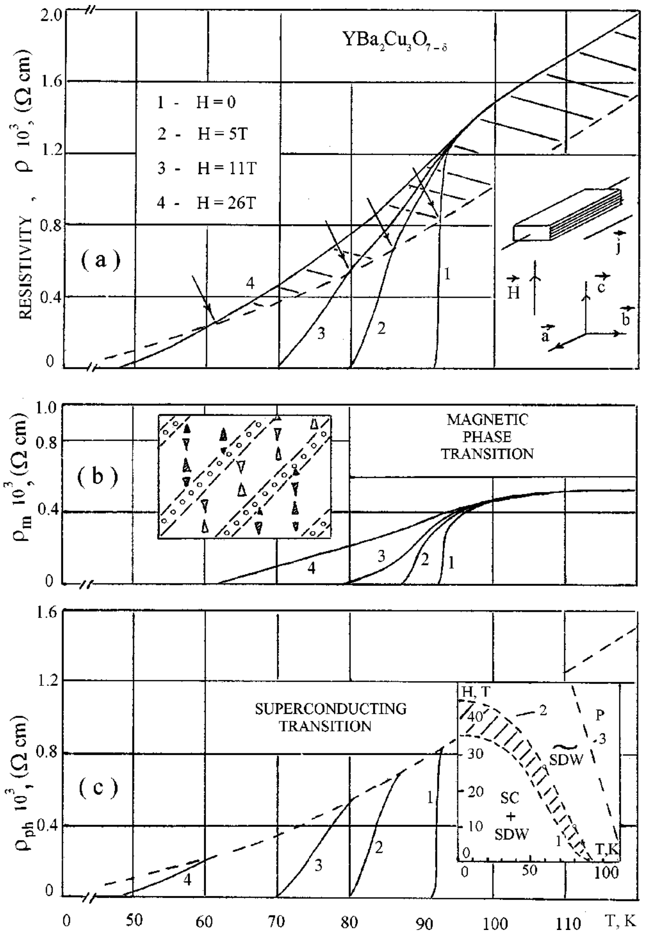

FIG. 3. (a) Shows in-plane $\rho(T)$ curves (solid lines) from Ref. 8. The arrows indicate the "shoulder" points at $T=T_k(H)$. The total resistivity ρ_{tot} is here considered as a sum of two contributions: phonon $\rho_{\mathrm{ph}}(T)$ [dashed curve corresponding to (1)] and magnetic scattering $\rho_m(T)$ ones (shaded area). The inset shows the geometry of experiment. (b) Shows $\rho_m(T)$ dependencies (solid lines) [see shaded area in Fig. 1 (a)]. The decrease in $\rho_m(T)$ (sharp drop at $H=0$) from $\rho_m=$const at $T \geqslant T^* = T_{\mathrm{SDW}}^{\mathrm{onset}} \approx 120$ K to zero $(\rho_m=0)$ at $T=T_k(H)=T_{\mathrm{SDW}}^{\mathrm{order}}$ ("shoulder" point) is here treated as evidence of magnetic (AF SDW) phase transition before SC transition in the cuprates. The inset shows a schematic view of the SDW/CDW state in the CuO_2-plane. (c) Shows phonon contribution in resistivity (solid lines), dashed curve corresponds to (1). It is seen that in the present treatment the SC transition starts only at $T=T_k(H)=T_{\mathrm{SDW}}^{\mathrm{order}}(H)=T_c^{\mathrm{onset}}(H)$ ("shoulder" point). The inset shows $T_c^{\mathrm{onset}}(H)$ dependence plotted from "shoulder" points (curve 2) with $H_{c2}(0)=45T$ as compared with the $T_{zp}(H)$ dependence from zero-resistance [$\rho=0$, Fig. 3(a)] points (curve 1). Curve 3 represents the proposed $T^*(H)=T_{\mathrm{SDW}}^{\mathrm{onset}}(H)$ dependence for this system (see, also Ref. 7).

T-independent scattering of mobile charge carriers by localized magnetic moments (LMM) in the paramagnetic (PM) region for magnetic metals and alloys (see, e.g., Ref. 10):

$$\rho_m = \frac{(m/m_0)^2 N G^2 s(s+1)}{(\pi/3)^{1/3} e^2 h^3} n^{-2/3}, \qquad (2)$$

where G is the coupling constant, s is the spin of fluctuating LMM, N is the effective number of these LMM in unit volume, m and n are the effective mass and density of mobile charge carriers, respectively. It is seen from Figs. 1 and 2 that the magnitude of ρ_m in the normal state is near $\rho_m \approx 1.3 \times 10^{-4}\ \Omega$ cm and $\rho_m \approx 2.5 \times 10^{-5}\ \Omega$ cm for BSLCO and LSCO single crystals, respectively; such values seem to be reasonable for magnetic metals and alloys.[15] Note that these estimations do not take into account the zero-T residual resistivity ρ_{res}, arising, e.g., because of possible disorder due to the doping procedure, since according to the BG-fit with the data from Fig. 3 (see, Ref. 7) the value of ρ_{res} is negligible as compared with that of normal-state magnetic contribution ρ_m.

On the other hand, with a decreasing T, the magnetic contribution $\rho_m(T,0)=\rho_{ab}(T,0)-\rho_{ph}(T)$ disappears at $T=T_k(0)$ corresponding to the intersection point of the $\rho_{ab}(T,0)$ dependence and the BG one (dashed curve); see Figs. 1 and 2.

Such a behavior of $\rho_m(T)$ [cf. with Fig. 3(b)] indicates[10] to a phase transition in the magnetic subsystem of the cuprates from spin-disordered ($\rho_m \approx$ const in the normal state) to the magnetically-ordered state ($\rho_m=0$) with a modulated magnetic structure [like the spin density wave (AF SDW)][14,16] coexisting with the SC at $T \leqslant T_k(H)$. As follows from the analysis of literature data available at the time (see, Ref. 7), the SDW in the system is realized in the form of a quasistatic stripe structure in the CuO_2-plane [see the inset in Fig. 3(b)] when magnetic stripes (triangles) alternate with charge stripes (circles) [charge density wave (CDW) accompanying the SDW with a wavelength $\lambda_{CDW}=\lambda_{SDW}/2$] (see, also the review Ref. 17).

So, in the intersection point $T=T_k(H=0)$ in Figs. 1 and 2 [cf. with "shoulder" points marked by arrows in Fig. 3(a)], the transition of the HTSC system to the magnetically-ordered (SDW) state is over and the SC transition starts $[T_k(H=0)=T_{SDW}^{order}(0)=T_c^{onset}(0)]$ (cf. with recent elastic neutron scattering[18] and specific heat[19] results). Moreover, the "shoulder" points plotted in the $H-T$ plane fall in the linear part of the $H_{c2}(T)$ curve with $H_{c2}(0)\approx 45T$ ($\xi_{ab}\approx 25$ Å) [see inset in Fig. 3(c)] whose linearity near $T_c(0)$ is characteristic for the s-wave BCS and GL theories.

The picture obtained was not unexpected: from the theory of itinerant electron systems with interplay between the SC and magnetism[20] it follows that with a decreasing T the SDW-gap is formed in symmetrical parts of the Fermi surface (FS) before the SC gap (see Fig. 4) with the magnitude $\Delta_{SDW} > \Delta_{SC}$ (see Fig. 5). Such anisotropy of the SDW-gap with a large energy scale is in agreement with the $d_{x^2-y^2}$-wave symmetry of the pseudogap with onset at $T=T^*$ ($=T_{SDW}^{onset}$, in our treatment) observed in many experiments (for review, see, e.g., Ref. 21). Since the pseudogap also persists in the SC state, its d-wave symmetry mimics the symmetry of the order parameter measured in the SC state (e.g., using of ARPES-technique or tunnel experiments),[22] while a genuine SC order parameter remains to be s-wave in nature. Note that such a conclusion was then 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[23] which is still considered the strongest one up to date. In addition, the s-wave symmetry of the SC order parameter was drawn in Ref. 24 on the basis of analysis of thermodynamic, transport, and other properties of the cuprates.

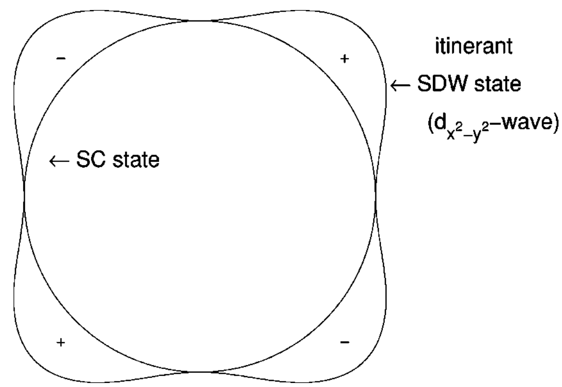

FIG. 4. Schematic sketch for coexistence of itinerant SDW and SC states in the cuprates.

According to the theory of itinerant electron magnetism,[25] the T-independence of ρ_m well above $T=T_c(0)$ was described in Ref. 7 in terms of so-called T-induced localized magnetic moments (LMM). Note that such T-induced LMM were studied in a number of magnets. As shown in Ref. 25, such LMM, when both amplitude and orientation fluctuate in time, arise in the itinerant electron system due to saturation of the amplitude fluctuations of the local spin density (FLSD) above some characteristic temperature T^*, when the transverse components become dominant in the FLSD spectra (self-organization process). On the other hand, decrease of ρ_m down to zero with a decreasing T was considered in Ref. 7 as a consequence of the disappearance of transverse components in the FLSD spectra of the HTSC magnetic subsystem. Then, the value of T^* was attributed in Ref. 28 to the onset temperature T_{SDW}^{onset} for the itinerant SDW state.

So, at $T \geqslant T^*$ (ρ_m=const, T-induced LMM regime) the MR effect is *negative* in sign and negligible in magnitude (as in the PM state of ordinary magnets), due to the linearity of the Langevin formula in this temperature region (cf. with Ref. 26).

On the contrary, at $T < T^*$ (SDW regime), when the amplitude of FLSD is out of saturation, the transverse magnetic field H leads to a *positive* MR effect due to enhancement of spin fluctuations in a magnetic field characteristic for AFM

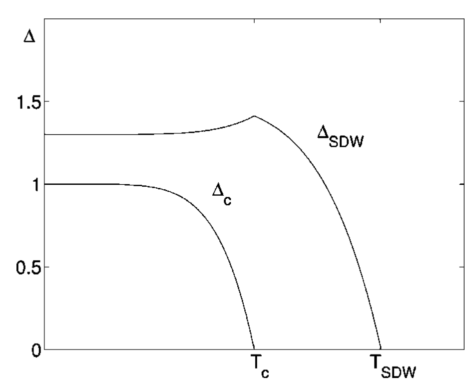

FIG. 5. Temperature dependence of the SC and SDW order parameters in the cuprates (scheme).

systems (see Ref. 7). This enhancement can restore the T-induced LMM regime in the HTSC system. However, the value of H should be high enough: first, to suppress SC ($H > H_{c2}(0)$) and, second, to enhance the spin fluctuations up to saturation of the FLSD amplitude [cf. with depression of T_{SDW}^{order} in Fig. 3(b)]. The value of $H=60T$ satisfies this condition: it is higher than $H_{c2} \approx 45T$ (see Fig. 1 in Ref. 6) and there is saturation of the positive MR effect specifically at $H \geqslant 60T$. Note that the data in Ref. 6 represent the normal-state behavior not only at $H=60T$ (as concluded in Ref. 6) but for $H \geqslant H_{c2} \approx 45T$ as well.

Suppression of the SDW-state [including the SDW-state in the vortex cores (normal state) of HTSC (cf. with Ref. 29)] suggests (in our treatment) disappearance of both the stripe structure in the CuO_2 plane and the pseudogap [SDW-gap (Refs. 22 and 28)]. Such closing of the pseudogap due to the Zeeman splitting in a high magnetic field ($H \geqslant 60T$) was actually reported in a recent work.[27] This splitting, in our model, results in an $e-h$ pairbreaking effect for the CDW, thus suppressing the SDW-state (see Ref. 28).

Note that the earlier attempts to estimate the normal-state value of ρ_{ab} in both $H \to \infty$ (Ref. 30) and $H \to 0$ (Ref. 31) extrapolation limits take no into account the positive MR effect, so, only BG-like (rather than a genuine BG) curves were obtained.

As for the metal-to-insulator crossover studied in Ref. 6, in underdoped samples an increase in $\rho_{ab}(T \to 0, H=60T)$ (see Fig. 2 in Ref. 6) is (in our treatment) due to that in $\rho_m(T,H) = \rho_m^{SDW} + \rho_m^{scat}$, where ρ_m^{SDW} and ρ_m^{scat} are contributions from the SDW-gap formation in the nesting parts of the FS ($e-h$ pair condensation) and from other (conduction) parts of the FS (scattering of noncondensed in $e-h$ pairs carriers), respectively.

Note that the unusual metallic behavior of a Bi-based compound down to $T_c = 7$ K, considered now as evidence against EPI mechanism in the cuprates, can also be explained here. Since at $T/\Theta_D < 0.2$ the BG curve deviates from linearity a $\rho_m(T)$ decrease with decreasing T [like that in Fig. 3(b)] can compensate for this deviation down to low T_c requested [$\rho_m(T)=0$; see Figs. 1–3]. So, for the sample of BSCO with a linear low-T behavior of ρ_{ab},[4] it follows that $\Theta_D \approx 220$ K from our BG fit (cf. with $\Theta_D^* \approx 35K$ in Ref. 4). Moreover, a very weak upturn in the behavior of ρ_m at low T can mimic also the BG-like curve with a high residual resistivity before the SC transition at $T_c \approx 3$ K.[6,32]

Another fact which is also considered as argument against the EPI mechanism of HTSC is (near) zero isotope effect in YBCO. But as it was noted yet in Ref. 33 (see, also recent reviews, Refs. 34 and 35) absence of isotopic effect (and even negative isotope effect) can be a natural consequence of small-scale static and dynamic structure disorder when microdomains separated by the domain wall (cf. with stripe structures, see above) are formed in nonmonoatomic media at low temperatures. Also, there are a number of questions on technological procedure during oxigen atoms replacement as well as a role of the sample surface in this process (see, e.g., Ref. 36). Moreover, recently, a pronounced site-selective oxygen-isotope effect on the transition temperature T_c as well as on the in-plane penetration depth in Y-based compounds was observed using the muon-spin rotation technique. The result clearly indicates a strong coupling of the electronic subsystem to phonon modes involving movements of the oxygen atoms in the CuO_2-plane. Their finding implies that even in optimally doped cuprate superconductors for which only a small isotope effect on T_c was observed, the supercarriers are strongly coupled to the lattice (see Ref. 37). Such observation additionally supports the conclusion that phonons are at the "core" of possible pairing mechanism but, according to our treatment, around this "core" it is a SDW/CDW state (additional order parameter) which provides conditions for pairing due to phonons at so high temperatures. As for the problem of lattice stability then it was in detail discussed in Ref. 1 and 2 and in Ref. 41.

In conclusion, high-field evidence of the BG behavior of a phonon contribution in resistivity is obtained. Such a conclusion indicates to the Fermi-liquid behavior of the electron system in the cuprates, discussed in the literature (for review, see Refs. 2 and 38–40) and, hence, to the s-wave BCS picture with Cooper pairing due to EPI. The conditions for such pairing at higher temperatures seem to be provided by formation of an additional order (cf. with Refs. 38 and 41) (SDW/CDW state, dynamical in nature) in the cuprates well before the SC transition.

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