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IN THE NEW SUPERCONDUCTORS

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On the linear temperature dependence of the resistivity
in the new superconductors

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Abstract

We present an elementary proof that, irrespective of dimensionality, the electrical resistivity of a simple conductor should be linear with temperature if $T > 2P_F s/\hbar \ll \theta_D$ if $P_F \ll a$, where P_F is the Fermi momentum, s the speed of sound, a the lattice constant, and θ_D the Debye temperature.

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The properties of the new high- T_c superconductors¹ have attracted widespread interest over the last year. In particular, it has been felt by many researchers that the electrical resistivity in the normal state in some samples is linear over too-wide a range of temperature². Indeed, in well-oxygenated samples³ this linear dependence starts right at the transition temperature and extends, with a constant slope, to the highest temperatures that have been measured, 1100K. The absence of saturation at high temperatures means that the electron mean-free-path is still longer than the lattice constant at those temperatures, and at low temperatures should be much longer than the extremely short coherence lengths which have been deduced⁴ for these materials, which should accordingly be treated as clean superconductors⁵. What is deemed to be unusual about the linear temperature behavior of the electrical resistivity is that, while it is the expected one for temperatures larger than θ_D , the Debye temperature of the solid, if it is due to electron-phonon interaction, in these materials it can start at temperatures markedly lower than θ_D . The situation is specially striking in first generation high- T_c superconductors, with their lower transition temperatures: in Fig. 1 we show a typical resistivity curve for $\text{La}_{1.9}\text{Sr}_{0.2}\text{CuO}_4$ taken from reference 3. The Debye temperature, as obtained from low-temperature specific-heat measurements⁶ or independently, from ir and Raman measurements⁷ is shown on the T axis. The slight upturn at high temperatures is attributed⁸ to loss of oxygen over the finite time taken by the resistivity measurements.

Recently, Micnas, Ranninger and Robaszkiewicz² have addressed this problem: they find that this behavior might be linked to the two-dimensional character of electrical conduction (along Cu-O₂ planes) in these materials⁹, provided that the Fermi momentum, P_F , is much less than $\pi\hbar/a$, where a is the lattice constant. They find that under these conditions, whenever the temperature is higher than $T^* = 2sp_F/k_B \ll \Theta_D$, where s is the speed of sound in the medium, a linear temperature dependence of the resistivity should be observed.

We shall show in this note, using the simplest arguments, that the above defined T^* should replace Θ_D in determining the different temperature regimes for the electrical resistivity, in agreement with Micnas et al². It will be evident from our arguments that the results need not be restricted to two-dimensional systems, and that dimensionality is in fact irrelevant in this context.

For the sake of simplicity we shall work with the same assumptions as Micnas et al²: quasi free electrons with a parabolic dispersion relation and Fermi velocity V_F ; and Debye phonons with speed of sound s . That $V_F \gg s$ is well known^{6,7,10}.

Electron-phonon interactions cause the electric current carried by electrons with momentum $\underline{p}$ and energy $\epsilon(\underline{p})$ to decay at a rate given by¹¹

$$\Gamma(\epsilon_{\underline{p}}) = \int \frac{d^D \underline{q}}{(2\pi)^{D-1}} |\mathbf{v}(\underline{p}-\underline{q})|^2 \left(1 - \frac{\underline{p} \cdot \underline{q}}{p^2}\right) \left\{ \left[N(\omega_{\underline{p}-\underline{q}}) + 1 - f(\epsilon_{\underline{q}}) \right] \delta(\epsilon_{\underline{q}} - \epsilon_{\underline{p}} + \omega_{\underline{p}-\underline{q}}) \right.$$

$$+ \left[N(\omega_{\vec{p}-\vec{q}}) + f(\epsilon_{\vec{q}}) \right] \delta(\epsilon_{\vec{q}} - \epsilon_{\vec{p}} - \omega_{\vec{p}-\vec{q}}) \quad (1)$$

where $\omega_{\vec{q}}$ is the energy of a phonon with momentum $\vec{q}$, $N(\omega)$ and $f(\epsilon)$ are equilibrium Bose and Fermi distribution functions at temperature T respectively, and $v(\vec{k})$ is the electron-phonon scattering matrix element. D is the dimensionality of the system.

In normal situations, the only temperature scale in expression (1) is provided by the Debye temperature θ_D : There are no phonons with energies larger than $k_B \theta_D$. The second energy entering (1), the chemical potential of the electrons ϵ_F , is so much as to be irrelevant at ordinary temperatures. Consequently, there are two distinct regimes in $\Gamma(\epsilon_{\vec{p}})$ (and also in the electrical resistivity $\rho(T)$, as its calculation from $\Gamma(\epsilon_{\vec{p}})$ entails no energy constants other than ϵ_F): For $T \ll \theta_D$, as T is raised, new, more energetic phonon modes come into play which cause wider-angle electron scatterings, thus increasing their efficiency to relax the electric current. The result is the well known T^5 (in 3D, or T^4 in 2D) dependence of $\rho(T)$ at low temperatures. For $T \gg \theta_D$ all phonon modes are classically excited, electron scattering by phonons is as wide-angle as it can be, and raising the temperature only produces more processes of the same kind. The number of processes increases linearly with temperature, and the linear regime in $\rho(T)$ is obtained.

The time-proven Grüneisen-Bloch relation¹²

$$\rho(T) = C \left(\frac{T}{\theta_R} \right)^5 \int_0^{\theta_R/T} \frac{x^5 dx}{(e^x - 1)(1 - e^{-x})} \quad (2)$$

gives a useful interpolation between these two regimes in terms of only one parameter (C is scale factor), the temperature θ_R . For most metallic elements this θ_R coincides with θ_D within a factor of two (even within 20% in most cases)¹³.

Consider now what happens if we assume that $p_F \ll \frac{\hbar \pi}{a}$, i.e. that the Fermi surface is much smaller than the Brillouin zone. The conservation relations that electron-phonon collisions must satisfy should be studied now. Energy conservation is explicitly contained in the delta functions in (1). In normal processes, momentum is also conserved. Figure 2 shows which phonons may be either absorbed or emitted by an electron with initial momentum $\underline{p}$ ¹⁴. Neglecting terms of order $s/v_F \ll 1$, we see that phonons with momenta larger than $2p$ cannot interact with such an electron.

At temperatures much lower than the Fermi temperature ϵ_F/k_B , the only electrons which contribute to the transport of electrical current are in a narrow energy region around ϵ_F . This implies that phonons with momenta larger than $2p_F$ do not contribute to normal scattering processes. Although such phonons lead to valid Umklapp processes, these will be exponentially scarce if $T \ll \theta_D$, as discussed by Micuas et al², and can be safely neglected.

If phonons with momenta larger than $2p_F$, or energies larger than $2p_F s$, cannot take part in electron scattering, the electrical resistivity should behave as if they were not there: its temperature dependence will be that of a solid with $\theta_D \approx 2p_F s/k_B$. This was obtained in reference 2; we can see that dimensionality is not relevant.

The Grüneisen-Bloch temperature should then be given, within a factor of two, by

$$\theta_R \simeq \min[\theta_D, 2p_F s/k_B]$$

and as $\theta_D \simeq \frac{\hbar v_s}{k_B a}$, we have

$$\theta_R \simeq \theta_D \min \left[1, p_F a / \hbar \right] \quad (3)$$

This result is easily generalized to non-spherical Fermi surfaces: $p_F a / \hbar$ in (3) is basically the ratio between the "diameters" of the Fermi surface and the first Brillouin zone.

Does (3) allow us to derive any conclusion on the size of the Fermi surface in, say, La-Sr-Cu-O? Not really. Although it would be tempting to conclude from the fact that La-Sr-Cu-O shows a linear resistivity for $T \geq 40K$ and a $\theta_D \simeq 400K$ ^{6,7} that $p_F a / \hbar \leq 0.1$, the conclusion would be unwarranted (albeit probably true²). The fact is that in normal conductors the linear regime extends very often to temperatures rather lower than θ_D . This is shown in the standard Grüneisen-Borelius relation¹⁵: $\rho(T)/\rho(\theta_R)$ is linear in T/θ_R for $T/\theta_R \geq 0.2$ for isotropic metals. Deviations do occur. In addition to this, θ_R can be markedly lower than θ_D . Some examples contained in Meaden's monograph¹³ should suffice: for calcium $\theta_R/\theta_D \simeq 0.65$; for uranium 0.62, for Zn 0.71. A linear behavior starting at $0.15\theta_D$ does not constitute an exception, and for none of these metals can we draw the above conclusion.

There is another factor that should be taken into account:

the Debye temperature of La-Sr-Cu-O is taken as 400K in order to obtain the right specific heat at high temperatures. It has to account for the 21 phonon branches. The Debye temperature from low-temperature specific heat⁶ which takes into account only the three acoustical branches, is nearer 200K, and this would be more appropriate for comparison in (3).

We conclude that, while the existence of a small Fermi surface in the center of the first Brillouin zone should extend downwards, due to the conservation rules for electron-phonon processes, the range of linear temperature dependence of the resistivity, the available data for La-Sr-Cu-O do not allow one to draw useful conclusions, either about the size of its Fermi surface, or about the dimensionality of the system that effectively conducts the electricity in this material. For Y-Ba-Cu-O, with its lower θ_D and higher T_C , the same conclusion applies.

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References

- 1) J.G. Bednorz and K.A. Müller, Z. Phys. B64, 189 (1986).
- 2) R. Micnas, J. Ranninger, and S. Robaszkiewicz, Phys. Rev. B36, 4051 (1987).
- 3) D.A. Esparza, C.A. D'Ovidio, J. Guimpel, E. Osquiguil, L. Civale, and F. de la Cruz, Solid State Comm. 63, 137 (1987).
- 4) E. Osquiguil, R. Decca, G. Nieva, L. Civale, and F. de la Cruz, Solid State Comm. 65, 491 (1987).
- 5) F. de la Cruz, L. Civale, E. Osquiguil, H. Safar, R. Decca, D.A. Esparza, and C.A. D'Ovidio in IX Winter Meeting on Low Temperature Physics of High- T_c Superconductors, Mexico 1988.
- 6) G. Nieva, E.N. Martinez, F. de la Cruz, D.A. Esparza and C.A. D'Ovidio, Phys. Rev. B36, ... (1987).
- 7) T. Brun, M. Grimsditch, K.E. Gray, R. Bhadra, V. Maroni, and C.K. Loong, Phys. Rev. B35, 8837 (1987).
- 8) E. Osquiguil, L. Civale, R. Decca, and F. de la Cruz, unpublished.
- 9) J.D. Jorgensen, H.B. Schüttler, D.G. Hinks, D.W. Capone II, H.K. Zhang, and M.B. Brodsky, Phys. Rev. Lett., 58, 1024 (1987).
- 10) K.W. Kwok, G.W. Crabtree, D.G. Hinks, D.W. Capone II, J.D. Jorgensen, and H.K. Zhang, unpublished.
- 11) K. Baumann and J. Ranninger, Ann. Phys. (N.Y.) 20, 157 (1962).
- 12) E. Grüneisen, Ann. Physik 16(5), 530 (1933).
- 13) G.T. Meaden, "Electrical resistance of Metals", Plenum, New York, 1965.

- 14) N.N. Ashcroft and N.D. Mermin, "Solid State Physics", Holt, Rinerhart and Winston, New York, 1976.
- 15) A.N. Gerritsen, Handbuch der Physik, p.137, Springer, Berlin, 1956.

Figure Captions

Figure 1: Electrical resistivity vs. temperature for optimally-oxygenated $\text{La}_{1.8}\text{Sr}_{0.2}\text{CuO}_4$ sample. The Debye temperature θ_D is marked on the T-axis.

Figure 2: One-phonon scattering of electron with initial momentum p . The tips (tails) of allowed phonons lie on the full outer (inner) energy surface for phonon absorption (emission). The ϵ_p constant energy surface is shown by a dotted line. The ratio s/v_F is vastly exaggerated, to 0.1.

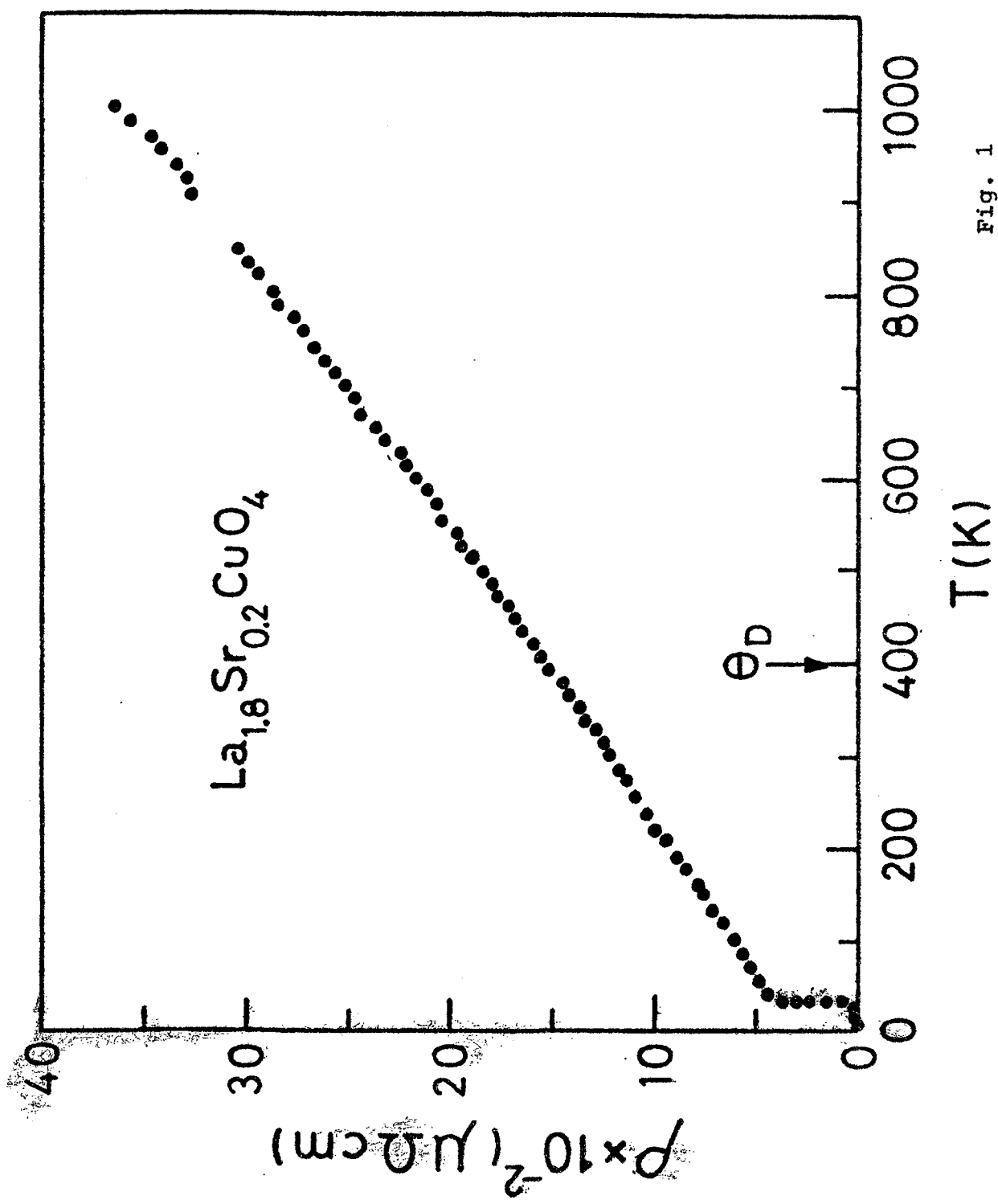
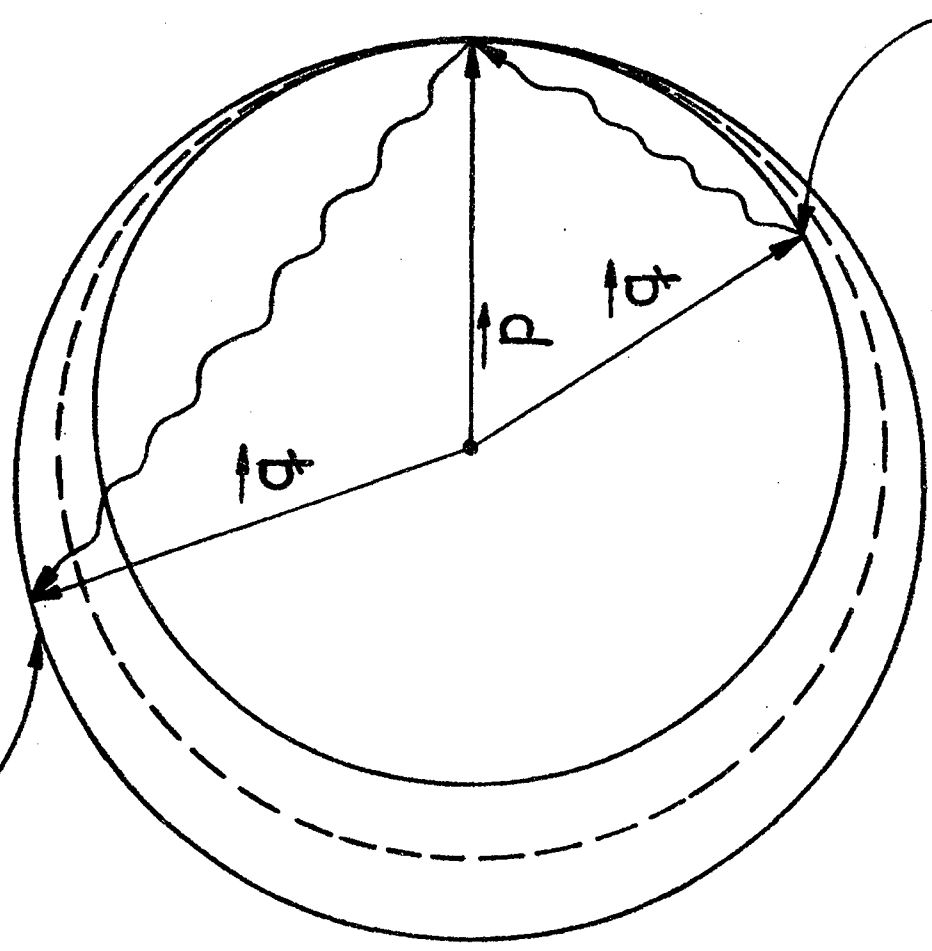


Fig. 1

absorption $\epsilon_{\vec{q}} = \epsilon_{\vec{p}} + \omega_{\vec{p}-\vec{q}}$



emission $\epsilon_{\vec{q}} = \epsilon_{\vec{p}} + \omega_{\vec{p}-\vec{q}}$

Fig. 2

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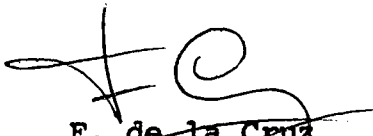
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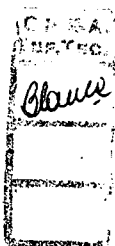
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