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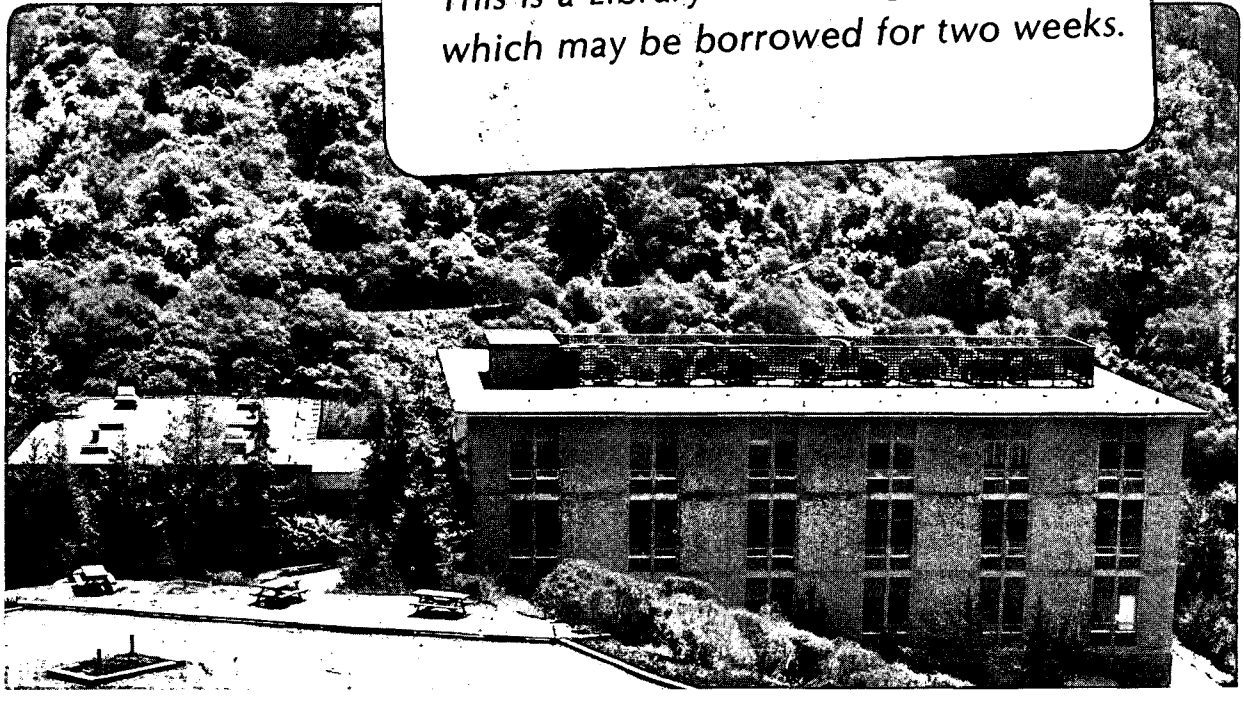

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EXOTIC NORMAL AND SUPERCONDUCTING PROPERTIES OF HIGH T_c OXIDES AND SMALL E_f*

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ABSTRACT

A key feature of the high T_c oxides is a very small value of the Fermi energy. This feature leads to peculiar thermodynamic and transport properties in the normal and superconductive state.

Introduction. A small value of the Fermi energy in the new high T_c oxides [1, 2] and its consequences form the essence of this paper. Of course, it means that these new materials can be described by general Fermi liquid approach with the concept of a Fermi surface. Recent positron annihilation data [3] indeed show the existence of the Fermi surface in Y-Ba-Cu-O. Furthermore, the results obtained in [3] are in agreement with our previous theoretical analysis. [4]

Fermi Energy. In this section we are going to focus on the value of E_f. It will be shown that the new oxides, indeed, have a small value of E_f relative to conventional superconductors. In conjunction with a high T_c this leads to a number of peculiar features. Our approach is based on the analyses of heat capacity, critical behavior, thermal conductivity, etc.

New high T materials are highly anisotropic systems. For example, $\sigma_\perp/\sigma_\parallel \simeq 10$ for La-Sr-Cu-O [5]. The dispersion relation $E(\vec{p})$ is anisotropic and as a result, the Fermi surface $E(\vec{p})=E_f$ has a cross section that is far being spherical.

The Fermi surface of La-Sr-Cu-O has an almost cylindrical shape. [4] Small deviations from this shape are connected with interlayer transitions. The Fermi energy can be calculated from the expression [4]:

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$$E_f = \frac{\pi h^2 d_c n}{m^*(0)} \qquad (1)$$

Using experimental data on heat capacity [6] which allow us to evaluate m*[4] and Hall effect data for n we obtain:

$$E_f \simeq 0.1 \text{ ev} \qquad (2)$$

This value is very small (usually for metals $E_f \sim 5$-10 ev). The small value of E_f is due to a small carrier concentration and a large value of the effective mass ($m^* \simeq 5\ M_e$, see [4]).

In conventional superconductors the parameter (T_c/E_f), or the related parameter $E(o)/E_f$ is very small ($\lesssim 10^{-4}$), here E(o) is the energy gap at T=0 K. In the cuprates the situation is different. In La-Sr-Cu-O the parameter $E(o)/E_f \sim 0.1$; it means that a large fraction of carriers is paired[4]; the coherence length appears to be small (~20Å).

These features lead us to conclude that the unusual critical behavior of the new high T_c superconductor is similar to that of liquid He. Such a conclusion has been stated by one of the present authors [7] (see also [8]). The role of the fluctuations is very important; of course, such behavior manifests itself stronger in Y-Ba-Cu-O.

The analysis of the heat capacity date in the region near T_c carried out in [9-11] has allowed us to observe the effect of fluctuations. Indeed, the temperature behavior of the heat capacity appears to be similar to the observations for liquid helium.

Based on the expression $\tau < [(13/\eta)\ (T_c/E_f)]^{1/4}$ (see [7]), $\tau = |T-T_c|/T_c$, $\eta = 2E(0)/3.5\ T_c$, with the use of the experimental data one can estimate the value of E_f for Y-Ba-Cu-O and we obtain $E_f \simeq 0.1$ - 0.3 ev, that is E_f has the same order of magnitude as for La-Sr-Cu-O.

We think that a small value of E_f, along with strong anisotropy, are the key features of new systems responsible for many peculiar, normal, and superconducting properties. We will discuss below some of the consequences of the small value of E_f.

Heat Capacity. In this section we will discuss a peculiar behavior of the heat capacity due to the small value of E_f. As is well known, the electronic heat capacity C_{el} is usually small relative to the total value C, except the region $T \to 0$; this small value is connected with the large value of E_f, because C_{el} represents a series expansion in the parameter $(T/E_f) \ll 1$. Usually $C_{el} \ll C_{ph}$ and only in the region $T \to 0$ the sharper decrease of C_{ph} allows us to separate the electronic contribution.

A small value of E_f makes the situation in cuprates entirely different. Contrary to the usual metals, the inequality $T \ll E_f$ does not hold in the region $T > \omega_D$. In this region C_{ph} depends slowly on T, because of anharmonicity, see e.g. [9, 10]; the temperature dependence C(T) is caused, mainly, by the electronic part $C_{el}(T)$, which is not small in cuprates. Of course, a small carrier concentration is a diminishing factor, but, nevertheless, the closeness T and E_f makes the contribution C_{el} noticeable. Thus, for these unusual materials, the electronic contribution can be separated in the high, rather than low, temperature region.

Let us evaluate C_{el} for a layered system. The total energy for a cylindrical Fermi surface can be written in the form $E = \nu \int d\varepsilon\ \varepsilon [\exp(\varepsilon-\mu)/T+1]^{-1}$ where $\nu = m^*(\pi h^2 d_c)^{-1}$ is the density of states. In addition to the direct temperature dependence, it is necessary to take into account the temperature

dependences of the chemical potential $\mu(T)$ and the effective mass $m^*(T)$. The dependence $m^*(T)$ is due to the electron-phonon coupling [15]. As for the temperature dependence of $\mu(T)$, this can be determined from the equation describing a number of carriers. As a result, we obtain $C_v = \gamma F(T)$ here γ is the Sommerfeld constant for a cylindrical Fermi surface, and $F(T) = G(\tilde{E}_f/T) - 1/2\ G^{-1}(\tilde{E}_f/T)\tilde{E}_f/T[1+(T/m^*(T))dm^*(T)/dT]$; $\tilde{E}_f = (m^*(o)/m^*)E_f$ (3)

The function $G(t)$ is equal to $G(t) = dx\ x(e^x e^{-tv(t)}+1)^{-1}$

If $T \ll E_f$, we obtain a linear law $C = \gamma T$. The temperature region $\omega_D < T < E_f$, is of particular interest. As was noted above, the lattice term in this region C_{ph} slowly depends on temperature (in fact, this dependence can be determined from thermal expansion data, see e.g. [9, 10]). The Fermi energy (see above) leads to a situation when the ration (T/E_f) is not small in the region $T > \omega_D$ (for La-Sr-Cu-O, $\omega_D \sim 350K$, $E_f \simeq 10^3 K$). As a result, one can separate a noticeable electronic temperature-dependent contribution $C_{el}(T)$.

In the region $E_f > T > \omega_D$, C_{el} (see Fig. 1) is not described by a linear law. This is important in order to obtain C_v from the measurement of C_p, because the difference $C_p - C_v$ does depend linearly on T.

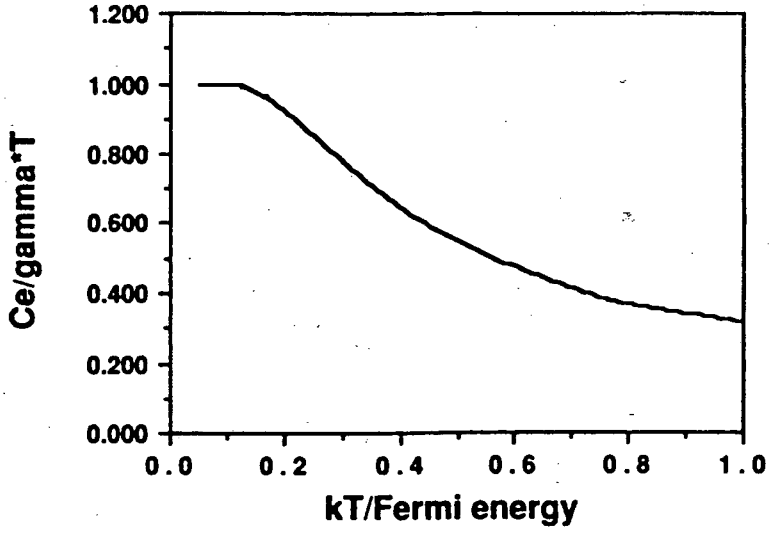

Fig. 1

The measurements of the electronic heat capacity allow us to determine an important parameter, namely, the strength of the electron-phonon coupling λ. The usual method for evaluating λ is based on tunneling spectroscopy. At present, there are no experimental tunneling spectroscopy data on the cuprates. It is also known that the short coherence length, interface problems, etc., make such spectroscopy very complicated. That is why it is very important to explore possibilities of determining λ.

The heat capacity data allows us to determine the value of the effective mass m^* (see [15]). It is essential that the effective mass depends on temperature. In the region $T \to 0$, $m^* = m_b(1+\lambda)$, where m_b is the band value. Hence, in the low temperature region the quantity measured experimentally, is the value renormalized by the electron-phonon coupling. The intensive thermal motion in the region $T > \omega_D$ leads to an absence of the renormalization and hence, we measure m_b. A direct comparison $m^*|_{T\to 0}$ and $m^*|_{T \gtrsim \omega_D} = m_b$ allows us to determine the value of λ. We can determine λ from low temperature data. [16] Then the band value of m_b can be expressed as $m_b = (3\ \hbar^2/\pi)\ K_B^{-2}\ d_c\ \gamma(1+\lambda)^{-1}$. In the high temperature region $m^* = m_b$. $C_e(T)$ depends parametrically only on (the last term in Eq.(3)

is negligibly small in the region $T>\omega_D$), and 1 can be determined from heat capacity data.

Note that heat capacity data was used by Knapp [15] in order to determine λ, and his efforts were caused by a lack of the tunneling spectroscopy data by that time. Our motivation aimed on determination λ of the cuprates is similar.

The determination of λ is important for the understanding of the origin of high T_c. It would be very interesting to carry out the corresponding experiments.

Normal Conductivity. Unusual temperature dependence of one normal conductivity has attracted a lot of interest. This problem has been discussed in [17]. We think that a linear dependence of the resistance on temperature is due to a strong anisotropy of the system and to a small carrier concentration.

Carrier's subsystem of the cuprates forms a layered structure. This leads to an anisotropy of the phonon spectrum. Indeed, according to the adiabatic theory, the phonon's degrees of freedom are greatly affected by the electronic motion. Electronic terms form potential for the ionic motion. (see e.g. the review [18])

As a result, the electronic term is highly anisotropic and an analysis based on the crystal's anisotropy (see [23]) is relevant to the cuprates. The phonon spectrum of such an anisotropic system differs drastically from the usual 3D picture. Name, one should distinguish two different Debye temperatures. $\theta_{max} \simeq$ and θ_{min}, where $\theta_{min} = \eta\ \theta_{max}$, $\eta \simeq d_a, d_c$ where d_c is the interlayer distance, and d_a is the interatomic distance in the plane, $\theta_{max} \simeq 350K$.

Consider the temperature region $\eta\ \theta_{max} \ll T \ll \theta_{max}$. The major contribution to the lattice dynamics comes from the branch: $\omega \simeq \gamma_q^2$ [19] based on the relation $\sigma = n\ e^2 \tau/m^*$ one can obtain the dependence $\tau \sim T^{-1}$, and, hence $\rho \sim T$. Indeed, a number of phonons with dispersion relation $\omega \sim q^2$ is proportional to T. In addition, the Fermi momentum and the phonon momentum have the same order of magnitude. As a result, the additional temperature dependence of τ does not appear (as is well known, the small value $q_\gamma \ll P_f$ leads to an additional dependence $\tau \sim T^{-2}$). Hence, $\tau \sim T^{-1}$ and we obtain the linear dependence of the resistance.

The situation is different in the region $\eta^2\ \theta_{max} \ll T \ll \eta_2 \theta_{max}$. For La-Sr-Cu-O system it corresponds to the interval $25K \lesssim T \lesssim 10^2 K$ is noticeable and the dispersion relation should be written in the form (see [19]): $\omega \sim q$.

In this case $N_{ph} \sim T^2$ and $\tau \sim T^{-2}$. However, it is necessary to take into account the dependence of $m^*(T)$. The effective mass decreases almost linearly in this region (see [15]). As a result, we obtain, that in the region $\eta^2\ \theta_m \ll T \ll \eta\ \theta_m$ ρ also display linear dependence; $\rho \sim T$. In the region T n θ_m there is a change of one slope in the function of $\rho \sim T$.

Note that in the region $T \gtrsim \theta_D$ one should take into account the electron-electron scattering. For the ordinary metals with a large value of the Fermi energy this mechanism of relaxation does not play a noticeable role, because it is proportional $\sim (T/E_f)^2 \ll 1$, if $T \ll E_f$. For the cuprates the temperature in the region $T \lesssim \theta_D$ is not small relative to E_f. As a result, the temperature dependence of Pee is different from being quadratic, and, in addition, the contribution of this channel become important. A more detailed analysis of Pe-e will be given elsewhere.

Thermal Conductivity. The behavior of the thermal conductivity in cuprates is affected strongly by a small value of the Fermi energy. As is known, the total thermal flow consist of two parts: $\mathcal{R} = \mathcal{R}_{el} + \mathcal{R}_{latt}$. In ordinary metals $\mathcal{R}_{el} >> \mathcal{R}_{latt}$, that is, the thermal conductivity is dominated by the electrons (see e.g. [20]). Even for dirty metals with a small mean free path, the lattice contribution does not exceed several percent.

Thermal conductivity of the new oxides has been studied experimentally in [21] and the picture appears to be entirely different. Namely, main contribution to the thermal flow comes from phonons, the electronic part is only $\sim$ 20% of the total thermal conductivity.

Such abnormal behavior is due to a small value of the Fermi energy. Indeed, the electronic term $\mathcal{R}_e$ depends on E_f : $\mathcal{R}_e \sim E_f$ (see e.g. [22]). The value of the Fermi energy in cuprates is $\sim$ two order of magnitude less than in ordinary metals and it leads to a decrease of $\mathcal{R}_e$ observed experimentally.

An experimental investigation of the dependence $\mathcal{R}(T)$ is the region T/T_c has resulted in a very important observation. Namely, $\mathcal{R}(T)$ increases with decreasing temperature below T_c; and at the same value T_o one can observe $\mathcal{R}_{max}$, and then $\mathcal{R} \to o$ if $T \to o$.

Such behavior is not unusual. As is known (see e.g. [22]) there are six relaxation mechanisms determining the behavior of the thermal conductivity. An increase of $\mathcal{R}$ below T_c corresponds to the lattice contribution due to scattering of phonons by electrons. It is described by the same electron-phonon interaction which is the major mechanism of BCS theory. In the region $T \sim T_o$ the phonon mean free path $l_{pe} \sim l_{p, imp}$ and the subsequent decrease in T leads to a decrease of $\mathcal{R}$.

Such a manifestation of the electron-phonon coupling, which appear to be a dominant mechanism of the thermal conductivity, is very important from a point of view of the understanding of the mechanisms of high T_c. The described behavior of the thermal conductivity means that the electron-phonon coupling plays an important role in the cuprates.

Note that the strength of the electron-phonon coupling also is connected with the value of the Fermi energy. As is known, the electron-phonon coupling is a deviation from the adiabatic picture (see e.g. the review [18]) and this non-adiabaticity is described by the ration ω_D/E_f. A small value of E_f means a large non-adiabaticity and, hence, a strong electron-phonon coupling.

Conclusion. A small value of the Fermi energy ($\sim$o, lev) is a key feature of the new high T_c oxides. A large value of T_c/E_f leads to a noticeable contribution of fluctuation. Such a small value of E_f allows us to separate the electronic contribution to the heat capacity in the high temperature region $E_f > T > \theta_D$ to determine the value of the electron-phonon coupling constant λ.

The linear temperature dependence of the normal resistance is mainly due to a large anisotropy of the system. A small value of E_f leads to the situation when the lattice contribution to the thermal conductivity plays a dominant role.

A strong electron-phonon coupling is manifested in the increase of the thermal conductivity in the region $T < T_c$ and the appearance of such coupling is also connected with a small value of E_f

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