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SOME THEORETICAL ASPECTS OF HIGH T_c SUPERCONDUCTIVITY

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INTRODUCTION

This paper is concerned with properties of new superconducting oxides discovered in [1,2] and with mechanisms of high T_c superconductivity. At present, there are many experimental data which allow us to conclude that we are dealing with very unusual systems. At the same time, we should stress that the new superconducting oxides display usual, BCS-type superconductivity. This means that: 1) the superconducting state is due to an effective electron-electron attraction caused by some intermediate field, 2) this attraction leads to Cooper pairing, and 3) the spectrum of excitations possesses an energy gap.

However, this state has many peculiar features, such as a small coherence length, non-phonon contribution to the pairing, a multigap structure, etc.

EXOTIC PROPERTIES OF NEW MATERIALS

A method allowing one to evaluate the main parameters of the new high T_c oxides has been developed by S. Wolf and the present author [3]. We have focused on the properties of the La-Sr-Cu-O compound. One should note that, according to the interesting paper [4], this compound and Y-Ba-Cu-O have a lot in common.

We have developed a method allowing one to use heat capacity data [5] in order to calculate the main parameters of the system. The reduced dimensionality was taken into account in a consistent way. We think that heat capacity measurements are the most reliable source of information, because these data are not sensitive to the mutual orientation of single crystals in a polycrystalline sample.

Consider a model containing 2D sheets. Each of them contains a 2D Fermi gas of carriers. There are a small number of interlayer transitions which are important if we are concerned with 2D fluctuations. But for our present purpose we can consider isolated 2D subsystems.

The effective mass can be determined directly from the equation

$$m^* = (3\hbar^2/\pi)\, k_B^{-2} a\gamma \,, \qquad (1)$$

where a is the interlayer distance, and $\gamma = C_e/T$.

As a result, we obtain the following values for $La_{1.8}Sr_{0.2}CuO_4$: $m^*=4m_e$, $\epsilon_F \approx 0.12$ eV, $\xi_0=23.5$Å (m^*, ϵ_F, and ξ_0 are the effective mass, the Fermi energy and the coherence length, correspondingly). We would like to stress two inter-related features of the system allowing one to consider it as a strongly correlated state. First of all, the value of the parameter $\alpha=\epsilon(0)/\epsilon_F$ ($\epsilon(0)$ is the energy gap at T=0K; the parameter α is negligibly small for conventional superconductors) appears to be large. This means that a large fraction of carriers are paired. In this sense, the new high T_c oxides differ in a striking way from the usual superconductors.

Secondly, the coherence length is small. Such a small value of ξ_0 allows one to meet the Anderson criterion $\xi_0 << \ell$, ℓ is the mean free path, and observe a multigap structure.

The same result can be obtained if we consider a 3D system with a cylindrically shaped Fermi surface with $P_{zmax} = \pi/a$.

The new high T_c materials provide a unique opportunity to observe, under certain conditions, effects due to the presence of several gaps.

The two-gap model has been introduced by Suhl, Matthias and Walker [6]. Afterwards it has been studied by Geilikman, Zaitsev and the present author [7] and by the present author in ref. 8. The difficulty of observing multigap effects, as well as effects caused by gap anisotropy are due to the Anderson theorem. Namely, the inequality $\ell << \xi_0$ (ξ_0 is the coherence length, ℓ is the mean free path) results in the gaps averaging out into a single one. Interband transitions are the main mechanism of this averaging.

New high T_c oxides are characterized by a small value of ξ_0 (see above). As a result, for relatively clean samples the criterion $\xi_0 \lesssim \ell$ can be met. Hence, we have a case of very small ξ_0 and the opportunity to observe several gaps in the presence of overlapping bands becomes apparent. If we study, for example, a system with two gaps then even in the weak coupling approximation the ratios $\beta_i = \epsilon_i/T_c$ ($i = 1,2$) can differ drastically from $\beta_{BCS} = 1.76$. A situation when $\beta_1 << \beta_{BCS}$ while $\beta_2 << \beta_{BCS}$ is perfectly realistic. Strictly speaking each subgroup of electrons is characterized by its value of $\xi_0^i = hv_F^i(2\pi\kappa T_c)^{-1}$.

Note that the Anderson criterion allows one to determine whether one is dealing with a multigap case. Indeed, additional doping of these materials will result in a decrease of ℓ and, subsequently, in ℓ becoming less than ξ_0 when a transition to the one-gap picture will take place. Such a transition can be observed experimentally, because the tunneling spectrum and the temperature dependence, e.g., of the kinetic coefficients are different in the one-gap and multigap cases.

Note that anisotropy of the energy gap and multigap structure are similar phenomena. Both of them are due to a deviation of the Fermi surface from the spherical shape. A layered structure in the absence of interlayer transitions has a cylindrical Fermi surface. The small number of transitions (these transitions are necessary in order to eliminate the contribution of fluctuations; fluctuations make it impossible for the superconducting state to appear in pure 2D and 1D cases) corresponds to a very stretched eclipsoid with a large value of the effective mass along the "c" axis.

The anisotropy of the Fermi surface does not play a noticeable role in conventional superconductors because of the averaging into an isotropic energy gap. This averaging is connected with the same Anderson's criterion (see above) and is due to the large value of the coherence length.

The large anisotropy of the Fermi surface along with the small value of the coherence length make the energy gap anisotropy an important feature of the new high T_c materials.

A layered structure and large anisotropy do not mean that pairing occurs between carriers which belong to the same sheet with Josephson coupling between different sheets. Such a picture assumes that a 2D superconductor can exist by itself, but its superconducting state would be destroyed by fluctuations. In reality, pairing occurs in momentum space, that is, the states $(\vec{\kappa}, k_z)$ and $(-\vec{\kappa}, -k_z)$ are paired ($\vec{\kappa}$ is 2D quasi-momentum); their wave functions are spread out over the entire crystal, and the anisotropy is manifested in the anisotropy of the Fermi surface.

Recent experimental data [9] show the presence of two energy gaps in Y-Ba-Au-O: $\varepsilon_1 \simeq 8\ T_c$, $\varepsilon_2 \simeq 2\ T_c$. It is interesting to note that the value $\varepsilon \simeq 8\ T_c$ has been obtained recently by the infrared techniques [10]. This means that the authors [10] have observed the larger gap. The anisotropy of superconducting properties observed in [11] also is a manifestation of the small coherence length.

2D PLASMONS. COEXISTENCE OF THE PHONON AND PLASMON MECHANISM

The problem of one coexistence of the usual phonon and non-phonon (plasmon) mechanisms has been discussed by the present author in ref. [12]. Here I would like to stress several important features of the plasmon mechanism.

1. Low dimensionality and a small carrier concentration makes the contribution of 2D plasmons very favorable. Reduced dimensionality along with the presence of overlapping energy bands leads to the appearance of two plasmon branches: 1) the branch $\omega(q) \sim q^{1/2} (q \to 0)$, which is specific to a 2D system. Note that in the short-wave region which is important for the pairing, the interlayer interaction is not essential; 2) acoustic branch $\omega \sim q$, which is due to the presence of several bands.
2. The presence of 2D plasmons is not an assumption. They exist and in the presence of electron-phonon interaction they can provide an additional contribution to the pairing. Note that 2D plasmons in layered systems similar to La-Sr-Cu-O have been observed experimentally in [13].
3. A hybridization of plasmons and phonons leads to an opportunity to observe a peak in the reflectance (see ref. 12b).
4. Electron-plasmon coupling increases with decreasing carrier concentration n.

T_c in the presence of both phonon and plasmon mechanisms is described by the expression [12]:

$$T_c = T_c^{ph}(\tilde{\omega}_{p\ell}/T_c^{ph})^r \qquad (2)$$

where $r = \lambda_{p\ell}(\lambda_{ph}+\lambda_{p\ell})^{-1}$. I would like to emphasize that the large value of $\tilde{\omega}_{p\ell}/T_c^{ph}$, that is, large scale of the plasmon mechanism, leads to a noticeable change of T_c with respect to T_c^{ph} even for relatively small $\lambda_{p\ell}$. Indeed, if $\lambda_{ph}\simeq 2, \tilde{\Omega}\simeq 150K$, we obtain T_c^{ph} = 21K (see ref. [14]). Putting then $\tilde{\omega}_{p\ell}/T_c^{ph}\simeq 20$ and assuming $\lambda_p\simeq 0.5$, we obtain $T_c\simeq 1.8T_c^{ph}\simeq 38K$. Hence, the coexistence of the phonon and plasmon contributions may provide the observed high T_c of the La-Sr-Cu-O sytem.

CONCLUSION

The new high T_c materials are highly anisotropic. A large value of the ratio $\varepsilon_0/\varepsilon_F$ and the smallness of the coherence length makes these systems unique. They provide an opportunity to observe multigap structure and energy gap anisotropy.

High T_c is caused by a coexistence of the phonon and plasmon mechanisms.

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