INELASTIC ELECTRON SCATTERING INFLUENCE ON THE STRONG-COUPLING OXIDE SUPERCONDUCTORS

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The superconducting order parameter Δ and energy gap Δ_g are calculated taking into account the pair-breaking inelastic quasiparticle scattering by thermal Bose-excitations, e.g., phonons. The treatment is self-consistent because the scattering amplitude depends on Δ. The superconducting transition for any strength of the inelastic scattering is the phase transition of the first kind and the dependences $\Delta(T)$ and $\Delta_g(T)$ tend to rectangular curves that agrees well with the experiment for high-T_c oxides. On the basis of the developed theory the nuclear spin-lattice relaxation rate R_s in the superconducting state is calculated. The Hebel-Slichter peak in $R_s(T)$ is shown to disappear for strong enough inelastic scattering.

For high-T_c oxides one of the most important distinctions from the BCS behaviour is the almost rectangular temperature, T, dependence of those characteristics which are measured by resistive (tunnel and point-contact), infrared or Raman spectroscopies, and are generally identified with the superconducting order parameter Δ or the energy gap Δ_g in the quasiparticle spectrum. The other unusual feature of the these superconductors is the absence of the Hebel-Slichter peak in the nuclear spin-lattice relaxation rate R_s below T_c. This peak is a clear manifestation of the s-wave Cooper pairing and traditionally serves as a check of its realization for various specific superconductors. We suggest that these phenomena are due to the inelastic quasiparticle scattering in the superconducting state.

Here we develop a phenomenological approach, based on the BCS scheme, which treats the scattering processes as pair-breaking factors [1]. All these processes are described by a single pair-breaking factor $\nu = (\tau T_{c0})^{-1}$, where τ is the inverse inelastic relaxation time, T_{c0} is the critical temperature of the metal with no inelastic thermal scattering ($\nu = 0$), and $\hbar = k_B = 1$. We suggest that ν depends on T as well as on the order parameter Δ of the superconductor. In turn, Δ is defined by the equation derived within the framework of Abrikosov-Gor'kov theory for superconductors with paramagnetic impurities [2]. This equation includes ν as a parameter, so the problem becomes self-consistent.

We consider Cooper pairing to be of the s-type. We think that this assumption agrees well with experiment (the situation is quite different from that for heavy-fermion substances). But there is another point of view suggesting a spin-singlet anisotropic d-wave pairing. It is based, in particular, on experiments where the low temperature power dependences of transport properties were observed. Nevertheless, the s-wave character of the high-T_c oxide superconductivity is supported by gap-like Giaver one-particle tunnel currents for oxides, the conventional magnetic flux quantization in Nb-$YBa_2Cu_3O_7$ rings, and usual temperature and magnetic field dependences of the Josephson current in Pb/insulator/$Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ tunnel junctions.

We select the dependence $\nu(t)$ in a rather general form $\nu(t) = At^{\beta}f[t, \delta(t)]$, where $t = T/T_{c0}$, $\delta = \Delta/T_{c0}$, A and β are the dimensionless parameters of the theory. The exponent β can be found both from theoretical considerations and from resistive measurements, and usually falls into the interval 1 to 3.

The function $f(t,\delta)$ allows for the reverse effect of the electron spectrum gap on the scattering process. In particular, it can be chosen as a constant, which makes the problem non-self-consistent. But if the quasiparticle recombination processes make the dominant contribution into inelastic scattering, it is reasonable to select $f(t,\delta)$ in the form

$$f(t,\delta) = \exp[-\delta(t)/t]. \tag{1}$$

This equation has been obtained [3] from Eliashberg equations not allowing for the reduction of the real spectrum gap $\Delta_g(T)$ against the order parameter $\Delta(T)$:

$$\delta_g(t) = \delta(t)\left\{1 - \left[\nu(t)/\delta(t)\right]^{2/3}\right\}^{3/2}, \tag{2}$$

where $\delta_g = \Delta_g/T_{c0}$ is the dimensionless energy gap. So, we assume that the following model will be more correct:

$$f(t,\delta) = \exp[-\delta_g(t)/t]. \tag{3}$$

In Fig. 1 the temperature dependences of the superconducting order parameter $\delta(t)$ are shown for various types of the pair-breaking factor. The dashed curve is the Mühlschlegel curve within a factor $T_{c0}/\Delta(0) = \gamma/\pi$, where $\gamma = 1.7810...$ is the Euler constant. Curve 1 corresponds to our model with a temperature-dependent pair-breaking scattering but without self-consistency: $\nu(t) = 0.5t$. We remark that even in this version of the theory the ratio $2\Delta(0)/T_{c0}$ is far in excess of its BCS value

$2\pi/\gamma$, the conclusion being in agreement with the majority of experimental data for HTSC. Curves 2 and 3 were calculated in the self-consistent framework of Eqs.(1) and (3), respectively. Here $A = 0.5$ and $\beta = 1$, the latter being common to $YBa_2Cu_3O_7$. The calculations were performed only in the gap region defined by the condition $\nu(t) < \delta(t)$. One can see from Fig.1 that the order parameter becomes double-valued when treating self-consistently. The dashed portions of curves 2 and 3 describe the lower branches connecting the branching points and the points where the condition $\nu(t) < \delta(t)$ fails. One should note that curve 3 ends at the intersection point with curve 1 since $\nu(t) = \delta(t)$ here.

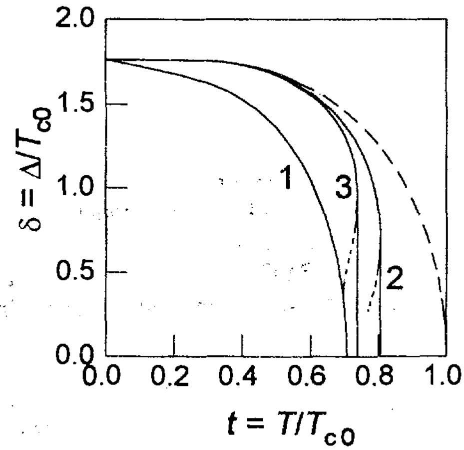

Fig.1.

The double-valued character of $\Delta(T)$ in Fig.1 at the first glance resembles one for the gap edge obtained in [4,5] within the Eliashberg theory. However, the calculations of these works led to the single-valued behaviour of the order parameter $\Delta(T)$ and the energy gap $\Delta_g(T)$, which vanished continuously when T approached T_c in line with the theory of second-order phase transitions. The double-valued nature of the order parameter $\Delta(T)$ and hence the gap $\Delta_g(T)$ survives, as our calculations show, for arbitrary small A and $\beta > 0$, but the branching point rapidly shifts towards the close vicinity of T_c when A becomes small. Therefore, the predicted effect would not be observed for low-T_c superconductors since it goes there beyond the accuracy of the experiment.

The lower branches of curves 2 and 3 correspond to unstable states which can not be realized since the free energies of the superconducting state for them exceed the free energies of the corresponding stable branches with larger order parameter $\Delta(T)$. Therefore, the continuous behaviour of $\Delta(T)$ is interrupted at the branching point and the phase transition of the first kind into the normal state occurs, so that the order parameter goes discontinuously to zero at $T = T_c$. The transition is depicted by the vertical solid parts of curves 2 and 3. The transformation of the phase transition order in a similar situation, when the instability is driven by a non-equilibrium external electromagnetic radiation, was obtained in Ref.6.

The T-dependence of the nuclear spin-lattice relaxation rate in the superconducting state is the most popular among transport characteristics of high-T_c oxides. First of all, here the BCS theory leads to the non-monotonous behaviour of $R_s(T)$, whereas in experiments for high-T_c ceramics $R_s(T)$ is monotonous. The other reason is its importance for understanding of magnetic properties of Cu-based oxides, being magnetically unstable for definite compositions. Without any intrinsic or extrinsic cut-off processes the ratio $\rho = R_s/R_n$, where R_n is the nuclear spin-lattice relaxation rate in normal state, diverges logarithmically below T_c. With allowance made for these processes, the divergence transforms into the so-called Hebel-Slichter peak. In our case the elimination of the singularity is due to the inelastic electron scattering by thermal excitations. The main challenge for any theory describing relaxation in the superconducting state is to explain the absence of the peak below T_c for high-T_c oxides. The modification of the dependences $\rho(\theta)$, where $\theta = T/T_c$, for the most realistic self-consistent model (3) is shown in Fig.2 for $\beta = 1$. Here curves 1-5 correspond to parameter values A = 0.1, 0.2, 0.5, 1, and 1.5. From Fig.2 it follows that in this model the coherent peak disappears and the dependence $\rho(T)$ becomes monotonous with jump to unity at $T = T_c$. Such a behaviour agrees with the experiment for ceramic oxides.

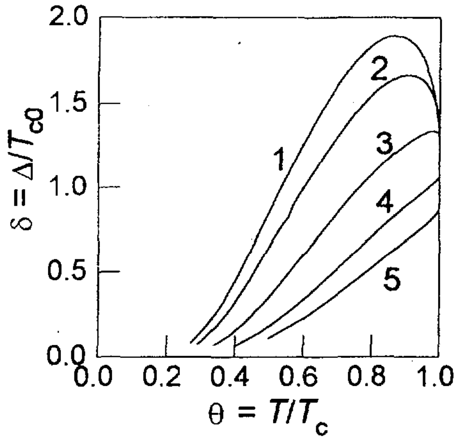

Fig.2.

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