LOCALIZATION EFFECTS IN HIGH-TEMPERATURE SUPERCONDUCTORS

M. V. Sadovskii
Institute for Electrophysics, USSR Academy of Sciences,
Ural Branch, Sverdlovsk, 620219, USSR

Basic facts on the interplay of Anderson localization and superconductivity in high-T_c oxides are presented. The "minimal metallic conductivity" for the quasi-two-dimensional case is enhanced owing to a small overlap of electronic states on the nearest neighbor conducting planes. This leads to a much stronger influence of localization effects than in ordinary (three- dimensional) superconductors. From this point of view high-temperature oxides are very close to the Anderson transition even for rather weak disorder. Anomalies of the upper critical field are also analyzed as well as degradation of T_c under disordering, due to the enhanced Coulomb effects caused by the disorder-induced decrease of localization length.

INTRODUCTION

The concept of Anderson localization [1] is basic for the modern theory of electrons in disordered systems [2-6]. According to this concept the introduction of sufficiently large disorder transforms the initial metallic system to an insulator, because of the transition from extended to spatially localized electronic states at the Fermi level.

At the same time, since the classic BCS-paper [7], it is well known that even the slightest attraction of electrons near the Fermi level leads to superconductivity, which is relatively insensitive to disorder which conserves time-invariance (normal, nonmagnetic impurities, etc.) [8,9].

Thus, an interesting problem arises of the possible interplay of the localization transition and superconductivity in a strongly disordered metal. This problem is important from both the theoretical point of view, because it is a question of the interplay of apparently opposite kinds of ground states (insulator versus superconductor), as well as the experimental point of view, because in many cases the superconducting transition is observed close to the metal-insulator transition in highly disordered systems. It is specially important for high-T_c oxides, which are close to the metal-insulator transition from the very beginning.

The general picture of the interplay of Anderson localization and superconductivity was analyzed in several papers in recent years [10-17]. Here we present the basic results applied especially to high-T_c oxides, where many experimental results were also obtained, mainly for the case of radiation-disordering by fast neutrons [18-21].

High-T_c oxides are quite appropriate for studying the interplay of localization and superconductivity. First of all, the high values of T_c are important in order to overcome rather strong mechanisms of the degradation of T_c after disordering [11].

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Secondly, the smallness of Cooper pairs in these materials is also very important, because of the basic criteria of the possible coexistence of localization and superconductivity - the Cooper pairs must be smaller than the localization length in the insulating phase [10, 11]. These strict criteria are difficult to satisfy in ordinary superconductors. And finally the high-T_c oxides are close to a metal-insulator transition probably of the Mott-Hubbard type. The parent compounds such as La_2CuO_4 and $YBa_2Cu_3O_6$ are antiferromagnetic insulators, but disorder effects are also quite important owing to inherent disorder present in all real samples. These effects are manifested among other things by the variable range hopping behavior of conductivity in these insulating phases [22,23] as well as the remnants of it in disordered superconducting phases [19-21].

Fast neutron irradiation is probably the purest method for investigating the effects of disordering on physical properties of high-T_c superconductors because of the absence of any chemical effects in case of low temperature irradiation. The appropriate growth of structural disorder leads to rather drastic changes in the behavior of both single-crystalline and ceramic samples [18-21]:

(a) continuous metal-insulator transition at very slight disordering;
(b) rapid degradation of T_c;
(c) apparent coexistence of hopping conductivity and superconductivity at intermediate disorder and anomalous (exponential) growth of resistivity with defect concentration;
(d) approximate independence of the derivative of the upper critical field H_{c2}' on the degree of disorder.

These anomalies were interpreted using the ideas of possible coexistence of Anderson localization and superconductivity and in the following we present mainly theoretical aspects of this problem for strongly anisotropic (quasi-two-dimensional) high-T_c systems. For the extensive discussion of experimental data we refer to Refs. 18-21.

1. LOCALIZATION AND SUPERCONDUCTIVITY IN QUASI-TWO-DIMENSIONAL SYSTEMS.

All the known high-T_c systems (with $T_c > 30K$) are strongly anisotropic, or even quasi-two-dimensional conductors. For such systems it is natural to expect the strong enhancement of localization effects due to the known role of spatial dimensionality of $d=2$: in the purely two-dimensional case localization appears for infinitely small disorder [3-6].

Exact electronic states $\phi_\nu(r)$ in a disordered system are defined by the solution of the appropriate Schroedinger equation in a random field. These states may be both extended or localized. Cooper pairing can be realized between the time-reversed partners $\phi_\nu(r)$ and $\phi^*_\nu(r)$. For the case of the self-averaging superconducting order parameter this problem was solved by Anderson [9] , who showed that for the given value of pairing interaction, T_c is essentially independent of the nature of these states: either extended or localized. The only limitation for the latter case is due to the known effects of the discrete level repulsion in the localization region [2,11]. It is clear that Cooper pairing can be realized in the localized phase only for the electrons with the centers of localization within the volume of the characteristic size determined by R_{loc} - the localization length, because only such electrons have overlapping wave functions and can interact with each other. However, these states are split in energy on the scale of the order of $[N(E_F)R^3_{loc}]^{-1}$, where $N(E_F)$ is the density of states at the Fermi level.

Obviously, to observe superconductivity we must demand that this splitting be smaller than the value of the superconducting energy gap at T=0:

$$\Delta, T_c \gg [N(E_F)R_{loc}^3]^{-1} , \tag{1}$$

or for strongly anisotropic high-T_c systems:

$$\Delta, T_c \gg [N(E_F)R_{loc}^a R_{loc}^b R_{loc}^c]^{-1} , \tag{2}$$

where we introduced the appropriate values of localization lengths along the axes of an orthorhombic lattice. This inequality is equivalent to the condition of rather large localization lengths [10,11], e.g. for an isotropic case:

$$R_{loc} \gg [N(E_F)\Delta]^{-1/3} \approx (\xi_0 \hbar^2/p_F^2)^{1/3} \approx (\xi_0 a^2)^{1/3} , \tag{3}$$

where $\xi_0 \approx \hbar V_F/T_c$ is the coherence length of the BCS theory and $p_F \approx \hbar/a$ is the Fermi momentum (a is the lattice spacing, V_F is the Fermi velocity). For high-T_c oxides with rather large values of Δ and small ξ_0 this condition can can be satisfied rather easily. Actually the physical meaning of of it is very simple: R_{loc} must be much larger than the characteristic size of the Cooper pair in the strongly disordered system [10,11].

The main properties of a superconductor can be analyzed via the Ginzburg-Landau theory, and to do this we must derive the GL-expansion coefficients for the strongly disordered quasi-two-dimensional system near the localization transition [18]. As a one-electron model of the Anderson transition we use a self-consistent theory of localization [3,5] for the quasi-two-dimensional case [24]. The electron motion in such a system is determined by the two-particle Green's function with a characteristic diffusion form:

$$\phi(q\omega) = -N(E_F)/\{\omega + iD_{\parallel}(\omega)q_{\parallel}^2 + iD_{\perp}(\omega)[1-\phi(q_{\perp})]\} \tag{4}$$

where $D_{\parallel,\perp}(\omega)$ are the longitudinal and transverse generalized diffusion coefficients (with respect to conducting planes), $\phi(q_\perp)=\cos(q_\perp a_\perp)$, and $q_{\parallel,\perp}$ are longitudinal and transverse components of **q**, $a_\perp$ is the interplane distance in the quasi-two-dimensional lattice. For simplicity we assume isotropic motion of electrons in the conducting plane.

The generalized diffusion coefficient can be determined from the self-consistency equation [24]:

$$D_{\parallel,\perp}(\omega) = D_{\parallel,\perp}^0(\omega) - \frac{1}{\pi N(E_F)} \int \frac{d^3q}{(2\pi)^3} \frac{D_{\parallel,\perp}(\omega)}{-i\omega + D_{\parallel}(\omega)q_{\parallel}^2 + D_{\perp}(\omega)(1-\phi(q_\perp))} , \tag{5}$$

where $D_{\parallel}^0 = V_F^2\tau/2$, $D_{\perp}^0 = (wa_\perp)^2\tau$ are Drude-like diffusion coefficients, w is the interplane transfer integral and τ is the mean-free time in the conducting plane.

The mobility edge position on the energy axis is determined by:

$$E_c = \hbar/\pi\tau \ln(2^{1/2}\hbar/w\tau) , \tag{6}$$

so that $E_c \to \infty$ for $w \to 0$ reflecting the complete localization for $d=2$ [3,6]. For $E=E_c$

the Drude conductivity in the plane is equal to the so called "minimal metallic conductivity" [2]:

$$\sigma_c^{\parallel} = 2e^2 D_{\parallel}^0 (E_F = E_c) = \frac{1}{\pi^2}\frac{e^2}{\hbar a_\perp}\ln(2^{1/2}\hbar/w\tau) \ . \tag{7}$$

From that expression we can see that σ_c for the quasi-two-dimensional system is significantly enhanced in comparison to the Mott estimates for the isotropic case, due to a logarithmic factor which grows with diminishing overlap of electronic states on the nearest-neighbor planes. Thus for the strongly anisotropic (or quasi-two-dimensional) systems, such as high-T_c oxides, the value of "minimal metallic conductivity" may be larger than the usual estimates of $(3-5)\times 10^2\ \mathrm{ohm}^{-1}\mathrm{cm}^{-1}$, and actually can exceed $10^3\ \mathrm{ohm}^{-1}\mathrm{cm}^{-1}$ for typical values of $\sigma_\perp/\sigma_\parallel \propto 10^2$ and $E_F\tau \propto 1$. While there is no rigorous definition of "minimal metallic conductivity" now, owing to the continuous nature of the Anderson transition [3-6], it actually defines the scale of conductivity near the metal-insulator transition caused by disorder. From these estimates it is clear that most of the real samples of high-T_c superconductors are quite close to the Anderson transition and even very slight disordering is sufficient [18-21] to transform them to the Anderson insulators.

Using the expressions for $D_{\parallel,\perp}(\omega)$ from Ref. 24 we can derive the microscopic expression for the coefficient of gradient term in the GL-expansion similar to Refs. 10-13:

$$C_{\parallel,\perp} = N(E_F)\xi_{\parallel,\perp}^2 \ , \tag{8}$$

where for the coherence lengths $\xi_{\parallel,\perp}$ we have slightly different expressions depending on the values of the dimensionless parameter $w^2\tau/2\pi T_c\hbar$, determining the crossover from anisotropic to quasi-two-dimensional superconductor. For $w^2\tau/2\pi T_c\hbar \gg 1$ we have:

$$\xi_{\parallel,\perp}^2 = (\pi/8T_c)D_{\parallel,\perp}^0(E_F - E_c)/E_c = \xi_{\parallel,\perp}^0 l_{\parallel,\perp}(E_F - E_c)/E_c \ , \tag{9}$$

where $\xi_\parallel^0 \approx \hbar V_F/T_c$, $\xi_\perp^0 \approx \hbar w a_\perp/T_c$, $l_\parallel = V_F\tau$, $l_\perp = w a_\perp \tau$. Eq.(7) is valid for $\sigma_\parallel > \sigma^*$, where:

$$\sigma^* \approx \sigma_c^{\parallel}\xi_\parallel^0/l_\parallel (T_c^2/E_F w)^{2/3} \ , \tag{10}$$

and $w^2\tau/2\pi T_c\hbar \gg 1$ is equivalent to $\xi_\perp \approx \sqrt{\xi_\perp^0 l_\perp} \gg a_\perp$, i.e. the size of a Cooper pair is larger than $a_\perp$, and we have just the anisotropic superconductor.

In the vicinity of the Anderson transition for $\sigma_\parallel < \sigma^*$:

$$\xi_{\parallel,\perp}^2 \approx D_{\parallel,\perp}^0/[(E_F T_c w)^{2/3}\tau] \approx (\xi_{\parallel,\perp}^0)^2 (T_c^2/E_F w)^{2/3} \ . \tag{11}$$

For the isotropic case, for $w \approx E_F$ these expressions transform into that of Refs. 10,11, where close to the Anderson transition we obtained (Cf. (3)):

$$\xi \approx (\xi_0 l^2)^{1/3} \approx (\xi_0 a^2)^{1/3} \ , \tag{12}$$

which is valid for $\alpha<\alpha^*$ with α^* given by:

$$\alpha^* \approx \alpha_c(p_F\xi_0/\hbar)^{-1/3} \approx \alpha_c(T_c/E_F)^{1/3} , \tag{13}$$

where $\alpha_c = e^2 p_F/\pi^3\hbar^2$ is the Mott estimate for "minimal metallic conductivity". For the case of $w^2\tau/2\pi T_c<1$ corresponding to the quasi-two-dimensional superconductor we get:

$$\xi^2_{\parallel,\perp} \approx \frac{D^0_{\parallel,\perp}}{\pi T_c}\left\{\frac{(E_F-E_c)}{E_c}+\left[\frac{\pi^2}{8}-1\right]\left[1-\frac{1}{2\pi E_F\tau}\ln\left[\frac{1}{2\pi T_c\tau}\right]\right]\right\} , \tag{14}$$

for $\alpha>\alpha^*$, where α^* is again determined by (10), and for $\alpha<\alpha^*$ we obtain the same expression as in (14) but with first term replaced by (11). For high-T_c oxides $\xi^0_\parallel \approx l_\parallel$, $T_c \approx w$, $T_c \approx 0.1\,E_F$ and actually $\alpha^* \approx \alpha^c_\parallel$, so that these systems are close to the Anderson transition also in their superconducting behavior. Also, it is clear that for most of these systems we have apparently $w^2\tau/2\pi T_c\hbar \approx 1$, i.e. $\xi_\perp \approx \sqrt{\xi^0_\perp l} \approx a_\perp$, so that they are on the edge of quasi-two-dimensional behavior.

For the derivative of the upper critical field in the isotropic case we have [10,11]:

$$-\frac{\alpha}{N(E_F)}\left[\frac{dH_{c2}}{dT}\right]_{T_c} \approx \begin{cases} 8e^2/\pi\hbar\phi_0 & \alpha>\alpha^* \\ \phi_0/2\pi\alpha/[N(E_F)T_c]^{1/3} & \alpha<\alpha^* \end{cases} \tag{15}$$

where $\phi_0 = \pi c\hbar/e$ is the magnetic flux quantum. The classic Gorkov relation [25] given in the upper expression in (15) is invalid near the Anderson transition, where $(\alpha<\alpha^*)$ the value of H_{c2}' becomes independent of conductivity and only slightly depends on disorder via the appropriate behavior of $N(E_F)$ and T_c diminished by the cubic root in the lower expression in (15).

For an anisotropic (quasi-two-dimensional) case we have:

$$(dH^\perp_{c2}/dT)_{T_c} = -\phi_0/(2\pi\xi^2_\parallel T_c)$$

$$(dH^\parallel_{c2}/dT)_{T_c} = -\phi_0/(2\pi\xi_\parallel\xi_\perp T_c) , \tag{16}$$

with $\xi_{\parallel,\perp}$ given above in (9)-(14) and the behavior is similar to that in (15). The most important relation is given by:

$$(H^\parallel_{c2})'/(H^\perp_{c2})' = \xi_\parallel/\xi_\perp = V_F/wa_\perp , \tag{17}$$

and we see that the anisotropy of H_{c2}' is actually determined by the anisotropy of the Fermi velocity irrespective of the regime of superconductivity: from the "pure" limit, through the usual "dirty" case, up to the vicinity of the Anderson transition.

2. SUMMARY OF EXPERIMENTS ON RADIATION DISORDERING IN SINGLE-CRYSTALS OF HIGH-T_c SUPERCONDUCTORS.

The experiments were performed [20,21] on a series of $YBa_2Cu_3O_{7-\delta}$ single-crystals with the sizes of the order of $1\times1\times0.03\,mm^3$ grown from the melt. Initial values of T_c were between 91 and 92K. Anisotropy of electrical resistivity ρ_c/ρ_{ab} at T=300K varied between 40 and 150, and ρ_c demonstrated semiconductor-like temperature behavior. Both ρ_{ab} and ρ_c were measured by the Montgomery method during irradiation by fast neutrons in the core of nuclear reactor at liquid nitrogen temperature. ρ_{ab} increases exponentially with fluence ϕ (i.e. defect concentration) starting from the smallest doses, while ρ_c grows slower, only for $\phi > 10^{19}\,cm^{-2}$ both ρ_c and ρ_{ab} grow with the same rate. T_c rapidly drops with ϕ and there is no superconductivity at $T > 1.5$K for $\phi > 6\times10^{18}\,cm^{-2}$. Anisotropy ρ_c/ρ_{ab} at 80K drops rapidly to the value of order of ≈ 30 for $\phi = 10^{19}\,cm^{-2}$ and then practically does not change. Structural neutronography has shown that lattice changes under such doses of neutron irradiation are rather small [18-21].

From the comparison of these results with earlier data obtained on ceramic samples we may conclude that the exponential growth of electrical resistivity, which was interpreted as a manifestation of hopping-like conduction [18,19] due to localization, is an inherent property of high-T_c superconductors.

The upper critical fields of $YBa_2Cu_3O_{7-\delta}$ single-crystals were measured before and after irradiation in the fields up to 5T. Temperature dependence of H_{c2} in the disordered samples is essentially nonlinear in these fields, especially for samples with low T_c. $(H_{c2}^{\perp})'$ as determined from the high-field region increases with disorder. To obtain unambiguous results it is necessary to perform the measurements in high fields. $(H_{c2}^{\parallel})'$ drops in the beginning and then does not change or increases very slightly. However, the anisotropy of H_{c2} decreases for any field as disorder grows and in the samples with $T_c \approx 10$ K the ratio of $(H_{c2}^{\parallel})'/(H_{c2}^{\perp})'$ is close to unity. These data showing the absence of direct correlation of resistivity and H_{c2} behavior characteristic of "dirty" superconductors (such as the Gorkov relation) can be interpreted as due to closeness to the Anderson transition, or even as a consequence of superconductivity in the localized (insulating) phase [18-21]. From the point of view expressed by (17) the experimentally observed isotropization of slopes of $H_{c2}^{\parallel}$ and $H_{c2}^{\perp}$ under disordering is the manifestation of the isotropization of Cooper pairs. The remanent anisotropy of resistivities may be due to the anisotropy in the scattering mechanism, e.g. due to interplane defects. This behavior shows that just before the destruction of superconductivity the disordered high-T_c oxides become essentially isotropic (from the point of view of their superconducting properties) and we return to three-dimensional H_{c2} behavior. It will be of much interest also to try to observe the predicted $H_{c2}' \propto T^{-1/3}$ behavior (Cf.(15)) as superconductivity vanishes. Note however, that all this analysis assumes more or less smooth disorder dependence of the density of states.

Hall effect data [20,21] obtained on irradiated ceramic samples of $YBa_2Cu_3O_{7-\delta}$ show that the temperature dependence of Hall concentration n_H weakens, remaining linear in the high temperature region as in initial samples. At low T< 100K n_H practically does not change under disordering in sharp contrast with its behavior in oxygen deficient samples. This constancy of n_H for low T under disordering agrees well with the assumption that Anderson localization the main reason for metal-insulator transition under disordering [26,27]. However we must stress that it is difficult to explain the observed temperature dependence of n_H. There is also no unambiguous correlation between n_H and T_c.

3. LOCALIZATION AND DEGRADATION OF T_c.

In the absence of any accepted microscopic theory for T_c in high-T_c oxides it is rather difficult to discuss mechanisms for its degradation under disordering. Among general reasons for a drop of T_c apparently important for any BCS-like model of high-temperature superconductivity we can mention:
(a) growth of Coulomb repulsion within Cooper pairs [11,28];
(b) growth of spin-scattering effects due to the appearance of disorder induced local moments [18];
(c) incipient inhomogeneities due to "statistical fluctuations" near the Anderson transition [17].

Assuming that the experimentally observed exponential growth of resistivity is directly connected with the Mott law for hopping conduction we have analyzed [18-20] the fluence dependence of R_{loc} for radiationally disordered high-T_c oxides. Using these data for R_{loc} and estimating $N(E_F)\approx 5\times10^{33}$ $(\mathrm{erg\,cm})^{-1}$ (for one electron per lattice cell in the free-electron model) and $\Delta\approx 5T_c$ (as for extremely strong coupling regime of superconductivity) we deduced that the inequality (1) determining the critical value of R_{loc} for the observation of superconductivity becomes invalid for $\phi>(5-7)\times10^{18}$ cm^{-2}. This is in surprisingly good accord with experimental data on superconductivity destruction by fast neutron irradiation.

To analyze the R_{loc} dependence of T_c in localized phase we used the exact analysis of Ref. 11 for T_c suppression due to the growth of Hubbard-like repulsion in a single quantum state, which becomes important in Anderson insulator [2,29,5]. Owing to the observed isotropization of superconducting properties under disordering we consider only three-dimensional isotropic case. According to Ref. 11 T_c in a disordered superconductor can be determined from the linearized gap equation:

$$\Delta(\omega)=\lambda\Theta(<\omega>-\omega)\int_0^{<\omega>}\frac{d\omega'}{\omega'}\Delta(\omega')\mathrm{th}\left[\frac{\omega'}{2T_c}\right]-$$

$$\Theta(E_F-\omega)\int_0^{E_F}\frac{d\omega'}{\omega'}K_c(\omega-\omega')\Delta(\omega')\mathrm{th}\left[\frac{\omega'}{2T_c}\right], \qquad (18)$$

where λ is the pairing interaction constant, $<\omega>$ the characteristic frequency range, where the pairing interaction is important,

$$K_c(\omega)=\int d\mathbf{r}\int d\mathbf{r}'\,V(\mathbf{r}-\mathbf{r}')<<\rho_E(\mathbf{r})\rho_{E+\omega}(\mathbf{r}')>>_{E=E_F} \qquad (19)$$

is the generalized Coulomb kernel, where:

$$<<\rho(\mathbf{r})\rho(\mathbf{r}')>>=\frac{1}{N(E_F)}<\sum_{\mu\nu}\phi^*_\nu(\mathbf{r})\phi_\mu(\mathbf{r})\phi^*_\mu(\mathbf{r}')\phi_\nu(\mathbf{r}')\delta(E-\varepsilon_\nu)\delta(E+\omega-\varepsilon_\mu)> \qquad (20)$$

is the spectral density (averaged over disorder) defined by Berezinskii and Gorkov [30] and $V(\mathbf{r}-\mathbf{r}')=V_0\delta(\mathbf{r}-\mathbf{r}')$ is the point-like interelectron interaction. The appearance of

Hubbard-like repulsion in a single (localized) quantum state is directly connected [5] with the characteristic $\delta(\omega)$ -contribution to (18) within the localization region [30], where we get:

$$K_c(\omega) = V_0 A(E_F)\delta(\omega) + \ldots ; \quad A(E_F) \approx R_{\rm loc}^{-3}(E_F) \; . \tag{21}$$

This singular contribution in (18) can be treated exactly and we obtain the following equation for T_c [11]:

$$1 = \lambda \int_0^{<\omega>} d\omega \, \mathrm{th}(\omega/2T_c)[\omega + \mu A(E_F)/2N(E_F)\, \mathrm{th}(\omega/2T_c)]^{-1} \; , \tag{22}$$

where $\mu = N(E_F)V_0$. Approximately (22) reduces to:

$$\ln(T_{co}/T_c) \approx \Psi(1/2 + \mu/[4T_c N(E_F) R_{\rm loc}^3]) - \Psi(1/2) \; , \tag{23}$$

where T_{co} is the initial value of T_c before disordering, $\Psi(x)$ is the digamma-function. Assuming the hopping conduction described by the Mott law [2]:

$$\rho(T) = \rho_0 \exp(Q/T)^{1/4}; \quad Q \approx 2.1\, [N(E_F) R_{\rm loc}^3]^{-1} \; . \tag{24}$$

We may directly express T_c via resistivity $\rho(T_{ex})$ in localized phase of strongly disordered superconductor [18,19] at temperature $T_{ex} > T_c$:

$$\ln(T_{co}/T_c) \approx \Psi\{1/2 + 0.013\mu T_{ex}[\ln(\rho(T_{ex})/\rho_0)]^4\} - \Psi(1/2) \; . \tag{25}$$

This expression gives a rather satisfactory fit to experimental data on $T_c(\rho)$ dependence in high-T_c superconductors disordered by radiation, assuming $\mu \approx 0.3$–1.0 [18,19]. Though speculative in nature this explanation of T_c degradation due to the growth of Coulomb effects may be of some interest.

Among other important data on high-T_c oxides disordered by radiation, we must also keep in mind the disorder - induced appearance of the Curie-Weiss contribution to magnetic susceptibility [18]. According to Mott [2,29] we may also try to connect this contribution with the appearance of single-occupied states in a narrow energy region below the Fermi level, once again induced by the Hubbard-like Coulomb repulsion in a single (localized) quantum state. We may estimate the value p (in Bohr magnetons) of the localized moment due to this mechanism as [5]:

$$p^2 = \mu R_{\rm loc}^{-3} \Omega_0 \; , \tag{26}$$

where again $\mu = N(E_F)V_0$ is the dimensionless Coulomb potential, Ω_o is the volume of a unit cell. For large disorder ($\phi = 2\times10^{19}\ \mathrm{cm}^{-2}$) we estimate [18] $R_{\rm loc} \approx 8\,\mathrm{\AA}$ and for $\mu \approx 1$ we get $p^2 = 0.66$ for $YBa_2Cu_3O_{7-\delta}$, which is in precise agreement with experimental value of 0.661 determined from Curie constant. However for smaller degrees of disorder (fluences) p^2 estimated from (26) is considerably smaller than experimental data. Here we must note that (26) is valid only for rather small values of $R_{\rm loc}$ (deep in the localized region), when we can neglect overlap of localized states, and that Curie constants are determined in weakly disordered samples with considerably less accuracy than in case of strong disorder owing to smaller values of the Curie-Weiss contribution and the small interval of T where this contribution is observed (because of high-T_c). If we estimate T_c via (23) using R_{loc} determined from (26) and experimental data for Curie constant, then even at $\phi=2\times10^{18}\,cm^{-2}$ we obtain $T_c \approx 15$ K. This discrepancy may be not so impressive taking into account the crude nature of our analysis as well as other important contributions to Coulomb suppression of T_c [11,28]. The question remains however, if there is also additional suppression of T_c by magnetic moments themselves, or why do they have so little influence on superconductivity?

CONCLUSION

The extreme sensitivity of high-T_c oxides to disordering may have several explanations, some among them based upon the idea of exotic types of pairing. However, here we presented another point of view: that this instability of T_c can be explained as due to Anderson localization. The quasi-two-dimensional nature of high-T_c oxides (with $T_c > 30K$) leads to significant enhancement of localization effects at relatively weak disorder. This may help to realize rather exotic situation of superconducting transition in the system of localized states (Anderson insulator). High-T_c oxides are especially promising in this respect owing to the small size of the Cooper pairs, so that there may be a wide region where the localization length is larger than the Cooper pair. There is some serious evidence that such a situation is actually realized in high-T_c superconductors disordered by radiation, although much more work is needed to confirm the specific predictions of the theory, as well as further theoretical analysis of microscopic mechanisms of T_c in highly-disordered systems. An important theoretical problem for further studies concerns the role of "statistical fluctuations" in quasi-two-dimensional systems. It was shown in Ref. 17 that these incipient inhomogeneities become important near the Anderson transition and roughly speaking lead to rather substantial smearing of the superconducting transition, as actually is seen in the experiments. We need further theoretical analysis of measurable characteristics such as critical fields, specific heat, etc.

Especially important may be experiments on radiation disordering in isotropic oxides like $Ba_{1-x}K_xBiO_3$, where a different behavior can be expected: these oxides may be more stable to disordering like A-15 or Chevrel phases.

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