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Effects of Localisation in Atomic-Disordered High-T_c Superconductors

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ABSTRACT

The influence of disordering on the properties of high-T_c superconductors is investigated. The results show that pairing takes place in the systems of localised electrons even in slightly disordered samples. Superconductivity exists till radius of localisation exceeds the typical size of Cooper pairing in highly disordered system.

INTRODUCTION

Fast neutron irradiation is one of the most pure methods to investigate effects of disordering on physical properties of high-temperature superconductors (HTSC). It is known that disorder which is not connected with magnetic impurities according to Anderson theorem should not appreciably affect superconducting transition temperature T_c of the conventional (wide-band) superconductors. However, the properties of such superconducting compounds as A-15, C-15 and Shevrel phases turn out to be highly sensitive to disorder. Thus, response of the system to introduction of defects helps to better understand the peculiarities of its electronic properties in the ordered state characterised in our case by high values of T_c.

Previously [1-3] we have shown that disordering of YBaCuO and LaSrCuO leads to a rapid decrease in T_c. The derivative of the upper critical field H'_{c2} practically does not change. At large fluences instead of linear dependence the Mott-type temperature dependence of $\rho(T)$ is observed in the temperature interval $5 < T < 300K$:

$$\rho(T) = A\exp(Q/T^{1/4}), \quad Q = 2.1\left[N(E_F)R_{loc}^3\right]^{-1/4}. \qquad (1)$$

While measuring ρ of both systems at 80 K directly during fast neutron irradiation we found that ρ_{80} grows exponentionally with fluence Φ, i.e. $\rho_{80} \sim \exp(a\Phi)$ beginning with the smallest Φ. The observed variation of ρ depending both on fluence and temperature may be described using the empirical formula [1]:

$$\rho(T) = f(T)\exp\left(a\Phi/T^{1/4}\right). \qquad (2)$$

According to experimental data localisation effects are essential in these systems even at the smallest extent of disorder.

The present study is further investigation of localisation effects in high T_c superconductors including BiSrCaCuO (zero resistivity at T=70 K, $\rho_{300} \approx 2$ mohm·cm and linear temperature dependence of ρ (T)),single-crystal sample of YBaCuO ($T_c \approx 80$ K, $\rho_{300} \approx 2$ mohm·cm). Here we investigated also the influence of isochronous low-temperature annealing ($T_{ann} \leq 300$ K) on electrical resistivity of high-

T_c materials disordered under fast neutron irradiation (T_{irr} = 80 K). Besides, we present here the data on the NQR spectrum and spin-lattice relaxation time T_1 for the sample of $YBa_2Cu_3O_{6.95}$ irradiated by a fluence of 5 x 10^{18} cm^{-2}.

EXPERIMENTAL RESULTS

Radiation disordering, deviation from oxygen stoichiometry, introduction of impurities into Cu sublattice suppress superconductivity in $YBa_2Cu_3O_{7-\delta}$. Structural changes are different in all cases. Orthorhombic parameter (b-a) gradually decreases with decreasing oxygen content. In this case oxygen is removed from sites O4 (in chains). As for sites O5, they are filled slightly with increasing ρ just before the tetragonal phase transition [4] . Radiation disordering results in oxygen distribution over sites O4 and O5 and growth of the mean-quadratic atomic displacements. The structure, however, remains orthorhombic. Appearance of oxygen vacancies in sites O4 is well seen in the NQR spectra for the irradiated sample of YBaCuO (Fig.1). The structure of the NQR line on the ^{63}Cu atoms in Cu2 site is associated with vacancy configurations in O4 sites as well as in oxygen-deficient samples [5] . Spin-lattice relaxation time T_1 on ^{63}Cu nuclei in Cu2 sites in normal state ($T > T_c$) increases from 0.5 to 150 msec on changing the oxygen content from $\delta \approx 0$ to $\delta \approx 0.2$. Radiation disordering ($T_c \approx 70$ K, Φ = 5 x $10^{18} cm^{-2}$) leads also to increase in T_1 but to a lesser extent. Assuming that the whole T_1 increase is connected with the change of electron states density on the Fermi level $N(E_F)$ it will decrease more than by order in the first case and by 25% in the second. Distribution of relaxation times over Cu1 sites of the irradiated sample points to appearance of disorder in the electron environment of the Cu atoms in these sites. Measuring T_1 in a superconducting state ($T_c \approx 70$ K) of the irradiated sample yields the value $2\Delta/kT_c \sim 12$ (as in the initial sample). This evidences a very strong coupling regime (bearing in mind the maximum value of a gap). In an oxygen-deficient sample with approximately the same T_c ($\delta \approx 0.2$) the value of a reduced gap decreases to $2\Delta/kT_c \sim 4$-6 for both sites of the Cu atoms. Temperature independent contribution to magnetic susceptibility χ_0 also behaves differently in both cases under consideration, i.e. it drops with increasing δ and grows under irradiation. Growth of χ_0 under irradiation and simultaneous increase of spin-lattice relaxation time shows that an attempt to explain their change only by $N(E_F)$ variations leads to a contradiction.

Variation of the oxygen content directly alters electron structure of the YBaCuO system since the concentration of charge carriers changes. Radiation disordering affects the electron structure only through disorder. Differences in behavior of

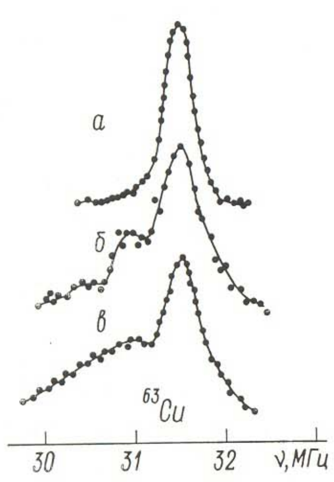

FIGURE 1. Evolution of the NQR spectrum on the ^{63}Cu nuclei in Cu2 site for $YBa_2Cu_3O_{7-}$:a)δ=0.05; б) the sample irradiated by a fluence of 5 x $10^{18}cm^{-2}$($T_c \approx 70$ K); B) δ = 0.2 ($T_c \approx 70$ K). Frequency is given in MHz.

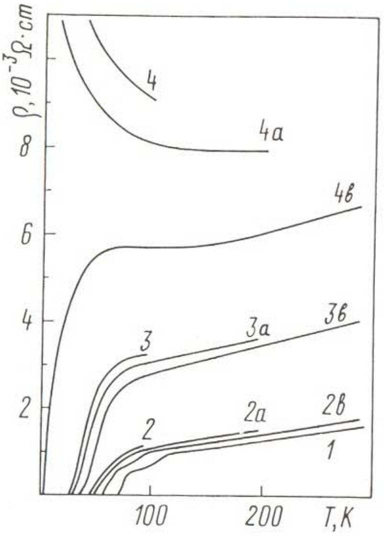

FIGURE 2
Temperature dependence of electrical resistivity for the disordered BiSrCaCuO sample: 1)the initial sample; 2) ϕ = 2 x x 10^{18}; 3) ϕ = 5 x 10^{18}; 4) ϕ =7 x 10^{18} cm^{-2}. Indexes a and b correspond to annealing at T = 200 K and T = 300 K, respectively.

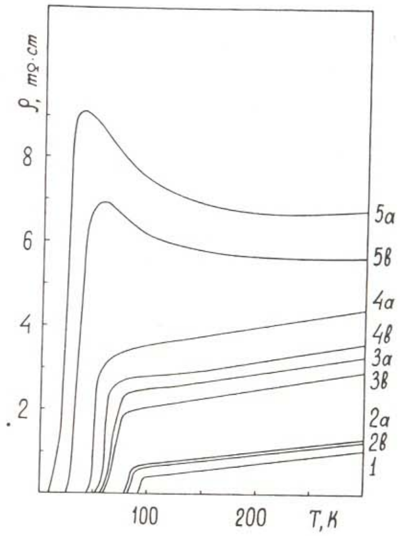

FIGURE 3
Temperature dependences of electrical resistivity for the disordered $YBa_2Cu_3O_{6.95}$ samples: 1)the initial sample; 2) ϕ = 2 x 10^{18}; 3) 5 x 10^{18}; 4) 7 x 10^{18}; 5) 10 x 10^{18} cm^{-2}. Indexes a and b correspond to annealing at T = 300 K for 20 min and two weeks

YBaCuO on introduction of defects of different types underline, however, the general property: degeneration of T_c always goes with transition to dielectric behavoir of resistivity.

The samples of BiSrCaCuO, as well as YBaCuO, with high enough T_c (relatively small disordering) are characterised by linear growth of electrical resistivity with temperature (Figs.2,3). Increasing extent of disorder leads to exponential temperature dependence of electrical resistivity described by eq.(1). After annealing for 20 min at T = 300 K T_c appears and linear dependence of ρ (T) reestablishes practically within the whole temperature range beginning from T_c to 300 K. For $\phi \geq 10^{19} cm^{-2}$ annealing at T$\leq$300 K leads only to decrease in coefficients A and Q in eq.(1) while T_c does not appear at all. Fig.4 shows the dependence of ρ_{80} on fluence of fast neutrons for materials under study. The value of ρ_{80} grows exponentially with fluence. According to measurements made in the basal plane of a single crystal YBaCuO sample exponential growth of resistivity of ρ_{80} is the property of the material itself and not the consequence of the preparation technique of ceramic samples. The data from Fig.4 as well as the behavior of dH'_{c2}/dT [6] and ρ(T) in the disordered HTSC sample show that localisation effects are likely to appear well before the disappearance of T_c. But the superconducting transition does not allow to observe this experimentally on the temperature dependence of ρ(T).

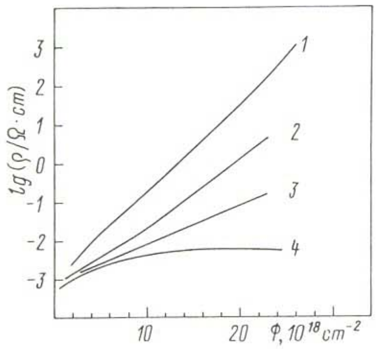

FIGURE 4. Dependences of ρ_{80} on fluence of fast neutrons for ceramic and single-crystal YBaCuO samples (curve 1 and 2, respectively), BiSrCaCuO (3) and $SnMo_6S_8$ (4).

DISCUSSION

It is well known that full enough disorder may result in the metal-insulator transition due to electron localisation (Anderson transition). Anderson showed [7] that in localised electron system Cooper pairing may take place only between the electrons with centres of localisation lying within the sphere of the order of localisation length R_{loc}. The states of such electrons are splitted by energy to a value of the order $[N(E_F)R^3_{loc}]^{-1}$ [8] . Apparently the condition should be held that the value of a superconducting gap Δ (at T=0) is essentially higher than the value of this splitting :

$$\Delta \sim T_c \gg \left[N(E_F) R^3_{loc} \right]^{-1} \qquad (3)$$

Eq.(3) is equivalent to the requirement that localisation radius should be essentially higher than the typical size of the Cooper pair in highly disordered systems [6] . Using experimental data on electrical resistivity for the disordered samples of $YBa_2Cu_3O_{7-\delta}$ (for fluences of $\Phi > 5 \times 10^{18} cm^{-2}$) and empirical formula (2) for smaller fluences one may calculate the variation of localisation radius R_{loc} as a function of fluence. On the other hand eq.(3) gives the limited values of R_{loc}, at which superconductivity may still exist in the system of localised electrons. Assuming that for all fluences $N(E_F) = 5 \times 10^{33}$ $(erg \cdot cm^3)^{-1}$ (in the model of free electrons this corresponds to one electron per a unit cell, i.e. a carrier concentration of $6 \times 10^{21} cm^{-3}$) and the left-hand side of eq.(3) equals 5 T_c, one will obtain the result shown in Fig.5. From this figure it is seen that eq.(5) is not valid for $\Phi >$ (5-7) x $10^{18} cm^{-2}$. Bearing in mind the qualitative character of this estimate it should be noted that it is in surprisingly good agreement with the experiment. Fig.5 allows to easily interprete the data concerning the influence of low-temperature annealing. In the vicinity of $\Phi \sim$ (5-7) x $10^{18} cm^{-2}$ annealing results in R_{loc} increasing, eq.(3) is valid and superconductivity appears. At high fluences low-temperature annealing is not enough for appearance of superconductivity.

From the given estimates, however, it is not clear why the superconducting transition temperature should drop for high (in comparison with the limited) values of R_{loc}. It is difficult to make a conclusion about the reasons of T_c decreasing with increasing disorder because of lack of theoretical understanding of the nature of T_c in HTSC. However, proceeding from the traditional considerations about the pairing interaction one may expect that one of the reasons for suppression of T_c may be connected with the growth of the Coulomb pseudopotential μ^* ,

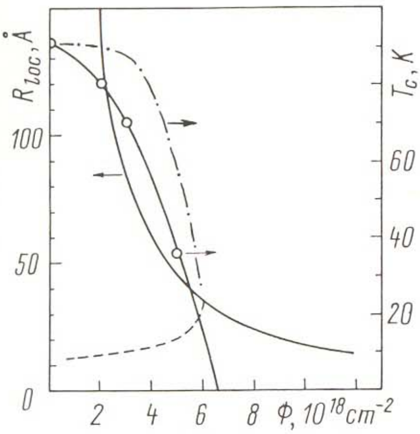

FIGURE 5. Dependence of R_{loc} (solid line) and T_c (open circles) on fluence of fast neutrons for YBaCuO. The dashed line shows the values of R_{loc} calculated by eq.(3). The dash-dot line shows the values of T_c calculated by eq.(5).

which describes Coulomb repulsion of electrons forming the Cooper pair. This effect is connected with growing lag effects of Coulomb repulsion in Cooper pair with decreasing diffusion coefficient during the Anderson transition. According to [6] in localisation region we have

$$\ln \frac{T_{co}}{T_c} = \Psi\left(\frac{1}{2} + \frac{\mu A_{E_F}}{4\pi T_c N(E_F)}\right) - \Psi\left(\frac{1}{2}\right), \tag{4}$$

where Ψ is the digamma function, $\mu = V_0 N(E_F)$ is the Coulomb potential, $A_{E_F} \sim R_{loc}^{-3}$. This formula describes T_c suppression due to growing effects of Coulomb repulsion in a single quantum (localised) state. Taking into account eqs.(1) and (2) from eq.(4) we get

$$\ln \frac{T_{co}}{T_c} = \Psi\left(\frac{1}{2} + \frac{\mu T \left(\ln \frac{\rho(T)}{A}\right)^4}{4\pi T_c (2.1)^4}\right) - \Psi\left(\frac{1}{2}\right). \tag{5}$$

Then using the data from Fig.4 and assuming that $\mu \approx 1$ one may easily calculate T_c as a function of disordering extent (Fig.5). As for the functional dependence it slightly differs from the experimental one (note that in the theoretical curve the derivative $dT_c/d\Phi \to 0$ for $\Phi \to 0$) however, the qualitative agreement is out of question. Faster suppression of T_c at small extent of disorder observed experimentally may be connected with additional regular contribution of electron densities correlator which was neglected in eq.(4).

This approach helps to elucidate some typical features in behavior to disordered HTSC. The fact that these materials are close to Anderson transition metal-insulator and the existence of superconductivity with high enough T_c in a system of localised electrons is likely to be a specific feature of HTSC. This "nonmetalic" behavior of these compounds becomes evident when comparing, for example, with A-15 superconductors. The latter behave themselves more like metals than HTSC's. As for the superconductors with the structure of Shevrel phase, they present an intermediate case between the A-15 and HTSC.

CONCLUSION

Quasi-two-dimensional systems to which the superconductors under study belong are expected to show strengthening of effects of localisation that occurs at values of conductivity appreciably exceeding typical values of three-dimensional systems The properties of electronic system of HTSC's make them close to Anderson metal-insulator transition even in the ordered state. This feature differs new HTSC's from previously known superconductors of other systems. In the first case pairing is likely to occur in systems of localised electrons even at the smallest disorder. T_c sharply decreases when at low temperatures the dependence ρ (T) of type (1) is observed. Superconductivity is fully suppressed when energetic splitting between the localised states becomes comparable with the value of a superconducting gap.

REFERENCES

1. S.A.Davydov, A.E.Karkin et al. Pis'ma JETP 47, 193 (1988).
2. B.A.Aleksashin, I.F.Berger et al. Effect of disordering on the properties of high-T_c superconductors, in : Proceedings of M^2HTSC (Switzerland, Interlaken, 1988).
3. B.A.Aleksashin, I.F.Berger et al. Effect of disordering on the properties of high-T_c superconductors, in : Series of preprints of scientific reports "Problems of high-temperature superconductivity" (USSR, Sverdlovsk, 1988) N1.
4. V.I.Voronin et al. to be published.
5. V.V.Serikov, Yu.I.Zhdanov, S.V.Verkhovskii. Pis'ma JETP 47, 571 (1988).
6. L.N.Bulaevskii, M.V.Sadovskii. Pis'ma JETP 39, 524 (1984); J.Low Temp.Phys. 59, 89 (1985).
7. P.W.Anderson. J.Phys.Chem.Solids 11, 26 (1959).
8. N.F.Mott, E.A.Davis, Electron Processes in Non-Crystalline Materials (Clarendon Press, Oxford, 1979).