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HIGH TEMPERATURE SUPERCONDUCTIVITY FROM RUSSIA

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A.I. Larkin
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EFFECTS OF LOCALISATION IN ATOMIC-DISORDERED HIGH T_c SUPERCONDUCTORS

B.N.Goshchitskii, S.A.Davydov, A.E.Karkin, A.V.Mirmelstein,
M.V.Sadovskii, V.I.Voronin

Institute for Metal Physics and Institute of Electrophysics,
USSR Academy of Sciences, Ural Branch, 620219 Sverdlovsk
GSP-170, USSR

ABSTRACT

The influence of disordering induced by fast neutron irradiation at 80 K on physical properties of the oxidic ceramics $RBa_2Cu_3O_{7-\delta}$ (R=Y,Ho,Er), $La_{1.83}Sr_{0.17}CuO_{4-y}$, Bi-Sr-Ca-Cu-O and a single crystal $YBa_2Cu_3O_{7-\delta}$ has been investigated. The obtained results show that localisation states exist in the system even at small disorder. The effects are interpreted in terms of the localisation theory.

1. INTRODUCTION

A comprehensive study of new high-temperature superconductors (HTSC) started after their discovery in 1986 [1] allowed to establish important experimental facts characterising superconductivity of these oxides. Fast neutron irradiation is one of the most developed methods used to affect ordered compounds in order to obtain unique information about their properties. This method allows to carefully introduce defects macroscopically homogeneously distributed over the volume of the sample to study the behavior of T_c and other properties during disorder with high reproducibility of results, the stoichiometry being unchanged. As known decrease in the electron free path ℓ with increasing concentration of defects does not itself affect the value of T_c in ordinary wide-band

superconductors [2] . However, in A-15 compounds an essential variation of T_c during disorder may be explained by variation of such parameters as $N(E_F)$ (the density of electron states at Fermi level) and $\langle\omega\rangle$ (typical phonon frequencies) due to substantial rebuilding of a crystal structure at high defect concentration. Electrical resistivity in this case shows the behavior characteristic of metals, i.e.: for small fluences of fast neutrons Φ residual electrical resistivity ρ(o) grows proportionally to Φ , while for high Φ it saturates at the values of the order of 150-300 ohm·cm. The derivative $d\rho/dT$ decreases with increasing ρ(o) and when ℓ is close to interatomic distance $\rho(T)$ practically does not depend on temperature [3] . This is not the case for HTSC. Disorder caused by neutron irradiation decreases T_c and leads to qualitatively different changes in electrical resistivity, viz.: linear dependence of electrical resistivity ρ(T) transforms into exponential characteristic of "jump-like" conductivity by localised states [4] . The first investigations on HTSC irradiated by fast neutrons have already shown [4-7] that disorder alters their properties in such a combination that has never been observed experimentally.

Here in terms of the localisation theory we'll discuss the previous [4-7] and new results including BiSrCaCuO (zero resistivity at T=70 K, $\Delta T_c \simeq 10$ K, $\rho_{120} = 0.95 \times 10^{-3}$ ohm·cm, $\rho_{300}/\rho_{100} = 1.8$), $RBa_2Cu_3O_{7-\delta}$, where R=Ho,Er, and a single crystal $YBa_2Cu_3O_{7-\delta}$ ($T_c \simeq 80$ K, $\rho_{300} \simeq 2$ mohm·cm) as well as effects of low-temperature annealing on T_c and electrical resistivity of HTSC disordered under fast neutron irradiation (T_{irr} = 80 K).

300K while non metallic dependence $\rho(T)$ ($d\rho/dT < 0$) still remains. In $La_{1.83}Sr_{0.17}CuO_{4-y}$ and $YBa_2Cu_3O_{6.95}$ the value of the derivative of the upper critical field H'_{c2} remains the same (within the experimental uncertainty connected with broadening of the transitions) with increasing by order. Note that in metallic ordered compounds increasing electrical resistivity should lead to increase in H'_{c2} observed previously in the irradiated A-15 [3] and Shevrel phases [8].

At small fluences of fast neutrons $\Phi < 5 \times 10^{18} cm^{-2}$ $\rho(T)$ remains linear for $T > T_c$. For (5-10) x $10^{18} cm^{-2}$ the $\rho(T)$ curves are characterised by simultaneous presence of the fractions with $d\rho/dT > 0$ and $d\rho/dT < 0$ at high and low temperatures, respectively. For $\Phi > 1 \times 10^{19} cm^{-2}$ $\rho(T)$ is described by the known formula

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

Radiation effects in HTSC induced by fast neutron irradiation at t=80K are relatively unstable, i.e.: isochronous annealing for 20 min at T=200 and 300K leads not only to partial recovery of T_c but also of $\rho(T)$ (Figs.2,3). Fig.4 depicts exponential growth of ρ_{80K} with increasing fluence (measurements

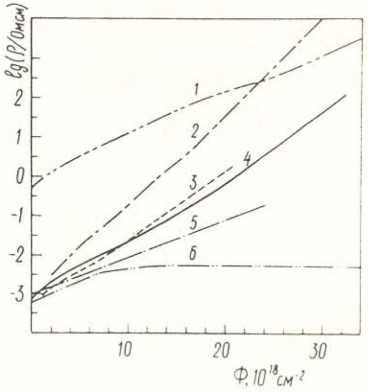

FIGURE 4. Dependence of $lg\,\rho$ on fluence obtained during irradiation at 80K. 1)La_2CuO_4; 2)$YBa_2Cu_3O_{6.95}$; 3)single crystal YBaCuO, ρ is measured perpendicular to the c-axis; 4)$La_{1.83}Sr_{0.17}CuO_4$; 5)BiSrCaCuO; 6) $SnMo_6S_8$.

are performed directly during irradiation). Here we present also the analogous dependence for $SnMo_6S_8$ electrical resistivity of which is proportional to fluence for small and saturates for large Φ, respectively. The observed variation of ρ depending both on fluence and temperature may be described by the empirical formula [4] :

$$\rho(T) = f(T)\exp(a\,\Phi/T^{1/4}). \tag{2}$$

3. DISCUSSION

Though the dependence of type (1) is observed directly in the experiment only at large fluences (when T_c is either low or absent) localised states are likely to occur well before. Exponential growth of $\rho(T)$ during irradiation beginning from the smallest fluences as well as invariability of the derivative H'_{c2}, inspite of fast growth of electrical resistivity, and , probably, Curie-Weiss contribution to magnetic susceptibility [6] may be naturally considered as the evidence for existence of the localised states even in a slightly disordered sample (since the nature of temperature linear dependence of $\rho(T)$ in the initial sample is not clear it can't be evidence for absence of the localised states). Hence, suppression of superconductivity may be assumed to be connected not with the appearance of the localised states itself but with appreciable decrease in localisation radius with increasing disorder in the system. In the system with strong two-dimensional anisotropy of conductivity the minimum value of metallic conductivity may be appreciably higher than that typical of the three-dimensional isotropic system, viz. (3-5) x 10^2 $ohm^{-1}cm^{-1}$, and reach the value of $\geqslant 10^3$ $ohm^{-1}cm^{-1}$

for the compounds under study [9]. In terms of these estimates even the initial HTSC samples used in our investigations may be considered to close to Anderson transition.

In the isotropic three-dimensional system we have [10]:

$$-\frac{\sigma}{N(E_F)}\left(\frac{dH_{c2}}{dT}\right)_{T_c} = \begin{cases} \frac{8e^2}{\pi^2\hbar}\,\phi_0\,, & \sigma > \sigma^* \\ \frac{\varphi_0}{2\pi}\,\frac{\sigma}{[N(E_F)T_c]^{1/3}} \sim \frac{\phi_0\,\sigma}{2\pi T_c(\xi_0\ell^2)^{2/3}}\,, & \sigma < \sigma^* \end{cases} \qquad (3)$$

Here H_{c2} is the upper critical field, ϕ_0 is the magnetic flux quantum, σ is conductivity, ℓ is the electron free path, $\sigma^* = \sigma_c\ (T_c/E_F)^{1/3}$ is the typical conductivity, $\sigma_c = e^2 p_F/\pi^3\hbar^2$ is the minimal metallic conductivity by Mott [11]. Thus, in the vicinity of the metal-insulator transition, when $\sigma < \sigma^*$, the relation of Gor'kov (the upper expression in eq.(3)) is not valid, and further H'_{c2} does not depend on σ. Such a behavior is observed experimentally for ceramic samples [6]. As for the quasi-two-dimensional systems $(H_{c2}^{\parallel,\perp})'$ shows qualitatively the same behavior for $\sigma < \sigma^*$. Experiments on single crystals undertaken now will help us to elucidate this problem in details.

Anderson showed [2] that for a given pairing interaction near the Fermi level assuming that superconducting order parameter is self-averaging T_c does not practically depend on whether the states are delocalised or localised. The only restriction existing for localised states is connected with the known discreteness of the electron spectrum in the localisation region (repulsion level effect) [11]. The states close enough by energy are located on large distances from each other. 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}. However, these states are splitted by energy to the value of order $[N(E_F)R^3_{loc}]^{-1}$ [11]. Apparently the condition should be held that the value of the superconducting gap Δ (at T=0) is essentially higher than the value of this splitting:

$$\Delta \sim T_c \gg \left[N(E_F)\,R^3_{loc}\right]^{-1}, \qquad (4)$$

i.e. the energy interval $\sim\Delta$ should contain a lot of discrete levels with the localisation centres being within the region R_{loc}. Eq.(4) is equivalent to the requirement that R_{loc} should be essentially higher than the typical size of Cooper pair in highly disordered system [10]. This is the qualitative criterion for existence of superconductivity in the Anderson insulator.

Using the experimental data on electrical resistivity of the radiation-disordered $YBa_2Cu_3O_{7-\delta}$ samples (for $\Phi > 5\times10^{18}\,cm^{-2}$) and the empirical formula (2) for less fluences

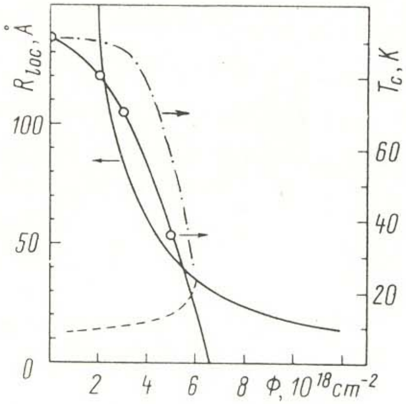

FIGURE 5. Dependence of T_c on fluence for YBaCuO (—o—). The solid line shows R_{loc}, calculated by formulas (1) and (2); dash-dot line shows T_c calculated by eq.(5a); dots show the minimal R_{loc} at which there may exist superconductivity with the given T_c according to eq.(3) (refer to the text).

one may calculate variation of R_{loc} depending on fluence. On the other hand, eq.(4) yields the limiting values of R_{loc} at which superconductivity may still exist in the system of localised electrons. Suppose that the left-hand side of eq.(4) equals $5T_c$ and for all fluences $N(E_F) = 5 \times 10^{33} (\mathrm{erg \cdot cm^3})^{-1}$ (here only the order of magnitude is of importance) one obtains the result shown in Fig.5. It is seen that the criterion of eq.(4) is not held for $\Phi > (5-7) \times 10^{18}\,\mathrm{cm}^{-2}$, being in good agreement with the experiment.

From the given estimates it is not clear why T_c should drop for high (in comparison with the limiting ones) values of R_{loc}. It is difficult to make a conclusion about the reason of T_c decreasing with increasing disorder because of lack of theoretical understanding of the nature of T_c in HTSC. Besides, in terms of the traditional considerations about the pairing interaction one may assume that suppression of T_c is connected with increasing effects of Coulomb repulsion in a single quantum (localised) state. According to [10] in the localisation region we have:

$$\ln \frac{T_{co}}{T_c} = \Psi\left(\frac{1}{2} + \frac{\mu A_{E_F}}{4 T_c N(E_F)}\right) - \Psi\left(\frac{1}{2}\right), \qquad (5)$$

where Ψ is the digamma function, μ is the Coulomb potential, $A_{E_F} \approx R_{loc}^{-3}$. For T_c calculations it is convenient to express the argument of Ψ -function through resistivity using eq.(1):

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

Now dependence of T_c on disorder may be easily calculated using the values of resistivity $\rho(T=80K)$ from Fig.4 and

assuming that $\mu \approx 1$ (Fig.5). The functional dependence $T_c(\Phi)$ differs slightly from the experimental one (in the theory $dT_c'/d\Phi \to 0$ for $\Phi \to 0$). However, the qualitative agreement is out of question.

4. CONCLUSION

In terms of the localisation theory one manages to elucidate some typical features of the behavior of disordered HTSC. A number of the experimental facts, however, remains unexplained, for example, magnetic moments (although for small R_{loc} it is principally possible from the considered point of view), variation of spin-lattice relaxation rate on ^{63}Cu, heat capacity during disorder etc. [4,9] . Nevertheless, one may state that the fact that these materials are close to Anderson metal-insulator transition and existence of superconductivity with high enough T_c in the system of localised electrons is likely to be a specific feature of HTSC. This "non-metallic" behavior of these compounds becomes more evident when comparing, for example, with A-15 superconductors. With all their peculiarities the latter behave more like metals than HTSC. As for superconductors with the structure of the Shevrel phase, they present an intermediate case between the A-15 and HTSC, though they have lower T_c values than A-15.

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HIGH - T_c CERAMIC WEAK LINKS, rf-SQUIDs and THEIR APPLICATIONS

N.V.Zavaritsky and V.N.Zavaritsky
Institute for Physical Problems, USSR Academy of Sciences
117334 Moscow
General Physics Institute, USSR Academy of Sciences, 117942 Moscow

Abstract

123 : YBCO - ceramic "weak link" with dimensions of ~ $(10^{-2}\text{cm})^3$ have displayed point contact Josephson junction characteristics in interference contour and under microwave radiation. Possibility of active devices realization with operation range up to 3.5 10^{12} Hz at 77 K was confirmed by superior order Shapiro steps up to $n \geq 100$ at 35.5 GHz observation on "weak links" characteristics. Rf-SQUIDs operated up to 90 K with external field sensitivity reduced by ambient noise to $2.10^{-8}\,\text{Oe}\cdot s^{1/2}$ and flux noise of $5\cdot 10^{-4}\Phi_o\cdot s^{1/2}$ for single- and double-hole sensors at 77K correspondingly were produced and studied. The applications of these SQUIDs were briefly discussed and illustrated by ceramic shields and magnetic moment investigations.

1. Introduction

Recent discovery of ceramic oxide superconductors with critical temperatures well above that of liquid nitrogen has opened up the potential for use of superconductivity at readily accessible cryogenic temperatures. Possible applications of such a materials fall broadly into categories of power engineering and active devices. Realisation of devices based on a weakly coupled superconductors seems to be more attainable, for they do not need high values of critical current densities, than those from the first category, which need.

The preliminary results have shown that a sample of high-T_c ceramic intrinsically consists of superconducting grains connect-