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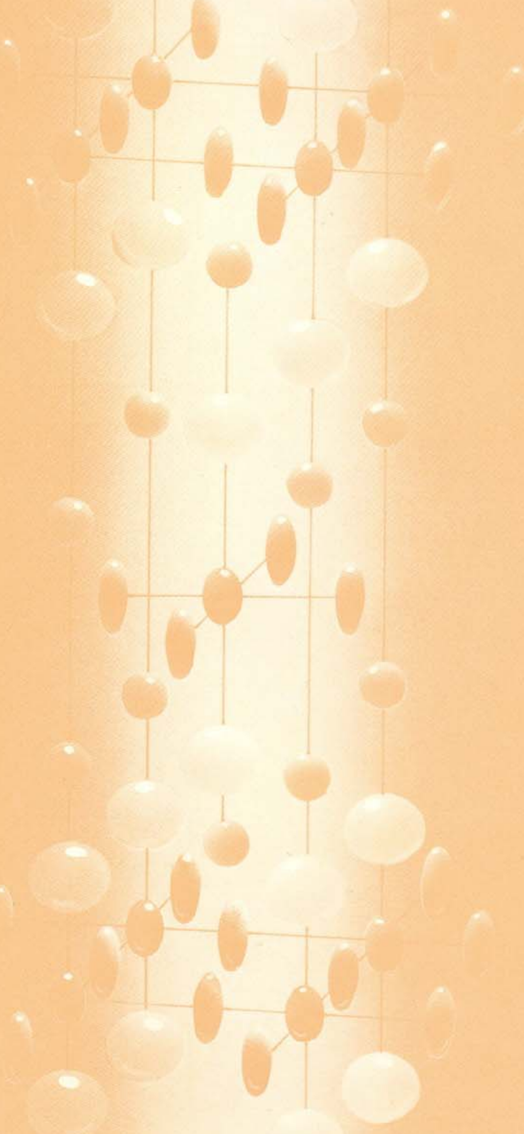

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LOCALIZATION EFFECTS IN RADIATIONALLY DISORDERED HIGH-TEMPERATURE SUPERCONDUCTORS: THEORETICAL INTERPRETATION

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ABSTRACT: *Theoretical interpretation of recent experiments on radiationally disordered high-temperature superconductors is presented, based on the concepts of mutual interplay of Anderson localization and superconductivity.*

Fast neutron irradiation is probably purest method to investigate the effects of disordering on physical properties of high-temperature superconductors, due to the absence of any chemical effects in case of low temperature irradiation [1-5]. The growth of structural disorder leads to rather drastic changes in the behaviour of HTSC systems [1-5], both ceramics and single-crystals:

(a) continuous metal-insulator transition (from linear T behaviour of resistivity to Mott $T^{-1/4}$ hopping law) at very slight disordering;
(b) rapid degradation of superconductivity (fast drop of T_c with disorder);
(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 [4] using the idea of possible coexistence of Anderson localization and superconductivity [6,7].
In the following we present the basic theoretical concepts on the interplay of localization and superconductivity, especially for the strongly anisotropic (quasi-two-dimensional) HTSC systems [4].

Basically the appearance of Cooper pairing does not depend on the nature of electronic states (extended or localized), pairs can be formed of exact eigenstate $\varphi_\nu(r)$ in the random field and its time-reversed partner $\varphi^*_\nu(r)$ [6-9] (with opposite spins in case of singlet pairing). This is valid for localized states until [6,7]:

$$T_c \gg (N(E_F)R^3_{loc})^{-1}$$
$$R_{loc} \gg \xi \sim (N(E_F)\Delta)^{-1/3} \sim (\xi_0 h^2/p_F^2)^{-1/3} \quad (1)$$

where $\xi_0 \sim hv_F/T_c$ is the BCS coherence length, R_{loc}- localization radius, $N(E_F)$- density of states at the Fermi level, T_c and Δ -superconducting transition temperature and gap, p_F- Fermi momentum. The physical meaning of (1) is obvious: R_{loc} must be greater than characteristic size of a Cooper pair near Anderson transition [6].
There are several reasons opposing the Cooper pairing

near the Anderson transition:
(a) growth of Coulomb repulsion within the pair[6];
(b) growth of spin fluctuations [1-4];
(c) "statistical" fluctuations (incipient inhomogeneities at the transition [7]).

These lead to the rapid destruction of superconductivity inside the localization region [6,7] in accordance with the experiment [1-5].

Considerable importance of localization effects in HTSC is primarily due to a quasi-two-dimensional nature of most of these materials: localization is much easier to be achieved in such systems[9,10]. In particular this can be seen from the following estimate of the "minimal metallic conductivity" (i.e. conductivity scale near continuous Anderson transition)[4,10] for in-plane conduction:

$$\sigma_c^{\parallel} \simeq \frac{1}{\pi^2} e^2/ha \ \ln(\sqrt{2}h/w\tau) \quad (2)$$

where $a_\perp$ is interplane distance, w - interplane transfer integral, τ - is the mean free time. Due to a smallness of w in comparison to the Fermi energy E_F, $\sigma_c^{\parallel}$ can be considerably enhanced in comparison with Mott estimates of $\sigma_c \sim 10^2\ \mathrm{Ohm^{-1}cm^{-1}}$.
For realistic values of parameters for HTSC systems this enhancement may be up to an order of magnitude, so that even the best samples available at the moment (both ceramic and single-crystalline) are in fact very close to the Anderson transition. This explains the development of metal-insulator transition in quasi-two-dimensional HTSC at very low disordering[1-5]. It would be very important to perform similar experiments with fast neutron irradiation for isotropic three-dimensional HTSC e.g. $Ba_{1-x}K_xBiO_3$ which from our point of view must be rather more stable to the disorder induced metal-insulator transition.

G-L coefficients, and especially that of gradient term, are significantly changed close to the Anderson transition[6]. We give here basic results for quasi-two-dimensional case[4]. For these coefficients we have:

$$C_{\parallel,\perp} = N(E_F)\,\xi^2_{\parallel,\perp} \quad (3)$$

where $\xi_\parallel$ and $\xi_\perp$ actually define the in-plane and out-of-plane size of Cooper pair. Two important limits are determined by the condition:

$$w^2\tau/2\pi T_c h \gtrless 1$$
$$\text{i.e. } \xi_\perp \sim \sqrt{\xi^0_\perp l_\perp} \gtrless a_\perp \quad (4)$$

where $\xi^0_\parallel \sim hv_F/T_c$, $\xi^0_\perp \sim hwa_\perp/T_c$ are BCS values of coherence lengths, $l_\parallel = v_F\tau$, $l_\perp = wa_\perp\tau$ - are longitudinal and transverse mean free path. Eq.(4) define either anisotropic three dimensional or "nearly" two-dimensional behaviour[4]. Real HTSC are somewhere in the middle. Characteristic conductivity scale is determined by[4]:

$$\sigma^* \sim \sigma_c \frac{\xi^0_\parallel}{l_\parallel}(T_c/E_F w)^{2/3} \quad (5)$$

For $w \sim E_F$ (5) reduce to
$$\sigma^* \sim \sigma_c (p_F\xi_0/h)^{-1/3} \approx \sigma_c (T_c/E_F)^{1/3}.$$
For real HTSC we have more or less $\sigma^* \sim \sigma_c$. The importance of σ^* is due to the fact that for $\sigma > \sigma^*$ we have the usual behaviour of GL-coefficients, upper critical field H_{c2} etc., as in the theory of "dirty" superconductors, while for $\sigma < \sigma^*$ we have "localization regime"[6], where

H_{c2} do not hold. Here the the characteristic sizes of Cooper pairs are estimated as

$$\xi_{\parallel,\perp} \sim \xi^0_{\parallel,\perp}(T_c^2/E_F W)^{1/3} \quad (6)$$

For the derivatives of the upper critical field we have (ϕ_0 is magnetic flux quantum)

$$(H_{c2}^{\perp})' = -\phi_0/2\pi\xi_{\parallel}^2 T_c$$
$$(H_{c2}^{\parallel})' = -\phi_0/2\pi\xi_{\parallel}\xi_{\perp} T_c \quad (7)$$
$$(H_{c2}^{\parallel})'/(H_{c2}^{\perp}) = \xi_{\parallel}/\xi_{\perp} = v_F/wa_{\perp}$$

Most important fact is that the ratio of $(H_{c2}^{\parallel})'/(H_{c2}^{\perp})'$ is *always determined just by the ratio of in-plane and transverse velocities* irrespective of regime (from "pure" limit through "dirty" case to "localization" regime). From this point of view experimentally observed[5] isotropisation in the slopes of H_{c2} and H_{c2} is due to the isotropisation of velocities of current carriers, i.e. the *isotropisation of Cooper pairs*. The remanent anisotropy of resistivities may be due to the anisotropy in the scattering mechanisms: $\tau^{\parallel} > \tau^{\perp}$.

Just before the destruction of superconductivity the system becomes essentially isotropic and we return to three-dimensional H_{c2} behaviour[6] with essential independence of H_{c2}' on $\sigma^{\parallel}$ for $\sigma^{\parallel} < \sigma^*$. Absence of observable σ -dependence of H_{c2}' in HTSC samples as given by standard Gor-kov relation is also an evidence of closeness of the available samples to Anderson transition[4]. The often observed upward curvature of $H_{c2}(T)$ curve can also be explained[6] for systems close to Anderson transition.

Among the reasons leading to T_c degradation in localized region probably the main is due to the appearance of characteristic "Hubbard-like" repulsion in single quantum state[11], leading to destruction of Cooper pairs[6], as well as the formation of localized magnetic moments[11,1,4]. The T_c drop due to this mechanism is determined by the equation[6]:

$$1 = \lambda \int_0^{\langle\omega\rangle} d\omega \frac{\operatorname{th}\frac{\omega}{2T_c}}{\omega + \frac{\mu}{2N(E_F)R_{loc}^3}\operatorname{th}\frac{\omega}{2T_c}} \quad (8)$$

where $\mu = N(E_F)v_0$ is usual Coulomb potential, λ is the pairing constant, $\langle\omega\rangle$-characteristic frequency of pairing interaction. It was shown[3,4] that this relation can give a satisfactory fit of experimental dependence of T_c on the fluence of fast neutrons using the "experimentally" determined behaviour of R_{loc} (from the observed ex - ponential fluence growth of resistivity, interpreted as due to Mott hopping law).

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