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# Irradiation-induced suppression of the critical temperature in high-$T_c$ superconductors: Pair breaking versus phase fluctuations

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Experiments on the irradiation-induced suppression of the critical temperature in high-$T_c$ superconductors are analyzed within the mean-field Abrikosov-Gor'kov-like approach. It is shown that the experimental data for $YBa_2Cu_3O_{7-\delta}$ single crystals can be quantitatively explained by the pair breaking effects under the assumption of the combined effect of potential and spin-flip scattering on the critical temperature and with account for a non-pure $d$-wave superconducting order parameter.

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Particle irradiation is a powerful tool that gives an opportunity to modify the physical properties of superconductors. Irradiation-induced defects act as effective pinning centers [1], thus causing the critical current density to increase. Apart from the practical benefits, irradiation effects may be used to probe the fundamental characteristics of superconductors. For example, peculiarities of the disorder-induced suppression of the critical temperature $T_c$ are expected to depend on the pairing mechanism and the symmetry of the superconducting order parameter $\Delta(\mathbf{p})$. In this respect, a study of the response of high-$T_c$ cuprates to the intentionally incorporated impurities or radiation defects provides an indirect way to elucidate the cause of their unusual normal and superconducting properties. Among other things, depending on the symmetry of $\Delta(\mathbf{p})$, clear differences were predicted for the defect-induced variations of the experimentally accessible characteristics such as $T_c$ [2, 3], the density of states [4], the isotope coefficient [5], the specific heat jump [6], etc.

Various mechanisms of the disorder-induced $T_c$ suppression have been considered, including, e.g., the pair breaking [7], localization [8], and phase fluctuations [9] effects, etc. The main problem here is that the disorder results not only in the decrease of $T_c$ but also in the strong increase in the width of the superconducting transition, $\Delta T_c$, so that the functional form of $T_c$ versus, e. g., the defect concentration $x_d$ appears to be poorly defined at $T_c \ll T_{c0}$, where $T_{c0}$ is the initial value of $T_c$ in the absence of the disorder. In fact, the value of $\Delta T_c$ usually becomes comparable to the value of $T_c$ at $T_c/T_{c0} \approx 0.3$ [10, 11]. While the measured $T_c$ versus $x_d$ curve in high-$T_c$ cuprates was commonly observed to be approximately linear at $T_c/T_{c0} > 0.3$ [10], the details of $T_c(x_d)$ behavior at $T_c/T_{c0} \ll 1$ remained unclear.

In a recent paper [12], Rullier-Albenque et al. reported the results of experimental studies of $T_c$ degradation under electron irradiation of underdoped and optimally doped $YBa_2Cu_3O_{7-\delta}$ single crystals. They have measured $T_c$ and in-plane resistivity $\rho_{ab}$ in a very broad range of $x_d$, the value of $x_d$ being proportional to $\Delta\rho_{ab}$, the increase in $\rho_{ab}$ upon irradiation. The authors of Ref. [12] succeeded in creation of an extremely uniform distribution of radiation defects over the sample, so that the value of $\Delta T_c$ never exceeded 5 K. Moreover, the value of $\Delta T_c$ did not increase monotonously with radiation dose but had a maximum at $T_c/T_{c0} \approx 0.3$ and next decreased again down to $\Delta T_c < 1$ K at the highest dose for which the resistive superconducting transition was still observed at $T_c \approx 1$ K. So, the dependence of $T_c$ on $\Delta\rho_{ab}$ (or $x_d$) was obtained with an excellent accuracy from $T_c/T_{c0} = 1$ down to $T_c/T_{c0} = 0$ (or, at least, $T_c/T_{c0} \sim 10^{-2}$).

It was found in Ref. [12] that $T_c$ unexpectedly decreased quasilinearly with $x_d$ in the *entire* range from $T_{c0}$ down to $T_c = 0$. Having compared the results obtained with the predictions of Abrikosov–Gor'kov (AG) pair breaking [13] and Emery–Kivelson phase fluctuations [9] theories, the authors of Ref. [12] arrived at a conclusion that the experimental data are at variance with AG theory and point to a significant role of phase fluctuations of the order parameter in high-$T_c$ superconductors.

To compare the pair breaking theory with the experiment, the authors of Ref. [12] made use of the AG formula [13] for a $d$-wave superconductor (we set $\hbar = 1$ hereafter)

$$\ln(T_{c0}/T_c) = \Psi(1/2 + 1/4\pi T_c\tau) - \Psi(1/2), \qquad (1)$$

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where $\Psi(z)$ is the digamma function and $\tau$ is the electron scattering time [14], $\tau^{-1} \propto x_d \propto \Delta\rho_{ab}$. This formula gives a negative curvature of the $T_c$ versus $\Delta\rho_{ab}$ curve, contrary to the experimental observations. Note, however, that, first, the symmetry of $\Delta(\mathbf{p})$ in $YBa_2Cu_3O_{7-\delta}$ is different from pure $d$-wave due to an orthorombic lattice distortion [15] and, second, irradiation may result in appearance of spin-flip scatterers along with potential ones since radiation defects created in $CuO_2$ planes disturb antiferromagnetic correlations between copper spins. The AG-like formula that accounts for both those effects reads [3, 16]

$$\ln\left(\frac{T_{c0}}{T_c}\right) = (1-\chi)\left[\Psi\left(\frac{1}{2}+\frac{1}{2\pi T_c\tau_s}\right) - \Psi\left(\frac{1}{2}\right)\right] + \\ + \chi\left[\Psi\left(\frac{1}{2}+\frac{1}{4\pi T_c}\left(\frac{1}{\tau_p}+\frac{1}{\tau_s}\right)\right) - \Psi\left(\frac{1}{2}\right)\right], \quad (2)$$

where $\tau_p$ and $\tau_s$ are scattering times due to potential and spin-flip scatterers, respectively, the coefficient

$$\chi = 1 - \langle\Delta(\mathbf{p})\rangle^2_{FS}/\langle\Delta^2(\mathbf{p})\rangle_{FS} \quad (3)$$

is a measure of the degree of in-plane anisotropy of $\Delta(\mathbf{p})$, $\langle...\rangle_{FS}$ means the Fermi surface (FS) average. The range $0 \le \chi \le 1$ covers the cases of isotropic $s$-wave ($\Delta(\mathbf{p})$=const, $\chi = 0$), $d$-wave ($\langle\Delta(\mathbf{p})\rangle_{FS} = 0$, $\chi = 1$), and mixed $(d+s)$-wave or anisotropic $s$-wave ($0 < \chi < 1$) symmetries of $\Delta(\mathbf{p})$.

In fact, the assumption about the combined effect of potential and spin-flip scatterers on $T_c$ and account for a non-pure $d$-wave $\Delta(\mathbf{p})$ in $YBa_2Cu_3O_{7-\delta}$ (i. e., $\chi \neq 1$) allow for a quantitative explanation of the experimental data [12] within the modified pair breaking AG-like theory [17], without resorting to phase fluctuations effects [9]. Fig.1 shows the measured $T_c/T_{c0}$ versus $\Delta\rho_{ab}$ taken from Ref. [12] along with theoretical curves computed with Eq. (2) for $\chi = 0.9$ and various values of the coefficient

$$\alpha = \tau_s^{-1}/(\tau_p^{-1}+\tau_s^{-1}) \quad (4)$$

that specifies the relative contribution of spin-flip scatterers to the total scattering rate. Here we represent the scattering time in terms of the in-plane residual resistivity $\rho_0$ obtained by the extrapolation of $\rho_{ab}(T)$ to $T = 0$,

$$\tau_p^{-1}+\tau_s^{-1} = (\omega_{pl}^2/4\pi)\rho_0, \quad (5)$$

where $\omega_{pl}$ is the plasma frequency, see Refs. [7] and [16]. We also make use of the fact that $\rho_0 = \Delta\rho_{ab}$ in a very good approximation [12]. From Fig.1 one can see that at $\chi = 0.9$ and $\omega_{pl} = 0.75$ eV the quasilinear experimental dependence of $T_c$ on $\Delta\rho_{ab}$ in $YBa_2Cu_3O_7$ is quantitatively reproduced at $\alpha = 0 \div 0.01$.

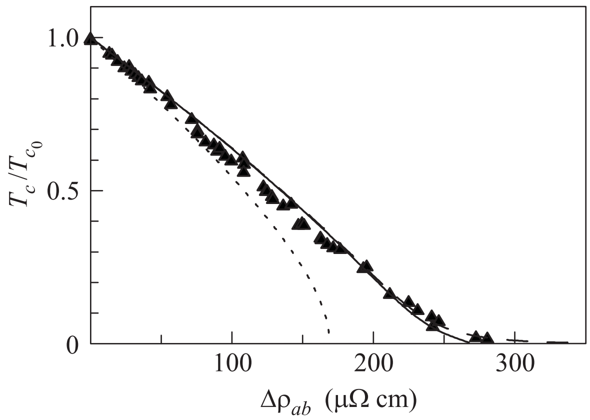


Fig.1. $T_c/T_{c0}$ versus $\Delta\rho_{ab}$ in electron irradiated $YBa_2Cu_3O_7$ crystals. Experiment [12] (triangles). Theory, Eqs. (2)–(5), for $\omega_{pl} = 0.75$ eV, $\chi = 0.9$, and $\alpha = 0$ (dashed line), 0.01 (solid line), and 1 (dotted line)

We emphasize that the quantity $\omega_{pl}$ that enters Eq. (2) for $T_c$ through the relation (5) should be considered as just a characteristic energy which does not necessarily coincide with the value of the plasma frequency determined by, e.g., the optical spectroscopy. Based on general grounds, one could expect $\omega_{pl} \sim 1$ eV. In this respect, although our choice of $\omega_{pl} = 0.75$ eV is, to some extent, arbitrary, the change in $\omega_{pl}$ results just in the change of the best fitting values of $\chi$ and $\alpha$. For example, $\chi \approx 0.8$ and 0.6, $\alpha = 0.04 \pm 0.01$ and $0.045 \pm 0.01$ for $\omega_{pl} = 0.8$ and 1.0 eV, respectively, see Figs.2 and 3. Meanwhile, for $\chi = 1$, i.e., for pure $d$-wave symmetry of $\Delta(\mathbf{p})$, the experimental data cannot be described at any value of $\omega_{pl}$, see Fig.4. This is not surprising because of the orthorombic crystal structure of $YBa_2Cu_3O_{7-\delta}$ which excludes the pure $d$-wave symmetry of $\Delta(\mathbf{p})$ and

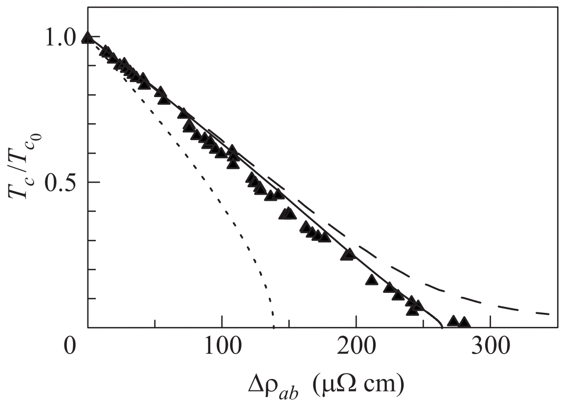


Fig.2. The same as in Fig.1 for $\omega_{pl} = 0.8$ eV, $\chi = 0.8$, and $\alpha = 0$ (dashed line), 0.04 (solid line), and 1 (dotted line)

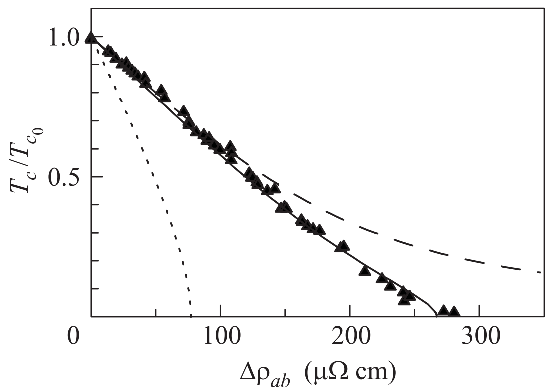


Fig.3. The same as in Fig.1 for $\omega_{pl} = 1.0$ eV, $\chi = 0.6$, and $\alpha = 0$ (dashed line), 0.045 (solid line), and 1 (dotted line)

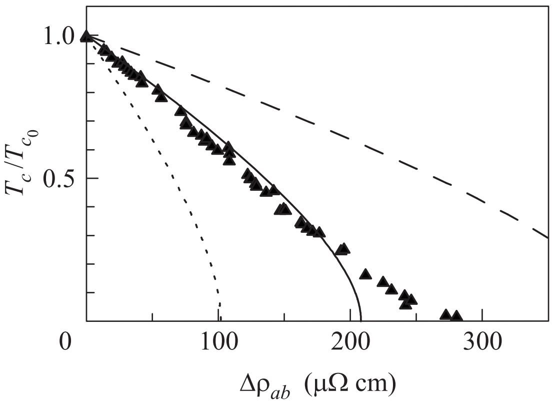


Fig.4. The same as in Fig.1 for $\chi = 1$ and $\omega_{pl} = 0.5$ eV (dashed line), 0.7 eV (solid line), and 1 eV (dotted line), see Ref. [18]

points to an admixture of the $s$-wave component to $d$-wave, so that $\Delta(\mathbf{p})$ is of $(d+s)$-wave or $(d+is)$-wave type [15]. So, the experimental data [12] for $YBa_2Cu_3O_7$ single crystals can be quantitatively explained by the pair breaking theory taking a non-pure $d$-wave $\Delta(\mathbf{p})$ and the combined effect of potential and spin-flip scatterere on $T_c$ into account.

As for the underdoped single crystals $YBa_2Cu_3O_{6.6}$, the experimental dependence [12] of $T_c/T_{c0}$ versus $\Delta\rho_{ab}$ is close to that for $YBa_2Cu_3O_7$ and can be fitted within the same approach at similar values of $\omega_{pl}$, $\chi$, and $\alpha$. The discussion of the probable effect of the oxygen content, i.e., the hole concentration, on the value of $\omega_{pl}$, the gap anisotropy, and the relative amount of spin-flip scatterers in the sample is, however, beyond the scope of this paper.

Note that $\chi < 1$ not only for a mixed $(d+s)$-wave $\Delta(\mathbf{p})$, but also for an anisotropic $s$-wave $\Delta(\mathbf{p})$. Recently the $d$-wave symmetry of $\Delta(\mathbf{p})$ in hole-doped cuprate superconductors [19] has been doubted by several authors (see, e.g., Refs. [20, 21]). The re-analysis of the results obtained by the angle-resolved photoemission spectroscopy, the Fourier transform scanning tunneling spectroscopy, the low-temperature thermal conductivity, etc., including the phase-sensitive techniques, has shown that the combined data agree quantitatively with the extended $s$-wave symmetry [20, 21]. Making use of the fit [21] $\Delta(\theta) = 24.5(\cos 4\theta + 0.225)$ meV to single-particle tunneling spectra of $YBa_2Cu_3O_{7-\delta}$, the angle $\theta$ being measured from the Cu–O bonding direction, we have $\chi \approx 0.9$ for $YBa_2Cu_3O_{7-\delta}$. It follows from the fits presented in Ref. [21] that even more lower value of $\chi$ may be expected for $Bi_2Sr_2CaCu_2O_{8+y}$. In this respect, it would be very interesting to study the behavior of $T_c$ versus $\rho_{ab}$ in this and other high-$T_c$ cuprates down to $T_c = 0$.

Finally, a note is in order about one more argument presented in Ref. [12] in favour of the phase fluctuations theory and against the pair-breaking mechanism of $T_c$ suppression in high-$T_c$ cuprates. According to Ref. [12], the positive curvature of the $T_c(\Delta\rho_{ab})$ curve is necessarily required to explain the maximum of the transition width $\Delta T_c$ as a function of $\Delta\rho_{ab}$ that was experimentally observed at $T_c/T_{c0} \approx 0.3$. Note, however, that, first, this argument is incompatible with the experimental data themselves since the curvature of the *measured* $T_c(\Delta\rho_{ab})$ dependence is (with a few exceptions) close to zero in the whole range of $\Delta\rho_{ab}$ and, respectively, in the whole range of $T_c/T_{c0}$, including the region near $T_c/T_{c0} \approx 0.3$. Second, the line of reasoning in Ref. [12] is based on a naive assumption that $\Delta T_c(x_d) \propto x_d(dT_c/dx_d)$. Such an assumption is at least questionable for the resistive superconducting transition whose critical temperature and width are determined by the zero-resistance path and the uniformity of the defect distribution, respectively. Besides, the value of $\Delta T_c$ depends on a specific criterion used for its evaluation from the curve $\rho_{ab}(T)$. Thus, the knowledge of the function $T_c(x_d)$ alone is obviously insufficient to draw the definite conclusions about the function $\Delta T_c(x_d)$, and vice versa.

We note that the phase fluctuations theory [9] goes beyond the standard mean-field theory and implies that the so called pseudogap [22] is a precursor to superconductivity. This contradicts the experiments which give evidence for interplay between competing and coexisting (superconducting and non-superconducting) ground states, see, e.g., Ref. [23]. We note also that the AG-like pair breaking approach is based on the BCS-Bogolubov mean-field theory that seems to describe the spatial-momentum quasiparticle states in high-$T_c$ cuprates, at least in the optimally doped samples such as, e.g., $YBa_2Cu_3O_7$, rather well [24, 25].

In summary, we have shown that experiments on the irradiation-induced $T_c$ suppression in $YBa_2Cu_3O_{7-\delta}$ can be quantitatively explained within the AG-like pair breaking mean-field theory under the assumption of the combined effect of potential and spin-flip scattering on $T_c$ and with account for a nonzero Fermi surface average of the superconducting order parameter, without resorting to phase fluctuations effects. One can not exclude, however, a possibility that the latter become important at $T_c \to 0$, i.e., in the very vicinity of the superconductor-insulator transition.

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