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Effect of pressure on T_c and the ''intrinsic'' T_c of cuprates

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We propose that the transition temperature in the layered cuprates is affected by a peculiar interplay between doping and pair-breaking scattering. This scattering can lead to a depression of T_c relative to its ''intrinsic'' value. Using this picture, one can explain the large value of T_c in the three-layered cuprates relative to the two- and one-layer cuprates and also understand the large pressure effects observed. We predict that one can raise T_c above the usual maximum value by applying pressure on underdoped TI-2201 samples and the maximum value of T_c under pressure is evaluated. The temperature dependence of the pressure coefficient is also discussed.

I. INTRODUCTION

It is well known that pressure has a large effect on the properties of the high-T_c oxides (see, e.g., reviews[1,2]), and particularly on the value of T_c. This pressure effect greatly exceeds that for ordinary metallic superconductors. In addition, it is well known that the value of T_c depends strongly on the level of doping. It is remarkable that, if one applies pressure to an underdoped sample which has a value of $T_c=T_{c;i}$ which is smaller than the value $T_{c;m}$ ($T_{c;m}$ is the maximum value of T_c which can be reached by oxygen addition or other chemical doping), one can reach a value of T_c which exceeds $T_{c;m}$. For example, the Tl-based 2223 compound has a $T_c=T_{c;m}=125$ K at ambient pressure. This value, for a sample with $T_c=T_{c;m}$ is not very much affected by external pressure. However, pressure applied to a sample with $T_c=T_{c;i}=116$ K moves it up to the value $T_c=T_{c;p}=132$ K,[3] which exceeds the value $T_{c;m}$. Note also that this pressure effect is not universal. For example, the pressure dependence of T_c is very small for $Nd_{1.85}Ce_{0.15}CuO_{4-x}$, which is also a layered cuprate.[4]

All these properties can be understood on the basis of the approach we have developed earlier.[5,6] This paper contains a brief description of our approach and an analysis of the pressure effect on T_c. This analysis is the main focus of this paper. A new concept of ''intrinsic'' critical temperature will be introduced. This paper also contains a specific prediction for the 2201 Tl-based cuprate.

The structure of the paper is as follows. Section II contains a description of the pair-breaking effect and the experimental data which provided strong support for this idea. The concept of ''intrinsic'' T_c is introduced in Sec. III. The effect of external pressure along with our specific prediction is described in Sec. IV. Finally, an unusual behavior of the pressure coefficient is discussed in Sec. V.

II. MAGNETIC IMPURITIES: PAIR BREAKING

The overdoped state of the cuprates is characterized by a drastic decrease in T_c upon overdoping. For example, one can observe a decrease: $T_c=90\ \text{K}\rightarrow T_c=14$ K for the overdoped $Tl_2Ba_2CuO_{6+x}$ compound;[7] a similar decrease was observed for the Bi-based cuprate.[8] We strongly believe that this decrease is mainly caused by the pair-breaking effect of magnetic impurities. The influence of magnetic impurities (pair breaking, appearance of gaplessness at some concentration of magnetic impurities, depression in T_c, etc.) was described previously,[9–11] see also the reviews.[12–14] The interaction between localized magnetic moments and Cooper pairs which are in the singlet state, destroys the pair correlation. It is important that this process is accompanied by spin-flip scattering (such scattering provides the conservation of total spin).

The existence of such pair-breaking effect in the cuprates is supported by a number of experiments. Specifically, heat-capacity measurements on YBaCuO (see, e.g., reviews, Ref. 15) which show low-temperature Shottky anomalies, are direct experimental evidence for the presence of magnetic impurities. The heat-capacity data[16] on the Tl-based 2201 compound also displays the presence of upturns at low temperatures similar to the data on YBaCuO and can also be attributed to Shottky anomalies. It is important to note that the heat capacity measurements on the Tl-2201 compound[16] were performed on the very same sample which had been used to measure the dependence of H_{c2} on T, analyzed by us in Ref. 6, where pair breaking was postulated to explain the exotic increase in H_{c2} at low temperatures.

It is important to note that magnetic impurities provide a pair-breaking effect and indeed, pair breaking has been used to explain the doping dependence of the depolarization rate in μSR spectroscopy data on a series of one layer Tl-2201 cuprates.[17,18] These experiments measure the ''local'' field

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distribution around a vortex which can be directly related to the penetration depth. The depression of T_c upon overdoping was accompanied by a decrease in the ''superfluid'' component and this corresponds to pair breaking with doping for overdoped samples.[17,18]

Pair breaking leads to a depression in T_c (Refs. 9–11) and, eventually, at some value of the concentration $n_M = n_{M;\mathrm{cr}}$, to the total suppression of superconductivity. This suppression is proceeded by the appearance of the gapless state.[9–14,5] This gaplessness has also been reported as manifested in the temperature dependence of the penetration depth.[17,18] Therefore, our viewpoint about the pair-breaking effect by magnetic impurities in the cuprates, has strong experimental support.

III. INTRINSIC T_c

An analysis of the overdoped state allows us to introduce an important parameter, the so-called ''intrinsic'' T_c. Consider the effect of magnetic impurities; the superconducting state of the Cu-O plane is greatly affected by their presence. The effect of magnetic impurities on the dependence of H_{c2} on temperature has been studied by us in Ref. 6 and has resulted in excellent agreement with experimental data.[7,8] Overdoping leads to a drastic decrease in T_c (as was noted above for the $\mathrm{Tl_2Ba_2CuO_{6+x}}$ compound studied in Ref. 7, T_c decreases from $T_{c,m} = 90$ K to the value of $T_c = 14$ K). This decrease in T_c and the concomitant decrease in H_{c2} allowed direct measurements of the dependence of H_{c2} on T. It was important to realize that the applied magnetic field leads to a parallel shift in the resistive transition without any significant broadening. This lack of broadening at lower reduced temperature is what gives confidence in the determination of the critical field from resistivity data. In fact, this simplified the determination of the dependence of H_{c2} on temperature because it was basically independent of the method for choosing H_{c2} (see the discussion in Ref. 7).

Contrary to the conventional understanding,[19] the critical field displays a positive curvature over the entire temperature range with a sharp increase in the region near $T = 0$ K. According to the physical picture, developed in Ref. 6, spin-flip scattering leads to a depression of the superconducting state, and this is reflected in relatively small values of T_c and H_{c2} (near T_c). In this temperature region, the magnetic impurities can be treated as independent (see Refs. 9 and 14), and the spin-flip scattering by the impurities provides conservation of total spin. However, at low temperatures (in the region $T \cong 1$ K), because of the correlation of the magnetic moments, the trend to ordering of the moments becomes important, and this trend frustrates the spin-flip scattering. Pairing becomes less depressed, and this leads to a large increase in the value of H_{c2} and, correspondingly, to a positive curvature in H_{c2} vs T (for a more detailed discussion see Ref. 6). Note that a similar effect has been observed in the Sm-Ce-Cu-O,[20] La-Sr-Cu-O,[21] and, recently, in Y-Ba-Zn-Cu-O (Ref. 22) systems. It is interesting to note that according to a recent NMR spectroscopy study,[22b] the depression in T_c in the Y-Ba-ZnCu-O compound is caused by a pair-breaking effect which supports our approach. The measurements in Refs. 20 and 21 were carried out in the region $T > 1$ K. The ordering of the impurities was observed for the Sm-Ce-Cu-O compound by direct measurements of the magnetic susceptibility.[20] The sharp increase in the susceptibility which reflects the correlation of the moments, has been also observed in Ref. 21. Note also that the effect of magnetic ordering on the curvature in $H_{c2}(T)$ has been observed for the Ni/V system.[23] The appearance of positive curvature appears when $T_c > T_{\mathrm{Cu}}$ (T_{Cu} is the Curie temperature). Indeed, the spin-flip scattering is frustrated in the region $T < T_{\mathrm{Cu}}$.

The general equation describing a layered superconductor in the presence of magnetic impurities and an external field (at $H = H_{c2}$,) has the form (see Ref. 6):

$$\ln(2\gamma\Gamma_{\mathrm{cr}}/\pi T) - [\psi(0.5 + (\Gamma/2\pi T)) - \psi(0.5)] = f(H_{c2}, T),$$

$$f(H_{c2}, T) = (H_{c2}2/\Gamma)\{\Gamma^{-1}[\psi(0.5 + (\Gamma/2\pi T)) - \psi(0.5 + (\Gamma/4\pi T))] - (4\pi T)^{-1}\psi'(0.5 + (\Gamma/2\pi T))\}. \tag{1}$$

Here ψ is the psi function, $\ln\gamma = C = 0.58$ is the Euler constant, $\Gamma = \tau_s^{-1}$ is the amplitude of the spin-flip scattering, τ_s is the relaxation time; Γ_{cr} corresponds to the complete suppression of superconductivity ($T_c = 0$). The analysis carried out in Ref. 6, allows us to evaluate the dependence $H_{c2}(T)$. Equation (1) relates the critical field H_{c2}, the amplitude of the spin-flip scattering $\Gamma = \tau_s^{-1} \propto n_M$ (where n_M is the impurity concentration), and the critical value $\Gamma_{\mathrm{cr}} \propto n_{\mathrm{cr}}$, which corresponds to the total suppression of superconductivity ($T_c = 0$). Based on the study,[6] one can obtain the value $\Gamma_{\mathrm{cr}} = 137$ K for the 2201 Tl-based cuprate. Using the relation $T^0_{c;m} = 2\gamma\Gamma_{\mathrm{cr}}/\pi$,[9] where $T^0_{c;m}$ is the value of critical temperature in the absence of magnetic impurities, one obtains $T^0_{c;m} \cong 155$ K for the *same* layered compound. Although this value is only approximate based on the accuracy of the equations (for example we do not consider in-plane anisotropy), it is remarkable that it greatly exceeds the experimental value $T_{c;m} = 90$ K, observed at the optimum ambient pressure doping. Therefore, the material contains magnetic impurities even at optimum doping, and the value of the critical temperature $T^{\mathrm{dop}}_{c;m}$ is depressed relative to the ''intrinsic'' value $T^0_{c;m}$. The amplitude of the spin-flip scattering for the doped sample with $T_c = T^{\mathrm{dop}}_{c;m}$ can be evaluated from the equation:[9,11]

$$\ln(T^0_{c;m}/T_{c;m}) = \psi(0.5 + (\Gamma_{s;m}/2\pi T_{c;m})) - \psi(0.5). \tag{2}$$

Here $\Gamma_{s;m} = \tau^{-1}_{s;m}$ is the amplitude of spin-flip scattering for the sample with $T_c = T^{\mathrm{dop}}_{c;m}$. Equation (2) can also be obtained from Eq. (1) (at $T = T_c$; Γ_{cr} can be expressed in terms of $T^0_{c;m} = T_{c;\mathrm{intr}}$, if we set $n_M = 0$). As was noted above, Eq. (1) was derived in Ref. 6 for a layered superconductor. The same is true for Eq. (2). We do not consider the effects of in-plane anisotropy nor do we consider the multigap structure which is important for the YBCO compound.[5] To study the pressure effect, we have focused mainly on the Tl- and Bi-based cuprates; they do not have a chain structure and the contribution of a second gap for the Bi-O (Tl-O) layer is probably relatively small.

There is an interesting question about the location of the magnetic moments. Because of transport measurements on the overdoped Tl-2201 (Ref. 7) and the analysis carried out in Ref. 6 which indicates the effect of pair breaking on H_{c2}, we have concluded that the pair-breaking effect is caused by out-of-plane magnetic moments. Indeed, magnetic impurities located in the plane would provide not only pair breaking, but the usual elastic scattering as well. However the transport data[7] show that the mean free path in this Tl-2201 system is very large and greatly exceeds the coherence length. In the case of an out-of-plane location, momentum transfer, which manifests itself in the normal conductivity and is related to the usual potential scattering, is small, whereas the spin-flip scattering can be quite a strong effect; it is the layered structure which allows such an unusual combination. We think that the magnetic moments are localized on the Ba-O layer, which is adjacent the Cu-O layer in overdoped Tl- and Bi-based compounds. The impact of these impurities is strong because of the overlap of the Ba-O wave function with the Cu-O plane. Localized magnetic moments can be formed on the apical oxygen site (O^- ions). Another possibility is the formation of a paramagnetic radical, O_2^-, and this also involves the apical oxygen, as well as the additional oxygen in the Tl-O (Bi-O) layers. This picture is supported by calculation[24] even though they were performed for the YBCO compound. According to Ref. 24, the doping O_6 to O_7 is accompanied by charge redistribution so that the charge on the O(4) site changes from -2.03 to -0.67; this corresponds to the formation of magnetic moments in the Ba-O layer. This analysis[24] is in good agreement with the NQR data.

The presence of magnetic moments on the apical oxygen site is a key factor which can provide the cause for the large difference in the values of T_c between the 2201 and the 1223 (or 2223) structures. Indeed, the properties of the $Tl_2Ba_2CuO_6$ compound, and its value of T_c, in particular, can be greatly affected by the two O^- apical ions. In the case of $Tl_2Ba_2Ca_2Cu_3O_{10-x}$, the pair-breaking effect is much weaker since the apical oxygens are located outside of the total set of three planes, so that the middle plane is hardly affected by the magnetic ions and the influence on the two other planes is not as strong as for the 2201 compound, where the Cu-O plane is affected on each side. As a result, the Tl-based 2223 compound has a $T_c=125$ K, which is much closer to the ''intrinsic'' limit $T_{c;\mathrm{int}}$ of the order of 155 K (see above). For compounds with more than three Cu-O planes, we believe it is difficult to adequately dope the inner planes and T_c would saturate or decrease.

IV. EXTERNAL PRESSURE

Let us turn to a discussion of the pressure effect. Consider the Tl-based 2201 cuprate with a doping level on the underdoped side which corresponds to $T_c=T_{c;i}=80$ K. There are two ways to further increase the T_c. One is to continue the usual doping, that is to add more oxygen; then one can achieve the well-known value of $T_c=T_{c;m}^{\mathrm{dop}}=90$ K. Another possibility is to apply external pressure. Let us evaluate (this is our main goal) the value of $T_{c,p}$ which can be reached in this way. It will be shown that $T_{c,p}>T_{cm}^{\mathrm{dop}}$.

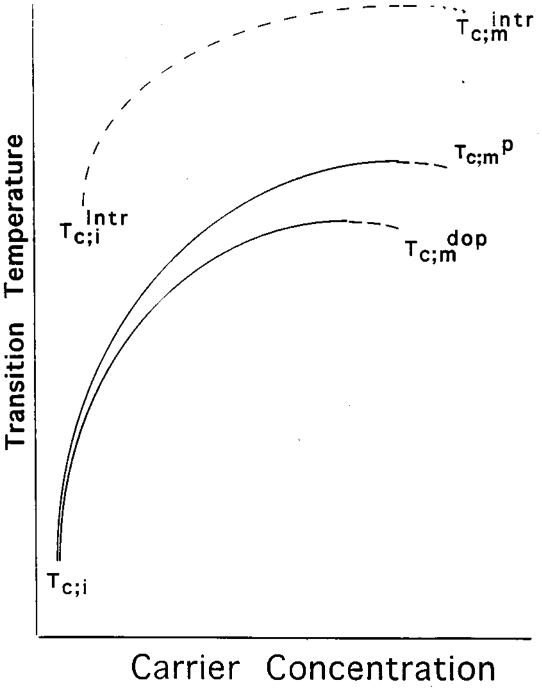

FIG. 1. Illustration of the relative values of the temperatures referred to in the text.

If we increase T_c by the usual additional doping ($T_{c;i}\rightarrow T_{c;m}$), then in our view, the oxygen addition is accompanied by the generation of additional local magnetic moments, so that $n_{s;m}>n_{s;i}$, and correspondingly, $\Gamma_{s;m}=\tau_{s;m}^{-1}>\Gamma_{s;i}=\tau_{s;i}^{-1}$. Contrary to this scenario, external pressure decreases the c-lattice parameter which we presume increases the charge transfer, hence the doping and, therefore, T_c, without adding magnetic moments (see below). As a result, the state with $T_c=T_{c,p}$ is characterized by the same concentration of localized magnetic moments as the initial state i, whereas the value of the carrier concentration increases relative to n_i. Therefore, one can write the equation, similar to Eq. (2):

$$\ln(T_{c;m}^{0}/T_{c;p})=\psi(0.5+(\Gamma_{s;i}/2\pi T_{c;p}))-\psi(0.5). \qquad (3)$$

We have chosen for this specific example a sample that has $T_{ci}=80$ K. Such a sample with $T_{ci}=80$ K contains magnetic impurities with concentration $n_{s;i}$. By analogy with the state with the maximum ambient pressure T_c (i.e., $T_{c;m}^{\mathrm{dop}}$) (see above), one can introduce the intrinsic critical temperature $T_{c;i}^{0}$ for the i state. The value of $T_{c;i}^{0}$ is determined by the equation [cf. Eq. (2)]:

$$\ln(T_{c;i}^{0}/T_{c;i})=\psi(0.5+(\Gamma_{s;i}/2\pi T_{c;i}))-\psi(0.5). \qquad (4)$$

The values $T_{c;i}^{0}$ and $T_{c;m}^{0}$ correspond to the situation when the sample does not contain localized magnetic moments but is characterized by different carrier concentrations (see Fig. 1). The values $T_{c;i}^{0}$ and $T_{c;m}^{0}$ are different because of different carrier concentrations n_i and n_m and, correspondingly, because of the different values of the coupling constants λ_i and λ_m, since $\lambda\propto n$.[25] We think that the critical temperature is substantially determined by the electron-phonon coupling. We have previously considered this scenario and have concluded that the electron-phonon mechanism can adequately account for the T_c, which is discussed in detail in our earlier publications (see, e.g., Ref. 5). Following this assumption and others made previously, we can make several predictions that can be experimentally checked. Assuming a proportional increase in magnetic scatterers with increased carrier concentration, and using the equation[26a] $T_c = 0.25\tilde{\Omega}[\exp(2/\lambda) - 1]^{-1}$, $\tilde{\Omega} = \langle \Omega^2 \rangle^{1/2}$, where $\tilde{\Omega}$ is the average phonon energy (according to Ref. 26b, $\tilde{\Omega} = 40$–50 meV; for simplicity we put $\mu = 0$), and the values $T_{c;i} = 80$ K, $T_{c;m} = 90$ K, $T^0_{c;m} = 155$ K, one can evaluate the values $T^0_{c;i}$, $\Gamma_{s;i}$, and $T_{c;p}$. Using Eqs. (2)–(4), we obtain $T^0_{c;i} = 130$ K, $\Gamma_{s;i} = 75.5$ K. Most importantly, the value of $T_{c;p}$ we obtain is 105 K. One can see that applied pressure leads to a value of T_c which is noticeably higher than the experimental value $T^{\mathrm{dop}}_{c;m} = 90$ K. This prediction can be checked experimentally.

The value of T_c equal to 105 K obtained above, is approximate. An uncertainty in our calculation is due, for example, to the fact that the expression for T_c contains $\tilde{\Omega} = \langle \Omega^2 \rangle^{1/2}$ which is different from the average phonon frequency determined by neutron spectroscopy; according to the definition (see, e.g., Ref. 27) $\tilde{\Omega}$ contains $\alpha^2(\Omega)F(\Omega)$ that is, there is an additional factor $\alpha^2(\Omega)$ describing the coupling. One can use the equation for T_c derived in Ref. 27a; it contains two characteristic frequencies $\Omega_{\ln}$ and $\Omega_2 = \tilde{\Omega}$ that require knowledge of $\alpha^2(\Omega)F(\Omega)$ to determine. In the future, reliable tunneling measurements of $\alpha^2(\Omega)F(\Omega)$ will permit more detailed calculations. However, we believe that our estimations based on Ref. 26a are valid to draw the conclusion we have.

We have focused on the $Tl_2Ba_2CuO_6$ compound since our analysis was based on critical field data[7] and the corresponding theoretical study.[6] As a result, we were able to calculate the value of the ''intrinsic'' T_c for this compound and then to evaluate $T_{c,p}$. To the best of our knowledge, the experimental study of the pressure effect for various dopings has not been performed for this compound and it would be interesting to carry out such measurements to confirm our prediction.

We should note, however, that the pressure effect has been studied experimentally for the $Tl_2Ba_2Ca_2CuO_{10-x}$ compound[3] and, although we are unable, at present, to calculate $T_{c,p}$ for this cuprate (the measurements of the critical field in the overdoped region have not been performed for the $Tl_2Ba_2Ca_2Cu_3O_{10-x}$ compound), the data[3] described in the Introduction provide strong qualitative experimental support for our model.

V. PRESSURE COEFFICIENT

Pressure affects the lattice parameters. However, for the cuprates, this change not only modifies the phonon spectrum, but the doping level as well. Consider this aspect in more detail. The doping is strongly affected by the dynamics of the apical oxygen.[28] A very interesting phenomenological model which introduced the dependence of the carrier concentration on the isotopic substitution was described in Ref. 29. According to a microscopic model developed by the authors,[30] the charge transfer between the chains and planes in the YBCO compound (the same is true, e.g., for the charge transfer between the TlO and CuO planes in the Tl-based cuprates) is affected by the nonadiabatic behavior of the apical oxygen and is accompanied by a transition between two electronic terms. As a result, the carrier concentration is described by the relation: $n \propto \Delta\varepsilon \exp(-kr^2/M)$; here $\Delta\varepsilon$ is the splitting between the vibrational terms (each electronic term is characterized by its own vibrational manifold), M is the mass of the apical oxygen, k is related to the elastic constants, and r is the distance between two potential minima for the apical oxygen. According to Ref. 30, the carrier concentration n could be affected by the isotope substitution of the apical oxygen. Since $T_c = T_c(n)$, this leads to a novel isotope effect (see detailed discussion[30]). As a result, the value of the isotope coefficient depends on the doping level and, consequently, on the value of T_c. The contribution of the apical oxygen to the total oxygen isotope effect is very small near $T_c = T_{c;\max}$ ($\partial T_c/\partial n = 0$ at $T_c = T_{c;\max}$). An experimental study of the selective isotope effect,[31] indeed has shown that the small value of the isotope coefficient α near T_c is due to contributions of the in-plane oxygen, not apical oxygen. However, the decrease in doping leads to an increase in the contribution of the apical oxygen, and this leads to an increase in α with decreasing T_c. Recent experiments[32] totally support this picture; indeed, the increase in α is related to a change in the carrier concentration upon isotope substitution.

Nonadiabaticity studied in Ref. 30, leads to the presence of two minima for the apical oxygen. Although experimentally, the presence of these two minima is still somewhat controversial because of the possible existence of multiple phases in some of the samples that have been studied, there are, in fact, several reports that claim to have clear evidence for these two minima. For example, two minima for the apical oxygen have been postulated to explain the two nearest-neighbor distances in extended x-ray-absorption fine-structure data,[33] broadened and split peaks in Raman data,[34] and irreversible behavior in transport measurements.[35]

The pressure coefficient can be written in the form

$$\beta - (\partial T_c/\partial n)(\partial n/\partial p) = (sn^2/T_c)(\partial T_c/\partial n). \tag{5}$$

Here $s = \text{const}$, $s = (kr/M)(\partial r/\partial p)$; the pressure applied in the c direction affects the value of the parameter ''r'' (see above). One can see directly from Eq. (5) that an increase in T_c towards its maximum value (then the derivative $\partial T_c/\partial p$ decreases) leads to a smaller influence of pressure on T_c. This conclusion corresponds to the experimental situation. For example, as mentioned previously, pressure, applied to the underdoped $Tl_2Ba_2Ca_2Cu_3O_{10-x}$ compound (then $T_c = 116$ K) moves T_c up to 132 K,[3] whereas the change in T_c, for the same material at optimum doping ($T_c = 125$ K), is much smaller.

The study of uniaxial pressure allows one to separate the contribution of charge transfer which corresponds to pressure applied in the c direction (β_c).[36,37] Phenomenological charge-transfer models were studied in Ref. 38, see also the review.[1]

One should distinguish the maximum value, $T^{\mathrm{pres}}_{c,m}$, of the critical temperature which can be achieved with external pressure and the value of $T_{c,m} = T^{\mathrm{dop}}_{c,m}$ obtained by the usual doping. In the latter case, the value of $T_{c,m}$ is determined mainly by the competition between the increase in the carrier concentration, which increases the value of the coupling constant (see above) and, therefore, T_c and the pair-breaking effect. As for the pressure effect, it increases T_c because of the increase in the carrier concentration; unlike usual doping, this increase is not accompanied by an increase in the concentration of magnetic moments. In this case the maximum value of T_c is caused, mainly, by a crossover effect[25] between $2p^F \propto n$ and the phonon momentum. Experimentally, such a maximum has been observed in Ref. 38. Note that $\beta > 0$ in the region $T_{c,m}^{\text{pres}} > T_{c,m}^{\text{dop}}$, in agreement with the data.[36] The YBCO compound represents a special case (see below).

It is very important to stress that in our picture the dependence $T_c(n)$ is not universal, but depends strongly on the type of doping. As was noted above, if we study, e.g., the Tl- and Bi-based cuprates, and increase T_c in the usual way, that is, by adding oxygen, then such an addition, we propose, is accompanied by the formation of localized magnetic moments and by the pair-breaking effect. The increase in T_c is frustrated by this pair-breaking effect; therefore, the value of the derivative $\partial T_c / \partial n$ and the value of $T_{c,m} = T_{c,m}^{\text{dop}}$ depends on the amount of impurities. In other words, Eq. (5) contains a derivative for fixed n_{imp}. As a whole, $T_{c,m}^{\text{pres}} > T_{c,m}^{\text{dop}}$. Speaking of the pressure coefficient, it is important to note that the absolute value of β always decreases with an increase in T_c in the overdoped region which is beyond the value $T_{c,m}^{\text{pres}}$.

We focus in this paper on the Tl- and Bi-based overdoped cuprates. For these compounds the large pressure effect is caused by the influence of pressure on the level of the doping which is dependent on the nonadiabaticity of the apical oxygen. As a result, we are dealing with the unusual situation where pressure raises T_c higher than usual doping does. This phenomenon is due, in our view, to the fact that the usual doping by the addition of oxygen is accompanied by the formation of additional magnetic moments.

The situation with the YBCO compound is different from that for the Tl- and Bi-based systems since overdoping is quite difficult. YBCO contains a well developed chain structure, and in general the deviation from a stoichiometric composition which corresponds to the underdoped region, is accompanied by the depletion of the oxygen on the chain sites or in some cases near to ideal stoichiometry to oxygen on the adjacent nonchain site. This depletion leads to the formation of Cu^{++} ions on the chains. This phenomenon was studied by us in detail in Ref. 5 and differs drastically from the picture described above when we are dealing with a much more direct impact of magnetic impurities on the Cu-O plane (although in both cases one can observe a gapless state, see Refs. 5 and 6). Since overdoping in YBCO is difficult, the values of $T_{c,m}^{\text{dop}}$ and $T_{c,m}^{\text{pres}}$ practically coincide, and one can directly use the relation (5). Indeed, one can observe experimentally[38,40] that β_c is very small at $T_c = T_{c,m}$, and the signs for the underdoped and overdoped regions are different.

The Nd-based compound $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_{4-y}$ represents a different remarkable example; its behavior in a peculiar way totally supports our view. Indeed, this cuprate does not have an apical oxygen, nor does it have a chain structure. Therefore, there is no source of intrinsic magnetic impurities. As a result, one should expect a well defined gap (absence of a pair-breaking effect), and, in addition, a weak dependence of T_c on pressure. Indeed, all these properties are observed experimentally (see Ref. 4). It is interesting that a large pressure effect has been observed for the $\text{Nd}_{1.3}\text{Ce}_{0.3}\text{Sr}_{0.5}\text{CuO}_{4-x}$ compound which does contain an apical oxygen.[39]

VI. CONCLUSION

Pair-breaking studied by us in Refs. 5 and 6 and the concept of ''intrinsic T_c'' presented above allows us to propose a peculiar effect of external pressure on T_c in layered cuprates. Since the ''intrinsic'' value is depressed by pair breaking, one can raise T_c above the maximum ambient pressure measured value by pressure induced doping. In fact, one should distinguish two methods of doping, one is by the usual oxygen addition, and the second is pressure induced doping. The latter method is not accompanied by the formation of additional localized magnetic moments. We conclude that T_c for the 2201 Tl-based compound can be raised up to approximately 105 K, and this is noticeably higher than the usual value $T_{c;m}^{\text{dop}} = 90$ K. Based on our microscopic model[30] which is strongly supported by data,[31,32] one can show also that the value of the pressure coefficient decreases as we approach the maximum value of T_c.

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[1] J. Schilling and S. Klotz, in *Physical Properties of High Temperature Superconductors*, edited by D. Ginsberg (World Scientific, Singapore, 1982), Vol. 3.

[2] P. Chu *et al.*, in *Frontiers of High Pressure Research*, edited by H. Hochheimer and R. Etters (Plenum, New York, 1991), p. 383.

[3] D. Berkley *et al.*, Phys. Rev. B **47**, 5524 (1993).

[4] C. Mirayama *et al.*, Nature (London) **339**, 293 (1989).

[5] V. Kresin and S. Wolf, Phys. Rev. B **46**, 6458 (1992); **51**, 1229 (1995); M. Reeves *et al.*, *ibid.* **47**, 6065 (1993).

[6] Yu. Ovchinnikov and V. Kresin, Phys. Rev. B **52**, 3075 (1995).

[7] A. P. Mackenzie *et al.*, Phys. Rev. Lett. **71**, 1938 (1993); J. Supercond. **7**, 27 (1994); A. Carrington *et al.*, Phys. Rev. B **49**, 13 243 (1994).

[8] M. Osofsky *et al.*, Phys. Rev. Lett. **71**, 2315 (1993).

[9] A. Abrikosov and L. Gor'kov, Sov. Phys. JETP **12**, 1243 (1961).

[10] P. de Gennes, J. Phys. Condens. Matter **3**, 79 (1964); P. de Gennes, *Superconductivity in Metals and Alloys* (Benjamin, New York, 1966).

[11] S. Skalski, O. Betbeder, and P. Weiss, Phys. Rev. **136**, A1500 (1964).

[12] D. Saint-James, G. Sarma, and E. Thomas, *Type II Superconductors* (Pergamon, Oxford, 1969).

[13] K. Maki, in *Superconductivity*, edited by R. Parks (Marcel Dekker, New York, 1969), p. 1035.

[14] A. Abrikosov, *Fundamentals of the Theory of Metals* (North-Holland, Amsterdam, 1988).

[15] N. Phillips, R. Fisher, and J. Gordon, in *Progress in Low-Temperature Physics*, edited by D. Brewer (North-Holland, The Netherlands, 1992), Vol. 13, p. 267; A. Junod, in *Studies of High Temperature Superconductors*, edited by A. V. Narliker (Nova Science, New York, in press).

[16] J. Wade *et al.*, J. Supercond. **7**, 261 (1994).

[17] C. Niedermayer *et al.*, Phys. Rev. Lett. **71**, 1764 (1993).

[18] J. Tallon and J. Loram, J. Supercond. **7**, 15 (1994); J. Tallon *et al.*, Phys. Rev. Lett. **74**, 1008 (1995).

[19] L. Gor'kov, Sov. Phys. JETP **10**, 593 (1960); E. Helfand and N. R. Werthamer, Phys. Rev. Lett. **13**, 686 (1964); Phys. Rev. **147**, 288 (1966).

[20] Y. Dalichaouch *et al.*, Phys. Rev. Lett. **64**, 599 (1990).

[21] M. Suzuki and M. Hikita, Phys. Rev. B **44**, 249 (1991).

[22] (a) D. Walker *et al.*, Phys. Rev. B **51**, 9375 (1995); (b) G. Williams, J. Tallon, and R. Meinhold, *ibid.* **52**, R7034 (1995).

[23] H. Homma *et al.*, Phys. Rev. B **33**, 3562 (1986); we are grateful to I. Schuller for bringing our attention to this study.

[24] V. Gusakov, Physica C **235-240**, 513 (1994).

[25] V. Kresin and H. Morawitz, Solid State Commun. **74**, 1203 (1990); Y. Uemura, Phys. Rev. Lett. **62**, 2317 (1989).

[26] (a) V. Kresin, Phys. Lett. A **122**, 434 (1987); (b) S. Chaplot *et al.*, Physica B **174**, 378 (1991).

[27] (a) P. Allen and R. Dynes, Phys. Rev. B **12**, 905 (1975); (b) E. Wolf, *Tunneling Electron Spectroscopy* (Oxford, New York, 1985).

[28] K. A. Mueller, Z. Phys. B **70**, 193 (1990).

[29] T. Schneider and H. Keller, Phys. Rev. Lett. **69**, 3374 (1993).

[30] V. Kresin and S. Wolf, Phys. Rev. B **49**, 3652 (1994).

[31] D. Zech *et al.*, Nature (London) **371**, 681 (1994).

[32] D. Zech, K. Conder, M. Keller, E. Kaldis, and K. A. Muller (unpublished); we are grateful to the authors for sending a copy of the manuscript prior to publication.

[33] J. Mustre de Leone, Phys. Rev. Lett. **64**, 2575 (1990).

[34] L. Gasparov *et al.*, J. Supercond. **8**, 27 (1995); G. Ruani, P. Guptasarma, and C. Taliania, Solid State Commun. **96**, 653 (1995); also in *Anharmonic Properties of High T_c Cuprates*, edited by D. Mihailovoc, G. Ruani, E. Kaldis, and K. A. Mueller (World Scientific, Singapore, 1995).

[35] A. Jezowski, J. Klamut, and B. Dabrowski, Phys. Rev. B **52**, 7030 (1995).

[36] U. Welp *et al.*, Phys. Rev. Lett. **69**, 2130 (1992); U. Welp *et al.*, J. Supercond. **7**, 159 (1994).

[37] G. Meingast *et al.*, Phys. Rev. B **41**, 11 299 (1990); G. Meingast *et al.*, Physica C **209**, 591 (1993).

[38] J. Jorgensen *et al.*, Physica C **171**, 93 (1990); O. Kraut *et al.*, *ibid.* **205**, 139 (1993).

[39] N. Mori *et al.*, J. Phys. Soc. Jpn. **59**, 3839 (1990); A. Moulton *et al.*, Phys. Rev. B **44**, 12 632 (1991).

[40] I. Berman *et al.*, Sov. Phys. JETP **47**, 733 (1988).