Internal friction and ultrasonic attenuation related to carriers in high-T_c superconductors

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For various samples of Bi-Sr-Ca-Cu-O (2:2:2:3 phase, 2:2:1:2 phase, and 2:2:2:3-2:2:1:2 mixed phases) and Tl-Ba-Ca-Cu-O (2:2:2:3 phase) with different T_c, the internal friction (Q^{-1}) in the kHz range reveals a plateau (Q_p^{-1}) above T_c and drops drastically below T_c with the turning point at T_c. This kind of anomaly has not been observed for nonsuperconducting samples. The results of ultrasonic attenuation (α) in Tl-Ba-Ca-Cu-O (2:2:2:3) are similar to that of the internal friction mentioned above. Moreover, it is discovered that the Q_p^{-1} is nearly proportional to Hall carrier density (n_H) for $Y_{1-x}Pr_xBa_2Cu_3O$ and $Gd_{1-x}Pr_xBa_2Cu_3O$ with various Pr content. These results indicate that the drastic drop of Q^{-1} and α below T_c is caused by superconducting condensation. The energy dissipation (Q_p^{-1} and a_p) related to carriers can be explained reasonably by using a coupling model of carriers with local dynamic distortion. Furthermore, by taking into account the smearing of the superconducting gap structure caused by the recombination of quasiparticles and by modifying the BCS relative jump rate as $S(E,E',\Gamma)=\mathrm{Re}\{1-\Delta^2/[(E-i\Gamma)(E'-i\Gamma)]\}$, the calculated results of internal friction and ultrasonic attenuation below T_c agree fairly well with the experimental data. The superconducting gap Δ and the damping rate Γ for both Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O have also been obtained and are in accordance with those obtained by tunneling-spectrum, NMR methods, etc.

I. INTRODUCTION

In conventional superconductors, the ultrasonic attenuation drops exponentially below T_c and generally obeys the formula derived from BCS theory.[1] This attenuation, being called the electronic damping, is attributed to electron-phonon scattering. So ultrasonic measurements can be used to determine the energy gap and offer an additional verification of the mechanism of superconductivity.

In high-T_c oxide superconductors (HTSC's), Sun and Wang[2] discovered that the internal friction in the kHz range for Bi-(Pb)-Sr-Ca-Cu-O reveals an obvious plateau (Q_p^{-1}) above T_c and drops linearly as a function of temperature below T_c with an apparent turning point at T_c. These results are similar to those measured in the MHz range by Saint-Paul *et al.*[3] and Pankert *et al.*[4] Although the turning point is obscured in Y-Ba-Cu-O as a result of the existence of relaxation peaks around T_c, the Q_p^{-1} above T_c is obviously higher than those below T_c.[2,5] Moreover, the Q_p^{-1} in Y-Ba-Cu-O decreases monotonically with the decreasing of oxygen content.[2,5] For while it is generally recognized that the concentration of carriers decrease as the oxygen content is reduced in Y-Ba-Cu-O,[6] the Q_p^{-1} may be speculated to be related to carriers.[2] However, it is better to study the relationship between the Q_p^{-1} and the carriers by direct measurements of the carrier density, such as the Hall effect, rather than speculated from other results indirectly.[2] In HTSC's the electronic damping should be too small to be detected in the kHz range according to traditional theory,[1] and the Q_p^{-1} in the kHz range only increases about 10%–15% for both Bi-(Pb)-Sr-Ca-Cu-O (Ref. 2) and Y-Ba-Cu-O (Ref. 7) when the frequency changes three to four times, which is quite different from the expected results of conventional electronic damping.[1,2] So the mechanism of Q_p^{-1} needs to be researched further. Moreover, it is necessary to study whether the Q_p^{-1} drops linearly or exponentially below T_c for HTSC's, which is important to determine the superconducting gap.

One of the striking features of HTSC's is the smearing of the superconducting gap structure,[8–10] which is usually observed in experiments of the tunneling spectrum. Whether this phenomenon will appear in the measurements of internal friction and ultrasonic attenuation is both interesting and useful for gaining insight into the superconductivity of HTSC's.

In this paper, we have carefully studied the internal friction (Q^{-1}) in the kHz range for Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O, and the ultrasonic attenuation (α) in the MHz range for Tl-Ba-Ca-Cu-O as a function of temperature. The relationship between Q_p^{-1} and carrier density (n_H) in $Y_{1-x}Pr_xBa_2Cu_3O$ and $Gd_{1-x}Pr_x Ba_2Cu_3O$ is investigated in detail. The mechanism of Q_p^{-1} and α_p is discussed, and the energy gaps Δ and the damping rate Γ have been calculated by a modified BCS formula.

II. SAMPLES AND EXPERIMENTAL METHOD

In order to measure the internal friction related to carriers, we selected the method of reed vibration with a very low strain amplitude ($< 10^{-6}$), which can minimize the influence of some kinds of amplitude-dependent peaks, such as those induced by phaselike transitions.[11] We elaborately calibrated the nodes of the samples and the distance between the samples and electrodes until the exponential decay and the reproducibility were very good, and the Q^{-1} would not become smaller.

Four kinds of Bi-Sr-Ca-Cu-O ceramic samples were used in our experiments of internal friction. The first (Bi-I) is mainly 2:2:2:3 phase which is determined by x-ray diffraction, and the T_c measured by ac susceptibility is 104.5 K; the second (Bi-II) is 2:2:2:3-2:2:1:2 mixed phases and shows two superconducting transitions with one T_c at 102 K and another T_c around 88 K; the third (Bi-III) is mainly 2:2:1:2 phase, and the T_c is 84 K; and the fourth is nonsuperconducting above 54 K. Two kinds of Tl-Ba-Ca-Cu-O ceramic samples were used. The first (Tl-I) used in the measurements of internal friction is mainly 2:2:2:3 phase, and the T_c measured by dc resistivity is 98 K; the second (Tl-II) used in ultrasound experiments is also mainly 2:2:2:3 phase with the T_c being 112 K, which is determined by ac susceptibility, as shown in Table I in detail.

The critical temperatures (T_c) of $Y_{1-x}Pr_xBa_2Cu_3O_{7-d}$ and $Gd_{1-x}Pr_xBa_2Cu_3O_{7-d}$ ceramic samples with various Pr content are shown in Table II.

The dimensions of all the samples used in the measurements of internal friction are about $40\times4\times0.5$ mm^3. The Tl-Ba-Ca-Cu-O (Tl-II) for ultrasound measurements has a diameter of 15 mm and thickness of 10 mm. The cooling or heating rate is 0.5 K/min.

III. EXPERIMENTAL RESULTS

The results of the internal friction in Bi-Sr-Ca-Cu-O (Bi-I,II,III,IV) and Tl-Ba-Ca-Cu-O (Tl-I) are shown in Fig. 1. They reveal an obvious plateau of internal friction (Q_p^{-1}) above T_c, and the Q_p^{-1} drops drastically below T_c with an apparent turning point at T_c for the superconducting samples (curves I, II, III, and V), but no such anomaly appears for nonsuperconducting samples (curve IV). Moreover, there are two turning points for the second kind of Bi-Sr-Ca-Cu-O (Bi-II) with one at 102 K and another around 88 K, which correspond to the two critical temperatures. In order to determine the reliability of our results, we have measured more than ten samples of Bi-Sr-Ca-Cu-O (BSCCO) and two of Tl-Ba-Ca-Cu-O (TBCCO), and all the results manifest the same features as those shown in Fig. 1. The results for the samples during heating are almost coincident with those during cooling, and the data for successive cycles are nearly the same.

The data of internal friction with the changing of frequency for BSCCO (Bi-I) and TBCCO (Tl-I) are shown in Fig. 2 and indicate that the Q_p^{-1} (above T_c) only increase about 15% when the frequency changes three times. These results are similar to that of Refs. 2 and 7, and different from those according to conventional electronic damping.[1]

The experimental results of the ultrasonic attenuation in Tl-Ba-Ca-Cu-O (Tl-II) at 4.2 and 6.8 MHz are shown in Figs. 3 and 4 [the sound velocity (V) at 100 K is 3520 m/s]. They reveal an obvious plateau of ultrasonic attenuation (α_p) above T_c and the α_p drops drastically below T_c with an apparent turning point at T_c. Besides, two small and one large peaks are located at about 125, 170, and 220 K, respectively, and they are all expected to be related to the phaselike transitions.[2,11] These results are in accordance with those of Refs. 3 and 4 in BSCCO.

The internal friction of Y-Pr-Ba-Cu-O (Fig. 5) and Gd-Pr-Ba-Cu-O (Fig. 6) ceramic samples with various Pr content (x) was also measured in order to investigate the mechanism of the Q_p^{-1}. As shown in Figs. 5 and 6, two peaks appear at about 100 and 220 K, respectively. The peak near 220 K changes a little when the Pr content increases, and it has been confirmed to be related to the phase transition.[2,11] The peak around 100 K decreases obviously with the increasing of Pr content. As pointed out in Refs. 2 and 5, this peak is a relaxation one which is suggested to be due to the jump of oxygen atoms. Because the radius of Pr^{3+} ions (1.013 Å) is larger than that of Y^{3+} (0.893 Å) and Gd^{3+} (0.938 Å) ions, the oxygen atoms would be difficult to move after the Pr atoms are introduced. This may be the reason why the relaxation peak decreases as the samples were doped by Pr.

In Y-Pr-Ba-Cu-O [Y(Pr)BCO] and Gd-Pr-Ba-Cu-O [Gd(Pr)BCO], the turning point at T_c, which is expected to appear as that of BSCCO and TBCCO mentioned above, becomes obscure because there are one or two relaxation peaks around T_c. However, the plateau Q_p^{-1} (above T_c) denoted by the dashed line in Figs. 5 and 6 decreases obviously with the increasing of Pr content (x), which is similar to the results for decreasing oxygen content in YBCO.[2,5] To get the relationship between Q_p^{-1} and the carriers, the Hall carrier density (n_H) was measured at 100 K for Y-Pr-Ba-Cu-O and at 273 K for Gd-Pr-Ba-Cu-O, and the data show that n_H decreases with the increasing of Pr content (as shown in Table III). It is thus obtained that Q_p^{-1} is nearly proportional to n_H (the insets of Figs. 5 and 6), which can be approximately written as $Q_p^{-1}=5.2\times10^{-25}n_H$ (holes cm^{-3}) at 100 K for Y(Pr)BaCuO (the inset of Fig. 5) and $Q_p^{-1}=3.4\times10^{-4}+9.2\times10^{-25}n_H$ (holes cm^{-3}) at 273 K for Gd(Pr)BaCuO (the inset of Fig. 6).

From the results mentioned above in BSCCO, TBCCO, Y(Pr)BCO, and Gd(Pr)BCO, it may be concluded that the Q_p^{-1} above T_c is related to the carriers and the drastic decrease of Q_p^{-1} as well as α_p below T_c for supercon-

TABLE I. Phases and T_c of Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O used in our experiments.

Samples	Bi-I	Bi-II	Bi-III	Bi-IV	Tl-I	Tl-II
Phases	2:2:2:3	mixed 2:2:2:3-2:2:1:2	2:2:1:2		2:2:2:3	2:2:2:3
T_c (K)	104.5	102 and 88	84	<54	98	112

TABLE II. T_c of Y-Pr-Ba-Cu-O and Gd-Pr-Ba-Cu-O with various Pr content x.

	$Y_{1-x}Pr_xBa_2Cu_3O_{7-d}$					$Gd_{1-x}Pr_xBa_2Cu_3O_{7-d}$		
x	0	0.1	0.2	0.4	0.55	0	0.35	0.45
T_c (K)	93	82	71	39	11	90	28	<4.2

ducting samples (Figs. 1–4 and Refs. 3 and 4) may be regarded as caused by the superconducting condensation.

IV. DISCUSSION

In HTSC's the internal friction due to carriers will be too small to be detected in the kHz range according to the theory of conventional electronic damping.[1] On the other hand, the experimental results show that Q_p^{-1} related to carriers is some 10^{-3}–10^{-4}, and the relation between the dissipation (Q_p^{-1} and α_p) and the frequency in the kHz to MHz rangle (Figs. 2 and 4 and Refs. 2 and 7) is also not in agreement with traditional electronic damping[1] (according to conventional theory, the internal friction or ultrasonic attenuation caused by carriers is proportional to frequency f or f^2, respectively[1]). Therefore the mechanism of Q_p^{-1} and α_p needs further studying.

One of the striking features of strong-correlation systems is the coupling property,[12] which can be successfully described by the coupling model. HTSC's are strong-correlation systems, and photoinduced absorption measurements[13] and neutron-scattering experiments[14] have shown that there exists lattice distortion around the carriers (which may be accompanied by the distortion of magnetic orders). This kind of distortion with various effective orientations is expected to be associated with the softest shear modulus $C'=[(C_{11}+C_{22})/2-C_{12}]/2$.[15] So it is proposed here that the relaxation of carriers accompanied by distortion clouds is due to the stress-induced preferred orientations in the distortion variants and obeys the coupling model. According to this model,[12] when $\omega\tau \ll 1$, the internal friction is

$$Q^{-1}=A(\omega\tau)^{1-n}\,, \tag{1}$$

where τ is the relaxation time and n is the correlation factor ($0\le n\le 1$). It indicates the Debye relaxation when $n=0$ and the strong-correlation limit[12] when $n=1$. A is the relaxation strength,[1] and

$$A=\frac{4n_H m^* V_F^2}{15\rho V^2}\,, \tag{2}$$

where m^* and V_F are the effective mass and the Fermi velocity of carriers, respectively, ρ and V are the density and the sound velocity of the samples, respectively.

Based on the discussion above, the results of internal friction and ultrasonic attenuation related to carriers (Q_p^{-1} and α_p) in HTSC's could be explained reasonably. When $n\neq 0$, the energy loss will decrease slower than those according to traditional electronic damping[1] with the decreasing of frequency, and the dissipation will be high enough to be detected at the kHz to MHz range if n is large enough.

Figure 7 shows the internal friction (from Figs. 2 and 3 and Refs. 4, 7, and 16) related to carriers at the normal state for YBaCuO, BSCCO, and TBCCO as a function of frequency. By best fitting between the data in Fig. 7 and Eq. (1), it is obtained that $n=0.57$ ($T=100$ K, at which Q_p^{-1} was taken), 0.52 ($T=120$ K), and 0.49 ($T=120$ K) for Y-Ba-Cu-O (1:2:3), Bi-Sr-Ca-Cu-O (2:2:2:3), and Tl-Ba-Ca-Cu-O (2:2:2:3), respectively, as shown in Table IV in detail. In Fig. 7 the backgrounds of internal friction and ultrasonic attenuation unrelated to carriers, such as that caused by the scattering between acoustic waves and

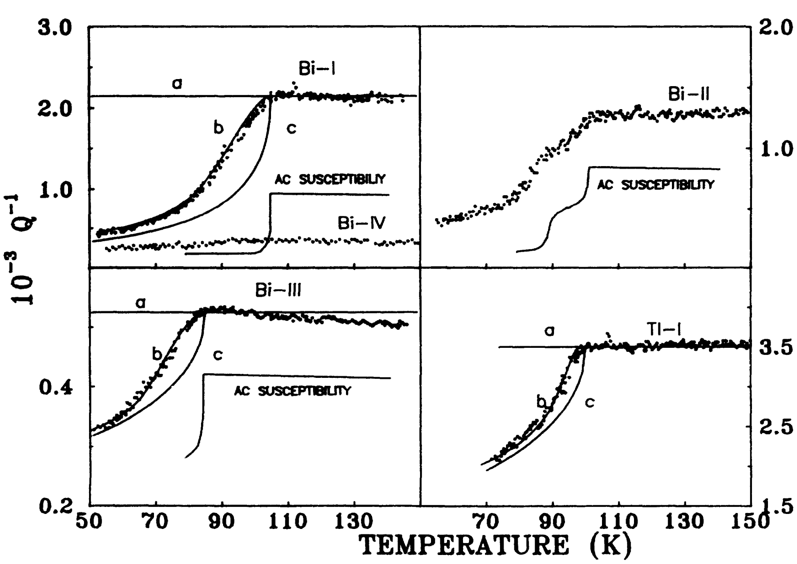

FIG. 1. Q^{-1} of Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O vs T measured at 0.8 and 1.2 kHz, respectively. Experimental data (●). Curves a, expected Q_p^{-1} in the normal state; curves b, the fits according to formula (6); and curves c, the curves derived from traditional BCS theory in the weak-coupling limit.

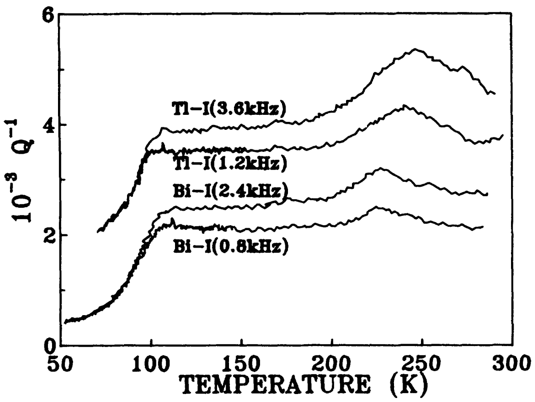

FIG. 2. Q^{-1} of Bi-I and Tl-I samples vs T measured at different frequencies.

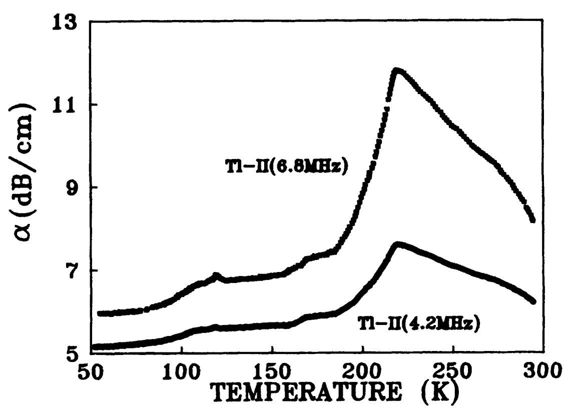

FIG. 3. α of Tl-II samples vs T (50–300 K) measured at different frequencies.

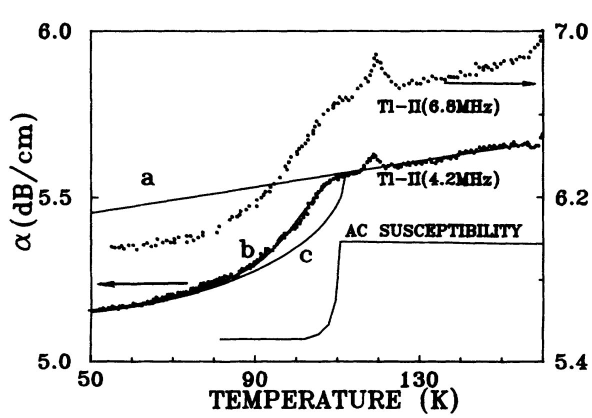

FIG. 4. α of Tl-II samples vs T (50–160 K) measured at 4.2 and 6.8 MHz. Curves a, expected α_p in the normal state; curves b, the fits according to formula (6); and curves c, the curves derived from traditional BCS theory in the weak-coupling limit.

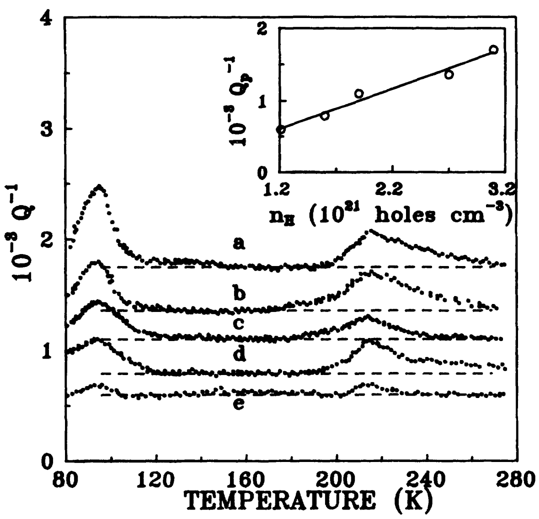

FIG. 5. Q^{-1} vs T for Y-Pr-Ba-Cu-O with various Pr content measured near 1.7 kHz. $x=0$ (curve a), 0.1 (curve b), 0.2 (curve c), 0.4 (curve d), and 0.55 (curve e). Experimental data (●) and the expected Q_p^{-1} related to carriers (dashed lines). The inset shows Q_p^{-1} vs n_H for Y-Pr-Ba-Cu-O at $T=100$ K. The solid line (inset) expresses the fit of experimental data by using a linear function.

crystal boundaries, etc., have been subtracted, and ultrasonic attenuation has been converted to internal friction ($\alpha = Q^{-1}\omega/2V$).

Table IV shows that $n \approx 0.5$ in YBCO (1:2:3), BSCCO (2:2:2:3), and TBCCO (2:2:2:3); this result indicates further that the Q_p^{-1} and/or α_p are all related to carriers for the three systems of HTSC's, and can be described by the coupling model.

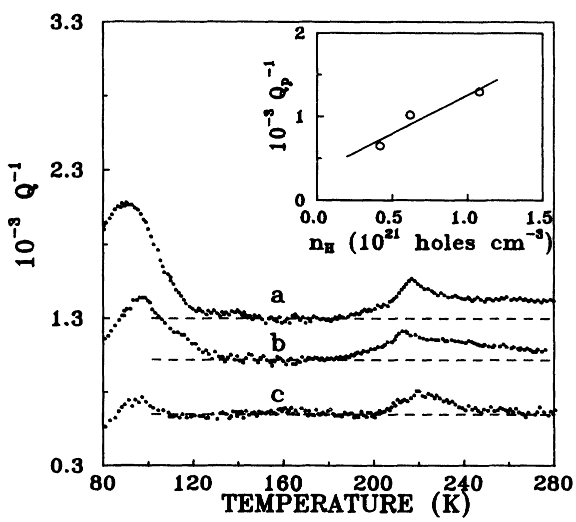

FIG. 6. Q^{-1} vs T for Gd-Pr-Ba-Cu-O with various Pr content measured near 0.7 kHz. $x=0$ (curve a), 0.35 (curve b), and 0.45 (curve c). Experimental data (●) and the expected Q_p^{-1} related to carrier (dashed lines). The inset shows Q_p^{-1} vs n_H for Gd-Pr-Ba-Cu-O at $T=273$ K. The solid line (inset) expresses the fit of experimental data by using a linear function.

TABLE III. n_H of Y-Pr-Ba-Cu-O and Gd-Pr-Ba-Cu-O with various Pr content x.

	$Y_{1-x}Pr_xBa_2Cu_3O_{7-y}$ ($T=100$ K)					$Gd_{1-x}Pr_xBa_2Cu_3O_{7-y}$ ($T=273$ K)		
x	0	0.1	0.2	0.4	0.55	0	0.35	0.45
n_H (10^{21} holes cm^{-3})	3.1	2.7	1.9	1.6	1.2	1.1	0.65	0.45

As pointed out by Ref. 17, the energy dissipation in HTSC's is too small to be detected even at the MHz range according to traditional electronic damping. This question can also be solved when the coupling property of carriers is taken into account. According to traditional electronic damping,[1] $\alpha_{tra}=A\omega^2\tau/2V$, and by Eq. (1), $\alpha_{cou}=A\omega(\omega\tau)^{1-n}/2V$. Therefore $\alpha_{cou}=\alpha_{tra}/(\omega\tau)^n$. When $\omega\sim10^6$ Hz, and $\tau\sim10^{-13}$ s (determined by optical conductivity),[18] and according to Ref. 17, $\alpha_{tra}\sim10^{-4}-10^{-5}$ dB/cm. Then it can be obtained that $\alpha_{cou}\sim0.1$ dB/cm for $n\approx0.5$, and this value is quite in accordance with that of experimental data (Figs. 3 and 4 and Refs. 4 and 16).

In HTSC's one puzzling question is that the experimental data of optical conductivity cannot be described by the conventional Drude formula;[18] another one is the continuous background of Raman-scattering intensity from 0 to 1 eV, etc.[19] To solve these problems, a relaxation time which is dependent on frequency is proposed.[18,19] On the other hand, according to the coupling model,[20] the relaxation time is dependent on time. This means that the relaxation time is also frequency dependent. This similarity may indicate that there would be common origins among the mechanical dissipation, optical conductivity,[18] Raman-scattering intensity, etc.,[19] in HTSC's.

According to BCS theory,[1] the Q_p^{-1} and α_p will drop after the carriers condensate below T_c, and the superconducting gap (Δ) could be calculated by using the results of internal friction and ultrasonic attenuation below T_c. In Y-Ba-Cu-O (1:2:3) the ultrasonic attenuation[16,21] and

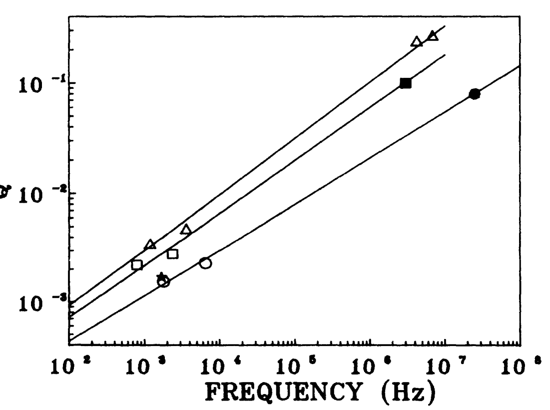

FIG. 7. Q^{-1} related to carriers as a function of frequency. $n=0.57$, 0.52, and 0.49 for YBCO (1:2:3) at 100 K [Fig. 5 (*), Ref. 7 (○), Ref. 16 (●)], BSCCO (2:2:2:3) at 120 K (Fig. 2 (□), Ref. 4 (■))], and TBCCO (2:2:2:3) at 120 K [Figs. 2–4], respectively. The solid lines express the best fitting between the experimental data and Eq. (1).

the internal friction[2,7] also decrease below T_c and often manifest exponential variations with temperature. So they have been used to calculate the superconducting gaps (Δ).[7,16] However, as mentioned above, there always exist relaxation peaks around T_c (Refs. 2, 5, and 21) for Y-Ba-Cu-O; the decrease of the ultrasonic attenuation or internal friction below T_c cannot be recognized to be related to the superconducting condensation only. But fortunately there is no such problem for both Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O samples; the drastic decrease of Q^{-1} and α below T_c may be used to determine the energy gaps if the anomaly near T_c is actually due to superconducting condensation.

Curves C shown in Figs. 1 and 4 are results according to traditional BCS theory in the weak-coupling limit[1] (i.e., $2\Delta_0/k_BT_c=3.52$), and they are much lower than the experimental data. This may indicate that conventional BCS theory may not apply to HTSC's and implies that other mechanisms would be active in HTSC's. In fact, by using the density of states as $N_s(E)=N_n(E)E/[E^2-\Delta^2]^{1/2}$ according to conventional BCS theory, it cannot explain the tunneling spectrum of HTSC's well either.[8-10]

In HTSC's one striking feature of tunneling data, which is usually observed, in the smearing of the gap feature.[8,9] Hasegawa, Ikuta, and Kitazawa[19] have used a broadening BCS density of states in the superconducting state, which was modeled by Dynes, Narayanamurli, and Garno,[22] to explain the tunneling results of HTSC's in the form

$$N_s(E,\Gamma)=\mathrm{Re}\left\{N_n(E)\frac{E-i\Gamma}{\sqrt{(E-i\Gamma)^2-\Delta^2}}\right\}, \quad (3)$$

where Γ is the damping rate or the linewidth of quasiparticle energy (E),

$$\Delta/\Delta_0=1.82(1-T/T_c)^{1/2}$$
$$+(1-T/T_c)[-0.82+0.09(T/T_c)$$
$$+0.3175(T/T_c)^2]$$

(Ref. 23), Δ_0 is the superconducting gap at zero temperature, and $N_n(E)$ is the density of states in the normal state.

TABLE IV. Correlation factors (n) in Y-Ba-Cu-O, Bi-Sr-Ca-Cu-O, and Tl-Ba-Ca-Cu-O.

Samples	Correlation factor (n)	Temperature (K)
YBCO (1:2:3)	0.57	100
BSCCO (2:2:2:3)	0.52	120
TBCCO (2:2:2:3)	0.49	120

Based on traditional BCS theory, the relative jump rate $S(E,E')$ from energy E to E' in the superconducting state is expressed as $S(E,E')=1-\Delta^2/EE'$.[1] However, the results of Q^{-1} and α below T_c calculated by using $S(E,E')=1-\Delta^2/(EE')$ and Eq. (3) are also much lower than the experimental data (not shown here). Therefore we modify the relative jump rate for HTSC's as the following form, i.e., by adding an imaginary part to E, which is similar to the method of Dynes, Narayanamurli, and Garno[22] for dealing with $N_s(E,\Gamma)$, when the recombination of quasiparticles is taken into account:

$$S(E,E',\Gamma)=\mathrm{Re}\left\{1-\frac{\Delta^2}{(E-i\Gamma)(E'-i\Gamma)}\right\}, \tag{4}$$

where $E'=E+\hbar\omega$, $\hbar$ being Plank constant. Different from the traditional relative jump rate $S(E,E')=1-\Delta^2/(EE')$,[1] there is a nonzero part for $S(E,E',\Gamma)$ inside the gap near the Fermi level, and the effective gap Δ_{eff}, which equals to Δ for $\Gamma=0$, becomes smaller after the smearing of the superconducting gap ($\Gamma\neq 0$) is taken into account (as shown in Fig. 8).

As done by Coffey[24] and Wolf, Tao, and Busla,[25] Γ is taken as the following form for HTSC's:

$$\Gamma=\Gamma_0+Gk_BT_c\left[\frac{T}{T_c}\right]^3, \tag{5}$$

where Γ_0 and G are constants independent of temperature; k_B is Boltzmann's constant.

From (3) and (4) and Ref. 1, it is obtained that

$$\frac{Q_s^{-1}-Q_b^{-1}}{Q_n^{-1}-Q_b^{-1}}=\frac{\int_0^\infty W_s(E)dE}{\int_0^\infty W_n(E)dE}, \tag{6}$$

where

$$W_s(E)=\Theta[S(E,E',\Gamma)]S(E,E',\Gamma)\times[f(E)-f(E')]N_s(E,\Gamma)N_s(E',\Gamma),$$

$\Theta[S(E,E',\Gamma)]=0$, when $S(E,E',\Gamma)\le 0$, and $\Theta[S(E,E',\Gamma)]=1$, when $S(E,E',\Gamma)>0$; $f(E)$ is a Fermi function; $W_n(E)=[f(E)-f(E')]N_n(E)N_n(E')$; Q_s^{-1} and Q_n^{-1} are internal frictions related to carriers in superconducting and normal states, respectively, and Q_b^{-1} is the background of internal friction unrelated to carriers.

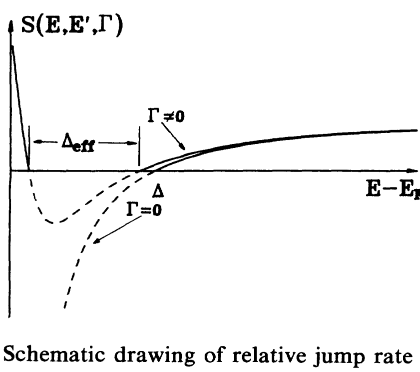

FIG. 8. Schematic drawing of relative jump rate $S(E,E',\Gamma)$ vs energy E.

By best fitting between the data of superconducting Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O (Figs. 1 and 4) and formula (6), the values of $2\Delta_0/k_BT_c$, G, and Γ_0 are obtained and shown in Table V. The fitted curves (curves b in Figs. 1 and 4) are in fair agreement with the experimental results [the background (Q_b^{-1}) has been subtracted].

As shown in Table V, the superconducting gap and damping rate calculated from experimental data are almost identical in the kHz to MHz range; these results indicate that the mechanisms in kHz and MHz are the same.

Because the samples used in our experiments are polycrystal, the superconducting gap calculated from the experimental data is the weight average along the c direction and in the basal plane. Moreover, the results show that $2\Delta_0/k_BT_c=4-8$ in the basal plane and ≈ 3.5 along the C direction in tunneling measurements.[8,9] This means that our results are reasonable. The values of Γ measured by tunneling and NMR methods are dispersive.[9,24,25] Our results of Γ are also reasonable when they are compared with other experiments.

Although the comparison between experimental data and calculated results according formula (6) is good, the use of an imaginary term in the relative jump rate as is done in Eq. (4) is based on a hypothesis because there is no widely accepted theory of the mechanism of high-T_c superconductivity,[8,9] and further studies are expected.

Because the variation of the Q_p^{-1}-related carriers above and below T_c is about $10^{-3}-10^{-4}$, it can only be observed with careful adjustment of the nodes of samples which can minimize the external energy dissipation, and with good samples in which the amount of superconducting phase must be high enough. Moreover, the large backgrounds of 5–20 dB/cm (Figs. 3 and 4 and Refs. 4 and 26), which may be associated with the scattering between the acoustic waves and crystal boundaries, etc., for polycrystal of HTSC's, always appear in the measurements of ultrasonic attenuation, and the dissipation caused by carriers is only 0.1–0.7 dB/cm (Figs. 3 and 4 and Refs. 4, 16, and 21). So the anomaly of ultrasonic attenuation near T_c may be smeared by the large background. On the other hand, Γ is sensitive to the defects in the samples used, and it is obtained that there will be no turning of the dissipation at T_c when the Γ is large enough from formula (6). These may be the reason why some authors observed no obvious drops or slower drops of internal friction and ultrasonic attenuation below T_c.[2–4,26,27]

A few method are used to determine the energy gaps of

TABLE V. $2\Delta_0/k_BT_c$, G, and Γ by best fitting between the experimental data of Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O, and formula (6).

	$2\Delta_0/k_BT_c$	G	Γ_0 (meV)	Frequency
Bi-Sr-Ca-Cu-O (2:2:2:3)	3.9	0.51	2.4	0.8 kHz
Bi-Sr-Ca-Cu-O (2:2:1:2)	3.8	0.85	0.7	0.8 kHz
Tl-Ba-Ca-Cu-O (2:2:2:3)	4.0	0.35	0.8	1.2 kHz
Tl-Ba-Ca-Cu-O (2:2:2:3)	4.1	0.80	0.1	4.2 MHz

HTSC's, such as tunneling spectroscopy,[8–10] infrared light scattering,[28,29] Raman scattering,[30,31] and so on. It is still controversial whether the methods of infrared light scattering[28] and Raman scattering[31] can be used to determine the superconducting gap. Otherwise, the coherence length is very short in HTSC's; it makes the results extremely sensitive to surface conditions for the tunneling method, etc., while the surface tends to deteriorate as a result of exposure to water vapor or the loss of oxygen.[8,9] However, these surface conditions do not affect the results significantly in measurements of internal friction and ultrasonic attenuation; therefore, the method of internal friction may be one of the effective means to study superconductivity and to determine the energy gap and broadening lifetime of quasiparticles especially near T_c for HTSC's.

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