Quasiparticle relaxation dynamics in underdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ by two-color pump-probe spectroscopy


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We investigate the relaxation dynamics of photoexcited quasiparticles (QPs) in underdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ ($T_c = 78$ K). By changing the excitation energy and polarization of the probe beam, two different types of relaxation dynamics, associated with superconducting (SC) and pseudogap (PG) QPs, are quantitatively analyzed independently. From the temperature dependencies, we obtained the SC gap, $\Delta_{\text{SC}}(0) = 24$ meV, using BCS-type temperature-dependent gap and the pseudogap, $\Delta_{\text{PG}} = 41$ meV. The pump fluence ($F$) dependence of the SC-dominated transients shows a contribution of the PG component above the saturation condition of the SC component ($F_{\text{th}} = 16 \, \mu J/cm^2$), where Cooper pairs with long-range order are fully destroyed within the photoexcited volume. Assuming a temperature-independent PG decay time, we successfully isolate the native SC transient even above $F_{\text{th}}$ by subtracting the PG response from the original data. In the saturation regime, the exponential decay (recovery of SC) is fast ($\tau_{\text{SC}} \sim 2-3$ ps), suggesting an efficient nonequilibrium phonon relaxation in this compound. We also find a flat-top response preceding the exponential decay at $F > F_{\text{th}}$, which appears as a delay of SC recovery in the original data. This response is visible over the whole temperature range below $T_c$ and its duration increases with increasing $F$. The response is attributable to a photoinduced SC to non-SC phase transition arising from excitation by the nonthermal QPs and/or high-frequency phonons. The consistently near-constant magnitude of the PG response at the start of the SC state recovery from the non-SC phase suggests a correlation between the SC and PG QPs.

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I. INTRODUCTION

The coexistence of superconducting (SC) gap and pseudogap (PG) is a fascinating feature in high-$T_c$ superconductors, and underdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (UD-Bi$_2$2212) is one of the most extensively studied cuprates from this point of view.\textsuperscript{1} Scanning tunneling microscopy/spectroscopy (STM/STS) and angle-resolved photoemission spectroscopy (ARPES) are the two major techniques of investigating the connection between SC and PG, where the former characterizes the spatial variations of the gaps, while the latter characterizes their momentum distributions. The recent STS and ARPES studies on UD-Bi$_2$2212 and Bi$_2$2201 (La) reveal that the SC gap located in the nodal region starts to open below $T_c$ and its duration increases with increasing $F$.\textsuperscript{2-4} The coexistence of superconducting (SC) gap and pseudogap, type temperature-dependent gap and the pseudogap, $\Delta_{\text{PG}} = 41$ meV, are quantitatively analyzed independently. From the temperature dependencies, we obtained the SC gap, $\Delta_{\text{SC}}(0) = 24$ meV, using BCS-type temperature-dependent gap and the pseudogap, $\Delta_{\text{PG}} = 41$ meV. The pump fluence ($F$) dependence of the SC-dominated transients shows a contribution of the PG component above the saturation condition of the SC component ($F_{\text{th}} = 16 \, \mu J/cm^2$), where Cooper pairs with long-range order are fully destroyed within the photoexcited volume. Assuming a temperature-independent PG decay time, we successfully isolate the native SC transient even above $F_{\text{th}}$ by subtracting the PG response from the original data. In the saturation regime, the exponential decay (recovery of SC) is fast ($\tau_{\text{SC}} \sim 2-3$ ps), suggesting an efficient nonequilibrium phonon relaxation in this compound. We also find a flat-top response preceding the exponential decay at $F > F_{\text{th}}$, which appears as a delay of SC recovery in the original data. This response is visible over the whole temperature range below $T_c$ and its duration increases with increasing $F$. The response is attributable to a photoinduced SC to non-SC phase transition arising from excitation by the nonthermal QPs and/or high-frequency phonons. The consistently near-constant magnitude of the PG response at the start of the SC state recovery from the non-SC phase suggests a correlation between the SC and PG QPs.

In our previous paper, we selectively isolated the transient dynamics associated with SC and PG QPs in UD-Bi$_2$2212 by changing the probe beam energy and polarization.\textsuperscript{22} We also showed that two distinct components can be detected simultaneously below $T_c$. However, the paper lacked quantitative details. In this paper, we report experimental studies on UD-Bi$_2$2212 by using a similar selective method as before. The photoexcitation with a low-repetition-rate laser allows quantitative analysis of the dynamics with high precision. In addition to the temperature dependence, we carry out the pump fluence dependence of the dynamics. At fluences where the...
SC component is saturated, the PG component rises above the SC signal. At the same time, a delay of SC recovery appears and increases linearly with increasing pump fluence. We also extract the saturated SC dynamics by subtracting the PG component obtained above $T_c$ from the original data. The response is clearly visible even in the vicinity of $T_c$, indicating a SC to non-SC phase transition with an efficient nonthermal phonon distribution.

**II. EXPERIMENTAL**

The sample used in this work was underdoped Bi2212 single crystal with $T_c \approx 78$ K grown by the traveling solvent floating zone method. The time-resolved reflectivity change $\Delta R$ was measured using a two-color pump-probe setup and was carried out with a freshly cleaved sample mounted in an optical liquid-He flow cryostat. The two pulses were derived from a 250-kHz Ti:sapphire regenerative amplifier (RegA) and a signal of an optical parametric amplifier (OPA) pumped by RegA. Due to the low repetition rate, we can neglect the laser heating, as justified in Sec. III A from the data obtained at $T_c$. Due to the low repetition rate, we can neglect the laser heating. We employed a combination of the excitation energies (wavelengths) of 1.55 eV (800 nm) and 0.95 eV (1300 nm), where the latter energy is slightly lower than that used in the previous report ($1.30 \mu$m) with $\Delta R/ R = 0.7$ and $900 \mu$m at the sample position, respectively. In most cases, the collinearly overlapped and focused onto the $ab$ plane of the crystal by a lens ($f = 50$ mm) located on-axis, allowing for the precise spatial overlap between the beams. The beam diameters from RegA and OPA were measured to be 30 and 40 $\mu$m at the sample position, respectively. In most cases, the collinearly polarized pump and probe beams were set to be parallel to $a$ axis of the crystal ($E_{pu} \parallel E_{pr} \parallel a$). The fluence of the pump beam ($F$) ranged from 9 to $\sim 900 \mu J/cm^2$. We set the probe fluence about three orders of magnitude smaller than the pump. Owing to the energy difference between the pump and probe beams, we can spectroscopically distinguish the reflection beams for detection. The time resolution was estimated to be around 75 fs from cross correlation measurements.

**III. RESULTS AND DISCUSSIONS**

**A. Temperature dependence**

In Fig. 1, we plot the temperature dependence of $\Delta R/R$ transients at various excitation conditions at low excitation fluences. The upper panels show the density plots of the data, where the red and blue correspond to positive and negative signs of $\Delta R$, respectively. With excitation/probe energies of $E_{pu}/E_{pr} = 0.95/1.55$ eV [see Figs. 1(a) and 1(d)], only a negative $\Delta R/R$ transient is present below $T_c$, characteristic of the QP relaxation associated with the SC state. No remarkable polarization dependence was observed with this pump-probe energy combination. In contrast, a positive component is dominant in the reverse combination; $E_{pu}/E_{pr} = 1.55/0.95$ eV [see Figs. 1(b) and 1(c)]. This component remains constant across $T_c$, then decreases monotonically with further increasing temperature, and finally disappears around $T^* \approx 180 \sim 210$ K. Thus we assign the positive $\Delta R/R$ transient to QP relaxation associated with the PG. In the case of $E_{pr} \parallel a$ probe polarization [see Figs. 1(c) and 1(f)], an additional small negative component appears in the temperature region below $T_c$, which can be identified as a small contribution of the SC component observed in Figs. 1(a) and 1(d). On the other hand, the negative component is nearly absent and only the positive component is apparent when $E_{pr} \parallel b$ [see Figs. 1(b) and 1(e)].

As shown in Figs. 1(d) and 1(e), $\Delta R/R$ transients are well reproduced by a single exponential relaxation (thin solid lines), ensuring that we can uniquely evaluate the relaxation dynamics.

**FIG. 1.** (Color online) (Top) Density plots of $\Delta R/R$ transients as a function of temperature, obtained at (a) $E_{pu}/E_{pr} = 1.55/0.95$ eV (800/1300 nm) with $F = 9 \mu J/cm^2$ and (b) and (c) $E_{pu}/E_{pr} = 0.95/1.55$ eV (1300/800 nm). $F = 75 \mu J/cm^2$ and $E_{pr} \parallel a$ in (b) and $F = 25 \mu J/cm^2$ and $E_{pr} \parallel b$ in (c). (Bottom) Corresponding $\Delta R/R$ transients at typical temperatures.
of the SC and PG QPs at each excitation condition. Let us briefly comment on the selectivity of SC/PG component in the optical pump-probe measurement. In cuprates superconductors, a two-component signal consisting of SC and PG components has been widely observed, where the magnitude of the signal reflects the change of the interband transition probabilities induced by the photoexcited QPs. Since the transition probability depends on the probe energy and polarization, we can enhance/suppress one of the SC/PG components by changing the excitation condition. Since the transition probability depends on the probe energy and polarization, we can enhance/suppress one of the SC/PG components by changing the excitation condition.

Under the saturation condition, the assumption of weak photoexcitation (so that the photoinduced QPs and phonon occupations are small compared to their equilibrium concentrations) and a momentum-independent gap, $\Delta R/R$ amplitude is given by

$$\frac{\Delta R}{R} \propto \left[ \frac{\Delta \text{SC}(T) + \frac{k_B T}{2}}{\Delta \text{PG}(T)} \right]^{-1} \times \left\{ 1 + g \sqrt{\frac{k_B T}{\Delta \text{SC}(T)}} \exp \left( -\frac{\Delta \text{SC}(T)}{k_B T} \right) \right\}^{-1},$$  

(1)

where $g$ represents the ratio of bosonic and electronic density of states that contribute the photoinduced QP density. We used BCS-type $\Delta \text{SC}(T)$ and obtained $\Delta \text{SC}(0) = 24$ meV, which is slightly larger than the values obtained from other experiments, but still consistent by taking into account the variation in the momentum space. The agreement with the data is also good enough to ensure the identification of the SC component. For the PG component, assuming the strong bottleneck condition (QP relaxation is governed by the hot phonon relaxation) and weak photoexcitation, $\Delta R/R$ amplitude is given by

$$\frac{\Delta R}{R} \propto \left[ 1 + \frac{2 v k_B T}{N(0) \hbar \Omega \omega} \exp \left( -\frac{\Delta \text{PG}}{k_B T} \right) \right]^{-1},$$  

(2)

where $N(0) \approx 2 \text{eV}^{-1} \text{cm}^{-3} \text{spin}^{-1}$ is the electronic density of states per unit cell and $v$ and $\Omega$ are, respectively, the number of bosons in the PG relaxation and their cutoff frequency. The best fit to the data at $E_{\text{pr}} \parallel a$ (open circles) with Eq. (2) using $T$-independent $\Delta \text{PG}$ shows $\Delta \text{PG} = 41$ meV, which is also consistent with the value obtained from the STS. In the same figure, we plot the amplitude of $\Delta R/R$ at $E_{\text{pr}} \parallel b$ (triangles) whose $T$ dependence is consistent with the data at $E_{\text{pr}} \parallel a$ and its fitting curve.

In order to check the amount of sample heating from the laser, we compare the $T$ dependencies of SC amplitudes measured at various pump fluences [inset of Fig. 2(a)]. Here, the fluences of the two data sets correspond to $\mathcal{F}$ above saturation condition for SC component (where the SC condensate is temporally destructed, see Sec. III B). A similar $T_c$ was found at $\mathcal{F} = 70 \mu J/cm^2$ (closed triangles) while a small ($\sim 5$ K) apparent shift of $T_c$ due to the laser heating is observed at $\mathcal{F} = 300 \mu J/cm^2$ (open triangles). This implies that the laser heating is negligibly small for $\mathcal{F}$ up to a few hundred $\mu J/cm^2$.

Under the saturation condition, the assumption of weak photoexcitation in Eq. (1) is no longer valid. Instead, we employ the Mattis-Bardeen (MB) formula to characterize the data, which are given by

$$\frac{\Delta R}{R} \propto \frac{\Delta \text{SC}(T)^2}{\hbar \omega} \ln \left( \frac{\hbar \omega}{\Delta \text{SC}(T)} \right),$$  

(3)

where $\hbar \omega$ is the photon energy. This formula represents a $T$-dependent difference in reflectivity between the normal (non-SC) and SC states and an assumption that the reflectivity in

![FIG. 2. (Color online) Temperature dependencies of normalized amplitudes of $\Delta R/R$ obtained from (a) $E_{\text{pr}}/E_{\text{pl}} = 0.95/1.55$ eV [data extracted from Fig. 1(a)] and from (b) $E_{\text{pr}}/E_{\text{pl}} = 1.55/0.95$ eV, [from Figs. 1(b) and 1(c)]. The thin lines in (a) and (b) are the fits by Eqs. (1) and (2), using BCS-type $\Delta \text{SC}(T)$ and $T$-independent $\Delta \text{PG}$, respectively. Inset shows two data sets at higher fluences, where the fitting curve of (a) is reproduced as a dot-dashed line. The solid and dashed lines are given by Eq. (3), where the dashed line is obtained by shifting the solid line by $-5$ K.](image)
the non-SC state does not depend (or weakly depends) on temperature. We see a good agreement with the data at $\mathcal{F} = 70 \, \mu J/cm^2$. Note that the comparison with the fit by Eq. (1) (dot-dashed line) shows a noticeable difference between low-$\mathcal{F}$ and high-$\mathcal{F}$ amplitudes. On the other hand, the data obtained far above the saturation ($\mathcal{F} = 300 \, \mu J/cm^2$, open triangles) are slightly shifted downward at each temperature, suggesting that the heating by the laser may occur. Indeed, the MB fit by shifting the temperature by $\sim 5 \, K$ shows excellent agreement with the data (dashed line in the inset).

For completion of the analysis, we plot the decay times of SC and PG components at the low fluence as a function of temperature in Figs. 3(a) and 3(b), respectively. Analogous to the amplitude, the decay time in each component shows a significantly different $T$ dependence. The SC decay time ($\tau_{SC}$) shows a remarkable $T$ dependence: with increasing temperature below $T_c$, $\tau_{SC}$ first decreases, then reaches a minimum value of $\sim 2 \, ps$, and then shows a divergent-like increase as the temperature approaches $T_c$. Although the decay times are different, qualitatively similar $T$ dependences have been observed in various types of superconductors,\cite{8,12,14,18,19,25,27} clearly indicating the universal nature of superconductors. In contrast to the characteristic $T$ dependence of $\tau_{SC}$, the decay time of the PG component ($\tau_{PG}$) shows a featureless dependence ($\tau_{PG}$ gradually varies around $0.7 \, ps$ below $\sim 100 \, K$) in Fig. 3(b). This featureless $T$ dependence is also consistent with $\tau_{PG}$ observed in other cuprates.\cite{7,13,22} The decay time of $\Delta R/R$ at $E_{pr} \parallel b$ (triangles), where we expect the single PG component above $T_c$, is also plotted in Fig. 3(b). The consistency of the decay time [as well as the amplitude in Fig. 2(b)] at different polarizations manifests the assignment of PG.

We now characterize $\tau_{SC}$ on the basis of Rothwarf-Taylor (RT) model in the strong bottleneck regime. At the temperature below $T_c$, QP relaxation rate ($\tau_{SC}^{-1}$) is given by\cite{8,18}

$$\tau_{SC}^{-1} = 2(n_{ph} + n_{T})\gamma,$$

where $n_{T}$ is the equilibrium density of QP, $n_{ph}$ is the density of photoinduced QPs (equivalent to the density of hot phonons), and $\gamma$ is the effective relaxation rate of hot phonons to thermal equilibrium. The essential point of this equation is the relaxation rate determined by the total density of QPs. At the lowest temperature, $\tau_{SC}^{-1}$ is governed by $n_{ph}$, which accounts for the dependence on the photoexcitation fluence demonstrated in the next subsection (Sec. III B). When increasing the temperature, the thermal phonons increase the effective phonon density for QP relaxation, and thus increase $\tau_{SC}^{-1}$. When approaching $T_c$, $\tau_{SC}^{-1}$ is dominated by the phonon relaxation rate $\propto \Delta_{SC}$, resulting in a divergent-like increase of $\tau_{SC}$. Assuming the $T$-independent $\gamma$, we fit the low-$T$ data very well with Eq. (4) shown by the thin line in Fig. 3(a). Here, we used $n_{ph}$ extracted from the measured $T$ dependence of amplitude [see Fig. 2(a)] and $n_{T} = N(0)\sqrt{2}\pi\Delta_{SC}(T)k_B T\exp[-\Delta_{SC}(T)/k_B T]$ using $\Delta_{SC}(T)$ given by the BCS functional form. From the fit, we obtained $\Delta_{SC}(0) = 4.3 \, meV$, which is significantly smaller as compared with $\Delta_{SC}(0) = 24 \, meV$ estimated from the fit to the $T$ dependence of the amplitude. Similar underestimation was observed by Kabanov et al.,\cite{8} where they suggested that both the assumption of temperature-independent $\gamma$ and the underestimate of the laser heating lead to a reduction of $\Delta_{SC}(0)$. However, we can exclude the latter contribution, especially in the measurement with low pump fluence, because of both the low repetition rate of the laser and identical $T_c$ of $\Delta R/R(T)$ at various fluences demonstrated in the inset of Fig. 2(a). Thus we can attribute the inconsistency between the fit of the temperature dependence of $\tau$ and the experimental data to the fact that the model does not account for external processes of phonon escape, particularly those associated with nanoscale textures (stripes).\cite{31}

### B. Pump-fluence dependence

SC and PG $\Delta R/R$ transients at 10 K are shown in Figs. 4(a) and 4(b) for various pump fluences $\mathcal{F}$. While the PG component shows qualitatively identical transients at all fluences, the SC component shows changes with increasing $\mathcal{F}$: faster relaxation and saturation of the amplitude together with the appearance of an additional positive component. The saturation behavior has been observed in various superconductors and ascribed to the destruction of the superconducting condensate.\cite{3,11,24,25} In the present case, the additional positive component appearing at higher $\mathcal{F}$ is attributed to the PG that exhibits higher saturation threshold and therefore becomes dominant after the saturation of the SC component.\cite{9}

For the comprehensive assignment of coexisting SC and PG components, we show the $T$ dependence of $\Delta R/R$ transients at $E_{pr}/E_{pe} = 0.95/1.55 \, eV$ with $\mathcal{F}$ above the saturation condition in Fig. 5. The raw data set shown in (a) and (c) indicate that there is a temperature-independent component (instantaneous negative response) that remains above $T^*$. 
In this section, we concentrate our attention to the SC dynamics above the saturation condition at $E_{pu}/E_{pr} = 0.95/1.55$ eV. Figure 6(a) shows $\Delta R/R$ transients excited with various $F > F_{th}$ at 10 K, where, due to the saturation of the SC component, the contribution of the PG component becomes apparent as a positive peak together with an instantaneous negative peak that exists throughout the whole temperature range as mentioned in Fig. 5(a). The most striking feature of the saturated dynamics in the SC component is the appearance of a delay preceding the onset of the SC component recovery marked by arrows in Fig. 6(a).

In order to minimize the PG component contribution to $\Delta R/R$ in the delay region at high $F$ to obtain better insight
Here, we assumed that the PG amplitude dependence of the PG component up to $F/D_{1R}$ obtained with the lowest $F$ exponential decay time ($\Delta_{1R}/R$ error bars represent the standard deviation noise of subtracting transients measured above into the prerecovery evolution of the SC component, we subtract the transients measured at $T_c$ [at $T = 90$ K shown in Fig. 6(b)] from the transients measured at 10 K. To compensate for the $T$ dependence of the PG amplitude at low $T$, $\Delta R/R(90 \text{ K})$ is multiplied before subtraction by $C(T) = \Delta R_{\text{PG}}(T)/\Delta R_{\text{PG}}(90 \text{ K})$ [$C(10 \text{ K}) = 1.3$], derived from the $T$-dependent amplitude of the PG component in Fig. 2(b). Here, we assumed that the PG amplitude $T$ dependence does not significantly change with $F$ due to the near-linear $F$ dependence of the PG component up to $\sim 200 \mu J/cm^2$. Also note that the above manipulation is correct only under the assumption that the PG decay time is temperature independent.

FIG. 6. (Color online) Typical $\Delta R/R$ transients at $E_{\text{pw}}/E_{\text{pu}} = 0.95/1.55$ eV with various $F > F_{\text{th}}$ at 10 K ($<T_c$) and (b) at 90 K ($>T_c$). Each plot is shifted vertically. For comparison, $\Delta R/R$ obtained with the lowest $F$ are shown in the top. (c) Plot of the exponential decay time ($\tau_{\text{SC}}$, open circles) and the delay of the exponential decay ($\tau_{\text{fin}}$, closed circles and triangles) as a function of $F$. The positions of $\tau_{\text{fin}}$ are indicated by arrows in (a) and (b). (d) $\Delta R/R(T = 10 \text{ K}) = C \Delta R(90 \text{ K})$ fitted with a delayed exponential decay (dashed line), where $C$ is $\Delta R_{\text{th}}(10 \text{ K})/\Delta R_{\text{th}}(90 \text{ K}) \approx 1.3$. (e) $\Delta R(t_{\text{fin}})/R - \Delta R_{\text{eq}}/R$ at 90K, where $\Delta R_{\text{eq}}/R$ is defined in (b). The amplitude of the PG component at $F_{\text{th}}$ is also shown (triangle). The error bars represent the standard deviation noise of $\Delta R/R$.

The subtracted transients [shown in Fig. 6(d)] show at the highest $F$ a flat-top response, which follows the initial negative $\sim 100$ fs peak. While it is not clear whether the initial peak is an artifact of the subtraction procedure, the flat-top response seems a quite robust feature, since it is consistently present also in $T$-dependent subtracted intermediate-$F$ transients shown in Fig. 7.

The $F$ dependence of the flat-top duration, $\tau_{\text{fin}}$, obtained from the delayed-exponential-function fits, is shown by the solid circles in Fig. 6(c) and appears consistent with the shifts of the negative peak position obtained from the raw data (triangles), ensuring the validity of the subtraction procedure. A linear fit to the data shows that the delay of the SC recovery intercepts zero at $F \approx 20 \mu J/cm^2$, which is approximately equal to $F_{\text{th}} \approx 16 \mu J/cm^2$, suggesting that the delayed recovery starts with the saturation of the SC response. From the delayed-exponential fits [dashed lines in Fig. 6(d)], we obtain more accurate values of $\tau_{\text{SC}}$ in the saturation regime [shown as open circles in Fig. 6(c)], that show a much weaker dependence on $F$ than $\tau_{\text{SC}}$ obtained by the nondelayed exponential fit [see inset of Fig. 4(c)].

In Fig. 7 we summarize the $T$ dependence of the saturated SC component dynamics obtained by the subtraction procedure performed on the data of Fig. 5. The flat-top response is clearly visible throughout the whole temperature range below $T_c$. Unlike the divergent-like increase of the superconducting response duration with increasing $T$ near $T_c$, the flat-top shows a finite $\tau_{\text{fin}}$ ($\sim 3$ ps at $F = 70 \mu J/cm^2$) even in the vicinity of $T_c$. Note that the delay of SC recovery is confirmed also by the shift of the negative peak in the raw data [see Figs. 5(a) and 5(c)].
The flat-top response indicates, due to the saturation properties of the SC component, that the real volume the SC gap is temporarily completely closed and the SC condensate remains completely destroyed during \( t_\text{ns} \). Despite the unreliability of the subtraction during the initial few hundred femtoseconds, the raw data around the threshold indicate [see Fig. 4(a)] that the SC gap closing happens rather fast on a few hundred fs timescale, which is slightly faster than in La\(_{1−x}\)Sr\(_{x}\)CuO\(_4\). During the flat-top duration, QPs and hot phonons relax but do not contribute to the SC condensation. The subsequent fast (\(~2\) ps) partial recovery of the SC condensate indicates that the relaxation, during and immediately after the flat-top response, can not be associated with the heat diffusing thermally out of the experimental volume, but it must be associated with relaxation of a transient nonthermal state of the system characterized by an excess of the high-energy excitations. The existence of the transient nonthermal state is supported also by the absence of an increase of the relaxation time near the saturation threshold, which is observed in the case of the thermal transition near \( T_c \) [see Fig. 3(a)].

The two most obvious relaxation pathways in such nonthermal system are (i) the diffusion of hot nonthermal QPs and/or high-frequency phonons out of the experimental volume and (ii) their energy relaxation to the thermal (low-frequency) phonon bath. The lower bound for the timescale of (i) can be estimated on the basis of the measured in-plane low-\( F \) hot-QP diffusion constant in YBa\(_2\)Cu\(_3\)O\(_6\),\(^{35}\) \( \kappa_{ab} \approx 20−24 \text{ cm}^2/\text{s} \). In the present case, due to the pancake-like geometry of the excitation volume, only the out-of-plane diffusion can contribute. Taking into account the high anisotropy of UD-Bi2212, the timescale of (i), \( \tau_c \gg \tau_{ab} = \lambda_{pu}^2/k_{ab} \approx 6 \text{ ps} \), clearly indicates the dominance of process (ii).

Our observations therefore suggest that, after the initial fast closure of the SC gap, the system remains in a transient nonthermal normal state for up to \( t_\text{ns} \sim 2 \text{ ps} \) at the highest excitation density. During this time, the hot nonthermal QPs and high-frequency phonons are cooled by the low-frequency phonon bath. After \( t_\text{ns} \), the population of the hot QPs and high-frequency phonons drops to such level that the SC condensate (and gap) can start to recover. Due to the nonthermal character of the transient normal state a fundamental question appears: what is the exact pathway of the SC state destruction and recovery?

Recently, it was proposed that the photoinduced transition to the normal state (and back) might be of first order.\(^{24,25}\) Our data indicate that there is no abrupt changes in the photoinduced reflectivity during the recovery, which would be an indication of the first-order transition. However, the excitation density is, due to the finite penetration depth, highly inhomogeneous and any abrupt changes could be easily smeared out. Moreover, the SC rise-time dynamics is obscured by other components preventing us to reliably observe any fast SC component switching during the SC state destruction. On the basis of the present data and in the absence of a second-order transition model valid at high \( F \), which would fit the data, it is therefore not possible to rule out a first-order transition.

Finally, we comment on the contribution of the PG QPs to the photoinduced SC to non-SC phase transition. Assuming that in the PG state \( \Delta R/R(t_\text{ns}) \) directly corresponds to the population of the nonequilibrium PG QPs, we use the data above \( T_c \) in Fig. 6(b) to estimate the population of the nonequilibrium PG QPs at the moment when the SC condensate starts to recover. In Fig. 6(e), we therefore plot \( \Delta R(t_\text{at})/R = \Delta R_{\text{eq}}/R \) at 90K, where \( \Delta R_{\text{eq}}/R \) is the \( \Delta R/R \) averaged between 9 and 10 ps [see Fig. 6(b)]. For comparison, the amplitude of the PG component at \( F_{\text{th}} \) is also shown [triangle in Fig. 6(e)]. The result shows a virtually constant QP density at \( t_\text{ns} \), suggesting the existence of a critical PG QPs density level correlated with the start of the SC condensation. In other words, the PG QPs also need to cool below a critical level before the SC condensate can recover, suggesting the correlation between the SC and PG QPs.\(^{36}\)

It is surprising that the gap recovery starts so fast after the complete gap destruction. However, we note that the recovery time of the SC state is also very fast, a few picoseconds, which is much faster than that of MgB\(_2\) (\(~100 \text{ ps} \)) and even faster than in La\(_{2−x}\)Sr\(_x\)CuO\(_4\) (\(~10 \text{ ps} \)). Also note that the fast recovery time in Bi2212 was widely observed not only for UD samples,\(^{22,25}\) but also for the optimally-doped (\(~2.5 \text{ ps} \) from time-resolved ARPES\(^{3,37}\)) as well as overdoped samples (\(~3.3 \text{ ps} \)).\(^{24}\)

IV. CONCLUSIONS

We investigated the relaxation dynamics of photoexcited quasiparticles (QPs) in UD Bi2212 (\( T_c = 78 \text{ K} \)). The transient \( \Delta R/R \) dynamics associated with SC and PG QPs were selectively isolated from each other by changing the probe beam energy and polarization, enabling us to evaluate the individual dynamics quantitatively. Below the saturation condition, both the temperature and pump-fluence dependencies of SC transients agree well with those predicted from Rothwarf-Taylor model. From the temperature dependencies, we obtained \( \Delta_{\text{SC}}(0) = 24 \text{ meV} \) using BCS-type temperature-dependent gap and \( \Delta_{\text{PG}} = 41 \text{ meV} \), both of which are consistent with the values obtained from other measurements.

The pump fluence dependence of the SC-component-dominated transients shows a contribution of the PG component above the saturation of the SC component (\( F_{\text{th}} = 16 \mu\text{J/cm}^2 \)), where the SC condensate is fully destroyed within the photoexcited volume. We also found a delay of the SC state recovery whose duration time increases linearly with increasing \( F > F_{\text{th}} \). The delay of the SC state recovery is associated with a picosecond-timescale transient normal state. The subsequent fast (picosecond) partial SC state recovery suggests that the phonon and QP population remain highly nonthermal upon photoexcitation, on a time scale of a few picoseconds. During the nonthermal relaxation phase, the energy relaxation proceeds from the high-energy QPs and phonons, which are strongly coupled to phonons that do not break SC pairs. The latter can be the low-frequency phonons or maybe the phonons in the layer isolated from the Cu-O plane.

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34The T-independent negative peak, which is observed at high T [see Figs. 5(a) and 5(c)] might be overestimated by the scaling by C.
36On the basis of this scenario, one can expect the T-independent T_mn, which is confirmed in the T range below ~50 K of Fig. 7. The increase of T_mn (decrease of PG QPs at T_mn) above T ~ 50 K could be explained by the increasing number of the thermal PG QPs.