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Rotational symmetry breaking in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ probed by polarized femtosecond spectroscopy

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The quasiparticle (QP) dynamics with different symmetry is investigated in the superconducting (SC) and normal state of the high-temperature superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) using optical pump-probe experiments with different light polarizations at different doping levels. The observation of distinct selection rules for SC excitations present in $A_{1g}$ and $B_{1g}$ symmetries, and for the pseudogap (PG) excitations present in $A_{1g}$ and $B_{2g}$ symmetries by the probe, and absence of any dependence on the pump beam polarization leads to the unequivocal conclusion of the existence of a spontaneous spatial symmetry breaking in the PG state not limited to the sample surface.

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I. INTRODUCTION

Ultrafast pump-probe spectroscopy has been widely used to investigate the high-$T_c$ superconductivity from various viewpoints [1–5]. Nonequilibrium studies give a unique insight into quasiparticle (QP) dynamics, revealing universal two-component QP dynamics associated with the superconducting (SC) gap and pseudogap (PG) excitations in high-$T_c$ materials. The two types of excitations were characterized by distinct relaxation times, temperature dependencies, and/or sign of the optical signal, depending on the material, doping level, photoexcitation intensity, and the wavelengths of light used in the pump-probe experiments [6–10]. The dependence on the probe photon polarization of the two-component reflectivity dynamics has also been reported [11,12]. However, the absence of a fundamental understanding of the optical processes involved in pump-probe experiments so far prevented analysis of the symmetry of excitations or detailed theoretical analysis of the excitations on a microscopic level. Here, by performing a concise symmetry analysis of pump-probe experiments on Bi2212 high temperature superconductors and identifying the processes involved, we open the way to investigations of hidden broken symmetry and local or mesoscopic symmetry breaking in systems with competing orders.

Generally pump-probe experiments can be described as a two step process. In the first step, the pump pulse excitation can be viewed as a process which can be divided into a coherent stimulated Raman excitation [13] and an incoherent dissipative excitation. In pseudotetragonal ($D_{4h}$) symmetry, considered appropriate for the cuprates [14], $A_{1g}$ and $A_{2g}$ as well as $B_{1g}$ and $B_{2g}$ excitations can be coherently excited by the coherent excitation process for the photon polarizations lying in the CuO$_2$ plane [15]. On the other hand, the dissipative excitation cannot coherently excite nonsymmetric modes. However, an additional possibility exists, where in the presence of a local, dynamic, or hidden symmetry breaking nonsymmetric modes can be excited coherently also by the totally symmetric dissipative excitation. This allows us to probe symmetry breaking by means of the pump-probe spectroscopy.

In the second step of the pump-probe experiment, the transient change of reflectivity $\Delta R$ detected by the probe can be described by the Raman-like process [13]. Assuming the pseudotetragonal structure ($D_{4h}$ point group) for Bi2212, we can obtain the simple form of the angle dependence of the transient reflectivity (for details see the Supplemental Material [16]):

$$\Delta R(\theta) \propto \Delta R_{A_{1g}} + \Delta R_{B_{1g}} \cos(2\theta) + \Delta R_{B_{2g}} \sin(2\theta).$$

Here $\theta$ is defined in Fig. 1(a), and $A_{2g}$ symmetry is omitted because it does not contribute in our experimental configuration. Thus, in principle, by measuring the temperature dependence of $\Delta R(\theta)$ and using Eq. (1) we can separate the $T$-dependent QP dynamics associated with different symmetries and consequently identify the states involved [17].

Previous analysis in the cuprates have indicated that the electronic Raman scattering in the $B_{2g}$ symmetry probes excitations in the nodal ($\pi/2,\pi/2$) direction in $k$ space, while the $B_{1g}$ scattering probes excitations in the antinodal directions ($\pi/2,0$) and ($0,\pi/2$) [15,18–20] as shown in Fig. 1(b). An $A_{1g}$ symmetry component is also present, whose origin is still highly controversial [15]. Recent studies suggest the presence of the PG in the nodal direction [21] implying an $s$-wave symmetry, in contrast to the common assumption of a PG with nodes, indicating that the PG symmetry is still an open issue. Some important progress has been made on the broken symmetry of the PG in Bi2212 and related compounds [22–24]. A rotational broken symmetry of the PG in YBCO and LSCO has also been reported in the THz region very recently [25]. A detailed symmetry analysis of optical pump-probe experiments can therefore potentially give important new information on the symmetry, lifetime, and temperature dependence of nodal and anti-nodal excitations in the cuprates and other superconductors with an enhanced bulk sensitivity with respect to the time-resolved angle-resolved photoemission spectroscopy (ARPES) [2,4].

II. EXPERIMENT

The optical measurements were performed on freshly cleaved slightly overdoped (OD, $T_c \approx 82$ K) and underdoped (UD, $T_c \approx 69$ K) Bi2212 single crystals grown by the traveling solvent floating zone method. For optimal signal-to-noise ratio we used a pump at $E_{pu} = 3.1$ eV ($\lambda_{pu} = 400$ nm) and...
probe at $E_{\text{pr}} = 1.55$ eV ($\lambda_{\text{pr}} = 800$ nm) from a cavity-dumped Ti:sapphire oscillator with a 120 fs pulses and a repetition rate of 270 kHz (to avoid heating). The pump and probe beams were coaxially overlapped by a dichroic mirror and focused to a 20 $\mu$m diameter spot on the $ab$ plane of the crystal with an objective lens ($f = 40$ mm). Low-pass filters were used to suppress any remaining scattered pump beam. We use the notation where $x$ and $y$ point along the Cu-O bonds [Fig. 1(b)]. The sample orientation was checked by x-ray diffraction, in which the $b$ axis is determined by the direction of the multiple peaks responsible for a one-dimensional (1D) superlattice modulation.

III. RESULTS

First we note that $\Delta R$ is found to be independent of the pump polarization within the experimental error of the measurements ($< 2\%$), while the probe polarization dependence of $\Delta R$ is very temperature dependent.

The angular dependencies of $\Delta R$ at selected temperatures, obtained by rotating the probe polarization from $\theta = 0^\circ$ to $360^\circ$ at each temperature, are presented in Figs. 2(a)–2(f) for OD and Figs. 2(g)–2(l) for UD samples, respectively. The upper panels (a)–(c) and (g)–(i) show the intensity plots of $\Delta R(\theta)$ together with the cross-sectional views at $\theta = 0^\circ$. The polar plots (d)–(f) and (j)–(l) show the angular dependence of the signal amplitude $\Delta R(\theta)$.

At the lowest temperature, where the SC signal is dominant, $\Delta R(\theta)$ is slightly elliptic, with the long axis close to, but not coincident, with the Cu-O bonds direction [Figs. 2(a) and 2(d) and Figs. 2(g) and 2(j)]. The amplitude of the signal increases with increasing $\mathcal{J}$, showing saturation behavior near $\mathcal{J}_{\text{th}}^\text{SC} = 1 \mu J/cm^2$ [26]. With increasing $\mathcal{J}$, an additional fast relaxation signal with opposite sign with respect to the SC signal appears, which persists above $T_c$ and disappears around $T^*$. This component has been previously assigned to the PG QPs [8,27], where $T^* \simeq 140$ K for OD and 240 K for UD samples, respectively, and is consistent with previous measurements [28]. The reason for the PG signal appearing at higher $\mathcal{J}$ is that the PG component has a higher saturation threshold than the SC signal, and therefore becomes visible below $T_c$ with increasing $\mathcal{J}$ [27].

In the PG state above $T_c$, but below $T^*$, the long axis is oriented along the crystalline axes ($\theta \simeq 45^\circ$) [Figs. 2(b) and 2(e) and Figs. 2(h) and 2(k)]. Above $T^*$, a signal with opposite sign to the PG (the same sign as SC) becomes visible, which has been attributed to the electron energy relaxation in the metallic state [29]. This high-temperature signal is almost independent of $\theta$ [Figs. 2(c) and 2(f) and Figs. 2(i) and 2(l)].

In Fig. 3 we present the $T$ dependencies of the $B_{1g}$, $B_{2g}$, and $A_{1g}$ components of $\Delta R$ obtained by fitting Eq. (1) to experimental data. The $B_{1g}$ and $B_{2g}$ components show clear dominance of the SC and PG responses, respectively. The $B_{1g}$ component increases strongly below $T_c$, while above $T_c$ it is consistent with the observed SC fluctuations [33]. On the other hand, the $B_{2g}$ component shows a gradual decrease with increasing the temperature across $T_c$ and a faster subpicosecond relaxation time, which is consistent with the general behavior observed for the PG QPs [6,32]. The difference of the $T$ dependencies between OD and UD samples reflects the systematic variation of the gaps with the doping level.
In Fig. 4 we plot the amplitudes of different components for both OD and UD samples as a function of temperature. The $B_{1g}$ and $A_{1g}$ components show dominant intensity below $T_c$, and their $T$ dependencies can be fit well using the Mattis-Bardeen formula \[31,34\]. The $B_{2g}$ component can be fit well by the Kabanov’s relaxation model \[32,35\] which gives a $T$-independent $\Delta R_{2g} = 30$ meV for OD and $\Delta R_{2g} = 41$ meV for UD samples. The values of $\Delta R_{2g}$ in each sample are consistent with the values obtained from other experiments \[36,37\]. While the $B_{1g}$ component shows a significant change at $T_c$, the $B_{2g}$ component does not show any measurable change within the noise level.

**FIG. 4.** (Color online) $T$ dependencies of the $A_{1g}$, $B_{1g}$, and $B_{2g}$ component amplitudes for UD and OD samples. Note that both $B$ components begin to show an increase of the amplitude below $T^*$. $T^*$’s obtained from tunneling \[30\] are within the region indicated by the shaded area. In the case of the $A_{1g}$ symmetry the PG contribution is superimposed on top of the nearly temperature-independent signal, and has a negative sign. The solid and dashed lines are fits using Mattis-Bardeen \[31\] and Kabanov \[32\] models, respectively.

**FIG. 5.** (Color online) (a) The reduction of symmetries consistent with the observed polarization anisotropy. The CuO$_2$ layers are shown. Using the centrosymmetric refinement \[39\], the highest possible symmetry below $T^*$ is $C_{2h}$. The relevant irreducible representations are given in each case. (b) Schematic representations corresponding to nematic ordering, (c) short stripe ordering \[41–46\], and (d) local polaronic order \[47\].

**IV. DISCUSSIONS**

The absence of any pump polarization anisotropy has important consequences. It rules out stimulated Raman excitation as the excitation mechanism for any nontotally-symmetric modes. At the same time, the fact that the $B$-symmetry responses are observed by the probe means that they are somehow excited by the pump pulse.

During the dissipative excitation, each high-energy QP created by a photon relaxes the excess energy independently by nonelastic scattering with emission of excitations of various symmetries. Due to the stochastic nature of the involved processes the phases of the created excitations are random so their modulation of the dielectric tensor cannot be detected coherently. At the same time, the state of the system is characterized by time-dependent scalar densities corresponding to different excitations, which can only couple to the totally symmetric representation of the dielectric tensor and coherently excite only the totally symmetric modes \[38\]. We are therefore left with the only remaining possibility that the $B$-symmetry modes are excited coherently because the underlying tetragonal point group symmetry is spontaneously broken below $T^*$.

Formally, $B_{2g}$ symmetry breaking of the pseudotetragonal symmetry is already present at room temperature in Bi2212 due to the weak inherent orthorhombicity of the underlying crystal structure from the Bi-O chain modulation arising from the mismatch of Bi-O and Cu-O layers \[39\]. In the resulting $D_{2h}$ point group symmetry the $a$ and $b$ axes are rotated at $\sim 45^\circ$ with respect to the Cu-O bonds. The presence of any coherent $B_{1g}$ symmetry excitation, on the other hand, requires breaking of both the CuO$_2$ plane pseudotetragonal ($D_{4h}$) and $D_{2h}$ symmetry down to $C_{2h}$ [see Fig. 5(a)] \[40\].

In our data however, both symmetry breakings are suppressed at the room temperature appearing clearly below $T^*$, implying that the $B_{2g}$ component is not simply a consequence of the underlying Bi2212 orthorhombicity. The data in Fig. 4...
clearly show the $B_{1g}$ symmetry breaking to occur slightly below $T^*$ and clearly above $T_c$ in both samples. Furthermore, while the BiO chain ordering discussed above can in principle cause the $B_{2g}$ symmetry breaking effect it cannot cause the observed $B_{1g}$ symmetry breaking neither above nor below $T_c$.

Despite the fact that the $d$-wave SC order parameter corresponds to $B_{1g}$ symmetry, the observed effect cannot be linked directly to the symmetry of the SC order parameter. The SC order parameter is complex so any expansion of the dielectric constant in terms of the SC order parameter can only contain powers of $\Delta_{SC}^2$, which are of $A_{1g}$ symmetry. This is consistent with the strong response of the SC state observed in the $A_{1g}$ channel.

The appearance of the SC response in the $B_{1g}$ symmetry can therefore only be associated with a preexisting underlying order oriented along the Cu-O bonds (see Fig. 5). This finding is consistent with previous scanning-tunneling microscopy (STM) measurements indicating the presence of stripe order oriented along one of the two orthogonal Cu-O bond directions on the crystal surface [41–44]. The magnitude of the $B_{1g}$ component significantly exceeds 10% of the $A_{1g}$ magnitude. Since the optical probe penetration depth is of order of 100 nm [27] this indicates that the stripe order and the $B_{1g}$ component are not limited to the surface, but are present also in the bulk. The sensitivity of the $B_{1g}$ component to the SC order also suggests that the instability towards formation of the stripe order and the superconductivity are intimately connected.

The distinct absence of the SC response in the $B_{2g}$ channel is consistent with the sensitivity of the corresponding Raman vertex to the nodal $(\pi/2,\pi/2)$ direction in the $k$ space, where the SC gap has nodes. On the other hand, the presence of the PG response in $B_{2g}$ channel indicates that the PG response can, at least in part, be associated with the nodal QPs. Remarkably this implies the presence of the PG in the nodal region, consistently with recent Raman results [21]. We note that this does not contradict the results of ARCES studies. However, in contrast to ARCES, pump-probe spectroscopy probes hundreds of nanometers in depth and detects also the unoccupied states. It suggests however, that the ARCES picture of the nodal region might be incomplete.

Upon reduction of symmetry from tetragonal to orthorhombic each of the $B$ symmetry breakings of the fourfold axis can occur in two equivalent directions (e.g., along $x$ or along $y$). Since our experiment is stroboscopic and averages over many pulses $B_{1g}$ and $B_{2g}$ channels do not average out only if there exist an underlying anisotropy persisting between subsequent pulses separated by 4 $\mu$s, which aligns the symmetry breakings. This can be imposed by extrinsic defect structure or strain. In the case of Bi2212 it appears that the anisotropy responsible for the $B_{2g}$ channel alignment can originate in the weak orthorhombicity of the crystal, while the anisotropy responsible for the $B_{1g}$ is of extrinsic origin amplified by the softness of the CuO$_2$ planes towards stripe ordering or similar textures.

The symmetry reduction and broken symmetry textures compatible with the observed symmetry breaking are shown schematically in Fig. 5. Assuming a homogeneous broken-symmetry state, the deformation would be uniform [Fig. 5 b)]. Alternatively, in an inhomogeneous state the observed anisotropy is consistent with a picture of locally ordered commensurate charge-density-wave (CDW) patches along the Cu-O bonds [48,49], nematic order [22,50,51], or stripe order with different size stripes [45–47]. Note that incommensurate CDW order would be expected to lead to further reduction in point group symmetry, beyond $C_{2h}$. In all such cases, the observed signal is a (nonzero) spatial average over different possible domain orientations shown schematically in Figs. 5(b)–5(d).

V. CONCLUSIONS

We conclude by noting that the presented symmetry analysis of the response observed in pump-probe spectroscopy opens up new possibilities for investigating the dynamics of spatial symmetry breaking, as well as the $k$-space anisotropy of electronic excitations beyond established methods like Raman and Kerr-effect spectroscopy, while offering a complementary information on unoccupied states and bulk properties compared to related new techniques such as time-resolved ARCES.

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Note that this symmetry analysis is valid also within the probe angle dependence of $\Delta R$.

See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevB.90.094513 for the threshold is different than in Ref. [27] due to a different pump wavelength.

Conventionally the $x$ an $y$ axes are chosen along the Cu-O bond directions.

Note that this symmetry analysis is valid also within the photoinduced absorption (PIA) picture commonly considered until now.