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Ubiquitous suppression of the nodal coherent spectral weight in Bi-based cuprates

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High-temperature superconducting cuprates exhibit an intriguing phenomenology for the low-energy elementary excitations. In particular, an unconventional temperature dependence of the coherent spectral weight (CSW) has been observed in the superconducting phase by angle-resolved photoemission spectroscopy (ARPES), both at the antinode where the d-wave pairing gap is maximum, as well as along the gapless nodal direction. Here, we combine equilibrium and time-resolved ARPES to track the temperature dependent meltdown of the nodal CSW in Bi-based cuprates with unprecedented sensitivity. We find the nodal suppression of CSW upon increasing temperature to be ubiquitous across single- and bi-layer Bi cuprates, and uncorrelated to superconducting and pseudogap onset temperatures. We quantitatively model both the lineshape of the nodal spectral features and the anomalous suppression of CSW within the Fermi-Liquid framework, establishing the key role played by the normal state electrodynamics in the description of nodal quasiparticles in superconducting cuprates.

I. INTRODUCTION

Copper-oxide high- T_c superconductors host a variety of emerging and competing quantum phases. On the one hand, their low temperature physics is mainly characterized by unconventional d-wave superconductivity (SC); on the other hand, the normal state is actually a “strange metal” exhibiting various complex phenomena, such as pseudogap physics and charge density wave order^{1–4}. Since the discovery of cuprates, the existence (or lack thereof) of well-defined quasiparticles in the normal state, as well as their temperature and doping dependence, have been the subject of intense debate. The characteristic onset temperature T_c has been associated not only with the SC phase transition but also with the emergence of coherent quasiparticles^{5,6}. In this regard, specific insight has come from angle-resolved photoemission spectroscopy (ARPES), either at equilibrium or in pump-probe configuration, which provides access to the low-energy electronic structure and its dynamics^{5–15}. In particular, an unconventional temperature dependence of the coherent spectral weight (CSW) for antinodal quasiparticles has been reported by ARPES studies on $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi2212); this was described either as a manifestation of the c-axis superfluid density, or as a testament to the different role played by the quasiparticle coherence in the emergence of SC in underdoped versus overdoped regimes^{8,9}.

Towards unveiling the detailed evolution of quasiparticle weight and lifetime from normal to SC state, the study of the antinodal region of cuprates is hindered by

the interplay of several intertwined contributions, such as SC gap, pseudogap, charge order, as well as strong band renormalization. More promising is in principle the exploration of the gapless and more pristine nodal direction. Similarly to what was reported at the antinode, a time-resolved ARPES (TR-ARPES) study of optimally doped Bi2212 has suggested a direct relation between nodal CSW and the SC condensate¹³. However, a recent theoretical work has questioned such a direct link, proposing instead the key role of a different competing order¹⁶. As a consequence, for both nodal and antinodal regions of the CuO_2 plane electronic structure, a comprehensive and conclusive description of the evolution of CSW across the superconducting-to-normal-state phase transition is still missing.

In laying the basis for discussing the temperature-dependence (T-dependence) of CSW in cuprates, we remark that the many-body renormalization of lifetime and pole structure is captured by the complex electron self-energy $\Sigma(\omega, T) = \Sigma'(\omega, T) + i\Sigma''(\omega, T)$, where the momentum dependence is commonly neglected. ARPES experiments provide access to $\Sigma(\omega, T)$ by measuring the single-particle removal spectral function $A(\mathbf{k}, \omega, T)$, with its corresponding many-body self-energy corrections¹. In the hypothetical scenario of a non-interacting system, $A(\mathbf{k}, \omega, T)$ collapses to a series of delta functions whose area is not expected to vary as a function of temperature. However, in the presence of electron interactions $\Sigma(\omega, T)$ may lead to the broadening and redistribution of the spectral weight within the momentum-energy phase space. Therefore, one may argue that

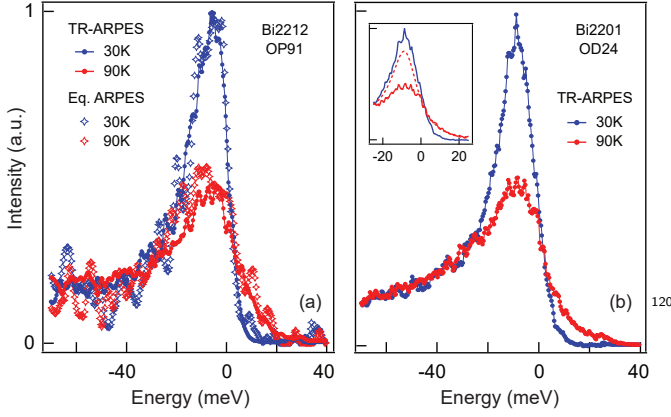


FIG. 1. (a) Energy distribution curves (EDCs) at the Fermi momentum $\mathbf{k}_F$ along the nodal direction of Bi2212-OP91 for 30 K and 90 K, as measured by TR-ARPES ($h\nu=6.2$ eV) and equilibrium ARPES ($h\nu=27$ eV). (b) Nodal EDCs at $\mathbf{k}_F$ for Bi2201-OD24 acquired by TR-ARPES. Inset: comparison between the same experimental data (solid lines) and the EDC₁₃₀ obtained from the 30 K data via the thermal broadening of the Fermi-Dirac distribution at 90 K (dashed line). All EDCs have been deconvoluted from the energy resolution broadening via the Lucy-Richardson algorithm^{15,20,21} (TR-ARPES energy resolution is 11 meV and 18 meV for panels (a) and (b), respectively; equilibrium ARPES energy resolution is 5.3 meV).

the observed T-dependence of CSW for a well defined momentum – specifically the Fermi momentum $\mathbf{k}_F$, $\text{CSW}(\mathbf{k}_F, T) = \int_{-\infty}^{\infty} A(\mathbf{k}_F, \omega, T) d\omega$ – is determined by the underlying electron interactions encoded in $\Sigma(\omega, T)$ (note that our discussion is centered solely on the $d_{x^2-y^2}$ anti-bonding band, see Appendix B).

In this work, we establish the role played by the normal-state self-energy to the integrity of quasiparticles by tracking the T-dependence of both the $\omega=0$ and energy-integrated nodal spectral function at $\mathbf{k}_F$. This is achieved for both single- and bi-layer Bi cuprates at various dopings by employing TR-ARPES, which offers an enhanced sampling and signal-to-noise for the T-dependence of the nodal spectra. This approach, corroborated by conventional equilibrium ARPES, reveals a ubiquitous suppression of nodal CSW that bears no relation to T_c , but instead directly stems from the ω - and T-dependence of the complex self-energy. By analyzing the data in terms of existing models, such as Fermi Liquid (FL)¹⁷, Marginal Fermi Liquid (MFL)¹⁸ and T-cubic¹⁹ models, we find that solely the FL framework reproduces comprehensively the T-dependence of the nodal CSW, as well as the overall nodal quasiparticle phenomenology encoded in the lineshape and amplitude of energy and momentum distribution curves (EDCs and MDCs).

II. EXPERIMENTAL STRATEGY

Equilibrium and time-resolved ARPES measurements were performed on high quality $\text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+\delta}$ (Bi2201) and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi2212) single crystals at various doping levels along the nodal $\bar{\Gamma}$ - $\bar{Y}$ direction (details in Appendix A). Figure 1 shows EDCs at $\mathbf{k}_F$ along the nodal direction, for two different temperatures of optimally doped Bi2212 ($T_c=91$ K, OP91) and overdoped Bi2201 ($T_c=24$ K, OD24) – energy resolution broadening was removed via the Lucy-Richardson algorithm^{15,20,21}. For both compounds, we observe a clear suppression of CSW close to the Fermi energy (E_F), as the temperature increases from 30 to 90 K. As an alternative approach to standard T-dependent ARPES, in this work we employ TR-ARPES to meticulously track the temperature-dependent modifications of the low-energy nodal spectral features by tuning the transient electronic temperature T_e via optical pumping. Due to the strong electron interactions underlying the cuprates, quasiparticles excited via near-infrared light thermalize on an ultrashort timescale (*i.e.* ~ 100 fs; **note that a similar timescale has been reported also for the photodoping effects**²²), entering a state of quasi-equilibrium where an effective electronic temperature can be defined at each pump-probe delay^{13,23,24}. This method allows one to directly link the transient electronic temperature to the progression of the ARPES spectral features, effectively performing a T-dependent measurement with minimal repercussions from surface degradation and sample drifting. In order to convert the measured time dependence of our data into a temperature evolution, we fit the Fermi edge width of the momentum-integrated EDCs along the

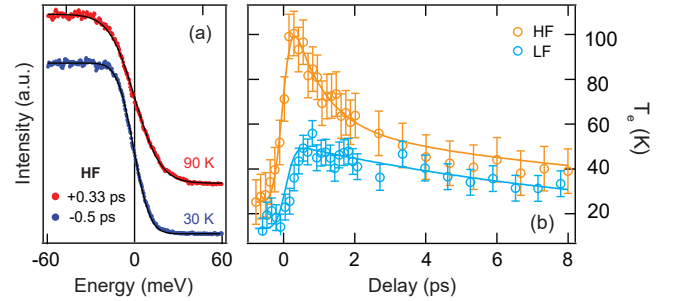


FIG. 2. (a) Momentum-integrated EDCs along the nodal direction before (-0.5 ps) and after (+0.33 ps) the pump excitation for Bi2201-OD24. Fermi-Dirac distribution fits are shown as solid black lines; **temperature values are defined by a 99%-confidence-interval**. (b) Transient electronic temperature T_e obtained by fitting the Fermi edge width along the nodal direction of Bi2201-OD24, for two different pump fluences ($12 \mu\text{J}/\text{cm}^2$, LF; $90 \mu\text{J}/\text{cm}^2$, HF). The solid lines represent (single-) double-exponential decay fit to (LF) HF data. Error bars in panel (b) reflect the systematic errors associated with the experiment and the number of averaging cycles acquired for each fluence. All data acquired via TR-ARPES at 6.2 eV.

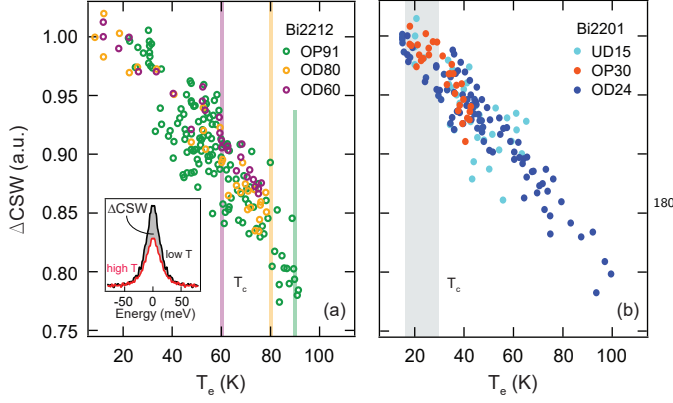


FIG. 3. (a) Relative variation of the nodal coherent spectral weight ΔCSW as a function of the electronic temperature T_e tracked via TR-ARPES, for three different doping levels of Bi2212. The inset illustrates the difference in the integrated area of the symmetrized EDCs in the $[-0.08, 0.08]$ eV range, which defines ΔCSW . (b) Same as in (a), but for three doping levels of Bi2201. Colored (a) and gray (b) vertical bars mark the range of T_c for the different compounds. The estimated temperatures at negative pump-probe-delays are listed in Appendix A for each sample.

nodal direction, as illustrated in Fig. 2 for overdoped Bi2201-OD24. Note that the resulting transient electronic temperature T_e can be phenomenologically described by an exponential-decay function (panel b, solid line).

Although this ultrafast approach ensures equivalent experimental conditions for each temperature (*e.g.* same probed spot on the samples surface and momentum-space position), it might raise doubts on (i) whether the probed behaviour is an exclusive property of the transient state, and (ii) how different transient lattice and electronic temperatures may complicate the data interpretation. To address these points, we compare in Fig. 1a the nodal EDCs at $\mathbf{k}_F$ measured by TR-ARPES at 6.2 eV and conventional equilibrium ARPES at 27 eV. The good agreement between the two different probing methods indicates that the suppression of CSW is inherently related to the electronic temperature of the system, thus validating the TR-ARPES approach as our main experimental strategy throughout the entire work, as well as suggesting the predominant role played by electron-electron interactions in the suppression of nodal CSW. Moreover, the data in Fig. 1a exclude the explicit breaking of the “sudden-approximation” with low-energy photons²⁵ (also note that only the antibonding state is probed using both 6.2 eV and 27 eV, and nonlinear effects in the photoelectrons’ detection²⁶ have been ruled out; details in Appendix B-C). Finally, as illustrated in the inset of Fig. 1b, the mere thermal broadening of the Fermi-Dirac distribution at 90 K does not account for the observed T-dependence of the experimental data.

III. RESULTS AND ANALYSIS

Having defined the experimental strategy, we now examine the temperature-dependent modifications of the nodal spectral features of various Bi-based compounds. To quantitatively describe the variation of CSW as a function of T_e , we focus our analysis on the evaluation of the area of the symmetrized TR-ARPES EDCs (SEDCs) at $\mathbf{k}_F$. In fact, provided the particle-hole symmetry of the spectral function – which has been experimentally verified at $\mathbf{k}_F$ in the near-nodal region of Bi2212^{15,27} – SEDCs directly map onto the spectral function, $\text{SEDC}(\omega) \propto A(\mathbf{k}_F, \omega)$ ^{28,29}. Here, we define the relative suppression of coherent spectral weight, ΔCSW , as the difference between the integrated area under the SEDCs at $\mathbf{k}_F$ at low and high T_e (*i.e.* before and after the pump excitation), in the $[-0.08, 0.08]$ eV range (see inset of Fig. 3a). This approach makes our analysis bias-free from the choice of specific models or fitting procedures of the SEDCs. The obtained ΔCSW is plotted directly as a function of T_e in Fig. 3 for different doping levels of Bi2212 and Bi2201. Despite the large number of dopings and related T_c across the studied compounds, a remarkable similarity characterizes the T-dependent suppression of ΔCSW in the explored 100 K temperature range. Most importantly, the decrease of $\Delta\text{CSW}(T_e)$ does not exhibit any modification – abrupt or otherwise – across the superconducting-to-normal state phase transitions, and continues for $T_e \gg T_c$ (colored and gray bars in Fig. 3 highlight T_c for the various dopings studied here; see Fig. 4c for data of Bi2212-OP91 above T_c). These findings demonstrate the absence of a direct contribution of the superconducting phase to $\Delta\text{CSW}(T_e)$, and establish the T-dependence of the nodal coherent spectral weight as a ubiquitous behavior of Bi-based cuprates. The data reported in Fig. 3 also exclude a possible relation of the observed nodal suppression of CSW to the pseudogap phenomenon. In fact, despite no equilibrium pseudogap having been reported for the very overdoped Bi2212-OD60 compound^{30–32}, its ΔCSW (purple open circles in Fig. 3a) is comparable to that observed for the other compounds.

Upon ruling out any dependence on the characteristic T_c , we explore the possible contribution of normal state properties to the T-dependence of CSW. In the following we demonstrate that the progressive meltdown of the nodal CSW can be understood in terms of the intrinsic ω - and T-dependence of the self-energy within the Fermi Liquid model. The FL self-energy can be written as^{1,17}:

$$\Sigma_{\text{FL}}(\omega, T) = -\alpha\omega - i[\Gamma + \beta(\omega^2 + \pi^2 T^2)], \quad (1)$$

where α , β , and Γ are positive parameters. Γ represents a scattering rate term associated with static impurities, and is thus independent of energy and temperature³³. Using Eq. 1, we can calculate the T-dependence of the spectral function and compute the resulting ΔCSW^{FL} . We emphasize that the discussion is limited to $\mathbf{k}=\mathbf{k}_F$ (*i.e.* $\varepsilon_{\mathbf{k}}^b = 0$), which allows for a direct comparison to the ex-

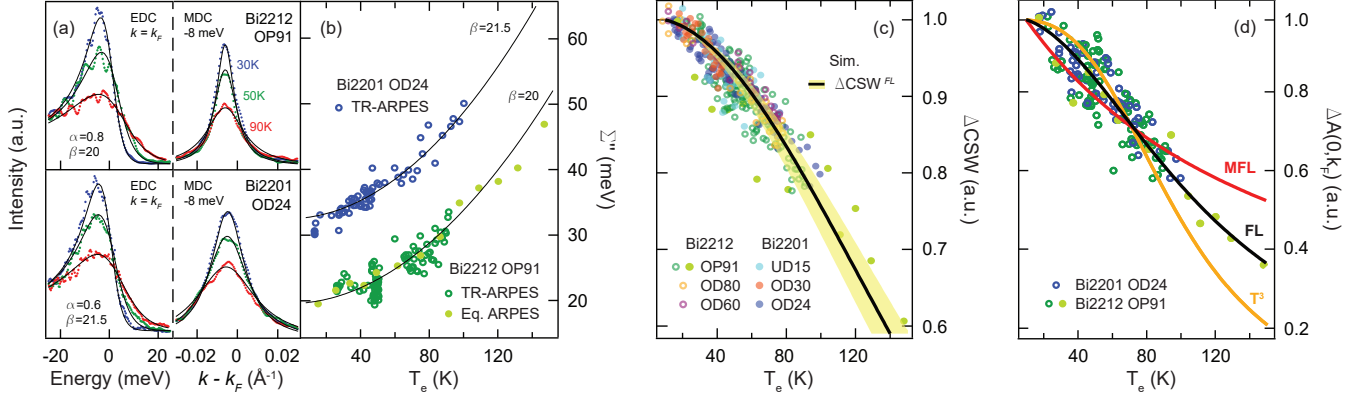


FIG. 4. (a) Nodal EDCs at $\mathbf{k}_F$ and MDCs at -8 meV for Bi2212-OP91 and Bi2201-OD24, probed by TR-ARPES at different temperatures. Black solid lines represent the results of the EDC-MDC global fitting procedure using Eq. 1, as explained in the main text. Optimal fits to the data are found with $(\alpha=0.8, \beta=20)$ and $(\alpha=0.6, \beta=21.5)$ for Bi2212-OP91 and Bi2201-OD24, respectively. (b) Temperature evolution of the imaginary part of the electron self-energy extracted via fitting of MDCs at -8 meV (integration windows $\pm 5\text{ meV}$) via a Lorentzian-like function for Bi2201-OD24 and Bi2212-OP91. The solid black lines are quadratic curves defined by the β coefficients obtained via the global fit procedure of panel (a). (c) Comparison between the experimental CSW suppression (TR-ARPES data from Fig.3; equilibrium ARPES for Bi2212-OP91 in full green circles) and the simulated ΔCSW^{FL} within the FL model via Eq.1. The solid black line is computed for $\alpha=0.7, \beta=20.75, \Gamma=0.02$, while the yellow shading accounts for the parameters' range defined by the global fit. (d) Normalized temperature evolution of the spectral function $\Delta A(0, \mathbf{k}_F)$, for Bi2201-OD24 (TR-ARPES data) and Bi2212-OP91 (TR- and equilibrium ARPES). The integration range in momentum and energy is $0.005 \text{ \AA}^{-1}$ and 6 meV , respectively. The solid lines are best fits to the experimental data by using Eq.2 for the different models with $\Gamma=0.02$: FL (black, $\beta=20.35$), MFL (red, $\lambda=0.96$) and T^3 (orange, $\eta=3.28 \cdot 10^4$). All spectra have been deconvoluted from the energy resolution before extracting EDCs and MDCs in panels (a), (b), and (d).

perimental data presented in Fig. 3. In order to estimate the values of α and β , and thus provide a more quantitative modeling of ΔCSW^{FL} , we developed a global fit analysis of EDCs and MDCs in terms of Eq. 1. Figure 4a shows the results of this global fitting procedure for three different temperatures of Bi2212-OP91 and Bi2201-OD24. We assume a bare velocity $v_0=3.8\text{ (3.35) eV} \cdot \text{\AA}$ for Bi2212 (Bi2201), as reported from previous studies^{34–36}. Note that the parameter α can be related to the bare velocity by the expression $\alpha = \frac{v_0}{v_F} - 1$, where v_F is the renormalized Fermi velocity. Despite several mechanisms playing a role in determining the self-energy, in our analysis we do not differentiate the various contributions,²⁷⁰ and assume a linear renormalized dispersion in the first 0.2 eV below E_F . The best simultaneous global fit to EDCs and MDCs is achieved for $\alpha=0.8$ and $\beta=20$ ($\alpha=0.6$ and $\beta=21.5$) for Bi2212-OP91 (Bi2201-OD24). These values are consistent with the band renormalization reported in previous ARPES studies^{35,37,38}, and capture the quadratic temperature dependence of the imaginary part of the self-energy (see Fig. 4b), further validating our global fit results. We recognize that extracting the underlying functional form of the self-energy relying solely on the ω - and/or T -evolution of the MDC width is extremely challenging, as evidenced by variance in the reported behaviours ranging from linear to cubic^{18,33–35,39}. To this end, we emphasize that the EDC-MDC global fit procedure presented here was tested against a general functional form of the imaginary part of the self-energy,

namely $\Sigma''(\omega, T) = -\Gamma - \beta(\omega^2 + \pi^2 T^2)^{1/a}$. While $a=1$ describes the FL self-energy, $a=2$ and $a=2/3$ resemble the linear ω - and T -dependence of the phenomenological MFL self-energy^{18,33} and the cubic T -evolution of Σ'' ^{19,39}, respectively. The global fit analysis consistently converges to $a=1 \pm 0.1$, pointing towards a description of the experimental data in terms of the FL model.

Having established an effective range for the parameters in Eq.1, we now simulate the suppression of spectral weight ΔCSW^{FL} at $\mathbf{k}_F$ (integration window $[-0.08, 0.08]\text{ eV}$, normalized to the 10 K value; see Appendix D for analytical expression of CSW^{FL}). This is plotted in Fig. 4c superimposed to the TR-ARPES experimental data shown in Fig. 3 and additional equilibrium ARPES data for Bi2201-OP91. In particular, $\alpha=0.7, \beta=20.75$, and $\Gamma=0.02$ were used to simulate the solid black line, while the yellow shading corresponds to the parameters' range defined by the global fit in Fig. 4a. A remarkable agreement is observed between the FL simulation and the experimental suppression of CSW, both in terms of functional form and magnitude, with a quenching of the CSW as large as $\sim 25\%$ at 100 K . Despite the significant suppression of CSW at $\mathbf{k}_F$, we note that the tomographic density of states along the nodal direction⁴⁰ (*i.e.* $\int_{-\infty}^{\infty} A(\bar{k}, \omega, T) d\bar{k}$, where $\bar{k}$ defines the $\bar{\Gamma}$ - $\bar{Y}$ direction) does not vary within a 3% uncertainty over the explored temperature range, consistent with general spectral-function sum rules (more details in

Appendix E).

In further support of our interpretation, we examine also the T-dependence of the spectral function at $\omega=0$, $A(0, \mathbf{k}_F, T)$, which can be written as:

$$A(0, \mathbf{k}_F, T) = \begin{cases} \frac{1}{\pi} \frac{1}{\Gamma + \beta(\pi k_B T)^2}, & \text{for FL} \\ \frac{1}{\pi} \frac{1}{\Gamma + \lambda(\frac{\pi}{2} k_B T)}, & \text{for MFL} \\ \frac{1}{\pi} \frac{1}{\Gamma + \eta(k_B T)^3}, & \text{for } T^3 \end{cases} \quad (2)$$

where Γ is a scattering rate term independent of energy and temperature as in Eq. 1. We remark that the T-dependence in Eq. 2 is solely determined by the parameters β , λ , and η , offering a simpler and novel comparison with existing models. Figure 4d shows the relative variation of the spectral function, $\Delta A(0, \mathbf{k}_F)$, for the three models of Eq. 2 (solid lines, normalized to the 10 K value) superimposed to its experimental counterpart for Bi2201-OD24 and Bi2212-OP91. While the FL model captures remarkably well the experimental data, MFL and T^3 instead fail in reproducing the observed T-dependence over the entire explored range. This finding is consistent with optical and transport studies reporting evidences of a FL regime in the underdoped region of other high- T_c cuprates^{41–43}, as well as with a recent ARPES study of an overdoped La-based cuprate, which reports a FL-to-MFL crossover moving from the nodal to the antinodal region⁴⁴. We note that recent angle-dependent magnetoresistance measurements of Tl- and La-based compounds indicate the potential coexistence of quadratic and linear contributions to the scattering rate in either isotropic or anisotropic form^{45,46}. As for the Bi-based cuprates, whether a deviation from the FL description reported here is observed upon moving from the nodal to the antinodal region remains an open question, requiring additional momentum-resolved investigations.

IV. CONCLUSIONS

In conclusion, we have reported a comprehensive study of the meltdown of the nodal CSW as a function of the electronic temperature in Bi-based cuprates. By employing ARPES, both in its conventional and time-resolved fashion, we have investigated various doping levels and compounds over a broad temperature range, and revealed a ubiquitous T-dependence of the nodal CSW bearing no direct relation to the superconducting

or pseudogap temperature scales. Instead, the observed suppression of the nodal CSW at $\mathbf{k}_F$ naturally stems from the temperature and energy dependence of the FL electron self-energy. We remark that these conclusions have been attained via a multi-analysis approach which combines EDC-MDC global fitting, and scattering rate analysis with a novel investigation of the T-evolution of the $\omega=0$, as well as energy-integrated, nodal coherent spectral weight. While our findings demonstrate the Fermi Liquid nature of quasiparticles along the gapless nodal direction of Bi-based cuprates, further investigations are needed to address whether such a scenario holds along the whole Fermi arc or if a crossover to a Marginal Fermi Liquid or T^3 behavior occurs instead. To this end, the pump-probe approach presented here for the study of the CSW temperature evolution may soon be extended to the antinodal region of cuprates, owing to the advent of TR-ARPES in the extreme-ultra-violet regime^{47,48}.

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Appendix A: Materials and Methods

$\text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+\delta}$ (Bi2201) and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi2212) samples have been aligned via Laue diffraction along the nodal $\bar{\Gamma}$ - $\bar{Y}$ direction in order to avoid replica bands^{49–51}, and cleaved in vacuum at pressures and base temperature lower than $8 \cdot 10^{-11}$ Torr and 20 K, respectively. Equilibrium ARPES measurements have been performed at the Quantum Materials Spectroscopy Centre (QMSC) beamline at the Canadian Light Source using 27 eV σ -polarized light, with energy and momentum resolutions better than 5.5 meV and $0.007 \text{ \AA}^{-1}$, respectively. Additional ARPES

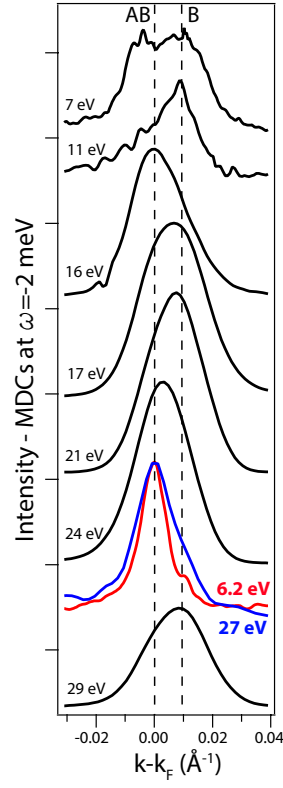


FIG. 5. Momentum distribution curves (MDCs) at $\omega = -2$ meV (5 meV integration window) along the nodal direction Γ -Y of Bi2212-OP91. Black curves have been acquired at the Elettra synchrotron, BaDElPh beamline; the blue curve has been acquired at the CLS, QMSC beamline, with 27 eV photons; the red curve has been acquired at the UBC-Moore Center for Ultrafast Quantum Matter with 6.2 eV photons. The latter two represent the photon energies employed in this work. Vertical dashed lines highlight the separation between antibonding (AB) and bonding (B) states, which is approximately $0.01 \text{ \AA}^{-1}$.

experiments have been conducted at the BaDElPh endstation at the Elettra synchrotron with tunable photon energy in the range 7 - 30 eV. TR-ARPES data have been acquired at the UBC-Moore Center for Ultrafast Quantum Matter by pumping and probing with σ -polarized 1.55 eV and 6.2 eV pulses, and with overall energy, momentum, and temporal resolution of 18 meV, $0.0025 \text{ \AA}^{-1}$, and 250 fs, respectively¹⁵, unless specified differently in the main text. All TR-ARPES experiments were performed at a base cryostat temperature of 10 K; however, overall pump thermal effects have to be taken into account independently for each experiment. We estimate an approximate temperature for negative pump-probe delays as follow, for the different samples: 15 K and 25 K at low and high pump fluences respectively ($12 \mu\text{J}/\text{cm}^2$, LF; $90 \mu\text{J}/\text{cm}^2$, HF) for Bi2201-OD24; 12 K for Bi2201-OD30, LF; 15 K for Bi2201-UD15, LF; 25 K and 45 K for Bi2212-OP91, LF and HF respectively; 12 K for Bi2212-OD80, LF; 15 K for Bi2212-OD60, LF.

Appendix B: Photon energy dependence of the bilayer splitting

In an effort to compare the nodal quasiparticle lineshape, as well as the temperature dependence of the coherent spectral weight, as probed by different photon energies for Bi2212, it is important to verify matrix-elements-related effects. The two interacting CuO_2 planes in Bi2212 lead to bilayer band splitting, *e.g.* two separate antibonding (AB) and bonding (B) states crossing E_F ^{52,53}. Therefore, different photon energies may probe either one of these states (or both equivalently), as shown in Fig. 5. In this work, we accurately selected 6.2 eV and 27 eV photon energies for time-resolved and equilibrium ARPES measurements, respectively, in order to have similar matrix-elements for Bi2212 compounds. In this specific case, with the selected photon energies we mainly probe the AB state, as shown in Fig. 5 by the blue and red lines.

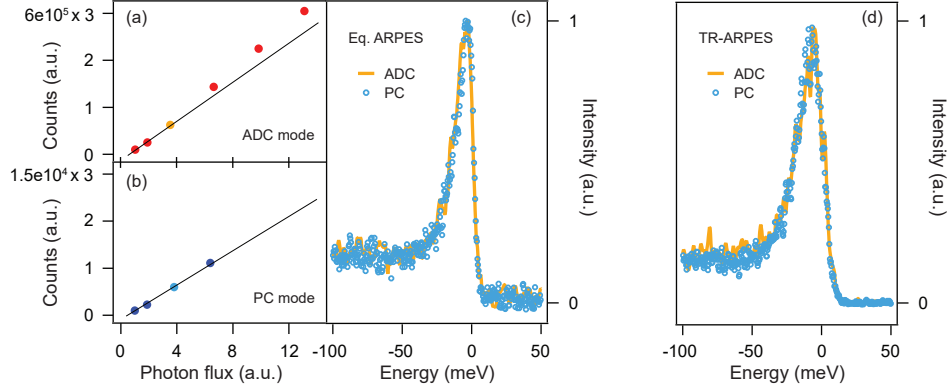


FIG. 6. (a)-(b) Characterization of the response of the Scienta R4000 analyzer at the QMSC beamline: count-rate under the quasiparticle peak in the analog-to-digital converter (ADC) and single-pulse-counting (PC) detection mode, respectively. The orange and light blue markers indicate the maximum count-rate employed in this work. (c) Comparison between nodal EDCs at $\mathbf{k}_F$ of Bi2212-OP91 acquired at the QMSC beamline with ADC (orange line) and PC (light blue markers) mode at the maximum count-rate. Temperature 20 K and photon energy 27 eV. (d) Nodal EDCs at $\mathbf{k}_F$ of Bi2212-OP91 acquired with the TR-ARPES setup at UBC using a Scienta DA30 analyzer in the two different detection modes. Temperature 10 K and photon energy 6.2 eV. All EDCs shown here have not been deconvoluted for the energy resolution broadening.

Appendix C: Ruling out nonlinear effects in the photoelectron detection

The nonlinear response of the photoelectron detection may affect a correct assessment of ARPES spectral features, especially when sharp and intense quasiparticle peaks occur along with a low level background, as often is the case of ARPES measurements on cuprates. This can result in an artificial suppression/enhancement of the quasiparticle peak, thus preventing the correct evaluation of small modifications of the coherent spectral weight (CSW). Post-acquisition algorithms have been developed to correct ARPES maps acquired in a nonlinear detection regime^{26,54}, however such procedures may not perfectly compensate all nonlinear effects.

In order to avoid possible contributions of the detectors nonlinearity to the observed evolution of CSW, all the data presented in this work were acquired at an extremely low count-rate, in a regime benchmarked by spectra obtained in the single-pulse-counting (PC) mode, which is intrinsically linear at a low count-rate. Figure 6a-b show the response of the detector employed at the QMSC beamline for the equilibrium ARPES measurements (Scienta R4000) in the analog-to-digital converter (ADC) and PC mode, respectively; a clear deviation from the linear response develops in the ADC mode as the photon flux increases. In acquiring our equilibrium ARPES data, we therefore limited the maximum ADC count-rate to a value which ensures a linear response of the detector, as well as a quasiparticle lineshape equivalent to that probed via PC mode, as shown by the energy distribution curves (EDCs) in Fig. 6c. Similarly, the maximum count-rate employed for TR-ARPES measurements performed at UBC was limited to achieve an *effective* PC mode regime with both the spectrometers used in this work, namely a Scienta DA30 (data on Bi2212-OP91, see Fig. 6d) and a SPECS Phoibos 150 (data on all others compounds, not shown).

This approach rules out any suppression/enhancement of coherent spectral weight artificially induced by nonlinear effects in the photoelectron detection, while providing higher statistics and reduced acquisition time.

Appendix D: Analytical form of Coherent Spectral Weight

In the scenario of the Fermi liquid framework, *i.e.* using the self-energy of Eq. 1 in the main text, the full temperature dependence of the coherent spectral weight at the specific momentum $\mathbf{k}_F$, $\text{CSW}(\mathbf{k}_F, T) = \int_{-\infty}^{\infty} A(\mathbf{k}_F, \omega, T) d\omega$, can be expressed analytically via application of the residue theorem:

$$\text{CSW}(\mathbf{k}_F, T) = \frac{2}{\sqrt{(1 + \alpha)^2 + 4\beta^2[\Gamma/\beta + (\pi k_B T)^2]}}. \quad (\text{D1})$$

By visual inspection of Eq. D1, it is evident that $\text{CSW}(\mathbf{k}_F, T)$ depends on the temperature T , as directly shown by the experimental data in Fig. 3 and Fig. 4a-c.

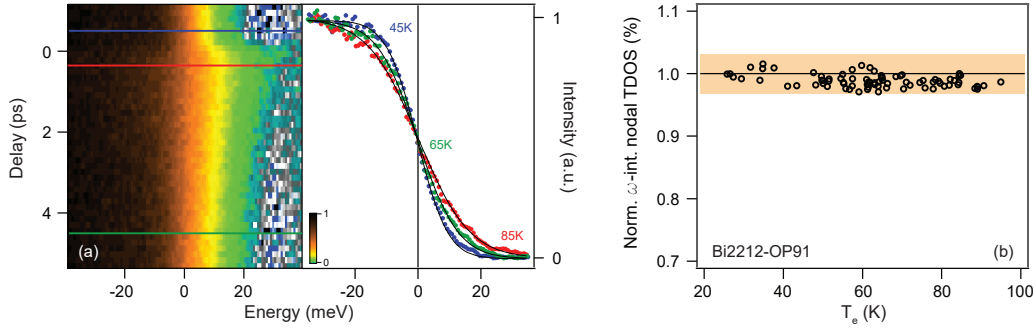


FIG. 7. (a) Momentum-integrated TR-ARPES map along the nodal direction of Bi2212-OP91 as a function of the pump-probe delay (integration window $[-0.1 \text{ \AA}^{-1}, 0.1 \text{ \AA}^{-1}]$ about $\mathbf{k}_F$; high fluence data). Non-coherent/background contributions to the spectral weight have been subtracted as explained in the text. Right panel: Momentum integrated energy distribution curves for selected pump-probe delays; black lines are fits to Fermi-Dirac like functions. (b) ω -integrated nodal TDOS of Bi2212-OP91 as a function of the effective electronic temperature, normalized to the lowest temperature value. The momentum and energy integration windows are $[-0.1 \text{ \AA}^{-1}, 0.1 \text{ \AA}^{-1}]$ and $[-40 \text{ meV}, 40 \text{ meV}]$, respectively. The orange shaded area highlights variations of $\pm 3\%$.

Appendix E: Nodal Tomographic Density of States

Even if the nodal coherent spectral weight at $\mathbf{k}_F$ decreases as a function of the increasing temperature, the nodal tomographic density of states (TDOS) along the cut perpendicular to the Fermi surface⁴⁰ does not vary within a 3% uncertainty. Here we provide more experimental evidences in support of this claim for Bi2212-OP91.

The nodal TDOS can be expressed as $\int_{-\infty}^{\infty} A(\bar{k}, \omega, T) d\bar{k}$, with $\bar{k}$ representing the $\bar{\Gamma}$ - $\bar{Y}$ direction. In order to remove spurious background contributions to the experimental spectral weight (such as incoherent spectral weight, secondary electrons, and electrons scattered in the detection process), and thus achieving a precise evaluation of the temperature evolution of the nodal TDOS, we applied the following procedure. First, we fit the time-resolved nodal momentum distribution curves (MDCs) with a Lorentzian-like function defined by only four parameters: peak position, width, area, and offset. The latter accounts for all non-coherent/background contributions to the spectral weight and it can be subsequently subtracted from the ARPES nodal map. Once these contributions are removed, the experimental spectral weight is integrated in momentum ($-0.1 \text{ \AA}^{-1} < \bar{k} < 0.1 \text{ \AA}^{-1}$), as shown in Fig. 7a. Given that the ARPES intensity is directly proportional to both the spectral function and electronic distribution, Fig. 7a resembles the TDOS multiplied by the Fermi-Dirac distribution for any pump-probe delay, *i.e.* any transient electronic temperature T_e (see right panel of 7a). In order to average out thermal broadening effects, *i.e.* Fermi-Dirac broadening, we integrate in energy symmetrically across E_F in the region relevant to the quasiparticle peak ($-40 \text{ meV} < \omega < 40 \text{ meV}$; note that for $T=120 \text{ K}$, $k_B T \approx 10 \text{ meV}$). Figure 7b shows the evolution of this ω -integrated nodal TDOS at E_F as a function of the transient electronic temperature extracted for Bi2212-OP91, where values have been normalized to that of the lowest temperature. Only a very limited variation ($< 3\%$, orange shaded area) is observed over the entire 100 K temperature range.

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