Particle-hole asymmetric superconducting coherence peaks in overdoped cuprates

Changwei Zou1,8, Zhenqi Hao1,8, Xiangyu Luo2, Shusen Ye1, Qiang Gao2, Miao Xu1, Xintong Li1, Peng Cai3,3, Chengtian Lin4, Xingjiang Zhou2, Dung-Hai Lee5,6 and Yayu Wang3,17✉

As doping increases in cuprate superconductors, the superconducting transition temperature increases to a maximum at the so-called optimal doping, and then decreases in the overdoped regime. In the past few decades, research has primarily focused on the underdoped and optimally doped regions of the phase diagram. Here, phenomena such as the pseudogap and strange metal non-superconducting states make it difficult to determine the superconducting pairing mechanism. More recently, experiments have shown unconventional behaviour in strongly overdoped cuprates, in both the normal and superconducting states. However, a real-space investigation of the unconventional superconductivity in the absence of the pseudogap is lacking, and the superconductor-to-metal phase transition in the overdoped regime remains controversial. Here we use scanning tunnelling microscopy to investigate the atomic-scale electronic structure of overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ cuprates. We show that, at low energies, the spectroscopic maps are well described by dispersive d-wave quasiparticle interference patterns. However, as the bias increases to the superconducting coherence peak energy, a periodic and non-dispersive pattern emerges. The position of the coherence peaks exhibits particle–hole asymmetry that modulates with the same period. We propose that this behaviour is due to quasiparticle interference caused by pair-breaking scattering between flat antinodal Bogoliubov bands.

It is commonly believed that superconductivity is more conventional in overdoped cuprates. Transport and spectroscopic studies suggest that the non-superconducting ‘normal’ state becomes less strange$^{1–3}$ and the superconducting (SC) state exhibits canonical Bardeen–Cooper–Schrieffer (BCS) d-wave features$^{4–6}$. However, recent experiments have shown unconventional behaviour in strongly overdoped cuprates in both the normal$^{7,8}$ and superconducting$^{9–12}$ states. Penetration depth$^9$ and optical conductivity$^{14}$ measurements on overdoped La$_{2−x}$Sr$_x$CuO$_4$ reveal that a large portion of Drude weight remains uncondensed, even in the ground state. On a different front, angle-resolved photoemission spectroscopy (ARPES) on overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi-2212) shows clear evidence that Cooper pairs already form at a temperature substantially above the SC transition temperature$^T_c$ (refs. $^{8,16}$). These phenomena are in sharp contrast to a conventional picture, where superconducting vortices$^25$.

However, recent experiments have shown unconventional behaviour substantially above the SC transition temperature in overdoped La$_{2−x}$Sr$_x$CuO$_4$ reveal that a large portion of Drude weight remains uncondensed, even in the ground state. On a different front, angle-resolved photoemission spectroscopy (ARPES) on overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi-2212) shows clear evidence that Cooper pairs already form at a temperature substantially above the SC transition temperature$^T_c$ (refs. $^{8,16}$). These phenomena are in sharp contrast to a conventional picture, where superconducting vortices$^25$.

In real space the crystal symmetry-breaking patterns are no longer visible at the expected energy of the coherence peak$^28$. These facts motivate one to think that the BQP excitations at the antinode should continue to reveal the quasiparticle interference (QPI) phenomenon. However, evidence against this line of thought is found in the fact that ARPES found that the BQP dispersion parallel to the Brillouin zone boundary is extremely flat$^{15,29}$. In fact, that dispersion width is comparable to, if not smaller than, the value of the superconducting gap. Therefore, we have a situation in apparent contradiction to the BCS limit. Moreover, one would expect the flat dispersion to give rise to a large density of states and hence enhance the antinode–antinode disorder scattering. Such scattering takes place between momentum regions where the d-wave gap function assumes opposite signs, so it should be pair breaking. In view of the above consideration, it is much less clear what the STM pattern should be at the coherence peak energy.

Trilayer Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+y}$ (Bi-2223) is an ideal system with which to study the local electronic structure of overdoped cuprates. In part this is because Bi-2223 has the highest$^T_c$ in the Bi-based family, making the detection of low-energy excitations more accurate. In addition, Bi-2223 crystals can be cleaved easily to expose a clean BiO surface (Fig. 1a, inset) and are thus highly suitable for STM studies$^{30,31}$. Our previous experiment on Bi-2223 has revealed a shrunken Bogoliubov QPI near the gap node with increasing doping$^3$. In this Article we extend the STM studies to the more enigmatic antinodal electronic states in Bi-2223 samples with different doping levels.

$^1$State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing, P. R. China. $^2$Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing, P. R. China. $^3$Department of Physics and Beijing Key Laboratory of Opto-electronic Functional Materials and Micro-nano Devices, Renmin University of China, Beijing, P. R. China. $^4$Max Planck Institute for Solid State Research, Stuttgart, Germany. $^5$Department of Physics, University of California at Berkeley, Berkeley, CA, USA. $^6$Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA. $^7$Frontier Science Center for Quantum Information, Beijing, P. R. China. $^8$These authors contributed equally: Changwei Zou, Zhenqi Hao. $^✉$E-mail: yayuwang@tsinghua.edu.cn

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Results

Figure 1a displays the topographic image of slightly underdoped Bi-2223 with $T_c = 110$ K (sample 1 of the six Bi-2223 samples studied in this work; Methods and Supplementary Table 1). Here the Bi atoms separated by lattice constant $a \approx 0.38$ nm (ref. 1) are clearly resolved, and the Cu–O–Cu bonds ($x$ and $y$) are along the horizontal and vertical directions. In Fig. 1b we plot the spatially averaged $dI/dV$ spectra sorted by the local gap size $\Delta$. This shows that spectra with smaller $\Delta$ have sharper coherence peaks, while those with larger $\Delta$ are influenced by the pseudogap and exhibit broad peaks, which is a typical manifestation of the ubiquitous inhomogeneity appearing in underdoped cuprates12,21. To eliminate the influence of set-point and static charge order, a common practice is to plot the ratio of conductance maps at $\pm E$, namely, $\tilde{Z}(r,E) = g(r,E)/g(r,-E)$ (ref. 22; Supplementary Fig. 1). The low-energy states exhibit well-defined QPI patterns in the bias range covered by the green-shaded rectangle in Fig. 1b. An example is given by the $Z$ map at $E = 20$ meV in Fig. 1c. To achieve better momentum-space resolution, the Fourier-transformed (FT) map ($q$, 20 meV) in Fig. 1d is acquired in a larger field of view (as shown in Supplementary Fig. 2), which is rotated by 45° compared to the Cu–O–Cu orientations in Fig. 1a. This reveals the seven wavevectors expected by the octet model, as illustrated in Fig. 1g. To further reveal the phase of the superconducting gap function, we apply the phase-referenced (PR) technique that has been developed to investigate the momentum-space structure of the gap in cuprates and iron selenides24-26. The phase information of BQP scattering can be extracted from the complex FT QPI data $g(q,E) = |g(q,E)|e^{i\phi(q,E)}$. It is theoretically simulated18 that a negative (positive) $\cos(\delta \phi)$ value is obtained for scattering involving sign-reversing (sign-preserving) $q$, where $\delta \phi = \phi(q,-E) - \phi(q, +E)$ is the phase difference between negative and positive energies. Therefore, by further multiplying the FT amplitude, the PR map, defined by $PR(q,E) = |g(q,E)|\cos(\delta \phi)$, directly visualizes the phase information of each $q$. Shown in Fig. 1h is the PR map at $E = 20$ meV. The negative PR signals (blue) appear at $q_o, q_1, q_2, q_6, q_7, q_8$ which perfectly match the $d$-wave sign-reversing scattering between the eight ‘hotspots’ in Fig. 1g for nodal BQPs19.

When $E$ is increased towards the gap edge, the QPI patterns are replaced by ‘glassy stripe’ patterns (Fig. 1e) running along the Cu–O–Cu bond directions ($x$ and $y$), analogous to that found in underdoped Bi-2212 and Ca$_{x-y}$Na$_y$CuO$_2$Cl$_{2y}$ (Na-CCOC) (ref. 24). To minimize the influence of structural and chemical disorders, the energies in Fig. 1e are scaled to the local gap sizes with $e = E(r)/\Delta(r) = 1$, following the practice in ref. 27. In the FT image in Fig. 1f, $q_1^*$ and $q_2^*$ label the non-dispersive wavevectors corresponding to this stripe order14,19, which has been attributed to the incoherent antinodal states intimately linked to the pseudogap. As expected, $q_1^*$ and $q_2^*$ are not visible in the PR $Z$ map (Supplementary Fig. 2) for the absence of coherent BQP.

To investigate the electronic structure of antinodal BQP, we examined a heavily overdoped Bi-2223 sample (sample 5; Methods and Supplementary Table 1) with $T_c = 109$ K. The topography shown in Fig. 2a is similar to that in sample 1, but the gap sizes shown in Fig. 2b,c are considerably smaller, with an average of $\Delta \approx 30$ meV.
There still exists a heterogeneous gap pattern that anticorrelates with the coherence peak height. However, all the spectra display sharp coherence peaks consistent with the absence of a pseudogap (see also the vanishing stripe order in overdoped Bi-2223 samples in Supplementary Fig. 8). The \( \Delta \) map taken at low energy, \( \Delta = 10 \) meV, exhibits clear QPI patterns (Fig. 2d,g) obeying the prediction of the octet model. The maximum energy in which QPI is observed is reduced to \( \approx 20 \) meV, shown as the green-shaded area in Fig. 2c and Supplementary Figs. 5 and 7.

At bias close to the gap edge, the dispersive (meaning, bias-dependent) QPI is replaced by a nearly non-dispersive (see Supplementary Section 2 for the complete bias evolution), short-range \( \sqrt{2}a \times \sqrt{2}a \) pattern oriented along the diagonal direction of the CuO\(_2\) plaquette, as shown by the \( \Delta \) map at \( \epsilon = 0.75 \) in Fig. 2e. This new electronic structure is universal for heavily overdoped samples, but is absent in underdoped cuprates in our work (Supplementary Section 4) as well as previous studies. The FT \( \Delta \) map in Fig. 2h reveals four prominent, albeit broad, wavevectors...
To test the universality of the above phenomenon, we repeated the measurements on double-layer Bi-2212, including an underdoped sample with $T_c = 82\, {\text{K}}$ (denoted UD82K, with hole concentration $p = 0.12$) and three overdoped samples denoted as OD81K ($p = 0.20$), OD71K ($p = 0.21$) and OD65K ($p = 0.22$). The results are nearly identical to that in Bi-2223, as demonstrated by the $\delta \Delta/\Delta$ map of the OD65K sample in Fig. 4a (for the complete data see Supplementary Figs. 9 and 11). Similarly, the particle–hole asymmetric coherence peaks are also evident in the tunnelling spectra, as shown in the linecut taken in the OD65K sample in Fig. 4b.

We used a standard short-time FT method (Supplementary Section 6) to extract the modulation amplitude of the asymmetry parameter $\delta \Delta/\Delta$ and quantify its correlation with the pairing strength. Figure 4c summarizes the spatially averaged $\delta \Delta/\Delta$ amplitudes of the six Bi-2223 (red triangles) and four Bi-2212 (blue triangles) samples as a function of averaged $2\Delta$, which is anticorrelated with $p$. When the pseudogap vanishes with overdoping, the overall superconducting gap magnitude decreases while the modulation of the symmetry-breaking patterns becomes stronger (Supplementary Section 4), suggesting that the antinodal scattering also breaks Cooper pairs globally. The local pair-breaking nature mentioned earlier is directly seen by the black dots, which show the anticorrelation between the local $\delta \Delta/\Delta$ and $2\Delta$, adopted from Bi-2223 sample 5. Under the same $2\Delta$ value, the $\delta \Delta/\Delta$ amplitudes of the Bi-2212 samples are weaker than that in Bi-2223, which is probably why this phenomenon was missed in previous STM studies of Bi-2212. This trend also explains why the asymmetric gap modulations are not found or even suspected in the SC phase of overdoped Bi$_2$Sr$_2$CuO$_{2+x}$ (Bi-2201), in which the pseudogap persists to higher dopings and the flat antinodal BQP dispersion is much weaker.

We note that a similar momentum-space feature with broad peaks near $(\pm \pi/a, \pm \pi/a)$ has also been observed in Bi-2201. It coexists with a ‘triplet feature’ around $(2\pi/a, 0)$, and both features have been ascribed to QPI involving a large Fermi surface. Such QPI most likely originates from the normal-state band structure, because it smoothly evolves into the heavily overdoped non-superconducting regime without BQP. In the overdoped Bi-2212 and Bi-2223 studied here, the triplet feature is totally absent, so the phenomena and physical picture are very different from that in overdoped Bi-2201.

The main puzzle left to explain is why the coherence peaks are not particle–hole symmetric. The answer lies in the strong antinode–antinodal scattering triggered by disorder. Such scattering is enhanced by the large joint density of states associated with the flat BQP dispersion along the Brillouin zone face, as is evidenced by the high coherence peaks in the $dI/dV$ curves of overdoped cuprates (Fig. 2c and Supplementary Figs. 8 and 9). In Fig. 5a we show a caricature conveying our interpretation of the origin of the asymmetry. In the perfectly flat band limit, the BQP eigenenergy level at the antinode is represented by the black line segments in Fig. 5a. The inter-antinode scattering mixes the energy levels associated with $k_1 = (\pi, 0)$ and $k_2 = (0, \pi)$ with the BQP eigenfunctions $\Psi_{k_1} (r) = \frac{1}{\sqrt{\sigma}} \left( \begin{array}{c} 1 \\ e^{ik_1 \cdot r} \end{array} \right)$ and $\Psi_{k_2} (r) = \frac{1}{\sqrt{\sigma}} \left( \begin{array}{c} 1 \\ -1 \\ e^{ik_2 \cdot r} \end{array} \right)$ for, say, the $E < 0$ levels. Here the upper/lower component of the wavefunction denotes the particle/hole component of the BQP. Note the relative minus sign between the hole component is due to the opposite sign of the SC gap function at $k_1$ and $k_2$. Similarly, the eigenfunctions associated with the $E > 0$ energy level are $\Psi_{k_1} (r) = \frac{1}{\sqrt{\sigma}} \left( \begin{array}{c} 1 \\ e^{ik_1 \cdot r} \end{array} \right)$ and $\Psi_{k_2} (r) = \frac{1}{\sqrt{\sigma}} \left( \begin{array}{c} 1 \\ e^{ik_2 \cdot r} \end{array} \right)$. Assuming the inter-antinode scattering potential originates from scalar imperfections, it has the form $V(r) = \left( \begin{array}{c} 0 \\ 1 \\ 0 \\ -1 \end{array} \right)$. This scattering potential only mixes $\Psi_{k_1} (r)$ with $\Psi_{k_2} (r)$ and $\Psi_{k_1} (r)$ with $\Psi_{k_1} (r)$. After the mixing, the energy level split is as shown in Fig. 5a as the blue and red line segments.

Fig. 3 | Particle–hole asymmetric SC coherence peaks in sample 5. 
(a) Zoomed-in topography of the yellow square in Fig. 2a. Inset: schematic structure of the CuO$_2$ plane. Red and blue dots mark the two sublattices of the Cu sites beneath the BiO surface. (b) Z(r, $e = 0.75$) in the same field of view as in (a, c). The $dI/dV$ spectra along the two yellow cuts marked in (a) and (b), with the red and blue circles indicating the positions of the SC coherence peaks at Cu sites with the corresponding coloured dots. (d) The gap asymmetry map in the same field of view as in Fig. 2a(e). Scale bars, 2 nm.
Fig. 4 | Universality of the particle–hole asymmetry and its doping evolution. a, The $\delta \Delta/\Delta$ map taken from the OD65K Bi-2212 sample. The red arrows indicate the Cu–O–Cu x and y directions of the underlying lattice. The yellow arrow indicates the spectral line in b cutting through the five Cu sites marked with red and blue circles. b, Spectral line cuts taken on the OD65K Bi-2212 sample. c, The extracted $\delta \Delta/\Delta$ amplitudes. Red triangles show the average amplitude versus the average $2\Delta$ in six Bi-2233 samples. Blue triangles show the average amplitude in three overdoped Bi-2212 samples. Black circles show local $\delta \Delta/\Delta$ amplitude versus local $2\Delta$ values in Bi-2233 sample 5. The red and blue lines in the background represent the underdoped and overdoped regimes of cuprates, respectively. The schematic underlying Fermi surfaces are shown as insets, illustrating the universal nodal–antinodal dichotomy in the SC state. Scale bar, 2 nm.

The minimum gap $2\Delta_s$ is reduced by the scattering, implying it is pair breaking. Depending on the phase, $e^{i\alpha}$, of the matrix element $\int d^2r e^{-ik \cdot r} V(r)e^{i\alpha}$, we obtain the following spatial-modulating local density of states at the gap edges:

\[
\text{LDOS}(E, \mathbf{r}) = [L(E + \Delta_L) + L(E + \Delta_S)] + \cos(q \cdot \mathbf{r} + \theta)[L(E + \Delta_L - L(E + \Delta_S)) \text{ for } E < 0
\]

\[
\text{LDOS}(E, \mathbf{r}) = [L(E - \Delta_L) + L(E - \Delta_S)] - \cos(q \cdot \mathbf{r} + \theta)[L(E - \Delta_L) - L(E - \Delta_S)) \text{ for } E > 0
\]

Here $L(E)$ is a Lorentzian centred at $E=0$. Using the above formula, we simulate a line cutting through the Cu sites in Fig. 5b, which agrees well, qualitatively, with the experimental observation and suggests that the observed phenomenon originates from a strong inter-antinodal version of the QPI. This refers to the fact that the strong inter-antinode scattering not only causes a superposition of the BQP wavefunctions as in the octet model, but it has also modified the BQP eigenenergies (Fig. 5a and Methods). Importantly, within this explanation the modified BQP energy levels remain $\pm E$ symmetric. The apparent asymmetry is due to the interference of the split BQP eigenfunctions.

Discussions

The fact that the $\sqrt{2}a \times \sqrt{2}a$ pattern we observed is nearly non-dispersive prompts the question of whether it is a static charge order like that reported in Bi-2201 (refs. 9,39) and $\mathrm{La}_{2-x}\mathrm{Sr}_x\mathrm{CuO}_4$ (ref. 40). From this experiment alone it is difficult to completely rule out the possibility that it is a static charge order. Nevertheless, there are several strong reasons to support the inter-antinodal QPI picture. First, the $\sqrt{2}a \times \sqrt{2}a$ pattern observed in our experiment is rather short-ranged, and both the amplitude and phase distributions are disordered within a few nanometres (Supplementary Fig. 11). In particular, the amplitude of the $\sqrt{2}a \times \sqrt{2}a$ pattern is anticorrelated with the local gap size (Fig. 4c), which has been shown to be related to dopant disorder\(^{34,41}\). Second, if the $\sqrt{2}a \times \sqrt{2}a$ pattern is due to charge order, it should also be present in the low-bias $dI/dV$ maps near $E_F$, like the chequerboard charge order in Bi-2201, Bi-2212, Na-CCOC and the normal-state $\sqrt{2}a \times \sqrt{2}a$ charge order in ref. 10. By contrast, the $\sqrt{2}a \times \sqrt{2}a$ pattern observed here is only pronounced near the superconducting gap energy (Fig. 3c), and the low-bias range is dominated by the nodal QPI described by the octet model. Third, the chequerboard charge orders in underdoped cuprates are in phase at $\pm E$, so the charge order is more pronounced in the $dI/dV$ channel but is suppressed in the Z map\(^{20,22}\). This behaviour is in stark contrast to the observations here.

Our findings reveal a new version of nodal–antinodal dichotomy in overdoped cuprates due to the discrepancy between standard $d$-wave and strongly renormalized, flat BQPs. It is apparently different from what one would expect in a conventional picture, and is highly relevant to high-$T_c$ superconductivity in the overdoped phase diagram. It has been found that the QPI analysis based on the octet model indicates an absence of coherent $d$-wave BQP in the antibond Fermi surface\(^{27,32,37}\), which is further validated in the current work. This appears to be inconsistent with ARPES observations, which show coherent antinodal peaks in the SC state, even for overdoped materials\(^{42}\). Now this contradiction has a satisfactory explanation: the loss of antinodal coherence in QPI is a result of the universal nodal–antinodal dichotomy pervading the
zero-temperature superfluid density, and eventually leads to the normal metals. Such heterogeneity has the effect of reducing the conductors to evolve into superconducting islands embedded in the appearance of a flat band, this scattering causes the superconducting electrons in the overdoped cuprates La_{2-x}Sr_{x}CuO_{4}.

Another important indication revealed by our work is how superfluids vanish during the superconductor-to-metal transition. Owing to the nodal–antinodal dichotomy, the nodal electrons form densely overlapping Cooper pairs, are responsible for transport and thermodynamic properties, and thus are superfluids. On the other hand, antinodal electrons lack long-range phase coherence and act as a competitor to the superconductivity. Within our interpretation, δΔ/Δ measures the strength of the pair-breaking scattering, and the patch size shown in Figs. 3d and 4a manifests the correlation length of the disorder scattering potential. Thus, useful spectroscopic information is provided about the disorder potential. A recent theoretical study has shown that, even when the pairing interaction is held fixed, disorder-induced antinode–antinode scattering can cause the system to develop gap heterogeneity, like that exhibited in our work. With the appearance of a flat band, this scattering causes the superconductors to evolve into superconducting islands embedded in normal metals. Such heterogeneity has the effect of reducing the zero-temperature superfluid density, and eventually leads to the transition into a metallic state.

Online content
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Methods
Bi-2223 growth and post-annealing. Bi-2223 samples were successfully grown by the travelling solvent floating zone method. We used a very slow growth rate of ~0.05 mm h⁻¹ in a mixed Ar and O₂ gas flow, then the as-grown samples were annealed in O₂ flow for 120 h at 650 °C to obtain single-phase Bi-2223 crystals. In this way, the high-quality and sizable single crystals were slightly underdoped, with an onset Tₘ of ~110 K.

To obtain overdoped Bi-2223 samples, the high-quality samples described above were first cleaved to thinner pieces with flat and shiny surfaces, and then post-annealed in successive O₂ pressures, temperature and annealing times. To assure homogeneous doping and avoid surface contamination, both the top and bottom surfaces of each sample were covered with Bi-2223 powders during the annealing. The post-annealing conditions for the six Bi-2223 samples in this study are shown in Supplementary Table 1. The Tₘ values are all as high as ~110 K, as determined by susceptibility measurements, and the hardly changed Tₘ in the overdoped regime of Bi-2223 is consistent with previous studies. However, the actual hole doping levels are indeed increased from sample 1 to sample 6, as shown by the successively decreased SC gap and weakened tendency to glassy stripe order discussed in the main text (Supplementary Section 4). Another phenomenon associated with the increased hole density is the increased Fermi surface volume extracted by QPI analysis, as revealed in ref. 17.

STM measurements. We have studied six Bi-2223 and four Bi-2212 single crystals. Each sample was cleaved in the cryogenic ultrahigh-vacuum chamber at room temperature, and then immediately transferred into the STM system working at 4.3 K. A tungsten tip was treated and calibrated on the (001) surface before the measurement, as described in our previous paper. The differential conductance dI/dV(r,E) = g(r,E), which is approximately proportional to the local density of states, was obtained by the a.c. lock-in method with modulation frequency f = 571 Hz and modulation voltage (peak-to-peak) V₀ from 1 mV to 3 mV. To study the √2a × √2a modulation, each dataset used in this study was acquired with an atomically sharp tip to obtain clear atomic resolution, as shown in Figs. 1a and 2a and Supplementary Section 4.

We carried out spectroscopic imaging experiments on all the samples, each with 256 × 256 spectra in a 13 × 13 nm² field of view (Supplementary Section 4). In addition, the F1 maps in Figs. 1 and 2 were taken in larger areas, each with 256 × 256 spectra in a 42 × 42 nm² field of view. The set-up conditions (bias/ current) were ~0.25 V/600 pA for Bi-2223 sample 1, ~0.25 V/300 pA for Bi-2223 sample 2, ~0.2 V/300 pA for Bi-2223 sample 3, ~0.15 V/300 pA for Bi-2223 sample 4, ~0.15 V/300 pA for Bi-2223 sample 5, ~0.12 V/200 pA for Bi-2223 sample 6, ~0.35 V/300 pA for Bi-2212 UD82K, ~0.2 V/150 pA for Bi-2212 ODE81K, ~0.15 V/200 pA for Bi-2212 OD71K and ~0.12 V/200 pA for Bi-2212 OD65K. As thermal and piezoelectric drifts are unavoidable during the long-time measurements, the well-developed Lawler–Fujita’s algorithm was applied to each dataset to remove these effects and restore the square Bi/Cu lattice. After lattice correction, the fields of view we show in this work (for example, Figs. 1a, 2a and 4b) have dimensions of 12 × 12 nm².

Interpretation of the particle–hole asymmetric coherence peaks. Under the ideally flat band limit, we denote the E < 0 BQP eigen functions at momenta kₗ = (π,0) and kᵣ = (0,π) as ϕₗ,r(τ) = 1/√2 [1 eⁱᵏᵣ·r and ϕₗ,r(τ) = 1/√2 [1 e⁻ⁱᵏᵣ·r. Similarly, we denote the E > 0 BQP eigen functions as xₗ,r(τ) = 1/√2 [1 eⁱᵏᵣ·r and xₗ,r(τ) = 1/√2 [1 e⁻ⁱᵏᵣ·r, where the relative momentum is q = kₗ − kᵣ = (π,π)mod(0,2π) as discussed in the main text. Assuming the inter-antinode scattering originates from scalar impurities, it has the form

\[ H₀ = V(r) \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \]

Such a scattering potential mixes the BQP eigen levels at kₗ and kᵣ and causes them to split as shown in the blue and red line segments in Fig. 5a. The wavefunctions associated with the two, for example, E < 0 split energy levels are

\[ \Psi₋₋(\tau) = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{i \theta} e^{i k_{\tau} \cdot r} + e^{-i \theta} e^{-i k_{\tau} \cdot r} \\ e^{i \theta} e^{-i k_{\tau} \cdot r} + e^{-i \theta} e^{i k_{\tau} \cdot r} \end{pmatrix} \]

\[ \Psi₋₊(\tau) = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{i \theta} e^{i k_{\tau} \cdot r} + e^{-i \theta} e^{-i k_{\tau} \cdot r} \\ e^{i \theta} e^{-i k_{\tau} \cdot r} + e^{-i \theta} e^{i k_{\tau} \cdot r} \end{pmatrix}. \]

Thus the probability of finding the BQP in Ψ₋₋(τ) to be an electron is

\[ P₋₋(\tau) = \frac{1}{2} \left| e^{i \theta} e^{i k_{\tau} \cdot r} + e^{-i \theta} e^{-i k_{\tau} \cdot r} \right|^2 = 1 - \cos(q \cdot r + \theta). \]

Similarly, the probabilities associated with Ψ₋₊(τ) are

\[ P₋₊(\tau) = \frac{1}{2} \left| e^{i \theta} e^{i k_{\tau} \cdot r} + e^{-i \theta} e^{-i k_{\tau} \cdot r} \right|^2 = 1 - \cos(q \cdot r + \theta). \]

Thus the total local density state at E < 0 is

\[ LDOS(E,r) = P₋₋(\tau) L(E - Δ₋) + P₋₊(\tau) L(E + Δ₊) \]

which yields equation (1a). Similarly, the total local density of states at E > 0 is

\[ LDOS(E,r) = P₊₊(\tau) L(E + Δ₊) + P₊₋(\tau) L(E - Δ₋) \]

which yields equation (1b).

Data availability
The data used to support the findings of this work are available from the corresponding author upon request. Source data are provided with this paper.

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Author contributions
C.Z., Z.H. and Y.W. proposed and designed the research. C.Z., Z.H. and M.X. carried out the STM experiments. C.Z. analysed the data with help from Z.H., P.C., S.Y. and X. Li. C.L. provided the Bi-2223 single crystals. X. Luo and X.Z. performed high-pressure oxygen annealing of Bi-2223 samples. Q.G. and X.Z. grew the Bi-2212 single crystals and performed the post-annealing. D.-H.L. provided theoretical analysis. C.Z., D.-H.L. and Y.W. prepared the manuscript. All authors have read and approved the final version of the manuscript.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Yayu Wang.

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