Cascade of correlated electron states in the kagome superconductor CsV$_3$Sb$_5$

He Zhao$^1$, Hong Li$^1$, Brenden R. Ortiz$^2$, Samuel M. L. Teicher$^2$, Takamori Park$^3$, Mengxing Ye$^4$, Ziqiang Wang$^1$, Leon Balents$^{4,5}$, Stephen D. Wilson$^2$ & Ilija Zeljkovic$^{1,6}$

The kagome lattice of transition metal atoms provides an exciting platform to study electronic correlations in the presence of geometric frustration and nontrivial band topology$^{1-18}$, which continues to bear surprises. Here, using spectroscopic imaging scanning tunnelling microscopy, we discover a temperature-dependent cascade of different symmetry-broken electronic states in a new kagome superconductor, CsV$_3$Sb$_5$. We reveal, at a temperature far above the superconducting transition temperature $T_c$ ~ 2.5 K, a tri-directional charge order with a 2$a_0$ period that breaks the translation symmetry of the lattice. As the system is cooled down towards $T_c$, we observe a prominent V-shaped spectral gap opening at the Fermi level and an additional breaking of the six-fold rotational symmetry, which persists through the superconducting transition. This rotational symmetry breaking is observed as the emergence of an additional 4$a_0$ unidirectional charge order and strongly anisotropic scattering in differential conductance maps. The latter can be directly attributed to the orbital-selective renormalization of the vanadium kagome bands. Our experiments reveal a complex landscape of electronic states that can coexist on a kagome lattice, and highlight intriguing parallels to high-T$_c$ superconductors and twisted bilayer graphene.

Quantum solids composed of atoms arranged on a lattice of corner-sharing triangles (kagome lattice) are a fascinating playground for the exploration of novel correlated and topological electronic phenomena$^{2-4}$. Owing to their intrinsic geometric frustration, kagome systems are predicted to host a large number of exotic electronic states$^{5-18}$, such as bond and charge ordering$^{19-28}$, spin liquid phases$^{29,30}$ and chiral superconductivity$^{30,31,32}$. The majority of the experimental efforts thus far have focused on transition metal kagome magnets, such as Co$_3$Sn$_2$S$_2$ (ref. 19–23), FeSn (refs. 23,24) and Fe$_3$Sn$_2$ (refs. 25,26), in which different forms of magnetism dominate the low-temperature electronic ground state. Electronic correlations in the absence of magnetic ordering could in principle favour the emergence of new symmetry-broken electronic states, but this has been difficult to explore in many of the existing kagome materials owing to a tendency towards magnetic ordering.

AV$_3$Sb$_5$ (A = K, Rb or Cs) is a recently discovered class of kagome materials that do not exhibit resolvable magnetic order$^{28,29}$. This family of materials have already shown a glimpse of unusual electronic behaviour in a topologically nontrivial setting, such as the large anomalous Hall response born from substantial Berry curvature$^{30}$ and a rare occurrence of superconductivity in a kagome system$^{29,31}$. Theory indicates that the band structure of AV$_3$Sb$_5$ is characterized by a nontrivial topological invariant$^{30,31}$, which combined with emergent superconductivity draws an interesting parallel to the character of topological metals in the family of Fe-based high-T$_c$ superconductors$^{32,33}$. The large density of states due to a van Hove singularity that is located in the vicinity of the Fermi level, and quasi-one-dimensional (1D) regions of the Fermi surface$^{29}$, also provide an ideal playground for the search for elusive correlated states on a kagome lattice. While theory predicts numerous possibilities for spatial symmetry breaking of the kagome lattice electronic structure$^{30,31,32}$, their experimental realization has been challenging. In this Article, using spectroscopic imaging scanning tunnelling microscopy (SI-STM), we discover a cascade of symmetry-broken phases in a kagome superconductor, CsV$_3$Sb$_5$, as a function of temperature, detectable as different charge ordering states and an anisotropic quasiparticle scattering signature. These phases develop in the normal state and persist below the superconducting $T_c$. Our experiments demonstrate that superconductivity in CsV$_3$Sb$_5$ emerges from, and coexists with, an electronic state with an intrinsically broken rotational and translational symmetry. This could have strong implications for the superconducting order parameter in this family of kagome superconductors, where transport experiments recently suggested the possibility of unconventional pairing$^{34,35}$.

**Topographic characterization**

CsV$_3$Sb$_5$ is a layered superconductor ($T_c$ ~ 2.5 K)$^{29}$, with a hexagonal crystal structure (a = b = 5.4 Å, c = 9 Å) composed of V–Sb sheets stacked between complete Cs layers$^{29,36}$ (Fig. 1a, b). Each V–Sb sheet consists of a kagome network of V atoms, interlaced with a hexagonal lattice of Sb. Owing to a stronger bond expected between V and Sb atoms,
Fig. 1 | Surface identification. a, 3D crystal structure of CsV₃Sb, viewed from the side. b, Top view of the crystal structure (a−b plane), showing the kagome lattice of the V₃Sb layer and the triangular lattice of the Cs layer. c, d, 3D portrayal of a large-scale morphology of Cs (e) and Sb (d) layers from STM topographs. e, f, Atomically resolved STM topographs of Cs-terminated (e) and Sb-terminated (f) surfaces, with atom ball models superimposed. Green, grey and red spheres in a, b, e and f denote Cs, Sb and V atoms, respectively. STM setup condition: c, $V_{\text{sample}} = 200$ mV, $I_{\text{set}} = 40$ pA, $T = 4.5$ K; d, $V_{\text{sample}} = 200$ mV, $I_{\text{set}} = 10$ pA, $T = 4.5$ K; e, $V_{\text{sample}} = 20$ mV, $I_{\text{set}} = 200$ pA, $T = 4.5$ K; f, $V_{\text{sample}} = 50$ mV, $I_{\text{set}} = 30$ pA, $T = 59$ K.

Large-scale electronic band structure

In the remainder of the work, we focus on the Sb-terminated surface, located directly above the V kagome layer. Differential conductance $\frac{dI}{dV}$ spectra, proportional to the local density of states, exhibit several distinct features, which are denoted by arrows in Fig. 2b. By comparison to band structure calculations, which show good agreement with angle-resolved photoemission spectroscopy (ARPES) results, we attribute the two spectral peaks in the $\frac{dI}{dV}$ spectra below the Fermi level to van Hove singularities at the M point. The local minimum between them is then probably associated with the Dirac point at $k_\text{F}$ (Fig. 2a, b). To gain further insight into the electronic structure of our system, we use quasiparticle interference (QPI) imaging, rooted in the elastic scattering and interference of electrons visible as static modulations in $\frac{dI}{dV}(r, V)$ maps. Aside from Bragg peaks $Q_{\text{Bragg}}$ ($i = \alpha, \beta, \gamma$), the Fourier transforms (FTs) of $\frac{dI}{dV}(r, V)$ maps show an isotropic scattering vector $q_i$ near the FT centre (Fig. 2c and Extended Data Fig. 3). By comparing its dispersion as a function of energy to the theoretical band structure, we identify $q_i$ as the scattering vector connecting different states on the constant-energy contour (CEC) of the pocket centred at $\Gamma$ (Fig. 2a, c, d). The Fermi vector $k_\text{F} = 0.18$ Å$^{-1}$ obtained from our data ($q_i = 0$) is nearly identical to that measured by ARPES (ref. 29). This agreement, together with the identification of spectral features in $\frac{dI}{dV}$ spectra (Fig. 2a, b), demonstrates an approximate consistency between the large-scale electronic band structures measured by ARPES, STM and theory.

Temperature-dependent charge density waves

We proceed to investigate the system by temperature-dependent STM, starting at a high temperature well above the superconducting transition temperature. We find that STM topographs at 60 K exhibit a $2 \times 2$ superstructure, which breaks the translational symmetry of the lattice (Fig. 3a). In Fourier space, this pattern gives rise to a set of wavevectors at exactly $Q_{\text{Bragg}} = \frac{1}{2} q_i$ (i = $\alpha, \beta, \gamma$) (Figs. 2c and 3d–g). The vectors are extremely localized in reciprocal space (~1–2 pixels or ~0.006–0.012 Å$^{-1}$) and their positions do not disperse with energy (Figs. 2c and 3g and Extended Data Fig. 3). On this basis, we attribute these features to a static charge order with a $2a_0$ period, propagating along all lattice directions ($2a_0-CO$). This interpretation is bolstered by X-ray diffraction measurements that detected peaks at the same wavevectors emerging below $T^* = 94$ K (ref. 29) and reports of charge ordering at the same wavevector in the closely related compound K$_3$V$_3$Sb$_5$ (ref. 30).

As the system is cooled down further, the electronic structure of CsV₃Sb begins to display a pronounced unidirectional character. At approximately 50 K, another periodic modulation with a $4a_0$ wavelength propagating along one lattice direction emerges in STM topographs (Fig. 3b, c). This charge ‘stripe’ modulation corresponds to the FT wavevector $q_{\text{4a0-CO}} = 0.23$ Q$_{\text{Bragg}}$ (Fig. 3d–g). The small deviation between this average vector $q_{\text{4a0-CO}} = 0.23$ Q$_{\text{Bragg}}$ and the commensurate location 0.25 Q$_{\text{Bragg}}$ can be attributed to phase slips (inset in Fig. 3c). The wavevector $q_{\text{4a0-CO}}$ is again non-dispersive (Fig. 3g), and thus consistent with a unidirectional charge order (1Q-CO), which has not to our knowledge been experimentally observed in any kagome system to date. On closer inspection of FT intensities along the same direction, we notice several faint peaks, which are equally spaced by $-0.05$ Q$_{\text{Bragg}}$ around dominant wavevectors (Extended Data Fig. 4). These cannot be explained by a linear superposition of Q$_{\text{Bragg}}$ and $q_{\text{4a0-CO}}$ and could be a consequence of band folding, or possibly even indicative of another charge ordering state with the wavevector $-0.05$ Q$_{\text{Bragg}}$ coupling to other peaks via satellite reflections.

Quasi-1D QPI signature

In addition to static charge ordering, our SI-STM measurements reveal another intriguing aspect of the electronic structure. At low energies, FTs of $\frac{dI}{dV}(r, V)$ maps display long parallel features, which we label as $q_i$ and $q'_i$ (Fig. 4b and Supplementary Fig. 1). Each $q_i$ and $q'_i$ set of wavevectors consists of multiple parallel stripes in q-space. Importantly, the separation between these q-space stripes disperses noticeably over a narrow energy range where the feature is detected (Fig. 4c). This observation demonstrates that $q_i$ and $q'_i$ are related to...
elastic scattering between different points on the CEC—the separation between the \( q \) space features at different energies will evolve concomitantly with the change in the CEC in \( k \) space. To understand the origin of scattering in more detail, we examine the morphology of the Fermi surface. The CEC near zero energy consists of parallel quasi-1D bands along the \( M_1 \)–\( M_2 \) direction originating from \( V \) orbitals (inset in Fig. 4a and Extended Data Fig. 7). Scattering between them could naturally give rise to the unidirectional QPI observed. To visualize this, we simulate the QPI signature based on the approximate CEC, where \( q_1 \) and \( q'_2 \) can be beautifully reproduced (Fig. 4a and Supplementary Section 1).

Remarkably, \( q_1 \) and \( q'_2 \) are only observed along a single lattice vector parallel to \( q_{40-40} \), while they are notably absent at the equivalent \( q \) space positions along the other two lattice directions (dashed rectangles in Fig. 4b). This provides further evidence that the electronic band structure of CsV\(_3\)Sb\(_5\) breaks the six-fold rotational symmetry of the lattice. We rule out STM tip anisotropy effects, as the unidirectional electronic signature rotates across a domain boundary (Fig. 4f, g). As previously discussed, the \( C_2 \)-symmetric signal in the FTs of \( dV/dI(r, V) \) maps originates from scattering between the states characterized by \( V \) orbitals (Fig. 4a, Supplementary Fig. 4 and Supplementary Section 1). This observation suggests that the rotational symmetry breaking observed is intrinsic to the \( \Gamma \) kagome layer itself. It is also important to note that it is band specific. The QPI vector \( q_1 \) related to the Sb pocket at \( \Gamma \) does not show a noticeable \( q \) space anisotropy (Fig. 4d).

By a closer inspection of \( q_1 \) and \( q'_2 \) away from the Fermi energy, we find that these vectors get suppressed above 12 meV, around the same energy at which the equivalent vectors along the other two lattice directions emerge (Fig. 4d, e, Extended Data Fig. 8). This observation points towards a strong energy-dependent orbital renormalization, which is reminiscent of the orbital- and energy-dependent quasiparticle spectral weight in the electronic nematic state of Fe-based superconductors.\(^3\)

Rotational symmetry breaking could in principle be explained by either strong nematic susceptibility pinned by a small accidental strain during the sample cooldown, or an intrinsic symmetry-broken electronic phase. In strong support of the latter, we highlight the following. First, symmetry-breaking QPI has been consistently observed over >100 nm square regions in multiple different crystals. Second, we can observe electronic domains in the absence of obvious structural imperfections (Fig. 4f, g and Supplementary Fig. 2). Third, no \( 4a_0 \) charge stripe order occurs at 60 K, the temperature at which the majority of the sample

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**Fig. 2** | **Large-scale electronic characterization.** \( a \). Calculated band structure of CsV\(_3\)Sb\(_5\), with two of the van Hove singularities (vHs\(_1,2\)) at \( M \) called out by arrows (Methods and Extended Data Fig. 7). **b**, Spatially averaged differential conductance \( (dI/dV) \) spectrum acquired over the Sb-terminated surface. The inset displays the \( dI/dV \) spectrum with only a small chemical potential shift. The inset displays the \( dI/dV \) spectrum with only a small chemical potential shift. The inset shows the \( dI/dV \) spectrum with only a small chemical potential shift.

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Fig. 3 | Charge ordering at low temperature. a, b, Zoom-in comparison of atomically resolved STM topographs, taken over the Sb-terminated surface at 60 K (a) and 4.5 K (b), showing different charge modulation patterns (see also Extended Data Fig. 6). c, Low-temperature STM topograph over a large region. b is a zoom-in of the region outlined in black. The inset shows an example of a phase slip due to a $5a_0$ stripe charge modulation. The kagome V$\\text{Sb}_2$ layer structure is superimposed in a. d, The FT of the STM topograph in c. Green circles, brown circles and blue squares indicate the atomic Bragg peaks, $2a_0$-CO and $4a_0$-CO peaks, respectively. e, Temperature-dependent FT linecuts, along the $Q$-CO direction, all taken from data acquired over an identical region. Grey dashed lines are visual guides showing a non-dispersive nature of the peaks. f, FT linecuts along the three different lattice directions in d, g, FT linecuts of $I(r, \Phi)$ along three lattice directions at 4.5 K as a function of bias. STM setup condition: $V_{\text{sample}} = 20$ mV, $I_{\text{set}} = 30$ pA, $T = 60$ K; b, c, $V_{\text{sample}} = -20$ mV, $I_{\text{set}} = 20$ pA, $T = 4.5$ K; f, $V_{\text{sample}} = 100$ mV, $I_{\text{set}} = 600$ pA, $V_{\text{exc}} = 4$ mV, $T = 4.5$ K; g, $V_{\text{sample}} = -30$ mV, $I_{\text{set}} = 20$ pA.

Discussion

We hypothesize that the $2a_0$-CO arises from the nesting between the $V$-band van Hove points at $M$, giving rise to a charge order with exactly $2a_0$ wavelength. The formation of this $2a_0$-CO order leads to a spectral gap in the $dV/dI$ spectra with shoulders around ±20 meV (inset in Fig. 2b and Extended Data Fig. 9, c, d), which we identify on the basis of its temperature dependence (Supplementary Section 3) and recent ARPES measurements. The gap opening at the Fermi level should be primarily associated with $V$ bands, given that our QPM measurements put a bound on the gap of the Sb pocket to be 1–2 meV (Supplementary Fig. 1).

A fundamental property of a single-orbital model on the kagome lattice at the van Hove filling under long-range Coulomb interaction is the $q = 0$ Pomeranchuk instability towards a rotational symmetry breaking state. Our measurements uncover experimental signatures of rotational symmetry breaking on a kagome lattice, albeit with the concomitant breaking of the lattice translation symmetry. Subleading divergences of the susceptibility predicted to occur at all wavevectors along the M–M directions emanating from the Γ point may lead to the propensity of the electronic state to additionally break lattice translation symmetry for realistic band parameters and correlations. It is also conceivable that the translation symmetry breaking via charge ordering is related to the filling factor that is away from van Hove singularity in real materials. Such chemical potential changes or small band-structure variations could possibly explain the presence or the absence of the $4a_0$-CO order (4$a_0$-CO) in different members of the AV$_2$Sb$_2$ family.

Magnetotransport experiments on CsV$_3$Sb$_5$ observed resistivity anisotropy that onsets around 50–60 K (refs. 39,40), which agrees with the onset temperature of the $4a_0$-CO. This agreement strongly suggests that there is a bulk rotational symmetry breaking state that emerges below 50–60 K, which is either the interlayer coupled $4a_0$-CO, or a different rotational symmetry breaking state that manifests itself on the surface as the $4a_0$-CO. We note that a new phonon resonance also emerges around the temperature of the $4a_0$-CO onset, thus providing further evidence for the intimate relationship between the $4a_0$-CO and the bulk of this material. Given the difference in the onset temperatures of the non-dispersive $4a_0$-CO and the dispersive anisotropic quasiparticle scattering (Extended Data Fig. 9), it may be possible that the two phenomena are...
associated with different parts of the same electronic bands, or different bands altogether. It remains to be understood whether a vestigial order may develop from partially melting the $4a_0$ charge stripes. We note that weak quasi-1D correlations are often difficult to detect in traditional survey X-ray measurements owing to the diffuse scattering signal falling below the measurement’s ability to isolate it from the background. The likely presence of domain boundaries exacerbates this. Targeted scattering experiments, possibly in strained crystals to mitigate domain formation, will be necessary to determine whether the $4a_0$ charge stripe order exhibits bulk correlations.

Last, we note that sub-kelvin SI-STM measurements reveal that symmetry-broken states persist below the superconducting $T_c$ (Supplementary Fig. 3). The emergence of the $4a_0$–CO, V-shaped spectral gap opening in the normal state and superconductivity presents a remarkable similarity to the character of cuprate high-temperature superconductors\cite{113102}. At the same time, the coexistence of multiple charge orders with different wavevectors, geometries and temperature onsets in CsV$_3$Sb$_5$ adds to the complexity of the underlying physics. It remains to be seen whether the superconducting order parameter in CsV$_3$Sb$_5$ is unconventional, as possibly indicated by recent transport measurements\cite{113102,12377-12396}. Future experiments should address the competition of different phases by more detailed temperature-, energy- and doping-dependent measurements, while also searching for evidence of intrinsic topological superconductivity and Majorana modes expected to arise owing to the nontrivial band topology\cite{10.1038/s41586-021-03946-w}.

### Online content

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Single crystals of CsV3Sb5 were grown and characterized as described in more detail in ref. 29 (Extended Data Fig. 10b). To quantify the effect, we plot resistivity anisotropy $\delta = 2\rho(0°) + \rho(30°)$ as a function of temperature, and find that $\delta$ becomes increasingly pronounced at low temperature (Extended Data Fig. 10c). Magnetoresistance measurements were performed using a Quantum Design 14T Dynacool Physical Property Measurement System with a rotator option and electrical transport module. Electrical contacts were made to freshly exfoliated crystals of CsV3Sb5 using a Corbino-like geometry, silver paint and gold wires. Samples were initially mounted such that the $a$ axis is parallel to the magnetic field $H$ at $0°$. The crystal rotates such that the magnetic field is contained within the $a-b$ plane of the crystal. A small deviation of $5°$ was corrected for in Extended Data Fig. 10b. An a.c. probe current of 8 mA and 70 Hz was used to measure the magnetoresistance at 14 T.

STM measurements

We cold-cleaved and studied three different CsV3Sb5 crystals, all of which exhibited qualitatively the same phenomena described in the main text (Extended Data Fig. 5). STM data were acquired using a customized Unisoku USM1300 microscope at varying temperatures denoted in the figure captions. Spectroscopic measurements were performed using a standard lock-in technique with 915 Hz frequency and bias excitation as also detailed in the figure captions. The STM tips were custom-made using a standard lock-in technique with 915 Hz frequency and bias excitation. The STM measurements were performed using a Quantum Design 14T Dynacool Physical Property Measurement System with a rotator option and electrical transport module. Electrical contacts were made to freshly exfoliated crystals of CsV3Sb5 using a Corbino-like geometry, silver paint and gold wires. Samples were initially mounted such that the $a$ axis is parallel to the magnetic field $H$ at $0°$. The crystal rotates such that the magnetic field is contained within the $a-b$ plane of the crystal. A small deviation of $5°$ was corrected for in Extended Data Fig. 10b. An a.c. probe current of 8 mA and 70 Hz was used to measure the magnetoresistance at 14 T.

Density functional theory

The electronic structure of CsV3Sb5 is simulated in VASP v.5.4.4 (refs. 41-46) using projector-augmented wave potentials47,48 with identical computational parameters to previous work on CsV3Sb5 (ref. 29) and KV3Sb5 (refs. 31,32; Extended Data Fig. 7a). Calculations employ the PBE functional49 with D3 dispersion corrections50, a Γ-centred 11 × 11 × 5 $k$-mesh, a plane wave energy cutoff of 500 eV and the recommended projector-augmented wave potentials for VASP v.5.2. The lattice parameters a and c of the relaxed cell are 5.45 Å and 9.35 Å, respectively. Wannier-interpolated Fermi surfaces are generated from Wannier functions fitted in Wannier90 (ref. 51) starting from initial projectors corresponding to valence orbitals (Cs $s, p$; V $s, p, d$; Sb $s, p$; with a frozen fitting window $E_F \pm 2$ eV). The Fermi level in the calculation was set so that the size of the Sb pocket at zero energy matches that observed in ARPES measurements52. We note that this calculation does not take into account kagome breathing mode distortions, which will lead to additional renormalization of the band structure below the charge density wave transition, especially pronounced related to V bands near the Brillouin zone edge53.

Data availability

The data supporting the findings of this study are available upon request from the corresponding author. Source data are provided with this paper.

Code availability

The computer code used for data analysis is available upon request from the corresponding author.

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Author contributions

STM experiments and data analysis were performed by H.Z. and H.L. B.R.O. synthesized and characterized the samples under the supervision of S.D.W. S.M.L.T. and T.B. performed STM measurements and data analysis were performed by H.Z. and H.L. B.R.O. synthesized and characterized the samples under the supervision of S.D.W. S.M.L.T. and T.P. gratefully acknowledge support via the University of California Santa Barbara NSF Quantum Foundry funded via the Q-AMASE i-programme under award DMR-1806325. B.R.O. also acknowledges support from the California NanoSystems Institute through the Elings Fellowship programme. We acknowledge use of the shared computing facilities of the Center for Scientific Computing at University of California Santa Barbara, supported by NSF CNS-1725797, and the NSF Materials Research Science and Engineering Center at University of California Santa Barbara, NSF DMR-1720256. M.Y. is supported in part by the Gordon and Betty Moore Foundation through Grant GBMF8690 to UCSB. S.M.L.T. has been supported by the National Science Foundation Graduate Research Fellowship Program under grant no. DGE-1650114. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Z.W. acknowledges the support of US Department of Energy, Basic Energy Sciences grant no. DE-FG02-99ER45477.

Competing interests

The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Ilija Zešijak.

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Extended Data Fig. 1 | Cs clustering on as-cleaved Sb-terminated surface.
(a) 3D portrayal of a large-scale morphology of the Sb layer from an STM topograph. Inset is a 3D zoom-in of a small square region covering three Cs atoms. (b) As-cleaved STM topograph with several Cs atoms scattered on the surface. The apparent height of Cs atoms in (b) is approximately 2 Angstroms, and the color scale is saturated to emphasize the 4\(_{\text{g}}\)-CO modulation. STM setup condition: (a) \(V_{\text{sample}} = 200\) mV, \(I_{\text{set}} = 10\) pA; (b) \(V_{\text{sample}} = 200\) mV, \(I_{\text{set}} = 50\) pA. \(T = 4.5\) K in all panels.
Extended Data Fig. 2 | Large-scale STM topograph of the Sb-terminated surface. High resolution STM topograph over a large region encompassing the topograph from Fig. 3c. Inset shows a zoom-in on two defects that serve as main scattering sites for the wave-like QPI modulations, with different atoms superimposed on top (Cs – green, Sb – gray and V – red spheres). As it can be seen in the inset, the defects are located at the Cs site. STM setup condition: $V_{\text{sample}} = -20 \text{ mV}, I_{\text{set}} = 20 \text{ pA}, T = 4.5 \text{ K}$; (inset) $V_{\text{sample}} = 20 \text{ mV}, I_{\text{set}} = 60 \text{ pA}, T = 4.5 \text{ K}$.
Extended Data Fig. 3 | Quasiparticle interference imaging of the electron pocket around $\Gamma$. (a-f) Differential conductance ($dI/dV(r, V)$) maps over the same region of the sample used for the analysis of the dispersion in Fig. 2, and (g-l) corresponding Fourier transforms (FTs). Green, brown and blue circles denote the atomic Bragg peaks, $2a_0$ charge ordering peaks $q_{2a_0-CO}$ and unidirectional stripe charge order peaks $q_{4a_0-CO}$ in momentum-transfer space, respectively. The red and orange arrows indicate the QPI wave vectors that we attribute to the intra-electron pocket scattering around $\Gamma$. (m) Radially-averaged FT linecut as a function of STM bias $V$ showing the presence of $q_1$ across Fermi energy. STM setup condition: (a) $V_{sample} = -400$ mV, $I_{set} = 800$ pA, $V_{exc} = 5$ mV; (b) $V_{sample} = -300$ mV, $I_{set} = 600$ pA, $V_{exc} = 4$ mV; (c) $V_{sample} = -200$ mV, $I_{set} = 400$ pA, $V_{exc} = 4$ mV; (d) $V_{sample} = -100$ mV, $I_{set} = 200$ pA, $V_{exc} = 4$ mV; (e) $V_{sample} = -50$ mV, $I_{set} = 100$ pA, $V_{exc} = 4$ mV; (f) $V_{sample} = 0$ mV, $I_{set} = 400$ pA, $V_{exc} = 4$ mV; (g) $V_{sample} = 10$ mV, $I_{set} = 100$ pA, $V_{exc} = 1$ mV; $T = 4.5$ K.
Extended Data Fig. 4 | Identification of additional peaks in the Fourier transform linecut along the charge stripe direction. Fourier transform linecut of \( L(r, V) \) maps along the \( q_{4a0-CO} \) (charge stripe) direction at 4.5 K (same as Fig. 3g). The green dashed lines are visual guides showing the most prominent additional non-dispersive peaks. Green arrows denote all the satellite peaks we observe, approximately equally spaced from the dominant peaks. The black, blue and brown arrows indicate the dominant peaks: the low-frequency peak \( (q_{low}) \) likely associated with the satellite peaks, unidirectional charge order peak \( (q_{4a0-CO}) \) and tri-directional charge order peak \( (q_{2a0-CO}) \), respectively. STM setup condition: \( V_{\text{sample}} = 100 \text{ mV}, I_{\text{set}} = 600 \text{ pA}, V_{\text{exc}} = 4 \text{ mV}, \) \( T = 4.5 \text{ K} \).
Extended Data Fig. 5 | Data reproducibility across different CsV₃Sb₅ single crystals. (a–c) STM topographs acquired over different CsV₃Sb₅ samples. (d,e) Differential conductance ($dI/dV(r, V)$) maps obtained on sample #1 and #3, respectively. Panels (f–j) are the corresponding Fourier transforms of the images above. STM setup condition: (a) $V_{\text{sample}} = -20 \text{ mV}, I_{\text{set}} = 20 \text{ pA}$; (b) $V_{\text{sample}} = 300 \text{ mV}, I_{\text{set}} = 90 \text{ pA}$; (c) $V_{\text{sample}} = -40 \text{ mV}, I_{\text{set}} = 110 \text{ pA}$; (d) $V_{\text{sample}} = -4 \text{ mV}, I_{\text{set}} = 50 \text{ pA}, V_{\text{exc}} = 1 \text{ mV}$; (e) $V_{\text{sample}} = 4 \text{ mV}, I_{\text{set}} = 40 \text{ pA}, V_{\text{exc}} = 1 \text{ mV}$.
**Extended Data Fig. 6 | Bias dependence of STM topographs.** (a–d) STM topographs acquired over an identical region at 60 K under different biases. (e–h) STM topographs acquired over another region at 4.5 K under different biases. Insets in (a–h) are the associated Fourier transforms. Green, brown and blue circles denote the atomic Bragg peaks, tri-directional charge order peaks and unidirectional stripe charge order peaks in momentum-transfer space, respectively. STM setup condition: (a) $V_{\text{sample}} = 90$ mV, $I_{\text{set}} = 30$ pA; (b) $V_{\text{sample}} = 50$ mV, $I_{\text{set}} = 30$ pA; (c) $V_{\text{sample}} = -30$ mV, $I_{\text{set}} = 40$ pA; (d) $V_{\text{sample}} = -90$ mV, $I_{\text{set}} = 40$ pA; (e) $V_{\text{sample}} = 200$ mV, $I_{\text{set}} = 400$ pA; (f) $V_{\text{sample}} = 50$ mV, $I_{\text{set}} = 100$ pA; (g) $V_{\text{sample}} = 10$ mV, $I_{\text{set}} = 20$ pA; (h) $V_{\text{sample}} = -50$ mV, $I_{\text{set}} = 100$ pA.
Extended Data Fig. 7 | Density functional theory (DFT) calculation of the electronic band structure. (a) DFT calculated band structure of CsV₃Sb₅ along high symmetry directions across the Brillouin zone, visualized by SUMO (Supplementary Section 1). The blue and red colors represent the contributions from Sb and V orbitals, respectively. (b) Schematic of different high-symmetry points.
**Extended Data Fig. 8 | Energy dependence of the quasiparticle interference (QPI) near Fermi level.** (a–g) Two-fold symmetrized Fourier transforms (FTs) of differential conductance ($dI/dV(r, V)$) maps acquired over the same field-of-view on an Sb-terminated surface of sample 1. The dispersive QPI stripes are denoted by magenta (along $q_a$) and blue (along $q_{b,c}$) rectangles. At bias lower than 12 mV, the stripe features along $q_a$ are clearly visible (solid magenta rectangles), while the equivalent features along $q_b$ and $q_c$ are absent (dashed blue rectangles). The trend is reversed at a bias higher than 12 mV. Green circles denote the atomic Bragg peaks. For visual purposes, noise streaks in (c–e) along ~45 degree direction with respect to the horizontal are removed by subtracting a polynomial from each row of the raw $dI/dV$ map before the map is rotated, FT is performed and the FT is two-fold symmetrized. (h, i) Linecuts in FTs of $dI/dV(r, V)$ maps as a function of bias along the magenta and blue dashed lines in (d). Orange curves in (h, i) are visual guides showing the dispersion of QPI wave vectors. STM setup condition: (a) $V_{\text{sample}} = 18$ mV, $I_{\text{set}} = 90$ pA, $V_{\text{exc}} = 1$ mV; (b) $V_{\text{sample}} = 16$ mV, $I_{\text{set}} = 200$ pA, $V_{\text{exc}} = 1$ mV; (c) $V_{\text{sample}} = 14$ mV, $I_{\text{set}} = 100$ pA, $V_{\text{exc}} = 1$ mV; (d) $V_{\text{sample}} = 12$ mV, $I_{\text{set}} = 90$ pA, $V_{\text{exc}} = 1$ mV; (e) $V_{\text{sample}} = 10$ mV, $I_{\text{set}} = 70$ pA, $V_{\text{exc}} = 1$ mV; (f) $V_{\text{sample}} = 5$ mV, $I_{\text{set}} = 60$ pA, $V_{\text{exc}} = 1$ mV; (g) $V_{\text{sample}} = -5$ mV, $I_{\text{set}} = 60$ pA, $V_{\text{exc}} = 1$ mV; $T = 4.5$ K.
Extended Data Fig. 9 | Additional temperature-dependent STM data.
(a,b) STM topographs of an identical area of the sample at (a) 4.5 K, and (b) 50 K, and (c,d) corresponding spatially-averaged dI/dV spectra. As it can be seen from (b), the $4a_0$ charge ordering is nearly completely absent at this elevated temperature. The low-temperature dI/dV spectrum in (c) shows two shoulders at ±20 mV (black arrows) and gap-like features closer to Fermi energy around ±5 to 10 mV (orange arrows). dI/dV spectrum at higher temperature in (d) (just before entering the $4a_0$-CO state) only shows the broad shoulders at higher energy. (e) Large-scale STM topograph and (f) Fourier transform of simultaneous dI/dV(r, $V_{-6}$ mV) map showing the presence of $4a_0$-CO peak and the absence of QPI ($q_x$ and $q'_x$, enclosed by dashed rectangles) seen at low temperature in Fig. 4 and Fig. S1. STM setup condition: (a-d) $V_{sample}$ = 50 mV, $I_{set}$ = 50 pA, $V_{exc}$ = 1 mV; (e,f) $V_{sample}$ = −8 mV, $I_{set}$ = 80 pA, $V_{exc}$ = 1 mV.
Extended Data Fig. 10 | Magnetization and magnetotransport measurements of CsV₃Sb₅ single crystals. (a) Temperature (T) dependence of magnetization $M = 4\pi \chi$ ($\chi$ is magnetic susceptibility). Zero-field cooled (field cooled at 5 Oe field) magnetization is denoted by a black solid (dashed) line. (b) Angle-dependent magnetotransport measurements, plotting resistivity $\rho$ along the c-axis as a function of angle $\theta$, which is the direction of magnetic field $H = 14$ T applied in the ab-plane, as denoted in the inset. (c) Resistivity anisotropy as a function of temperature, calculated from the three data sets in (b) as $\delta = \frac{2\rho(0°) + \rho(180°) + \rho(60°) + \rho(120°) + \rho(240°) + \rho(300°)}{6}$. 