

Surface-sensitive electronic structure of kagome superconductor CsV_3Sb_5

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Citation: Chin. Phys. B, 2024, 33 (**10**): 107403. DOI: 10.1088/1674-1056/ad7016
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SPECIAL TOPIC — Recent progress on kagome metals and superconductors

Surface-sensitive electronic structure of kagome superconductor CsV_3Sb_5

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(Received 14 June 2024; revised manuscript received 13 August 2024; accepted manuscript online 16 August 2024)

We systematically study the electronic structure of a kagome superconductor CsV_3Sb_5 at different temperatures covering both its charge density wave state and normal state with angle-resolved photoemission spectroscopy. We observe that the V-shaped band around $\bar{\Gamma}$ shows three different behaviors, referred to as α/α', β and γ, mainly at different temperatures. Detailed investigations confirm that these bands are all from the same bulk Sb-p_z origin, but they are quite sensitive to the sample surface conditions mainly modulated by temperature. Thus, the intriguing temperature dependent electronic behavior of the band near $\bar{\Gamma}$ is affected by the sample surface condition, rather than intrinsic electronic behavior originating from the phase transition. Our result systematically reveals the confusing electronic structure behavior of the energy bands around $\bar{\Gamma}$, facilitating further exploration of the novel properties in this material.

Keywords: kagome, ARPES, charge density wave, surface sensitive

PACS: 74.25.Jb, 74.20.Pq, 71.18.+y, 79.60.–i **DOI:** 10.1088/1674-1056/ad7016

1. Introduction

Layered kagome-lattice materials provide a unique platform for investigating novel quantum phenomena due to the coexistence of topological non-trivial Dirac bands, strongly correlated flat bands and van Hove singularities (VHSs) in their band structures according to theoretical calculations.[1–12] Superconductivity has been observed in a layered vanadium-based kagome metal family AV_3Sb_5 (A = K, Rb and Cs), raising interests in understanding the relationship among its charge density wave (CDW), superconductivity and topological properties.[13–21]

Three-dimensional (3D) $2\times2\times2$ CDW order and in-plane 1×4 CDW order have been observed in AV_3Sb_5 (A = K, Rb and Cs) by scanning tunneling microscopy (STM).[15–18,22–25] However, it is still under debate which kind of lattice distortion, such as Star of David, inverse Star of David or their combination, is energetically favored in the CDW phase in these materials.[26–29] Considering the rich electronic properties including VHSs,[30–32] Dirac bands[14,33] and topological surface state[34] observed near the Fermi energy (E_F) by angle-resolved photoemission spectroscopy (ARPES), the corresponding temperature dependent electronic structure across the CDW transition is crucial to understand the underlying mechanism.[14,31,32] Interestingly, the V-shaped band dominated by Sb-p_z orbital around $\bar{\Gamma}$ attracts wide attention due to its complex temperature dependent behavior. In particular, a double V-shaped band structure has been observed. This is proposed to be related to a folded band going through CDW transition with a $2\times2\times2$ wave vector,[35] and quantum confinement effect from different layers is also suggested.[36] Detailed k_z-dependent experiment suggests that it could also be related to a surface state.[37] In addition, distinct kinds of cleavage termination surfaces, such as complete alkali atom surface, half alkali atom surface and complete Sb surface, together with surface reconstruction of alkali atoms in these materials are observed by STM, which can modulate the energy bands.[15–17,38] Thus, to shed light on its physical origin, it is necessary to systematically study the temperature evolution of the V-shaped band.

In this paper, we present a systematic study of the low-energy electronic structure at different temperatures in CsV_3Sb_5 using ARPES. We find that despite the different behaviors of the V-shaped band around $\bar{\Gamma}$ at different temperatures, they all originate from bulk Sb-p_z orbitals. However, this band behavior is sensitive to different surface conditions mainly modulated by temperature. Distinguished from the previously reported results, our results give strong evidence that the V-shaped band evolution is likely a trivial surface ef-

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fect. Thermal activations bring out different Cs defects or reconstructions on the surface, which might be the origin of the confusing behavior of the band around $\bar{\Gamma}$. Our result solves the confusing behavior of V-shaped band around $\bar{\Gamma}$ in the ARPES studies and provides a fundamental reference for further ARPES exploration of the novel physical properties in this kagome family.

2. Method

High-quality single crystals of CsV_3Sb_5 are grown using self-flux method.[13] The synchrotron ARPES experiments are conducted at beamline 13U of the National Synchrotron Radiation Laboratory (NSRL) and beamline BL3U of Shanghai Synchrotron Radiation Facility (SSRF) in China. The overall energy resolution for the combined instruments is set better than 15 meV and the angular resolution is better than 0.2°. The samples are cleaved *in situ* and measured in an ultrahigh vacuum better than 1.0×10^{-10} mbar.

3. Results

CsV_3Sb_5 is a layered vanadium-based kagome superconductor with *P6/mmm* (No. 191) space group. The V atoms form a kagome lattice with one Sb atom at the center of each V hexagon, as shown in Fig. 1(a). This V_3Sb layer is then intercalated by two honeycombed Sb layers and hexagonal Cs layers. Interesting physical phenomena are expected from the kagome V_3Sb layer. The 3D Brillouin zone (BZ) of CsV_3Sb_5 is shown in Fig. 1(b). In Figs. 1(c) and 1(d), the Fermi surface and band structures are marked by dashed lines with different colors, which correspond to different orbital contributions, respectively. It is apparent that the bands around E_F mainly originate from the V-3d orbitals and Sb-2p orbitals. Three Dirac points are clearly seen at different energy and momentum positions, which is consistent with our DFT calculation in Fig. 1(d). Moreover, there are three VHSs located around M point with two of them right below E_F and one of them above E_F, which are highly associated with the CDW formation in this material, as reported elsewhere.[14,30]

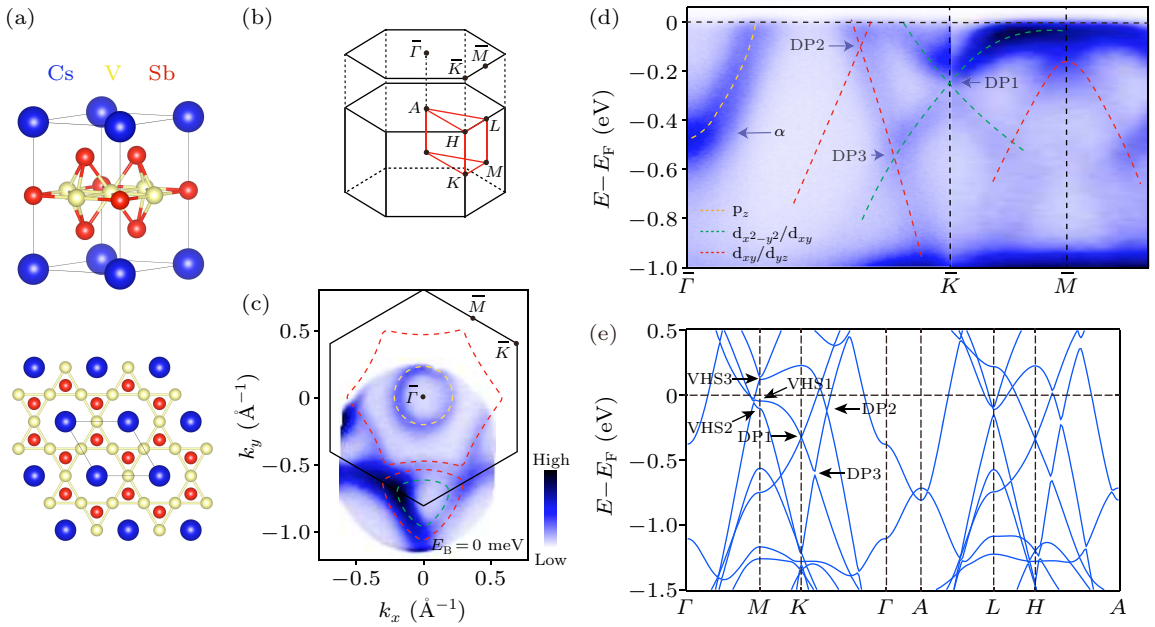


Fig. 1. (a) Crystal structure of CsV_3Sb_5 and the corresponding top view along the *c*-axis. (b) 3D BZ of CsV_3Sb_5. The high symmetry points are plotted. (c) Fermi surface mapping taken at 130 K with 23 eV photons. The dashed lines indicate different orbital contributions. (d) Band structure taken at 130 K. The arrows refer to the Dirac cones and the dashed lines refer to different dominating orbitals of the energy bands. (d) Calculated band structure by DFT. The arrows indicate the positions of the Dirac cones and VHSs.

Figure 2(a) shows the photon-energy-dependent electronic structure of the V-shaped energy band around $\bar{\Gamma}$ of sample 1 (#1), together with its corresponding second derivative spectrum in Fig. 2(b). From all the photon energies, one can clearly see that there exist two bands α and α'. The intensities of the two bands are obviously modulated by different photon energies, where the intensity of α is strongest around 110 eV and weakest around 98 eV, and α' shows the same intensity modulation behavior but in an opposite trend. This can also be clearly illustrated in their corresponding energy distribution curves (EDCs) at $\bar{\Gamma}$ in Fig. 2(c), which show the behavior of the band bottoms of α and α': the energy positions of the band bottoms of α and α' almost remain the same while the intensities are modulated periodically. Since there is only one band around $\bar{\Gamma}$ according to the theoretical calculation, the origin of the "splitting" α and α' bands has been discussed in previous ARPES work. It is proposed to result from the folded CDW bands if one considers the out-of-plane band folding induced by the $2 \times 2 \times 2$ charge order.[35] Other mechanisms such as quantum confinement effect and surface

state origin have also been proposed.[36,37] Overall, according to our k_z-dependent results, we think it likely originates from the k_z broadening effect, since if we extract the bands around Γ and A points from our DFT calculations and overlaid them on the 116 eV data in Fig. 2(a), both fit the α and α' bands pretty well. And this kind of k_z broadening effect is observed in many materials when the energy bands show strong dispersion along k_z.[41–44] Assuming this intensity modulation behavior is an effect from k_z broadening, we can assign the 104 eV across Γ and 94 eV across A as shown in Fig. 2(d), with an inner potential $V_0 = 10$ eV.

To confirm the physical origin of α and α', we conduct a comprehensive temperature-dependent experiment crossing the CDW phase transition temperature ($T_{\rm CDW}$). Interestingly, the α band shows different behaviors at different temperatures. In the following discussions, we identify three temperatures: low temperature which is far below $T_{\rm CDW}$ (LT), medium temperature which is slightly above $T_{\rm CDW}$ (MT) and high temperature which is far above $T_{\rm CDW}$ (HT). In Fig. 3(a), sample 2 (#2) is cleaved at LT around 12 K, clear α and α' bands can be resolved. When the temperature is increased to MT around 120 K, only one band referred to as β is resolved and it looks similar to the α band at LT. Then it is reasonable to consider that β at MT is actually α at LT, while α' is an additional band appeared in the CDW state which can be understood as a folded CDW band from the out-of-plane direction.[35] However, when we perform a temperature loop in Fig. 3(a) at 18 K, α' doesn't show up when #2 is further cooled down to LT. This temperature dependent behavior of α/α' at LT and β at MT can be better resolved from their EDCs in Fig. 3(b). One could notice that the band bottom of the α/β band is moving upward with time, which may be due to aging effect. Another sample (sample 3, #3) is cleaved at MT in Fig. 3(c). Surprisingly, only β band is resolved, consistent with the MT spectra of #2. However, when #3 is cooled down to LT, no additional α' band appears. A slightly aging effect is also observed in #3 when the temperature changing follows MT–LT–MT. Our observation strongly suggests that the change of the band around $\bar{\Gamma}$ is not intrinsic which excludes the previously proposed CDW folded-band mechanism.

Despite the fact that the $\bar{\Gamma}$ band is not sensitive to the CDW transition, it is very sensitive to temperature. We conduct another experiment on sample 4 (#4) in Fig. 3(e), which is cleaved at MT and further warmed up to around 257 K (HT). One can clearly see that the β band moves downward at HT, referred to as the γ band at HT. And when #4 is cooled down to MT again, the β band recovers to its original energy position, indicating its temperature sensitivity. Detailed temperature dependent data can be found in our supplementary materials.

To summarize our experimental observations, in most cases, the double V-shaped α/α' bands prefer to appear at LT, single V-shaped β band prefers to show up at MT and more electron-doped single V-shaped γ band prefers to appear at HT. However, it is not an intrinsic bulk effect since we observe β band at LT in both samples #2 and #3 in Figs. 3(a) and 3(c). Moreover, α/α' bands can also be detected on #4 at MT as shown in Fig. 3(g): #4 is cleaved at MT showing single β band but double α/α' bands are observed after a temperature cycle. All these observations indicate the fact that the behaviors of the band near $\bar{\Gamma}$ at different temperatures are probably not related to the CDW phase transitions.

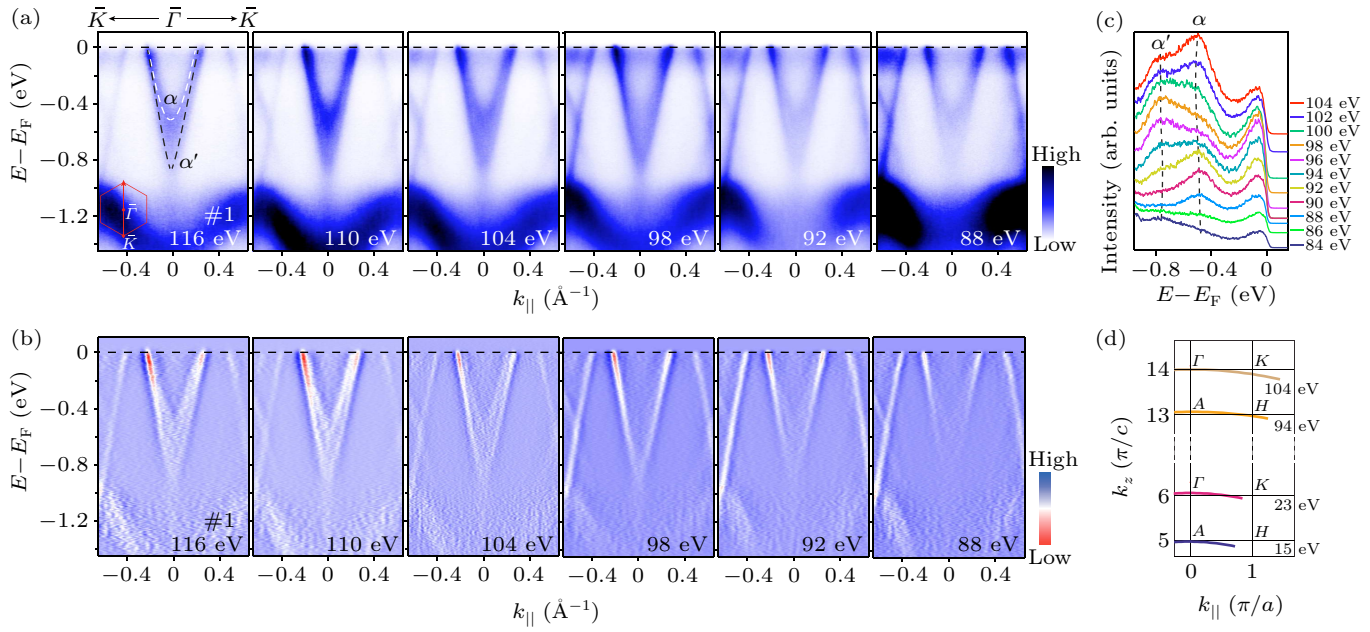


Fig. 2. (a) Photon-energy-dependent V-shaped energy bands around $\bar{\Gamma}$ of #1 taken at 13 K. The inset marks out the $\bar{K}$–$\bar{\Gamma}$–$\bar{K}$ cut. The white and black dashed lines describe the V-shaped energy bands at Γ and A respectively according to DFT calculation. (b) The corresponding second derivative spectra of panel (a). (c) Integral EDCs of (a) around $\bar{\Gamma}$. (d) Schematic diagram of BZ determination on the k_z–$k_{||}$ plane according to our data.

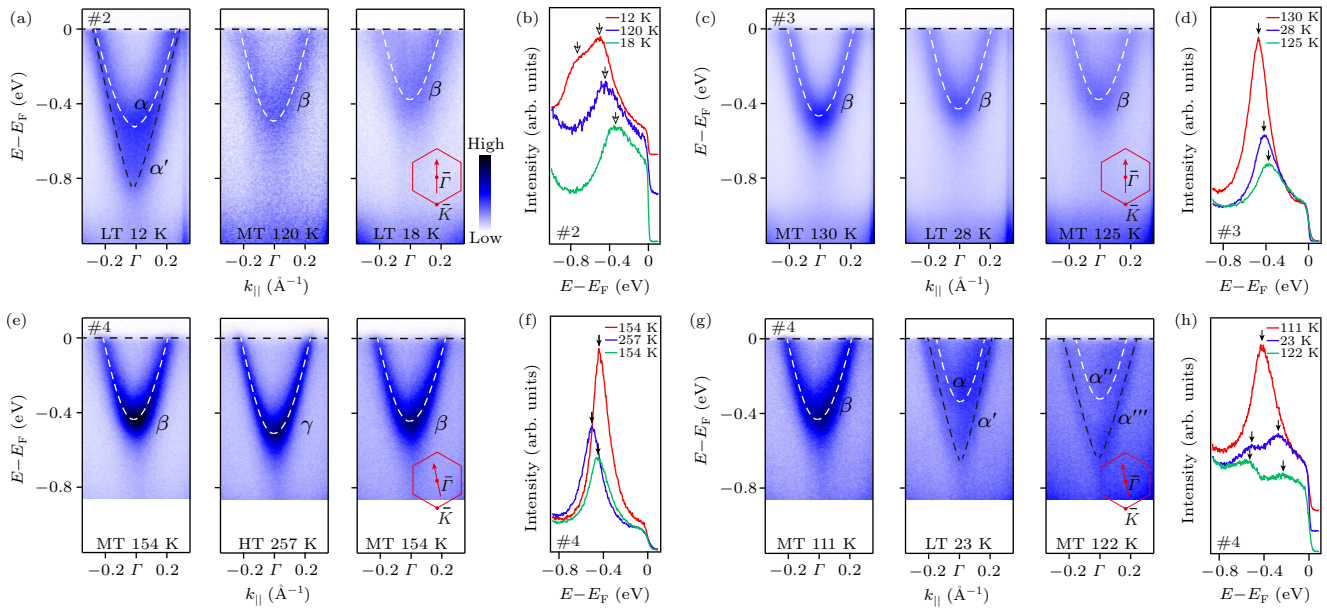


Fig. 3. (a) Temperature evolution of the V-shaped energy band around the high symmetry point Γ for #2. The white and black dashed lines describe the V-shaped energy bands at Γ and A respectively according to our DFT calculation. The inset marks out the cut around Γ. All data here are obtained with 23 eV photons. (b) Corresponding integral EDCs of (a) around Γ. (c)–(h) Similar data to (a), (b) but for other samples (#3 and #4).

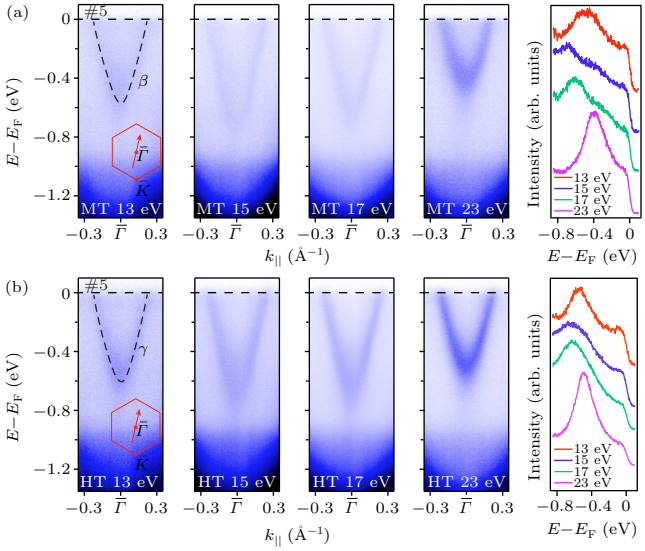


Fig. 4. (a) Photon-energy-dependent results of the V-shaped energy band around high symmetry point $\bar{\Gamma}$ for sample 5 (#5) at MT and corresponding integral EDCs around $\bar{\Gamma}$. The black dashed line here indicates V-shaped energy band. The inset marks out the cut around $\bar{\Gamma}$. (b) Similar data to (a) but for the same sample at HT.

In order to further figure out the physics behind the evolution of the double V-shaped α/α', single V-shaped β and single V-shaped γ bands, we perform k_z-dependent experiments at MT and HT as shown in Fig. 4 besides the k_z feature of the double V-shaped α/α' bands at LT discussed in Fig. 2. The β and γ bands show similar k_z-dependent behavior in Figs. 4(a) and 4(b), where 23 eV and 15 eV can be assigned as the Γ point and A point respectively as shown in Fig. 2(d). These results indicate that the β and γ bands are also of bulk origins. Thus, we believe that α/α', β and γ bands all originate from the bulk Sb-p_z orbitals, however, they are very sensitive to the surface conditions mainly modulated by temperature, resulting in different spectroscopic behaviors in our ARPES data.

The bands near $\bar{\Gamma}$ corresponding to different surface conditions are summarized in Fig. 5(a), including double V-shaped α/α' bands that possibly originate from k_z broadening, a single V-shaped bulk β band, and a more electron-doped V-shaped bulk γ band. The unique green shadow for LT bands illustrates the fact that α and α' bands can be detected simultaneously as well as the merged intensity between them. The exotic temperature-dependent behavior of the V-shaped bands strongly suggests that the surface condition changes with temperature. In most cases, the double V-shaped α/α' bands prefer to appear at LT, single V-shaped β band prefers to appear at MT and more electron-doped single V-shaped γ band prefers to appear at HT. However, it should be noted that these preferences are not absolute, as we also observe different scenarios at different temperatures.

A recent STM work[38] illustrates the desorption of surface alkali-metal atoms and corresponding surface reconstructions modulated by temperature in RbV_3Sb_5. The pristine surface exhibiting Rb-1×1 and Sb-1×1 structure, Rb-$\sqrt{3}\times1$ and Rb-$\sqrt{3}\times\sqrt{3}$ surface reconstructions are detected at the sample cleaved at 4 K, 77 K and room temperature, respectively. Furthermore, $\bar{\Gamma}$ bands are revealed to contain distinct energy positions of the V-shaped band bottom corresponding to different surface reconstructions according to their experimental and calculated results. Certain surface reconstruction is commonly obtained for the cleavage at the corresponding temperature range. This provides compelling evidence for the microscopic understanding of surface sensitive V-shape $\bar{\Gamma}$ bands. Moreover, micro-focused ARPES works[39,40] also claim the double V-shaped $\bar{\Gamma}$ bands are detected at Cs-termination-dominant surface, regardless of whether the temperature is above or be-

low T_{CDW}. Conversely, a consistent observation of a single V-shaped $\bar{\Gamma}$ band is made on Sb-termination-dominant surface. These results are consistent with our observations in Figs. 5(b) and 5(c).

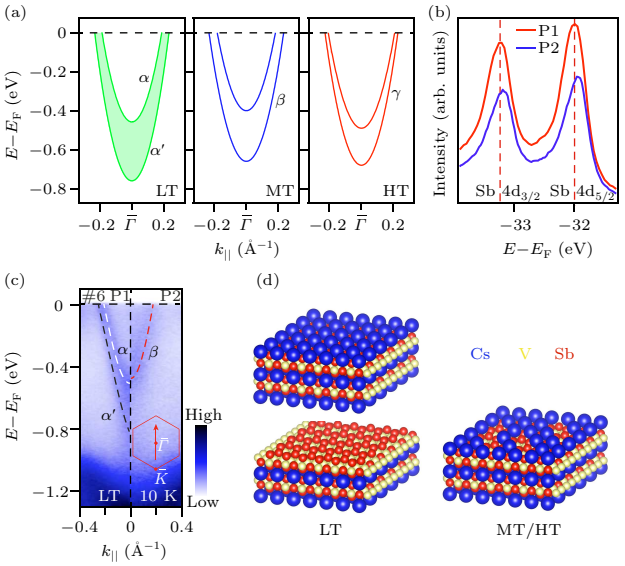


Fig. 5. (a) Fitted results of the V-shaped energy bands α, α', β and γ at different temperatures. The corresponding raw data are the spectra of #1 taken at LT using 110 eV photons (left panel), spectra of #3 taken at MT using 23 eV and 15 eV photons (middle panel), and spectra of #4 taken at HT using 23 eV and 15 eV photons (right panel). (b) EDCs in the Sb-4d core-level region, for the Cs (P1) and Sb (P2)-termination-dominant surfaces on sample 6 (#6). (c) Electronic structure of termination-dependent V-shaped energy bands measured at different surfaces on (#6). (d) Schematic diagram of the sample surface at different temperatures.

We can now present an ideal schematic diagram illustrating the surface conditions at different temperature ranges (LT, MT, and HT) based on our findings, as shown in Fig. 5(d). Although all the V-shaped $\bar{\Gamma}$ bands are of bulk origin, the increase of temperature leads to systematic disorder, desorption of Cs atom on the sample surface, different surface reconstructions and surface terminations as mentioned in previous work.[38] Consequently, the complete Cs or Sb surface becomes more challenging to detect using ARPES, resulting in the presence of surface-sensitive and intricate electronic structures around $\bar{\Gamma}$, as revealed by our data and previous studies. However, from our experimental results, it seems that these different surface conditions could affect the observation of the k_z broadening effect of the Sb-p_z orbital, which leaves an open question. Moreover, such surface-sensitive electronic structure is only observable on the Sb-p_z orbitals, and not evident on other bands, which is consistent with the orbital-selective doping picture of AV_3Sb_5 (A = K, Rb and Cs) proposed in previous literatures.[38,45]

4. Conclusion and perspectives

We systematically studied the electronic structure of a kagome superconductor CsV_3Sb_5 single crystal at different temperatures. We observed that the V-shaped energy band around $\bar{\Gamma}$ is sensitive to the sample surface mainly modulated by temperature. This finding effectively clarifies the previously confusing behavior of the electronic structure observed in ARPES experiments. Our results provide a solid foundation for future explorations of the novel properties exhibited by this material, thereby paving the way for further advancements in our understanding of CsV_3Sb_5.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant Nos. 12174362 and 92065202), the Innovation Program for Quantum Science and Technology (Grant No. 2021ZD0302803), and the New Cornerstone Science Foundation. Part of this research used Beamline 03U of the Shanghai Synchrotron Radiation Facility, which is supported by ME2 project under contract No. 11227902 from the National Natural Science Foundation of China.

References

[1] Han M Y, Inoue H, Fang S A, John C, Ye L D, Chan M K, Graf D, Suzuki T, Ghimire M P, Cho W J, Kaxiras E and Checkelsky J G 2021 *Nat. Commun.* **12** 5345

[2] Kang M G, Fang S A, Ye L D, Po H C, Denlinger J, Jozwiak C, Bostwick A, Rotenberg E, Kaxiras E, Checkelsky J G and Comin R 2020 *Nat. Commun.* **11** 4004

[3] Lin Z Y, Wang C Z, Wang P D, Yi S H, Li L, Zhang Q, Wang Y F, Wang Z Y, Huang H, Sun Y, Huang Y B, Shen D W, Feng D L, Sun Z, Cho J H, Zeng C G and Zhang Z Y 2020 *Phys. Rev. B* **102** 155103

[4] Kang M G, Ye L D, Fang S A, You J S, Levitan A, Han M Y, Facio J I, Jozwiak C, Bostwick A, Rotenberg E, Chan M K, McDonald R D, Graf D, Kaznatcheev K, Vescovo E, Bell D C, Kaxiras E, Brink J V D, Richter M, Ghimire M P, Checkelsky J G and Comin R 2020 *Nat. Mater.* **19** 163

[5] Ye L D, Kang M G, Liu J W, Cube F V, Wicker C R, Suzuki T, Jozwiak C, Bostwick A, Rotenberg E, Bell D C, Fu L, Comin R and Checkelsky J G 2018 *Nature* **555** 638

[6] Liu Z H, Li M, Wang Q, Wang G W, Wen C H P, Jiang K, Lu X L, Yan S C, Huang Y B, Shen D W, Yin J X, Wang Z Q, Yin Z P, Lei H C and Wang S C 2020 *Nat. Commun.* **11** 4002

[7] Liu E, Sun Y, Kumar N, Muechler L, Sun A, Jiao L, Yang S Y, Liu D F, Liang A J, Xu Q N, Kroder J, Süß V, Borrmann H, Shekhar C, Wang Z S, Xi C Y, Wang W H, Schnelle W, Wirth S, Chen Y L, Goennenwein S T B and Felser C 2018 *Nat. Phys.* **14** 1125

[8] Liu D F, Liang A J, Liu E K, Xu Q N, Li Y W, Chen C, Pei D, Shi W J, Mo S K, Dudin P, Kim T, Cacho C, Li G, Sun Y, Yang L X, Liu Z K, Parkin S S P, Felser C and Chen Y L 2019 *Science* **365** 1282

[9] Li M, Wang Q, Wang G W, Yuan Z H, Song W H, Luo R, Liu Z T, Huang Y B, Liu Z H, Lei H C, Yin Z P and Wang S C 2021 *Nat. Commun.* **12** 3129

[10] Wang Y, Liu Y X, Hao Z Y, Cheng W J, Deng J Z, Wang Y X, Gu Y H, Ma X M, Rong H T and Zhang F Y 2023 *Chin. Phys. Lett.* **40** 037102

[11] Yu F H, Wen X K, Gui Z G, Wu T, Wang Z Y, Xiang Z J, Ying J J and Chen X H 2022 *Chin. Phys. B* **31** 017405

[12] Gong C S, Tian S J, Tu Z J, Yin Q W, Fu Y, Luo R T and Lei H C 2022 *Chin. Phys. Lett.* **39** 087401

[13] Ortiz B R, Gomes L C, Morey J R, Winiarski M, Bordelon M, Mangum J S, Oswald I W H, Rodriguez-Rivera J A, Neilson J R and Wilson S D 2019 *Phys. Rev. Mater.* **3** 094407

[14] Ortiz B R, Teicher S M L, Hu Y, Zuo J L, Sarte P M, Schueller E C, Abeykoon A M M, Krogstad M J, Rosenkranz S, Osborn R, Seshadri R, Balents L, He J F and Wilson S D 2020 *Phys. Rev. Lett.* **125** 247002

[15] Xu H S, Yan Y J, Yin R T, Xia W, Fang S J, Chen Z Y, Li Y J, Yang W Q, Guo Y F and Feng D L 2021 *Phys. Rev. Lett.* **127** 187004

[16] Zhao H, Li H, Ortiz B R, Teicher S M L, Park T, Ye M X, Wang Z Q, Balents L, Wilson S D and Zeljkovic I 2021 *Nature* **599** 216

[17] Chen H, Yang H T, Hu B, Zhao Z, Yuan J, Xing Y Q, Qian G J, Huang Z H, Li G, Ye Y H, Ma S, Ni S L, Zhang H, Yin Q W, Gong C S, Tu Z J, Lei H C, Tan H X, Zhou S, Shen C M, Dong X L, Yan B H, Wang Z Q and Gao H J 2021 *Nature* **599** 222

[18] Shumiya N, Hossain M S, Yin J X, Jiang Y X, Ortiz B R, Liu H X, Shi Y G, Yin Q W, Lei H C, Zhang S T S, Chang G Q, Zhang Q, Cochran T A, Multer D, Litskevich M, Cheng Z J, Yang X P, Guguchia Z, Wilson S D and Hasan M Z 2021 *Phys. Rev. B* **104** 035131

[19] Jiang Y X, Yin J X, Denner M M, Shumiya N, Ortiz B R, Xu G, Guguchia Z, He J Y, Hossain M S, Liu X X, Ruff J, Kautzsch L, Zhang S, Chang G Q, Belopolski L, Zhang Q, Cochran T A, Multer D, Litskevich M, Cheng Z J, Yang X P, Wang Z Q, Thomale R, Neupert T, Wilson S D and Hasan M Z 2021 *Nat. Mater.* **20** 1353

[20] Feng X, Jiang K, Wang Z and Hu J 2021 *Sci. Bull.* **66** 1384

[21] Li H, Zhao K, Ortiz B R, Oey Y, Wang Z, Wilson S D and Zeljkovic I 2023 *Nat. Phys.* **19** 637

[22] Liang Z W, Huo X Y, Zhang F, Ma W R, Wu P, Zhang Z Y, Yu F H, Ying J J, Jiang K, Shan L, Wang Z Y and Chen X H 2021 *Phys. Rev. X* **11** 031026

[23] Wang Q, Kong P F, Shi W J, Pei C Y, Wen C H P, Gao L L, Zhao Y, Yin Q W, Wu Y S, Li G, Lei H C, Li J, Chen Y L, Yan S C and Qi Y P 2021 *Adv. Mater.* **33** 2102813

[24] Wang Z W, Jiang Y X, Yin J X, Li Y K, Wang G Y, Huang H L, Shan S, Liu J J, Zhu P, Shumiya N, Hossain M S, Liu H X, Shi Y G, Duan J X, Li X, Chang G Q, Dai P C, Ye Z J, Xu G, Wang Y C, Zheng H, Jia J F, Hasan M Z and Yao Y G 2021 *Phys. Rev. B* **104** 075148

[25] Li H Z, Wan S Y, Li H, Li Q, Gu Q Q, Yang H, Li Y K, Wang Z W, Yao Y G and Wen H H 2022 *Phys. Rev. B* **105** 045102

[26] Ortiz B R, Teicher S M L, Kautzsch L, Sarte P M, Ratcliff N, Harter J, Ruff J P C, Seshadri R and Wilson S D 2021 *Phys. Rev. X* **11** 041030

[27] Tan H X, Liu Y Z, Wang Z Q and Yan B H 2021 *Phys. Rev. Lett.* **127** 046401

[28] Hu Y, Wu X X, Ortiz B R, Han X L, Plumb N C, Wilson S D, Schnyder A P and Shi M 2022 *Phys. Rev. B* **106** L241106

[29] Nie L P, Sun K, Ma W R, Song D W, Zheng L X, Liang Z W, Wu P, Yu F H, Li J, Shan M, Zhao D, Li S J, Kang B L, Wu Z M, Zhou Y B, Liu K, Xiang Z J, Ying J J, Wang Z Y, Wu T and Chen X H 2022 *Nature* **604** 59

[30] Hu Y, Wu X X, Ortiz B R, Ju S L, Han X, Ma J Z, Plumb N C, Radovic M, Thomale P, Wilson S D, Schnyder A P and Shi M 2022 *Nat. Commun.* **13** 2220

[31] Liu Z H, Zhao N N, Yin Q W, Gong C S, Tu Z J, Li M, Song W H, Liu Z T, Shen D W, Huang Y B, Liu K, Lei H C and Wang S C 2021 *Phys. Rev. X* **11** 041010

[32] Cho S, Ma H Y, Xia W, Yang Y C, Liu Z T, Huang Z, Jiang Z C, Lu X L, Liu J S, Liu Z H, Li J, Wang J H, Liu Y, Jia J F, Guo Y F, Liu J P and Shen D W 2021 *Phys. Rev. Lett.* **127** 236401

[33] Hao Z Y, Cai Y Q, Liu Y X, Wang Y, Sui X L, Ma X M, Shen Z C, Jiang Z C, Yang Y C, Liu W L, Jiang Q, Liu Z T, Ye M, Shen D W, Liu Y, Cui S T, Chen J B, Wang L, Liu C, Lin J H, Wang J F, Huang B, Mei J W and Chen C Y 2022 *Phys. Rev. B* **106** L081101

[34] Jiang K, Wu T, Yin J X, Wang Z Y, Hasan M Z, Wilson S D, Chen X H and Hu J P 2023 *Nat. Sci. Rev.* **10** nwac199

[35] Luo Y, Peng S T, Teicher S M L, Huai L W, Hu Y, Han Y L, Ortiz B R, Liang Z W, Wei Z Y, Shen J C, Ou Z P, Wang B Q, Miao Y, Guo M Y, Hashimoto M, Lu D H, Qiao Z H, Wang Z Y, Wilson S D, Chen X H and He J F 2022 *Phys. Rev. B* **105** L241111

[36] Cai Y Q, Wang Y, Hao Z Y, Liu Y X, Sui X L, Liang Z W, Ma X M, Zhang F Y, Shen Z C, Zhang C C, Jiang Z C, Yang Y C, Liu W L, Jiang Q, Liu Z T, Ye M, Shen D W, Gao H, Xiao H B, Liu Z K, Sun Z, Liu Y, Cui S T, Chen J B, Wang L, Liu Cai, Lin J H, Huang B, Wang Z Y, Chen X H, Mei J W, Wang J F and Chen C Y 2024 *Communications Materials* **5** 31

[37] Li C, Wu X X, Liu H X, Polley C, Guo Q D, Wang Y, Han X, Dendzik M, Berntsen M H, Thiagarajan B, Shi Y G, Schnyder A P and Tjernberg O 2022 *Phys. Rev. Research* **4** 033072

[38] Yu J W, Xu Z, Xiao K B, Yuan Y H, Yin Q W, Hu Z Q, Gong C S, Guo Y K, Tu Z J, Tang P Z, Lei H C, Xue Q K and Li W 2022 *Nano Lett.* **22** 918

[39] Kato T, Li Y K, Nakayama K, Wang Z W, Souma S, Kitamura M, Horiba K, Kumigashira H, Takahashi T and Sato T 2022 *Phys. Rev. B* **106** L121112

[40] Kato T, Li Y K, Liu M, Nakayama K, Wang Z W, Souma S, Kitamura M, Horiba K, Kumigashira H, Takahashi T, Yao Y G and Sato T 2023 *Phys. Rev. B* **107** 245143

[41] Denner M M, Thomale R and Neupert T 2021 *Phys. Rev. Lett.* **127** 217601

[42] Fu Y, Zhao N N, Chen Z, Yin Q W, Tu Z J, Gong C S, Xi C Y, Zhu X D, Sun Y P, Liu K and Lei H C 2021 *Phys. Rev. Lett.* **127** 207002

[43] Liu Z H, Zhao N N, Yin Q W, Gong C S, Tu Z J, Li M, Song W H, Liu Z T, Shen D W, Huang Y B, Liu K, Lei H C and Wang S C 2021 *Phys. Rev. X* **11** 041010

[44] Wang Z G, Ma S, Zhang Y H, Yang H T, Zhao Z, Ou Y, Zhu Y, Ni S L, Lu Z Y W, Chen H, Jiang K, Yu L, Zhang Y, Dong X L, Hu J P, Gao H J and Zhao Z X 2021 arXiv:2104.05556 [cond-mat.supr-con]

[45] Nakayama K, Li Y K, Kato T, Liu M, Wang Z W, Takahashi T, Yao Y G and Sato T 2022 *Phys. Rev. X* **12** 011001