Discovery of Two Families of VSb-Based Compounds with V-Kagome Lattice

Yuxin Yang(杨雨欣)$^{1,2,}$†, Wenhui Fan(樊文辉)$^{1,2,}$†, Qinghua Zhang(张庆华)$^{*}$, Zhaoxu Chen(陈昭旭)$^{1,2}$, Xu Chen(陈旭)$^{1,2}$, Tianping Ying(应天平)$^{1,2}$, Xianxin Wu(吴贤新)$^{3,}$, Xiaofan Yang(杨小帆)$^{4}$, Fanqi Meng(孟繁琦)$^{5,}$, Gang Li(李岗)$^{1,6}$, Shiyuan Li(李世燕)$^{2}$, Lin Gu(谷林)$^{1,6}$, Tian Qiao(钱天)$^{1,6}$, Andreas P. Schnyder$^{3}$, Jian-gang Guo(郭建刚)$^{1,6,†}$, and Xiaolong Chen(陈小龙)$^{1,6,†}$

$^1$Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
$^2$School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
$^3$Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-70569 Stuttgart, Germany
$^4$State Key Laboratory of Surface Physics, Department of Physics, Fudan University, Shanghai 200438, China
$^5$School of Materials, Tsinghua University, Beijing 100084, China
$^6$Songshan Lake Materials Laboratory, Dongguan 523808, China

(Received 19 November 2021; accepted 22 November 2021; published online 27 November 2021)

We report the structure and physical properties of two newly discovered compounds $\text{AV}_8\text{Sb}_{12}$ and $\text{AV}_6\text{Sb}_6$ ($\text{A} = \text{Cs, Rb}$), which have $C_2$ (space group: $\emph{C}nnmm$) and $C_3$ (space group: $\emph{R}3m$) symmetry, respectively. The basic V-kagome unit appears in both compounds, but stacking differently. A $V_2\text{Sb}_2$ layer is sandwiched between two $V_3\text{Sb}_3$ layers in $\text{AV}_8\text{Sb}_{12}$, altering the V-kagome lattice and lowering the symmetry of kagome layer from hexagonal to orthorhombic. In $\text{AV}_6\text{Sb}_6$, the building block is a more complex slab made up of two half-$V_3\text{Sb}_3$ layers that are intercalated by $\text{Cs}$ cations along the c-axis. Transport property measurements demonstrate that both compounds are nonmagnetic metals, with carrier concentrations at around $10^{12}$ cm$^{-3}$. No superconductivity has been observed in $\text{CsV}_8\text{Sb}_{12}$ above 0.3 K under in situ pressure up to 46 GPa. Compared to $\text{CsV}_8\text{Sb}_{12}$, theoretical calculations and angle-resolved photoemission spectroscopy reveal a quasi-two-dimensional electronic structure in $\text{CsV}_6\text{Sb}_6$ with $C_2$ symmetry and no van Hove singularities near the Fermi level. Our findings will stimulate more research into V-based kagome quantum materials.

DOI: 10.1088/0256-307X/38/12/127102

The kagome net, a corner-sharing tiling pattern of triangular plaquettes, is a standard model for understanding nontrivial topology, frustrated magnetism, and correlated phenomena. The frustrated lattice geometry endows a wealth of unique physical features to the lately intensely researched kagome metals, including flat bands, van Hove singularity, and topological band crossover. Pure kagome layers, on the other hand, cannot stand alone and are usually intergrown with other building blocks. The stacking-induced interaction and charge donation bring rich varieties to the band structures inherited from the kagome lattice. Prominent examples are noncollinear antiferromagnetism in $\text{Mn}_3\text{Sn}_{10}$,[1] Dirac fermionic in ferromagnetism in $\text{Fe}_3\text{Sb}_2$,[2] Chern-gapped Dirac fermion in ferromagnetic $\text{TbMn}_{2}\text{Sb}_6$,[3] and Weyl fermions in the ferromagnet $\text{CO}_3\text{Sb}_2\text{S}_2$.[4]

The seminal discovery of $\text{AV}_3\text{Sb}_3$[5,6] has inspired a new surge of interest. As seen in Fig. 1, the vanadium sublattice forms a perfect kagome net that is interwoven with Sb atoms both within and outside of the plane to build a $V_3\text{Sb}_3$ monolayer. Despite the lack of magnetization, $\text{AV}_3\text{Sb}_5$ is discovered to be $\mathbb{Z}_2$ topological materials with alternative ground states such as the charge density wave (CDW) ordering and superconductivity.[7,8] This CDW ordering is later proved not driven by strong electron-phonon coupling[9−16] and competes with superconductivity.[17] Subsequent studies further discovered exciting discoveries including the reentrance of superconductivity under high pressure,[18−22] the enormous anomalous Hall effect,[23,24] pair density wave,[13] and evidence of plausible unconventional superconductivity.[13,25] Changing the stacking sequence of the kagome layer with different building components and seeing the consequences on physical characteristics is both exciting and practically doable, given the very weak interlayer interactions. However, only partial removal of A element has been realized through selective oxidation of thin flakes, resulting in a shift of van Hove singularity,[26,27] enhanced $T_c$,[17,28−31] and A-vacancy ordering.[32] The construction of novel vanadium-based kagome structures by altering the stacking sequence has not been realized so far.

In this Letter, we investigate the possibility of
constructing novel A–V–Sb compounds by rearranging the constituent layers. As a result, the AV₈Sb₁₂ and AV₆Sb₆ (A = Rb, Cs) families of compounds are found. The initial Cs₀ symmetry is decreased to C₂ᵥ and C₃ᵥ in AV₈Sb₁₂ and AV₆Sb₆, respectively, by inserting alternative building blocks or changing the stacking sequences. Their band structures and electric conductivity are substantially altered when the symmetry is broken. Theoretical calculations and angle-resolved photoemission spectroscopy (ARPES) measurements reveal previously unseen features compared to those of AV₃Sb₅.

**Experimental—Single Crystal Growth.** Single crystals of AV₈Sb₁₂ and AV₆Sb₆ (A = Cs, Rb) were grown via the self-flux method. AV₈Sb₁₂ (AV₆Sb₆) single crystals were grown by mixing Cs (99.99%) and Sb (powder, 99.999%) with the molar ratio of 1.2:6:15 (1.2:6:18), loaded into an alumina container and then sealed into a silica tube in vacuum. The mixture was subsequently heated to 1373 K and kept for 24 h, then cooled to 1173 K (1273 K) in 72 h. The excess flux was removed by centrifuging at corresponding temperature.

**Characterization.** The diffraction was performed on a Panalytical X’pert diffractometer with a Cu Kα anode (1.5481 Å). The composition and structure of the sample were determined by the combination of an energy dispersive spectroscopy and a scanning transmission electron microscope (STEM). The atomic arrangement of the two phases was observed by a spherical aberration-corrected ARM200F (JEOL, Tokyo, Japan) STEM operated at 200 kV with a convergence angle of 25 mrad and collected angle from 70 to 250 mrad. The high angle annular dark field STEM (HAADF-STEM) image was collected with a dwell time of 10 µs per pixel. The transport measurement under ambient and high pressure was performed on a Quantum Design physical property measurement system (PPMS). A Keithley 2182A, a Keithley 2400 were used to measure the transport properties under external magnetic fields. Magnetization measurements were performed using a Quantum Design magnetic properties measurement system (MPMS3). The high-pressure resistivity of CsV₄Sb₁₂ samples was measured by a diamond anvil cell (DAC) range from 2 K to 400 K with the van der Pauw method. The resistance experiments were performed using Be–Cu cells. The cubic boron nitride (cBN) powders (200 and 300 nm in diameter) were employed as the medium to transfer pressure. The pressure was calibrated using the ruby fluorescence method at room temperature before and after the measurement.

**Angle-Resolved Photoemission Spectroscopy.** All the ARPES data shown are recorded at the “Dreamline” beamline of the Shanghai Synchrotron Radiation Facility. The energy and angular resolutions are set to 15 to 25 meV and 0.2°, respectively. All the samples for ARPES measurements are mounted in a BIP argon (>99.9999%) filled glove box, cleaved in situ, and measured at 25 K in a vacuum better than 5 × 10⁻¹¹ torr.

### Fig. 1. Crystal structure of AV₃Sb₅, AV₈Sb₁₂, and AV₆Sb₆ (A = K, Rb, Cs). Blue, violet and green balls are A, V, and Sb atoms, respectively.

**Theoretical Calculation.** Our DFT calculations employ the projector augmented wave method [33] encoded in the Vienna ab initio simulation package (VASP) [34] and both the local density approximation and generalized-gradient approximation for the exchange-correlation functional are used. Throughout this work, the cutoff energy of 500 eV is taken for expanding the wave functions into a plane-wave basis. In the calculation, the Brillouin zone is sampled in the k space within the Monkhorst–Pack scheme. The number of these k points is 9 × 9 × 5 for the primitive cell. We relax the lattice constants and internal atomic positions, where the plane wave cutoff energy is 600 eV. Forces are minimized to less than 0.01 eV Å⁻¹ in the relaxation. The obtained lattice constants of CsV₄Sb₁₂ are a = 5.455 Å, b = 9.515 Å and c = 18.25 Å, which are in good agreement with the experimental values of a = 5.451 Å, b = 5.451 Å, and c = 18.128 Å.

**Results and Discussions.** The crystal structures of AV₈Sb₁₂ and AV₆Sb₆ are obtained by combining an x-ray diffractometer and an STEM, as shown in Fig. 1, together with the structure of AV₃Sb₅ for comparison. The three A–V–Sb compounds all have a V-based kagome lattice with a centered Sb atom as a common building block. Each V-based kagome layer is sandwiched by two sets of Sb honeycomb lattices in the AV₃Sb₅, which has a space group of P6/mmm with Cs₀ symmetry. The crystal structure is rather simple, with the lattice constants of a = 5.4922 Å.
and \( c = 9.8887 \text{ Å} \). \( \text{AV}_8\text{Sb}_{12} \) and \( \text{AV}_6\text{Sb}_6 \), on the other hand, reveal richer crystal structures due to the intercalation of low symmetric structural units. In \( \text{AV}_8\text{Sb}_{12} \), an orthorhombic \( \text{V}_3\text{Sb}_2 \) layer is sandwiched between two \( \text{V}_3\text{Sb}_5 \) units, forming a \( \text{V}_8\text{V}_{12} \) unit. The space group is \( \text{Cmmm} \) with lattice constants of \( a = 5.4510 \text{ Å} \), \( b = 9.5164 \text{ Å} \), and \( c = 18.1282 \text{ Å} \). The \( a \)-axis is approximately \( \sqrt{3} \) times that of \( \text{AV}_3\text{Sb}_5 \). As for \( \text{AV}_6\text{Sb}_6 \), the basic unit can be viewed as a two-\( \text{V}_3\text{Sb}_5 \)-connected slab by deleting the middle two Sb layers. Each half-\( \text{V}_3\text{Sb}_5 \) unit is displaced by \( (1/2, 1/2, 0) \), and the Cs atoms run down the \( c \)-axis to separate the slabs. The space group is \( \text{R}\overline{3}m \) with \( a = 5.3172 \text{ Å} \) and \( c = 34.0741 \text{ Å} \), in which the \( c \)-axis is almost 3 times that of \( \text{AV}_3\text{Sb}_5 \). \( \text{AV}_8\text{Sb}_{12} \) and \( \text{AV}_6\text{Sb}_6 \) can be viewed as derivative phases of the \( \text{AV}_3\text{Sb}_5 \) phase. Since the V-based kagome lattice is mostly intact, exotic properties like superconductivity and charge order are highly expected.

We have grown the single crystals of three \( \text{A–V–Sb} \) compounds [insets of Fig. 2(a)]. All the three samples have a layered structure with metallic luster and a shining surface. From the XRD patterns, we can index the lattice constant \( c \) based on the 001 peak. The calculated \( c \) values in the three compounds agree well with the proposed lattice constants after structural relaxation. We further perform atomic resolved STEM imaging and EELS spectra mapping along the two main zone axes: [100] and [110]. The atomic arrangements in each layer can be identified clearly, as shown in Figs. 3(a) and 3(b). The elemental mapping along the [100] projected also verified this double kagome lattice at an atomic scale. The false-color image of
elemental mapping of AV$_8$Sb$_{12}$ (AV$_6$Sb$_6$) is shown in Figs. 3(c) and 3(f), from which we can see the atomic arrangements match with the proposed crystal structure shown in Fig. 1.

We use CsV$_8$Sb$_{12}$ and RbV$_6$Sb$_6$ to represent the general behavior of the two newly discovered families. Both the samples exhibit metallic behavior from 300 to 2 K without any anomalies observed [Fig. 4(a)]. We have also measured CsV$_8$Sb$_{12}$ and CsV$_6$Sb$_6$ down to 0.3 K and 100 mK, respectively. No superconductivity can be observed. The residual-resistance ratios (RRR) are generally low, with the highest value of 2.8 for CsV$_8$Sb$_{12}$. Figure 4(b) shows the magnetization of CsV$_8$Sb$_{12}$ and RbV$_6$Sb$_6$. Both the samples exhibit Pauli magnetism down to 100 K. The upturn at low temperatures may originate from magnetic impurities. Both in and perpendicular to the ab plane, the overall magnetic susceptibility of CsV$_8$Sb$_{12}$ is nearly four times higher than that of RbV$_6$Sb$_6$.

![Graph showing temperature-dependent resistance and magnetization](image)

Fig. 4. Electrical transport and magnetization of CsV$_8$Sb$_{12}$ and RbV$_6$Sb$_6$. [(a), (b)] Temperature-dependent resistivity and magnetization of CsV$_8$Sb$_{12}$ and RbV$_6$Sb$_6$ within the ab plane and along the c-axis. (c) Temperature-dependent resistance of CsV$_8$Sb$_{12}$ under different external pressure. The measured temperature ranges from 2–400 K. We superimpose the resistivity curve at ambient pressure as the dotted line. Inset: the high-pressure measurements down to 0.3 K. (d) Carrier concentration of CsV$_8$Sb$_{12}$ against temperature.

![X-ray photoelectron spectroscopy (XPS) of V 2p and Sb 3d](image)

Fig. 5. X-ray photoelectron spectroscopy (XPS) of (a) V 2p and (b) Sb 3d for CsV$_8$Sb$_{12}$, CsV$_6$Sb$_6$, and CsV$_8$Sb$_{12}$.

The recently discovered reentrance of superconductivity in CsV$_8$Sb$_{12}$ provokes us to further investigate the influence of external pressure on the electric transport properties in AV$_8$Sb$_{12}$ and AV$_6$Sb$_6$. As shown in Fig. 4(c), the resistance initially decreases from 2.4 to 10.8 GPa. With further increasing the applied pressure, the resistance gradually increases to a high value. We note that the shape of the RT curve at 2.4 GPa resembles that of resistivity measured at ambient pressure. A prominent feature is the RT curves changing from a convex to concave over 10.8 GPa, indicating a dramatic change of the electrical properties. However, our high-pressure and low-temperature measurements do not show any sign of superconductivity down to 0.3 K [inset in Fig. 4(c)]. Despite the relatively low RRR value found in CsV$_8$Sb$_{12}$, the extracted carrier concentration is comparable to that of CsV$_6$Sb$_6$. The Hall coefficient is strongly temperature-dependent, indicating that CsV$_8$Sb$_{12}$ should be a multi-band system with both hole and electron pockets. Thus, the absence of superconductivity may be closely related to the insertion of the C$_2$-V$_2$Sb$_2$ layer, which may distort the kagome lattice and alter the pairing mechanism.

The variation of stacking sequence should be directly reflected in the valence state of the investigated elements. To substantiate the influence of the acquired double-layered kagome compounds, we measured the XPS of CsV$_8$Sb$_{12}$, CsV$_6$Sb$_6$, and CsV$_8$Sb$_{12}$, as shown in Fig. 5. The peak positions of Cs are identical for all the three compounds at 723.8 eV, indi-
cating the complete loss of out shell electrons in all the compounds. An interesting discovery is the opposite evolution of V and Sb valence states in CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$. In CsV$_6$Sb$_6$, the valence state of V 2p shifts to lower binding energy, and the peak of Sb 3d remains unchanged. Meanwhile, the valence state of V remains intact in CsV$_8$Sb$_{12}$, which is accompanied by the noticeable peak shift of the Sb 3d towards higher binding energy. This dramatic difference lies in the fundamental structural difference in their crystal structures. From Fig. 1, the V$_3$Sb$_5$ kagome layer is identical in both CsV$_3$Sb$_5$ and CsV$_4$Sb$_{12}$, while the building block in CsV$_6$Sb$_6$ evolves into V$_3$Sb$_3$ with the loss of two Sb atoms on one side. This modification of the kagome layer directly alters the valence state of the V. On the contrary, the inserted building block of V$_2$Sb$_2$ in CsV$_8$Sb$_{12}$ connects with the inside V indirectly. Valence modulation of vanadium in the A–V–Sb system through the judicious design of the stacking sequence is realized.

![Fig. 6](https://example.com/fig6.png)

**Fig. 6.** [(a), (c)] ARPES intensity plots at Fermi surface and constant energy contours at $E_F$ and $E_F - 0.2\, eV$ recorded on the (001) surface with $h\nu = 84\, eV$. [(b), (d)] DFT calculation at $E_F$ and $E_F - 0.2\, eV$. [(e), (f)] ARPES intensity plots showing band dispersions along $\bar{\Gamma} - \bar{X}$, $\bar{\Gamma} - \bar{Y}$, $\bar{\Gamma} - \bar{Z}$. [(g), (h)] Calculated band structure along the $\bar{\Gamma} - \bar{X}$, $\bar{\Gamma} - \bar{Y}$. [(i)] Three-dimensional bulk Brillouin zone of CsV$_8$Sb$_{12}$.

To determine the band structure of CsV$_8$Sb$_{12}$, we have carried out systematical ARPES measurements on the (001) cleavage surface of CsV$_8$Sb$_{12}$ single crystall. We summarized constant energy contours and band dispersion in Fig. 6. In-plane Fermi surface (FS) measured with $h\nu = 84\, eV$ in Fig. 6(a) clearly shows the $C_2$ symmetry feature verified in the calculated FS [Fig. 6(b)], and this testifies that the inserted V$_2$Sb$_2$ layer has strong modulation on the overall band structure. Constant energy contour [Fig. 6(c)] at 0.2 eV below the Fermi level has a good agreement with DFT calculation in Fig. 6(d). We also measured the band dispersion along $\bar{\Gamma} - \bar{X}$ and $\bar{\Gamma} - \bar{Y}$, as shown in Figs. 6(e) and 6(f), respectively, whose momentum locations are indicated in Fig. 6(a). These results match with our DFT calculations [Figs. 6(g) and 6(h)]. The absence of the electron bands near the $\bar{\Gamma}$ point may be caused by the matrix element effect or possible hole-doping of surface Cs loss.

Due to the V$_2$Sb$_2$ layer between kagome layers, the point group of CsV$_8$Sb$_{12}$ is $D_{2h}$, where only a two-fold rotational symmetry persists, in contrast to CsV$_3$Sb$_5$. Near the Fermi level, the states are dominantly attributed to V 3d orbitals, from both the kagome V layer and the intercalated V$_2$Sb$_2$ layer. The electron-like band around $\bar{\Gamma}$ point is attributed to $p_z$ orbitals of Sb atoms in the kagome layer, similar to CsV$_3$Sb$_5$. The two hole bands around $\bar{\Gamma}$ point are mainly contributed by the V 3d orbitals in the V$_2$Sb$_2$ layer. The band at $-0.9\, eV$ around $\bar{\Gamma}$ point is mainly attributed to V $d$ orbitals from both kagome and intercalated layers.

In summary, we have discovered two new families of VSB-based layered compounds, which possess a basic V-kagome lattice similar to that of AV$_3$Sb$_5$. The intercalation of the V$_2$Sb$_2$ layer and reorganization of the half-V$_3$Sb$_5$ layer lead to a lower symmetry of $C_2$ ($Cmma$) and $C_3$ ($R3\bar{m}$) compared to $C_6$.
on CsV$_6$Sb$_6$ [arXiv:2110.09782] and CsV$_8$Sb$_{12}$ [arXiv:2110.11452].

References

[1] Nakatsuji S, Kiyohara N and Higo T 2015 *Nature* **527** 212
[2] Lin Z, Choi J H, Zhang Q, Qin W, Yi S, Wang P, Li L, Wang Y, Zhang H, Sun Z, Wei L, Zhang S, Guo T, Lu Q, Zhao J H, Zeng C and Zhang Z 2018 *Phys. Rev. Lett.* **121** 096401
[3] Yin J, Ma W, Cochran T A, Xu X, Zhang S S, Tien H, Shumiya N, Cheng G, Li D, Liu S, Zhang H, Chen H, Jin K, Cheng J, Hu B, Zhao Z, Yuan J, Xing Y, Qian G, Chen H, Yang H, Hu B, Zhao Z, Yuan J, Xing Y, Qian G, Huang Z, Li G, Ye Y, Ma S, Ni S, Zhang H, Yin Q, Gong C, Tu Z, Lei H, Tan H, Zhou S, Chen C, Dong X, Yan B, Wang Z and Gao H J 2021 *Nature* **599** 222
[4] Zhao H, Li H, Ortiz B R, Teicher S M L, Park T, Ye M, Wang Z, Balents L, Wilson S D and Zeldov I 2021 *Nature* **599** 216
[5] Uykur E, Ortiz B R, Wilson S D, Dressel M and Tsirlin A A 2021 arXiv:2103.07912 [cond-mat.str-el]
[6] Denner M M, Thomale R and Neupert T 2021 arXiv:2103.14045 [cond-mat.str-el]
[7] Song Y, Ying T, Chen X, Han X, Huang Y, Wu X, Schnyder A P, Guo J G and Chen X 2021 arXiv:2105.09898 [cond-mat.supr-con]
[8] Chen X, Zhan X, Wang X, Deng J, Liu X B, Chen X, Guo J G and Chen X 2021 *Chin. Phys. Lett.* **38** 057402
[9] Yu F, Luo S, Ortiz B R, Chen Y, Duan W, Zhang D, Lu X, Wilson S D, Song Y and Yuan H 2021 *Phys. Rev. B* **103** L220504
[10] Yu F H, Ma D H, Zhuo W Z, Liu S Q, Wen X K, Lei B, Yang J J and Chen X H 2021 *Nat. Commun.* **12** 3645
[11] 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, Wilson S D, Ertekin E, McQueen T M and Toberer E S 2019 *Phys. Rev. Mater.* **3** 094407
[12] Ortiz B R, Teicher S M L, Hu Y, Zuo J L, Sarte P M, Schueller E C, Abeykoon A M M, Krosgstad M J, Rosenkranz S, Osborn R, Seshadri R, Balents L, He J and Wilson S D 2020 *Phys. Rev. Lett.* **125** 247002
[13] Ni S, Ma S, Zhang Z, Yuan J, Yang H, Lu Z, Wang N, Sun J, Zhao Z, Li D, Liu S, Zhang H, Chen H, Jin K, Cheng J, Yu L, Zhou F, Dong X, Hu J, Gao H J and Zhao Z 2021 *Chin. Phys. Lett.* **38** 075403
[14] Yin Q, Tu Z, Gong C, Fu Y, Yan S and Lei H 2021 *Chin. Phys. Lett.* **38** 037403
[15] Jiang Y X, Yin J X, Denner M M, Shumiya N, Ortiz B R, Xu G, Guguchia Z, He J, Hossain M S, Liu X, Ruff J, Kautzsch L, Zhang S S, Chang G, Belopolski I, Zhang Q, Cochran T A, Multer D, Litskevich M, Cheng J Z, Yang X P, Wang Z, Thomale R, Neupert T, Wilson S D and Hasan M Z 2002 *Nat. Mater.* **1** 1125
[16] Li H, Zhang T T, Yilmaz T, Pai Y Y, Marvinney C E, Said A, Yin Q W, Gong C S, Tu Z J, Vescovo E, Nelson C S, Moore R G, Murakami S, Lei H C, Lee H N, Lawrie B J and Miao H 2021 *Phys. Rev. X* **11** 031050
[17] Liang Z, Hou X, Zhang F, Ma W, Wu P, Zhang Z, Yu F, Ying J J, Jiang K, Shao L, Wang Z and Chen X H 2021 *Phys. Rev. X* **11** 031026
[18] Tan H, Liu Y, Wang Z and Yan B 2021 *Phys. Rev. Lett.* **127** 046401
[19] Chen H, Yang H, Hu B, Zhao Z, Yuan J, Xing Y, Qian G, Huang Z, Li G, Ye Y, Ma S, Ni S, Zhang H, Yin Q, Gong C, Tu Z, Lei H, Tan H, Zhou S, Shen C, Dong X, Yan B, Wang Z and Gao H J 2021 *Nature* **599** 222
[20] Ortiz B R, Wilson S D, Dressel M and Tsirlin A A 2021 arXiv:2103.07912 [cond-mat.str-el]
[21] Denner M M, Thomale R and Neupert T 2021 arXiv:2103.14045 [cond-mat.str-el]
[22] Song Y, Ying T, Chen X, Han X, Huang Y, Wu X, Schnyder A P, Guo J G and Chen X 2021 arXiv:2105.09898 [cond-mat.supr-con]
[23] Chen X, Zhan X, Wang X, Deng J, Liu X B, Chen X, Guo J G and Chen X 2021 *Chin. Phys. Lett.* **38** 057402
[24] Yu F, Luo S, Ortiz B R, Chen Y, Duan W, Zhang D, Lu X, Wilson S D, Song Y and Yuan H 2021 *Phys. Rev. B* **103** L220504
[25] Yu F H, Ma D H, Zhuo W Z, Liu S Q, Wen X K, Lei B, Yang J J and Chen X H 2021 *Nat. Commun.* **12** 3645
[26] Ortiz B R, Teicher S M L, Hu Y, Zuo J L, Sarte P M, Schueller E C, Abeykoon A M M, Krosgstad M J, Rosenkranz S, Osborn R, Seshadri R, Balents L, He J and Wilson S D 2020 *Phys. Rev. Lett.* **125** 247002
[27] Ni S, Ma S, Zhang Z, Yuan J, Yang H, Lu Z, Wang N, Sun J, Zhao Z, Li D, Liu S, Zhang H, Chen H, Jin K, Cheng J, Yu L, Zhou F, Dong X, Hu J, Gao H J and Zhao Z 2021 *Chin. Phys. Lett.* **38** 075403
[28] Yin Q, Tu Z, Gong C, Fu Y, Yan S and Lei H 2021 *Chin. Phys. Lett.* **38** 037403
[29] Jiang Y X, Yin J X, Denner M M, Shumiya N, Ortiz B R, Xu G, Guguchia Z, He J, Hossain M S, Liu X, Ruff J, Kautzsch L, Zhang S S, Chang G, Belopolski I, Zhang Q, Cochran T A, Multer D, Litskevich M, Cheng J Z, Yang X P, Wang Z, Thomale R, Neupert T, Wilson S D and Hasan M Z 2002 *Nat. Mater.* **1** 1125
[30] Li H, Zhang T T, Yilmaz T, Pai Y Y, Marvinney C E, Said A, Yin Q W, Gong C S, Tu Z J, Vescovo E, Nelson C S, Moore R G, Murakami S, Lei H C, Lee H N, Lawrie B J and Miao H 2021 *Phys. Rev. X* **11** 031050
[31] Liang Z, Hou X, Zhang F, Ma W, Wu P, Zhang Z, Yu F, Ying J J, Jiang K, Shao L, Wang Z and Chen X H 2021 *Phys. Rev. X* **11** 031026
[32] Tan H, Liu Y, Wang Z and Yan B 2021 *Phys. Rev. Lett.* **127** 046401