Multiple topological nodal structure in LaSb$_2$ with large linear magnetoresistance

Y. X. Qiao,$^{1,2,*}$ Z. C. Tao,$^3$ F. Y. Wang,$^{4,5,*}$ Huaiqiang Wang,$^{4,5,*}$ Z. C. Jiang,$^1$ Z. T. Liu,$^{1,2}$ Soohyun Cho,$^1$ F. Y. Zhang,$^{1,6}$ Q. K. Meng,$^7$ W. Xia,$^{3,8}$ Y. C. Yang,$^1$ Z. Huang,$^{1,3}$ J. S. Liu,$^{1,2}$ Z. H. Liu,$^{1,2}$ Z. W. Zhu,$^7$ S. Qiao,$^{1,2,3}$ Y. F. Guo,$^{3,8,†}$ Haijun Zhang,$^{4,5,§}$ and Dawei Shen$^{1,2,¶}$

$^1$State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China
$^2$Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, China
$^3$School of Physical Science and Technology, ShanghaiTech University, Shanghai 201210, China
$^4$National Laboratory of Solid State Microstructures, School of Physics, Nanjing University, Nanjing 210093, China
$^5$Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, China
$^6$Shenzhen Institute for Quantum Science and Technology and Department of Physics, Southern University of Science and Technology, Shenzhen 518055, China
$^7$Wuhan National High Magnetic Field Center and School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China
$^8$ShanghaiTech Laboratory for Topological Physics, ShanghaiTech University, Shanghai 201210, China

(Dated: August 23, 2022)

Unconventional fermions in the immensely studied topological semimetals are the source for rich exotic topological properties. Here, using symmetry analysis and first-principles calculations, we propose the coexistence of multiple topological nodal structure in LaSb$_2$, including topological nodal surfaces, nodal lines and in particular eightfold degenerate nodal points, which have been scarcely observed in a single material. Further, utilizing high resolution angle-resolved photoemission spectroscopy in combination with Shubnikov-de Haas quantum oscillations measurements, we confirm the existence of nodal surfaces and eightfold degenerate nodal points in LaSb$_2$, and extract the π Berry phase proving the non-trivial electronic band structure topology therein. The intriguing multiple topological nodal structure might play a crucial role in giving rise to the large linear magnetoresistivity. Our work renews the insights into the exotic topological phenomena in LaSb$_2$ and its analogous.

Since the proposal of Weyl semimetal in 2011 [1], various kinds of topological semimetals (TSMs) characterized by gapless band touching nodes have been discovered and continuously attracted extensive research interest [2–6]. Generally speaking, three types of nodes can occur in TSMs, namely, nodal points [7], nodal lines [8–15], and nodal surfaces [16–18]. These nodal states in TSMs manifest themselves not only in exotic surface states, such as Fermi-arc [19, 20] and drumhead surface states [17, 21, 22], but also in unique transport behaviors, e.g., the chiral negative magnetoresistance (MR) [23–25], and the chiral magnetic effect [26, 27]. Intriguingly, it has been shown that nonsymmorphic symmetries can give rise to many fancy degeneracies in band structures, say, unconventional quasiparticles with higher-order degeneracies beyond Dirac and Weyl fermions [28–34]. To date, both three- and six-fold degenerate points (DPs) have been confirmed experimentally [20, 35–37]. Whereas, unambiguous experimental observations of eightfold DPs is still rare [38, 39], partly because of the lack of realistic materials hosting eightfold DPs near the Fermi level.

Recently, rare earth diantimonide LaSb$_2$ has aroused great interest, since it exhibits charge density wave [40, 41], superconductivity [42, 43] and anomalous transport properties [44–46]. More importantly, owning to its large linear magnetoresistance (LMR) (~10000%), it has been viewed as a compelling candidate for high-field sensors [45]. However, so far the origin of the LMR in LaSb$_2$ still remains unknown, even though there have been some explanations based on classical [47–50] and quantum effects [51], respectively. As a nonsymmorphic crystal, LaSb$_2$ holds promises for harboring topological nodal states [52], which has been previously largely overlooked. Further, considering the intimate relationship between gapless Dirac-like nodal states and LMR [53], more in-depth theoretical and experimental studies on LaSb$_2$ are thus highly desired.

In this Letter, with a combination of symmetry analysis and first-principles calculation, we propose a plethora of topological nodal structures in LaSb$_2$, covering all three types of nodes. Notably, we uncover symmetry-protected eightfold DPs on the nodal surface near the Fermi level. Using high-resolution angle-resolved photoemission spectroscopy (ARPES), we unambiguously confirm the predicted nodal surface and most importantly, the eightfold DPs. Our further transport measurements reveal the imperfect carriers compensation in LaSb$_2$ [46, 51], and a nontrivial π Berry phase from
the quantum oscillation analysis. Our findings suggest that the LMR observed in LaSb$_2$ should be attributed to Dirac nodal states rather than the electron-hole compensation mechanism. In addition, given that LaSb$_2$ shows a unique superconducting transition ($T_c = 1.2$ K) among all rare earth diantimonides, it might provide an ideal platform to explore the interplay between symmetry, non-trivial band topology and superconductivity in systems with multiple topological nodal states.

LaSb$_2$ belongs to the RSb$_2$ (R = La-Nd, and Sm) family which crystallize in the orthorhombic, highly layered SmSb$_2$-like structure. Here, alternating La/Sb layers and two-dimensional rectangular sheets of Sb atoms are stacked along the c axis [54], as displayed in Fig. 1(a). Details on the methods of sample growth, characterization, ARPES and calculation are described in Note I of Supplementary Material (SM) [55]. We note that our calculations mainly focus on the result without considering the spin-orbit coupling (SOC) because of the relatively weak SOC in LaSb$_2$. Unless otherwise specified, henceforth spin degeneracy has been assumed. The case with the SOC is discussed in Note II of SM [55].

Based on the symmetry analysis, nodal surface states with fourfold degeneracy inevitably emerge in the band structure in the $k_z = \pi$ plane [shaded in yellow in Fig. 1(d)], as validated by the red-colored bands along the $R$-$Z$-$T$ path in Fig. 1(c). Such nodal surfaces stem from the Kramer’s degeneracy imposed by the combined antiunitary symmetry operator $S_{2z}\Theta$ in the $k_z = \pi$ plane with $(S_{2z}\Theta)^2 = -1$ [see more details in Note I of SM [55]], where $S_{2z} = \{C_{2z} | 0,1/2,1/2\}$ [Fig. 1(b)] and $\Theta$ denote the screw rotation and time-reversal operators, respectively. It is worth mentioning that the similar Kramer’s degeneracy gives rise to fourfold degenerate straight nodal lines along $R$-$S$ direction [55], where $(G_z\Theta)^2 = -1$ with $G_z = \{m_z | 0,1/2,1/2\}$ representing the glide symmetry operation, as shown in Fig.1(b).

Intriguingly, two eightfold DPs related to each other by the time-reversal symmetry, from the crossing of two set of nodal surface bands, appear in the high symmetry $Z$-$T$ line, as can be seen in Fig. 1(c) and its zoomed-in inset (i). Each eightfold DP consists of two fourfold DPs from the two spin species. For each spin, the fourfold DP results from the crossing between two set of doubly degenerate bands with distinct two-dimensional irreducible representations along the $Z$-$T$ direction, which are labelled by $B_1B_3$ and $B_2B_4$, respectively. One notable feature of the eightfold DPs in LaSb$_2$ is that they reside rather close to the Fermi energy ($E_F$), thus enabling their experimental observation and further potential applica-
FIG. 2: Verification of nodal surface in LaSb₂. (a) Integrated photoemission intensity map in the $k_y - k_z$ plane taken at $E_F$, corresponding second-derivative plot and calculation result. (b) Schematic of momentum locations of cuts C1 to C5, $Z-T$ and $\Gamma-Y'$ in the bulk BZ. (c) Schematic 3D plot of the electronic structure of C1 to C5. The band dispersion along $k_z$ direction probed by different photon energies and corresponding calculations plotted by the black curves. The red line illustrates the four-fold degenerate band shown in (f). Momentum distribution curves of C1 plotted at left bottom. (e) Schematic plot of the band structure in $k_z = 0$ and nodal surface plane. Thin and dotted red curves represent the degenerate band on the nodal surface and the non-degenerate bands away from the nodal surfaces, respectively. (d) and (f) The band structure dispersion along $\Gamma - Y$ and $Z-T$ directions and the corresponding calculation results as shown in top and middle of (e), respectively. Typical non-degenerated and double degenerated band are highlighted by red dots line.

Moreover, away from the $Z-T$ line in the $k_x = 0$ plane, due to the reduced symmetry, each eightfold DP would split into four nodal points, as shown in the lower zoomed-in inset (ii) of Fig. 1(c). Intriguingly, these nodal points form two nodal lines in the $k_z = 0$ plane [shaded in grey in Fig. 1(d)], and are protected by the $M_z$ mirror symmetry schematically shown in Fig. 1(b). For a better clarification, in Fig. 1(f), by choosing three representative cuts along the $k_y$ direction with different $k_z$ values, we demonstrate how the two nodal lines merge into the nodal point.

In addition, there are Dirac-type linear bands within a large energy range (2 eV) along $\Gamma-X$, which are dominated by the $p_{x/y}$ orbitals of Sb1 atoms [see Fig. S2(b) in SM [55]]. Similar to the case of square-net materials [56], such as ZrSiS [17, 22], the Dirac-like bands result from the BZ folding of the slightly distorted square-net Sb1 atoms in the $\sqrt{2} \times \sqrt{2}$ supercell structure [see the left panel of Fig. 1(e)]. Such Dirac-type crossings form a diamond-like nodal loop in the $k_z = 0$ plane, as shown by pink lines in the right panel of Fig. 1(e).

To verify these predicted nodal surface states in LaSb₂, we firstly carried out photon-energy-dependent measurements to identify the $k_z$-dependent electronic structures. The left and middle panels of Fig. 2(a) show the photoemission intensity map taken at $E_F$ ($h\nu = 28 \sim 70$ eV) and the corresponding second-derivative plot, respectively. One can distinguish the warped chainlike band feature with a pronounced periodic modulation along the $k_z$ direction, indicating that our measurements can probe the bulk states of LaSb₂. With an inner potential of 14 eV and $c = 18.671$ Å, we fitted the periodic variation according to the free electron final-state mode [57], and we thus determined $h\nu = 75, 69$ eV are close to $\Gamma$ and $Z$ point, respectively. The fitted result is in good agreement with the bulk band calculation [the right panel of Fig. 2(a)].

According to our calculations, nodal surfaces with fourfold degenerated band crossings are located in $k_z = \pi$ planes [Fig. 2(b)]. As the most pronounced fingerprint, any bands would show Dirac-like feature when crossing the nodal surface, and the degenerated band would split away from the nodal surface. Figure 2(c) presents photoemission intensity plots along cuts C1 to C5, which are all perpendicular to the nodal surface. For spectra along these cuts shown in Fig. 2(c), we can distinguish a series of Dirac-like band crossings through the corresponding momentum distribution curves (MDCs) (with the representative MDCs for C1 shown in the inset), which is as well roughly in line with the bulk calculation (black lines). We note that these crossing points (red dots) constitute the degenerate bands along $Z-T$ (the red dashed
line) in Fig. 2(f). In sharp contrast, once a cut deviates from the $k_z = \pi$ plane, e.g., the cut along $\Gamma - Y$ in the $k_z = 0$ plane, the originally degenerated band would split, as illustrated in Fig. 2(d), which is in good agreement with our calculation [Fig. 2(e)]. Thus, we can conclude that Dirac-like band crossings on the $k_z = 0$ plane are protected by the Kramer’s degeneracy, leading to the formation of the nodal surface.

According to our symmetry analysis and first-principles calculation, there should exist accidental crossings between two degenerate bands along the $T - Z - T$ high symmetry direction, which results in the formation of eightfold degenerate nodal point. However, this predicted degenerate point is suggested to be located slightly above $E_F$, beyond the probing scope of photoemission spectroscopy. To explore the unoccupied states, we performed relatively high temperature (210 K) ARPES measurements and the resulting data have been divided by the resolution convoluted Fermi-Dirac distribution function to highlight band dispersions above $E_F$. A schematic plot of the band structure near the eightfold degenerate point in the $Z - T$ line is displayed in Fig. 3(a). Along Cut 1, which would go through the eightfold degenerate nodal point, the calculated dispersion suggests the touching of the hole- (1,2 branches) and electron-like (3,4 branches) bands at the degenerate point, as shown in Fig. 3(b). Our photoemission intensity plot along Cut 1 shows general agreement with the calculation [Fig. 3(c)]. In particular, the corresponding MDCs for the zoomed-in region in the vicinity of $E_F$ could well resolve the touching point ($E_D$) of all the four band branches, strongly suggesting the existence of the nodal point. Given that all points on the $k_z$ plane should be fourfold degenerate, such a crossing point between two degenerate bands would be eightfold degenerate. Note that our data could not resolve the proposed gap owing to the SOC, which might be due to the relatively poor energy resolution of ARPES at such a high temperature. For comparison, we measured the band dispersion along Cut 2, which slightly deviates from Cut 1 but is parallel to that, as illustrated in Fig. 3(e). We found that there is no band crossing between band 2 and 3 within cut2 and its corresponding MDCs. Through careful comparison to the calculation [Fig. 3(d)], we could discover the splitting of nodal point between the hole- (1,2 branches) and electron-like (3,4 branches) bands. In this way, we experimentally verify the existence of eightfold degenerate nodal point on the nodal surface of LaSb$_2$.

Magneto-transport measurements were also performed on LaSb$_2$ to explore the topological nature of electronic bands which are located rather close to $E_F$. As shown in Note III of SM [55], the magneto-transport measurements unveil clear quantum oscillations at $B > 30$ T below 10 K and exhibit striking Shubnikov–de Haas (SdH) oscillations after subtracting a sixth-order polynomial background, as shown in SM [55] Fig. S4. The Berry phase $\varphi_B$ was examined by using the Landau level (LL) index fan, which gives the Berry phases $\varphi_B$ of 0.17$\pi$ and 1.01$\rmi$ for the electronic pocket $\alpha$ and hole pocket $\beta$, respectively. The Berry phase for the $\beta$ frequency is close to $\pi$, thus demonstrating the nontrivial topological state in LaSb$_2$.

As we mentioned above, LaSb$_2$ hosts unconventional LMR [45, 46], while its origin still remains elusive. To experimentally examine this, we conducted both magnetic field dependent Hall conductivity and ARPES measurements on LaSb$_2$ to estimate the carrier density of holes and electrons (see details in Notes III and IV of SM [55]). We found that there exists a huge difference in the hole and electron carrier density in LaSb$_2$, which unambigu-
ously excludes the carriers compensation mechanism for the LMR therein. Our finding is as well consistent with the previous theoretical research [51]. Instead, we suggest that the quantum limit of Dirac-like nodal fermions with high Fermi velocities in high fields might play a more crucial role in resulting the unconventional LMR.

In summary, by combining first-principles calculations and ARPES measurements, as well as Shubnikov–de Haas oscillations, we unambiguously confirmed the existence of nodal surface and eightfold degenerate nodal points in the vicinity of $E_F$ in LaSb$_2$. The discovery of multiple nodal phenomena in this single material enables further identification of abundant topological properties in this old light rare-earth dianimonides system, making it a versatile platform for studying the interplay between topological characters and LMR.

We thank D. X. Shao and Prof. Gang Mu for the useful discussion. This work was supported by the the National Science Foundation of China (Grants No. U2032208, 12222413, 11874264, 12074181, 11834006 and 12104217) and the Natural Science Foundation of China (Grants No. U2032208, 12222413, 11874264, 11834006 and 12104217) and the National Key Projects for Research and Development of China (Grant No. 21YFA1400400), the Fundamental Research Funds for the Central Universities (Grant No. 020141380185), Natural Science Foundation of Jiangsu Province (No. BK20200007) and the Fok Ying-Tong Education Foundation of China (Grant No. 161006).

---

* These authors contributed equally to this work
† Electronic address: hqwang@nju.edu.cn
‡ Electronic address: guoyf@shanghaitech.edu.cn
¶ Electronic address: shen@mail.sim.ac.cn

[1] X. Wan, A. M. Turner, A. Vishwanath, and S. Y. Savrasov, Phys. Rev. B 83, 205101 (2011).
[2] H. Weng, X. Dai, and Z. Fang, J. Phys. Condens. Matter 28, 303001 (2016).
[3] Z. K. Liu, B. Zhou, Y. Zhang, Z. J. Wang, H. M. Weng, D. Prabhakaran, S. K. Mo, Z. X. Shen, Z. Fang, X. Dai, et al., Science 343, 864 (2014).
[4] B. Q. Lv, H. M. Weng, B. B. Fu, X. P. Wang, H. Miao, J. Ma, P. Richard, X. C. Huang, L. X. Zhao, G. F. Chen, et al., Phys. Rev. X 5, 031013 (2015).
[5] A. A. Soluyanov, D. Gresch, Z. Wang, Q. Wu, M. Troyer, X. Dai, and B. A. Bernevig, Nature 527, 495 (2015).
[6] S. Y. Xu, I. Belopolski, N. Alidoust, M. Neupane, G. Bian, C. Zhang, R. Sankar, G. Chang, Z. Yuan, C. C. Lee, et al., Science 349, 613 (2015).
[7] N. P. Armitage, E. J. Mele, and A. Vishwanath, Rev. Mod. Phys. 90, 015001 (2018).
[8] A. A. Burkov, M. D. Hook, and L. Balents, Phys. Rev. B 84, 235126 (2011).
[9] C. Fang, H. Weng, X. Dai, and Z. Fang, Chin. Phys. B 25, 117106 (2016).
[10] R. Yu, Z. Fang, X. Dai, and H. Weng, Front. Phys. 12, 127202 (2017).
[11] S.-Y. Yang, H. Yang, E. Derunova, S. S. P. Parkin, B. Yan, and M. N. Ali, Adv. Phys. X 3, 1414631 (2018).
[12] Y. K. Song, G. W. Wang, S. C. Li, W. L. Liu, X. L. Lu, Z. T. Liu, Z. J. Li, J. S. Wen, Z. P. Yin, Z. H. Liu, et al., Phys. Rev. Lett. 124, 056402 (2020).
[13] Z. Liu, R. Lou, P. Guo, Q. Wang, S. Sun, C. Li, S. Thirupathaiah, A. Fedorov, D. Shen, K. Liu, et al., Phys. Rev. X 8, 031044 (2018).
[14] T. Bzdusek, Q. Wu, A. Ruegg, M. Sigrist, and A. A. Soluyanov, Nature 538, 75 (2016).
[15] Q. Yan, R. Liu, Z. Yan, B. Liu, H. Chen, Z. Wang, and L. Lu, Nat. Phys. 14, 461 (2018).
[16] W. Wu, Y. Liu, S. Li, C. Zhong, Z.-M. Yu, X.-L. Sheng, Y. X. Zhao, and S. A. Yang, Phys. Rev. B 97, 155125 (2018).
[17] B. B. Fu, C. J. Yi, T. T. Zhang, M. Caputo, J. Z. Ma, X. Gao, B. Q. Lv, L. Y. Kong, Y. B. Huang, P. Richard, et al., Sci. Adv. 5, eaau6459 (2019).
[18] C. Song, L. Jin, P. Song, H. Rong, W. Zhu, B. Liang, S. Cui, Z. Sun, L. Zhao, Y. Shi, et al., Phys. Rev. B 105, L161104 (2022).
[19] S. Y. Xu, C. Liu, S. K. Kushwaha, R. Sankar, J. W. Krizan, I. Belopolski, M. Neupane, G. Bian, N. Alidoust, T. R. Chang, et al., Science 347, 294 (2015).
[20] Z. Rao, H. Li, T. Zhang, S. Tian, C. Li, B. Fu, C. Tang, L. Wang, Z. Li, W. Fan, et al., Nature 567, 496 (2019).
[21] G. Bian, T. R. Chang, R. Sankar, S. Y. Xu, H. Zheng, T. Neupert, C. K. Chiu, S. M. Huang, G. Chang, I. Belopolski, et al., Nat. Commun. 7, 10556 (2016).
[22] L. M. Schoop, M. N. Ali, C. Strasser, A. Topp, A. Varykhalov, D. Marchenko, V. Duppel, S. S. Parkin, B. V. Lotsch, and C. R. Ast, Nat. Commun. 7, 11696 (2016).
[23] M. N. Ali, J. Xiong, S. Flynn, J. Tao, Q. D. Gibson, L. M. Schoop, T. Liang, N. Haldolaarachige, M. Hirschberger, N. P. Ong, et al., Nature 514, 205 (2014).
[24] X. Huang, L. Zhao, Y. Long, P. Wang, D. Chen, Z. Yang, H. Liang, M. Xue, H. Weng, Z. Fang, et al., Phys. Rev. X 5, 031023 (2015).
[25] H. Li, H. He, H. Z. Lu, H. Zhang, H. Liu, R. Ma, Z. Fan, S. Q. Shen, and J. Wang, Nat. Commun. 7, 10301 (2016).
[26] F. Fukushima, D. E. Kharzeev, and H. J. Warringa, Phys. Rev. D 78, 074033 (2008).
[27] N. B. M. Schröter, D. Pei, M. G. Vergniory, Y. Sun, K. Manna, F. de Juan, J. A. Krieger, V. Süss, M. Schmidt, P. Dudin, et al., Nat. Phys. 15, 759 (2019).
[28] B. Bradlyn, J. Cano, Z. Wang, M. G. Vergniory, C. Felser, R. J. Cava, and B. A. Bernevig, Science 353, aa5037 (2016).
P.-J. Guo, Y.-W. Wei, K. Liu, Z.-X. Liu, and Z.-Y. Lu, Phys. Rev. Lett. 127, 176401 (2021).
J.-P. Sun, D. Zhang, and K. Chang, Phys. Rev. B 96, 045121 (2017).
P. Tang, Q. Zhou, and S.-C. Zhang, Phys. Rev. Lett. 119, 206402 (2017).
L. Wu, F. Tang, and X. Wan, Phys. Rev. B 104, 045107 (2021).
J. P. Sun, D. Zhang, and K. Chang, Phys. Rev. B 96, 045121 (2017).
P. Tang, Q. Zhou, and S.-C. Zhang, Phys. Rev. Lett. 119, 206402 (2017).
L. Wu, F. Tang, and X. Wan, Phys. Rev. B 104, 045107 (2021).
X. Zhang, Z.-M. Yu, X.-L. Sheng, H. Y. Yang, and S. A. Yang, Phys. Rev. B 95, 235116 (2017).
B. Q. Lv, L. Z. Feng, Q. N. Xu, X. Gao, J. Z. Ma, L. Y. Kong, P. Richard, Y. B. Huang, V. N. Strocov, C. Fang, et al., Nature 546, 627 (2017).
J. Z. Ma, J. B. He, Y. F. Xu, B. Q. Lv, D. Chen, W. L. Zhu, S. Zhang, L. Y. Kong, X. Gao, L. Y. Rong, et al., Nat. Phys. 14, 349 (2018).
Z. P. Sun, C. Q. Hua, X. L. Liu, M. Ye, S. Qiao, Z. H. Liu, J. S. Liu, Y. F. Guo, Y. H. Lu, et al., Phys. Rev. B 101, 155114 (2020).
L. M. Schoop, A. Topp, J. Lippmann, F. Orlandi, L. Muchier, M. G. Vergniory, Y. Sun, A. W. Rost, V. Duppel, M. Krivenkov, et al., Sci. Adv. 4, eaar2317 (2018).
T. Berry, L. A. Pressley, W. A. Phelan, T. T. Tran, and T. M. McQueen, Chem. Mater. 32, 5827 (2020).
I. Palacio, J. Obando-Guevara, L. Chen, M. N. Nair, M. A. González Barrio, E. Papalazarou, P. Le Fèvre, R. F. Luccas, H. Suderow, P. Canfield, et al., arXiv:2202.03161 (2022).
S. L. Bud'ko, S. Huyan, P. Herrera-Siklody, and P. C. Canfield, arXiv:2208.04997 (2022).
S. Guo, D. P. Young, P. W. Adams, X. S. Wu, J. Y. Chan, G. T. McCandless, and J. F. DiTusa, Phys. Rev. B 83, 147520 (2011).
J. A. Galvis, H. Suderow, S. Vieira, S. L. Bud'ko, and P. C. Canfield, Phys. Rev. B 87, 214504 (2013).
S. L. Bud'ko, P. C. Canfield, C. H. Mielke, and A. H. Lacerda, Phys. Rev. B 57, 13624 (1998).
R. G. Goodrich, D. Browne, R. Kurtz, D. P. Young, J. F. DiTusa, P. W. Adams, and D. Hall, Phys. Rev. B 69, 125114 (2004).
D. P. Young, R. G. Goodrich, J. F. DiTusa, S. Guo, P. W. Adams, J. Y. Chan, and D. Hall, Appl. Phys. Lett. 82, 3713 (2003).
M. M. Parish and P. B. Littlewood, Nature 426, 162 (2003).
X. Wang, Y. Du, S. Dou, and C. Zhang, Phys. Rev. Lett. 108, 266806 (2012).
M. K. Dasoudhi, I. Rajput, D. Kumar, and A. Lakhani, J. Phys. D. Appl. Phys 54, 195103 (2021).
D. X. Qu, Y. S. Hor, J. Xiong, R. J. Cava, and N. P. Ong, Science 329, 821 (2010).
P. Ruszala, M. J. Winiarski, and M. Samsel-Czekala, Acta. Phys. Pol. A 138, 748 (2020).
A. Leonhardt, M. M. Hirschmann, N. Heinsdorf, X. Wu, D. H. Fabini, and A. P. Schnyder, Phys. Rev. Mater. 5, 124202 (2021).
A. A. Abrikosov, Phys. Rev. B 58, 2788 (1998).
K. F. Fischer, N. Roth, and B. B. Iversen, J. Appl. Phys 125, 045110 (2019).
See Supplemental Material for details of methods (calculations, ARPES and single crystal synthesis and characterization, which includes Refs. [45, 46, 51, 54, 58–61].
S. Klemenz, S. Lei, and L. M. Schoop, Annu. Rev. Mater. Sci. 49, 185 (2019).
D. Liebowitz and N. J. Shevchik, Phys. Rev. B 17, 3825 (1978).
A. B. Pippard, Magnetoresistance in Metal (Cambridge University Press, Cambridge, England, 1989).
E. M. Lifshits and A. M. Kosevich, J. Phys. Chem. Solids 4, 1 (1958).