Enhanced anisotropic superconductivity in the topological nodal-line semimetal In$_x$TaS$_2$

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Coexistence of topological bands and charge density wave (CDW) in topological materials has attracted immense attentions because of their fantastic properties, such as axionic-CDW, threedimensional quantum Hall effect, etc. In this work, a nodal-line semimetal In$_x$TaS$_2$ characterized by CDW and superconductivity is successfully synthesized, whose structure and topological bands (two separated Weyl rings) are similar to In$_{0.35}$TaSe$_2$. A 2 × 2 commensurate CDW is observed at low temperature in In$_x$TaS$_2$, identified by transport properties and STM measurements. Moreover, superconductivity emerges below 0.69 K, and the anisotropy ratio of upper critical field $|\Gamma = H_{c2}^{ab}(0)/H_{c2}^{||}(0)|$ is significantly enhanced compared to 2H-TaS$_2$, which shares the same essential layer unit. According to the Lawrence-Doniach model, the enhanced $\Gamma$ may be explained by the reduced effective mass in $k_x$–$k_y$ plane, where Weyl rings locate. Therefore, this type of layered topological systems may offer a platform to investigate highly anisotropic superconductivity and to understand the extremely large upper critical field in the bulk or in the two-dimensional limit.

I. INTRODUCTION

Topological nodal-line semimetals (TNLSMs) have been attracting tremendous attentions due to the closed loop of band crossing formed in momentum space. Typical TNLSMs have been experimentally reported in the so-called 112 systems (In$_x$TaSe$_2$ and PbTaSe$_2$), LiFeAs structure (ZrSiS$^3$), PtSn$^3$ and so on. Unlike the zero-dimensional nodal points in Dirac semimetals$^2$ and Weyl semimetals$^2$–$^12$ the one-dimensional (1D) nodal lines can be protected by certain symmetry$^13$ no matter whether the spin-orbital coupling (SOC) is included. Several intriguing properties have been predicted and experimentally observed in TNLSMs, such as drumhead surface states$^{31,37}$, anomalous quantum oscillations$^{15}$, three-dimensional quantum Hall effect (3D QHE)$^{16}$, and topological superconductivity$^{17}$. As regards searching for bulk topological superconductors (TSCs), one of the employed strategies is to induce superconductivity in topological material$^{18}$ through the application of high pressure$^{22,24}$, intercalation between layers$^{25,26}$, or chemical doping$^{27}$ etc.

Among these approaches, intercalation of atoms and molecules into the layered transition-metal dichalcogenides (TMDs) $MX_2$ ($M$ is the transition metal, $X = S, Se, Te$) and other layered compounds is an effective one to significantly modify their properties. For example, superconductivity can be induced in Cu$_x$TiSe$_2$$^{28}$ and Cu$_x$Bi$_2$Se$_3$$^{29}$ the intercalated graphite exhibits more excellent electric and optical feature$^{27}$, which greatly contributes to extensive applications; the TNLSM PbTaSe$_2$ viewed as Pb atoms intercalation in TaSe$_2$ introduces not only topological bands, such as InTaSe$_2$$^2$, TlTaSe$_2$$^{10}$, InNbS$_2$, and InNbSe$_2$$^{25}$ but also possible Majorana bound states in the superconducting vortices$^{24,27}$. Moreover, the intercalated layered compounds possibly host the higher superconducting transition ($T_c$) or highly anisotropic superconductivity$^{20,31}$.

In this paper, the In-intercalated TNLSM In$_x$TaS$_2$ hosting both superconductivity and charge density wave (CDW) is successfully synthesized. It has the same structure and similar topological bands as InTaSe$_2$ whose two separate Weyl rings exist at the H point. It is a little different that the only one 2 × 2 commensurate CDW (CCDW) remains. The superconductivity is observed, and the extremely large anisotropy ratio of upper critical field is obtained in four samples, which may be related to the small effective mass in the $ab$ plane.

II. EXPERIMENT

The polycrystalline InTaS$_2$ and single crystals In$_x$TaS$_2$ were prepared using the solid-state reaction method and the vapor transport method, respectively, also referred to In$_x$TaSe$_2$$^2$. The x-ray diffraction (XRD) data were collected using a monochromatic Cu K$_{α1}$ radiation. An energy-dispersive x-ray spectroscopy (EDS) was employed to analyze chemical compositions of samples. A standard six-probe technique was carried out to measure the longitudinal resistivity and Hall resistivity on an Oxford $^3$He-based cryostat and a physical properties measurement system (PPMS). Scanning tunneling mi-
Fig. 1. (a) Rietveld refinement of powder XRD data for polycrystalline InTaS$_2$. The inset is a side view of the InTaS$_2$ structure. (b) XRD spectrum for the (00$l$) facet of single crystals In$_x$TaS$_2$. The optical photograph of two selected samples are shown in the inset. (c) One of typical EDS spectrums collected on these flat clean surfaces of single crystals. The In content $x$ is between 0.51 and 0.59. (d) Band structures of InTaS$_2$ with SOC. Two separated Weyl rings appear at the H point in the first Brillouin zone, as shown in the inset.

coscopy (STM) measurements were performed in a commercial unisoku-UHV1500S STM system. The samples were cleaved in situ at ~77 K, then inserted into the STM measurement stage.

The density function theory (DFT) calculations were performed using the generalized gradient approximation (GGA) method and the Perdew-Burke-Ernzerhoff (PBE) exchange correlation functional. The lattice constants and the atomic coordinates were used from Rietveld-refined XRD data. A $18\times18\times6$ Monkhorst-Pack $k$-point mesh and SOC were applied in the computations.

### III. RESULTS

#### A. Structure and topological bands

InTaS$_2$ has the same noncentrosymmetric structure $P\bar{6}m2$ as InTaSe$_2$ as shown in the inset of Fig. 1(a), the side view of the crystal structure. This structure can be well verified by the Rietveld refinement of polycrystalline powder XRD data [Fig. 1(a)]. The both reliable factor $R_{wp} = 10.8\%$ and small difference between observed data and calculations illustrate the good refinement. The refined lattice constants are $a = b = 3.3290$ Å and $c = 7.9891$ Å. High-quality single crystals In$_x$TaS$_2$ with various In content can be grown by the vapor transport method, and the plate-like samples are obtained as large as $3\text{ mm} \times 2\text{ mm}$ [inset of Fig. 1(b)]. Their XRD spectrums for the (00$l$) facet are collected in Fig. 1(b), suggesting the good single crystal quality. The grown single crystals usually have a large amount of In vacancy. A typical EDS pattern of a In$_x$TaS$_2$ single-crystalline sample S1 is shown in Fig. 1(c), in which the chemical composition is In:Ta:S = 0.51:1:2. The $x$ value of four In$_x$TaSe$_2$ samples varies between 0.51 and 0.59, and phase separation easily emerges beyond this $x$ range.

Fig. 1(d) shows the band structure of InTaS$_2$ with the
FIG. 2. (a) Electrical resistivity $\rho_{xx}$ of four In$_x$TaS$_2$ samples exhibiting a CDW-like transition. The differential resistivity in the inset displays the transition temperatures $\sim 130$ K. (b) Low-temperature specific heat of In$_x$TaS$_2$ showing a distinct jump at $\sim 129$ K and zero magnetic field. The small $\gamma = 1.01$ mJ mol$^{-1}$K$^{-1}$ is obtained in the inset. (c-f) Magnetic-field dependent $\rho_{xx}$ at different temperatures. (g) Hall coefficients of four samples. The magenta range marks the transition. (h) STM images ($V_b = -1$V, $I_t = 20$ pA) of the sample surface at 77 K. An enlarged range of a perfect surface is shown in the inset ($V_b = 1$V, $I_t = 100$ pA), implying the 2x2 superlattice. (i) FFT image of (h). The 2 x 2 CDW is marked by the red circle.

inclusion of SOC obtained by the DFT calculations. The main features are quite similar to the other 112 systems, such as InTaSe$_2$, InNbS$_2$, PbTaSe$_2$, and TlTaSe$_2$. The band inversion exists at the H point due to the hybridization of a hole pocket from Ta-5d orbitals and an electron pocket derived from In-5p orbitals. When the mirror reflection with respect to the In atomic plane is taken into consideration, these inverted bands are topological invariant. The four-fold-degenerate Dirac-type nodal ring splits into a pair of two-fold-degenerate nodal rings (Weyl rings) at the H point in the presence of SOC, as seen in the inset of Fig. 1(d). These Weyl rings remain gapless as a result of the symmetry protection, and they locate at $E - E_F \sim -0.25$ eV, slightly below the Fermi level. Interestingly, the In vacancy in In$_x$TaS$_2$ is supposed to shift the Fermi level down to the Weyl rings, which is also observed in In$_{0.58}$TaSe$_2$. Each Weyl ring possesses a Berry phase of $\pi$, and they can be connected by drumhead surface states, a kind of nearly flat bands, which may exhibit a van Hove singularity, as discussed in Refs[3,16,28,32].

B. CDW states

More fantastic features can be observed in the temperature dependence of resistivity for In$_x$TaS$_2$, shown in Fig. 2. Fig. 2(a) shows the residual resistivity ratios ($RRR$) of samples S1, S2, S3, and S4 are 11.5, 10.8, 6.9, and 5.7, respectively. All resistivity curves exhibit a CDW-like transition in In$_x$TaS$_2$, shown in Fig. 2. Fig. 2(a) shows the residual resistivity ratios ($RRR$) of samples S1, S2, S3, and S4 are 11.5, 10.8, 6.9, and 5.7, respectively. All resistivity curves exhibit a CDW-like transition in In$_x$TaS$_2$, shown in Fig. 2(a) and (b). The transition temperatures can be identified by the differential resistivity in the inset of Fig. 2(a), and also confirmed by the jump of specific heat at $\sim 129$ K in Fig. 2(b). The small $\gamma = 1.01$ mJ mol$^{-1}$K$^{-1}$ is obtained by fitting the low-temperature specific heat [inset of Fig. 2(b)]. In Fig. 2(c-f), the positive and linear Hall resistivity as a function of magnetic field ($H$) indicates the dominated carrier is hole in this system. In Fig. 2(g), the associated transitions of Hall coefficients ($R_H$) are also observed in the magenta range of temperature, in agreement with the longitudinal resistivity and specific heat measurements. Upon decreasing temperature, $R_H$ decreases at this transition point in In$_x$TaS$_2$, different from the increase of $R_H$ in In$_{0.58}$TaSe$_2$. This behavior implies the possible distinct transition behavior or multiband feature, and the latter one is supposed to dominate here. The Hall
coefficient in the multiband system, such as In$_x$TaS$_2$, can be approximatively described by the two-band model
$$R_H = \frac{R_H^h (\sigma_{xx}^h)^2 - R_H^e (\sigma_{xx}^e)^2}{(\sigma_{xx}^h + \sigma_{xx}^e)^2},$$
where $R_H^h$ and $R_H^e$ denote the Hall coefficient for hole and electron, respectively, $\sigma_{xx}^h$ and $\sigma_{xx}^e$ are the hole conductivity and electron conductivity, respectively. Therefore, the Hall coefficient of the multiband system changes much complicatedly, especially in CDW systems, where band gaps emerge.

To further investigate this transition, we perform STM measurements at liquid nitrogen temperature (77 K). In Fig. 2(h), we show a STM topography obtained with a bias voltage $V_b = -1$ V and a tunneling current $I_t = 20$ pA, from which a triangular lattice can be observed. The triangular lattice can be further discerned in an enlarged small-area topography [inset of Fig. 2(f)]. The distance between adjacent bright spots is 6.951 Å ($\sim 2a$, $a$ is the lattice constant). The basic element of lattice is the 2×2 superlattice, instead of the 1×1 atomic lattice. The superlattice is also confirmed in the fast Fourier-transformed (FFT) result in Fig. 2(i). The pattern marked by the red circle represents the 2×2 lattice, with a wave vector $\vec{Q}_0$ ($\vec{Q}_0 = 4\pi/\sqrt{3}a$). The absence of atomic lattice in STM topography is similar to that for 1T-TaS$_2$[33]. The low-temperature state below the transition is thus a 2×2 CCDW state. This type of 2×2 CCDW can also be observed in other intercalated $MX_2$[34], including In$_{0.58}$TaSe$_2$[35]. In addition, the random black spots in Fig. 2(h) may stem from In atoms, which are randomly exfoliated from the In layer when the sample is cleaved.

FIG. 3. (a) $\rho_{xx}$ of samples S1, S2, S3, and S4 showing the superconducting transition at $T_c^{50\%} = 0.34$ K, 0.36 K, 0.48 K, and 0.69 K, respectively. $T_c^{50\%}$ is determined by 50% drop of the normal-state resistivity. (b-i) Temperature dependence of in-plane and out-of-plane resistivity for four samples.
C. Anisotropic superconductivity

In Fig. 3, superconductivity of samples is observed at low temperature. The superconducting transition temperature \( T_c^{50\%} \) is 0.34 K, 0.36 K, 0.48 K, and 0.69 K for samples S1, S2, S3, and S4, respectively, which is extracted by 50% drop of normal-state resistivity. \( T_c \) in \( \text{In}_x\text{TaS}_2 \) is a little smaller than \( T_c \sim 0.8 \) K in 2H-TaS\(_2\) with the 3×3 CDW at 78 K\(^{20}\) and also smaller than \( T_c = 0.91 \) K for \( \text{In}_{0.58}\text{TaS}_2 \) with two CDW transitions (2×\( \sqrt{3} \) CDW at 117 K and 2×2 CDW at 77 K\(^{20}\)). The lower \( T_c \) for \( \text{In}_x\text{TaS}_2 \) may be due to its higher 2×2 CDW transition (130 K), which is higher than \( \text{In}_{0.58}\text{TaS}_2 \). This is consistent with the typical phase diagram of CDW superconductors, i.e., \( \text{Cu}_x\text{TiSe}_2 \)\(^{20}\), in which \( T_c \) is enhanced upon suppressing CDW. The widths of superconducting transitions for samples S1 and S2 are much narrower than samples S3 and S4, indicating higher sample quality. The temperature dependence of resistivity under different magnetic fields are shown in Fig. 3 (b-l) for both \( H \) applied in the \( ab \) plane and along the \( c \)-axis.

The upper critical fields \( H_{c2} \) as a function of \( T \) is summarized in Fig. 4(a) and (b), and approximatively fitted by the Ginzberg-Landau (GL) model (solid lines), \( H_{c2}(t) = H_{c2}(0)(1 - t^2)/(1 + t^2) \), where \( t = T/T_c \). Taking the sample S1 for example, \( H_{c2}^{ab}(0) = 2238 \) Oe and \( H_{c2}^c(0) = 84 \) Oe, while the parameters of other samples are listed in Table I. Further effective mass can also be obtained according to the Lawrence-Doniach model\(^{27,39}\) and the anisotropy ratio \( \Gamma \) is given by the following relation

\[
\Gamma = \frac{H_{c2}^{ab}}{H_{c2}^c} = \left( \frac{m_c}{m_{ab}} \right)^{1/2} = \frac{\xi_{ab}}{\xi_c},
\]

where \( m_c \) and \( m_{ab} \) are the effective mass tensor along the \( c \)-axis and \( ab \) plane, respectively, and \( \xi_{ab} \) and \( \xi_c \) are the coherence length along the \( ab \) plane and \( c \)-axis, respectively. The anisotropy ratio \( \Gamma \) vs. \( t \) of these samples are displayed in Fig. 4(c). The resultant \( \Gamma \) for samples are all larger than 12, implying the highly anisotropic superconductivity. The \( \Gamma \) value estimated at the extrapolated zero temperature is \( \sim 26, 23, 23, \) and 12 for samples S1, S2, S3, and S4 with different RRR, respectively, much larger than the most layered compounds, such as 2H-TaS\(_2\)\(^{39}\) (\( \Gamma = 6.7 \) in Table I), typical iron-based superconductors (IBS) \( \text{“}122\text{”}-\)type (Ba,K)\text{Fe}_2\text{As}_2 (\( \Gamma < 2\)\(^{39}\)), \( \text{“}111\text{”}-\)type \( \text{Fe}_1+y\text{Ti}_{0.6}\text{Se}_{0.4} \) (\( \Gamma < 1.8 \)), \( \text{“}1111\text{”}-\)type \( \text{NdFeAsO}_{0.8}\text{Fe}_{0.2} \) (\( \Gamma < 5 \)), \( \text{“}1144\text{”}-\)type \( \text{RbEuFeAs}_4 \) (\( \Gamma < 1.7\)\(^{39}\)), \( \text{“}122\text{”}-\)type \( \text{Ca}_{1-x}\text{La}_x\text{FeAs}_2 \) (\( \Gamma < 4.2\)\(^{11}\)), etc. Several TMDs-related compounds are listed in Table I. Unfortunately, the guided relation between \( T_c \) and layer distance \( d \) or \( \Gamma \) in these TMDs-related compounds seem not to be widely concluded. However, intercalated layered compounds seems a good method to possess highly anisotropic superconductivity and large \( H_{c2}^{ab} \) in bulk state, even exceeding the Pauli limit \( H_{c2}^{ab} \).

According to the anisotropic Ginzburg-Landau formulas, \( H_{c2}^c = \Phi_0/2\pi \xi_c^2 \) and \( H_{c2}^{ab} = \Phi_0/2\pi \xi_{ab} \), where \( \Phi_0 \) is the flux quantum, the GL coherence lengths \( \xi_{ab} \) and \( \xi_c \) are obtained according to the Lawrence-Doniach model (solid lines), \( H_{c2}(t) = H_{c2}(0)(1 - t^2)/(1 + t^2) \), where \( t = T/T_c \). Taking the sample S1 for example, \( H_{c2}^{ab}(0) = 2238 \) Oe and \( H_{c2}^c(0) = 84 \) Oe, while the parameters of other samples are listed in Table I. Further effective mass can also be obtained according to the Lawrence-Doniach model (solid lines). The anisotropy ratio \( \Gamma \) is given by the following relation

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\Gamma = \frac{H_{c2}^{ab}}{H_{c2}^c} = \left( \frac{m_c}{m_{ab}} \right)^{1/2} = \frac{\xi_{ab}}{\xi_c},
\]

where \( m_c \) and \( m_{ab} \) are the effective mass tensor along the \( c \)-axis and \( ab \) plane, respectively, and \( \xi_{ab} \) and \( \xi_c \) are the coherence length along the \( ab \) plane and \( c \)-axis, respectively.
TABLE II. Comparison of physical properties and anisotropy ratio of several TMD-related superconductors.

| Material       | $T_c$ (K) | $T_{CDW1}$ (K) | $T_{CDW2}$ (K) | $\gamma$ | $c$ (Å) |
|----------------|-----------|----------------|----------------|----------|-----------|
| 2H-TaSe$_2$   | 0.14      | 90 (121)       | 12.71          | 2.6      |           |
| PbTaSe$_2$    | 3.8       | -              | 9.35           | ~4       |           |
| In$_{0.58}$TaSe$_2$ | 0.91    | 77 (117)       | 8.3231         | 4.6      |           |
| In$_{0.51}$TaS$_2$ | 0.34   | 132            | 7.9647         | >12      |           |
| 2H-TaS$_2$    | 0.8       | 78             | 12.097         | 6.7      |           |
| Na$_0.1$TaS$_2$ | 4.3      | -              | 12.082         | 6.4      |           |
| Cu$_x$TaS$_2$ | 4.03      | 55             | 12.11          | 5.1      |           |

and $\xi$, at zero temperature are calculated for four samples. The coherence length $\xi$, perpendicular to the TaS$_2$ layer is more than 7 times larger than the distance $d = c = 7.9647 \AA$ between TaS$_2$ layers (Table I), illustrating that the superconductivity of In$_x$TaS$_2$ remains three dimensional in nature. The carrier density and $\rho_0$ at 2 K are estimated from $R_H$ and low-temperature resistivity, respectively. The Fermi vector $k_F$ and the mean free path $\ell$ are approximately inferred from the relation $\ell = \hbar k_F / \rho_0 \pi \ell^2$ and $k_F = (2\pi^2 n)^{1/3}$, respectively. All the physical parameters for four samples are summarized in Table I.

Due to the limit on the lowest temperature which we can reach in our measurements, the intrinsic anisotropy ratio may be a little overestimated, but its value is still supposed to be very large (> 10). Subsequently, a remarkably large effective mass ratio $m_e/m_ab$ (> 100) can be extracted from Eq. (1). Taking into consideration of small $\gamma = m^* k_F^2 / \hbar^2 = 43.76 J/m^3/K^2$ from the Landau Fermi-liquid theory, which is obtained from the specific heat at constant volume, the geometric mean of effective mass $m^*$ is approximately 2.2 $m_e$, suggesting the possible small effective mass $m_ab$ in the $ab$ plane. The decreased effective mass may result from the linear band crossings (Weyl rings), which locate in the $ab$ plane near the Fermi level due to the In vacancy.

IV. CONCLUSIONS

We systematically investigate anisotropic upper critical field in a nodal-line semimetal In$_x$TaS$_2$. Similar to In$_{0.58}$TaSe$_2$, CDW, nodal-line topological states, and superconductivity coexist in In$_x$TaS$_2$. A 2x2 CCDW transition is observed at approximately 130 K supported by STM and transport measurements, and then superconducting transitions of four samples emerge in the temperature range between 0.34 K and 0.69 K.

Among these physical phases in this system, one of the interesting points is the gigantic anisotropy of upper critical field, which is significantly larger than that of 2H-TaS$_2$. Several origins may account for this property in 3D materials. In IBS, the anisotropy ratio $\Gamma$ appears to be related to the inter-layer coupling strength and the distance $d$ between the charge reservoir layers and the conducting layers. In the FeSe system, the larger $\Gamma$ may result from the larger $d$, which is likely correlated with the higher $T_c$. From the Lawrence-Oniach model, the anisotropic effective mass has an influence on the $\Gamma$ value. Considering the lower $T_c$ in this In-intercalated TaS$_2$ system, the origin of large $\Gamma$ may be different from the IBS system. We propose that the large $\Gamma$ in In$_x$TaS$_2$ may result from gigantic anisotropic effective mass, because linear band crossings (Weyl rings) locate in the $ab$ plane and reduce the effective mass tensor in this plane. The vacancy of In shifts Weyl rings much close to the Fermi level, and the superconducting gap may emerge in the Weyl rings as well. Therefore, we suppose the induced Weyl rings in this 112 system may contribute to the enhanced anisotropic effective mass, then generating the large superconducting anisotropy. This scenario may also be applied to the topological materials with similar band structures, such as In$_x$TaSe$_2$, PbTaSe$_2$, etc.

In addition, the correlation between the large anisotropic superconductivity and band crossing in topological materials deserves further investigation. Whether the superconducting gap emerges in the Weyl rings and the possible topological superconductivity also need further study.

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[1] A. A. Burkov, M. D. Hook, and L. Balents, Topological nodal semimetals. Phys. Rev. B 84, 235126 (2011).
[2] Y. Li, Y. Wu, C. Xu, N. Liu, J. Ma, B. Lv, G. Yao, Y. Liu, H. Bai, X. Yang, L. Qiao, M. Li, L. Li, H. Xing, Y. Huang, J. Ma, M. Shi, C. Cao, Y. Liu, C. Liu, J. Jia, and Z.-A. Xu, Anisotropic gapping of topological Weyl rings in the charge-density-wave superconductor In$_x$TaSe$_2$, arXiv:2004.03441.
[3] G. Bian, T.-R. Chang, R. Sanjuk, S.-Y. Xu, H. Zheng, T. Neupert, C.-K. Chiu, S.-M. Huang, G. Q. Chang,
I. Belopolski, D. S. Sanchez, M. Neupane, N. Alidoust, C. Liu, B. K. Wang, C.-C. Lee, H.-T. Jeng, C. L. Zhang, Z. J. Yuan, S. Jia, A. Bansil, F. C. Chou, H. Lin, and M. Z. Hasan, Topological nodal-line fermions in spin-orbit metal PbTaSe₂, Nat. Commun. 7, 10556 (2016).

[4] L. M. Schoop, M. N. Ali, C. Straßer, A. Topp, A. Varykhalov, D. Marchenko, V. Doppel, S. S. P. Parkin, B. V. Lotsch, and C. R. Ast, Dirac cone protected by non-symmorphic symmetry and three-dimensional Dirac line node in ZrSiS, Nat. Commun. 7, 11696 (2016).

[5] Y. Wu, L.-L. Wang, E. Mun, D. D. Johnson, D. X. Mou, L. N. Huang, Y. B. Lee, S. L. Bud, P. C. Canfield, and A. Kaminski, Dirac node arcs in PtSn, [Nat. Phys. 88], 667 (2016).

[6] J.-M. Carter, V. V. Shanlkar, M. A. Zeb, and H.-Y. Kee, Semimetal and topological insulator in perovskite iridates, Phys. Rev. B 85, 115105 (2012).

[7] Z. K. Liu, B. B. Zhou, Y. Zhang, Z. J. Wang, H. Z. Weng, D. Prabhakaran, S.-K. Mo, Z. X. Shen, Z. Fang, X. Dai, Z. Hussain, and Y. L. Chen, Discovery of a three-dimensional topological Dirac semimetal, Na3Bi, Science 343, 864 (2014).

[8] M. Neupane, S.-Y. Xu, R. Sankar, N. Alidoust, G. Bian, C. Liu, I. Belopolski, T.-R. Chang, H.-T. Jeng, H. Lin, A. Bansil, F. C. Chou, and M. Z. Hasan, Observation of a three-dimensional topological Dirac semimetal phase in high-mobility Cd₃As₂, Nat. Commun. 5, 3786 (2014).

[9] H. Weng, C. Fang, Z. Fang, B. A. Bernevig, and X. Dai, Weyl semimetal phase in noncentrosymmetric transition-metal monophosphides, Phys. Rev. X 5, 011029 (2015).

[10] B. Q. Lv, H. M. Weng, B. B. Fu, X. P. Wu, H. Miao, J. Ma, P. Richard, X. C. Huang, L. X. Zhao, G. F. Chen, Z. Fang, X. Dai, T. Qian, and H. Ding, Experimental discovery of Weyl fermion semimetal and topological Fermi arcs, Phys. Rev. X 5, 031013 (2015).

[11] S.-Y. Xu, I. Belopolski, N. Alidoust, M. Neupane, G. Bian, C. Zhang, R. Sankar, G. Chang, Z. Yuan, C.-C. Lee, S.-M. Huang, H. Zheng, J. Ma, D. S. Sanchez, B. Wang, A. Bansil, F. Chou, P. P. Shibayev, H. Lin, S. Jia, and M. Z. Hasan, Discovery of a Weyl fermion semimetal and topological Fermi arcs, Science 349, 613 (2015).

[12] D.-F. Xu, Y.-P. Du, Z. Wang, Y.-P. Li, X.-H. Niu, Q. Yao, P. Dudin, Z.-A. Xu, X.-G. Wan, and D.-L. Feng, Observation of Fermi arcs in non-centrosymmetric Weyl semimetal candidate NbP, Chin. Phys. Lett. 32, 107101 (2015).

[13] Z. Wang, Y. Zheng, Z. Shen, Y. Lu, H. Fang, F. Shen, Y. Zhou, X. Yang, Y. Li, C. Feng, and Z.-A. Xu, Helicity-protected ultrahigh mobility Weyl fermions in NbP, Phys. Rev. B 93, 121112(R) (2016).

[14] Y. Li, Z. Wang, P. Li, X. Yang, Z. Shen, F. Sheng, X. Li, Y. Lu, Y. Zheng, and Z.-A. Xu, Negative magnetoresistance in Weyl semimetals NbAs and NbP: Intrinsic chiral anomaly and extrinsic effects, Front. Phys. 12, 127205 (2017).

[15] C. Fang, H. Weng, X. Dai, and Z. Fang, Topological nodal line semimetals, Chin. Phys. B 25, 117106 (2016).

[16] G. Bian, T.-R. Chang, H. Zheng, S. Velury, S.-Y. Xu, T. Neupert, C.-K. Chiu, S.-M. Huang, D. S. Sanchez, I. Belopolski, N. Alidoust, P.-J. Chen, G. Q. Chang, A. Bansil, H.-T. Jeng, H. Lin, and M. Z. Hasan, Drumhead surface states and topological nodal-line fermions in TlTaSe₂, Phys. Rev. B 93, 121113(R) (2016).

[17] Y.-H. Chan, C.-K. Chiu, M. Y. Chou, and A. P. Schnyder, Ca₃P₂ and other topological semimetals with line nodes and drumhead surface states, Phys. Rev. B 93, 205132 (2016).

[18] C. Li, C. M. Wang, B. Wan, X. Wan, H.-Z. Lu, and X. C. Xie, Rules for Phase Shifts of Quantum Oscillations in Topological Nodal-Line Semimetals, Phys. Rev. Lett. 120, 146602 (2018).

[19] R. A. Molina and J. González, Surface and 3D quantum Hall effects from engineering of exceptional points in nodal-line semimetals, Phys. Rev. Lett. 120, 146601 (2018).

[20] S.-Y. Guan, P.-J. Chen, M.-W. Chu, R. Sankar, F. Chou, H.-T. Jeng, C.-S. Chang, and T.-M. Chuang, Superconducting topological surface states in the noncentrosymmetric bulk superconductor PbTaSe₂, Sci. Adv. 2, e1600894 (2016).

[21] Y. Li and Z.-A. Xu, Exploring topological superconductivity in topological materials, Adv. Quantum Technol. 2, 1800119 (2019).

[22] J. L. Zhang, S. J. Zhang, H. M. Weng, W. Zhang, L. X. Yang, Q. Q. Liu, S. M. Feng, X. C. Wang, R. C. Yu, L. Z. Cao, L. Wang, G. Yang, H. Z. Liu, W. Y. Zhao, S. C. Zhang, X. Dai, Z. Fang, and C. Q. Jin, Pressure-induced superconductivity in topological parent compound Bi₂Te₃, Proc. Natl. Acad. Sci. U.S.A. 108, 24770 (2011).

[23] D. Kang, Y. Zhou, W. Y., C. Yang, J. Guo, Y. Shi, S. Zhang, Z. Wang, C. Zhang, S. Jiang, A. Li, K. Yang, Q. Wu, G. Zhang, L. L. Sun, and Z. X. Zhao, Superconductivity emerging from a suppressed large magnetoresistive state in tungsten ditelluride, Nat. Commun. 6, 7804 (2015).

[24] Y. Li, C. An, C. Hua, X. Chen, Y. Zhou, Y. Zhou, R. Zhang, C. Park, Z. Wang, Y. Lu, Y. Zheng, Z. Yang, and Z.-A. Xu, Pressure-induced superconductivity in topological semimetal NbAs₂, npj Quantum Materials 3, 58 (2018).

[25] Y. S. Hor, A. J. Williams, J. G. Checkelsky, P. Roushan, J. Seo, Q. Xu, H. W. Zandbergen, A. Yazdani, N. P. Ong, and R. J. Cava, Superconductivity in Cu₃Bi₂Se₂ and its implications for pairing in the undoped topological insulator, Phys. Rev. Lett. 104, 057001 (2010).

[26] E. Morosan, H. W. Zandbergen, B. S. Dennis, J. W. G. Bos, Y. Onose, T. Klimczuk, A. P. Ramirez, N. P. Ong, and R. J. Cava, Superconductivity in Cu₃Bi₂Se₂, Nat. Phys. 5, 544 (2009).

[27] M. S. Dresselhaus and G. Dresselhaus, Intercalation compounds of graphite, Adv. Phys. 51, 1 (2002).

[28] Y. P. Du, X. Y. Bo, D. Wang, E.-J. Kan, C.-G. Duan, S. Y. Savrasov, and X. G. Wan, Emergence of topological nodal lines and type-II Weyl nodes in the strong spin-orbit coupling system InNbX₂ (X=S,Se), Phys. Rev. B 96, 235152 (2017).

[29] S. S. Zhang, J.-X. Yin, G. Dai, L. Zhao, T.-R. Chang, N. Shumiya, K. Jiang, H. Zheng, G. Bian, D. Multer, M. Litskevich, G. Chang, I. Belopolski, T. A. Cochran, X. Wu, D. Wu, J. Luo, G. Chen, H. Lin, F.-C. Chou, X. Wang, C. Jin, R. Sankar, Z. Wang, and M. Z. Hasan, Field-free platform for Majorana-like zero mode in superconductors with a topological surface state, Phys. Rev. B 101, 100507(R) (2020).

[30] C.-L. Zhang, Z.-J. Yuan, G. Bian, S.-Y. Xu, X. Zhang, M. Z. Hasan, and S. Jia, Superconducting properties...
in single crystals of the topological nodal semimetal PbTaSe$_2$, Phys. Rev. B 93, 054520 (2016)

[31] L. Fang, Y. Wang, P. Y. Zou, L. Tang, Z. Xu, H. Chen, C. Dong, L. Shan, and H. H. Wen, Fabrication and superconductivity of Na$_x$TaS$_2$ crystals, Phys. Rev. B 72, 014534 (2005)

[32] Y. Li, C. Xu, M. Shen, J. Wang, X. Yang, X. Yang, Z. Zhu, C. Cao, and Z.-A. Xu, Quantum transport in a compensated semimetal W$_2$As$_3$ with nontrivial Z$_2$ indices, Phys. Rev. B 93, 054520 (2016)

[33] L. Fang, Y. Wang, P. Y. Zou, L. Tang, Z. Xu, H. Chen, C. Dong, L. Shan, and H. H. Wen, Fabrication and superconductivity of Na$_x$TaS$_2$ crystals, Phys. Rev. B 93, 054520 (2016)

[34] Y. Li, C. Xu, M. Shen, J. Wang, X. Yang, X. Yang, Z. Zhu, C. Cao, and Z.-A. Xu, Possible strain induced Mott gap collapse in 1T-TaS$_2$, Commun. Phys. 2, 146 (2019)

[35] Z. Dai, Q. Xue, Y. Gong, C. G. Slough, and R. V. Coleman, Scanning-probe-microscopy studies of superlattice structures and density-wave structures in 2H-NbSe$_2$, 2H-TaSe$_2$, and 2H-TaS$_2$ induced by Fe doping, Phys. Rev. B 48, 14543 (1993)

[36] R. C. Morris and R. V. Coleman, Anisotropic superconductivity in layer compounds, Phys. Rev. B 7, 991 (1973)

[37] W. E. Lawrence and S. Doniach, Proceedings of the 12th International Conference on Low Temperature Physics, Kyoto, 1970, edited by E. Kanda (Keigaku, Tokyo, 1971), p. 361.

[38] Y. Jia, P. Cheng, L. Fang, H. Luo, H. Yang, C. Ren, L. Shan, C. Gu, and H.-H. Wen, Critical fields and anisotropy of NiFeAsO$_{0.82}$F$_{0.18}$ single crystals, Appl. Phys. Lett. 93, 032503 (2008)

[39] H. Q. Yuan, J. Singleton, F. F. Balakirev, S. A. Baily, G. F. Chen, J. L. Luo, and N. L. Wang, Nearly isotropic superconductivity in (Ba,K)Fe$_2$As$_2$, Nature 457, 565 (2009)

[40] M. P. Smylie, K. Willa, J. K. Bao, K. Ryan, Z. Islam, H. Claus, Y. Simsek, Z. Diao, A. Rydh, A. E. Koshelev, W. K. Kwok, D. Y. Chung, M. G. Kanatzidis, and U. Welp, Anisotropic superconductivity and magnetism in single-crystal RbEuFe$_4$As$_4$, Phys. Rev. B 98, 104503 (2018)

[41] W. Zhou, J. C. Zhuang, F. F. Yuan, X. Li, X. Z. Xing, Y. Sun, and Z. X. Shi, Anisotropic superconductivity of Ca$_{1-x}$La$_x$FeAs$_2$ (x ~ 0.18) single crystal, Appl. Phys. Express 7, 063102 (2014)

[42] H. Bai, M. Wang, X. Yang, Y. Li, J. Ma, X. Sun, Q. Tao, L. Li, and Z.-A. Xu, Superconductivity in tantalum self-intercalated 4Ha-Ta$_{1.03}$Se$_2$, J. Phys.: Condens. Matter 30, 095703 (2018)

[43] H. Bai, X. Yang, Y. Liu, M. Zhang, M. Wang, Y. Li, J. Ma, Q. Tao, Y. Xie, G.-H. Cao, and Z.-A. Xu, Superconductivity in a misfit layered compound (SnSe)$_{1.16}$(NbSe$_2$)$_2$, J. Phys.: Condens. Matter 30, 355701 (2018)

[44] H. Bai, L. Qiao, M. Li, J. Ma, X. Yang, Y. Li, Q. Tao, and Z.-A. Xu, Multi-band Superconductivity in a misfit layered compound (SnSe)$_{1.16}$(NbSe$_2$)$_2$, Mater. Res. Express 7, 016002 (2020)

[45] K.-I. Yokota, G. Kurata, T. Matsui, and H. Fukuyama, Superconductivity in the quasi-two-dimensional conductor 2H-TaSe$_2$, Physica B 284-288, 551 (2000)

[46] X. Zhu, Y. Sun, S. Zhang, J. Wang, L. Zou, L. E. DeLong, X. Zhu, X. Luo, B. Wang, G. Li, Z. Yang, and W. Song, Anisotropic intermediate coupling superconductivity in Cu$_{0.83}$TaS$_2$, J. Phys.: Condens. Matter 21, 145701 (2009)

[47] G. Baym and C. Pethick, *Landau Fermi-liquid theory: concepts and applications* (John Wiley & Sons, 2008).

[48] S. Sun, S. Wang, R. Yu, and H. Lei, Extreme anisotropy and anomalous transport properties of heavily electron doped Li$_3$(NH$_4$)$_y$Fe$_2$Se$_2$ single crystals, Phys. Rev. B 96, 064512 (2017)