Letter

Unusual upper critical fields of the topological nodal-line semimetal candidate \( \text{Sn}_x\text{NbSe}_2 - \delta \)

Riffat Munir\(^1\), K A M Hasan Siddiquee\(^1\), Charuni Dissanayake\(^1\), Xinzhe Hu\(^2\), Yasumasa Takano\(^2\), Eun Sang Choi\(^3\) and Yasuyuki Nakajima\(^1,\)\(^*\)

\(^1\) Department of Physics, University of Central Florida, Orlando, Florida 32816, United States of America
\(^2\) Department of Physics, University of Florida, Gainesville, Florida 32611, United States of America
\(^3\) National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32310, United States of America

E-mail: yasuyuki.nakajima@ucf.edu

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Abstract

We report superconductivity in \( \text{Sn}_x\text{NbSe}_2 - \delta \), a topological nodal-line semimetal candidate with a noncentrosymmetric crystal structure. The superconducting transition temperature \( T_c \) of this compound is extremely sensitive to Sn concentration \( x \) and Se deficiency \( \delta \). 5.0 K for \( \text{Sn}_0.13\text{NbSe}_{1.70} \) and 8.6 K for \( \text{Sn}_{0.14}\text{NbSe}_{1.71} \) and \( \text{Sn}_{0.15}\text{NbSe}_{1.69} \). In all samples, the temperature dependence of the upper critical field \( H_{c2}(T) \) differs from the prediction of the Werthamer–Helfand–Hohenberg theory. While the zero-temperature value of the in-plane upper critical field of \( \text{Sn}_x\text{NbSe}_2 - \delta \) with the higher \( T_c \) is lower than the BCS Pauli paramagnetic limit \( H_P \), that of the lower \( T_c \) sample exceeds \( H_P \) by a factor of \( \sim 2 \). Our observations suggest that a possible odd-parity contribution dominates the superconducting gap function of \( \text{Sn}_x\text{NbSe}_2 - \delta \), and it can be fine-tuned by the Sn concentration and Se deficiency.

Keywords: upper critical field, Pauli paramagnetic limit, topological nodal-line semimetals, topological superconductors

Supplementary material for this article is available online
(Some figures may appear in colour only in the online journal)

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Topological superconductors, characterized by a topologically nontrivial gapped state in the bulk with gapless surface states [1], have attracted great interest because of potential applications to topologically protected quantum computing [2, 3]. Such nontrivial gapped states can be stabilized by odd-parity Cooper pairing, occasionally realized in noncentrosymmetric superconductors with strong spin-orbit coupling. The lack of inversion symmetry in the crystal structures allows superposition of spin singlet (even parity) and spin triplet (odd parity) in superconducting gap functions. This mixing of parity can be fine-tuned by the spin-orbit coupling strength, as observed in the crossover from even to odd-parity pairing states in \( \text{Li}_2(\text{Pd},\text{Pt})_3\text{Bi} \) as the Pt concentration is varied [4]. Hence, the search for noncentrosymmetric superconductors with strong spin-orbit coupling serves as one of the routes toward the realization of topological superconductivity. The
noncentrosymmetric $ABSe_2$ ($A = Sn$ or Pb and $B = Nb$ or Ta) family is a promising candidate for a topological superconductor. Recent experimental studies have revealed superconductivity in PbTaSe$_2$ at $T_c = 3.8$ K [5, 6], with a fully opened superconducting gap probed by various measurements, including specific heat [7], thermal conductivity [8], and penetration depth measurements [9]. Moreover, angle-resolved photoemission spectroscopy has identified this materials as a topological nodal-line semimetal with drumhead surface states [10, 11]. Although the parity of the superconducting pairing state is yet to be determined, the lack of inversion symmetry along with the nontrivial topological band structure can induce topological superconductivity in this system in PbTaSe$_2$.

In addition to this compound, PbNbSe$_2$, SnNbSe$_2$, and SnTaSe$_2$ are predicted by ab-initio calculations to be superconductors with nontrivial topological nodal lines in the band structure [12]. According to the calculations, the superconducting transition temperatures, $T_c$, of these materials are expected to be higher than that of PbTaSe$_2$, and notably, the predicted $T_c$ of SnNbSe$_2$ is 7 K, suggestive of a possible realization of topological superconductivity in this material with a relatively high $T_c$, compared with known bulk topological superconductor candidates, such as half Heusler compounds YPtBi ($T_c = 0.6$ K) [13] and YPdBi ($T_c = 1.6$ K) [14], In-doped SnTe ($T_c = 1.2$ K) [15], metal-intercalated Bi$_2$Se$_3$ ($T_c = 3.2$ K) [16–18], and β-Bi$_2$Pd ($T_c = 5.4$ K) [19, 20]. The higher $T_c$ can be advantageous to detect Majorana bound states with the energy spacing $\Delta^*/E_F$, where $\Delta$ and $E_F$ are the superconducting gap and Fermi energy, respectively, and can eliminate one bottleneck in the exploration for topological superconductivity [21].

We here report unusual superconductivity in Sn$_x$NbSe$_{2-x}$, which retains the noncentrosymmetric crystal structure of stoichiometric $ABSe_2$. Although theoretical predictions specific to this compound are presently lacking, we propose by analogy to stoichiometric $ABSe_2$ that Sn$_x$NbSe$_{2-x}$ can be a promising candidate for a topological nodal-line semimetal. The superconducting transition temperature of Sn$_x$NbSe$_{2-x}$ varies with Sn concentration and Se deficiency—up to 8.6 K, a relatively high $T_c$ among bulk topological superconductor candidates known to date. The measured upper critical fields of Sn$_x$NbSe$_{2-x}$ cannot be described by the Werthamer–Helfand–Hohenberg (WHH) theory for conventional type-II superconductors [22], and the zero-temperature value of the upper critical field for Sn$_{0.15}$NbSe$_{1.69}$ exceeds the BCS Pauli paramagnetic limit by a factor of $\sim$2. The unusual temperature dependence of the upper critical fields and the enhancement beyond the Pauli paramagnetic limit suggest that a possible odd-parity component dominates the superconducting gap function of Sn$_x$NbSe$_{2-x}$, indicating that this compound is a promising candidate for realizing topological superconductivity.

Single crystals of Sn$_x$NbSe$_{2-x}$ were grown by using a self-flux method. A mixture of NbSe$_2$ and Sn in the ratio of NbSe$_2$:Sn = 1:2—6 was sealed in a quartz tube, heated up to 900°C, kept for 2–3 days, and slowly cooled down to 600°C. The excess of molten Sn flux was removed by centrifuging.

![Figure 1. Crystal structure and x-ray diffraction pattern of Sn$_{0.15}$NbSe$_{1.69}$](image)

The typical size of obtained flake-like crystals is about $1 \times 1 \times 0.3$ mm$^3$.

Our measured single-crystal x-ray diffraction pattern is consistent with the noncentrosymmetric crystal structure of Sn$_{0.15}$NbSe$_{1.69}$ with the space group P6/m2 [23]. (b) X-ray diffraction pattern for single crystal Sn$_{0.15}$NbSe$_{1.69}$, measured with Cu $K_\alpha$ radiation. We only observe (00$\ell$) Bragg peaks from the $ab$ plane. The obtained lattice constant $c$ is $9.2976(12)$ Å. Inset: optical image of a Sn$_{0.15}$NbSe$_{1.69}$ single crystal. The typical crystal size is $\sim 1 \times 1 \times 0.3$ mm$^3$.

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Our measured single-crystal x-ray diffraction pattern is consistent with the noncentrosymmetric crystal structure of Sn$_{0.15}$NbSe$_{1.69}$ with the space group P6/m2. As shown in figure 1(b), we observed only (00$\ell$) reflections, which yielded the lattice constant $c = 9.2976(12)$ Å close to the reported value of 9.30 Å for polycrystalline Sn$_{0.15}$NbSe$_{1.69}$ [24]. The atomic ratio of the crystals was found to be Sn: Nb: Se = 0.11–0.15:1:1.60–1.74 with x-ray fluorescence spectroscopy, suggestive of slightly intercalated Sn and deficiency of Se. Although the Sn concentrations in our samples are only 11%–15% of the stoichiometric value, the identified crystal structure is the same as that of $ABSe_2$ and different from the 2H–NbSe$_2$-type structure of Sn-intercalated NbSe$_2$ with $x$ up to 0.04 [25].

We reveal superconductivity in Sn$_x$NbSe$_{2-x}$ with resistivity measurements from 300 K down to 2 K. Figure 2(a) shows a typical temperature dependence of the resistivity of Sn$_x$NbSe$_{2-x}$. The resistivity at $T = 300$ K is about 700 $\mu\Omega$ cm. Upon cooling, the resistivity shows metallic behavior, followed by a superconducting transition at low temperatures (figure 2(a)). The superconducting transition temperatures $T_c$, determined by the midpoint of resistive transitions, are 5.0 K for Sn$_{0.13}$NbSe$_{1.70}$ and 8.6 K for
both Sn and NbSe, indicating superconducting transitions at 5.0 K for Sn$_{0.13}$NbSe$_{1.70}$ and 8.6 K for Sn$_{0.14}$NbSe$_{1.69}$ and Sn$_{0.15}$NbSe$_{1.69}$ (figure 2(a) inset). In contrast, no superconductivity has been observed down to 1.5 K in polycrystalline Sn$_2$NbSe$_2$ [26]. We observe Meissner screening at low temperatures starting at $T \sim 7$ K, where the resistivity becomes zero in Sn$_{0.14}$NbSe$_{1.71}$ (figure 2(b)). The superconducting volume fraction determined by a calibration using tin is $\sim 30\%$, comparable to typical volume fractions achieved by early works on Cu$_x$Bi$_2$Se$_3$ [16, 17]. It has been pointed out that sample qualities of ABSe$_2$ can be correlated with the presence of stacking faults [7], which is in fact supported by our powder x-ray diffraction result (see supplementary material (https://stacks.iop.org/JPCM/33/23LT01/mmedia)). The imperfect volume fraction found in our sample suggests that stacking faults may, by affecting local stoichiometry, be causing some regions to remain nonsuperconducting.

The normal-state resistivity of Sn$_{0.14}$NbSe$_{2-\delta}$ right above $T_c$ is much higher than that of PbTaSe$_2$. Because of this high residual resistivity, the values of the residual resistivity ratio RRR = $\rho(300 \text{ K})/\rho(T_c)$ are $2.3$ for Sn$_{0.13}$NbSe$_{1.70}$, $2.7$ for Sn$_{0.14}$NbSe$_{1.71}$, and $3.0$ for Sn$_{0.15}$NbSe$_{1.69}$, $30$–$50$ times as small as that of single-crystal PbTaSe$_2$ [6, 7, 27]. Interestingly, despite the high residual resistivity, or the low RRR, the $T_c$ of 8.6 K not only surpasses the theoretical prediction of $7$ K [12] but also those of most known topological superconductor candidates.

To determine the upper critical fields of Sn$_{0.14}$NbSe$_{2-\delta}$, we measured the resistivity in a 35 T resistive magnet equipped with a $^3$He cryostat at the National High Magnetic Field Laboratory in Tallahassee, Florida. We show magnetoresistance of Sn$_{0.14}$NbSe$_{2-\delta}$ in two different magnetic field configurations: $H \parallel I \parallel ab$ (in-plane configuration) and $H \perp ab, I \parallel ab$ (out-of-plane configuration). For both field configurations and in both Sn$_{0.13}$NbSe$_{1.70}$ and Sn$_{0.14}$NbSe$_{1.71}$, the magnetoresistance is indiscernible even at an applied magnetic field of 35 T (figure 3), indicative of short mean free paths of charge carriers due to disorder caused most likely by slightly intercalated Sn and deficiency of Se. On the other hand, we find a notable difference in the anisotropy of upper critical fields, $\Gamma = H_{c2}/H_{c1}$, between these two samples. In the out-of-plane configuration for Sn$_{0.13}$NbSe$_{1.70}$ (figure 3(b)), the upper critical field parallel to the $c$ axis, $H_{c2}$, defined by the midpoints of sharp resistive transitions, is 5 T at 0.3 K. In the in-plane configuration for Sn$_{0.14}$NbSe$_{1.70}$ (figure 3(a)), the transition widths are broad, and the upper critical field parallel to the $ab$ plane, $H_{c2}^{ab}$, is extremely high, extracted to be $15$ T at 0.3 K. These values of $H_{c2}$ yield a large anisotropy of the upper critical field, $\Gamma = 3$, for Sn$_{0.15}$NbSe$_{1.69}$. In contrast, we observe similar transition widths with very similar $H_{c2}$ in both field configurations for Sn$_{0.14}$NbSe$_{1.71}$, suggestive of a nearly isotropic upper critical field with $\Gamma = 1.1$ (figures 3(d) and (e)). In the isostructural compound PbTaSe$_2$, the anisotropy of $H_{c2}$ is measured to be 11.6 [6], much larger than the observed anisotropy in Sn$_{0.14}$NbSe$_{2-\delta}$, although the two compounds share similar electronic band structures [12]. The striking difference in the upper critical fields and the transition temperatures between Sn$_{0.13}$NbSe$_{1.70}$ and Sn$_{0.14}$NbSe$_{1.69}$ and Sn$_{0.15}$NbSe$_{1.71}$ may be correlated with carrier densities determined by the Sn concentration and Se deficiency. A slight change in the carrier densities can cause a drastic change in superconducting properties and may even induce a superconducting pairing symmetry transition.

We also measured in-plane anisotropy of the upper critical field in Sn$_{0.11}$NbSe$_{1.70}$. As shown in figure 3(c), magnetoresistance at fields parallel to the $ab$-plane but perpendicular to the applied current shows broad transitions accompanied by kinks indicated by black arrows. The upper critical fields in this configuration, determined by 50% of resistive transitions, are slightly lower than those in the configuration for $H \parallel I \parallel ab$, as can be seen in figure 3(a), suggesting a discernible in-plane anisotropy.

Figure 3(f) shows the Hall resistivity $\rho_{xy}$ of Sn$_{0.11}$NbSe$_{1.60}$ in the normal state. The Hall resistivity is positive and perfectly
Figure 3. Magnetotransport in Sn$_x$NbSe$_2$$_{−\delta}$. Resistivity of Sn$_{0.13}$NbSe$_{1.70}$ as a function of magnetic fields parallel to (a) the $ab$ plane and (b) the $c$ axis at several temperatures. Electrical current is applied in the $ab$ plane. While the resistive transitions for $H \parallel c$ are sharp, the transitions for $H \parallel ab$ are broad. The upper critical fields obtained by the midpoints of the resistive transitions show high anisotropy \( \Gamma = \frac{H_{c2}^{ab}}{H_{c2}^{c}} = 3 \) in Sn$_{0.13}$NbSe$_{1.70}$. (c) Transverse magnetoresistance of Sn$_{0.13}$NbSe$_{1.70}$ in magnetic fields parallel to the $ab$ plane. The resistive transitions are broad, and show kinks indicated by arrows, associated with vortex motion due to the Lorentz force. The extracted $H_{c2}^{ab}$ for $H \perp I$ is slightly lower than $H_{c2}^{c}$ for $H \parallel I$, obtained from the curves shown in panel (a). Resistivity of Sn$_{0.14}$NbSe$_{1.71}$ as a function of magnetic fields parallel to (d) the $ab$ plane and (e) the $c$ axis at various temperatures. Despite the layered structure of the compound, the upper critical field is nearly isotropic, $\Gamma = 1.1$, in Sn$_{0.14}$NbSe$_{2.71}$. (f) Field dependence of the Hall resistivity of Sn$_{0.11}$NbSe$_{1.60}$ at 7 K ($H \parallel c, I \parallel ab$). The Hall resistivity $\rho_{xy}$ is linear in $H$ with the positive sign indicating that the hole band dominates the transport in Sn$_x$NbSe$_{2−\delta}$. The extracted Hall coefficient $R_H$ from the slope of $\rho_{xy}$ is $5.3 \times 10^{-3}$ cm$^3$ C$^{-1}$, yielding a carrier density of $1.2 \times 10^{21}$ cm$^{-3}$. 
linear in magnetic fields in the normal state above $T_{c}$, indicative of a dominant contribution to the charge transport from a large cylindrical hole band, around the Γ point, predicted by theoretical calculations [12, 28]. The slope of the Hall resistivity gives the Hall coefficient $R_H = 5.3 \times 10^{-3}$ cm$^3$ C$^{-1}$, hence the carrier density $n = 1.2 \times 10^{21}$ cm$^{-3}$.

The upper critical fields of Sn$_{0.13}$NbSe$_{2.70}$ exhibit quite unusual behavior, as shown in figure 4. With decreasing temperature starting from $T_{c}$, $H_{c2}$ increases linearly in all the field configurations for both Sn$_{0.13}$NbSe$_{2.70}$ and Sn$_{0.14}$NbSe$_{2.71}$. The initial slopes of the upper critical fields parallel to the $ab$ plane for $H || I$, $dH_{c2}/dT|_{T=T_{c}}$, are $-3.2$ T/K for Sn$_{0.13}$NbSe$_{2.70}$ and $-1.5$ T/K for Sn$_{0.14}$NbSe$_{2.71}$, extremely larger than $-0.19$ K/T for PbTaSe$_2$ for $H || ab$ [7]. The observed temperature dependence of $H_{c2}$ for Sn$_{0.13}$NbSe$_{2.70}$ completely differs from those of conventional type-II superconductors. In conventional type-II superconductors, upper critical fields due to the orbital effect are explicated by the WHH theory [22]. In the WHH theory, the zero-temperature value of upper critical field can be written as $H_{c2}(0) = \alpha T_c dH_{c2}/dT|_{T=T_{c}}$, where $\alpha$ is 0.69 for the dirty limit and 0.73 for the clean limit [22]. However, as shown in the insets to figures 4(a) and (b), the normalized upper critical field $h = H_{c2}/(-T_c dH_{c2}/dT|_{T=T_{c}})$ strikingly deviates from the WHH values and is close to the calculations for the Pauli paramagnetic limit $\mu_0H_P$ = 15.6 T, indicated by a blue dashed line. Inset: normalized upper critical field $h$ as a function of $T$ for Sn$_{0.14}$NbSe$_{2.71}$. The normalized upper critical fields for both $H || ab$ and $H || c$ depart from the WHH model at low temperatures and are close to the calculation for the polar $p$-wave state [29].

In Sn$_{0.14}$NbSe$_{2.71}$, $\mu_0H_{c2}^{ab}(0)$ is 13 T, comparable to but slightly lower than $\mu_0H_P = 15.6$ T enhanced by the higher $T_c$ of 8.6 K (figure 4(b)). The zero temperature values of out-of-plane upper critical fields $\mu_0H_{c2}^{c}(0)$ of Sn$_{0.14}$NbSe$_{2.71}$ are lower than the Pauli paramagnetic limit $\mu_0H_P$. Utilizing the Ginzburg–Landau relation, $\mu_0H_{c2}^{c}(0) = \phi_0/2\pi\xi_{ab}$, and $\mu_0H_{c2}^{c}(0) = \phi_0/2\pi\xi_d$, where $\phi_0$ is the magnetic flux quantum, we can estimate the coherence lengths: $\xi_{ab} = 15$ nm and $\xi_c = 4.5$ nm for Sn$_{0.14}$NbSe$_{2.70}$ and $\xi_{ab} = 5.0$ nm and $\xi_c = 6.0$ nm for Sn$_{0.13}$NbSe$_{2.70}$. Although our observations suggest the presence of a possible odd-parity contribution to the pairing states at least in Sn$_{0.13}$NbSe$_{2.70}$ with $T_c$ of 5.0 K, its superconductivity is robust against scattering due to nonmagnetic disorder. In general, nonmagnetic scattering strongly suppresses unconventional superconductivity [33], including odd-parity pairing states, as described by the Abrikosov–Gor’kov model [34]. The Abrikosov–Gor’kov model shows that $T_c$ of unconventional superconductors are dramatically suppressed to zero by non-magnetic scattering, as the mean free path $\ell$ becomes comparable to the coherence length, $\xi \sim \ell$. To estimate the mean free paths in Sn$_{0.13}$NbSe$_{2.70}$, we exploit the Hall effect, along with electrical resistivity. Assuming a single cylindrical hole band,
we can extract mean free paths by using $\ell = (\hbar/e^2)\sqrt{2\pi c/e n}$, where $c$ is the lattice constant along the $c$ axis. The extracted mean free paths at $T_c$ are $\ell = 5.9$ nm for Sb$_{0.13}$NbSe$_{1.70}$ and 3.1 nm for Sn$_{0.14}$NbSe$_{1.71}$. Here we have used the carrier density $n$ from the Hall coefficient for Sb$_{0.11}$NbSe$_{1.60}$. Surprisingly, these values are much smaller than the coherence lengths in the $ab$ plane, intuitively inconsistent with the possible odd-parity pairing state.

However, there is a precedence in which odd-parity superconductivity was found to be invulnerable to nonmagnetic disorder—metal-intercalated Bi$_2$Se$_3$ [17, 32, 35]. In this topological superconductor, the robustness of the odd-parity superconductivity is thought to be due to strong spin–orbit coupling [36, 37]. Similarly, nonnegligible spin–orbit coupling due to Sn, a relatively heavy element, may be protecting superconductivity in Sn$_{0.13}$NbSe$_{1.70}$ against strong nonmagnetic disorder. The shared features of superconductivity in the two compounds—the upper critical fields beyond the Pauli paramagnetic limit and the robust superconductivity against disorder—possibly suggest that the odd-parity superconductivity is realized in Sn$_{0.13}$NbSe$_{1.70}$.

We briefly comment on a possible nematic superconducting state in the PbTaSe$_2$ family. Nematic superconductivity, accompanied by a rotational symmetry breaking in the superconducting state, is observed in metal-intercalated Bi$_2$Se$_3$, evidencing topological superconductivity in the system [38–41]. Similarly, in PbTaSe$_2$, soft point-contact spectroscopy [42] elucidates the rotational symmetry breaking in superconducting properties, possibly associated with nematic superconductivity. In Sn$_{0.13}$NbSe$_{1.70}$, we observe clear anisotropy in in-plane upper critical fields for two different configurations, $H \parallel I$ and $H \perp I$, as shown in figure 4(a). However, the measured anisotropy can be attributed to the presence/absence of flux flow due to the Lorentz force as observed in MgB$_2$ [43], masking intrinsic twofold symmetry associated with electronic nematicity in this system, if present. Indeed, we observe kinks in the resistive transition associated with vortex motion due to the Lorentz force only in the $H \perp I$ configuration as shown in figure 3(c) [44]. To determine the intrinsic in-plane anisotropy, further experimental investigations will be required.

In summary, we have grown single crystals of Sn$_x$NbSe$_{2−x}$ with a noncentrosymmetric crystal structure, and found superconductivity with relatively high $T_c$, 8.6 K, among known topological superconductor candidates. The upper critical field of Sn$_{0.13}$NbSe$_{1.70}$, with $T_c = 5$ K, exceeds the Pauli paramagnetic limit, suggestive of a possible contribution of odd-parity pairing in the superconductivity. The possible odd-parity pairing component, a prerequisite for topological superconductivity, makes this system a promising material for further study.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Yasuyuki Nakajima https://orcid.org/0000-0002-4584-3621

References

[1] Sato M and Ando Y 2017 Rep. Prog. Phys. 80 076501
[2] Kitaev A Y 2003 Ann. Phys. NY 303 2
[3] Nayak C, Simon S H, Stern A, Freedman M and Das Sarma S 2008 Rev. Mod. Phys. 80 1083
[4] Harada S, Zhou J J, Yao Y G, Inada Y and Zheng G-q. 2012 Phys. Rev. B 86 220502
[5] Ali M N, Gibson Q D, Klimczuk T and Cava R J 2014 Phys. Rev. B 89 020505
[6] Long Y-J, Zhao L-X, Wang P-P, Yang H-X, Li J-Q, Zhi H, Ren Z-A, Ren C and Chen G-F 2016 Chinese Phys. Lett. 33 037401
[7] Zhang C-L, Yuan Z, Bian G, Xu S-Y, Zhang X, Hasan M Z and Jia S 2016 Phys. Rev. B 93 054520
[8] Wang M X, Xu Y, He L P, Zhang J, Hong X C, Cai P L, Wang Z B, Dong J K and Li S Y 2016 Phys. Rev. B 93 020503
[9] Pang G M et al 2016 Phys. Rev. B 93 060506
[10] Bagenet G et al 2016 Nat. Commun. 7 10556
[11] Chang T-R et al 2016 Phys. Rev. B 93 245130
[12] Chen P-J, Chang T-R and Jeng H-T 2016 Phys. Rev. B 94 165148
[13] Butch N P, Syers P, Kirshenbaum K, Hope A P and Paglione J 2017 Phys. Rev. B 84 220504
[14] Nakajima Y et al 2015 Sci. Adv. 1
[15] Sasaki S, Ren Z, Taskin A A, Segawa K, Fu L and Ando Y 2012 Phys. Rev. Lett. 109 217004
[16] Hor Y S et al 2010 Phys. Rev. Lett. 104 057001
[17] Krien M, Segawa K, Ren Z, Sasaki S and Ando Y 2011 Phys. Rev. Lett. 106 127004
[18] Liu Z, Yao X, Shao J, Zuo M, Pi L, Tan S, Zhang C and Zhang Y 2015 J. Am. Chem. Soc. 137 10512
[19] Imai Y, Nabeishima F, Yoshinaka T, Miyatani K, Kondo R, Komia Y, Tsukada I and Maeda A 2012 J. Phys. Soc. Japan 81 113708
[20] Liu P-F, Li J, Tu X-H, Yin H, Su B, Zhang J, Singh D J and Wang B-T 2020 Phys. Rev. B 102 155406
[21] Beenakker C W J 2015 Rev. Mod. Phys. 87 1037
[22] Werthamer N R, Helfand E and Hohenberg P C 1965 Phys. Rev. 147 295
[23] Momma K and Izumi F 2011 J. Appl. Cryst. 44 1272
[24] Gentile P S, Driscoll D A and Hockman A J 1979 Inorg. Chim. Acta 35 249
[25] Naik S, Pradhan G K, Bhat S G, Behera B C, Kumar P S A, Samal S L and Samal D 2019 Physica C 561 18
[26] Karnezos N, Welsh L B and Shafer M W 1975 Phys. Rev. B 11 1808
[27] Sankar R, Rao G N, Muthuselvam I P, Chang T-R, Jeng H T, Murugan G S, Lee W-L and Chou F C 2017 J. Phys.: Condens. Matter. 29 095601
[28] Xu X, Kang Z, Chang T-R, Lin H, Bian G, Yuan Z, Qu Z, Zhang J and Jia S 2019 Phys. Rev. B 99 104516
[29] Schambon K and Klemm R A 1980 Phys. Rev. B 22 5233
[30] Clogston A M 1962 Phys. Rev. Lett. 9 266
[31] Bauer E et al 2004 Phys. Rev. Lett. 92 027003
[32] Bay T V, Naka T, Huang Y K, Luigjes H, Golden M S and de Visser A 2012 Phys. Rev. Lett. 108 057001
[33] Mackenzie A P, Haselwimmer R K W, Tyler A W, Lonzarich G G, Mori Y, Nishizaki S and Maeno Y 1998 Phys. Rev. Lett. 80 161
[34] Abrikosov A A and Gor’kov L P 1960 Zh. Éksp. Teor. Fiz. 39 1781
          Abrikosov A A and Gor’kov L P 1961 Sov. Phys. JETP 12 1243 (Engl. transl.)
[35] Sasaki S, Kriener M, Segawa K, Yada K, Tanaka Y, Sato M and Ando Y 2011 Phys. Rev. Lett. 107 217001
[36] Michaeli K and Fu L 2012 Phys. Rev. Lett. 109 187003
[37] Nagai Y, Ota Y and Machida M 2014 Phys. Rev. B 89 214506
[38] Matano K, Kriener M, Segawa K, Ando Y and Zheng G-q 2016 Nat. Phys. 12 852
[39] Pan Y, Nikitin A M, Araizi G K, Huang Y K, Matsushita Y, Naka T and de Visser A 2016 Sci. Rep. 6 28632
[40] Smylie M P et al 2017 Phys. Rev. B 96 115145
[41] Yonezawa S, Tajiri K, Nakata S, Nagai Y, Wang Z, Segawa K, Ando Y and Maeno Y 2017 Nat. Phys. 13 123
[42] Le T et al 2020 Sci. Bull. 65 1349
[43] Shi Z X, Tokunaga M, Tamegai T, Takano Y, Togano K, Kito H and Ihara H 2003 Phys. Rev. B 68 104513
[44] Zhu X D, Lu J C, Sun Y P, Pi L, Qu Z, Ling L S, Yang Z R and Zhang Y H 2010 J. Phys.: Condens. Matter. 22 505704