Nodeless superconductivity in the SnAs-based van der Waals-type superconductor NaSn$_2$As$_2$

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Abstract – We grew the single crystals of the SnAs-based van der Waals (vdW)-type superconductor NaSn$_2$As$_2$ and systematically measured its resistivity, specific heat, and ultralow-temperature thermal conductivity. The superconducting transition temperature $T_c = 1.60$ K of our single crystal is 0.3 K higher than that previously reported. A weak but intrinsic anomaly situated at 193 K is observed in both resistivity and specific heat, which likely arises from a charge-density-wave (CDW) instability. Ultralow-temperature thermal conductivity measurements reveal a fully gapped superconducting state with a negligible residual linear term in zero magnetic field, and the field dependence of $\kappa_0/T$ further suggests NaSn$_2$As$_2$ is an s-wave superconductor.

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Introduction. – Phonon-mediated conventional superconductors possess s-wave pairing symmetry, while unconventional ones prefer d-wave, p-wave or s$_\pm$-wave and their pairing glues are likely not phonon [1]. Unconventional superconductivity usually resides in quasi-two-dimensional (quasi-2D) compounds, such as cuprates, iron-based superconductors, Sr$_2$RuO$_4$, heavy-fermion and organic superconductors [2–6]. In the field of condensed-matter physics, one of the most intriguing themes is finding new quasi-2D superconductors and illuminating their underlying superconducting pairing mechanism.

Quasi-2D superconductors with weak vdW force in interlayers can be exfoliated into monolayer or few atomic-layers films [7]. By mechanically reducing the dimensionality of quasi-2D vdW-type superconductors or using molecular beam epitaxy (MBE), it is possible to realize a highly crystalline 2D superconducting system with exotic properties that differ from the bulk [8–11]. For example, Ising superconductivity and a field-induced Bose-metal phase were observed in atomically thin NbSe$_2$ [9,10], and the observation of a quantum Griffiths singularity was reported in Ga films [11]. Moreover, with the development of ionic gating techniques, the superconducting transition temperature can be tuned [12]. To explore more exotic phenomena and clarify the superconducting pairing mechanism in the vdW-type superconductors, different types of compounds are highly desirable.

Recently, the first superconducting 2D SnAs-based compound, NaSn$_2$As$_2$ with a bulk $T_c = 1.3$ K, was reported [13]. Later, its sister compound Na$_{1-x}$Sn$_2$P$_2$ with $T_c = 2.0$ K was also discovered [14]. As schematically shown in fig. 1(a), NaSn$_2$As$_2$ consists of SnAs bilayers separated by Na$^+$ cations crystallizing a trigonal $R3m$ unit cell, which is structurally different from the tetragonal “122” iron-based superconductors [3]. NaSn$_2$As$_2$ can be exfoliated into monolayer or few-layers films by using liquid-phase or mechanical lift-off techniques, making it a vdW-type superconductor [8,15]. Stoichiometric, NaSn$_2$As$_2$ is a non-electron-balanced compound assuming a $+2$ oxidation state for Sn, and $-3$ oxidation state for As [13]. In NaSn$_2$As$_2$, the Sn$_{2+}$ ions are accompanied by lone-pair electrons [13]. Lone-pair electrons lead to a strong anharmonicity because of the nonlinear terms in the total energy relevant to a large nonhybrid

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valence electronic contribution, resulting in low thermal conductivity as well as structural distortion [16]. This is reminiscent of the RE(O, F)BiS\textsubscript{2} compounds (RE represents rare-earth elements) which include Bi\textsuperscript{3+} lone pair electrons, and the lone-pair effect is likely relevant to superconductivity [17]. Recent literature also reported on unconventional superconducting pairing mechanism in RE(O, F)BiS\textsubscript{2} compounds [18], which is in contrast with previous study [19]. This inspires us to explore the superconducting pairing symmetry of NaSn\textsubscript{2}As\textsubscript{2} with lone-pair electrons.

In this paper, we present the growth of high-quality NaSn\textsubscript{2}As\textsubscript{2} single crystals, and systematic measurements of their resistivity, specific heat, and ultralow-temperature thermal conductivity. The \( T_c = 1.60 \) K of our single crystals is 0.3 K higher than that in ref. [13]. A previously unobserved anomaly around 193 K is evidenced from both resistivity and specific heat, with its origin closely related to the formation of CDW. Ultralow-temperature thermal conductivity measurements demonstrate that NaSn\textsubscript{2}As\textsubscript{2} is an \( s \)-wave superconductor with a nodeless superconducting gap.

**Experiments.** – Single crystalline NaSn\textsubscript{2}As\textsubscript{2} was synthesized by a Sn-flux method, which is different from that of previous reports [13,15]. Arsenic lumps (99.999%, Aladdin), sodium chunks (99.99%, Aladdin), and tin powder (99.999%, Aladdin) in the ratio Na : Sn : As = 1 : 10 : 2 were used as starting materials. A charge of 1.0 g was put in an alumina crucible and sealed in a quartz ampoule. The sealed ampoule was heated to 750°C and kept there for 3 days, then cooled at a rate of 1.5 K/h. The ampoule was taken out and decanted with a centrifuge to remove excess Sn flux at 350°C, acquiring plate-like single crystals, as shown in the left inset in fig. 1(c). The chemical composition of the NaSn\textsubscript{2}As\textsubscript{2} single crystals is Na : Sn : As = 1 : 1.89(6) : 2.09(7) determined by electro-probe microanalysis (EPMA).

For transport measurements, the NaSn\textsubscript{2}As\textsubscript{2} single crystal was cleaved and cut into a rectangular shape of dimensions 3.0 \times 0.5 mm\textsuperscript{2} in the \( ab \) plane, with 0.2 mm thickness along the \( c \)-axis. Four electrodes were directly attached on the sample surface with silver paint, and the typical contact resistance is 30 m\( \Omega \) at 0.3 K. Resistivity measurements from 300 to 2 K and down to 0.3 K were performed in a physical property measurement system (PPMS; Quantum Design) and a 3He cryostat, respectively. Heat capacity measurements were conducted using the relaxation method in a PPMS equipped with a dilution refrigerator. Microstructure analysis was performed on Tecnai F20 and H-9000NA transmission electron microscopes both equipped with low-temperature holders. The thermal conductivity study was conducted in a dilution refrigerator via a standard four-wire steady-state method with two RuO\textsubscript{2} chip thermometers calibrated in situ against a reference RuO\textsubscript{2} thermometer. Magnetic fields were normal to the \( ab \) plane and the heat current. To obtain a homogeneous field distribution in the NaSn\textsubscript{2}As\textsubscript{2} single crystal, magnetic fields were applied at a temperature above \( T_c \) for both resistivity and thermal conductivity measurements.

**Results and discussion.** – From X-ray diffraction measurements, as shown in fig. 1(c), the largest surface of the single crystals is identified to be the (001) plane of NaSn\textsubscript{2}As\textsubscript{2}. From an X-ray rocking curve of the (009) Bragg peak, the full width at half-maximum (FWHM) of 0.05° indicates the high quality of the NaSn\textsubscript{2}As\textsubscript{2} single crystal. In fig. 2(a), we present the resistivity of a NaSn\textsubscript{2}As\textsubscript{2} single crystal from 0.3 to 300 K. The resistivity curve from 2 to 10 K is fitted by adopting the formula \( \rho = \rho_0 + AT^n \), obtaining a residual resistivity \( \rho_0 = 60.3 \mu \Omega \text{cm} \) and \( n = 3.5 \). The residual resistivity ratio (RRR) \( \rho(300 \text{K})/\rho_0 \) of 3.7 is larger than the 1.6 reported in [13], manifesting better sample quality.

In addition to the superconducting transition at low temperature in fig. 2(a), there are two eye-catching features at the normal state that are worth pointing out and may imply rich physics. The first of all, the fitting factor of the lower region is 3.5 (as shown in the upper inset of fig. 2(a)), which is higher than the \( T^2 \) of the Fermi-liquid behavior but lower than the \( T^5 \) relation caused by phonon scattering. According to the notion proposed by A. H. Wilson, scattering from a low-mass band into a high-density one could induce a higher power law of

![Fig. 1](image_url)
Nodeless superconductivity in the SnAs-based van der Waals-type superconductor NaSn$_2$As$_2$

Fig. 2: (Colour online) (a) Low-temperature resistivity of the NaSn$_2$As$_2$ single crystal from 0.3 to 300 K; the weak anomaly at 193 K is marked as $T_a$. The inset in the upper left demonstrates the low-temperature power law by plotting $\rho$ vs. $T^\alpha$, with $n = 3.5$. The right inset shows the derivative of resistivity with respect to temperature together across the kink at 193 K. (b) Specific heat of a NaSn$_2$As$_2$ single crystal. A weak phase transition at 191 K is shown and marked with a red arrow. The left inset shows the phase transition and the derivative of the specific heat with respect to temperature. The right inset displays the susceptibility result with a magnetic field of 0.5 T. (c) and (d) show the electron diffraction patterns of NaSn$_2$As$_2$ at 300 and 95 K, respectively.

Fig. 3: (Colour online) (a) Low-temperature resistivity of the NaSn$_2$As$_2$ single crystal in zero field. The $T_c$ is defined as the intersection of two straight lines, which gives 1.60 K and 1.48 K for onset and zero-point $T_c$, respectively. (b) Temperature dependence of specific heat divided by temperature at low temperature. The red line shows the fitting above the superconducting state with $C_p/T = \gamma + \beta T^2 + \delta T^4$. (c) Low-temperature resistivity at magnetic fields perpendicular to the $ab$ plane. (d) The upper critical fields defined by onset and zero-point superconducting temperatures with field perpendicular and parallel to the $ab$ plane.

The superconducting transition in the resistivity is plotted in fig. 3(a), and the $T_c$’s are 1.60 and 1.48 K for the onset and zero-point ($T_{c,\text{onset}}$, $T_{c,\text{zero}}$) temperatures, respectively. The $T_c$ of our sample is 0.3 K higher than that in previous work [13]. We note that variations in Na content between our samples and those reported previously [13] may affect $T_c$, as it does in Na$_{1-x}$Sn$_2$P$_2$ [14]. However, EPMA detected no Na deficiency, and the stoichiometry of our crystals is well within the uncertainty of those reported previously [13]. Higher purity or crystallinity may be responsible for the higher $T_c$. Figure 3(b) shows the low-temperature specific heat divided by the temperature, $C_p/T$, as a function of temperature in zero field. The superconducting transition at 1.47 K appears. Recent electronic structure calculations on NaSn$_2$As$_2$ found that its electronic states near the Fermi level ($E_F$) are primarily derived from the contribution of nonmagnetic Sn-s, Sn-p, and some As-p orbitals [15], which further suggests that this compound lies far from magnetic instabilities. CDWs often appear in 2D compounds [21], and are accompanied by a superlattice [21–23]. Together with a weak broad peak in specific heat and a higher power law of temperature in resistivity, we speculate that the anomaly in 2D NaSn$_2$As$_2$ might arise from a CDW instability. The failed observation of a superlattice pattern at low temperature should be due to the weakness of the CDW in NaSn$_2$As$_2$. To verify this speculation, more solid evidence will be required.

To check if the anomaly arises from a magnetic phase transition, the susceptibility measurement was conducted. As shown in the inset of fig. 2(b), no anomaly around 193 K appears. The superconducting transition in the resistivity is plotted in fig. 3(a), and the $T_c$’s are 1.60 and 1.48 K for the onset and zero-point ($T_{c,\text{onset}}$, $T_{c,\text{zero}}$) temperatures, respectively. The $T_c$ of our sample is 0.3 K higher than that in previous work [13]. We note that variations in Na content between our samples and those reported previously [13] may affect $T_c$, as it does in Na$_{1-x}$Sn$_2$P$_2$ [14]. However, EPMA detected no Na deficiency, and the stoichiometry of our crystals is well within the uncertainty of those reported previously [13]. Higher purity or crystallinity may be responsible for the higher $T_c$. Figure 3(b) shows the low-temperature specific heat divided by the temperature, $C_p/T$, as a function of temperature in zero field. The superconducting transition at 1.47 K appears.
corresponds to the observation in resistivity. Above $T_c$, the data from 1.5 to 3 K of $C_p/T$ vs. $T$ can be well fitted by $C_p/T = \gamma + \beta T^2 + \delta T^4$. The electronic specific-heat coefficient $\gamma$ and the phononic coefficient $\beta$ are determined to be 1.90 mJ mol$^{-1}$ K$^{-2}$ and 0.94 mJ mol$^{-1}$ K$^{-4}$, respectively. The Debye temperature $\Theta_D \approx 218$ K is estimated by adopting the formula $\Theta_D = (12\pi^2 r N_A k_B / 5\beta)^{1/3}$, where $r = 5$ is the number of atoms per formula unit, $N_A$ is the Avogadro constant, and $k_B$ is the Boltzmann constant, respectively. Figure 3(c) plots the low-temperature resistivity of NaSn$_2$As$_2$ in various magnetic fields up to 0.3 T showing that the superconducting transition is gradually suppressed with magnetic field. Considering the Ginzburg-Landau theory, $\rho(T) = \rho_0(T) + \rho_s(T)$, here $T = T/T_c$, the zero-temperature upper critical field $\rho_s(T)$ is determined to be $0.12$ and $0.14$ T, the value of $\rho_0(0) = 0.003$ mW K$^{-2}$ cm$^{-1}$, which is negligible with our experimental error bar of $0.15$ mW K$^{-2}$ cm$^{-1}$.

As for the parameter of $\alpha$, its value is typically between 2 and 3 because of specular reflections of phonons at the sample surfaces [27]. For s-wave nodeless superconductors, there are no fermionic quasi-particles to conduct heat as $T \to 0$, since all electrons become Cooper pairs [27]. Therefore, there is no residual linear term of $\kappa_0/T$, as seen in Nb, InBi and NbSe$_2$ [28–30]. However, for nodal superconductors, a substantial $\kappa_0/T$ in zero field contributed by the nodal quasi-particles has been found. For example, $\kappa_0/T$ of the overdoped ($T_c = 15$ K) d-wave cuprate superconductor Tl$_2$Ba$_2$CuO$_{6+\delta}$ (Tl-2201) is 1.41 mW K$^{-2}$ cm$^{-1}$, $\sim \kappa_0/T$ [31]. For the p-wave superconductor Sr$_2$RuO$_4$ ($T_c = 1.5$ K), $\kappa_0/T$ is 17 mW K$^{-2}$ cm$^{-1}$ was reported, more than 9% $\kappa_0(T)/T$ [4]. Hence, the negligible $\kappa_0/T$ of NaSn$_2$As$_2$ strongly suggests a nodeless superconducting gap structure.

Figure 4(b) shows $\kappa/T$ vs. $T$ plots of temperature-dependent thermal conductivity for a NaSn$_2$As$_2$ single crystal under magnetic fields. All the data of $\kappa/T$ vs. $T$ are fitted and the $\kappa_0/T$ for each field is obtained. In 0.12 and 0.14 T, the value of $\kappa_0/T$ is $0.43 \pm 0.04$ and $0.42 \pm 0.04$ mW K$^{-2}$ cm$^{-1}$, respectively. We determined the normal-state expectation value of the Wiedemann-Franz law $L_0/\rho_0$ (0.12 T) $= 0.41$ mW K$^{-2}$ cm$^{-1}$, where the Lorenz number $L_0 = 2.45 \times 10^{-8}$ W Ω K$^{-2}$ and $\rho_0$ (0.12 T) = 60.3 μΩ cm. The value of $\kappa_0/T$ in 0.12 T meets the expectation, which means that the normal state
has been reached. Note that the $H_{c2}$ defined by $\rho = 0$ is 0.14 T, when the magnetic field is perpendicular to the $ab$ plane. Therefore, the upper critical fields of NaNb$_2$As$_2$ in our thermal conductivity and resistivity experiments are consistent, which demonstrates that our thermal conductivity measurements are reliable.

Further information on the superconducting pairing symmetry can be provided by examining the behavior of field-dependent $\kappa_0(H)/T$ as a function of $H/H_2$ [32], as shown in fig. 4(c). Data on the clean s-wave superconductor Nb [28], the dirty s-wave superconductor InBi [29], the multiband s-wave superconductor NbSe$_2$ [30], and the overdoped d-wave cuprate superconductor Tl-2201 [31] are plotted for comparison. For the single-band clean s-wave superconductor Nb, $\kappa_0(H)/T$ grows exponentially with the field [28], while for the s-wave InBi in the dirty limit, the curve is exponential at low $H$ and displays roughly linear behavior closer to $H_2$ [29]. For nodal superconductor Tl-2201, a small field can yield a quick growth due to the Volovik effect, and the low-field $\kappa_0(H)/T$ shows roughly a $\sqrt{T}$ dependence [31]. In the case of NbSe$_2$, the distinct $\kappa_0(H)/T$ behavior was well explained by multiple superconducting gaps with different magnitudes [30].

By comparing the curve of the normalized $\kappa_0(H)/T$ for NaNb$_2$As$_2$ with others, the field dependence of $\kappa_0(H)/T$ most closely resembles that of InBi. The faster growth has two possible explanations. One is that NaNb$_2$As$_2$ is a multiple-band superconductor. However, from ARPES experiments, there is only a hole-type band crossing $E_F$, and hole carriers dominate the density of states of the Fermi surface at low temperature [15]. Therefore, we exclude this explanation. The other possibility is that NaNb$_2$As$_2$ is a “dirty” superconductor. To check whether NaNb$_2$As$_2$ is in the dirty limit, we estimate its superconducting coherence length $\xi_0$. From $H_{c2}(0) = 0.14$ T defined by zero resistivity, we obtained $\xi_0 \approx 49.5$ nm through the relation $H_{c2}(0) = \phi_0/(2\pi \xi_0^2)$. Recently, magnetic penetration depth measurements found an electron mean free path $l \approx 1.7$ nm [33]. Assuming our crystals are not much cleaner, $l \ll \xi_0$, so NaNb$_2$As$_2$ is indeed a “dirty” superconductor.

**Summary** — In summary, we synthesized NaNb$_2$As$_2$ single crystals using a Sn-flux method, and a superconducting transition temperature $T_c = 1.60$ K is found. From ultralow-temperature thermal conductivity experiments, a fully gapped superconducting state has been revealed. The field dependence of $\kappa_0/T$ further confirms that NaNb$_2$As$_2$ is an s-wave superconductor. A weak anomaly at 193 K is discovered, and we propose that the anomaly might arise from a CDW instability. Further work is needed to determine whether the anomaly results from a CDW instability, and clarifies the interplay between CDW and superconductivity with lone-pair electrons.

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REFERENCES

[1] Norman M. R., Science, 332 (2011) 196.
[2] Lee P. A., Nagaosa N. and Wen X. G., Rev. Mod. Phys., 78 (2006) 17.
[3] Chen X. H., Dai P. C., Feng D. L., Xiang T. and Zhang F. C., Natl. Sci. Rev., 1 (2014) 371.
[4] Mackenzie A. P. and Maeno Y., Rev. Mod. Phys., 75 (2003) 657.
[5] Pfleiderer C., Rev. Mod. Phys., 81 (2009) 1551.
[6] Singleton J., Rep. Prog. Phys., 63 (2000) 1111.
[7] Novoselov K. S., Mishchenko A., Carvalho A. and Castro Neto A. H., Science, 353 (2016) 6298.
[8] Kim J. S., JPSJ News Comments, 14 (2017) 13.
[9] Xi X., Wang Z., Zhao W., Park J. H., Law K. T., Berger H., Forró L., Shan J. and Mak K. F., Nat. Phys., 12 (2016) 139.
[10] Tsen A. W., Hunt B., Kim Y. D., Yuan Z. J., Jia S., Cava R. J., Hone J., Kim P., Dean C. R. and Pasupathy A. N., Nat. Phys., 12 (2016) 208.
[11] Xing Y., Zhang H. M., Fu H. L., Liu H. W., Sun Y., Peng J. P., Wang F., Lin X., Ma X. C., Xue Q. K., Wang J. and Xie X. C., Science, 350 (2015) 6260.
[12] Xi X., Berger H., Forró L., Shan J. and Mak K. F., Phys. Rev. Lett., 117 (2016) 106801.
[13] Goto Y., Yamada A., Matsuda T. D., Aoki Y. and Mizuguchi Y., J. Phys. Soc. Jpn., 86 (2017) 123701.
[14] Goto Y., Akira Miura, Moriyoshi C., Kuroiwa Y., Matsuda T. D., Aoki Y. and Mizuguchi Y., Sci. Rep., 8 (2018) 12852.
[15] Arguilla M. Q., Katoh J., Krymowski K., Cultrera N. D., Xu J., Xi X., Hanks A., Jiang S., Ross R. D., Koch R. J., Ulstrup S., Bostwick A., Joziwick C., McComi D. W., Rotenberg E., Shan J., Windl W., Kawakami R. K. and Goldbergier J. E., ACS Nano, 10 (2016) 9500.
[16] Nielsen M. D., Ozolins V. and Heremans J. P., Energy. Environ. Sci., 6 (2013) 570.
[17] Mizuguchi Y., Paris E., Sugimoto T., Iadecola A., Kajitani J., Miura O., Mizokawa T. and Saini N. L., Phys. Chem. Chem. Phys., 17 (2015) 22909.
[18] Ota Y., Okazaki K., Yamamoto H. Q., Yamamoto T., Watanebe S., Chen C. T., Naga M., Watauchi S., Tanaka I., Takano Y. and Shin S., Phys. Rev. Lett., 118 (2017) 167002.
[19] Yamashita T., Tokiwa Y., Terazawa D., Naga M., Watauchi S., Tanaka I., Terashima T. and Matsuda Y., J. Phys. Soc. Jpn., 85 (2016) 073707.
[20] Wilson A. H., Proc. R. Soc. A, 167 (1938) 580.
[21] Gabovich A. M., Votenko A. I. and Ausloos M., Phys. Rep., 367 (2002) 583.
[22] Grner G., Rev. Mod. Phys., 60 (1988) 1129.
[23] Xing Y., Zhao K., Shan P., Zheng F. Q., Zhang Y. W., Fu H. L., Liu Y., Tian M. L., Xi C. Y., Liu H. W., Feng J., Lin X., Ji S. H., Chen X., Xue Q. K. and Wang J., Nano. Lett., 17 (2017) 6802.
Zhang W. H., Sun Y., Zhang J. S., Li F. S., Guo M. H., Zhao Y. F., Zhang H. M., Peng J. P., Xing Y., Wang H. C., Fujita T., Hirata A., Li Z., Ding H., Tang C. J., Wang M., Wang Q. Y., He K., Ji S. H., Chen X., Wang J. F., Xia Z. C., Li L., Wang Y. Y., Wang J., Wang L. L., Chen M. W., Xue Q. K. and Ma X. C., *Chin. Phys. Lett.*, **31** (2014) 017401.

Zhang H. M., Sun Y., Li W., Peng J. P., Song C. L., Xing Y., Zhang Q. H., Guan J. Q., Li Z., Zhao Y. F., Ji S. H., Wang L. L., He K., Chen X., Gu L., Ling L. S., Tian M. L., Li L., Xie X. C., Liu J. P., Yang H., Xue Q. K., Wang J. and Ma X. C., *Phys. Rev. Lett.*, **114** (2015) 107003.

Liu Y., Wang Z. Q., Zhang X. F., Liu C. F., Liu Y. J., Zhou Z.M., Wang J. F., Wang Q. Y., Liu Y. Z., Xi C. Y., Tian M. L., Liu H. W., Feng J., Xie X. C. and Wang J., *Phys. Rev. X*, **8** (2018) 021002.

ShakeriPour H., Petrovic C. and Taillefer L., *New J. Phys.*, **11** (2009) 055005.

Lowell J. and Sousa J. B., *J. Low. Temp. Phys.*, **3** (1970) 65.

Willis J. O. and Ginsberg D. M., *Phys. Rev. B*, **14** (1976) 1916.

Boaknin E., Tanatar M. A., Paglione J., Hawthorn D., Ronning F., Hill R. W., Sutherland M., Taillefer L., Sonier J., Hayden S. M. and Brill J. W., *Phys. Rev. Lett.*, **90** (2003) 117003.

Proust C., Boaknin E., Hill R. W., Taillefer L. and Mackenzie A. P., *Phys. Rev. Lett.*, **89** (2002) 147003.

Li S. Y., Taillefer L., Wu G. and Chen H. X., *Phys. Rev. Lett.*, **99** (2007) 107001.

Ishihara K., Takenaka T., Miao Y., Tanaka O. Mizukami Y., Usui H., Kuroki K., Konczykowski M., Goto Y., Mizuguchi Y. and Shibauchi T., *Phys. Rev. B*, **98** (2018) 020505.