Electronic nematic phases, which break the rotational symmetry, have been proposed in many unconventional superconductors, such as high-$T_c$ cuprates \cite{1}, iron-based superconductors \cite{2,3}, and heavy-fermion materials \cite{4,5}. These discoveries suggest a generic origin of the superconducting (SC) pairing mechanism in correlated electron systems, which is strongly related to nematicity \cite{6}. In the cuprate superconductor $\text{YBa}_2\text{Cu}_3\text{O}_7-x$, the nematic state is observed at the same temperature as the pseudogap state, which is well above the superconducting dome \cite{1}. In the phase diagram of iron-based superconductors, such as electron-doped $\text{BaFe}_2\text{As}_2$, the nematic state resides in the temperature region above the antiferromagnetic and superconducting phases \cite{3}. The nematic phases of heavy-fermions also appear at temperatures far above the superconducting transition temperature, $T_c$ \cite{4,5}. The nematic phases in correlated systems always seem to precede the superconductivity. This finding is crucial for elucidating the role of nematicity in establishing superconductivity (supporting, competing, or accidentally co-existing).

Recently, the nematic phase has also been observed in the topological superconductors $\text{M}_x\text{Bi}_2\text{Se}_3$ ($\text{M}=\text{Cu, Sr, Nb}$). Based on their strong spin-orbital coupling (SOC) and multi-orbital effect \cite{7,8}, these superconductors are theoretically predicted to possess a fully gapped order parameter but odd-parity, i.e. two-fold symmetry of the SC gap. The nematic state was first demonstrated by nuclear magnetic resonance (NMR) measurements of $\text{Cu}_x\text{Bi}_2\text{Se}_3$; the spin susceptibility exhibited a 2-fold symmetry in the SC state under a rotating magnetic field in the hexagonal plane \cite{9}. Subsequently, various angle-resolved techniques have confirmed the nematic state in all $\text{M}_x\text{Bi}_2\text{Se}_3$ compounds. Such techniques involve upper critical fields \cite{10,12}, specific heat \cite{13}, torque effects \cite{14}, and scanning tunneling microscopy (STM) \cite{15}. Interestingly, most of these reports found a spontaneous emergence of 2-fold symmetry with superconductivity. As a typical example, the angle-dependent specific heat measurements of $\text{Cu}_x\text{Bi}_2\text{Se}_3$, revealed a 2-fold quasi-particle (QP) oscillation, but only in the SC state \cite{13}. This kind of nematic phase in topological superconductors, which is called nematic superconductivity, obviously differs from the nematicity in other systems, such as cuprates, iron-based, and heavy-fermion superconductors. This difference is crucial for understanding the relation between nematicity and superconductivity.

However, the nature of nematic superconductivity remains debate. Angle dependent NMR and specific heat results yield different directions of the symmetric axis of $\text{Cu}_x\text{Bi}_2\text{Se}_3$ \cite{9,13}. Moreover, as revealed in recent angle-dependent magnetoresistance measurements, small single crystals of $\text{Sr}_x\text{Bi}_2\text{Se}_3$ also exhibit a 2-fold symmetry above $T_c$ \cite{16}. However, the transport result is sensitive to the current path, which may be largely affected by the multi-domain effect as well as by interface effects between the domains \cite{16}. Therefore, to confirm whether nematic superconductivity is common to all topological superconductors, we require bulk evidence from QPs.

In this Letter, we investigate the nematic state of $\text{Sr}_x\text{Bi}_2\text{Se}_3$ through angle-resolved specific heat (ARSH)-measurements. The SC volume \cite{17} and in-plane anisotropy \cite{10} are reportedly larger in $\text{Sr}_x\text{Bi}_2\text{Se}_3$ than in $\text{Cu}_x\text{Bi}_2\text{Se}_3$. These properties are advantageous for studying the nematic phase. The specific heat of $\text{Sr}_x\text{Bi}_2\text{Se}_3$ exhibited a clear two-fold symmetry in both the superconducting and normal states, unambiguously providing QP evidence of the nematic state above $T_c$.

Single crystals of superconducting $\text{Sr}_x\text{Bi}_2\text{Se}_3$ (nominal composition $x=0.1$) were grown by the flux method.
FIG. 1. (a) Crystal structure of Sr$_x$Bi$_2$Se$_3$ in the hexagonal plane. The orange and blue spheres represent the elements Bi and Se. The $x$- and $y$-axes and the azimuthal angle $\phi$ are defined in the main text. (b) Laue diffraction pattern of the analyzed crystal. (c) Temperature dependence of the in-plane resistivity measured at zero field. (d) Temperature dependence of the magnetic susceptibility $\chi$ measured under 1 Oe field perpendicular to the $xy$-plane. (e) Upper critical fields for $H \parallel x$-axis, $H \parallel y$-axis and $H \perp xy$-plane, obtained from the resistive transition under fields. (f) Polar plot of resistance versus angle $\phi$ at 2 K under various magnetic fields (1 ~ 5 T).

The crystal structure of the sample was investigated by a Laue X-ray imaging system (Photonic Science Ltd). The magnetization was measured by a commercial SQUID magnetometer (MPMS-XL5, Quantum Design). The resistivities under magnetic fields (up to 9 T) were measured by the four-probe method in a physical property measurement system. The field-orientation dependence of the specific heat was measured in an 8 T split-pair superconducting magnet with a $^3$He refrigerator. The refrigerator can be continuously rotated by a motor on top of the dewar with an angular resolution better than 0.01°. The calibration and validity of the measurement system are explained in the Supplemental Material S1 [18].

Sr$_x$Bi$_2$Se$_3$ consists of triangular-lattice layers of Bi and Se intercalated with Sr. Figure 1(a) shows the crystal structure looking down the hexagonal plane. The structure is obviously hexagonal with 6-fold symmetry. The crystal structure of the analyzed sample was confirmed by the Laue diffraction pattern (see fig. 1(b)). The $x$-axis is defined as the Se-Bi bond direction in the hexagonal plane, and the $y$-axis is the in-plane direction perpendicular to the $x$-axis. Meanwhile, $\phi$ defines the azimuthal angle of the magnetic field with respect to the $x$-axis (Fig. 1(a)), and $\theta$ is the polar-angle of the field from the hexagonal plane.

The superconducting transition temperature $T_c$ of Sr$_x$Bi$_2$Se$_3$, obtained from the temperature dependences of resistivity (Fig. 1(c)) and susceptibility (Fig. 1(d)), was $\sim$ 3.1 K. Here, $T_c$ defines the onset temperature of zero resistivity and deviation of the zero-field-cooling and field-cooling susceptibilities. Similar $T_c$ were reported in previous studies [10] [11] [17] [19]. The shielding volume fraction approached 80% at 1.8 K, confirming the bulk nature of the superconductivity. The upper critical fields for the magnetic fields in the directions parallel to ($H \parallel x$ and $y$) and perpendicular to ($H \perp xy$) the hexagonal plane were obtained from the resistive transitions under the respective fields, and are plotted as functions of temperature in Fig. 1(e). Besides the anisotropy in the in-plane and out-of-plane applied fields, the $H_c2$ manifests obvious anisotropy within the hexagonal plane ($H_{c2}^x / H_{c2}^y$) $\sim$ 2.5 at low temperatures. Indeed, the angle dependent resistivity under a rotating field in the hexagonal plane manifests 2-fold symmetry (see Fig. 1(f)), which is similar to previous reports [10] [11].

Figure 2(a) shows the azimuthal angle-resolved $\Delta C(\phi)/T$ values at 0.35 K under magnetic field ranging from 0.1 to 5 T. The $\Delta C(\phi)/T$ manifests a clear 2-fold symmetry, which is easily recognized in the polar plots (shown for selected fields in Figs. 2(b)-(g)). Such 2-fold symmetry is consistent with that observed in the angle-dependent resistivity measurements (Fig. 1(f)). As the ARSH measurements probe the bulk signal of QPs, our results provide bulk evidence of nemacity in Sr$_x$Bi$_2$Se$_3$. Similar observations were reported in a previous study of Cu$_2$Bi$_2$Se$_3$ [13]. When the field exceeded 4 T, parts of $\Delta C(\phi)/T$ probed the normal state properties, which may explain the irregular behavior observed at 4 T. Unexpectedly, increasing the magnetic field caused a directional shift in the symmetry axis, as indicated by the lines in Figs. 2(b)-(g). Recent STM measurements of Cu$_2$Bi$_2$Se$_3$ revealed the same behavior [15], possibly manifesting from a multi-domain effect, as discussed later.

Figure 3(a) shows the $\Delta C(\phi)/T$ values measured at 2.1 K under various magnetic fields (1 - 7 T). At 2.1 K, the
in-plane $H_{c2}$ under both $H \parallel x$ and $H \parallel y$ was below 3 T (see Fig. 1(e)). Thus, the $\Delta C(\phi)/T$ measured at $H \geq 3$ T can probe the normal-state properties of Sr$_2$Bi$_2$Se$_3$. Astonishingly, $\Delta C(\phi)/T$ in the normal state also manifested 2-fold symmetry, as clarified in the polar plots of selected data (Figs. 3(b)-(d) under 3, 4, and 6 T, respectively). 2-fold symmetry in the normal state was also confirmed at $T = 3.5$ K above $T_c$ (see Supplemental Material S2 [18]). To confirm that the observed 2-fold symmetry is the intrinsic property of the crystal, we carefully checked that our measurement-system contributes no oscillating background (Supplemental Material S1 [18]). We also measured the polar-angle dependence of the specific heat $\Delta C(\theta)/T$ in the normal state. The $\Delta C(\theta)/T$ was $\theta$-independent, as presented in Supplemental Material S3 [18]. Therefore, the in-plane two-fold symmetry cannot be attributed to an out-of-plane signal caused by misalignment of the sample setting. The above observation unambiguously proves that the nematic state emerges from the normal state at temperatures above $T_c$. Here, we should emphasize the difference between this observation and that of Cu$_2$Bi$_2$Se$_3$, which shows 2-fold symmetry only in the SC state [13].

To understand the observable normal-state nematicity in QPs measurements under a magnetic field, we should consider the special spin structure. Owing to the strong SOC, the spin direction is locked perpendicular to the momentum direction, forming the well-known spin-helical structure [7, 20, 21]. In an isotropic density of states (DOS) without nematicity, the spins are homogeneously distributed as schematized in Fig. 3(e). As the specific heat is a bulk measurement, the probed QPs should be mainly contributed by the bulk band, in which the up and down spins are paired as represented by the paired orange and blue arrows in Fig. 3(e). In the surface state, the spins are polarized [21] but still form the helical structure; hence, they will not affect our following discussion.

In an isotropic DOS, magnetic field along the $k_y$ direction causes a strong Zeeman effect on the QPs with spins along the $k_x$ and -$k_x$ directions because the Zeeman effect is proportional to the magnitudes of the spins parallel to the field. On the contrary, a field along the $k_x$ direction induces a strong Zeeman effect on the QPs with spins along the $k_y$ and -$k_y$ directions. The Zeeman effect is represented by the blue regions in Fig. 3(e). Although the maximum and minimum positions change when the field rotation shifts from the $k_y$ to the $k_x$ directions, the total magnitude of the Zeeman effect (area of blue region in Fig. 3(e)) is unchanged because of the isotropic spin structure. Thus, the change of QPs due to the band shift under the Zeeman effect is independent of
FIG. 3. (a) Azimuthal angle dependence of the specific heat \( \Delta C(\phi)/T \) that is measured under various magnetic fields at 2.1 K. \( \Delta C(\phi)/T \) is defined as \( C(\phi)/T - C(0^\circ)/T \), and each subsequent curve is shifted vertically by 0.8 mJ/molK². Symbols with black outlines are measured data, and those without are mirrored points to show the symmetry. (b)-(d) Polar plots of \( \Delta C(\phi)/T \) at 2.1 K under fields of 3 T, 4 T and 6 T, respectively. Sketches of the spin-helical structure in the situations of (e) isotropic density of states without nematicity, and (f) anisotropic density of states with nematicity. Paired spins are indicated by orange outlines are measured data, and those without are mirrored points to show the symmetry. (b)-(d) Polar plots of \( \Delta C(\phi)/T \) at 2.1 K under fields of 3 T, 4 T and 6 T, respectively. Sketches of the spin-helical structure in the situations of (e) isotropic density of states without nematicity, and (f) anisotropic density of states with nematicity. The blue and orange patterns in (e) and (f) represent the spatial distributions of the magnitude of the Zeeman effect under fields along the \( k_x \) and \( k_y \) directions, respectively. Sketches of the band shift due to the Zeeman effect under fields along the \( k_y \) and \( k_x \) directions in the situations of (g) isotropic density of states without nematicity, and (h) anisotropic density of states with nematicity.

the in-plane direction of the field (see Fig. 3(g); the constructed band structure was based on the angle-resolved photoemission spectroscopy results [22]). On contrary, in case of anisotropic DOS with nematicity (Fig. 3(f)), more spins are arranged in the \( \pm k_y \) directions in the top and bottom parts than in the \( \pm k_x \) directions on the left and right sides, reflecting a distorted shape of the DOS. In this case, the Zeeman effect is much larger under \( H \parallel k_x \) than under \( H \parallel k_y \) (orange regions in Fig. 3(f)). Hence, the change in QPs due to the band shift under the Zeeman effect depends on the direction of the applied field (see Fig. 3(h)). When the field rotates in the \( k_x, k_y \)-plane, the magnitude of the Zeeman effect manifests as a 2-fold symmetric oscillation. Under this 2-fold symmetric Zeeman effect, the nematicity in the normal state becomes observable in angle-resolved QPs measurements.

Note that the above explanation of why the normal-state nematicity can be observed through the Zeeman effect is very generic in a strong SOC system. Angle-dependent QPs measurement is a new spectroscopic method that detects the nematic state generally, not only to be restricted in the SC state. The same explanation applies to other thermodynamic quantities, such as torque and magnetization. The SC jump in specific heat \( \Delta C/T_c \) is very small (~ 1.1 mJ/mol K²; see Supplemental Material S4 [18] and previous reports [13, 23]). Conversely, the magnitude of the oscillation in \( \Delta C(\phi)/T \) is as large as ~ 0.1 mJ/mol K² (Fig. 2(a)), approaching 10% of the \( \Delta C/T_c \), much larger than in other superconductors such as heavy-fermions [24], and iron-based superconductors [25]. Thus, the 2-fold symmetries observed in the SC and normal state of Sr₂Bi₂Se₃ may share a common origin. Accordingly, the likely source of the 2-fold symmetry is the angle-dependent Zeeman effect, rather than QP excitation by the nodes in the SC gap.

In the normal state, the 2-fold symmetry was observed only in the ARSH measurements, and was absent in the transport measurements such as the anisotropy measurement of \( H_{c2} \) in our crystal (Fig. 1(f)) and in most other reports [10][12]. It may be originated from the multi-domain effect as reported in [10]. In the normal state, the current path will be largely affected by the domains and the interface effect between the domains (for instance, the \( T_c \) is higher at the interfaces than the bulk) [10]. Therefore, the interface effect between the domains (for instance, the \( T_c \) is lower at the interfaces than the bulk) [10].
fore, the current direction becomes randomly distributed and the 2-fold symmetry cancels out. The strongest evidence of 2-fold symmetry in the normal state appears in the transport measurements of a very small crystal with a single domain [16]. If the magnitude of the Zeeman effect differs among the domains, the multi-domain effect may also cause the directional change of the symmetry axis under different magnetic fields. As the symmetry axis also changes in the $H_{c2}$ and STM measurements [15], it appears to be a common feature of $\text{M}_x\text{Bi}_2\text{Se}_3$, and must be investigated in future efforts.

Finally, we emphasize that the nematicity above $T_c$ observed in $\text{Sr}_2\text{Bi}_2\text{Se}_3$ differs from that in the similar compound $\text{Cu}_x\text{Bi}_2\text{Se}_3$, which exhibits nematicity only in the SC state [13]. In fact, $\text{Sr}_2\text{Bi}_2\text{Se}_3$ shows a much larger in-plane $H_{c2}$ anisotropy ($\sim 2.5$; see Fig. 1(e) and [10]) than $\text{Cu}_x\text{Bi}_2\text{Se}_3$ ($\sim 1.3$; [13]). This implies that the DOS in $\text{Cu}_x\text{Bi}_2\text{Se}_3$ is nearly isotropic, and that the anisotropy is too weak to be distinguished in QPs measurements. Very recently, 2-fold symmetry around $T_c$ in the SC state of $\text{Sr}_2\text{Bi}_2\text{Se}_3$ has been future confirmed in specific heat measurements at fixed angles, although the normal state was not investigated in their study [23].

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*sunyue@phys.aoyama.ac.jp*

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Details about the angle-resolved specific heat (ARSH) measurement system is shown schematically in Fig. S1. A 3He refrigerator (Heliox, Oxford) was used to cool the samples to temperatures below 300 mK. Magnetic fields were generated by a split-pair superconducting magnet, capable of producing 8 T horizontal fields. Having no thick pumping tube outside, the refrigerator insert could be easily rotated using a stepper motor mounted at the top of a magnet Dewar. The overall angular resolution of the field direction is better than 0.01 deg. The hexagonal plan of the sample can be set either parallel or perpendicular (with a rectangular accessory) to the horizontal magnetic field to measure the azimuthal angle (\( \phi \)) or the polar angle (\( \theta \)) dependences of the specific heat. During the measurements, the angles obtained from the number of pulse to the motor were checked equal to those obtained from the goniometer on the motor, which confirms that the correct angles were obtained.

To confirm that the our measurement system contains no field-angle dependent background, we performed the ARSH measurements on a piece of Ag with almost the same weight as the Sr\(_x\)Bi\(_2\)Se\(_3\) sample. In such experiment, the whole system is the same as that used for the sample, and even the gravitational force to the addenda is nearly the same. Some typical results at 2.1 K and 3.5 K are shown in Fig. S2. Clearly, no oscillation of ARSH is observed, which proves that there is no field-angle dependent background of the system. Thus, the two-fold symmetric ARSH results observed in Sr\(_x\)Bi\(_2\)Se\(_3\) is the intrinsic property of the sample.

**S2 AZIMUTHAL ANGLE DEPENDENCE OF THE SPECIFIC HEAT \( \Delta C(\phi)/T \) AT 3.5 K**

Figure S3 shows the azimuthal angle dependence of the specific heat \( \Delta C(\phi)/T \) measured at 3.5 K under different fields. Since 3.5 K is already above \( T_c \) (\( \sim 3.1 \) K), the measurements probe the normal state properties of the Sr\(_x\)Bi\(_2\)Se\(_3\). Obviously, \( \Delta C(\phi)/T \) manifests two-fold symmetry in the normal state, which can be seen more clear in the polar plot shown in Figs. S3(b)-(d) for selected data at 2, 4, and 6 T.
FIG. S3. (a) Azimuthal angle dependence of the specific heat $\Delta C(\phi)/T$ measured under various fields at 3.5 K. $\Delta C(\phi)/T$ is defined as $C(\phi)/T$-$C(0^o)/T$, and each subsequent curve is shifted vertically by 2.5 mJ/molK$^2$. Symbols with black outlines are measured data, and those without are mirrored points to show the symmetry. (b)-(d) Polar plot of the $\Delta C(\phi)/T$ at 3.5 K under fields of 2 T, 4 T and 6 T, respectively.

S3 POLAR ANGLE DEPENDENCE OF THE SPECIFIC HEAT $\Delta C(\theta)/T$

Figure S4 shows the polar angle dependence of the specific heat $\Delta C(\theta)/T$ measured at 2.1 K and 3.5 K under different fields. During the polar angle dependent measurements, the azimuthal angle was kept as $\phi = 0^\circ$. Obviously, the specific heat result at fixed magnetic field is independent of the out-of-plane angle $\theta$, which proves that the two-fold symmetric $\Delta C(\phi)/T$ results could not be attributed to the $\Delta C(\theta)/T$ signal from the misalignment of the sample setting.

FIG. S4. Polar angle dependence of the specific heat $\Delta C(\theta)/T$ measured under different fields at (a) 2.1 K, and (b) 3.5 K. $\Delta C(\theta)/T$ is defined as $C(\theta)/T$-$C(0^o)/T$, and each subsequent curve is shifted vertically by 1 mJ/molK$^2$ in (a), and 2 mJ/molK$^2$ in (b), respectively. Black-outlined symbols are the measured data; the others are mirrored points to show the symmetry more clearly.

S4 SUPERCONDUCTING JUMP IN SPECIFIC HEAT $\Delta C/T_c$

Figure S5(a) shows the specific heat divided by temperature $C/T$ as a function of $T^2$ measured under zero-field. A jump attributed to the SC transition can be clearly witnessed although the magnitude is very small. Similar small SC jump in the specific heat of $\text{M}_2\text{Bi}_2\text{Se}_3$ is also reported previously \cite{13, 23}. After subtracting the normal state specific heat obtained simply by linear fitting of the data above $T_c (C/T = -3.94 + 4.18 T^2)$, the specific heat jump $\Delta C/T$ is obtained and shown in Fig. S5(b). The SC jump $\Delta C/T_c$ is estimated as $\sim 1.1$ mJ/mol K$^2$, which is also similar to previous reports \cite{13, 23}.

FIG. S5. (a) Raw data of the specific heat divided by temperature $C/T$, including the contributions from phonon and addenda as a function of $T^2$ measured under zero-field. The solid line represent the linear fit to the normal state specific heat. (b) Temperature dependence of the specific heat $\Delta C/T$ obtained by subtracting the fitting result of the normal state specific heat.