

Chiral domain and macroscopic orbital supercurrent along chiral domain wall in chiral superfluid ^3He

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Chiral superfluid ^3He -A contained in narrow-gapped parallel plate cell with in-plane external magnetic field is expected to form uniformly aligned texture of chiral vectors, which denote the direction of Cooper pair angular momentum. In the real experimental situation, we often observe the existence of a few millimeter sized chiral domains and chiral domain walls in between them. A persistent orbital supercurrent is expected to flow along the wall. We have succeeded in tilting chiral domain walls by applying external supercurrent, which interacts with the orbital supercurrent. This observation confirmed the existence of macroscopic orbital supercurrent along the chiral domain wall. The tilting angle depends on the direction and magnitude of the external supercurrent as well as the direction of the chiral vector in adjacent chiral domains. This allowed us to determine the direction of the chiral vector in each chiral domain. The measured tilting angle also suggests that the magnitude of macroscopic angular momentum of each chiral domain is as large as the ground-state angular momentum $\hbar$ times a number of ^3He particles divided by 2.

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I. INTRODUCTION

In recent years, there has been an increasing interest in exploring the topological properties of superconductors and superfluids [1–6]. The multicomponent superconductors are leading candidates for topological superconductors [7–9]. For example, the heavy-fermion superconductor UPt_3 exhibits chiral superconductivity with broken time-reversal symmetry in the B phase [10–12]. However, many other candidates of the chiral superconductors are still under hot debate. On the other hand, the chiral superfluid ^3He -A has emerged as a particularly captivating research subject due to its well-understood properties [13,14]. Chirality in the ^3He -A phase is characterized by the chiral axis $\hat{l}$, which aligns with the angular momentum of Cooper pairs [15,16]. Domains where $\hat{l}$ uniformly align are called chiral domains, and the boundaries between them with opposite $\hat{l}$ orientations are called chiral domain walls (CDWs). In the chiral superfluid, spontaneous mass supercurrent, called edge current, which originates from the orbital angular momentum of Cooper pairs, is expected to occur on the boundary of chiral domains [17]. A similar mass supercurrent should appear along the CDWs [18,19]. The edge current problem has been discussed extensively in the past decades. However, clear experimental evidence of the edge current in a chiral superfluid has not been obtained.

An experimental confirmation of the existence of macroscopically observable orbital supercurrent along the edge of chiral domain is highly desired to test the current understanding of chiral superfluid and superconductors.

The chirality of the ^3He -A was shown by Walmsley *et al.* through torsional oscillator measurements [20–22]. They observed the formation of monochiral domains in rotating ^3He -A and inferred the direction of $\hat{l}$ from the torsional oscillator's response to different rotation directions. Subsequently, Ikegami *et al.* detected the breaking of chiral symmetry on the free surface of ^3He -A by observing the behavior of electrons floating on the liquid surface [23,24]. They also noted the coexistence of multiple chiral domains. However, this experiment did not provide information about the spatial arrangement of individual chiral domains. Recently, Kasai *et al.* succeeded in visualizing the spatial arrangement of chiral domains and CDWs inside parallel plates, using magnetic resonance imaging (MRI) [25]. Later, they found spontaneously tilting CDWs and a possible relation with spontaneously trapped supercurrent through the parallel path. To further clarify this issue, we have developed a parallel plate cell with improved surface flatness and controllable supercurrent application.

In a spatially confined superfluid ^3He , the order parameter forms a spatial structure known as texture. In the A phase, texture is described with $\hat{l}$ and $\hat{d}$. $\hat{l}$ represents anisotropy axis in orbital space, while $\hat{d}$ represents anisotropy axis in spin space [26]. The stable texture is formed to minimize the free energy, which consists of various anisotropic energies as well as gradient energies. This spatial variation of the $\hat{l}$ generates spontaneous mass supercurrent. The mass supercurrent $\mathbf{g}_s$ is expressed as $\mathbf{g}_s = \rho_s \mathbf{v}_s + \mathbf{g}_{s,\text{orb}}$ [27–30]. The first term represents mass supercurrent due to the superfluid flow $\mathbf{v}_s$, which

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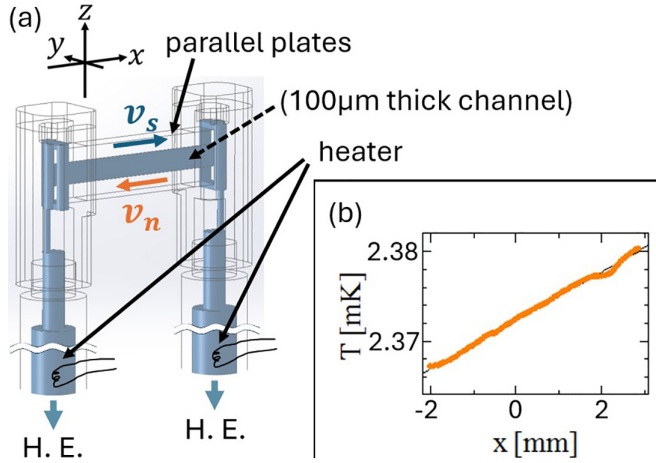


FIG. 1. (a) Schematic illustration of the parallel plate cell. The blue shaded part represents liquid ^3He . Each side of the 100- μm -thick channel is connected to a bulk column, an independent heat exchanger (H.E.), and an independent filling line. Heaters are installed on both sides of the channel to generate thermal counterflow. (b) Temperature distribution along the channel. The temperature gradient along x axis was measured to be $2.7 \mu\text{K}/\text{mm}$ under 1.5 nW of heat input to the right column at a temperature of 2.348 mK before heating (solid line represents linear fitting).

is expressed by the gradient of the phase of the wave function, $\nabla\phi$, and ρ_s , which represents the superfluid density tensor. In the A phase, orbital supercurrent $\mathbf{g}_{s,\text{orb}}$ exists in addition to $\rho_s \mathbf{v}_s$. The $\mathbf{g}_{s,\text{orb}}$ originates from the angular momentum of Cooper pairs, and is generated by spatial variations of $\hat{\mathbf{l}}$, and appears on the boundary of a uniformly aligned chiral domain. The $\mathbf{g}_{s,\text{orb}}$ influences the formation of textures because the gradient energy includes a term $\mathbf{v}_s \cdot \mathbf{g}_{s,\text{orb}}$. Therefore, examining the influence of externally applied $\mathbf{v}_s$ on textures provides information about $\mathbf{g}_{s,\text{orb}}$. As $\mathbf{g}_{s,\text{orb}}$ is sensitive to the orientation of $\hat{\mathbf{l}}$ within the chiral domains, the information about the chirality of the domains can be obtained.

II. PARALLEL PLATE CHANNEL AND STATIONARY SUPERCURRENT

Figure 1(a) shows our parallel plate cell with a 100- μm -gapped channel. The experimental setup consists of a parallel plate channel with a thickness of 100 μm (in the y direction), a height of 2 mm (in the z direction), and a length of 18 mm (in the x direction). Both ends along x direction of the channel are connected to separate bulk columns, each of which is equipped with a heater and a heat exchanger. This channel is made by casting STYCAST 1266 around a polished aluminum plate with a thickness of 100 μm . Then, the aluminum plate is dissolved in hydrochloric acid. The surface roughness of the channel is estimated to be a few micrometers. This roughness is determined by that of the polished aluminum plate. A static magnetic field of approximately 0.13 T for NMR and MRI is applied in the z direction. NMR transmitter and receiver coils are attached near the center of the channel with maximally available thermal insulation. The pressure of liquid ^3He is maintained at 2.93 MPa. Controlled external supercurrent $\mathbf{v}_s$ along the channel is generated by applying an

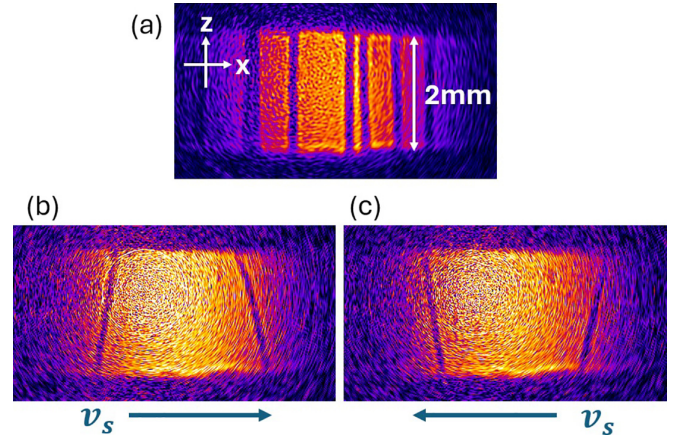


FIG. 2. MRI images projected along the y direction. (a) Image with several domain walls after annealing and freezing without $\mathbf{v}_s$. The dark vertical lines represent $\hat{\mathbf{l}}$ -walls. (b) Tilted $\hat{\mathbf{l}}$ -walls after annealing and freezing with rightward $\mathbf{v}_s$ induced by applying 1.5 nW to the heater on the right column. (c) Image of the same domain walls with opposite direction of tilt under leftward $\mathbf{v}_s$ induced by applying 1.5 nW to the heater on the left column.

adequate amount of heat into one of the heaters on the vertical columns near the heat exchangers. In this configuration, most of the heat goes through the heat exchanger. A temperature in the heated column rises moderately, for example, by 50 μK under 1.5 nW of heat, while a stationary temperature gradient along the channel appears. Figure 1(b) shows a measured temperature distribution along the channel when 1.5 nW is applied to the heater. Local temperature is estimated from the local resonance frequency measured by magnetic resonance spectroscopic imaging. The measured temperature gradient along the channel under 1.5 nW of heat is $2.7 \mu\text{K}/\text{mm}$ at a temperature of 2.348 mK before heating. Thus, stable supercurrent associated with thermal counterflow along the channel exists since it is in the hydrodynamic regime.

The ground-state texture inside narrow-gapped parallel plates is uniform $\hat{\mathbf{l}} = \pm \hat{\mathbf{y}}$ (except for tiny regions near the top and bottom edges of the plate), under a strong magnetic field in the z direction. However, Kasai *et al.* found that several chiral domains spontaneously form, and CDWs appear at the boundaries between these domains [25]. Inside the CDWs, $\hat{\mathbf{l}}$ cannot maintain the alignment in the domain and rotates from $\hat{\mathbf{l}} = \pm \hat{\mathbf{y}}$ to $\hat{\mathbf{l}} = \mp \hat{\mathbf{y}}$. Among them, two types of CDWs, in which the direction of $\hat{\mathbf{l}}$ changes from $\pm \hat{\mathbf{y}}$ to $\mp \hat{\mathbf{y}}$, are considered. One is an $\hat{\mathbf{l}}$ -wall, in which the direction of $\hat{\mathbf{l}}$ reverses without reversing the direction of $\hat{\mathbf{d}}$. The other is an $\hat{\mathbf{l}}\hat{\mathbf{d}}$ -wall, in which both the directions of $\hat{\mathbf{l}}$ and $\hat{\mathbf{d}}$ reverse while maintaining approximately parallel orientations. In addition to these two types of CDWs, $\hat{\mathbf{d}}$ -wall, in which the direction of $\hat{\mathbf{d}}$ reverses without reversing the direction of $\hat{\mathbf{l}}$, may exist. Figure 2(a) shows an MRI image of the ^3He -A, which is projected along the normal axis (y direction) of the parallel plates. The bright orange parts in the image represent local NMR signal intensity, and the gradual fading of the intensity to the horizontal edge reflects the spatial distribution of NMR sensitivity. The dark lines running vertically in the image represent domain walls. Domain walls appear as dark lines because of a

localized line broadening or a decrease in signal intensity. The three types of domain walls, $\hat{l}$ -walls, $\hat{l}\hat{d}$ -walls, and $\hat{d}$ -walls, can be distinguished by their MRI signal intensities and NMR spectra. The $\hat{l}\hat{d}$ -walls show a weaker dark line in the MRI image than other kinds of walls. This is because of the smaller dipole-unlocked region. This feature makes it easy to distinguish $\hat{l}\hat{d}$ -walls from other two walls. The $\hat{d}$ -walls can be generated by a large tipping angle NMR pulse. Since it shows particular spectral characteristics, it is possible to distinguish $\hat{d}$ -walls from other two walls. Domain walls that hold the characteristics of neither $\hat{l}\hat{d}$ -walls nor $\hat{d}$ -walls are considered to be $\hat{l}$ -walls. Note that Kasai *et al.* proposed that the domain walls observed in their MRI experiments were $\hat{l}\hat{d}$ -walls. However, based on our recent improved understanding, it is likely that their walls are mostly $\hat{l}$ -walls, which are still chiral domain walls. A detailed discussion of the characteristics of three types of domain walls will be presented elsewhere [31]. In this article, we focus on the flow property of the $\hat{l}$ -wall.

III. ANNEALING AND FREEZING OF DOMAIN WALLS

Typical MRI images in the A phase after rapid cooling through T_c show curved or tilted domain walls [25]. The energetically favorable shape of the domain wall should be straight along the z direction to reduce their length since domain walls incur extra energy costs. However, the pinning forces on the surface of the parallel plates hold the irregular shape of the domain walls. At temperatures very near T_c , the pinning forces weaken due to a decrease in condensation energy density, and the domain walls change their shapes to energetically stabler straight shapes. Taking advantage of this behavior, we conducted an operation called “annealing and freezing” to generate an energetically stabler shape of the domain wall under an external supercurrent. The procedure is as follows:

- (1) Apply localized heat to either the right or left column heater to generate a supercurrent, which crosses the domain wall under investigation.
- (2) Raise the temperature of $^3\text{He-A}$ in the channel to approximately $0.995T_c$ to generate a stable shape of the domain wall under the supercurrent.
- (3) Lower the temperature to pin the domain wall on the surface of the plates.
- (4) Stop the supercurrent at a sufficiently low temperature. The stable shape of the domain wall under the supercurrent remains pinned.

During the “annealing and freezing” procedure (3), the proportion of superfluid components increases as the temperature decreases from T_c , resulting in a decreasing $v_s = (\rho_n/\rho_s)v_n$ under a constant heat flow. Therefore, we should be aware that the frozen shape of the domain wall is determined by v_s at a temperature when the pinning force becomes strong enough to hold the domain wall. In this “annealing and freezing” process, the temperature $0.995T_c$ is an empirical temperature where most of the pinning centers release clamped domain walls.

IV. DOMAIN WALLS UNDER SUPERCURRENT

Here we investigate the equilibrium shape of the $\hat{l}$ -walls under v_s . When no v_s exists inside the channel during an-

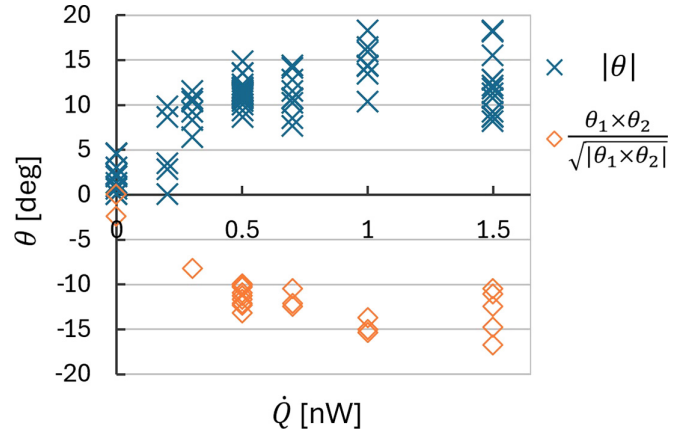


FIG. 3. The tilting angle θ of the $\hat{l}$ -wall from the z direction after annealing and freezing with v_s induced by applying heat $\dot{Q}$ to the heater. Cross symbols indicate the absolute value of θ for each independent $\hat{l}$ -wall, while open diamonds indicate the geometric mean of θ of two adjacent $\hat{l}$ -walls. The negative sign indicates that the adjacent $\hat{l}$ -walls tilt in opposite directions.

nealing and freezing, $\hat{l}$ -walls become straight along the z axis, as shown in Fig. 2(a). However, when v_s is induced inside the channel during annealing and freezing, $\hat{l}$ -walls tilt from the z direction, as shown in Fig. 2(b). Furthermore, in the case of the reversed direction of the v_s , the $\hat{l}$ -walls tilt toward the reversed direction as shown in Fig. 2(c). Therefore, the stable shape of the $\hat{l}$ -wall under v_s is a tilted straight wall, of which the tilting direction is determined by the direction of v_s . Figure 3 shows the flow dependence of the tilting angle. The heat power $\dot{Q}$ is shown as a measure for the magnitude of v_s generated by the thermal counterflow. All measurements are performed over straight-shaped stable domain walls after careful annealing and freezing procedures. The measured tilting angle θ under zero supercurrent ($\dot{Q} = 0$) scatters around zero within approximately 5° . Under a finite v_s ($\dot{Q} > 0$), the $\hat{l}$ -walls tilt more as v_s increases. The scattering in the data for the same $\dot{Q}$ is considered to be the effect of the limited locations of the pinning sites. However, since there are a sufficient number of pinning sites, the magnitude of the tilting angle is primarily determined by the strength of v_s . It also appears that the tilting effect saturates at $\dot{Q} \gtrsim 1$ nW. This might be because of the reduced pinning temperature for larger supercurrents. In addition to the magnitude of the tilting angle of the $\hat{l}$ -walls, a characteristic feature regarding the tilting direction was observed. The adjacent $\hat{l}$ -walls always tilted in staggered directions under finite v_s . The open diamond symbol in Fig. 3 shows that the geometric mean of the tilting angles of each adjacent $\hat{l}$ -walls is always negative. Thus, two adjacent walls tilt in opposite directions under the same v_s .

V. ORBITAL SUPERCURRENT AND TILTING DOMAIN WALL

We discuss the stable texture of $\hat{l}$ -walls without external supercurrent v_s . Since $\hat{l}$ -walls are structures that lose dipole energy and gradient energy, they are expected to orient themselves in the z direction to minimize their surface area. The gradient energy is expressed by three kinds of

terms [29,32]:

$$f_{\text{bend}} = f_s + f_c + f_n, \quad (1)$$

$$\begin{aligned} f_s &= \frac{1}{2} \rho_s v_s^2 = \frac{1}{2} \rho_s v_s^2 - \frac{1}{2} \rho_0 (\hat{l} \cdot v_s)^2, \\ f_c &= v_s \cdot g_{s,\text{orb}} = \frac{\hbar}{2m} [C v_s \cdot (\nabla \times \hat{l}) - C_0 (v_s \cdot \hat{l}) \hat{l} \cdot (\nabla \times \hat{l})], \\ f_n &= \frac{1}{2} \left(\frac{\hbar}{2m} \right)^2 \left\{ K_s (\nabla \cdot \hat{l})^2 + K_t [\hat{l} \cdot (\nabla \times \hat{l})]^2 + K_b [\hat{l} \times (\nabla \times \hat{l})]^2 \right\} \\ &\quad + \rho_{s\perp} \sum_{\alpha} [(\hat{l} \times \nabla) \hat{d}_{\alpha}]^2 + \rho_{s\parallel} \sum_{\alpha} [(\hat{l} \cdot \nabla) \hat{d}_{\alpha}]^2 \end{aligned} \quad (2)$$

where $\rho_s = \rho_{s\perp}$ and $\rho_0 = \rho_{s\perp} - \rho_{s\parallel}$ ($\rho_{s\perp,\parallel}$ are the perpendicular and parallel components of the superfluid density tensor to $\hat{l}$), $C = C_{\perp}$ and $C_0 = C_{\perp} - C_{\parallel}$ ($C_{\perp,\parallel}$ are the perpendicular and parallel components of the tensor coefficient of supercurrent), $\rho_{s\perp,\parallel}$ are the perpendicular and parallel components of the superfluid spin density tensor to $\hat{l}$, and m is the mass of ^3He atom. When there is no external supercurrent v_s , only the third term f_n contributes to the texture. This term arises from the spatial variation of $\hat{l}$ and $\hat{d}$. The spatial variation of $\hat{l}$ can be classified into splay type, twist type, and bend type. K_s , K_t , and K_b represent the coefficients of gradient energy for these three types of spatial variation. Consider a $\hat{l}$ -wall extending in the yz plane, where the direction of $\hat{l}$ reverses from $\hat{l} = \pm \hat{y}$ to $\hat{l} = \mp \hat{y}$ while moving along the x axis. Let $\hat{l}_w$ represent the direction of $\hat{l}$ at the center of the $\hat{l}$ -wall. When $\hat{l}_w$ is parallel to the z axis, the wall is a twist type. On the other hand, when $\hat{l}_w$ is perpendicular to the $\hat{l}$ -wall, the wall is a combination of splay and bend types. Among K_s , K_t , and K_b , K_b is largest. Thus, the $\hat{l}$ -wall with perpendicular $\hat{l}_w$ costs larger gradient energy than the parallel one. Due to the dipole unlock at the $\hat{l}$ -wall, there are no other major restrictions on the direction of $\hat{l}_w$. Therefore, the expected texture of $\hat{l}$ -wall is a twist type. Our numerical simulations of texture based on the dipole and gradient energy of these two types of $\hat{l}$ -walls also showed that the twist-type $\hat{l}$ -wall had lower energy.

We understand the tilting effect of $\hat{l}$ -walls under v_s as follows. When an external supercurrent v_s exists, its contribution to the gradient energy must be considered. Among them, the orbital supercurrent term $f_c = v_s \cdot g_{s,\text{orb}}$ has a primary effect in tilting $\hat{l}$ -walls. The orbital supercurrent $g_{s,\text{orb}}$ is expressed as follows:

$$\begin{aligned} g_{s,\text{orb}} &= \frac{\hbar}{2m} C (\nabla \times \hat{l}) - \frac{\hbar}{2m} C_0 \hat{l} [\hat{l} \cdot (\nabla \times \hat{l})] \\ &= g_{s,\text{orb}1} + g_{s,\text{orb}2}. \end{aligned} \quad (3)$$

In the parallel plate channel, a chiral domain is surrounded by the boundaries, which consists of the top and bottom container surfaces and $\hat{l}$ -walls. The first term $g_{s,\text{orb}1}$ generates a clockwise or counterclockwise orbital supercurrent along the boundary. In this case, the integral of the x component of $g_{s,\text{orb}1}$ over the entire space is zero. Therefore, when v_s flows in the x direction, $g_{s,\text{orb}1}$ does not contribute to integrated $f_c = v_s \cdot g_{s,\text{orb}}$ and the tilting of the $\hat{l}$ -walls. On the other hand, the second term $g_{s,\text{orb}2}$ causes the tilting of the $\hat{l}$ -walls. The $g_{s,\text{orb}2}$ appears when $\hat{l}$ has a twist-type spatial variation. At the top and bottom container walls, where $\hat{l}$ is perpendicular

to the wall, there is no twist-type spatial variation, thus $g_{s,\text{orb}2}$ does not flow. On the other hand, $\hat{l}$ -walls can exhibit twist-type spatial variation; thus, $g_{s,\text{orb}2}$ can flow along $\hat{l}$ -walls.

As shown in Fig. 4, the spatial variation of a tilting $\hat{l}$ -wall can be expressed with following parameters: the angle ψ , which represents the rotation of $\hat{l}$ from the $\pm \hat{y}$ direction ($\psi = \pm \pi/2$) to $\mp \hat{y}$ direction ($\psi = \mp \pi/2$), and the angle γ , which represents the direction of $\hat{l}$ at the center ($\psi = 0$) of the $\hat{l}$ -wall. γ is assumed to be a constant for simplicity. $\hat{N}$, which lies in the xz plane, is the normal vector of the $\hat{l}$ -wall,

$$\hat{l} = (\sin \psi) \hat{y} + \cos \psi \{ (\sin \gamma) \hat{N} + (\cos \gamma) (\hat{N} \times \hat{y}) \}. \quad (4)$$

When $\gamma = 0, \pm \pi$, $\hat{l}$ is parallel to the $\hat{l}$ -wall at the center. This is the twist-type $\hat{l}$ -wall. When $\gamma = \pm \pi/2$, $\hat{l}$ is parallel to $\hat{N}$. This is the splay-bend-type $\hat{l}$ -wall. Due to the anisotropy in the gradient energy coefficients, the twist-type $\hat{l}$ -wall is energetically favorable without v_s . In this situation, $g_{s,\text{orb}2}$ flows along the $\hat{l}$ -wall in the opposite direction to $g_{s,\text{orb}1}$. Since $g_{s,\text{orb}2}$ flows only along the $\hat{l}$ -wall, the integral of the x component of $g_{s,\text{orb}2}$ holds nonzero value for the tilted $\hat{l}$ -wall. Thus, $g_{s,\text{orb}2}$ contributes to integrated f_c and the tilting of the $\hat{l}$ -wall. When external supercurrent $v_s = v_s \hat{x}$ exists, and the $\hat{l}$ -wall tilts in the

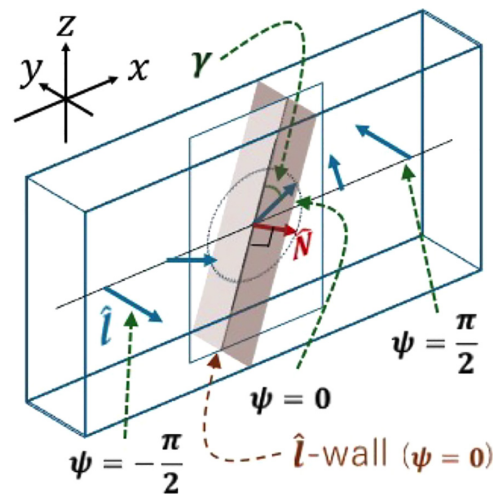


FIG. 4. The variation of $\hat{l}$ in the vicinity of the $\hat{l}$ -wall. As one crosses the $\hat{l}$ -wall along the x axis, $\hat{l}$ varies from $-\hat{y}$ ($\psi = -\pi/2$) to $\hat{y}$ ($\psi = \pi/2$). We define the plane where $\psi = 0$ as the $\hat{l}$ -wall plane, and assume that the $\hat{l}$ -wall plane intersects the xz plane at $x = kz$. On the $\hat{l}$ -wall plane, $\hat{l}$ is parallel to the xz plane, forming an angle γ with the line $x = kz$. $\hat{N}$ is the normal vector to the $\hat{l}$ -wall plane.

$x = kz$ direction,

$$\hat{N} = (\cos \theta)\hat{x} - (\sin \theta)\hat{z}, \quad (5)$$

where $\theta = \arctan k$. When $\partial\psi/\partial z = -k\partial\psi/\partial x$, we obtain

$$\hat{l} \cdot (\nabla \times \hat{l}) = [k \sin(\gamma + \theta) + \cos(\gamma + \theta)] \frac{\partial\psi}{\partial x}. \quad (6)$$

The term $\partial\psi/\partial y$ disappears. Then, by using $\cos \psi(\partial\psi/\partial x) = \partial l_y/\partial x$, we obtain

$$l_x[\hat{l} \cdot (\nabla \times \hat{l})] = (k \cos^2 \gamma + \sin \gamma \cdot \cos \gamma) \frac{\partial l_y}{\partial x}. \quad (7)$$

The energy term $f_{c0} = \mathbf{v}_s \cdot \mathbf{g}_{s,orb2}$ for the $\hat{l}$ -wall can be expressed as

$$f_{c0} \approx -\frac{\hbar}{2m} C_0 v_s (k \cos^2 \gamma + \sin \gamma \cdot \cos \gamma) \frac{\partial l_y}{\partial x}. \quad (8)$$

Without $\mathbf{v}_s$, it is expected that $k = 0$ and $\gamma = 0$, which represents an untilted twist-type $\hat{l}$ -wall. Under finite $\mathbf{v}_s$, f_{c0} makes it energetically favorable for k and γ to increase to positive value when $v_s(\partial l_y/\partial x) > 0$, and decrease to negative value when $v_s(\partial l_y/\partial x) < 0$. In particular, an increase or decrease in k means that the $\hat{l}$ -wall tilts toward a specific direction, which depends on the direction of $\mathbf{v}_s$. The direction of this tilt does not depend on γ . The magnitude and direction of the tilt depend on the magnitude and direction of $\mathbf{v}_s$. The direction of tilt also depends on $\partial l_y/\partial x$. When $\partial l_y/\partial x$ is integrated in the x direction, it becomes ± 2 regardless of the shape of the domain wall, because $\hat{l}$ varies from $\hat{l} = \pm \hat{y}$ to $\hat{l} = \mp \hat{y}$ in crossing the $\hat{l}$ -wall. The sign of the integrated value depends only on the direction of $\hat{l}$ in the adjacent chiral domains to the $\hat{l}$ -wall. When there are multiple $\hat{l}$ -walls, the direction of $\hat{l}$ in each adjacent domain alternates. This explains the staggered direction of tilt of the adjacent $\hat{l}$ -walls under $\mathbf{v}_s$.

The tilt of $\hat{l}$ -walls under $\mathbf{v}_s$ in a specific direction indicates the chirality of the A phase. This tilting direction is determined by $\mathbf{g}_{s,orb2}$ on the $\hat{l}$ -wall, which, in turn, relies on the direction of the chiral vector in the neighboring chiral domain. This feature suggests that the observed tilting direction of the $\hat{l}$ -wall under external supercurrent gives the direction of the chiral vector in each chiral domain. For the chiral domain structure shown in the MRI image of Fig. 5(b), we can determine the chiral vector's direction in each chiral domain, as shown in Fig. 5(a).

The equilibrium tilt angle of the $\hat{l}$ -wall is determined by a balance between the decrease in f_{c0} and the increase in other energies resulting from the wall's elongation. Major contribution among other energies comes from the gradient energy f_n near the singularity on the surface of parallel plates. f_n can be approximated as $f_n \approx (1/2)(\hbar/2m)^2 K_t (2/w)^2$, where w is the width of the $\hat{l}$ -wall in the x direction and $K_t \approx \rho_{s\parallel}/2$, where $\rho_{s\parallel}$ represents a parallel component of superfluid density tensor. Integrating this over the xy plane yields $\int f_n dx dy \approx (\hbar/2m)^2 \rho_{s\parallel} \cdot 2 \log(d_0/\xi_0)$, where d_0 is the distance between the parallel plates and ξ_0 is the coherence length, representing the approximate size of the singularity on the plates. When the $\hat{l}$ -wall tilts, this energy increases by a factor of approximately $(1/2)k^2$. On the other hand, integrating f_{c0} over the xy plane, using $C_0 \approx \rho_{s\parallel}$, yields $\int f_{c0} dx dy \approx -2(\hbar/2m)\rho_{s\parallel}d_0 v_s k$. Balancing the k^2 and $-k$ terms to minimize the energy gives the

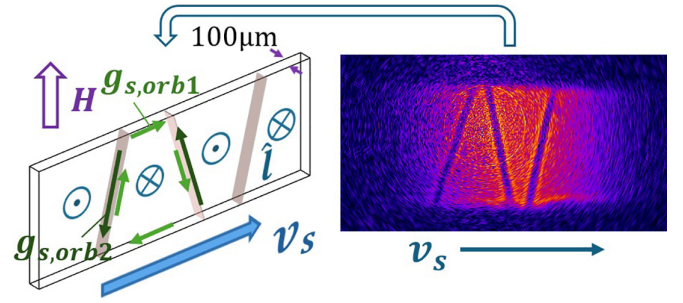


FIG. 5. (a) Illustration of the expected orientation of $\mathbf{g}_{s,orb}$ and the determined directions of the chiral vectors $\hat{l}$ in each chiral domain under applied rightward $\mathbf{v}_s$. The $\mathbf{g}_{s,orb}$ is shown for the case of twist-type $\hat{l}$ -walls. (b) MRI image of the measured chiral domain structure under rightward $\mathbf{v}_s$.

value of k , as

$$k \approx \frac{d_0 v_s}{(\hbar/2m) \log(d_0/\xi_0)} \approx 10^3 v_s. \quad (9)$$

Substituting $k = \tan 10^\circ$ yields $v_s \simeq 0.2$ mm/s.

Additionally, our numerical simulation of texture, under uniform $\mathbf{v}_s$, indicates that a flow of $v_s \simeq 0.2$ mm/s across the channel stabilizes a tilting $\hat{l}$ -wall by approximately 10° . The texture simulations are performed using software developed by one of the authors (T.T.), which was modified to enable calculations of tilted domain walls. In the simulations, the orientations of $\hat{l}$, $\hat{m}$, $\hat{n}$, and $\hat{d}$ at each point are adjusted to minimize the total energy f_{tot} , which is the sum of the gradient energy f_{bend} , the dipole energy f_{dip} , and the magnetic energy f_{mag} . Here, f_{dip} and f_{mag} are given by

$$f_{dip} = -\frac{1}{2} \left(\frac{\hbar}{2m} \right)^2 \rho_{s\parallel} \left(\frac{1}{\xi_D} \right)^2 (\hat{l} \cdot \hat{d})^2,$$

$$f_{mag} = \frac{1}{2} \Delta \chi (\hat{d} \cdot \mathbf{H})^2,$$

where ξ_D is the dipole coherence length, $\Delta \chi$ is the anisotropy of the magnetic susceptibility tensor, and $\mathbf{H}$ is the external magnetic field. A sufficiently large $\mathbf{H}$ in the z direction is applied to fix $\hat{d}$ within the xy plane. The vectors $\hat{m}$ and $\hat{n} = \hat{l} \times \hat{m}$ are unit vectors orthogonal to $\hat{l}$, and we can express $\mathbf{v}_s$ as $\mathbf{v}_{s,i} = (\hbar/2m)\hat{m} \cdot \nabla_i \hat{n}$. The simulations are performed in a region within the xy plane with dimensions $30\xi_D \approx 0.3$ mm in the x direction and $10\xi_D \approx 0.1$ mm in the y direction, using translational symmetry along the direction $\hat{z} + k\hat{x}$. The mesh size for the calculations is $0.05\xi_D$. The boundary conditions at the wall in the y direction are set such that $\hat{l} = \pm \hat{y}$ depending on the side of the $\hat{l}$ -wall.

Figure 6(a) shows the calculated changes in each energy component as a function of the tilting slope k of the $\hat{l}$ -wall under a superfluid flow of approximately $\bar{v}_s = 0.2\hbar/(2m\xi_D) \approx 0.2$ mm/s in the x direction. The $\mathbf{v}_s$ varies spatially due to the texture. It is expressed as $\mathbf{v}_s = -(\hbar/2m)(\nabla\gamma + \cos\beta\nabla\alpha)$, where α and β are the azimuthal and polar angles of $\hat{l}$, respectively, and γ represents the direction of $\hat{m}$ around $\hat{l}$. The boundary conditions at the inlet and outlet of the channel along the x direction were set such that the average value of $-(\hbar/2m)\nabla\gamma$ corresponds to $\bar{v}_s$. The vertical axis represents

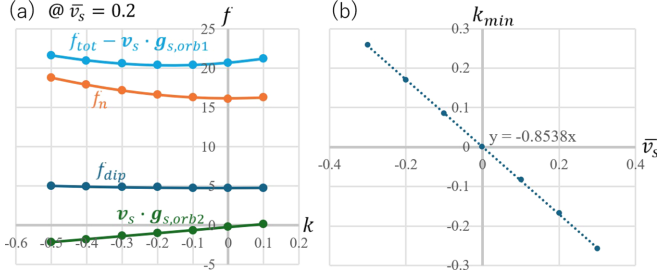


FIG. 6. (a) k dependence of the $\hat{l}$ -wall energy at $\bar{v}_s = 0.2\hbar/(2m\xi_D)$. The vertical axis represents the energy difference between the case with one $\hat{l}$ -wall and the case without an $\hat{l}$ -wall. The energy is integrated over the xy plane and is given in units of $(\hbar/2m)^2\rho_{s\parallel}$. (b) Tilt of the $\hat{l}$ -wall, $k_{\min}$, as a function of $\bar{v}_s$. For each $\bar{v}_s$, $k_{\min}$ was determined by fitting the values of $f_{\text{tot}} - \mathbf{v}_s \cdot \mathbf{g}_{s,\text{orb}1}$ as a function of k . The unit of the horizontal axis is $\hbar/(2m\xi_D) \approx 1 \text{ mm/s}$.

the energy difference between the case with one $\hat{l}$ -wall and the case without an $\hat{l}$ -wall. The term $\mathbf{v}_s \cdot \mathbf{g}_{s,\text{orb}2}$ exhibits a nearly linear dependence on k . On the other hand, f_n increases approximately as k^2 as the $\hat{l}$ -wall tilts. The actual tilt of the $\hat{l}$ -wall is considered to be determined by the value of k that minimizes $f_{\text{tot}} - \mathbf{v}_s \cdot \mathbf{g}_{s,\text{orb}1} = f_n + f_{\text{dip}} + \mathbf{v}_s \cdot \mathbf{g}_{s,\text{orb}2}$. This is because the contributions of $\mathbf{v}_s \cdot \mathbf{g}_{s,\text{orb}1}$ cancel after integrating along the perimeters of each domain. From the graph, $f_{\text{tot}} - \mathbf{v}_s \cdot \mathbf{g}_{s,\text{orb}1}$ is minimized at $k \approx 0.17$, suggesting that the $\hat{l}$ -wall tilts by about 10° . Figure 6(b) shows the value of k that minimizes $f_{\text{tot}} - \mathbf{v}_s \cdot \mathbf{g}_{s,\text{orb}1}$, $k_{\min}$, as a function of $\bar{v}_s$. It can be seen that the value of $k_{\min}$ is approximately proportional to $\bar{v}_s$. The magnitude of this flow is not greater than the typical critical velocity and is within the range that can flow through the channel.

A Fréedericksz transition occurs at $v_s \approx 0.3 \text{ mm/s}$ (according to Kopu and Thuneberg [33]) or $v_s \approx 0.4 \text{ mm/s}$ (according to Walmsley *et al.* [21]) when the spacing between the parallel plates is $100 \mu\text{m}$. As is written earlier, the tilting angle of the $\hat{l}$ -walls saturated at a flow velocity that corresponds to $\dot{Q} \approx 1 \text{ nW}$ in Fig. 3. This might also be related to the Fréedericksz transition. The tilting angle of the $\hat{l}$ -wall is determined by $\partial l_y/\partial x$ in f_{c0} . When the Fréedericksz transition occurs, $\hat{l}$ starts to align in the x direction. Then, $\partial l_y/\partial x$ decreases and thereby the tilting angle of the $\hat{l}$ -wall decreases.

One may argue that the tilt of $\hat{l}$ -walls may be caused by the temperature gradient rather than the supercurrent. However, the change in the gradient energy coefficients due to the temperature gradient is negligible; thus, the temperature gradient cannot be a primary cause of the tilt of the $\hat{l}$ -walls, neither is the effect of normal component flow across the channel.

VI. TILTING EFFECT OF OTHER WALLS

We have shown the supercurrent-induced tilting effect of the $\hat{l}$ -walls. We want to add some comments on the other kinds of domain walls, which are observed in the same apparatus as well. For the case of $\hat{l}$ -wall, a twist-type spatial variation ($\gamma = 0$) is expected under $\mathbf{v}_s = 0$. On the other hand, in the case of the $\hat{d}$ -wall, where $\hat{l}$ and $\hat{d}$ are dipole-locked, $\hat{d}$ rotates within the xy plane because of the anisotropic magnetic energy, and

thus, $\hat{l}$ also rotates within the xy plane. In this case, a relation $f_{c0} = -(\hbar/2m)C_0v_s k(\partial l_y/\partial x)$ can be obtained since $\cot \gamma = k$. This implies that the $\hat{d}$ -wall tilts in the same direction as the $\hat{l}$ -wall under finite $\mathbf{v}_s$. This behavior is attributed to the emergence of a twist component in the $\hat{d}$ -wall upon tilting. The expected angle of the $\hat{d}$ -wall is not significantly different from that of the $\hat{l}$ -wall. The angle of tilting is determined by the balance between f_{c0} and other energies. The reduction in f_{c0} associated with tilting is comparable for both types of walls. The increase in the gradient energy of these CDWs has a significantly large contribution from around the singular part of the texture on the parallel plate surface. Since the size of the singular part is almost the same for both $\hat{d}$ -wall and $\hat{l}$ -wall, the expected energy loss and tilting angle are of the same order of magnitude. According to our numerical simulations of the texture, $\hat{d}$ -walls are slightly less prone to tilting than $\hat{l}$ -walls. However, in the actual experiments, it was not possible to obtain clear evidence on the tilting of $\hat{d}$ -walls because of a stronger pinning effect at a temperature near T_c . On the other hand, $\hat{d}$ -walls should be insensitive to external supercurrent. We confirmed that they never tilted after annealing and freezing under supercurrent, which is generated by $\dot{Q} = 0.5 \text{ nW}$.

VII. DISCUSSION

In a chiral domain, each Cooper pair carries an angular momentum $\mathbf{L} = \hbar\hat{l}$. Consequently, the total angular momentum of a chiral domain is expected to be $n_c\hbar$, where n_c is the effective number of Cooper pairs. The value of n_c has been a subject of ongoing debate [15–17,26,29,34–43]. A prevailing theoretical viewpoint suggests that n_c is $\rho_{s\parallel}V/2m$ (where V is the domain volume), scaled by a factor of unity, which depends on the edge states of the chiral domain [17]. However, an alternative perspective proposes that n_c is $\alpha\rho_{s\parallel}V/2m$, which is reduced by a factor of $\alpha = \epsilon_0/\epsilon_F \approx 10^{-2}$, where ϵ_0 and ϵ_F are the energy gap and Fermi energy, respectively [15]. Definite experimental evidence to deny the latter possibility has not existed. As previously shown, the estimated magnitude of v_s when the $\hat{l}$ -wall is tilted by approximately 10° is 0.2 mm/s . This estimation is based on the model without the reduction factor α . On the other hand, estimation based on the model with $\alpha = \epsilon_0/\epsilon_F \approx 10^{-2}$ provides $v_s \simeq 20 \text{ mm/s}$ for 10° . Since it is unlikely that such a large v_s flows within the parallel plates, the experimental result supports the model without the reduction factor α .

VIII. SUMMARY

In summary, we investigated how externally applied supercurrent $\mathbf{v}_s$ affects the shape of chiral domains in $^3\text{He-A}$, which is confined between narrow-gapped parallel plates by using our state-of-the-art ultralow-temperature MRI measurement. We investigated the influence of $\mathbf{v}_s$ on chiral domain walls, particularly $\hat{l}$ -walls, through the interaction with the orbital supercurrent $\mathbf{g}_{s,\text{orb}}$ generated by spatial variations of the chiral vector $\hat{l}$ around chiral domains. We observed that $\hat{l}$ -walls tilted under finite $\mathbf{v}_s$, and the tilting direction depended on both the direction of $\mathbf{v}_s$ and the direction of $\hat{l}$ in neighboring chiral domains. This allowed us to determine the direction of $\hat{l}$ in each domain. Moreover, the observation of tilting confirmed that

the amount of orbital supercurrent at the chiral domain wall is as large as the macroscopic angular momentum ($\rho_{\parallel} V/2m$) $\hbar$ of the chiral domain. We also demonstrated that we can manipulate the macroscopic chiral domain by applying supercurrent generated in the chiral superfluid ^3He . The observed chiral domain has a large macroscopic size of millimeter scale in a known location and is ready to serve as a testing sample for future experiments on monochiral material.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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