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Magnus-driven Hall transport in a smectic vortex state

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Abstract

We report the emergence of an anomalous Hall response induced by smectic vortex order in a layered superconductor. By tuning the in-plane magnetic field and temperature, we uncover a distinct transport regime in which the longitudinal resistance remains low, whereas the transverse resistance becomes finite and even exceeds it -a definitive hallmark of unconventional vortex dynamics. This behavior arises from Magnus-force-driven motion of smectic dislocation vortices generated via interlayer smectic kink excitations, directed along the applied current within a smectic vortex liquid crystal phase, where partial translational symmetry breaking enables anisotropic and coherent vortex flow. These results establish smectic vortex matter as a new class of quantum vortex phases with hydrodynamic and topological character. Our findings open pathways to controlling topological vortex transport in anisotropic superconductors and suggest that the intrinsic entanglement of smectic vortex arrays may provide a platform for vortex-based quantum information functionalities.

Introduction

The dynamics of vortices in superconductors can exhibit remarkably fluid-like behavior. While vortex motion is commonly described by Lorentz-force-driven vortex flow, a hydrodynamic contribution known as the Magnus force can become prominent under certain conditions [1–5]. This force manifests experimentally as a Hall voltage associated with vortex motion [6, 7]. In particular, anomalous Hall effects [8–11], including sign reversals observed in cuprate superconductors, have been attributed to the interplay between liquid-crystalline superconducting order and the fluid nature of vortices. Similar hydrodynamic responses have been reported in the BCS-BEC crossover regime [12], where vortices exhibit increasingly bosonic characteristics. These unconventional vortex states, especially when accompanied by liquid-crystalline order, may host nontrivial Hall responses and even quantum entanglement, both absent in conventional line-like vortices. Despite these intriguing possibilities, experimental investigations of the Hall effect in vortex liquid crystals remain extremely limited, and their dynamical properties are still poorly understood.

NbS₂ is a layered two-dimensional superconductor that does not exhibit charge density wave order down to low temperatures and becomes superconducting around 5 K [13]. Re-

cent studies [14] suggest that pristine bulk NbS₂ may host an FFLO (Fulde-Ferrell-Larkin-Ovchinnikov) state under low temperatures and high magnetic fields, making it a promising platform to study unconventional superconductivity. In our recent work [15], we found that dilute Fe doping enhances the superconducting properties of NbS₂ and simultaneously induces a pronounced liquid-crystalline vortex phase. These results position Fe-doped NbS₂ as a unique system for exploring vortex matter with both hydrodynamic and topological character.

In this study, we investigate the vortex dynamics in Fe-doped NbS₂ single crystals, where a smectic-like vortex array has been previously identified. We focus on the anisotropic and topological nature of vortex motion by performing simultaneous measurements of longitudinal (R_{xx}) and Hall (R_{xy}) resistances on the same sample. By precisely controlling the in-plane magnetic field and the direction of applied current, we uncover a distinct regime within the smectic vortex phase where the hydrodynamic Magnus force dominates over the conventional Lorentz force. Our findings suggest a new avenue for quantum technologies, opening the possibility of manipulating quantum entanglement via vortex liquid crystals [16].

Results and discussion

Figure 1(a) shows the temperature dependence of the resistances R_{xx} and R_{xy} in Fe_{0.0011}NbS₂. The residual resistance ratios ($RRR = R(275\text{ K})/R(7\text{ K})$) were found to be 20 for R_{xx} and 15 for R_{xy} , indicating good sample quality. An enlarged view around the superconducting transition is shown in Fig. 1(b). At the IMR facility, a residual magnetic field of approximately 0.2 T remains even when the magnetic field is nominally set to zero. Thus, the data in Fig. 1(b) were taken under this residual-field condition. The onset transition temperature for R_{xx} is 6.4 K. R_{xy} shows a slight increase in resistance from 7 K and then transitions to zero resistance. As shown in the Supplemental Material Fig. S3 [17], no anomalous R_{xy} signal is observed under true zero-field conditions. As reported in our previous paper [15], the transition temperature is higher in dilute Fe-doped samples than in pure NbS₂.

In conventional two-dimensional Hall measurements, a magnetic field is applied perpendicular to the conducting plane, and the transverse voltage with respect to the current is defined as the Hall voltage. In this study, we apply the magnetic field parallel to the

conducting plane and define the transverse voltage component with respect to the current direction as V_{xy} . This configuration corresponds to the so-called planar Hall effect. Typically, Hall measurements involve reversing the magnetic field polarity to eliminate the longitudinal component R_{xx} from R_{xy} . Because magnetic field reversal is not available at the IMR facility, we carefully examined possible geometrical mixing between R_{xx} and R_{xy} using normal-state transport data (see Supplemental Material Text [17]). As shown in Supplemental Material Fig. S4 [17], the ratio R_{xy}/R_{xx} remains nearly constant (0.30–0.38) over a wide temperature range from 8 to 300 K and shows no appreciable magnetic-field dependence at 8 K. The absence of both temperature and magnetic-field dependence indicates that the measured transverse voltage ($R_{xy}^{\text{meas}} = R_{xy}^{\text{true}} + \alpha R_{xx}$) in the normal state does not originate from an intrinsic in-plane Hall response ($R_{xy}^{\text{true}} = 0$), but is instead dominated by geometrical admixture. Accordingly, the measured signal is well described by $R_{xy}^{\text{meas}} \approx \alpha R_{xx}$, with a temperature- and field-independent coefficient α . In contrast, in the superconducting state, the ratio R_{xy}/R_{xx} reaches its maximum value ($R_{xy}/R_{xx} \sim 10$) in the broader R_{xx} plateau region observed at low temperatures, specifically when the magnetic field direction is perpendicular to the current direction ($H \perp I$) (Figs. 2(a) and 3). This behavior cannot be accounted for by geometrical mixing alone. To further examine possible geometric admixture effects, we additionally performed magnetic-field-reversal measurements. The transverse signal exhibits predominantly odd-in-field behavior, while the longitudinal response remains even under field reversal (see Supplemental Material Fig. S6 [17]), confirming that the superconducting-state transverse response is intrinsic.

To investigate the anisotropic behavior of liquid-crystalline vortex states in this two-dimensional layered superconductor, we applied an in-plane magnetic field. Figure 2(a) shows the magnetic field dependence of R_{xx} and R_{xy} at various temperatures for the configuration $H \perp I$. As temperature decreases, the superconducting transition becomes broader. Remarkably, at low temperatures, superconductivity persists even at 24 T, and a plateau resistance for R_{xx} is found. The plateau resistance value of 0.038 m Ω is approximately one-tenth of the normal resistance. In contrast, R_{xy} in Fig. 2(a) transitions from a zero-resistance state to a finite resistance, reaches a peak, and then returns to normal resistance of $|R_{xy}| = 0.15$ m Ω . Similar plateau features and the same in-plane anisotropy between the $H \perp I$ and $H \parallel I$ configurations are also observed in samples with a different nominal Fe concentration (see Supplemental Material [17]). No sign reversal is observed in R_{xy} , in

contrast to certain other superconducting systems [7–9, 12]. This suggests that the Hall response is not controlled by competing contributions with opposite signs, but is instead dominated by vortex-motion-related transport.

Figure 2(b) displays the results for the configuration $H \parallel I$. The overall behavior of both R_{xx} and R_{xy} is qualitatively similar to that in the $H \perp I$ case, although the plateau region in R_{xx} is notably narrower. The presence of in-plane anisotropy in the vortex dynamics is consistent with our earlier findings [15]. To analyze this anisotropy in more detail, we extracted data at 0.5, 2, and 3 K, shown in Fig. 3. The following key features can be identified.

In the vortex solid state, both R_{xx} and R_{xy} exhibit zero resistance. Upon increasing the magnetic field, R_{xy} begins to show a finite resistance before R_{xx} does. At the field where anisotropy becomes apparent in R_{xy} with respect to field orientation (indicated by the black arrow), R_{xx} also becomes finite. Notably, in this regime, the magnitude of the Hall resistance exceeds that of the longitudinal resistance ($R_{xy} > R_{xx}$).

In the $H \perp I$ configuration, R_{xy} reaches a peak at the magnetic field (green arrow) where R_{xx} begins to rise from its plateau. After the peak, R_{xy} gradually transitions to the normal-state value, as seen in the 3 K data. At 0.5 K, however, the R_{xx} plateau persists even at 24 T, suggesting the presence of a highly unusual and robust vortex state. Similarly, in the $H \parallel I$ configuration, R_{xy} again exhibits a peak at the magnetic field (orange arrow) where the R_{xx} plateau terminates. A particularly striking feature is that in the transition from zero resistance to the high-field edge of the plateau, the magnitude of R_{xy} remains consistently larger than R_{xx} . It is important to note that in conventional Lorentz-force-driven vortex motion, vortices predominantly move perpendicular to the current, so the in-plane Hall response is expected to be very small and $R_{xy}/R_{xx} \ll 1$. Therefore, the observation of a regime where R_{xy} exceeds R_{xx} in the superconducting state is highly unconventional and requires a distinct physical mechanism. In a layered superconductor, if the transport were dominated by interlayer vortex motion, one would expect a larger resistance in the $H \perp I$ configuration, where the Lorentz force acting along the c axis is maximized; however, our observation is opposite, as shown in Fig. 3, consistent with our previous report [15]. This indicates that the detected dissipation is not governed by simple interlayer vortex flow.

We therefore consider a scenario in which the smectic vortex structure undergoes inter-layer hopping via smectic kink excitations. Such kink processes generate vortices penetrating

the conducting planes, which we refer to as smectic dislocation vortices, i.e., topological defects of the smectic order associated with distortions of the lamellar structure rather than simple phase singularities of the superconducting order parameter. Because an in-plane magnetic field exerts a Lorentz force along the interlayer direction, such kink-mediated processes are naturally promoted, and the resulting smectic dislocation vortices can dominate the in-plane transport. Accordingly, although the magnetic field is applied in-plane, our measurements are sensitive to the motion of vortices penetrating the conducting planes, as schematically illustrated in Fig. 5.

To further investigate vortex dynamics in relation to the in-plane magnetic field and current directions, we analyzed the Hall angle $\Theta_H = \tan^{-1} (|R_{xy}/R_{xx}|)$, as shown in Fig. 4. We define the $\frac{R_{xy}}{R_{xx}}$ as the Hall angle for the in-plane magnetic field (see Supplemental Material [17]). Θ_H approaches $\pi/2$ in the low magnetic field regime. This indicates that, in this regime, the vortices move almost parallel to the direction of the current, generating an electric field transverse to the current, and therefore cannot be explained solely by the conventional Lorentz force, which drives vortices perpendicular to the current.

To interpret this result, we consider the vortex motion based on theoretical models [3]. In typical superconductors, vortex motion is dominated by the Lorentz force. Since the Lorentz force is perpendicular to the current, vortices are not expected to move in the same direction as the current. However, to explain our observation, we invoke the Nozières-Vinen model [3], which accounts for both the Magnus force and the drag force in a vortex flow regime without pinning. The Magnus force acting on a vortex is given by

$$\mathbf{F}_M = n_s e (\mathbf{v}_s - \mathbf{v}_L) \times \phi_0, \quad (1)$$

where n_s is the superfluid electron density, $\mathbf{v}_s$ is the superfluid velocity, $\mathbf{v}_L$ is the vortex velocity, and ϕ_0 is the magnetic flux quantum.

As illustrated in Fig. 5, the flow is enhanced when the superfluid velocity is aligned with the sense of vortex rotation, whereas it is suppressed when the two are antiparallel. Consequently, Bernoulli's theorem dictates that a force in the $-y$ direction (upper left panel) or in the $+y$ direction (upper right panel) is exerted, respectively. As a vortex moves, an electric field is generated within its core. Because the vortex core is in a normal (non-superconducting) state, dissipation occurs as current flows through it. The drag force acting on the vortex core due to this dissipation is given by

$$\mathbf{f}_d = -\pi\xi^2 n_s \cdot m\mathbf{v}_s/\tau, \quad (2)$$

where ξ is the coherence length and τ is the scattering time of electrons within the core.

By setting the total force $\mathbf{F}_M + \mathbf{f}_d = 0$, we can derive the condition for steady-state vortex motion. Importantly, when the drag force vanishes (i.e., in the limit of low dissipation), $\mathbf{v}_s = \mathbf{v}_L$, meaning the vortices move in the same direction and at the same speed as the superfluid current -a situation reminiscent of vortex dynamics in Bose-Einstein condensates (BECs) such as superfluid helium.

In our previous work [15], we proposed the existence of a smectic vortex liquid crystal state based on observed two-fold symmetry in in-plane transport measurements. Here, we focus on the influence of the hydrodynamic Magnus force within such a smectic structure and interpret our experimental findings accordingly. As illustrated in Fig. 5, we consider a vortex structure exhibiting smectic order. These lamellar layers, or line nodes (green lines), are regions where the superconducting amplitude is locally suppressed and are oriented perpendicular to the applied magnetic field. Within this smectic framework, vortices can hop (or tunnel) between layers and exchange positions with adjacent layers, thereby allowing magnetic vortices to penetrate perpendicular to the conducting plane. Such inter-layer hopping corresponds to smectic kink excitations, while the vortices penetrating the conducting planes can be regarded as smectic dislocation vortices, which are topological defects of the smectic order and are distinct from conventional pancake vortices in layered superconductors.

Within the conducting planes, the vortex motion is influenced by both the Lorentz and Magnus forces. In the configuration shown in Fig. 5(a), where the magnetic field is applied perpendicular to the current, the lamellar layers are aligned such that the Magnus force dominates, resulting in vortex motion parallel to the current. This scenario likely explains the anomalous Hall response observed experimentally, where $R_{xy} > R_{xx}$. At sufficiently high magnetic fields, however, enhanced vortex density and interlayer coupling tend to destabilize the smectic order itself, leading to a crossover out of the smectic regime toward more conventional vortex flow and a gradual recovery of normal-state transport behavior, as seen in Figs. 2 and 3.

Furthermore, in the configuration shown in Fig. 5(b), where the magnetic field and current are parallel, the lamellar layers form in a direction perpendicular to both, making the

contribution of the Lorentz force more significant. In this geometry, Magnus-driven vortex motion necessarily involves crossing the lamellar structure, which enhances dissipation and suppresses coherent flow along the smectic channels.

In conventional vortex-flow transport, dissipation is expected to scale with the vortex density. In contrast, in a smectic vortex state, vortex motion is constrained to lamellar flow channels formed by the broken translational symmetry, and the effective number of conducting paths is determined primarily by the smectic channel structure rather than by the total vortex density. Once the smectic order is established, increasing the magnetic field mainly increases the number of vortices accommodated within each lamella, while the number of available flow channels is fixed. As a result, the longitudinal resistance becomes field independent, giving rise to the observed R_{xx} plateau. This behavior highlights that dissipation in the smectic phase is governed by channel-controlled vortex transport rather than conventional density-controlled vortex flow.

While the existence of the plateau reflects the channel-controlled nature of dissipation in the smectic phase, its width and robustness depend sensitively on how these channels are geometrically aligned with respect to the applied current. Within the field range where the smectic order is stabilized, the broader R_{xx} plateau observed for the $H \perp I$ configuration compared with the $H \parallel I$ configuration can be naturally understood from the geometric alignment between the smectic lamellar layers and the current direction. For $H \perp I$, the lamellar layers are oriented parallel to the current (Fig. 5(a)), providing one-dimensional flow channels along which smectic dislocation vortices can move coherently without crossing the lamellar boundaries. As a result, dissipative vortex motion associated with pinning or Lorentz-force-induced transverse displacement is minimized, stabilizing the smectic vortex phase over a wide magnetic-field range and leading to an extended R_{xx} plateau. In contrast, for $H \parallel I$, the lamellar layers are oriented perpendicular to the current (Fig. 5(b)), so that Magnus-driven vortex motion necessarily involves crossing the lamellar structure, destabilizing the smectic order and narrowing the field range over which the plateau persists. We therefore conclude that the geometric alignment between the current direction and the smectic order is the primary origin of the pronounced contrast in the plateau width between the two configurations.

Notably, in NbS_2 and NbSe_2 , there have been reports of superconducting states exhibiting spatial modulations such as Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) [14, 20] and pair-

density wave (PDW) states [21]. These spatially modulated states may facilitate the formation of smectic vortex liquid crystals. Taken together, our results show that the in-plane anisotropic Hall response can be consistently explained by invoking a smectic vortex liquid crystal framework and accounting for the dominance of the hydrodynamic Magnus force in specific regimes.

Conclusion

In summary, we have investigated the dynamics for the Hall response of vortex liquid crystals in Fe-doped NbS₂ single crystals, focusing on the smectic vortex phase. Our simultaneous measurements of longitudinal and Hall resistances revealed a highly anisotropic vortex flow, strongly influenced by the in-plane magnetic field orientation. Notably, we identified a regime in which the hydrodynamic Magnus force dominates over the conventional Lorentz force, consistent with vortex transport mediated by smectic dislocation vortices generated through interlayer smectic kink excitations, highlighting the fluid-like nature of vortices in this phase. These findings provide direct experimental evidence that liquid-crystalline vortex states can exhibit unconventional Hall responses, potentially linked to the dynamics of topological defect excitations in the smectic order and to quantum-entangled vortex configurations. This opens a new path toward manipulating vortex dynamics in quantum materials, with possible implications for novel superconducting devices and quantum information technologies.

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Data availability

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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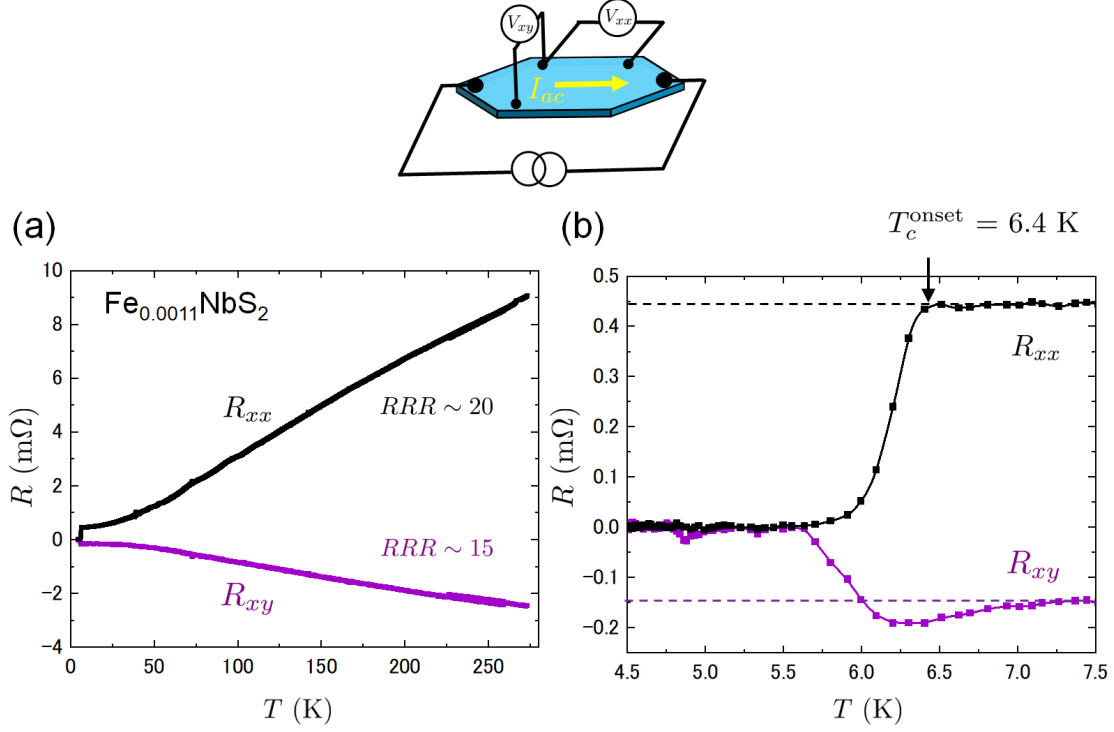


Figure 1. Electric transport properties in $\text{Fe}_{0.0011\%}\text{NbS}_2$. (a) Temperature dependence of R_{xx} and R_{xy} in the longitudinal and Hall directions. (b) Enlarged view near the superconducting transition temperature. R_{xx} and R_{xy} measured at the IMR facility under a residual magnetic field of approximately 0.2 T, which remains even when the field is nominally set to zero.

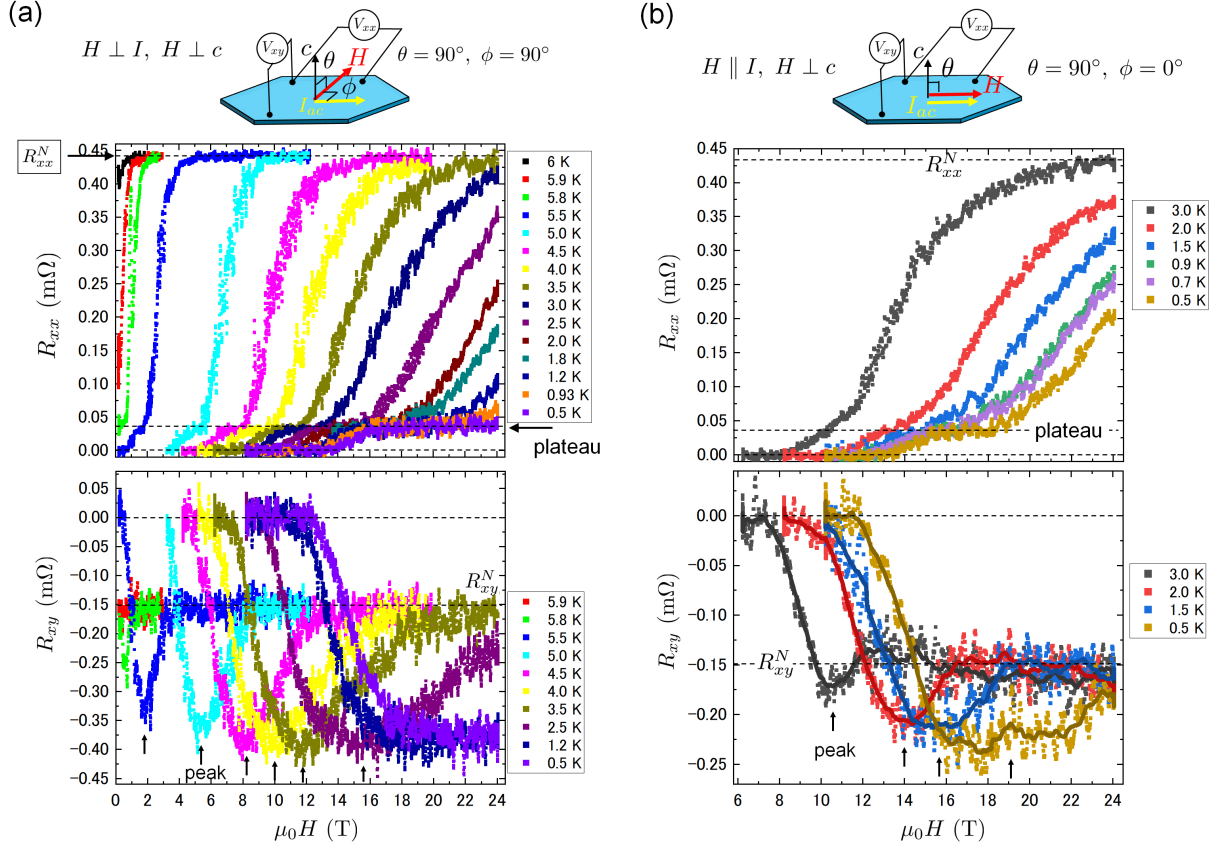


Figure 2. Vortex flow resistance. Magnetic field dependence of R_{xx} and R_{xy} when an in-plane magnetic field perpendicular (a) and parallel (b) to the current is applied.

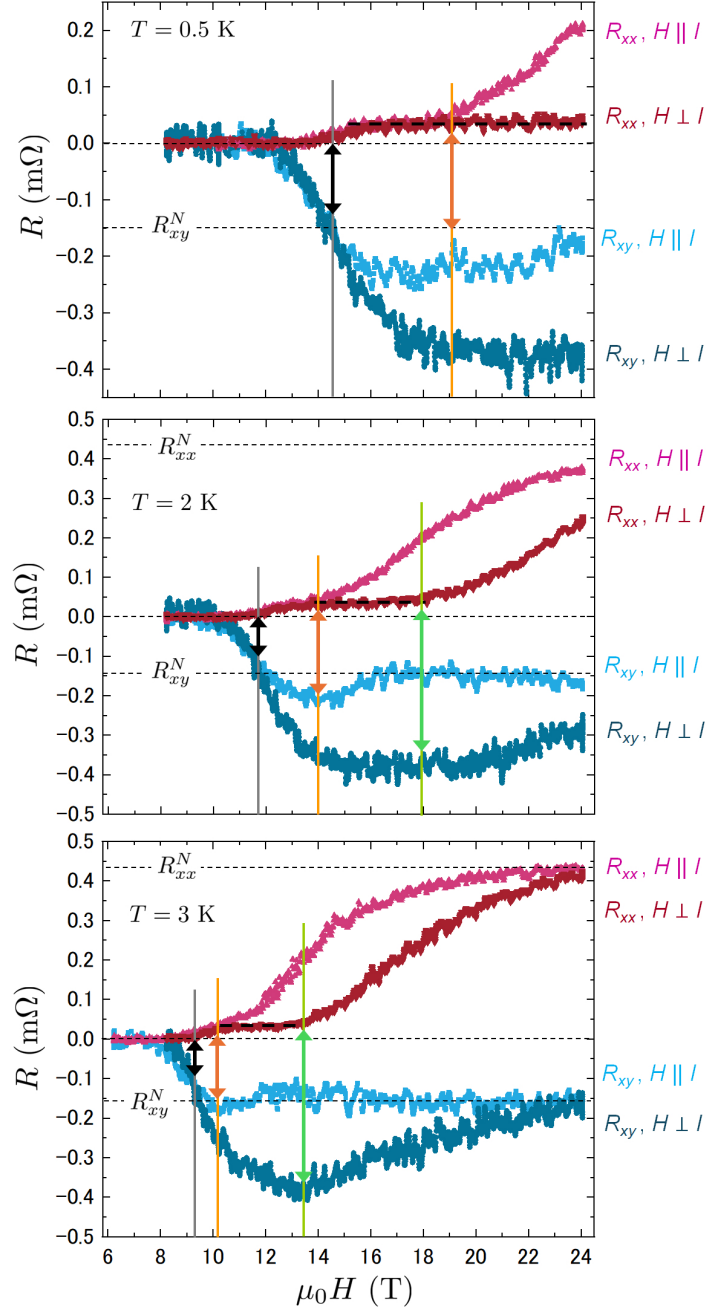


Figure 3. In-plane anisotropy of vortex flow. Comparison of R_{xx} for the $H \perp I$ and the $H \parallel I$ configurations extracted at 0.5, 2, and 3 K. Similarly, the comparison of R_{xy} is plotted.

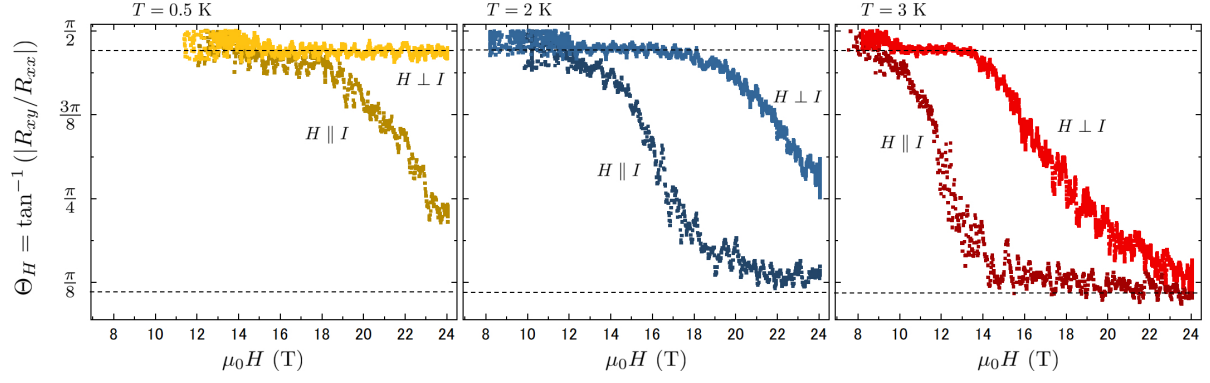


Figure 4. Magnetic field dependence of the Hall angle $\Theta_H = \tan^{-1}(|R_{xy}/R_{xx}|)$. In the region where $\Theta_H \sim \pi/2$, vortices move parallel to the current.

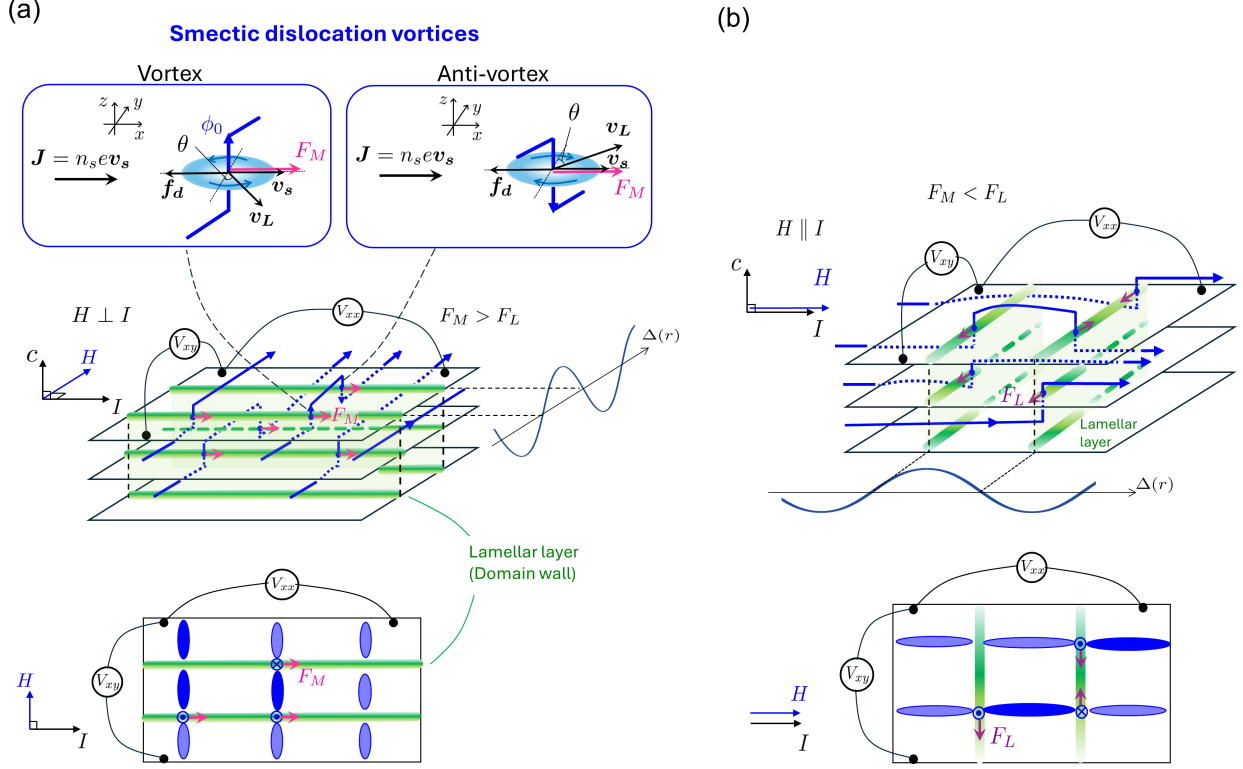


Figure 5. Schematic of smectic vortex dynamics. Smectic vortices within a layer tend to undergo reconnection at the lamellar layers. Such interlayer hopping corresponds to a smectic kink excitation, which generates a vortex penetrating the conducting plane, referred to as a smectic dislocation vortex. (a) Center panel: For $H \perp I$, a vortex located between layers can be thermally excited to hop to a neighboring layer, leading to the creation of a smectic dislocation vortex within the conducting plane. This in-plane vortex experiences both the hydrodynamic Magnus force and the Lorentz force. Because the lamellar layers are aligned with the direction of the Magnus force, the vortex can move parallel to the applied current. Spatial modulation of superconducting amplitudes, such as in the FFLO state, assists the formation of the smectic vortex. Top panel: Forces acting on a vortex in the vortex flow state. The vortex moves at an angle θ relative to the direction perpendicular to the applied current density $\mathbf{J}$. $\mathbf{F}_M$ denotes the Magnus force and $\mathbf{f}_d$ the drag force. Bottom panel: Smectic magnetic vortex lines are illustrated as rods. Reconnection of vortex lines readily occurs at the lamellar layers via smectic kink excitations. Vortex lines located beneath the conducting plane are depicted in light blue. (b) For $H \parallel I$, the lamellar layers are oriented perpendicular to the current, so the Lorentz force becomes more dominant for the motion of smectic dislocation vortices within the conducting plane.