

Identification of intrinsic and extrinsic in-plane twofold symmetry in CsV_3Sb_5 via transport measurements

Yu-Chi Yao ^{1,2}, Fei Sun ¹, Andrea Capa Salinas ³, Stephen D. Wilson ³, Phil D. C. King ², and Haijing Zhang ^{1,4,*}

¹Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany

²School of Physics and Astronomy, University of St Andrews, St Andrews KY16 9SS, United Kingdom

³Materials Department, University of California Santa Barbara, Santa Barbara, California 93106, USA

⁴School of Physics, Southeast University, Nanjing 211189, China



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The identification of in-plane twofold symmetry in layered superconductors has sparked considerable interest. While transport measurements often reveal pronounced anisotropy, interpretation of their origin remains challenging due to the difficulty in disentangling competing contributions. Here, we systematically investigate the challenges of resolving intrinsic twofold symmetry in CsV_3Sb_5 through angular-dependent in-plane magnetoresistance measurements on exfoliated micron-scale devices. The sub-10- μm devices, with well-defined current directions, minimize contributions from structural domain walls and facilitate current-direction switching. Our experiments reveal a persistent twofold anisotropy in the upper critical field (H_{c2}), whose principal axis rotates with the applied current, indicating an extrinsic origin. The anisotropy also grows with increasing current, consistent with vortex motion driven by the Lorentz force. Two-axis rotational mapping combined with theoretical calculations further reveals how field misalignment can mimic or amplify apparent in-plane anisotropy. These results suggest that if intrinsic twofold symmetry does exist, its anisotropy is likely weak and highly susceptible to extrinsic influences. Our findings highlight the necessity of multiaxis and current-swapping methodologies for probing rotational symmetry in layered superconductors, and provide a refined framework for such investigations.

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I. INTRODUCTION

The kagome superconductor family AV_3Sb_5 ($A = \text{K}, \text{Rb}, \text{Cs}$) has attracted considerable attention due to the coexistence of charge density wave (CDW) order and superconductivity (SC), both exhibiting intriguing symmetry-breaking phenomena [1–4]. In these crystals, a 2×2 charge modulation forms below the CDW transition temperature ($T_{\text{CDW}} \sim 78\text{--}104$ K), accompanied by signatures of possible time-reversal symmetry breaking [5,6]. At lower temperatures ($T_c \sim 1\text{--}3$ K), SC emerges from this symmetry-broken normal state, offering a fertile platform to investigate the interplay between competing electronic orders.

Among the AV_3Sb_5 compounds, CsV_3Sb_5 stands out for exhibiting in-plane twofold symmetry in its superconducting state [6–15], which is unexpected given its nominal hexagonal crystal symmetry. While the material develops a CDW order that lowers its global symmetry to orthorhombic at low temperatures, the in-plane kagome layers largely retain sixfold

rotational symmetry and dominate the in-plane transport. The emergence of twofold symmetry, often referred to as electronic nematicity, manifests as a twofold in-plane anisotropy in superconducting properties. Such twofold anisotropy has attracted considerable attention not only in CsV_3Sb_5 , but also across a number of correlated electron systems. Notable examples include iron-based superconductors [16,17], transition metal dichalcogenides [18–20], and magic-angle twisted bilayer graphene [21]. In iron-based superconductors, nematic fluctuations have been proposed to play an active role in the superconducting pairing mechanism, potentially giving rise to unconventional SC [22,23]. The interplay between nematic order and SC in these systems continues to be a central topic in the quest to understand the microscopic origins of high-temperature and unconventional SC. In this context, unambiguously identifying twofold symmetry in the superconducting state is crucial, not only for establishing the presence of nematic order, but also for clarifying the fundamental nature of the superconducting state.

However, experimental evidence for such symmetry breaking in CsV_3Sb_5 remains nuanced [10,14,15,24–27]. Thermodynamic probes, such as specific-heat measurements, have reported a modest twofold anisotropy in the in-plane upper critical field (H_{c2}), with an anisotropy ratio of approximately 2% [14]. In contrast, electrical transport measurements present a more pronounced twofold anisotropy, up to 30%, in the superconducting states [10,15]. It is important to note that magnetotransport is sensitive not only to intrinsic electronic

*Contact author: Haijing.Zhang@cpfs.mpg.de

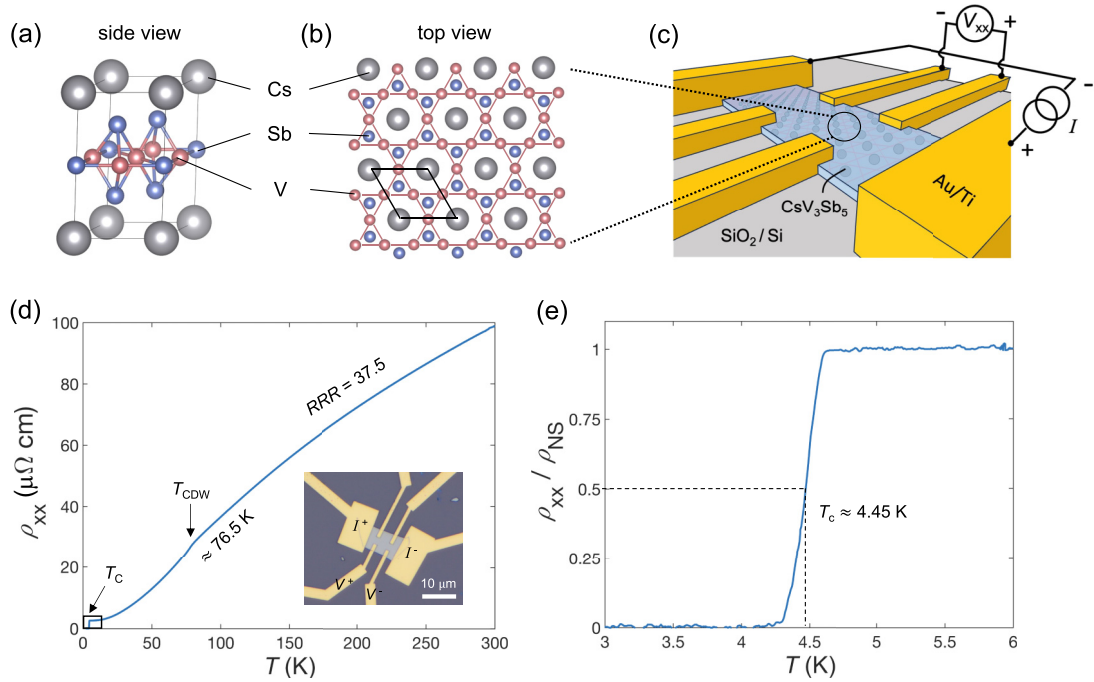


FIG. 1. Crystal structure of CsV_3Sb_5 and its electrical characterization. (a) Crystal structure of CsV_3Sb_5 viewed from the side, showing the kagome net sandwiched by the Cs atomic layers. (b) Top view of the crystal structure (along the c axis), which highlights the V kagome net and the Cs triangular lattice in the ab plane. (c) Schematic of a typical Hall bar device used for four-terminal measurements (I : bias current; V_{xx} : longitudinal voltage) on an exfoliated CsV_3Sb_5 flake, with electrical contacts formed by Ti/Au deposition. (d) Temperature dependence of resistivity for a 90-nm flake (sample C). The characteristic temperatures for the charge density wave (T_{CDW}) and SC (T_c) are marked. The inset shows an optical image of the device. The scale bar marks 10 μm . (e) Normalized resistivity ($\rho_{xx}/\rho_{\text{NS}}$) as a function of temperature across the superconducting transition, where T_c is marked as the temperature corresponding to 50% of the normal-state resistivity ρ_{NS} .

anisotropy but also to field-induced effects. For instance, Ref. [24] demonstrated overall in-plane rotational invariance in the absence of external perturbations, whereas an apparent anisotropic response emerges when weak magnetic fields or strain are present. Taken together, these findings raise fundamental questions: Is the observed twofold symmetry a genuine property of the superconducting pairing, or is it influenced, or even dominated, by extrinsic effects, such as structural domains or vortex dynamics?

In this work, we explore the in-plane twofold symmetry in CsV_3Sb_5 through systematic angular-dependent magnetoresistance measurements on exfoliated micron-scale devices. Angular-dependent magnetotransport measurements have been widely used in the literature to probe in-plane rotational symmetry [10, 15, 18–21, 24, 27–29]. The focus of this work is to explore the challenges in probing in-plane twofold symmetry using transport measurements and to establish a reliable transport-based strategy for its detection.

To this end, we systematically examine several factors that could potentially influence the detection of in-plane twofold anisotropy, including structural domain walls, Lorentz force effects, and magnetic field alignment. Our results reveal a persistent in-plane twofold anisotropy in the superconducting state, whose principal axis shifts with the direction of the applied current I , indicating an extrinsic origin of the anisotropy. Moreover, the anisotropy percentage exhibits a dependence on the magnitude of the applied current, which we attribute to vortex motion induced by the Lorentz force within the mixed superconducting state. By quantifying the effects of

field-alignment artifacts through two-axis rotational mapping, we further reveal how extrinsic contributions, including Lorentz force induced vortex motion and field misalignment, can dominate or artificially enhance rotational symmetry-breaking signatures. Our findings highlight the necessity of multiaxis, current-swapping methodologies to decouple intrinsic quantum behavior in symmetry-sensitive phenomena in layered quantum materials.

II. RESULTS

A. Micron-scale device characterization of CsV_3Sb_5

Figures 1(a) and 1(b) present the crystal structure of CsV_3Sb_5 . The side view in Fig. 1(a) shows a V kagome net sandwiched between Cs atomic layers, while the top view along the c axis [Fig. 1(b)] highlights the hexagonal symmetry of the V kagome lattice and the Cs triangular arrangement in the ab plane. The single crystals were grown using the self-flux method [2].

For electrical transport measurements, we fabricated four micron-scale devices with lateral dimensions ranging from 3 to 14 μm , as summarized in the Supplemental Material [30]. Thin flakes were exfoliated from bulk single crystals and transferred onto Si substrates. Bar-shaped flakes were selected to define electrical contacts in a Hall bar geometry. This device design is particularly important, as structural domains in bulk CsV_3Sb_5 typically span 10 to 100 μm [6]. While the domain size may change in exfoliated flakes, our sub-10- μm devices help minimize the influence of structural domain

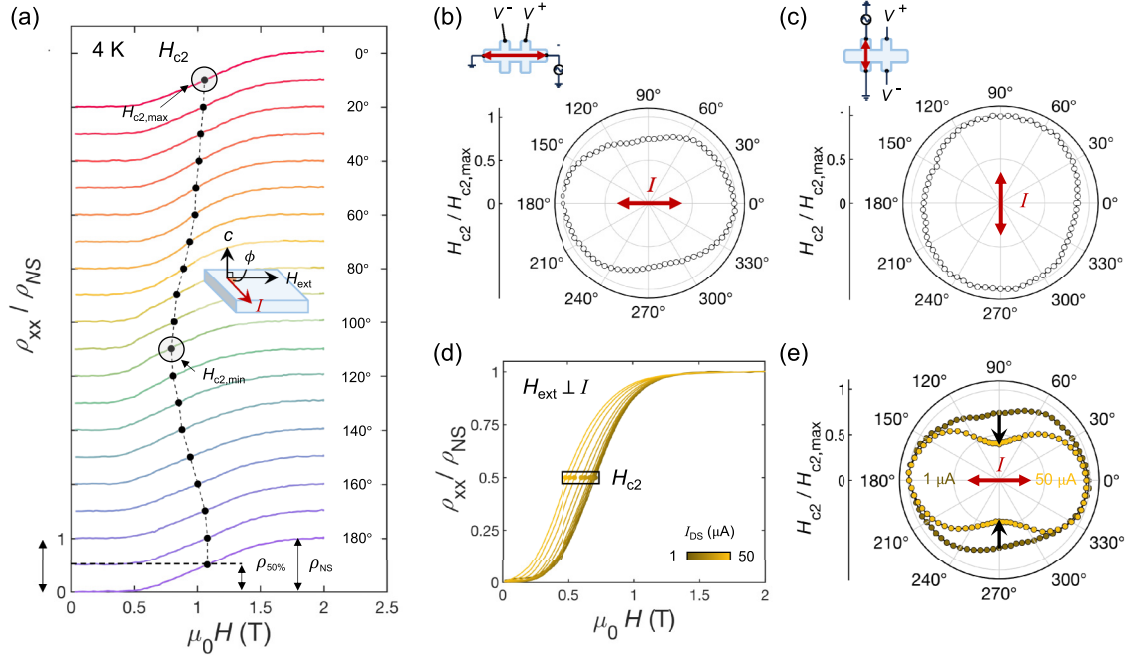


FIG. 2. Twofold symmetry in the azimuthal dependence of upper critical field for sample A at 4 K. (a) Normalized resistivity (ρ_{xx}/ρ_{NS}) as a function of magnetic field, with curves vertically offset for clarity. The H_{c2} , determined at 50% of the normal-state resistance, are marked by black solid circles. Inset: The schematic illustrates the relative orientations of external magnetic field (H_{ext}), the applied current, and the crystal's c axis. The rotation angle ϕ is defined as the angle between the current and the field direction. (b) Polar plot of the normalized H_{c2} ($H_{c2}/H_{c2,max}$)- ϕ extracted from (a) and the current direction is indicated with a red double-headed arrow. A schematic of the Hall bar device with the specified current path is shown above the plot. (c) Polar plot of the normalized $H_{c2} - \phi$ with the current direction rotated by 90° . (d) Normalized magnetoresistivity measured under different current amplitudes with the magnetic field oriented perpendicular to the current. The current amplitudes are indicated in the color bar. (e) Polar plot of the normalized $H_{c2} - \phi$ for different probe currents. The narrowing of the angular profile due to the Lorentz force is highlighted by black arrows.

walls that could obscure the intrinsic electronic behavior. In addition, the Hall bar configuration facilitates current direction switching during measurements, enabling more robust analysis of anisotropic transport behavior. The measurement schematic is shown in Fig. 1(c), and a representative device is displayed in the inset of Fig. 1(d).

We begin by investigating the transport properties of the micron-scale devices. Figures 1(d) and 1(e) present the temperature (T) dependence of resistivity, revealing two characteristic transitions: one into the charge density wave state (T_{CDW}) and the other into the superconducting state (T_c). Compared to bulk crystals, where T_{CDW} and T_c are 94 and 2.5 K, respectively [2], the micron-scale device exhibits a suppressed T_{CDW} at 76.5 K and an enhanced T_c at 4.45 K. Here, T_c is defined as the temperature at which the resistivity drops to 50% of the normal-state resistivity, ρ_{NS} . While the origin of this SC enhancement remains unclear, the observation is consistent with previous studies on exfoliated samples [31,32]. As shown in Fig. 1(e), the superconducting transition is remarkably sharp with a transition width ΔT_c of only 0.25 K, indicating the good quality of the device.

B. Apparent twofold anisotropy in H_{c2} and current-induced vortex dynamics

To probe the in-plane anisotropy of the superconducting state, we first performed angular-dependent

magnetoresistance measurements using a stepper-motor-driven rotator. This setup allows precise control over the orientation of the external magnetic field H_{ext} within the ab -crystal plane. By rotating the sample with respect to the applied magnetic field, we mapped out the angular dependence of the magnetoresistance, as shown in Fig. 2(a). The in-plane rotation angle ϕ is defined as the angle between the magnetic field and the applied current direction, as illustrated schematically in the inset. Here, $\phi = 0^\circ$ corresponds to the configuration where H is aligned parallel to the current I .

The upper critical field H_{c2} is determined here as the magnetic field at which the resistivity recovers to 50% of ρ_{NS} . This resistive critical field is commonly used to characterize H_{c2} , although it differs from the conventional thermodynamic definition, which identifies H_{c2} as the field below which vortices first appear in the sample [33]. In the Supplemental Material [30], we also examine an alternative criterion for H_{c2} , where H_{c2} is defined as the field at which the resistivity reaches 90% of ρ_{NS} . Both definitions yield consistent results and do not affect our overall conclusions.

As ϕ increases from 0° to 180° , H_{c2} first decreases and then returns to its maximum when $\phi = 180^\circ$, i.e., when the magnetic field is again aligned with the current. Figure 2(b) presents a polar plot of the normalized upper critical field $H_{c2}/H_{c2,max}$ as a function of ϕ , where $H_{c2,max}$ denotes the maximum value in the angular sweep. The plot reveals

a pronounced twofold symmetry with an anisotropy ratio, defined as $(1 - H_{c2,\min}/H_{c2,\max})$, of approximately 25%, and the principal axis of this anisotropy aligns with the current direction. The twofold anisotropy progressively decreases as the temperature is lowered, reaching 11% at 1.8 K (details are shown in the Supplemental Material [30]).

To further investigate the nature of this anisotropy, we rotated the current direction by $\sim 90^\circ$ using orthogonal electrode pairs in the Hall bar geometry to apply current, as illustrated schematically in Fig. 2(c). We note that this approach results in an inhomogeneous current density across the transverse direction of the sample, thus the current direction is not rotated by an exact 90° . The resulting H_{c2} data, also shown in Fig. 2(c), demonstrate that the principal axis of the twofold symmetry rotates in tandem with the current direction. In addition, when we interchanged the orthogonal current and voltage pairs, we obtained consistent results. We further repeated these current-swapping measurements on a second device (Sec. V, Supplemental Material [30]), which again yielded the same behavior. Taken together, these findings strongly suggest that the dominant observed anisotropy arises from extrinsic effects, rather than being an intrinsic feature of the superconducting order parameter.

To further explore the mechanism underlying the extrinsic anisotropy, we systematically varied the current amplitude while probing H_{c2} . We found that the anisotropy ratio of H_{c2} is strongly dependent on the magnitude of the applied current and is most sensitive when the magnetic field is oriented perpendicular to the current direction. As shown in Fig. 2(d), increasing the current leads to a gradual suppression of H_{c2} , which results in a narrowing of the angular profile along the direction perpendicular to the current flow in the polar plot, as illustrated in Fig. 2(e). The shape of the H_{c2} polar plot evolves from an elliptical form at low currents to a peanut shape at high currents. Based on this observation, all other measurements in this study were conducted using the minimal current density possible (current density less than 5×10^{-6} A/ μm^2).

This current-induced reduction of H_{c2} points to a crucial role of the Lorentz force, given by $\mathbf{F} = \mathbf{I} \times \mu_0 \mathbf{H}_{\text{ext}}$. The magnitude of this force is zero when the magnetic field is aligned with the current ($H_{\text{ext}} \parallel I$) and reaches a maximum when they are perpendicular ($H_{\text{ext}} \perp I$). This directional dependence of the Lorentz force modulates the dynamics of vortices in the superconducting state. In particular, the enhanced vortex motion under high Lorentz force leads to increased dissipation and a suppression of H_{c2} when $H_{\text{ext}} \perp I$, which we propose to give rise to the observed twofold anisotropy.

C. The impact of magnetic field alignment on H_{c2}

The above discussion has focused solely on the variation of the in-plane rotation angle ϕ . However, in real experiments, due to the finite angular precision with which the sample can be mounted, there often exists a misalignment between the sample plane and that of the rotator, as illustrated in Fig. 3(a). This misalignment introduces an additional angle, referred to as the canting angle γ . While such a tilt has minimal impact on isotropic superconductors, it can significantly affect measurements on anisotropic superconductors, particularly in layered materials like CsV_3Sb_5 , where the superconducting properties

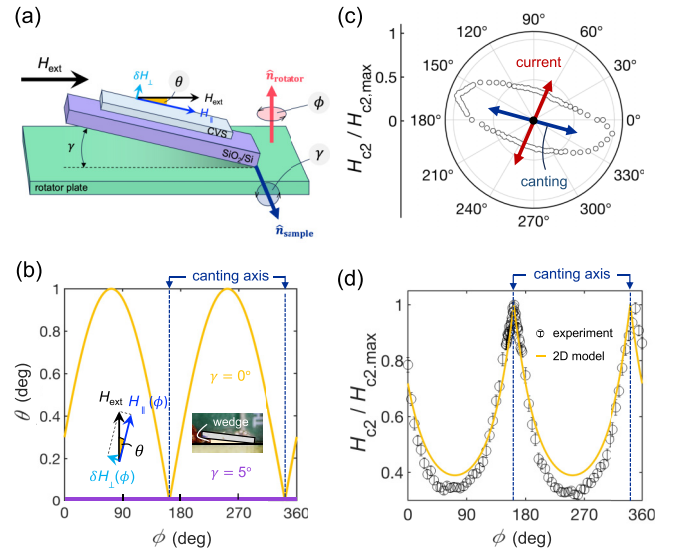


FIG. 3. The impact of magnetic field alignment on the twofold symmetry for sample A at 4 K. (a) Schematic illustration of a flake on a silicon substrate mounted with a canting angle γ . Two angular parameters are defined: the in-plane rotation angle ϕ , controlled precisely by a stepper motor, and the canting angle γ , introduced by manually inserting a wedge between the sample and the rotator plate. (b) Calculated field tilt angle (θ) as a function of the in-plane rotation (ϕ) for a canting angle $\gamma = 5^\circ$ (yellow curve), compared with the ideal case of $\gamma = 0^\circ$ (purple line). The relative orientations of external field (H_{ext}), its in-plane component ($H_{\parallel}$), and its out-of-plane component ($\delta H_{\perp}$) are indicated. The field tilt θ is defined as the angle between H_{ext} and $H_{\parallel}$. The inset is a photograph showing deliberately mounted with $\gamma = 5^\circ$. (c) Polar plot of the normalized H_{c2} - ϕ for the sample mounted as shown in (b). The red double-headed arrow indicates the current direction, while the dark blue double-headed arrow marks the canting axis, defined as the direction along which the field tilt angle θ is minimized. (d) Calculated normalized H_{c2} as a function of in-plane rotation angle ϕ at $\gamma = 5^\circ$, based on the out-of-plane anisotropy ratio $H_{c2}^{ab}/H_{c2}^c = 25$ ($H_{c2}^{ab} = 1.2$ T and $H_{c2}^c = 0.048$ T) determined at 4 K.

are highly direction dependent. As reported in Refs. [15,32], CsV_3Sb_5 exhibits a temperature-dependent anisotropy in H_{c2} , with the ratio of out-of-plane to in-plane values decreasing from 25 to 8 as the temperature is lowered from T_c to zero. Such a large ratio makes the sample highly sensitive to field misalignment, where even slight tilts can lead to an angular-dependent in-plane field projection and potentially obscure the intrinsic electronic response.

To quantify the impact of magnetic field alignment, we considered the contributions from two rotational axes. The first axis, denoted by $\hat{n}_{\text{rotator}}$ in Fig. 3(a), controls the in-plane rotation angle ϕ and is precisely controlled by a stepper motor. The second axis, denoted by $\hat{n}_{\text{sample}}$, controls the canting angle γ and is manually adjusted here by inserting a wedge between the sample plane and the rotator plate. More details of the setup are shown in the Supplemental Material [30]. The canting angle γ is measured and calibrated under an optical microscope, as shown in the inset of Fig. 3(b). This two-axis control allows us to systematically explore the effect of field alignment on the superconducting anisotropy.

The canting angle γ causes the external magnetic field H_{ext} to project onto the sample's ab plane with a ϕ dependence. A simple field projection calculation, shown in Fig. 3(b), illustrates this effect. Here, the tilt angle θ is defined as the angle between H_{ext} and its in-plane projection $H_{\parallel}$ on the sample surface. When a large canting angle, such as $\gamma = 5^\circ$, is deliberately introduced, θ varies between 0° and 5° during the rotation (controlled via the $\hat{n}_{\text{rotator}}$ axis), where $\theta = 0^\circ$ is defined as the canting axis. For reference, the case of perfect alignment ($\gamma = 0^\circ$), in which H_{ext} lies entirely within the rotation plane, is discussed in Sec. II B.

We performed a series of measurements at different canting angles γ to systematically investigate the effect of magnetic field alignment. In Fig. 3(c), we present the data for a relatively large canting angle, $\gamma = 5^\circ$, as a representative case to illustrate the impact of magnetic field misalignment. A pronounced twofold symmetry, with an amplitude reaching up to 60%, is observed, with the principal axis aligned along $\theta = 0^\circ$, where the magnetic field lies entirely in the ab plane. At this orientation ($\theta = 0^\circ$, i.e., $H_{\text{ext}} \parallel ab$), the out-of-plane field component $H_{\perp}$ vanishes, and the sample exhibits the highest H_{c2} . As θ increases, $H_{\perp} = H_{\text{ext}} \sin \theta$ grows, which suppresses SC and results in a lower H_{c2} . This canting-induced twofold symmetry dominates over any anisotropy introduced by the applied current.

To quantitatively account for this effect, we performed calculations using the projected field profile shown in Fig. 3(b), applying an anisotropic SC model [34,35] with an out-of-plane anisotropy ratio $H_{c2}^{ab}/H_{c2}^c = 25$ ($H_{c2}^{ab} = 1.2$ T and $H_{c2}^c = 0.048$ T), as determined at 4 K [32] (see Supplemental Material for details [30]). In Fig. 3(d), the experimental angular dependence of H_{c2} from Fig. 3(c) (hollow black circles) is compared with a fit using the two-dimensional (2D) Tinkham model (yellow curve). The fair agreement between experiment and calculation demonstrates the observed strong twofold symmetry arises from the high sensitivity of 2D superconductors to magnetic field orientation. Furthermore, the model predicts that the in-plane H_{c2} anisotropy ratio can reach up to 11% even for a small tilt angle of $\gamma = 0.5^\circ$. These findings underscore the importance of multiaxis rotation capabilities to eliminate artifacts arising from misalignment of the magnetic field.

D. Angular-dependent in-plane resistivity

Our results above highlight the importance of employing multiaxis rotation and current-swapping methodologies when detecting in-plane twofold symmetry in H_{c2} . On the other hand, there has been rising number of literatures in which angular-dependent resistivity measurements are employed to characterize in-plane rotational symmetry [18,19,21,27,28,36]. Compared to directly measuring H_{c2} , such resistivity measurements under a fixed magnetic field are more time efficient and can still capture key features related to SC. To cross check whether these measurements can provide information similar to that obtained from H_{c2} , we perform angular-dependent in-plane resistivity measurements near H_{c2} in CsV_3Sb_5 , using the same rotational and current-swapping strategies.

We measured resistivity as a function of in-plane rotation angle ϕ under various magnetic field strengths, as shown in Fig. 4. In Fig. 4, the rows correspond to different current configurations, while the columns represent distinct canting conditions. For clarity, the resistivity curves are normalized to their maximum values within each angular sweep and are arranged from bottom to top to reflect the evolution from the mixed state to the normal state as the field increases.

Figures 4(e) and 4(g) show the angular dependence of the in-plane resistivity $\rho(\phi)$ in the aligned configuration ($\gamma = 0^\circ$). The resistivity displays a twofold symmetry, with a minimum occurring when the in-plane magnetic field is aligned with the current direction ($H_{\text{ext}} \parallel I$). In this configuration, as for our measurements of H_{c2} , vanishing Lorentz force leads to minimal dissipation through vortex motion and thus lowering the resistivity. Conversely, when the field is perpendicular to the current ($H_{\text{ext}} \perp I$), the Lorentz force is maximized, enhancing vortex motion and increasing resistivity [37,38]. Rotating the current direction causes the resistivity minimum to shift by approximately 90° , indicating that the anisotropy tracks the current orientation and suggesting an extrinsic origin of the twofold symmetry.

In contrast, when a large canting angle of $\gamma = 5^\circ$ is introduced [Figs. 4(f) and 4(h)], the twofold symmetry in $\rho(\phi)$ persists, but the resistivity minimum consistently occurs when the magnetic field lies entirely within the ab plane ($H_{\text{ext}} \parallel ab$), regardless of the current direction. This behavior is consistent with both the upper critical field measurements and theoretical calculations shown in Fig. 3(d), which show that canting-induced effects dominate over current-induced anisotropy in this regime. As a result, the position of the resistivity minimum remains fixed upon rotating the current direction.

These observations reinforce the conclusions drawn from the angular dependence of H_{c2} and highlight current direction and magnetic field alignment as critical factors in determining the anisotropic response.

III. DISCUSSION

In our work, we have systematically examined several factors that could potentially affect the detection of in-plane twofold anisotropy, including structural domain walls, Lorentz force effects, and magnetic field alignment. One possible source of extrinsic influence stems from the CDW-driven formation of three-state nematic domains in CsV_3Sb_5 [6], where scattering at domain walls can mask the intrinsic collective transport behavior [14]. To minimize such effects, we performed measurements on exfoliated devices with lateral dimensions as small as $3 \mu\text{m}$, thereby minimizing contributions from structural domain boundaries. In these micron-scale devices, we investigated the effects of the Lorentz force by changing the current direction, and the effect of magnetic field alignment by conducting two-axis angular mapping. Despite these efforts, under perfectly aligned conditions, our experiments only revealed a twofold anisotropy in H_{c2} originating from Lorentz-force-induced vortex motion, with a magnitude reaching about 25% at 4 K and decreasing to 11% at 1.8 K. This anisotropy is comparable to those observed in single crystals, and remains significantly larger than the values reported by thermodynamic probes [14], highlighting the

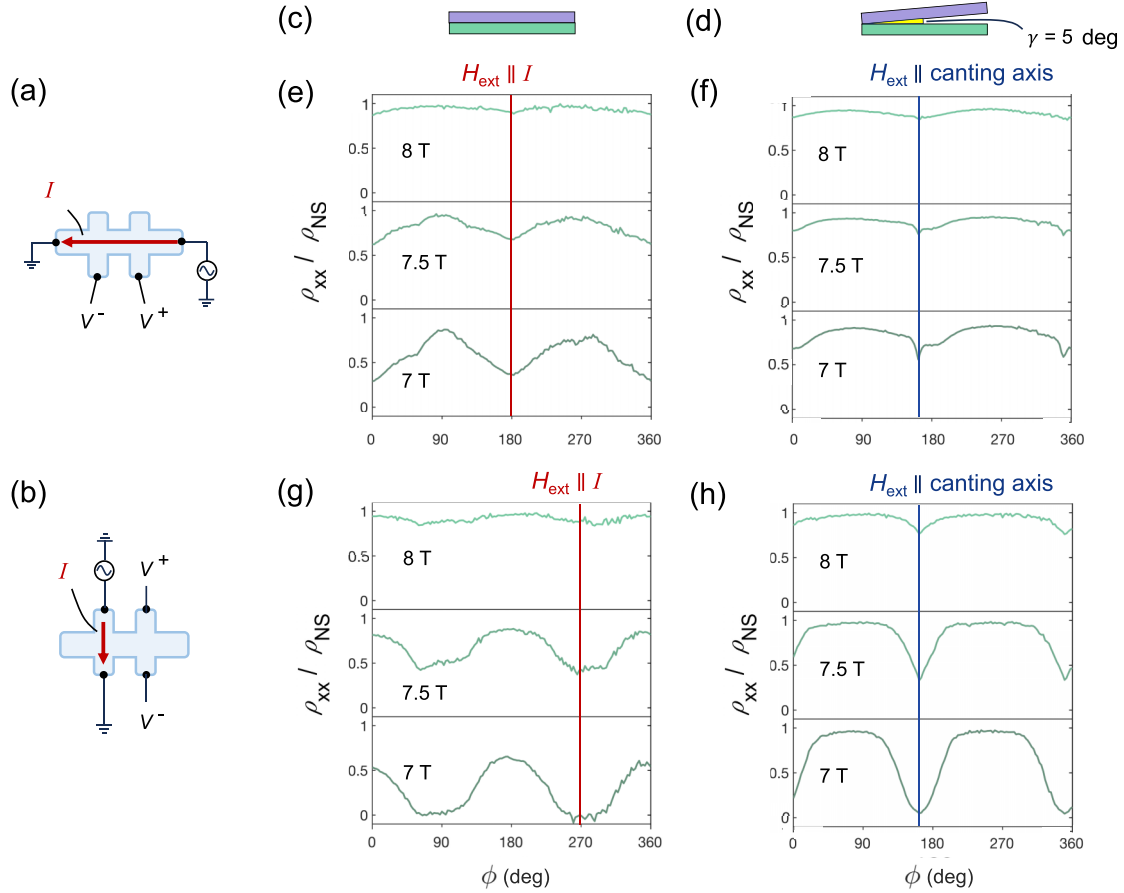


FIG. 4. Azimuthal dependence of the magnetoresistance under the influence of current direction and sample canting for sample A at 1.8 K. (a), (b) Schematics of the four-probe measurement configuration on the same device with current flowing along the long side and short side of the Hall bar, respectively. (c), (d) Schematics illustrating the sample under $\gamma \approx 0^\circ$ and $\gamma = 5^\circ$ canting conditions. (e), (f) Normalized resistivity ($\rho_{xx}/\rho_{\max}$) as a function of in-plane rotation ϕ at different magnetic field strengths for (c) and (d) canting conditions, respectively. $\rho_{\max}$ is the maximum resistance for each magnetic field in the angular sweep. The current flow direction is highlighted by the red line and indicated by (a). The canting axis, defined as the direction with minimum field tilt angle, is shown in the dark blue line. (g), (h) Analogous data presentation to (e) and (f) in the orthogonal current configuration for (c) and (d) canting conditions, respectively. The current flow direction is specified by the red line and indicated by (b) whereas the canting axis is shown as the dark blue line.

challenge of disentangling intrinsic symmetry breaking from extrinsic contributions in this system.

In general, symmetry detection via transport must be interpreted with caution. In addition to the domain effect, Lorentz force contributions, and magnetic field misalignment discussed in our work, further extrinsic factors, such as twin boundaries [37], strain-induced directional bias [24], and ballistic effects in micron-sized devices [39], can also give rise to apparent anisotropy. These considerations underline that transport is a powerful yet delicate probe of symmetry, and that it demands careful interpretation.

Nevertheless, we cannot exclude the presence of nanoscale nematic domains that may lie below our spatial resolution and lead to averaging effects that suppress detectable symmetry breaking. In addition, strain imparted by the substrate can also act as a perturbative factor, potentially stabilizing a specific domain orientation and thereby enhancing the in-plane anisotropy of the sample [24]. However, despite this possible substrate-induced contribution, our measurements reveal an apparent anisotropy whose principal

axis does not correlate with the intrinsic properties of the sample.

While an intrinsic in-plane twofold symmetry may still exist in the CsV_3Sb_5 , its anisotropy is likely subtle and easily masked by slight misalignments of the magnetic field. For example, our calculations show that in a layered system with an out-of-plane to in-plane H_{c2} ratio of 9, a value consistently reported for CsV_3Sb_5 at the zero-temperature limit, even a small canting angle of 0.5° can induce an artificial in-plane anisotropy of 3.8%, which increases to 7.4% at 1° . Thus, any genuine anisotropy smaller than this threshold would be indistinguishable from misalignment-induced artifacts. Such spurious effects become even more pronounced in materials with higher out-of-plane to in-plane anisotropy. This highlights the importance of precise alignment and rigorous control over angular positioning when interpreting subtle twofold features in H_{c2} or magnetotransport data. Such protocols, which were also previously reported in Refs. [24,28], play a crucial role in disentangling intrinsic anisotropy from extrinsic effects.

IV. CONCLUSION

To summarize, we investigate in-plane twofold symmetry in CsV_3Sb_5 using angular-dependent magnetoresistance measurements on micron-scale devices with controlled current directions. Our measurements reveal an apparent twofold anisotropy in the superconducting state that depends on both current direction and magnitude, indicating an extrinsic origin related to vortex dynamics. In our experiments, we do not observe conclusive evidence for an intrinsic twofold symmetry; if present, such anisotropy is likely subtle. Our findings are consistent with recent studies based on thermodynamic probes and elastoresistance measurements reporting either negligible or weak in-plane anisotropy on the same material system [14,25,26].

To ensure reliable detection of intrinsic in-plane anisotropy in layered superconductors, particularly those exhibiting strong out-of-plane vs in-plane anisotropy, we recommend addressing possible extrinsic contributions through the following approach. First, perform measurements with the current direction rotated (e.g., by 90°) to verify the origin of the observed anisotropy. If the anisotropy changes with the current direction, it is likely dominated by extrinsic factors, while accidental misalignment of the sample rotation plane with the magnetic field can be excluded as its origin; if it remains unchanged, it is likely genuine but still requires testing, such as careful field alignment. Second, consider multiaxis contributions by using measurement setups such as two-axis rotators, which allow precise control and alignment of the magnetic field to minimize alignment-induced artifacts. This combined strategy helps distinguish intrinsic electronic

behavior from extrinsic factors such as sample geometry, Lorentz force, and alignment errors.

Our study provides a guiding principle for probing twofold symmetry in layered superconductors. By carefully addressing extrinsic factors such as domain wall effects, magnetic field misalignment, and current-induced vortex motion, we establish a measurement framework that distinguishes intrinsic electronic anisotropy from experimental artifacts. This approach is broadly applicable to a wide range of anisotropic superconductors, particularly those exhibiting strong anisotropy between the out-of-plane and in-plane directions.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [40], embargo periods may apply.

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- [1] B. R. Ortiz, L. C. Gomes, J. R. Morey, M. Winiarski, M. Bordelon, J. S. Mangum, I. W. H. Oswald, J. A. Rodriguez-Rivera, J. R. Neilson, S. D. Wilson, E. Ertekin, T. M. McQueen, and E. S. Toberer, New kagome prototype materials: Discovery of KV_3Sb_5 , RbV_3Sb_5 , and CsV_3Sb_5 , *Phys. Rev. Mater.* **3**, 094407 (2019).
 - [2] B. R. Ortiz, S. M. L. Teicher, Y. Hu, J. L. Zuo, P. M. Sarte, E. C. Schueller, A. M. M. Abeykoon, M. J. Krogstad, S. Rosenkranz, R. Osborn, R. Seshadri, L. Balents, J. He, and S. D. Wilson, CsV_3Sb_5 : AZ_2 topological kagome metal with a superconducting ground state, *Phys. Rev. Lett.* **125**, 247002 (2020).
 - [3] K. Y. Chen, N. N. Wang, Q. W. Yin, Y. H. Gu, K. Jiang, Z. J. Tu, C. S. Gong, Y. Uwatoko, J. P. Sun, H. C. Lei, J. P. Hu, and J.-G. Cheng, Double superconducting dome and triple enhancement of T_c in the kagome superconductor CsV_3Sb_5 under high pressure, *Phys. Rev. Lett.* **126**, 247001 (2021).
 - [4] S. D. Wilson and B. R. Ortiz, AV_3Sb_5 kagome superconductors, *Nat. Rev. Mater.* **9**, 420 (2024).
 - [5] C. Mielke III, D. Das, J.-X. Yin, H. Liu, R. Gupta, Y.-X. Jiang, M. Medarde, X. Wu, H. C. Lei, J. Chang, P. Dai, Q. Si, H. Miao, R. Thomale, T. Neupert, Y. Shi, R. Khasanov, M. Z. Hasan, H. Luetkens, and Z. Guguchia, Time-reversal symmetry-breaking charge order in a kagome superconductor, *Nature (London)* **602**, 245 (2022).
 - [6] Y. S. Xu, Z. L. Ni, Y. Z. Liu, B. R. Ortiz, Q. W. Deng, S. D. Wilson, B. H. Yan, L. Balents, and L. Wu, Three-state nematicity and magneto-optical Kerr effect in the charge density waves in kagome superconductors, *Nat. Phys.* **18**, 1470 (2022).
 - [7] Z. Liang, X. Hou, F. Zhang, W. Ma, P. Wu, Z. Zhang, F. Yu, J.-J. Ying, K. Jiang, L. Shan, Z. Wang, and X.-H. Chen, Three-dimensional charge density wave and surface-dependent vortex-core states in a kagome superconductor CsV_3Sb_5 , *Phys. Rev. X* **11**, 031026 (2021).
 - [8] H. Zhao, H. Li, B. R. Ortiz, S. M. L. Teicher, T. Park, M. Ye, Z. Wang, L. Balents, S. D. Wilson, and I. Zeljkovic, Cascade of correlated electron states in the kagome superconductor CsV_3Sb_5 , *Nature (London)* **599**, 216 (2021).
 - [9] N. Ratcliff, L. Hallett, B. R. Ortiz, S. D. Wilson, and J. W. Harter, Coherent phonon spectroscopy and interlayer modulation of charge density wave order in the kagome metal CsV_3Sb_5 , *Phys. Rev. Mater.* **5**, L111801 (2021).
 - [10] Y. Xiang, Q. Li, Y. K. Li, W. Xie, H. Yang, Z. W. Wang, Y. G. Yao, and H. H. Wen, Twofold symmetry of c -axis resistivity in topological kagome superconductor CsV_3Sb_5 with in-plane rotating magnetic field, *Nat. Commun.* **12**, 6727 (2021).
 - [11] L. P. Nie, K. Sun, W. R. Ma, D. W. Song, L. X. Zheng, Z. W. Liang, P. Wu, F. H. Yu, J. Li, M. Shan *et al.*, Charge-density-wave-driven electronic nematicity in a kagome superconductor, *Nature (London)* **604**, 59 (2022).
 - [12] Q. Wu, Z. X. Wang, Q. M. Liu, R. S. Li, S. X. Xu, Q. W. Yin, C. S. Gong, Z. J. Tu, H. C. Lei, T. Dong, and N. L. Wang,

- Simultaneous formation of two-fold rotation symmetry with charge order in the kagome superconductor CsV_3Sb_5 by optical polarization rotation measurement, *Phys. Rev. B* **106**, 205109 (2022).
- [13] H. Li, H. Zhao, B. R. Ortiz, Y. Oey, Z. Q. Wang, S. D. Wilson, and I. Zeljkovic, Unidirectional coherent quasiparticles in the high-temperature rotational symmetry broken phase of AV_3Sb_5 kagome superconductors, *Nat. Phys.* **19**, 637 (2023).
- [14] K. Fukushima, K. Obata, S. Yamane, Y. J. Hu, Y. K. Li, Y. G. Yao, Z. W. Wang, Y. Maeno, and S. Yonezawa, Violation of emergent rotational symmetry in the hexagonal kagome superconductor CsV_3Sb_5 , *Nat. Commun.* **15**, 2888 (2024).
- [15] M. S. Hossain, Q. Zhang, E. S. Choi, D. Ratkovski, B. Lüscher, Y. K. Li, Y. X. Jiang, M. Litskevich, Z. J. Cheng, J. X. Yin *et al.*, Unconventional gapping behaviour in a kagome superconductor, *Nat. Phys.* **21**, 556 (2025).
- [16] C.-L. Song, Y.-L. Wang, P. Cheng, Y.-P. Jiang, W. Li, T. Zhang, Z. Li, K. He, L. Wang, J.-F. Jia, H.-H. Hung, C. Wu, X. Ma, X. Chen, and Q.-K. Xue, Direct observation of nodes and twofold symmetry in FeSe superconductor, *Science* **332**, 1410 (2011).
- [17] J.-H. Chu, H.-H. Kuo, J. Analytis, and I. Fisher, Divergent nematic susceptibility in an iron arsenide superconductor, *Science* **337**, 710 (2012).
- [18] A. Hamill, B. Heischmidt, E. Sohn, D. Shaffer, K. T. Tsai, X. Zhang, X. X. Xi, A. Suslov, H. Berger, L. Forró, F. J. Burnell, J. Shan, K. F. Mak, R. M. Fernandes, K. Wang, and V. S. Pribiag, Two-fold symmetric superconductivity in few-layer NbSe_2 , *Nat. Phys.* **17**, 949 (2021).
- [19] E. Z. Zhang, Y. M. Xie, Y. Q. Fang, J. L. Zhang, X. Xu, Y. C. Zou, P. L. Leng, X. J. Gao, Y. Zhang, L. F. Ai *et al.*, Spin-orbit-parity coupled superconductivity in atomically thin 2M-WS₂, *Nat. Phys.* **19**, 106 (2023).
- [20] I. Silber, S. Mathimalar, I. Mangel, A. K. Nayak, O. Green, N. Avraham, H. Beidenkopf, I. Feldman, A. Kanigel, A. Klein, M. Goldstein, A. Banerjee, E. Sela, and Y. Dagan, Two-component nematic superconductivity in 4Hb-TaS_2 , *Nat. Commun.* **15**, 824 (2024).
- [21] Y. Cao, D. Rodan-Legrain, J. M. Park, N. F. Q. Yuan, K. Watanabe, T. Taniguchi, R. M. Fernandes, L. Fu, and P. Jarillo-Herrero, Nematicity and competing orders in superconducting magic-angle graphene, *Science* **372**, 264 (2021).
- [22] R. M. Fernandes, A. V. Chubukov, and J. Schmalian, What drives nematic order in iron-based superconductors? *Nat. Phys.* **10**, 97 (2014).
- [23] A. E. Böhrer, J. H. Chu, S. Lederer, and M. Yi, Nematicity and nematic fluctuations in iron-based superconductors, *Nat. Phys.* **18**, 1412 (2022).
- [24] C. Y. Guo, G. Wagner, C. Putzke, D. Chen, K. Z. Wang, L. Zhang, M. Gutierrez-Amigo, I. Errea, M. G. Vergniory, C. Felser, M. H. Fischer, T. Neupert, and P. J. W. Moll, Correlated order at the tipping point in the kagome metal CsV_3Sb_5 , *Nat. Phys.* **20**, 579 (2024).
- [25] M. Frachet, L. Wang, W. Xia, Y. Guo, M. He, N. Maraytta, R. Heid, A.-A. Haghighirad, M. Merz, C. Meingast, and F. Hardy, Colossal *c*-axis response and lack of rotational symmetry breaking within the kagome planes of the CsV_3Sb_5 superconductor, *Phys. Rev. Lett.* **132**, 186001 (2024).
- [26] Z. Liu, Y. Shi, Q. Jiang, E. W. Rosenberg, J. M. DeStefano, J. Liu, C. Hu, Y. Zhao, Z. Wang, Y. Yao, D. Graf, P. Dai, J. Yang, X. Xu, and J.-H. Chu, Absence of E_{1g} nematic instability and dominant A_{1g} response in the kagome metal CsV_3Sb_5 , *Phys. Rev. X* **14**, 031015 (2024).
- [27] X. J. Wei, C. K. Tian, H. Cui, Y. X. Zhai, Y. K. Li, S. B. Liu, Y. J. Song, Y. Feng, M. L. Huang, Z. W. Wang, Y. Liu, Q. H. Xiong, Y. G. Yao, X. C. Xie, and J. H. Chen, Three-dimensional hidden phase probed by in-plane magnetotransport in kagome metal CsV_3Sb_5 thin flakes, *Nat. Commun.* **15**, 5038 (2024).
- [28] P. Wan, O. Zheliuk, N. F. Q. Yuan, X. Peng, L. Zhang, M. Liang, U. Zeitler, S. Wiedmann, N. E. Hussey, T. T. M. Palstra, and J. Ye, Orbital Fulde-Ferrell-Larkin-Ovchinnikov state in an Ising superconductor, *Nature (London)* **619**, 46 (2023).
- [29] Z. Li, A. Jindal, A. Strasser, Y. He, W. Zheng, D. Graf, T. Taniguchi, K. Watanabe, L. Balicas, C. R. Dean, X. Qian, A. N. Pasupathy, and D. A. Rhodes, Twofold anisotropic superconductivity in bilayer $\text{T}_d\text{-MoTe}_2$, *Phys. Rev. Lett.* **133**, 216002 (2024).
- [30] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/l6q3-lmj> for additional details on device preparation, experimental setup, and supporting information relevant to the interpretation of our data.
- [31] B. Song, T. Ying, X. Wu, W. Xia, Q. Yin, Q. Zhang, Y. Song, X. Yang, J. Guo, L. Gu *et al.*, Anomalous enhancement of charge density wave in kagome superconductor CsV_3Sb_5 approaching the 2D limit, *Nat. Commun.* **14**, 2492 (2023).
- [32] F. Sun, A. C. Salinas, S. D. Wilson, and H. Zhang, Clean-limit 2D superconductivity in a thick exfoliated Kagome film, *Adv. Funct. Mater.*, **e11314** (2025).
- [33] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Vortices in high-temperature superconductors, *Rev. Mod. Phys.* **66**, 1125 (1994).
- [34] M. Tinkham, Effect of fluxoid quantization on transitions of superconducting films, *Phys. Rev.* **129**, 2413 (1963).
- [35] M. Tinkham, *Introduction to Superconductivity* (Dover, New York, 2004).
- [36] J.-H. Chu, J. G. Analytis, K. De Greve, P. L. McMahon, Z. Islam, Y. Yamamoto, and I. R. Fisher, In-plane resistivity anisotropy in an underdoped iron arsenide superconductor, *Science* **329**, 824 (2010).
- [37] W. K. Kwok, U. Welp, G. W. Crabtree, K. G. Vandervoort, R. Hulscher, and J. Z. Liu, Direct observation of dissipative flux motion and pinning by twin boundaries in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystals, *Phys. Rev. Lett.* **64**, 966 (1990).
- [38] S. Yasuzuka, S. Uji, S. Sugiura, T. Terashima, Y. Nogami, K. Ichimura, and S. Tanda, Highly isotropic in-plane upper critical field in the anisotropic s-wave superconductor 2H-NbSe_2 , *J. Supercond. Nov. Magn.* **33**, 953 (2020).
- [39] M. D. Bachmann, A. L. Sharpe, G. Baker, A. W. Barnard, C. Putzke, T. Scaffidi, N. Nandi, P. H. McGuinness, E. Zhakina, M. Moravec, S. Khim, M. König, D. Goldhaber-Gordon, D. A. Bonn, A. P. Mackenzie, and P. J. W. Moll, Directional ballistic transport in the two-dimensional metal PdCoO_2 , *Nat. Phys.* **18**, 819 (2022).
- [40] Y. C. Yao, F. Sun, A. C. Salinas, S. D. Wilson, P. D. C. King, and H. J. Zhang, Dataset for Identification of intrinsic and extrinsic in-plane twofold symmetry in CsV_3Sb_5 via transport measurements, Zenodo (2025), doi: 10.5281/zenodo.17069727.