

# Quantifying magnetic field driven lattice distortions in kagome metals at the femtometer scale using scanning tunneling microscopy

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A wide array of unusual phenomena has recently been uncovered in kagome solids. The charge density wave (CDW) state in the kagome superconductor  $AV_3Sb_5$ , in particular, intrigued the community; the CDW phase appears to break the time-reversal symmetry despite the absence of spin magnetism, which has been tied to exotic orbital loop currents possibly intertwined with magnetic field tunable crystal distortions. To test this connection, precise determination of the lattice response to an applied magnetic field is crucial but can be challenging at the atomic scale. We establish a scanning tunneling microscopy (STM) based method to study the evolution of the  $AV_3Sb_5$  atomic structure as a function of magnetic field. The method substantially reduces the errors of typical STM measurements, which are at the order of 1% when measuring an in-plane lattice constant change. We find that the out-of-plane lattice constant of  $AV_3Sb_5$  remains unchanged (within  $10^{-6}$ ) by the application of both in-plane and out-of-plane magnetic fields. We also reveal that the in-plane lattice response to magnetic field is at most at the order of 0.05%. Our experiments provide further constraints on time-reversal symmetry breaking in kagome metals and establish a tool for higher-resolution extraction of the field-lattice coupling at the nanoscale applicable to other quantum materials.

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## I. INTRODUCTION

Magnetic phase transitions typically lead to a small volumetric expansion anomaly. This is due to a sudden internal strain buildup caused by the spontaneous alignment of spins in order to reduce the total energy of the material. Such a spontaneous internal strain is directional and can be quantified by a magnetostriction coefficient  $\lambda = dI/I$ . This coefficient is usually maximized along the magnetization axis and minimized perpendicular to it, and can be controlled by applying the magnetic field to align the domains. Beyond the rotation and alignment of spins, additional crystal expansion can occur by applying an even higher magnetic field to the material with already saturated spins. The magnetostriction effect is typically small but in some cases it can reach exceptionally large values at the order of several percent, in, for example,  $YMn_2$  [1]. To measure magnetostriction, traditional experiments rely on scattering techniques in magnetic field, which average the signal from an entire bulk sample. The presence of structural domains can, however, complicate the interpretation of these measurements. Measuring the local coupling between magnetic field and the lattice in nanoscale regions of the sample would be highly desirable, but this has been challenging. Here we establish a method based on scanning tunneling microscopy to quantify small magnetic field induced lattice

constant change and apply it to the intriguing example of  $AV_3Sb_5$  kagome superconductors.

The family of kagome superconductors  $AV_3Sb_5$  ( $A = K, Cs, Rb$ ) attracted tremendous attention in recent years [2–26] for their unusual superconductivity, surprising density wave states, and the unconventional anomalous Hall effect despite the absence of spin magnetism. Much of the effort has been focused on understanding the symmetry of the  $2a_0 \times 2a_0$  charge density wave (CDW) state in the kagome plane [6–8, 27–46]. Theory suggested that a chiral CDW phase composed of orbital loop flux currents could naturally explain the emergent time-reversal symmetry breaking and the anomalous Hall effect [32, 47–49]. Moreover, it has been reported that an externally applied magnetic field appears to control the anisotropy of the CDW signal by generating an in-plane shear strain of about 0.5% of the in-plane lattice constant [50]. Such strong connection between the crystal structure and the magnetic field could provide the elusive unifying signature associated with time-reversal symmetry breaking in  $AV_3Sb_5$ . To shed light on this emerging picture, comprehensive experiments probing the magnetic field driven lattice response in  $AV_3Sb_5$  along different crystalline directions and with control of the magnetic field direction are crucial.

Here we quantify magnetostriction and piezomagnetic response in  $AV_3Sb_5$  ( $A = Cs, K$ ) over nanoscale regions as a function of magnetic field. We introduce a scanning tunneling microscopy (STM) based method to detect tiny changes in the lattice constants. The method substantially decreases the uncertainty of determining in-plane lattice constant

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variation with applied field due to the inevitable experimental artifacts that artificially distort the images, including thermal and piezohysteresis and relaxation effects, which can be at the order of 1% in typical STM measurements. We observe that the out-of-plane lattice constant remains unaffected by an external magnetic field. In all the regions studied, we find that a magnetic field of a few tesla leads to at most a 0.05% change in the in-plane lattice constant change. Reversal of the magnetic field direction also leads to a similarly small effect. Our work reveals the upper bound of the magnitude of the coupling between the lattice and the external magnetic field in  $AV_3Sb_5$ , thus providing further constraints on the origin of time-reversal symmetry breaking in  $AV_3Sb_5$ . It also establishes a nanoscale method for the determination of magnetic field induced structural changes using STM with better accuracy, which could be widely applied to other quantum solids.

## II. RESULTS

Kagome superconductors  $AV_3Sb_5$  crystallize in the  $P6/mmm$  space group [2], and cleave between hexagonal Sb layers and alkali A layers [6–8,42,45]. We start our experiments with the most commonly studied Cs variant,  $CsV_3Sb_5$ . STM topographs of the Sb termination of  $CsV_3Sb_5$  [Fig. 1(b)] exhibit the expected hexagonal lattice, with in-plane lattice constants  $a \approx b \approx 5.4\text{\AA}$ . Consistent with previous experiments [7,10], Fourier transforms (FTs) of the STM topographs show the atomic Bragg peaks  $Q_{\text{Bragg}}$ , as well as the  $4a_0$  charge-stripe order and the  $2a_0 \times 2a_0$  CDW in the kagome plane [Fig. 1(a)]. Early STM experiments studying the effects of magnetic field primarily focused on the intensities of the CDW peaks as a function of magnetic field [6,8,51]. In all our measurements of  $AV_3Sb_5$  samples, we observe no substantial change in the CDW intensity of peaks [Fig. 1(c)]. To investigate the field-lattice coupling, here we specifically focus on the field-dependent measurements of the  $Q_{\text{Bragg}}$  wave vector lengths along different lattice directions.

Atomic Bragg peaks in the FTs are directly related to the lattice constant via a relation  $Q_{\text{Bragg}} = \frac{4\pi}{\sqrt{3}a}$ , where  $a$  is the real-space lattice constant. We determine the position of each atomic Bragg peak  $Q_{\text{Bragg}}$  in the FT by fitting a 2D Gaussian function [Figs. 1(a) and 1(d)]. We note that due to a small inequivalence between different piezoelectric scanner electrodes and piezorelaxation effects during scanning [52], there typically exists a small apparent difference between  $|Q_{\text{Bragg}}^a|$ ,  $|Q_{\text{Bragg}}^b|$ , and  $|Q_{\text{Bragg}}^c|$  extracted from STM topographs, even for a material characterized by a perfect hexagonal lattice. However, as we will show in the subsequent paragraphs, we establish a procedure such that a *relative* difference between  $|Q_{\text{Bragg}}^i|$  acquired in different fields can provide a robust measure of the relative lattice constant change.

For pedagogical purposes, let us examine a series of consecutively taken STM topographs over one area of the sample. As schematically depicted in Fig. 1(e), topographs are acquired in either forward or backward directions (which we define as the “fast” scan direction), with the tip gradually moving upward or downward (which we define as the “slow”

scan direction). We compare the apparent  $|Q_{\text{Bragg}}^i|$  magnitudes in the FTs of each of these topographs [Figs. 1(f)–1(h)]. Our first observation is that  $|Q_{\text{Bragg}}^a|$ , the atomic Bragg peak most closely aligned with the fast-scan direction in this data set, generally shows a consistent value. On the other hand, the variation of atomic Bragg peak magnitudes along the other two directions can be substantial, at the order of 1% seen in, for example,  $Q_{\text{Bragg}}^c$  [Fig. 1(f)]. This finding is consistent with the general expectation that drift effects will be minimized along the scan direction [52]. To examine this further, we acquire and analyze equivalent data with fast-scan directions most closely aligned with  $Q_{\text{Bragg}}^b$  [Fig. 1(g)] or  $Q_{\text{Bragg}}^c$  [Fig. 1(h)] directions. The data and the analysis show that  $|Q_{\text{Bragg}}^i|$  measured along the fast-scan direction consistently shows minimal variations, while the other two can show substantial fluctuations.

To further illustrate this issue, we turn to the comparison between STM topographs acquired at zero field and those at finite magnetic field  $B$  (Fig. 2). To quantify the apparent relative in-plane lattice constant change from this data, we define a coefficient:  $\lambda_{\text{in-plane}}^B = \frac{|Q_{\text{Bragg}}^i(B)| - |Q_{\text{Bragg}}^i(0T)|}{|Q_{\text{Bragg}}^i(0T)|}$ . Using this formula, we calculate and plot magnetostriction coefficients over an identical area of the sample for several representative fields [Figs. 2(a)–2(c)], with the fast-scan direction approximately along the  $Q_{\text{Bragg}}^a$  wave vector. We observe that the change in  $|Q_{\text{Bragg}}^a|$  after the initial scan is 0.05% or less for all fields [Figs. 2(a)–2(c)]. In contrast, the apparent change in  $|Q_{\text{Bragg}}^b|$  and  $|Q_{\text{Bragg}}^c|$  can be as large as 0.5% [Figs. 2(a)–2(c)]. This is summarized in the scatter plot of the average  $\lambda_{\text{in-plane}}^{B_z}$  vs  $B_z$  in Fig. 2(d). Importantly, the equivalent experiment performed over the same region of the sample, but with the fast-scan direction along the  $Q_{\text{Bragg}}^b$  wave vector yields striking differences [Fig. 2(e)]. In particular,  $|Q_{\text{Bragg}}^b|$  that is now along the fast-scan direction shows less than 0.05% change, in striking difference to the large  $\lambda_{\text{in-plane}}^{B_z}$  apparent in the rotated scan frame. This data and analysis demonstrate that the anomalously large coefficient measured in Fig. 2(d) is not an intrinsic feature of the sample, but instead an experimental artifact likely due to thermal or piezodrift. This cautions the use of STM data quantitative analysis and highlights the crucial need for examining a sequence of rotated scan frames for robust detection of lattice constant changes.

For these reasons, in the following field-dependent experiments, we acquire three sets of topographic scans, with fast-scan directions aligned to each of the atomic Bragg peaks within a few degrees; we calculate and use  $|Q_{\text{Bragg}}^i|$  values extracted from STM topographs for which the Bragg peak is most closely aligned with the fast-scan direction. When a magnetic field is applied along the  $z$  direction, we find that average  $\lambda_{\text{in-plane}}^{B_z}$  along the  $Q_{\text{Bragg}}^a$  and  $Q_{\text{Bragg}}^c$  directions is at most 0.01% [Fig. 3(b), Supplemental Material Fig. 1 [53]]. We note that  $\lambda_{\text{in-plane}}^{B_z}$  along  $Q_{\text{Bragg}}^b$  is slightly larger with more substantial error bars due to the quality of the particular data set. We then conduct the equivalent measurement on another sample, using a different microscope, to apply a  $\pm 2$  T in-plane magnetic field as schematically shown in Fig. 3(a). We again find that majority of data points are around 0.01% and all of them below 0.05% [Fig. 3(d)].

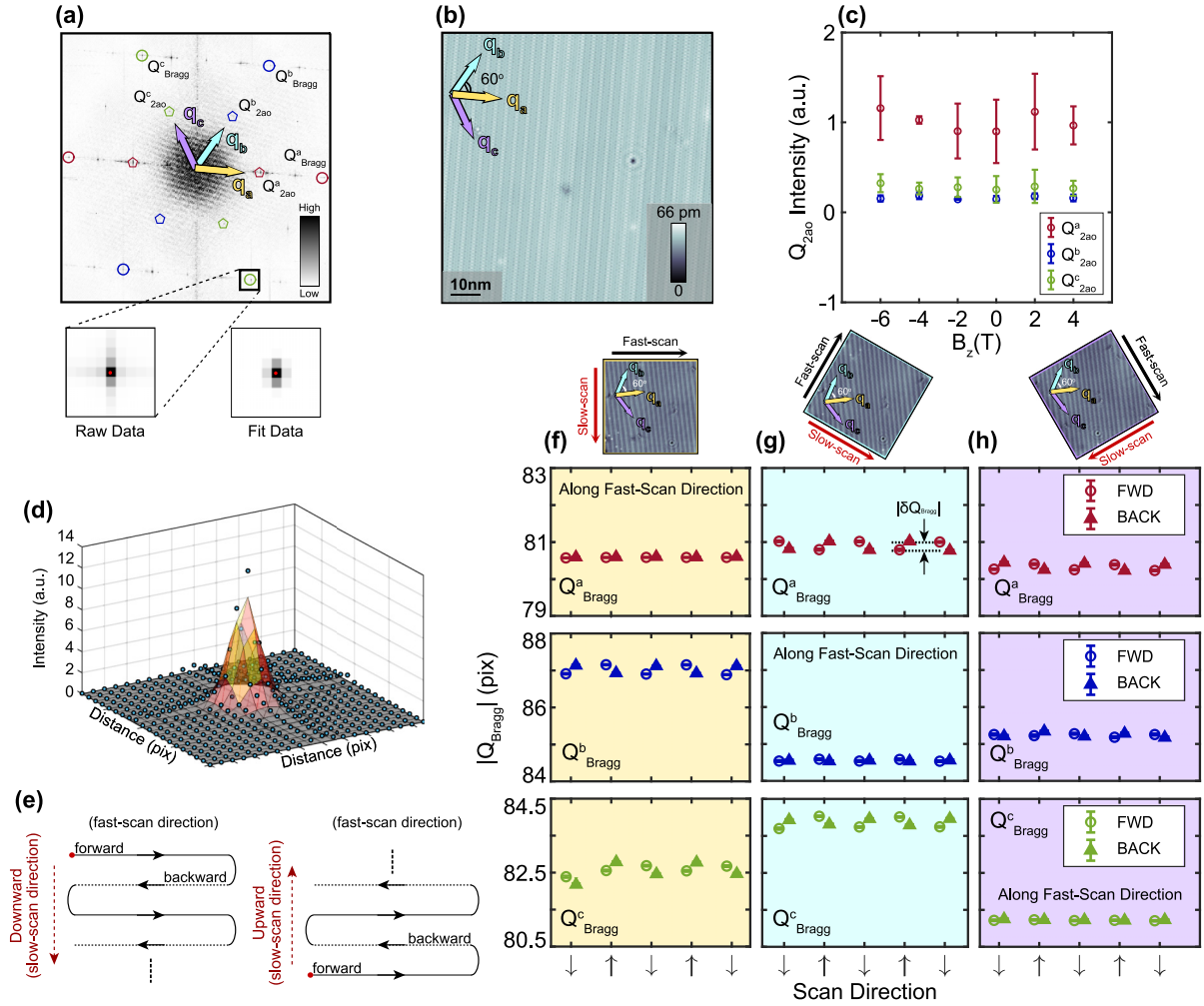


FIG. 1. Lattice constant measurements of  $\text{CsV}_3\text{Sb}_5$  from STM topographs as a function of different scan directions. (a) Fourier transform (FT) of an STM topograph shown in (b) with atomic Bragg peaks (enclosed in circles) and the  $2a_0$  charge density wave peaks (enclosed in pentagons) for the three in-plane lattice directions  $q_a$  (yellow),  $q_b$  (blue), and  $q_c$  (purple). Zoomed region shows the raw data around  $Q_{\text{Bragg}}^d$  (left) and fitted data by a 2D Gaussian (right) with a red dot representing the center of the peak determined from the fitting. The  $4a_0$  charge-stripe order is along the  $Q_{\text{Bragg}}^d$  direction. (b) Representative STM topograph of  $\text{CsV}_3\text{Sb}_5$  Sb termination with the three lattice directions denoted in upper left arrows. Setup conditions were 100 mV sample bias, 100 pA setpoint current, and fast-scan speed of 30 nm/s. (c) Intensity of the  $Q_{2a0}$  charge order peaks along the three directions showing minimal changes with magnetic field applied along the  $c$  axis. Error bars are defined by standard error from comparing five measurements of the intensity for each direction and each magnetic field. Data was acquired with a fast-scan speed of 10.2 nm/s over a  $90 \text{ nm} \times 90 \text{ nm}$  ( $400 \text{ pixel} \times 400 \text{ pixel}$ ) area. (d) A 3D model demonstrating the Gaussian peak fitting to atomic Bragg peak data. Blue dots represent the raw data; the surface is a mesh of the 2D Gaussian fit. (e) A schematic showing the STM tip scanning directions to generate topographs. The tip sweeps each line in both forward and backward directions (defined as the “fast” scan direction) before moving to the next line in either a downward (left) or upward (right) direction, which we term the “slow” scan direction. (f)–(h) Apparent atomic Bragg peak lengths in the units of pixels, extracted from topographs over the same region of the sample but with fast-scan directions oriented most closely with each of the three atomic Bragg peaks. Error bars are defined by standard error of the 2D Gaussian fit. Data was acquired with a fast-scan speed of 22.2 nm/s over a  $40 \text{ nm} \times 40 \text{ nm}$  ( $256 \text{ pixel} \times 256 \text{ pixel}$ ) area. The data in (c) is from sample #1, region #1. The data in (f)–(h) is from sample #1, region #2.

To investigate if magnetic fields oriented in opposite directions can induce more unusual types of deformations [50], we directly compare the lattice response when the magnetic field direction is reversed [Figs. 3(e) and 3(f)]. Referred to as a piezomagnetic response linear in magnetic field, this effect will in principle result in different lattice constants for  $\mathbf{B}$  vs  $-\mathbf{B}$ , magnetic fields of the same magnitude but applied in opposite directions [54]. To quantify this type of anti-symmetric response, we define a piezomagnetic coefficient

$$\mu_{\text{in-plane}}^{\mathbf{B}} = \frac{2(|Q_{\text{Bragg}}^i(\mathbf{B})| - |Q_{\text{Bragg}}^i(-\mathbf{B})|)}{|Q_{\text{Bragg}}^i(\mathbf{B})| + |Q_{\text{Bragg}}^i(-\mathbf{B})|},$$
 which yields the change in each in-plane lattice constant after the magnetic field direction is reversed. From the analysis of our data, we find that  $\mu_{\text{in-plane}}^{\mathbf{B}_z}$  is less than 0.05% in  $\text{CsV}_3\text{Sb}_5$  for all in-plane lattice directions [Fig. 3(e)]. We note that we performed similar experiments on cousin  $\text{RbV}_3\text{Sb}_5$  [Figs. 3(c) and 3(f)] and  $\text{KV}_3\text{Sb}_5$  samples for one scan rotation (Supplemental Material Fig. 2 [53]), and arrive at the same conclusion of minimal

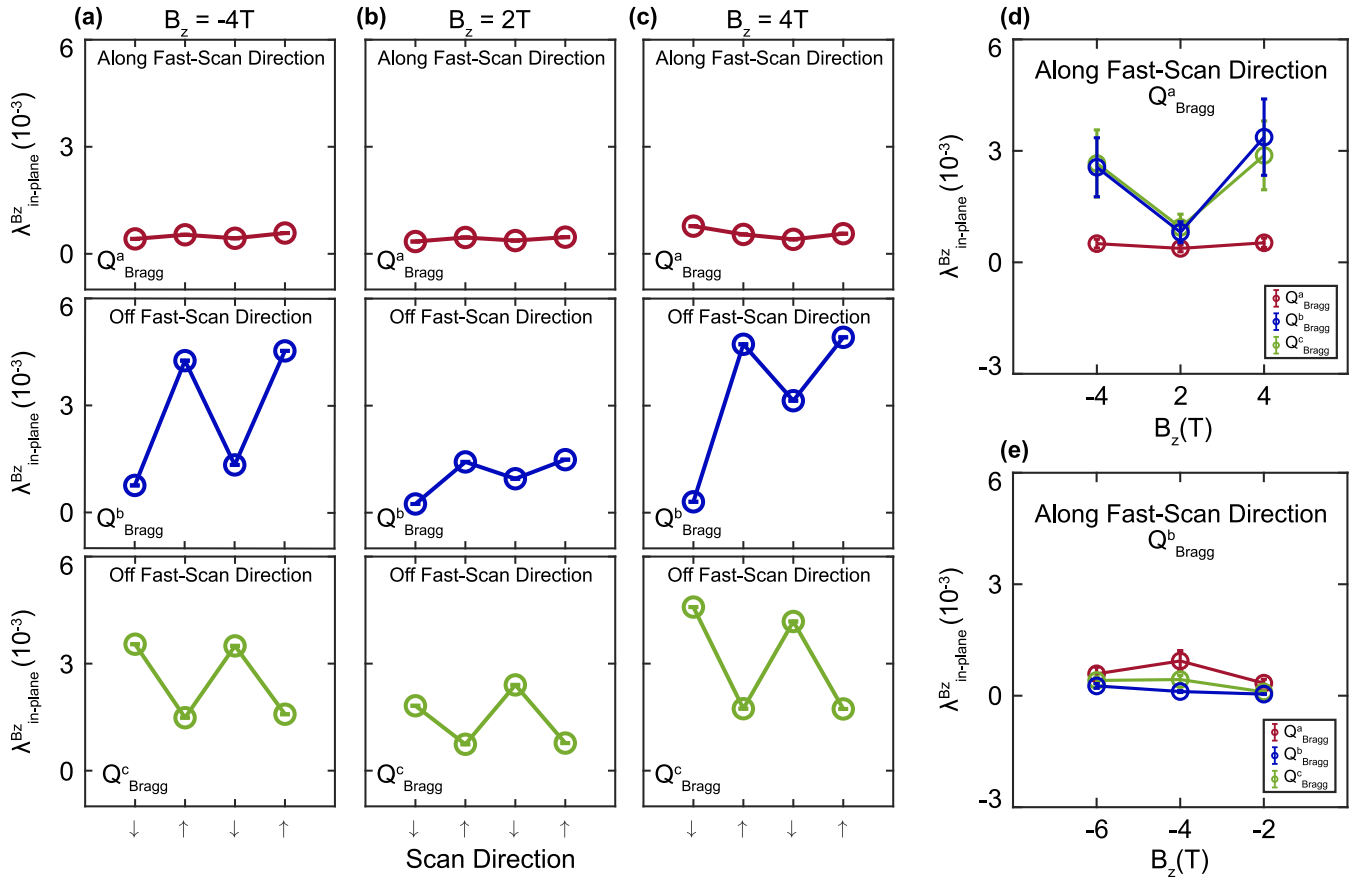


FIG. 2. Spurious detection of atomic Bragg peak changes by magnetic field due to experimental artifacts. (a)–(c) Coefficients  $\lambda_{in-plane}^B = \frac{|Q_{Bragg}^i(\mathbf{B})| - |Q_{Bragg}^i(OT)|}{|Q_{Bragg}^i(OT)|}$  for a series of upward and downward scans at different magnetic fields, with the fast-scan direction most closely oriented along the  $Q_{Bragg}^a$ . Only coefficients along  $Q_{Bragg}^a$  show consistent behavior. Error bars are defined by a standard error of 2D Gaussian fit. (d) Average  $\lambda_{in-plane}^{Bz}$  as a function of magnetic field extracted from (a)–(c), with the fast-scan direction along  $Q_{Bragg}^a$ . As can be seen, the changes in the atomic Bragg position  $Q_{Bragg}^a$  are minimal and similar across all magnetic fields. (e) Average  $\lambda_{in-plane}^{Bz}$  as a function of magnetic field over the same area of the sample as in (a)–(d), but with the fast-scan direction along the  $Q_{Bragg}^b$  direction. As can be seen, the change in the atomic Bragg peak position  $Q_{Bragg}^b$  are now minimal and consistent across all fields, in contrast to the, by comparison, enormous values measured in (d), which we conclude to be an artifact. The  $4a_0$  charge-stripe order is along the  $Q_{Bragg}^a$  direction. All data is from sample #1, region #1 and was acquired using a fast-scan speed of 10.2 nm/s over a  $90 \text{ nm} \times 90 \text{ nm}$  (400 pixel  $\times$  400 pixel) area. Error bars for (d) and (e) are defined by the following error propagation:  $\delta\lambda = \sqrt{\left(\frac{\delta Q_{Bragg}^i(\mathbf{B})}{|Q_{Bragg}^i(\mathbf{B})|}\right)^2 + \left(\frac{\delta Q_{Bragg}^i(OT)}{|Q_{Bragg}^i(OT)|}\right)^2} \times |\lambda|$  where  $\delta Q_{Bragg}^i(\mathbf{B})$  is the standard error of four measurements of  $Q_{Bragg}^i(\mathbf{B})$  and  $|Q_{Bragg}^i(\mathbf{B})|$  is the average value, and  $|\lambda|$  is the average magnetostriction observed.

in-plane lattice constant change along the fast-scan direction driven by magnetic field.

Different from a polycrystalline sample, which can be considered macroscopically isotropic and thus with a field-aligned magnetostriction coefficient independent of the measuring direction, magnetic field lattice response in a single crystal could also vary for different crystalline axes. STM cannot directly measure the lattice constant along the  $c$ -axis direction, but as we will show, it can be sensitive to changes in the overall sample thickness with subangstrom resolution. In particular, we proceed to use the change in the STM tip height  $\Delta Z$  in the tunneling regime as the proxy for the total sample thickness change [Fig. 4(a)]. We use specific impurities in the field of view as markers for tracking an identical region of the sample and extract the tip height difference  $\Delta Z$  as a function

of magnetic field. A similar procedure was previously applied to uncover a large out-of-plane lattice response in magnetically ordered systems [55] and here we use it to investigate whether subtle effects may be present in nonmagnetic kagome metals. It is important to note that while the magnetic field is being changed, the tip is withdrawn (negative voltage is applied to piezoelectric scanner electrodes) so that it is not in feedback, and no piezoelectric “walker” steps are taken to bring the entire scanner away from the sample surface.

Overall, we observe a nanometer-scale effect [Figs. 4(b)]. For example, applying a magnetic field of 4 T along the  $z$  direction leads to an apparent tip change of about 7 nm for  $\text{CsV}_3\text{Sb}_5$  [Fig. 4(c)] and a change of about 8 nm for  $\text{RbV}_3\text{Sb}_5$  [Fig. 4(g)]. To investigate the expansion of the entire microscope setup, including the sample holder, we study the tip

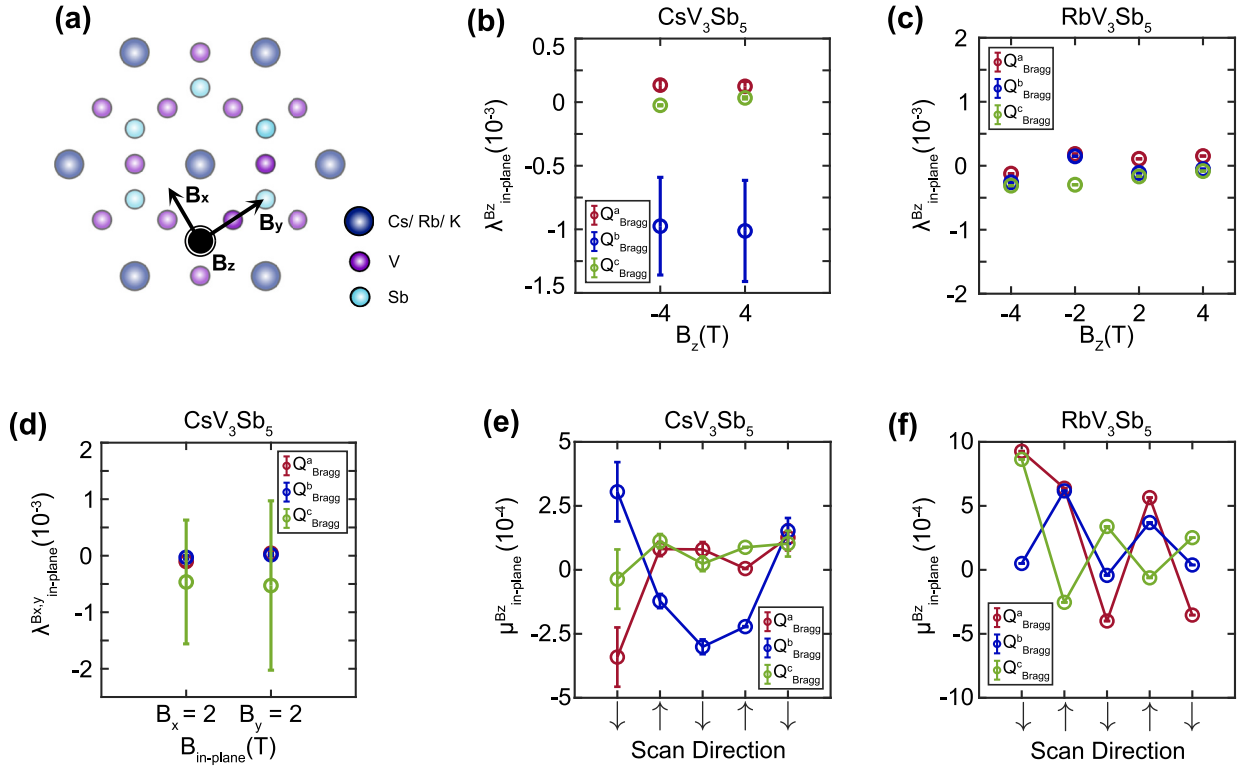


FIG. 3. Quantifying the in-plane lattice response of  $\text{CsV}_3\text{Sb}_5$  and  $\text{RbV}_3\text{Sb}_5$  to magnetic field. (a) A 2D ball model of the crystal structure in the  $ab$  plane showing the direction of the 3D vector magnetic field relative to the atomic structure. (b),(c) In-plane magnetostriction coefficient for (b)  $\text{CsV}_3\text{Sb}_5$  and (c)  $\text{RbV}_3\text{Sb}_5$  measured by applying an out-of-plane magnetic field  $B_z$  ( $\lambda_{\text{in-plane}}^{B_z}$ ). (d) In-plane magnetostriction coefficient for  $\text{CsV}_3\text{Sb}_5$  measured by applying in-plane magnetic field  $B_x$  or  $B_y$  ( $\lambda_{\text{in-plane}}^{B_{x,y}}$ ). Error bars for (b)–(d) are defined in the same way as those in Figs. 2(d) and 2(e). (e),(f) Piezomagnetic coefficient  $\mu_{\text{in-plane}}^B = \frac{2(|Q_{\text{Bragg}}^i(\mathbf{B})| - |Q_{\text{Bragg}}^i(-\mathbf{B})|)}{|Q_{\text{Bragg}}^i(\mathbf{B})| + |Q_{\text{Bragg}}^i(-\mathbf{B})|}$  for  $Q_{\text{Bragg}}^a$ ,  $Q_{\text{Bragg}}^b$ , and  $Q_{\text{Bragg}}^c$  for (e)  $\text{CsV}_3\text{Sb}_5$  and (f)  $\text{RbV}_3\text{Sb}_5$  obtained by comparing  $B_z = 4$  T and  $B_z = -4$  T data for a series of consecutive up and down scans. All data points shown in the figure for a particular lattice direction are extracted from data acquired with a fast-scan direction aligned with that same lattice direction (within a few degrees). The  $4a_0$  charge-stripe order is along the  $Q_{\text{Bragg}}^a$  direction. Error bars are defined by the following error propagation:

$$\delta\mu = \sqrt{\left(\frac{\delta Q_{\text{Bragg}}^i(-4T)}{|Q_{\text{Bragg}}^i(-4T)|}\right)^2 + \left(\frac{\delta Q_{\text{Bragg}}^i(4T)}{|Q_{\text{Bragg}}^i(4T)|}\right)^2} \times |\mu|$$
 where  $\delta Q_{\text{Bragg}}^i(\mathbf{B})$  is the standard error of 2D Gaussian fit and  $|Q_{\text{Bragg}}^i(\mathbf{B})|$  is the fit value, and  $|\mu|$  is the average piezomagnetic response observed. The data in (b) and (e) are from sample #1, region #2 and were acquired using a fast-scan speed of 22.2 nm/s over a  $40 \text{ nm} \times 40 \text{ nm}$  ( $256 \text{ pixel} \times 256 \text{ pixel}$ ) area. The data in (c) is from sample #1, region #1 and was acquired using a fast-scan speed of 30 nm/s over a  $30 \text{ nm} \times 30 \text{ nm}$  ( $400 \text{ pixel} \times 400 \text{ pixel}$ ) area. The data in (d) is from sample #2, region #1 and was acquired using a fast-scan speed of 20 nm/s over a  $20 \text{ nm} \times 20 \text{ nm}$  ( $256 \text{ pixel} \times 256 \text{ pixel}$ ) area.

height variation in the tunneling regime over a wide range of different materials, including cleaved bulk single crystals and thin films, of different thicknesses [Fig. 4(b)]. All of them show a linear evolution in magnetic field, with varying slopes. The helical antiferromagnet  $\text{YMn}_6\text{Sn}_6$  shows the largest slope [Fig. 4(b)], which may not be surprising given its magnetic nature with the expected continuous field-induced spin tilting up to a much higher magnetic field than used here [56–60]. Most other materials fall along a similar line with a lower slope. To approximate the background expansion of the sample holder, we calculate the smallest slope and subtract it from our raw measurements. Taking into account the thickness of the  $\text{CsV}_3\text{Sb}_5$  sample used in the experiment to be  $0.16 \pm 0.02$  mm, the resulting normalized value of the out-of-plane magnetostriction coefficient  $\lambda_{\text{out-of-plane}}^{B_z}$  is negligible, at most at the order of  $1 \times 10^{-6}$  per tesla [Fig. 4(d)]. The out-of-plane lattice constant change in response to an in-plane magnetic field is

also approximately zero [Figs. 4(e) and 4(f)]. Similar behavior was demonstrated in  $\text{RbV}_3\text{Sb}_5$  for the out-of-plane magnetic field [Figs. 4(g) and 4(h)]. We extracted similarly tiny changes of the  $c$ -axis lattice constant for other nonmagnetic kagome crystals such as  $\text{KV}_3\text{Sb}_5$  and  $\text{ScV}_6\text{Sn}_6$ , which are comparable to our result in  $\text{CsV}_3\text{Sb}_5$  and  $\text{RbV}_3\text{Sb}_5$  [Figs. 4(i) and 4(j)]. It is worth noting that the out-of-plane piezomagnetic response  $\mu_{\text{out-of-plane}}^{B_z}$  extracted from the data in Fig. 4(c) is also absent [inset in Fig. 4(c)].

### III. DISCUSSION

Measuring femtometer-scale crystal distortions generated in solids under an external magnetic field using traditional methods can be complicated by the inevitable presence of domains. We establish a procedure to conduct more accurate measurements of the magnetic field driven lattice response at

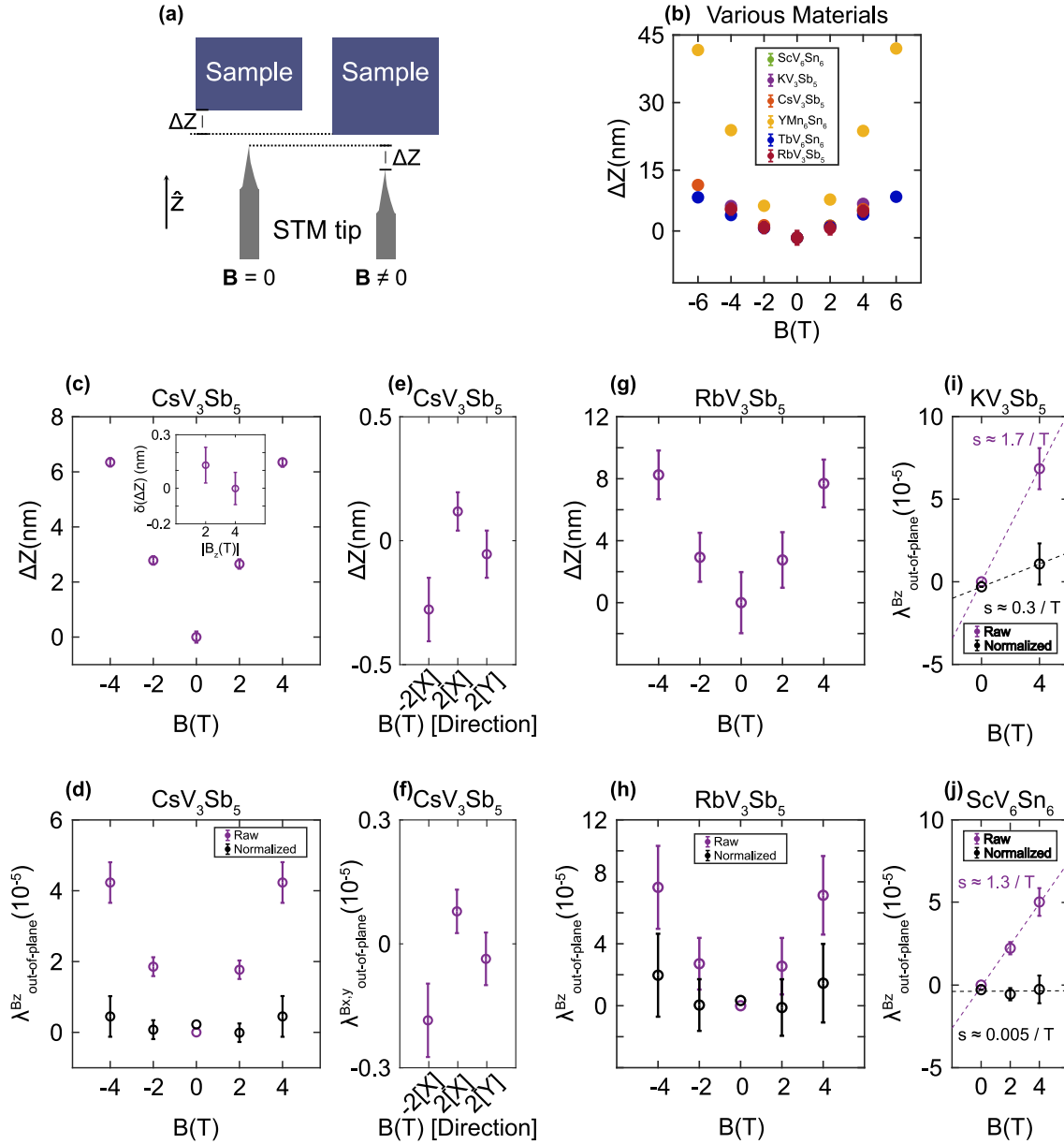


FIG. 4. Out-of-plane lattice constant response to external magnetic field. (a) Schematic of the measurement. The scanning tunneling microscope tip measures the expansion of the entire sample after magnetic field is applied. The sample in field expands by  $\Delta Z$ ; the feedback loop then adjusts the height of the tip by  $\Delta Z$  to achieve the tunneling regime again. (b) Summary of  $\Delta Z$  vs magnetic field for a range of different materials used. It is worth noting that the helical antiferromagnet  $\text{YMn}_6\text{Sn}_6$  shows a substantially larger effect compared to all other materials studied. Error bars are defined as the standard error from comparing multiple measurements (number of measurements varies sample to sample). (c) Relative change in the height of the scanning tunneling microscope tip in tunneling ( $\Delta Z$ ) over an identical region of the Sb surface of  $\text{CsV}_3\text{Sb}_5$  as a function of  $B_z$  compared to the tip height at 0 T (minus sign denotes the reversal of the field direction). Error bars are defined as standard error from comparing multiple measurements. Inset: Difference in  $\Delta Z$  between negative magnetic field and positive magnetic field of equal magnitudes, demonstrating a piezomagnetic effect less than  $10^{-6}$ . Error bars are defined by  $\sqrt{[\delta Z(-\mathbf{B})]^2 + [\delta Z(\mathbf{B})]^2}$  where  $\delta Z(\mathbf{B})$  is standard error of multiple measurements. (d) Coefficients  $\lambda_{\text{out-of-plane}}^{B_z} = \Delta Z/d$  calculated from (c), taking into account the thickness of the entire sample to be  $d = 0.16 \pm 0.02\text{mm}$ : assuming the expansion comes from the sample only (purple symbols), and by accounting for the expansion of the entire sample holder in magnetic field (black symbols). Error bars are defined by the following error propagation:  $\delta\lambda = \sqrt{\left(\frac{\sqrt{[\delta Z(\mathbf{B})]^2 + [\delta Z(0T)]^2}}{|Z(\mathbf{B}) - Z(0T)|}\right)^2 + \left(\frac{\delta d}{d}\right)^2} \times |\lambda|$  where  $\delta Z(\mathbf{B})$  is standard error from multiple measurements,  $|Z(\mathbf{B}) + Z(0T)|$  is the average from multiple measurements, and  $\delta d$  is the error in measuring thickness of the material. (e),(f) Equivalent measurements to those in (c) and (d), but for an in-plane magnetic field:  $\lambda_{\text{out-of-plane}}^{B_{x,y}}$ . Error bars are defined equivalently. (g),(h) Equivalent measurements to those in (c) and (d) but for the Sb surface of  $\text{RbV}_3\text{Sb}_5$ . (i),(j) The  $c$ -axis coefficients  $\lambda$  for the out-of-plane magnetic field  $B_z$  for (i)  $\text{KV}_3\text{Sb}_5$  and (j) kagome metal  $\text{ScV}_6\text{Sn}_6$  obtained using the same procedure as described in (c) and (d), which also show a negligible response to magnetic field. Error bars are defined by standard error from multiple measurements. The  $\text{CsV}_3\text{Sb}_5$  data in (c) and (d) is from sample #1, region #1. The  $\text{CsV}_3\text{Sb}_5$  data in (e) and (f) is from sample #2, region #1.

the nanoscale level using STM by examining a sequence of rotated scan frames. We note that this is a distinct procedure complementary to the established extraction of spatially varying crystal distortions typically examined at zero magnetic field [61–66] and the temperature-dependent expansion measurements [67]. We applied the method to study magnetic field effects in CDW kagome metals  $AV_3Sb_5$ . We find that the out-of-plane magnetostriction and piezomagnetic coefficients are approximately zero. We also reveal that the in-plane lattice deformation is limited by the resolution of current experiments, with the upper bound of about 0.05% for fields of a few tesla. These results demonstrate that the intrinsic magnetic field response of the lattice in  $CsV_3Sb_5$ ,  $KV_3Sb_5$ , and  $RbV_3Sb_5$  in all regions studied here is extremely small in comparison to other experiments on  $RbV_3Sb_5$  [50]. Consistent with our previous work, in the regions examined we observe no change in the CDW anisotropy when the magnetic field direction is reversed [Fig. 1(c)]. We also note that all experiments are done on sample regions that appear flat, away from obviously buckled regions occasionally seen in layered materials attached in the same geometry [66,68–70]. Future experiments should pursue the investigation of magnetic field coupling to the lattice in such strained regions. It would also be of high interest to apply the experimental method established here to any region where CDW anisotropy appears to be controlled by magnetic field to quantify the magnitude of magnetic field–lattice coupling more accurately.

Importantly, our work cautions the comparison of STM topographs acquired along a single scan direction for the quantitative determination of the atomic lattice constant change, as spurious changes as large as 1% can easily be observed due to experimental artifacts we describe here. The magnitude of these artifacts also appears to fluctuate in different experimental data sets, which we uncovered by examining topographs acquired along different scan directions. Our method mitigates the issue by a meticulous comparison of a series of continuous scans acquired along different crystalline directions, in different magnetic fields, to quantify intrinsic effects. This can be widely applicable to other materials of interest to investigate the coupling of the lattice and externally

applied field. We stress that our results do not imply that the CDW phase in  $AV_3Sb_5$  does not contain orbital currents or different forms of orbital flux phases [47–49]. However, we demonstrate that the out-of-plane lattice constant is unaffected by the magnetic field and that strong coupling of the magnetic field and the in-plane lattice structure is not a generic feature of all  $AV_3Sb_5$  regions and/or samples studied. Overall, our experiments provide further constraints on the origin of time-reversal symmetry breaking in  $AV_3Sb_5$  and establish a procedure to quantify nanoscale lattice effects more accurately in quantum materials.

#### IV. METHODS

Single crystals of  $CsV_3Sb_5$  were grown and characterized as described in more detail in Ref. [2]. Samples are glued to the sample holder using EPO-TEK H20E silver conducting epoxy and are cured at 175 °C for 20 min. The cleaving rod is glued to the top of the sample in the same way. We cold-cleave the  $CsV_3Sb_5$  crystals at around 20 K and quickly insert them into a scanning tunneling microscope for scanning. STM data was acquired using a customized Unisoku USM1300 microscope at approximately 4.5 K. The STM tips used were homemade chemically etched tungsten tips, annealed in UHV to bright orange color prior to STM experiments. All STM data shown was acquired at about 4.5 K.

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