Robust nature of the chiral spin helix in CrNb$_3$S$_6$ nanostructures studied by off-axis electron holography

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Magnetic soliton crystals with layered structures that host periodic chiral helimagnetic ordering are promising candidates for spintronic nanodevices. Among them, helimagnetic CrNb$_3$S$_6$ is unique owing to its crystallographic chirality and monoaXial Dzyaloshinskii-Moriya interaction. It is crucial to explore its magnetic configurations and properties with respect to the temperature and thickness, especially in reduced dimensions. Here, the chiral helimagnetic ground state in CrNb$_3$S$_6$ nanostructures is investigated using off-axis electron holography in the transmission electron microscope. The period of the helical state is found to be independent of both temperature and specimen thickness, while the temperature dependence of the saturation magnetization is shown to follow a classical Heisenberg spin model. Monte Carlo simulations based on a discrete classical Heisenberg model reproduce the experimental observations closely, confirming the applicability of a three-dimensional Heisenberg model even in a confined specimen geometry.

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I. INTRODUCTION

Chirality is common in nature, for instance in crystallography, where the absence of mirror symmetry in atomic configurations can be decisive for material properties. In magnetic materials, crystal symmetry can give rise to chiral interactions, such as the Dzyaloshinskii-Moriya interaction (DMI), which can be the source of multiferroic behavior [1,2] and can result in the formation of exotic magnetic objects such as skyrmions [3,4], chiral bobbers [5], and solitons [6]. DMI-hosting magnetic materials include B20-type FeGe, MnSi, and Cu$_2$OSeO$_3$, $\beta$-Mn-type CoZnMn and Fe$_x$Co$_{1-x}$Rh$_{0.5}$Mo$_{3.5}$N and hexagonal CrNb$_3$S$_6$ [1]. CrNb$_3$S$_6$ is a monoaXial helimagnet [7,8] as one of the promising candidates for magnetic two-dimensional crystals, in which competition between DMI and exchange coupling can lead to periodic chiral helimagnetic (CHM) order in the form of sinusoidal stripe domains [6–10]. If an external magnetic field is applied perpendicular to the helical axis of CrNb$_3$S$_6$, then a chiral magnetic soliton lattice (CSL) rather than a skyrmion lattice can form as a result of the uniaXial nature of the DMI [6]. Magnetotransport measurements have shown that conduction electrons can couple with CSLs, resulting in unique interlayer magnetoresistance [11] and electrical magnetochiral [12] effects. In magnetic nanostructures that have confined geometries, CrNb$_3$S$_6$ exhibits discretized magnetoresistance or magnetization jumps as a result of confinement of the CSL [13,14], motivating the need to understand the magnetic behavior of CHM order and CSLs in CrNb$_3$S$_6$ nanostructures on the nanoscale. Although Lorentz transmission electron microscopy (LTEM) has been used to image CHM order and CSLs [6,13,15–17] in thin plates of CrNb$_3$S$_6$, quantitative studies of their magnetization in nanostructures are still lacking.

Here, we use off-axis electron holography (EH) to measure the projected in-plane magnetic moment distributions in CrNb$_3$S$_6$ nanostructures [18], in order to investigate the period and magnetization of CHM order as a function of temperature and specimen thickness. We use Monte Carlo (MC) simulations that include DMI and ferromagnetic exchange interactions to validate our experimental findings. We find that the period of CHM order is independent of both
temperature and specimen thickness. We measure a saturation magnetization-temperature \((M_S - T)\) curve using off-axis EH and find it to be similar to that predicted using a classical Heisenberg model. Our results demonstrate the robust magnetic character of CHM order in geometrically confined CrNb\(_3\)S\(_6\) nanostructures.

II. EXPERIMENTAL DETAILS

Single-crystalline CrNb\(_3\)S\(_6\) was synthesized using a chemical vapor transport method. Two CrNb\(_3\)S\(_6\) nanostructures with desired geometries were prepared for TEM experiments using a top-down focused ion beam milling method. One of the nanostructures took the form of a thin plate with a uniform thickness of approximately 100 nm, while the other took the form of a wedge-shaped nanostripe with a continuously varying thickness of between 70 and 240 nm, as shown schematically in Fig. S1 in the Supplemental Material [19]. Off-axis EH experiments were performed in magnetic field free conditions in Lorentz mode using an image spherical aberration corrected FEI Titan 60–300 microscope operated at 300 kV. A liquid N\(_2\)-cooled TEM specimen holder (Gatan 636) was used to control the specimen temperature between 95 and 380 K. Off-axis electron holograms were recorded using a single electrostatic biprism and a direct electron counting camera (Gatan K2-1S) with an interference fringe spacing of 2.78 nm and a fringe contrast of more than 65% [20]. Each experiment involved the acquisition of 25 object holograms, followed by 25 vacuum reference holograms to remove image distortions associated with the imaging and recording system of the microscope. Averaging of the holograms, which were each acquired using an exposure time of 4 s, was used to improve the signal-to-noise ratio. Phase images were reconstructed using a standard Fourier transform-based approach in HOLOWORKS 6.0 software (Holowork LLC) [21]. The mean inner potential contribution to the phase was removed by taking the average of 25 object holograms, followed by 25 vacuum reference holograms to remove image distortions associated with the imaging and recording system of the microscope. The scale bar is in the unit of radians. The phase contour is 2\(\pi/100\) = 0.0628 radians. The green and red colors indicate that the projected in-plane magnetic induction is oriented upwards and downwards, respectively.

III. RESULTS AND DISCUSSIONS

CrNb\(_3\)S\(_6\) has a hexagonal layered structure with alternating Cr and NbS\(_2\) planes along the \(c\) axis, as shown in Fig. 1(a). The Cr atoms are ferromagnetically coupled in the \(ab\) plane, while CHM order forms in the \(c\) direction as a result of a monoaxial DM interaction. Figure 1(b) shows the CHM spin texture in CrNb\(_3\)S\(_6\), which has a period of \(L = 48\) nm and is determined by the relative strength of the DMI constant \(D\) and the ferromagnetic exchange interaction constant \(J\) [6,13,15]. TEM samples were prepared with the \(c\) axis aligned in the sample plane and perpendicular to the incident electron-beam direction (\(z\) axis), as marked by a red arrow in Fig. 1(b). The projected in-plane magnetization shown in Fig. 1(b) exhibits a sinusoidal variation along the \(c\) axis. It should be noted that only the magnetic field perpendicular to the electron-beam direction contributes to the magnetic phase shift \(\varphi_M\) recorded using off-axis EH [18]. \(\varphi_M\) is defined as 

\[-e/\hbar \int A_z dz,\]

where \(A_z\) is the \(z\) component of the magnetic vector potential and \(e\) and \(\hbar\) are the electron charge and the reduced Planck constant, respectively. If demagnetizing fields can be neglected, then for standard CHM order with \(m(x, y, z) = 0, \cos(2\pi x/L), \sin(2\pi x/L)\) in a specimen of uniform thickness \(t\), the magnetic phase shift is defined as \(\varphi_M = -\mu_0 m_0 L t/2\Phi_0 - \cos(2\pi x/L)\), where \(m\) is the magnetic moment, \(\mu_0\) is the vacuum permeability, \(\Phi_0\) is the magnetic flux quantum, \(M_S\) is the saturated magnetization, and the \(x\) axis is parallel to the crystallographic \(c\) axis. Figure 1(c) shows a typical calculated magnetic phase shift image in the form of sinusoidal stripe pattern with a period of 48 nm, assuming a CrNb\(_3\)S\(_6\) nanoplate thickness of 100 nm and a magnetic moment of 1.9 \(\mu_B\) per Cr atom at 95 K. The magnetic phase shift can be used to obtain a magnetic induction map by adding contours and colors that represent the strength and direction of the projected in-plane magnetic induction. Figure 1(d) shows a resulting magnetic induction map characteristic of CHM order, with zero \(x\) component of the projected in-plane magnetic induction.

Figure 2(a) shows experimental magnetic phase images recorded at four different temperatures between 95 and 133 K in a nanoplate of CrNb\(_3\)S\(_6\) that has a uniform thickness of approximately 100 nm, similar to that shown in Fig. 1(c). The CHM order can be seen to persist with increasing temperature. The line-intensity profiles of \(\varphi_M\) shown in Fig. 2(b) were extracted from the corresponding magnetic phase images shown in Fig. 2(a).
FIG. 2. Chiral helimagnetic structure in a CrNb$_3$S$_6$ nanoplate measured as a function of temperature in zero magnetic field. (a) Magnetic phase shift images recorded at four different specimen temperatures using off-axis electron holography. The white and black levels correspond to the magnitude of the phase shift $\phi_M$. The scale bar is in the unit of radians. (b) Line profiles of $\phi_M$ extracted along the blue lines marked in (a). (c) Magnetic induction maps of CHM order determined from the experimental magnetic phase images shown in (a). The phase contour spacing is $2\pi/100 = 0.0628$ radians. At 133 K, no measurable magnetic signal is present. All of the scale bars are 50 nm.

in Fig. 2(a). The decrease in the magnitude of $\phi_M$ suggests that the magnetization in the nanoplate decreases with increasing temperature. At 133 K, the variations in $\phi_M$ approach zero, corresponding to the CHM–paramagnetic phase transition. The magnetic induction contours shown in Fig. 2(c) are then more widely separated. They are completely absent when the temperature of the specimen reaches 133 K.

Quantitative real-space maps of the projected in-plane magnetic moment $m_{\text{xy}}$ were retrieved from the experimental magnetic phase shift images using a model-based iterative reconstruction algorithm [22]. Figure 3(a) shows the $y$ component of the projected in-plane magnetization (normalized to $\mu_B$ per Cr atom) calculated from the experimental phase images recorded at different specimen temperatures. The $x$ component of the projected in-plane magnetization is negligible, as shown in Fig. S3 in the Supplemental Material [19]. The magnetization profiles at different temperatures shown in Fig. 3(b) are consistent with the sinusoidal spin model of CHM shown in Fig. 1(b). The magnetic moment per Cr atom can be inferred to be approximately 1.9 $\mu_B$ at 95 K, in agreement with previous experimental macro-measurement results [8]. The saturated magnetization ($M_S$) was determined by averaging the peak values in each magnetic stripe shown in Fig. 3(b). The $M_S$–$T$ curve, which is shown in Fig. 3(c), exhibits a monotonic decrease in $M_S$ with increasing temperature, as it approaches the Curie temperature. By fitting

FIG. 3. Quantitative measurements of magnetization in a CrNb$_3$S$_6$ nanoplate. (a) Reconstructed real-space distributions of the $y$ component of the projected in-plane magnetization (normalized to $\mu_B$ per Cr atom) measured at the indicated temperatures using a model-based iterative reconstruction algorithm. The white and black levels correspond to the magnitude of the projected in-plane magnetization. The scale bars are 50 nm. (b) Line profiles of the $y$ component of the projected in-plane magnetization extracted from the images shown in (a) for the indicated temperatures. (c) Saturation magnetization ($M_S$) plotted as a function of temperature between 95 and 135 K. The Curie temperature is measured to be 130 K. Experimental data are plotted using red circles, while the results of MC simulations are plotted in blue.
the measured $M_S-T$ curve to a function of the form $M(T) = (1 - T/T_c)^\beta$, values of $\beta = 0.34$ and a Curie temperature of $T_c = 130\, \text{K}$ were obtained. The fitted value for $T_c$ is consistent with that expected for a bulk crystal ($130 \pm 2\, \text{K}$) in the literature [7,8] as well as our macro measurement ($130.4\, \text{K}$) in Fig. S4 in the Supplemental Material [19]. The phase transition from a chiral incommensurate state to paramagnetic state occurs at $T_c$ owing to thermal fluctuations. These observations show that a thin nanoplate has similar magnetic properties to those in a bulk crystal and exhibits high stability of CHM order in a dimensionally confined CrNb$_3$S$_6$ system.

Monte Carlo simulations were performed to interpret the experimental results using a classical Heisenberg model for a monoaixal chiral magnet. Models for equilibrium helical states at different temperatures were obtained using a MC method based on a discrete Hamilton, which contains terms describing Heisenberg ferromagnetic exchange, DMI, and magnetic anisotropy. The parameters $J_{ab} = 140\, \text{K}$, $J_c = 18\, \text{K}$, and $D = 2.9\, \text{K}$ were used in the simulations, where $J_{ab}$ and $J_c$ are the strengths of the intralayer and interlayer Heisenberg exchange, respectively, while $D$ is the strength of interlayer DMI. A value for the easy-plane anisotropy of $K = 2.1\, \text{K}$ was used. The system size was $32 \times 512 \times 32$ cells ($5.75 \times 12.10 \times 5.75\, \text{Å}^3$ per cell) and periodic boundary conditions were applied in the specimen plane to model the thin nanoplate studied experimentally. In order to simulate changes in periodic CHM order as a function of temperature, the system was annealed from a high temperature ($T = 1000\, \text{K}$) to each target temperature. 500 000 MC steps were performed before calculating the spin configuration at each temperature. The average spin configuration was calculated in real space using 5000 configurations separated by 20 MC steps. The final $M_S-T$ curve in Fig. 3(c) (blue line) shows a good match to the experimental results, suggesting that the magnetic behavior of a CrNb$_3$S$_6$ nanoplate can be described using a three-dimensional classical Heisenberg spin model even in the presence of a reduced dimension in the thickness direction. This robustness to confinement effects can be attributed to the uniform three-dimensional magnetic structure of CHM order in CrNb$_3$S$_6$, which originates from monoaixal DMI, strong easy-plane anisotropy, and strong in-plane exchange interactions.

The period $L$ of CHM order in the nanoplate was then analyzed as a function of temperature. Figure 4(a) shows the period $L$ measured using off-axis EH, LTEM, and MC methods. It takes a value of approximately 48 nm over the entire range of investigated temperatures. Similar experimental results are reproduced for another sample in Fig. S5 in the Supplemental Material [19]. As a result of the small field of view of off-axis EH measurements, the error in the values of $L$ measured using this technique is relatively large. In order to reduce the error, the nanoplate was also investigated using Fresnel defocus images in LTEM. Representative LTEM images are shown in Fig. S6 in the Supplemental Material [19] and Fig. S7 in the Supplemental Material [19]. Measurements of the period $L$ in the off-axis EH results, as well as with previous neutron diffraction results [7,8] and with three-dimensional mean-field theory [9,15,23], show a period again shows almost no change with thickness down to 48 nm. (b) Period $L$ of CHM order in a nanostructure that has a continuously varying thickness of between 70 and 240 nm, measured using LTEM and plotted as a function of specimen thickness for different temperatures.

![Graph](image)

**FIG. 4.** Temperature and thickness dependence of the period of chiral helimagnetic order in CrNb$_3$S$_6$ nanostructures. (a) Period $L$ of CHM order in a nanoplate that has a fixed thickness of 100 nm measured using off-axis EH (red squares) and LTEM (black triangles) below the Curie temperature. The period derived from Monte Carlo simulations is marked with blue stars. The dotted line marks a value of 48 nm. (b) Period $L$ of CHM order in a nanostructure that has a continuously varying thickness of between 70 and 240 nm, measured using LTEM and plotted as a function of specimen thickness for different temperatures.

CrNb$_3$S$_6$ lamella over a similar temperature range [15] and was explained using two-dimensional melting theory [24,25]. We believe that the specimen thickness had affected this previous report of the anomalous melting behavior of the period $L$. Therefore, we also studied a wedge-shaped nanostripe with a continuously varying thickness of between 70 and 140 nm to investigate the thickness dependence of the period $L$. The temperature dependence of CHM order shows the same behavior as that in the nanoplate, as shown in Fig. S7 in the Supplemental Material [19]. Measurements of the period $L$ in the wedge-shaped nanostripe are plotted in Fig. 4(b) as a function of specimen thickness for different temperatures. The period again shows almost no change with thickness down to 70 nm. The results demonstrate the robustness of the period $L$ of CHM order in CrNb$_3$S$_6$ nanostructures, which is found to be independent of temperature over the investigated range of specimen thickness.

The MC-simulated period of CHM order remains constant over a wide temperature range below the Curie temperature, in agreement with experimental results and three-dimensional mean-field theory [9,15,23]. The value of the period $L$ of the CHM order can be expressed in the form $L =$
2π/\arctan(D/Jc)c0, where c0 is the lattice parameter along the helical axis. The uniformity of the period with temperature suggests that the strength of the two interactions is constant with temperature. This behavior is anticipated because the Heisenberg ferromagnetic exchange and DMI originate from the same exchange tensor. It is safe to assume that D and J are determined by the strong spin-spin coupling and do not change significantly with temperature, even in a freestanding thin nanoplate, resulting in the robust nature of period L for CHM order observed here. Similar situations occur in most skyrmion-hosting materials, including FeGe and MnSi with the B20 structure [3,4]. An exception was reported for B20-type MnGe [26], in which an increased period of the skyrmion lattice was reported on approaching the Curie temperature. The latter behavior can be attributed to the relatively large magnetic anisotropy in this system, which is absent in CrNb3S6. Moreover, recent studies have demonstrated that the strength of DMI exhibits a nearly linear correlation with the exchange stiffness [27], resulting in an almost constant period L.

IV. CONCLUSION

In summary, the temperature dependence of the period and saturation magnetization of CHM order in CrNb3S6 nanostructures has been investigated quantitatively using LTEM, off-axis electron holography and Monte Carlo calculations. Real-space measurements of projected in-plane magnetization provide quantitative information about sinusoidal modulations of CHM order in CrNb3S6 on the nm scale. The saturation magnetization is measured as a function of temperature and the Curie temperature is determined to be 130 K in a CrNb3S6 nanoplate, in agreement with results obtained from a bulk crystal and with a classical Heisenberg spin model. The period is found to be independent of temperature and specimen thickness in CrNb3S6 nanostructures, reproduced in MC simulations, and consistent with a three-dimensional classical spin model. The present results suggest the robustness and stability of the magnetic character of CHM order in CrNb3S6 nanostructures with dimensional confinement, which is important for potential uses of this system in spintronic nanodevices.

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See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevB.102.064432 for detailed descriptions of the schematics of CrNb$_3$S$_6$ nanostructures, sequence of steps to retrieve magnetic phase using off-axis electron holography, real-space distributions of the $x$ component of projected in-plane magnetization reconstructed using a model-based iterative algorithm, magnetization curve of the bulk CrNb$_3$S$_6$ crystal as a function of temperature, temperature and thickness dependence of period for two CrNb$_3$S$_6$ nanoplates and a wedge-shaped nanostripe of CrNb$_3$S$_6$ measured using the Lorentz Fresnel imaging mode, respectively.

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