Electronic properties of correlated kagomé metals $\text{AV}_3\text{Sb}_5$ ($A = \text{K, Rb, Cs}$): A brief review

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Following the discovery of a new family of kagomé prototypical materials with structure $\text{AV}_3\text{Sb}_5$ ($A = \text{K, Cs, Rb}$), there has been heightened interest in studying correlation-driven electronic phenomena in these kagomé lattice systems. The study of these materials has gone beyond magneto-transport measurements to reveal exciting features such as Dirac bands, anomalous Hall effect, bulk superconductivity with $T_c \sim 0.9$ K-$2.5$ K, and the observation of charge density wave instabilities which suggests an intertwining of topological physics and new quantum orders. Moreover, very recent works on numerous types of experiments have appeared further examining the unconventional superconductivity and the exotic electronic states found within these kagomé materials. Theories on the strong interactions that play a role in these systems have been proposed to shed light on the nature of these topological charge density waves. In this brief review, we summarize these recent experimental findings and theoretical proposals to connect them with the concepts of topological physics and strongly-correlated electron systems.

I. INTRODUCTION

Materials with kagomé crystal structures have attracted significant interest due to emergence of flat bands with electronic band structures that can host Dirac cones and van Hove singularities. Various exotic phenomena can emerge from the interplay between nontrivial band topology and strong Coulomb correlations within these systems. Formation of superconducting ground states in layered kagomé compounds is rare, therefore the discovery [1] of a new family of kagomé metals, $\text{AV}_3\text{Sb}_5$ ($A = \text{K, Cs, Rb}$), exhibiting superconductivity at $0.9$ K-$2.5$ K and an intriguing charge-density-wave transition near $78$ K-$103$ K has spawned numerous results. These kagomé metals have uncovered a fascinating platform for new insights into the rich physics that lies at the interplay between strong electronic correlations, nontrivial band topology, unconventional superconductivity, and emergent quantum orders.

This brief review is organized as follows. In Section II, we will describe the crystal structure of these kagomé systems and their characterizations, under ambient and high pressures. We will expand on measurements of the large anomalous Hall effect (AHE) found in these systems (Section III) in addition to several experimental findings on different charge orders from scanning tunneling microscopy (STM) (Section IV). We will discuss some of the on-going efforts on the theoretical side to explain the phenomena observed in these systems in Section V. We will conclude with a discussion on the implications that derive from these experimental and theoretical studies on our understanding of strongly correlated topological kagomé systems and their unconventional superconductivity properties as well as potential applications using this new family of kagomé metals.

II. SYNTHESIS AND CHARACTERIZATION

$\text{AV}_3\text{Sb}_5$ ($A = \text{K, Cs, Rb}$) crystallizes in the hexagonal $P6/mmm$ (191) space group (Fig. 1a) where the vanadium sublattice forms a perfect two-dimensional kagomé net that is interwoven with a hexagonal net of tin atoms.
This V-Sb layer is sandwiched between two honeycomb layers of Sb atoms which form a different sublattice from the interwoven Sb atoms and altogether, these are intercalated by a hexagonal net of alkali (A) atoms. Due to the layered nature of the crystal structure, the crystals lend themselves to be easily exfoliable to thin 2D layered sheets. The general synthesis technique consists of milling the different constituent elements into grounded powders and synthesizing the crystal via the flux method. Special care must be taken due to the high reactivity of the alkali metals; therefore, the powders are purified and mixed in an argon glove box with a slight extra amount of the alkali to compensate for its reactivity.

Unlike other heavily studied kagomé lattice, this family of compounds does not exhibit resolvable magnetic ordering down to the lowest measurable temperatures by far. On the other hand, bulk electric transport, heat capacity, and magnetization measurements (Figs. 1b, c for CsV$_3$Sb$_5$) [1, 2] reveal the presence of an anomaly near 78 K-103 K for all three members of the family ($T_{\text{CDW}} = 78$ K (K), 94 K (Cs), 103 K (Rb)) which is due to the formation of a charge ordering state with the presence of a charge density wave (CDW) instability. More details on STM measurements of the CDWs and related instabilities are discussed further in Section IV.

Furthermore, the observation of bulk superconductivity in single crystals of AV$_3$Sb$_5$ has been reported with a superconducting transition temperature of $T_c = 0.93$ K (K), 2.5 K (Cs), 0.92 K (Rb) [2, 4, 5] with measurements suggesting that the superconductivity is in the strong-coupling regime ($2\Delta/k_BT_c = 5.2$). By calculating the electronic band structure with density functional theory (DFT), one can find the presence of numerous Dirac points near the Fermi surface with corresponding topological protected surface states that occur at the M points (a time-reversal invariant momentum (TRIM) point) in the Brillouin zone. When one calculates the $Z_2$ topological invariant between each pair of bands near the Fermi level (possible due to presence of time-reversal and inversion symmetries), one can categorize the family of kagomé metals as $Z_2$ topological metals thereby endowing it with nontrivial band topology. This is found to be consistent with angle-resolved photoemission spectroscopy (ARPES) measurements (Fig. 1d) and with quantum oscillations measurements [5, 6], which reveal very small Fermi surfaces with low effective mass, hinting the presence of a linear-dispersive Dirac band.

In kagomé lattices, unconventional superconductivity can emerge by nesting-driven interactions whereupon scattering occurs between saddle points of the band at the M (TRIM) points in the Brillouin zone. Indeed, in Josephson junctions formed with K$_1-x$V$_3$Sb$_5$ [7], measurements of the magnetoresistance and of the current versus phase provide possible evidence of spin-triplet superconductivity and localized conducting channels from the topological edge states. A stronger form of evidence for unconventional superconductivity in these compounds originates from intriguing high-pressure studies up to 100 GPa [3, 8–14]. As shown in Fig. 1e for CsV$_3$Sb$_5$, high-pressure measurements of the thermal conductivity, magnetic susceptibility and electrical resistivity reveal two superconducting domes. The first dome is suggested to be related to the suppression of CDW-instability mentioned previously whereas the second dome may present another exotic pairing mechanism. The presence of an interval of pressure which exhibits no superconductivity and the re-emergence of superconductivity as a second phase (typically called SC-II) would suggest nodal superconductivity, and it is very reminiscent of the behavior of the high-temperature cuprate superconductors. There is also an intimate competition between the CDW-like order and the superconductivity as revealed by the fact that the CDW transition temperature ($T_{\text{CDW}}$) decreases with pressure before vanishing at $\sim 2$ GPa in a first-order like manner while the second superconducting dome persists up to $\sim 100$ GPa. The re-emergence of the second dome is not well-understood as crystal structural stability persists at high pressures (albeit with a prevention of Sb displacements [15]), with some suggesting that it may be attributed to a pressure-induced Lifshitz transition resulting from strengthened electron-phonon coupling due to a change in the electronic structure. There is no consensus on the unconventional superconductivity as one study [16] would suggest that measurements of the magnetic penetration depth using a tunneling diode oscillator could be described by a two-gap s-wave (nodeless) superconducting model. Furthermore, the superconductivity in this family demonstrates anisotropic properties (of the upper and lower critical field $H_{c2}, H_{c1}$ along a versus along c) which may be driven by strong electron-electron correlations or a nematic electronic state [17, 18].

While ARPES measurements have established the $Z_2$ topology, high-resolution ARPES has also served to visualize the temperature-driven band renormalization [19] and the momentum dependence of the CDW gap (largest near M, gapless or small gap near the Dirac cones) [20–22]; whereupon they indicate how the CDW is driven by the scattering of electrons between neighboring M saddle points in the Brillouin zone. The band renormalization supports the evidence of a three-dimensional charge order. Ultimately, this results from the tuning of the van Hove singularities (vHs) at the M point such that they are perfectly nested as observed in CsV$_3$Sb$_5$ [23] and RbV$_3$Sb$_5$ [24] with two different types of vHs based on the distinct sublattice flavors. The Fermi surface is found to be very close to the vHs — mapped to be small pockets associated with the vanadium orbitals and the Dirac-like bandstructure that is brought about by the CDW [25]. ARPES has also been shown to reveal topological surface states as well as flat bands in CsV$_3$Sb$_5$ [26] with implications on the electron correlation phenomena. The nontrivial topological band structure may also have some ramifications for the stabilization of Majorana zero modes within the vortex core of proximitized superconducting surface states, as the case for the su-
perconducting Dirac surface states in Bi$_2$Te$_3$/NbSe$_2$ heterostructures. There is some preliminary evidence of a robust zero-bias conductance peak measured using STM inside the superconducting vortex core on the Cs surface which would resemble a Majorana bound state [27].

Measurements have been performed on exfoliated thin flakes of CsV$_3$Sb$_5$ [28–30] to investigate the superconductivity and CDW with sample thickness. They reveal that the superconducting transition temperature and the upper critical field of thin flakes are enhanced compared to bulk samples, which is accompanied by the suppression of the CDW ordering. The change with sample thickness is non-monotonic, which may be explained by a 3D to 2D crossover at a critical thickness of around 60 nm. This further supports the idea of a competition between CDW and superconductivity in the system.

Other measurements have been performed with hard x-ray scattering demonstrating that the CDW has a three-dimensional character ($2\times2\times2$ superstructure) and suggests the exclusion of strong electron-phonon coupling for the driving of the CDW, due to the failure of inducing acoustic phonon modes [31]. Optical conductivity and reflectivity measurements [32,33] have supplemented ARPES measurements by revealing more on the CDW and reflectivity [32,33] measurement shaves supplemented indicating acoustic phonon modes [31]. Optical conductivity for the driving of the CDW, due to the failure of inducing strong electron-phonon coupling suggests the exclusion of strong electron-phonon coupling which would resemble a Majorana bound state [27].

III. LARGE ANOMALOUS HALL EFFECT

The anomalous Hall effect (AHE), where charge carriers acquire a velocity transverse to an applied electric field, has been previously extensively studied in ferromagnetic ordering systems or in systems with magnetic field in order to break time-reversal symmetry. The signal from AHE is easily distinguishable from ordinary Hall effect as it is not commensurate with the applied magnetic field. Intrinsic AHE refers to the acquisition of a transverse momentum due to the electronic structure of a material endowing a large Berry curvature, and has been found in numerous topological materials such as Co$_9$Sb$_2$S$_2$. On the other hand, extrinsic AHE refers to the scattering off of structural defects or magnetic impurities in the system (also called skew scattering) which result in a transverse momentum.

As shown in Fig. 2, the extracted values of the AHE conductivity ($\sigma_{xy}^{\text{AHE}}$) for AV$_3$Sb$_5$ compounds reach extremely high values of $> 10^4 \, \Omega^{-1} \text{cm}^{-1}$ and large values of anomalous Hall ratio of $\sim 1.8\%$, both of which are one order of magnitude larger than Fe. The authors of Ref. [40] attribute this giant AHE to the enhanced skew scattering that scales quadratically, rather than linearly, with the longitudinal conductivity ($\sigma_{xx}$) as a result of highly conductive Dirac quasiparticles within the frustrated magnetic sublattice or due to scattering off of tilted spin clusters, local groups of coupled spins which can result from the magnetic atoms in kagomé nets. Through this new mechanism, this family of materials would open new frontiers for AHE in terms of conceivably reaching an anomalous Hall angle of $90^\circ$ and for the closely-related spin Hall effect (SHE) in spintronic-based applications. On the other hand, muon spin relaxation and rotation measurements [42] on KV$_3$Sb$_5$ seem to dispel this possible theoretical explanation for the AHE in this family of kagomé metals as there is no evidence for the existence of V local moments that would underlie the existence of these tilted spin clusters. It is therefore likely that the AHE has a complex origin possibly from both alternative skew scattering (lattice geometry intertwined with CDW, for example) and large Berry curvature [41].

IV. MULTITUDE OF ORDERING STATES

STM serves as a versatile technique to elucidate the phases and many-body phenomena in kagomé lattice systems, especially collective ordering states like CDWs, due to its high spatial resolution, detection of electronic states and tunability with magnetic field. The first high-resolution STM measurements of KV$_3$Sb$_5$ (Fig. 3a for topographic images of K and Sb surfaces) reveal a robust $2 \times 2$ superlattice structure and unconventional charge ordering through intensity reversals (Fig. 3b) of the charge modulation pattern at the opening of the energy gap near the Fermi level [43]. This was followed with measurements of RbV$_3$Sb$_5$ [44] with similar results. The authors explain the unconventional CDW order as a chiral CDW in a frustrated lattice, whereupon the chirality bestows an intensity anisotropy along different directions in the

Figure 2. Large AHE in AV$_3$Sb$_5$. (left) Extracted values of $\sigma_{xy}^{\text{AHE}}$ for (left) KV$_3$Sb$_5$ (with $\sigma_{xy}^{\text{AHE}}$ as an inset) and (right) CsV$_3$Sb$_5$ with comparison to KV$_3$Sb$_5$. Figures from [40, 41].
charge modulation vector peaks. Chiral CDWs would have implications for unconventional (nodal) superconductivity, correlation-driven quantum AHE and chiral Majorana zero modes.

![Figure 3. STM measurements of charge order in AV$_3$Sb$_5$. a) Atomically resolved topographic images of K and Sb surfaces on KV$_3$Sb$_5$ and b) atomically resolved $dI/dV$ imaging for the Sb surface at $\pm 30$ meV. c) Fourier transform of $dI/dV$ maps on Sb surface of CsV$_3$Sb$_5$ showing scattering vector $q_1$, atomic Bragg peaks (green circles) and charge order $q_{1Q-CO}$ (brown circles). d) 4.5 K STM topograph taken over an Sb-terminated surface with e) corresponding Fourier transform, indicating Bragg peaks (green circles), $q_{1Q-CO}$ peaks (brown circles) and $q_{2Q-CO}$ peaks (blue circles). a, b adapted from [43] and c, d, e adapted from [45].](image)

Subsequent STM measurements have established a cascade of correlated electron states [45]. In particular, as shown in Fig. 3c, aside from atomic Bragg peaks, the $2 \times 2$ superstructure that results from a Fourier transform of the $dI/dV$ maps give rise to a static charge order with a $2a$$_0$ period along all three lattice directions (called 3Q-CO). At low temperature (Figs. 3d-e), another periodic modulation with a $4a$$_0$ wavelength (called 1Q-CO) propagates unidirectionally, breaks rotation symmetry and possesses strongly anisotropic scattering – reminiscent of a charge stripe modulation. This is attributed to the orbital-selective normalization of the V kagomé bands. Further measurements [46] reveal that there is an intensity anisotropy of one $2a$$_0$ CDW direction (of the three) in comparison to the other two which would point to an intrinsic rotation symmetry breaking where the symmetry is broken from $C_6$ to $C_2$. STM measurements also suggest a three-dimensional $2 \times 2 \times 2$ charge density wave ordering [43] (complemented from NMR and hard x-ray scattering) and present preliminary hints of a mysterious $1 \times 4$ superlattice structure [47] and a $4a$$_0$/3 bidirectional pair density wave [48] with similarities to the phenomenology of cuprate high-temperature superconductors. Initial measurements of the superconducting gap may suggest multiband superconductivity with a sign-preserving order parameter [49].

V. THEORETICAL WORKS

Several theoretical proposals with associated calculations have been put forward to explain the different phenomena in this family of kagomé metals. Notably, one study involving first-principles calculations reveal that the $2 \times 2$ CDW ground state of the kagomé lattice is an inverse Star of David structure with the transition being driven by a Peierls instability [50]. This supports the conclusion of Ref. [31], that the electron-phonon coupling in the system is too weak to rationalize conventional superconductivity. On the other hand, a computational study under pressure would indicate conventional superconductivity, with a partial suppression at ambient and low pressures due to the magnetism from vanadium atoms [51]. DFT calculations have also showed the electronic correlations and magnetic properties in the normal state for this family of materials [52]. Another argument for the $2 \times 2$ charge orders and the emergence of an AHE comes from describing the ground state as a chiral flux phase [53, 54] (with possible experimental evidence in Ref. [36]), where a tight-binding model is used to rationalize an imaginary order parameter for the charge bond order. A similar tight-binding model containing vHs with a random phase approximation analysis for the superconducting instabilities may suggest further information on the nature of the superconductivity in these materials [55]. Additionally, some have suggested the existence of smectic bond-density wave [56] or density wave [57] mechanisms.

Landau theory has been used to explain the formation of complex orders due to the presence of vHs on the hexagonal lattice and electronic instabilities leading to different types of density waves. On the one hand, Refs. [58–60] demonstrate a rich Haldane-model phase diagram of the multi-component hexagonal (3Q) charge density waves, where they find trivial and Chern insulator phases with real or imaginary orders (such as the chiral flux phase mentioned previously). In particular, the coupled mean field theory of spin and charge orders describes the topological charge density wave found with STM as being identified with the complex orders of the Chern insulator phase and the rotation symmetry breaking results from secondary orders from the complex order ground states. Subsequent work along these lines showcases higher-order topological insulator states and superconducting pairing resulting from Pomeranchuk fluctuations which explain the double-dome superconductivity and large separation in energy scales between superconductivity and CDW. Ref. [61] builds upon this approach, using parquet renormalization theory, to reveal the enhanced electronic instabilities by vHs near the M saddle points of the Brillouin zone inducing scattering amongst these points, as observed through ARPES mea-
measurements. Similar ideas have emerged for graphene and more recently, magic-angle bilayer graphene. Their analysis provides constraints on the interpretation of several experiments with a focus on the density wave order. Ref. [62] classify the different types of multi-Q CDW orders to study the leading instabilities of these kagomé systems of which the phonon instabilities have been calculated using first-principles [63]. Ref. [64] develops a theory for the CDW formation using Ginzburg-Landau formalism, finding that it is possible that a nematic chiral charge order is the preferred ground state.

**OUTLOOK**

From these rapid development of experimental and theoretical results, the AV$_3$Sb$_5$ (A = K, Rh, Cs) class of kagomé metals exhibits an exciting opportunity to study the intertwining of a multitude of exotic phenomena all-in-one system: nontrivial topological band physics, unconventional superconductivity, display of different electronic orders and a strong anomalous Hall effect. As the material is an easily exfoliable kagomé metal, the potential for future work beyond what was presented in this paper is high since it is a two-dimensional correlated material, with possible experiments to probe into more depth the nature of unconventional superconductivity within the system, the mechanism behind the large AHE and possible twistronic devices similar the twisted bilayer graphene and transition metal dichalcogenides. Furthermore, in terms of potential practical applications, the large AHE could be useful for spintronics in terms of memory devices whereas the interplay of unconventional superconductivity, if present in the system, and nontrivial topology may lead itself to the realization of Majorana zero modes which would be beneficial to serve as qubits for topological quantum computation.

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