New kagome prototype materials: discovery of $\text{KV}_3\text{Sb}_5$, $\text{RbV}_3\text{Sb}_5$, and $\text{CsV}_3\text{Sb}_5$

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A new Kagome prototype structure: discovery of KV$_3$Sb$_5$, RbV$_3$Sb$_5$, and CsV$_3$Sb$_5$

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In this work, we present our discovery and characterization of a new Kagome prototype structure, KV$_3$Sb$_5$. We also present the discovery of the isostructural compounds RbV$_3$Sb$_5$ and CsV$_3$Sb$_5$. All materials exhibit a structurally perfect 2-dimensional Kagome net of vanadium. Density-functional theory (DFT) calculations indicate that the materials are metallic, with the Fermi level in close proximity to several Dirac points. Powder and single crystal syntheses are presented, with post-synthetic treatments shown to deintercalate potassium from single crystals. Considering the proximity to Dirac points, deintercalation provides a convenient means to tune the Fermi level. Magnetization measurements indicate that KV$_3$Sb$_5$ exhibits behavior consistent with Curie-Weiss behavior at high temperatures, although the effective moment is low (0.22μ$_B$ per vanadium ion). An anomaly is observed in both magnetization and heat capacity measurements at 80 K, below which the moment is largely quenched. Elastic neutron scattering measurements find no obvious evidence of long-range or short-range magnetic ordering below 80 K. The possibility of an orbital-ordering event is considered. Single crystal resistivity measurements show the effect of deintercalation on the electron transport and allow estimation of the Kadawaki-Woods ratio in KV$_3$Sb$_5$. We find that $A/\gamma^2 \sim 61 \text{ μΩ cm mol}_e^{-1/2} \text{ K}^{-2}$, suggesting that correlated electron transport may be possible. KV$_3$Sb$_5$ and its cogeners RbV$_3$Sb$_5$ and CsV$_3$Sb$_5$ represent a new family of Kagome metals, and our results demonstrate that they deserve further study as potential model systems.

1 Introduction

With its unique and elegant structure, few materials are as intensely studied in the field of condensed matter physics as the Kagome lattice. A sister to more common hexagonal tiling of graphene, the Kagome lattice (trihexagonal tiling) stands out as a model system for the genesis of unconventional electronic and magnetic properties. The additional chemical complexity enables tuning of the electronic and magnetic structures, enabling the Kagome lattices to host a wide range of exotic physics. From topologically nontrivial band structures with Dirac points to quantum disordered magnetic ground states, the Kagome lattices are keenly poised at the intersection of material science and physics.

The unconventional electronic states inherent to Kagome lattices are broadly categorized into the insulating and metallic (or semi-metallic) categories. Specifically, the more widely explored insulating Kagome lattices are most commonly studied in the frame of frustrated magnetism. One of the most noteworthy being ZnCu$_3$(OH)Cl$_2$, which has been proposed as a quantum spin liquid candidate.\(^{(1; 2; 3; 4; 5)}\) The relatively less explored metallic and semi-metallic variants are of increasing interest due to their potential to manifest non-trivial topologies and unique electronic structures endemic to a Kagome lattice of metal ions. For example, recent studies of Fe$_2$S$_3$ have shown that ferromagnetism leads to the splitting of the spin-degenerate Dirac bands, creating a topologically nontrivial phase and a 2D ‘Chern gap.’\(^{(6)}\) Additionally, within the metal Co$_3$S$_2$, a large anomalous Hall response and a favorable Berry curvature make it an attractive Weyl semi-metal candidate.\(^{(7)}\) Particularly within the metallic Kagome lattices, the delocalization of electrons provides an additional degree of freedom due to the propensity of metal-metal bonding. The creation of composite states through metallic bonding has the possibility of causing a dramatic renormalization of the electronic and magnetic ground states. Prominent examples of similar behavior have been observed in the electronic instabilities of the cluster magnets GaV$_4$S$_8$\(^{(8, 9)}\) and LiZn$_2$Mo$_3$O$_8$.\(^{(10; 11; 12)}\)

This work presents our discovery of a new family of Kagome metals: KV$_3$Sb$_5$, RbV$_3$Sb$_5$, and CsV$_3$Sb$_5$. In addition to powder synthesis, we present our method for growing single crystals of all three materials. All three materials possess a structurally perfect, 2D Kagome lattice of vanadium. Density functional theory (DFT) calculations further confirm the dispersionless bands and Dirac points expected of a Kagome system. Further, we find that many Dirac points are in close proximity to the Fermi level making these systems attractive candidates for further study.

This work also presents experimental transport, magnetic, and structural data on KV$_3$Sb$_5$. Post-synthetic treatments of single crystals are successful in leeching potassium from KV$_3$Sb$_5$, providing a convenient means to manipulate the Fermi level (E_F). Magnetization measurements on powders and single crystals of KV$_3$Sb$_5$ exhibit behavior consistent with Curie-Weiss behavior at high temperatures, although the effective moment is quite low (0.22μ$_B$ per vanadium). The low moment may be indicative of
a small concentration of impurity spins. An anomaly is noted in both heat capacity and magnetization at 80 K, below which the moment appears largely quenched. Although elastic neutron scattering experiments fail to detect long-range or short-range magnetic ordering within our resolution (∼0.5µm/atom), forms of orbital-ordering are still possible. Resistivity measurements on KV$_3$Sb$_5$ are indicative of a semi-metal or “bad-metal,” consistent with the calculated density of states. Further, we find that the Kadowaki-Woods ratio is quite large in KV$_3$ with the calculated density of states. Further, we find that the magnetic ordering within our resolution (scattering experiments fail to detect long-range or short-range ordering), the moment appears largely quenched. Although elastic neutron scattering experiments fail to detect long-range or short-range magnetic ordering, a small concentration of impurity spins. An anomaly is noted in both heat capacity and magnetization at 80 K, below which the moment appears largely quenched. Although elastic neutron scattering experiments fail to detect long-range or short-range magnetic ordering within our resolution (∼0.5µm/atom), forms of orbital-ordering are still possible. Resistivity measurements on KV$_3$Sb$_5$ are indicative of a semi-metal or “bad-metal,” consistent with the calculated density of states. Further, we find that the Kadowaki-Woods ratio is quite large in KV$_3$.

2 Methods

2.1 Experimental

Powders and single crystals of KV$_3$Sb$_5$, RbV$_3$Sb$_5$, and CsV$_3$Sb$_5$ were synthesized from K (ingot, Alfa 99.8%), Rb (ingot, Alfa 99.75%), Cs (liquid, Alfa 99.98%), V (powder, Sigma 99.9%), and Sb (shot, Alfa 99.999%). Powders were synthesized by ball-milling elemental reagents for 1 h in a Spex 8000D high-energy ball mill. To avoid iron contamination, tungsten carbide vials and balls were used. Powders were subsequently ground, sieved through a 50 micron mesh, and annealed for 48 h at 600 °C. Single crystals are synthesized via the flux method. For KV$_3$Sb$_5$, low melting point eutectics between K$_2$Sb$_3$K$_5$ or K$_2$Sb$_5$ make for convenient fluxes.(13) Flux mixtures containing 5 mol% of KV$_3$Sb$_5$ were heated to 1000°C, soaked for 24 h, and subsequently cooled at 2°C/hr. Analogous reactions were performed for RbV$_3$Sb$_5$ and CsV$_3$Sb$_5$.

The prototype structure (KV$_3$Sb$_5$) was first solved using powder diffraction data collected at the Advanced Photon Source (11-8M) with 0.412619 Å radiation. Powders were sealed in Kapton capillaries after being diluted at a molar ratio of 1:4 with amorphous SiO$_2$ to reduce X-ray absorption. Structure solution was performed using charge flipping methods and the Topas V6 software package.(14; 15; 16; 17) Subsequent single crystal diffraction was performed on a Bruker D8 Quest ECO diffractometer equipped with a microfocus Mo Kα radiation source and a Photon 50 CMOS half-plate detector. Structure solutions were completed using SHELXT and the intrinsic phasing method.(18; 19) Structures were verified through the phicIFC program.(20) Powder neutron diffraction data was collected on the MACS cold triple-axis spectrometer at the National Institute of Standards and Technology (NIST) Center for Neutron Research. Elastic measurements utilized Be filters to produce fixed initial and final energies of 5.0 meV.

Magnetization measurements were performed using a Quantum Design Magnetic Properties Measurement System (MPMS3). Densified powders and single crystals of KV$_3$Sb$_5$ were adhered to a Quantum Design quartz sample holder using GE varnish. Heat capacity and resistivity measurements (2-260 K) were performed using a Quantum Design Dynacool Physical Properties Measurement System (PPMS). Apiezon N-grease was used for thermal coupling of sample to the heat capacity stage. Resistivity measurements were performed using a probe current of 0.999 mA. Additional heat capacity measurements from 0.055 K-3.5 K were performed with a Quantum Design Dilution Refrigerator.

Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were performed using a JEOL JSM-7000F FE-SEM. High-resolution transmission electron microscopy (HRTEM) micrographs were acquired on an FEI Talos F200X TEM operating at an accelerating voltage of 200 keV. For TEM, crystals of KV$_3$Sb$_5$ were crushed and sonicated in isopropyl alcohol to create a suspension. The suspension was dropped onto carbon TEM grids. Selective, structure factor based Fourier filtering of reflections was used to decouple the V1-K1 and Sb1-Sb2 sublattices from each other. Further deconvolution of the V1 and K1 sublattices was performed on the basis of ionic radii.

2.2 Computational

The electronic structure of KV$_3$Sb$_5$, RbV$_3$Sb$_5$, and CsV$_3$Sb$_5$ were calculated using Kohn-Sham density functional theory (DFT) as implemented in the VASP software package.(21; 22; 23) Core and valence electrons were treated within the projected augmented wave (PAW) formalism.(24) The generalized-gradient approximation (GGA) is used for the exchange-correlation term within the Perdew Burke Ernzerhof (PBE) approach.(25) The Kohn-Sham orbitals were expanded using a plane-wave basis with a cutoff energy of 500 eV. Structural optimization of the lattice parameters and atomic positions was performed with a stringent force tolerance of 1 meV/Å on each atom. The Brillouin zone was sampled using a Γ-centered 8×8×4 Monkhost-Pack k-point grid.(26) Crystal orbital Hamilton population (COHP) analysis was performed using The LOBSTER package in conjunction with VASP.(27; 22; 23) Note that the COHP analysis was performed using a finer k-point mesh of 12×12×6. Total energies of the magnetic systems were calculated with the DFT+U approach, as proposed by Dudarev et al.(28) The additional Hubbard-like term is used to treat the on-site Coulomb interactions on the localized d-states of vanadium atoms. In this case, 2x2x1 supercells are used to model the different spin configurations.

3 Results and Discussion

We begin with a structural analysis of KV$_3$Sb$_5$, RbV$_3$Sb$_5$, and CsV$_3$Sb$_5$ through powder and single crystal X-ray diffraction, providing a conceptual interpretation of the new structural prototype. We also provide evidence for the deintercalation of potassium in KV$_3$Sb$_5$. Afterwards, we provide an extensive overview of the electronic structure in all three materials, examining the electron band diagrams, density of states, and crystal orbital Hamilton population. We have focused our experimental characterization efforts on KV$_3$Sb$_5$, examining magnetization, neutron scattering, and heat capacity experiments on polycrystalline powders. The effect of deintercalation on single crystal resistivity measurements is also investigated.

3.1 Discovery and Crystal Structure

The discovery of KV$_3$Sb$_5$, RbV$_3$Sb$_5$, and CsV$_3$Sb$_5$ emerged from our search for new transition metal Zintl antimonides for thermoelectric applications.(29; 30) The prototype KV$_3$Sb$_5$ was first...
isolated in powders, and the structure was solved using charge flipping methods on powder diffraction data. The resulting Rietveld refinement and associated crystallographic information are shown in ESI Figure S1. (31) Once we had identified KV₃Sb₅ as a new prototype structure, we explored all combinations of (K, Rb, Cs)(V, Nb, Ta)(Sb, Bi) under a variety of synthesis conditions. The vanadium sublattice is a structurally perfect Kagome lattice. There are two distinct Sb sublattices. The sublattice formed by the Sb₁ atom is a simple hexagonal net, centered on each Kagome hexagon. The Sb₂ sublattice creates a graphene-like Sb sheet below and above each Kagome layer. Bond distances for the V–V, V–Sb, and Sb–Sb nearest neighbor interactions are also shown. Fourier-filtered, false-colored atomic resolution TEM (b) is able to partially decouple the Sb sublattices (orange) from the K-V (red and purple) sublattices. While we cannot mathematically separate the K and V sublattices during Fourier analysis, the large ionic radius of K is evident from visual inspection alone.

A summary of crystallographic parameters and refinement statistics obtained from single crystal X-ray diffraction (SCXRD) for all three materials – details are outlined in the methods section. Crystals recovered from flux growths are thin (10-100 microns), silver-colored platelets. The crystals range from 1 mm × 1 mm to 5 mm × 5 mm in area. The platelets will often exhibit natural hexagonal faceting. All materials are easily deformed, and the platelets show a natural tendency to exfoliate (ESI Figure S2). (31)

Despite the intercalated structure, powders, single crystals, and densified pellets of KV₃Sb₅, RbV₃Sb₅, and CsV₃Sb₅ are remarkably stable. Samples are stable in air for >1 year without decomposing or tarnishing. KV₃Sb₅ is stable under cycling to cryogenic temperatures (<2 K). Densified pellets also tolerate temperatures up to 600 °C under vacuum, with no observable sublimation. Single crystal samples are not affected by common solvents (e.g. isopropyl, ethanol, acetone) and water, with no apparent reaction while submerged. Within the resolution of XRD and EDS, all samples prepared using solid state methods exhibit fully-occupied K₁ sites, regardless of whether the powder synthesis is performed under K-rich or K-poor conditions. Reminiscent of the process of “phase boundary mapping” from thermoelectrics, (32; 33; 34; 35) this suggests that the single-phase width of KV₃Sb₅ accessible from solid-state synthesis reactions is small. However, when crystals are etched in concentrated HNO₃, SCXRD suggests that the K₁ occupancy is depleted to approximately 85%. When the

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Fig. 1 The prototype structure KV₃Sb₅ (a) crystallizes in the P6/mmm space group and exhibits a layered structure of V-Sb sheets intercalated by K. The vanadium sublattice is a structurally perfect Kagome lattice. There are two distinct Sb sublattices. The sublattice formed by the Sb₁ atom is a simple hexagonal net, centered on each Kagome hexagon. The Sb₂ sublattice creates a graphene-like Sb sheet below and above each Kagome layer. Bond distances for the V–V, V–Sb, and Sb–Sb nearest neighbor interactions are also shown. Fourier-filtered, false-colored atomic resolution TEM (b) is able to partially decouple the Sb sublattices (orange) from the K-V (red and purple) sublattices. While we cannot mathematically separate the K and V sublattices during Fourier analysis, the large ionic radius of K is evident from visual inspection alone.
crystals are only treated with purified water, SCXRD measurements show that the K1 occupancy remains at 92%. While the changes in potassium occupancy are subtle, we note that the refined values track changes in the cell volume quite well: powder (100% occupied, 233.15Å³), water etched crystals (92% occupied, 232.86Å³), acid etched crystals (85% occupied, 231.93Å³).

3.2 Electronic Structure

As KV$_3$Sb$_5$, RbV$_3$Sb$_5$, and CsV$_3$Sb$_5$ are entirely new materials, our investigation first focuses on an in-depth study of the electronic structure and bonding through first-principles density functional theory (DFT) calculations. The band diagrams of KV$_3$Sb$_5$, RbV$_3$Sb$_5$, and CsV$_3$Sb$_5$ (Figure 2, top) are presented along the electronic density of states (DOS) and associated crystal orbital Hamilton population (COHP) analysis (Figure 2, bottom). All calculations were performed using spin-orbit coupling. Except a few avoided crossings in the relativistic result, we do not observe significant changes from the inclusion of spin-orbit coupling. Although we did not study the arsenides experimentally, first-principles calculations of the band diagrams are available in the ESI, Figure S4.(31) In general, the band structures are very similar between KV$_3$Sb$_5$, RbV$_3$Sb$_5$, and CsV$_3$Sb$_5$. One difference of note, however, is the gap at L, which narrows significantly as we transition from KV$_3$Sb$_5$ to CsV$_3$Sb$_5$.

All of the structures presented here are metallic, although there are a relatively limited number of band crossings near the Fermi level ($E_F$). Besides a set of dispersive bands near Γ and A, the majority of band crossings occur due to Dirac-like features at H, K, L and even H − A. An interesting feature of the band diagram emerges if one examines the features at K and H. These are not isolated Dirac cones; if we consider the dispersion along K-H, we see that the features are connected, forming a conical valley. We note that $E_F$ in these materials is remarkably close to several of the Dirac crossings (e.g. H-point in KV$_3$Sb$_5$ is approximately 0.25 eV below $E_F$).

Coupled with the facile deintercalation of the alkali metal, the large number of Dirac points provides a key opportunity for these materials. For example, the deintercalation of potassium in KV$_3$Sb$_5$ is a particularly attractive way to tune $E_F$, as we would not need to introduce any extrinsic dopants. A similar phenomenon has been observed in KNi$_2$Se$_2$, where potassium was removed through oxidative deintercalation.(36) The removal of one electron per unit cell, corresponding to complete deintercalation of K, is shown on the electronic structures in Figure 2 (shaded). Bader charge analysis indicates that the K atoms each transfer one electron to the V-Sb layer, leaving behind empty K 4s states that appear in the unfilled levels above the Fermi energy. We further observe limited to no charge sharing between the K
and the V-Sb layer, suggesting that the bonding between the K and V-Sb layers may be primarily driven by electrostatics. This is supported by electronic structure calculations on the hypothetical compound V₃Sb₅ (ESI, Figure S5), where the electronic structure near $E_F$ is largely unperturbed by the removal of potassium. (31) To understand why these systems tolerate alkali metal deintercalation, we turn to the bonding and chemical information provided by COHP.

COHP (Figure 2, bottom) partitions the band diagram into orbital-pair interactions, allowing us to resolve bonding and antibonding contributions from individual atomic orbitals. Integrating the contribution from each atom allows us to gain a sense of bond strength, allowing for a chemically intuitive interpretation of the electronic structure. All COHP results are shown alongside the electronic DOS in Figure 2. All symmetry-unique nearest-neighbor interactions have been included. The middle panel (red, orange, green) shows the COHP for bonds involving K atoms while the rightmost panel (blue, purple) shows the COHP for bonds between V and Sb atoms. Consistent with the large bond distance between K and the V-Sb layers, the magnitude of the COHP is much smaller for pairwise interactions with K (note the order of magnitude difference in the x-axis scale). We can see that the majority of the bonding interactions occur between V and Sb, as expected. In particular, the filled V-Sb1 bonds are entirely bonding in nature, suggesting that the Sb1 atoms woven into the Kagome lattice play a large role in the structure’s stability. Both Bader and COHP analysis suggests that the K atoms are very loosely bound to the structure – supporting deintercalation as a means to tune $E_F$.

### 3.3 Magnetization and Heat Capacity of KV₃Sb₅

As a new prototype Kagome lattice, a natural question is whether there is any experimental evidence of magnetism in these systems. Both powders and single crystal samples of KV₃Sb₅ were measured under a series of temperatures and fields. In the main body, we present magnetization data and heat capacity data on sintered polycrystalline samples of phase-pure KV₃Sb₅. Despite single crystals having appreciable dimensions (>1 mm × 1 mm), the samples are very thin (10-100 micron) and are not accurately massed. As such, multiple crystals (∼20-50) must be coaligned. While alignment along the c-axis is relatively easy, not all crystals exhibit facetting, diminishing our ability to extract orientation specific information. Further, the small sample masses and low moment make polycrystalline samples more quantitatively accurate for this study. However, the qualitative behavior of the single crystals is still valuable as a comparison, and is included in the ESI Figure S6. (31)

Figure 3a shows temperature dependent magnetization measurements performed on polycrystalline KV₃Sb₅ under a 0.1 T field. Both the zero field cooled (ZFC, black) and field cooled (FC, red) data are shown. A significant anomaly is noted at 80 K in both the ZFC and FC data. The transition is unaffected, both in temperature and magnitude, by application of magnetic fields up to 7 T (see Figure 3, inset). Another small anomaly appears below the transition (40-65 K), however, it is only apparent in the ZFC data. This feature is also retained under the application of various fields. We note that the primary anomaly at 80 K is also observed in single crystal measurements (ESI Figure S6). (31)

For the data above the primary anomaly at 80 K, KV₃Sb₅ exhibits behavior consistent with the Curie-Weiss model. As such, Figure 3b investigates a Curie-Weiss model on the inverse susceptibility data (b) is well characterized by a Curie-Weiss model (red). The $\chi$ correction was empirically determined, although estimates of the Pauli paramagnetic response in KV₃Sb₅ are consistent with the result. Curie-Weiss analysis reveals a small effective moment $\mu_{\text{eff}} \sim 0.22 \mu_B$ per vanadium.
As a check on the magnitude of \( \chi_0 \), we can estimate the expected Pauli paramagnetic response of KV\(_5\)Sb\(_5\). Using the typical expression \( \chi_p = \mu_0 n_0 g_0^2 (E_F) \), where \( g(E_F) \) is the density of states at the Fermi level determined by DFT (see Figure 2), we obtain \( \chi_p \sim 0.84 \times 10^{-4} \text{emu Oe}^{-1} \text{mol}^{-1} \), in excellent agreement with the empirically determined value (1.58 \times 10^{-4} \text{emu Oe}^{-1} \text{mol}^{-1}). Some divergence from the Curie-Weiss fit is noted near room temperature. At these temperatures, however, the background magnetization expected from the \( \chi_0 \) term is comparable to the measured values. As such, some divergence is to be expected.

Although simple charge counting arguments suggest that the expected moment in KV\(_5\)Sb\(_5\) should be small, our magnetization results found a mere 0.22\( \mu_B \) per vanadium. Consider the localized limit; assuming potassium exists as K\(^+\) and antimony as Sb\(^{3+}\), we require 14 electrons from the 3 vanadium atoms. This could be achieved by having 2 vanadium in the V\(^{5+}\) state (\( d^0 \), diamagnetic) and one in the V\(^{4+}\) state (\( d^1 \), magnetically active). On average, this schema would leave one spin per KV\(_5\)Sb\(_5\) formula unit which is still significantly larger (even at the \( J = 1/2 \) limit) than our observed values. As a check, we estimated the impurity spin concentration that could yield similar results. We estimate that our effective magnetization observed at high-temperatures could be explained with an effective concentration of 1.5% \((S = 1/2)\) impurity spins on the vanadium sites, which is a reasonable result considering the propensity for alkali vacancy formation.

Noting that the low-temperature data in Figure 3 also shows data consistent with a Curie tail (impurity spins), we also examined magnetization versus field measurements (ESI Figure S7) at 2 K, 60 K, 100 K, 200 K, and 325 K from 0-7 T.(31) All temperatures except for the 2 K measurement exhibit linear magnetization curves with no hysteresis or remnant magnetization, confirming that there are no bulk ferromagnetic contributions to the magnetism in KV\(_5\)Sb\(_5\). The magnetization versus field data at 2 K shows signs of a saturation magnetization, which was modeled with a Brilluoin function (ESI Figure S8) to estimate the concentration of unpaired impurity spins.(31) Assuming that these impurities would behave as \( J = 1/2 \) spins with a Lande g-factor of 2, we find that the magnetization response could be explained by an impurity concentration of 0.12% on the vanadium sites. Considering our approximations, the Curie-Weiss and low-temperature Brilluoin fits are both consistent with a small fraction of impurity spins.

Considering the Kagome structure and the magnetization anomaly, the potential for antiferromagnetic order was explored via elastic neutron diffraction. Measurements were taken above (110 K) and below (1.8 K) the 80 K anomaly (ESI Figure S9).(31) There are no signs of diffuse scattering (short-range correlations) or new magnetic peaks brought about by magnetic ordering within the experimental resolution (~0.5 \( \mu_B \)/atom). Even in the localized limit (charge counting), KV\(_5\)Sb\(_5\) would be expected to exhibit a low moment – challenging even for high-flux neutron experiments. Our experiments also do not rule out more subtle forms of ordering such as orbital-ordering. For example, a trimerization event akin to the effect observed in NaVO\(_3\) (37) would not be detectable by our current experiment. The possibility of trimerization is particularly interesting, as this would transform the Kagome crystal lattice into a honeycomb spin lattice. Regardless, additional studies are underway to unravel the underlying magnetic structure of KV\(_5\)Sb\(_5\).

With the ambiguity between the localized moment model and the impurity spins, our first-principles calculations were reexamined to check for changes in the total energy with the addition of localized spin. As standard DFT methods (GGA-PBE) rarely treat d- and f-orbitals accurately, we employed the DFT+U method to treat electron-electron interactions within the vanadium d-orbitals.(28) Unfortunately, \( U \) is difficult to determine \textit{a priori}. Therefore, we performed calculations with \( U = 0, +1, +3, +5 \), which are typical values for vanadium.(38; 39; 40) We considered ferromagnetic, ferrimagnetic, and antiferromagnetic configurations in supercells of KV\(_5\)Sb\(_5\). As the structure is frustrated, five distinct (disordered) antiferromagnetic configurations were evaluated. The different configurations and associated energies are shown in the ESI, Figures S10-11 and Table S5.(31) The total energy in DFT appears to decrease linearly with the number of antiferromagnetic nearest neighbor configurations, as in a simple nearest-neighbor Heisenberg exchange interaction. Thus, in DFT, the spin lattice shows a robust tendency to anti-align locally, regardless of long range symmetry.

Heat capacity measurements (Figure 4) on a sintered fragment of KV\(_5\)Sb\(_5\) reveal trends consistent with magnetization data. A small anomaly is noted at 80 K. The anomaly is unaffected by field, and no appreciable shift is noted between zero field measurements (black) an applied field of 7 T (red). Despite the prominent transition in the magnetization results, the heat capacity anomaly is comparatively weaker. The transition is also somewhat unusual in shape, and in not consistent with a lambda-type transition or a Schottky anomaly. This is consistent with the lack of an obvious magnetic ordering event in the elastic neutron data. A sharp upturn in the heat capacity is noted at di-
lution fridge temperatures (~0.25 K), which is likely a nuclear contribution. Figure 5 shows a magnified version of the low-temperature heat capacity. Note that the bottom axis in Figure 5 is scaled as $T^2$. The data is well-modeled with the Sommerfeld model ($C_p/T = \gamma T + \beta T^3$). The Sommerfeld coefficient $\gamma$ evaluates to 22.1 mJ mol$_{-1}$K$^{-2}$, which is relatively large when compared to simple elemental metals.

### 3.4 Electron Transport and Fermi Level Tuning in KV$_3$Sb$_5$

The small mass of the KV$_3$Sb$_5$ single crystals made powders the most robust platform for our initial studies into the magnetic and thermodynamic properties. However, the single crystals are the ideal form factor for resistivity. Additionally, resistivity measurements should be quite sensitive to the deintercalation of potassium – allowing us to examine the effect of our post-synthetic treatments on single crystals.

To test the effect of K deintercalation on the transport properties of KV$_3$Sb$_5$, we performed resistivity measurements on single crystals grown through the flux method. Figure 6 shows measurements on crystals with two different levels of potassium deintercalation. The blue curve corresponds to crystals which were etched in hot HNO$_3$ and show a significant reduction in potassium content (K$_{0.85}$V$_3$Sb$_5$). The black curve corresponds to crystals which are treated with water only, and show near stoichiometric compositions (K$_{0.92}$V$_3$Sb$_5$). As we deintercalate potassium, we observe an increase in the electronic resistivity, particularly at low temperatures. This is consistent with a decrease in the number of charge carriers, however, we must also be cautious of possible damage caused by aggressive etching. Consistent with DFT, KV$_3$Sb$_5$ exhibits metallic transport, although the resistivity is still significantly higher than would be expected for an elemental metal (~0.5 mOhm-cm at room temperature) suggesting that these materials more closely resemble semi-metals or “bad-metals.”

At low-temperatures (where electron-electron scattering dominates electron-phonon scattering), the electronic resistivity can be modeled by $\rho = \rho_0 + AT^2$. For the higher occupancy crystals (black), we estimate the quadratic component of the resistivity to be approximately 0.030 $\mu$Ohm cm K$^{-2}$. The resulting fit is shown in Figure 6 (red curve). A zoomed in version of the quadratic fit can be found in the ESI, Figure S12.(31) The quadratic resistivity term can be subsequently combined with the linear (electronic) term from the low-temperature heat capacity data to estimate the Kadowaki-Woods ratio (KWR) in KV$_3$Sb$_5$. The Kadowaki-Woods ratio ($A/\gamma^2$) is commonly used as a metric to probe the potential for correlated electron transport.(41) We estimate the Kadowaki-Woods ratio (KWR) in crystals of K$_{0.92}$V$_3$Sb$_5$ to be approximately 0.030 $\mu$Ohm cm K$^{-2}$. At this time, our results do not take into account dimensionality or electron density corrections to the KWR.(42) However, the result is typical of materials that exhibit heavy fermion behavior (~10 $\mu$Ohm cm mol$^{-1}$K$^{-2}$) which suggests that KV$_3$Sb$_5$ may be a candidate material for correlated electron transport.

### 4 Conclusion

Despite the relatively narrow suite of Kagome lattices, almost all of them exhibit unique and interesting phenomena. This work introduced a new, structurally intuitive Kagome prototype (KV$_3$Sb$_5$) and three new materials (KV$_3$Sb$_5$, RbV$_3$Sb$_5$, CsV$_3$Sb$_5$). All three compounds exhibit structurally perfect Kagome networks of vanadium. Furthermore, KV$_3$Sb$_5$ is currently one of smallest and simplest Kagome lattices available within the literature. We have developed powder and single-crystal syntheses for all three ma-
terials, proving robust samples for investigation of the electronic, magnetic, and thermodynamic properties. Using density functional theory (DFT), we have performed a detailed analysis of the electronic structure and bonding within K\textsubscript{V}Se\textsubscript{5}, RbV\textsubscript{S}Se\textsubscript{4}, and Cs\textsubscript{S}V\textsubscript{S}Se\textsubscript{4}. As expected of the Kagome and graphite-like sublattices, the Fermi level is in close proximity to several Dirac points. Considering the facile deintercalation of the alkali metal, post-synthetic methods may provide a convenient means to tune $E_F$ to the Dirac points. Magnetization measurements indicate behavior consistent with a localized moment at high temperatures, although the signal could originate from a small fraction of $S = 1/2$ impurity spins. An anomaly is observed in both magnetization and heat capacity measurements at 80 K, below which the local moment is largely quenched. Neutron scattering was unable to resolve signatures of long-range or short-range magnetic ordering below the magnetization anomaly. Orbital ordering events (e.g. trimerization) are still possible, although more evidence is required to confirm. Resistivity and heat capacity measurements reveal a large Kadowaki-Woods ratio (KWR), suggesting possibility of correlated transport. The combination of a new Kagome prototype structure, three new materials, Fermi level tuning through deintercalation, and the potential for correlated transport sets a solid foundation for further experimental and computational studies within these new compounds.

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